GEOGRAPHICAL ANALYSIS

RESEARCH ARTICLE

Spatial-Temporal Variations in Snow Cover in Himachal Pradesh, India - 2005-2015

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Abstract

Himachal Pradesh is a highly mountainous state located in the northern part of India and receive snow fall during winter season. Studying Snow Cover Variation in this region is important because it has an impact on both climate and water management and thus the life of the people. The study has been carried out using MODIS eight day (MOD10A2) snow cover data, ASTER DEM data has been used to study the Snow cover area variation with elevation, and also to do slope and aspect analysis of Himachal Pradesh. The snow extent data of eight day periods are summed up to get approximate monthly data for easy handling and analysis. Then Snow Cover Area (SCA) is calculated for each month during ten years time period from 2005 to 2015. The general trend observed is the SCA is increasing from January to March and from March it starts decreasing till August and again from September to December it increases. Generally, Snow cover is maximum in the month of March and minimum in the month of August except few years like in 2008, 2009, 2014 and 2015 it is maximum in February month, whereas in 2011 it is observed to be maximum in the month of January. The Maximum SCA is found in 2013 March i.e. calculated as 40246.57 square kilometre in this whole eleven year time period from 2005 to 2015 and the minimum snow cover was also observed in the same year 2013 September which is estimated to be 6545.80 square kilometres.

Keywords: Snow Cover Area Variation In Himachal Pradesh; MODIS Eight Day (MOD10A2) Snow Cover Data; ASTER DEM; Maximum and Minimum Elevation Snow Cover Area Reached

Introduction

Snow cover, is an important component of land cover, is one of the natural materials on the Earth's surface with wide distribution, obvious seasonal variation, and high sensitivity to climate change (Tang et al. 2017). Satellite-based remote sensing has provided a useful tool for spatial and temporal monitoring of variation and distribution of Snow Cover Area (SCA) in regional and global scales (Frayaza et al. 2013). The Moderate Resolution Imaging Spectroradiometer (MODIS), a major NASA EOS instrument, was launched aboard the Terra satellite on December 18, 1999 (10:30 AM equator crossing time, descending) for global monitoring of the atmosphere, terrestrial ecosystems, and oceans. On May 4, 2002, a similar instrument was launched on the EOS-Aqua satellite (1:30 PM equator crossing time, ascending). MODIS, flying on two satellites in orbits that complement

each other by providing observations in the late morning and early afternoon (Salomonson et al. 2004).

Study Area

Himachal Pradesh is a mountainous state located in North India, covers an area of 55,673 square kilometres. Himachal Pradesh has a total population of 6,864,602 among 3,481,873 are males and 3,382,729 females as per the final results of the Census of India 2011. Many perennial rivers flow in the state. Its hydro-electric power production is yet not utilized fully. Many plants produce excess hydroelectricity that is sold to other states, such as Delhi, Punjab, and Rajasthan. The below figures (Figures 1 and 2) shows the location of Himachal Pradesh in India as well as its satellite view.

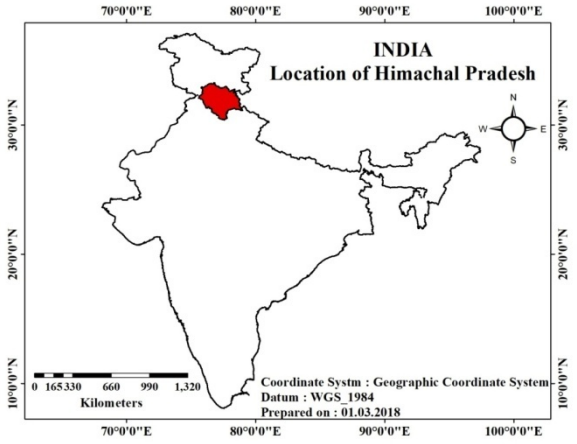

Fig. 1. Location of Himachal Pradesh in India

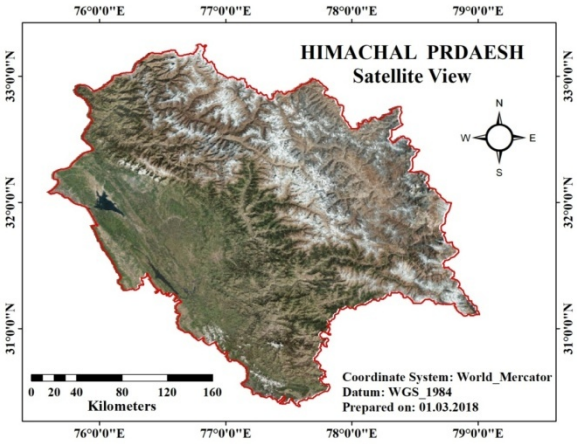

Fig. 2. Satellite view of Himachal Pradesh

Data Set

- Moderate Resolution Imaging Spectroradiometer (MODIS) Snow Cover Data

The dataset selected for this study is MODIS/Terra Snow Cover 8-Day L3 Global 500m Grid, Version 6 (MOD10A2) Dataset.

Table 1. A brief description of the dataset used in the study

P arameters	Snow/Ice > Snow Cover > Snow Extent
Sensor	MODIS
Satellite	Terra
Product	MOD10A2
Temporal Resolution	8 day
Spatial Resolution	500 m
Time Acquisition	January 2005 – December 2015
Data Format	HDF-EOS (.hdf)
Version	V6

The data is available in sinusoidal Projection with 500m resolution; tile number h25v05 covers the whole study area (Himachal Pradesh). These data sets give information about the maximum snow cover extent during an eight-day period in 1200 km x 1200 km tiles. These tiles are generated by compositing 500 m observations from the MODIS/Terra Snow Cover Daily L3 Global 500m Grid (MOD10A1) data set.

- Digital Elevation Model (DEM)

Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) DEM with 30m resolution data is downloaded from the platform of Earth Explorer of United States Geological Survey (USGS). It is available in 'Geotiff' format, Acquisition date is 17 October 2011 (Given in the website of Earth Explorer).

Table 2. Details of DEM Data Used in the Study

Serial No.	Entity ID of the Dataset
1.	ASTGTDEMV2_0N30E076
2.	ASTGTDEMV2_0N30E077
3.	ASTGTDEMV2_0N31E075
4.	ASTGTDEMV2_0N31E076
5.	ASTGTDEMV2_0N31E077
6.	ASTGTDEMV2_0N31E078
7.	ASTGTDEMV2_0N32E075
8.	ASTGTDEMV2_0N32E076
9.	ASTGTDEMV2_0N32E077
10.	ASTGTDEMV2_0N32E078
11.	ASTGTDEMV2_0N33E076

Methodology

As shown in the diagram (Figure 3) the downloaded snow cover data and DEM data have been reprojected to match with the study area (Himachal Pradesh) boundary shape file.

Fig. 3. Methodology flowchart

Then extracted the study area. Later combined the eight-day snow cover data to make it monthly and calculated month wise snow cover area. At last mapped it from January 2005 to December 2015. And also calculated minimum elevation SCA has reached with the help of DEM and tabulated it. The dataset consist of total 46 eight day periods in a year. In this study the eight-day periods are summed up to make it a monthly data. A period has been added to a particular month based on the maximum number of days of that particular period falling in any month.

Physiography

2.1.1 Elevation Analysis

The altitude ranges from 217 metres to over 6608 metres above sea level. The elevation increases from west to east and from south to north. The total area of Himachal Pradesh has been classified into seven elevation zones (Table 3) based on altitude. It can clearly seen in the map (Figure 4) the altitude in the first zone varies from 217 to 1000 m and it covers a 14836.92 sq km in Himachal Pradesh, and this zone is spread mostly in Western part and part is also can be seen in the South-West. The altitude of the second zone varies between 1000 – 2000 metres, and it is spread mainly in South-Western part and extends towards West. The altitude in the zone just above this varies between 2000 – 3000 metres and this zone is also can seen mostly in South-West and extends towards North-West. The fourth zone's altitude varies from 3000 – 4000 metres, which can be observed mostly in the middle of Himachal and in the Northern part extending from North-West to South-East. The region above this has 4000- 5000 m altitude, and spread in the Northern part of Himachal. The region having 5000 – 6000 m altitude is also spread in the northern part, and the highest altitude region is 6000 - 7000 m, the highest elevation in Himachal is only up to 6608 metre, the altitude up to 7000 is taken only for the purpose of making classes, and this region can be seen as patches in the northernmost part of Himachal.

Table 3. Elevations Zones in Himachal Pradesh

Altitude in metres	Area in sq km.
217 - 1000	14836.92
1000 - 2000	12714.88
2000 - 3000	10761.47
3000 - 4000	9363.96
4000 - 5000	16425.59
5000 - 6000	12533.35
6000 - 7000	151.07
Total	**76787.24**

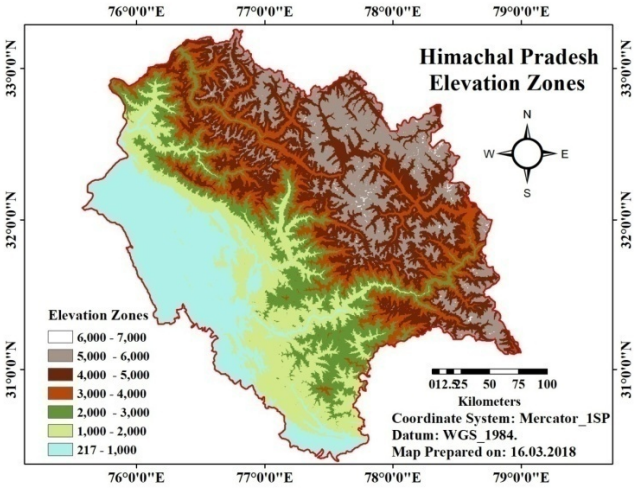

Fig. 4. Elevations Zones in Himachal Pradesh

2.1.2 Land Use Land Cover

Land use land cover represents the natural resources above surface of the earth. This analysis is based on the data obtained from BHUVAN (Figure 5). It is an Indian website which allows users to explore a 2D/3D representation of the surface of the Earth (India). Himachal Pradesh is very rich in natural resources; most of the area nearly 26% (14570.17 sq km) is covered by forest, Very less only 1% (622.53 sq km) of the area

is covered by Built up. 15% (8579.45 sq km) of area is covered by Agricultural land, 16% (8660.77 sq km) area is classified as Grass/Grazing, 24% (13530.65 sq km) is Barren or Waste land, 3% (14447.73 sq km) is covered by water bodies and the remaining 15% (8261.72 sq km) of the area is under snow.

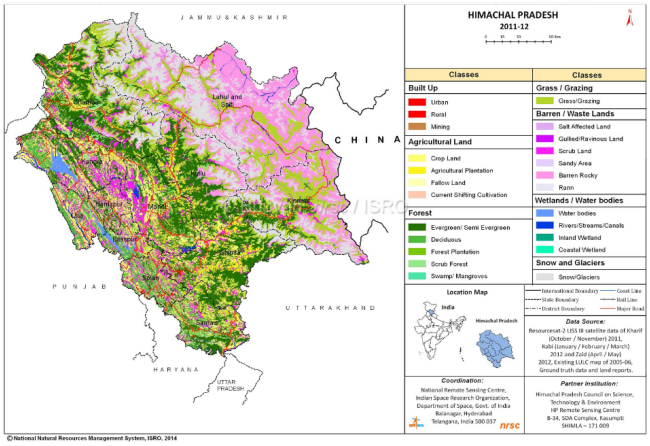

Fig. 5. LULC Classes in Himachal Pradesh: 2011-2012 (Source-BHUVAN Website)

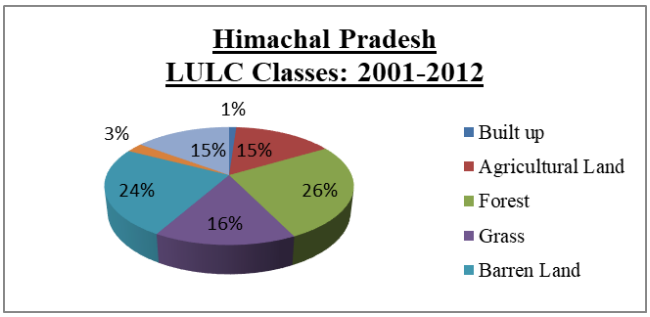

Fig. 6. Percent Area under LULC Classes in Himachal Pradesh (2011-2012)

Results and Discussion

There are mainly two types of analysis done in this study. Snow cover area is calculated for each month From January 2005 to December 2015 and tabulated (Table 5) and also snow cover area maps for each Month are prepared. Then snow cover area analysis with elevation is done, minimum elevation it has reached every month is identified, and the results are tabulated (Table 6) and also a line graph (Figure 13) is prepared showing elevation in metres.

1. Variations in Snow Cover Area.
2. Minimum Elevation of Snow Cover Area.

Variation in Snow Cover Area

In the year 2005 (Figure 7) the SCA has decreased gradually from January (35939.66 sq km) to February (16982.72 sq km) and increased in March month (38933.93 sq km) where it reaches its maximum and then from April (34667.81 sq km) onwards the snow starts melting or decreasing gradually in May (29363.59 sq km), June (21673.66 sq km), July (14440.52 sq km), August (10194.36 sq km) and until September (10126.74 sq km) where its reaches its minimum. And again from September onwards the snow increases in October (16772.36 sq km), November (14361.52 sq km) till December month (13753.83 sq km).

The SCA maps of Himachal Pradesh for the year 2006 (Figure 7) shows that the SCA has increased gradually from January (25218.74 sq km) to February (29422.62 sq km) and March (36264.01sq km) month and then from April (33456.92 sq km) onwards the snow starts melting or decreasing gradually in May (21125.42 sq km), June (12188.10 sq km), July (9398.62 sq km) and until August (7558.99 sq km) where it reaches its minimum value, and then from September (10126.74 sq km) again from September (10231.71 sq km) onwards the snow increases in October (12933.40 sq km), November (20367.46 sq km) till December month (36271.52 sq km) where it is observed to be maximum.

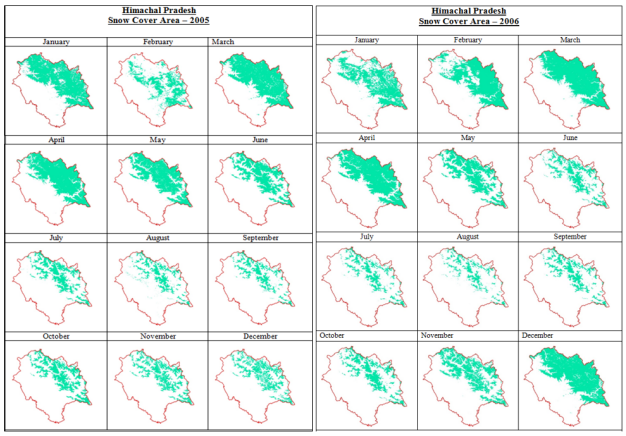

Fig. 7. Snow Cover Area in Himachal Pradesh (2005 and 2006)

In the year 2007 (Figure 8) the SCA has increased gradually from January (30578.99 sq km) to February (31040.29 sq km) and March month (39506.43 sq km) where it reaches its maximum value and then from April (30741.05 sq km) onwards the snow starts melting or decreasing gradually in May (23581.97 sq km), June (13193.57 sq km), July (8284.75 sq km) and until August (7441.57 sq km) where it reaches its minimum value, and then from September (9973.04 sq km) onwards the snow increases in October (20711.13 sq km), November (12700.71sq km) till December month (24158.55

Table 4. Area of LULC Classes in Himachal Pradesh (2011-12)

LULC classes in Himachal Pradesh 2011-2012			
Serial No.	**Classes**	**Area in sq km**	**Percent Area**
1.	Built up	622.53	1%
2.	Agricultural land	8579.45	15%
3.	Forest	14570.17	26%
4.	Grass/Grazing	8660.77	16%
5.	Barren/Wasteland	13530.65	24%
6.	Wet lands/Water bodies	1447.73	3%
7.	Snow and Glaciers	8261.72	15%
Total		**55673**	**100**

Table 5. Snow Cover Area in Himachal Pradesh (2005-2015)

Snow Cover Area in square kilometres											
Year / **Months**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Jan	35939.66	25218.74	30578.99	18114.40	34313.40	32132.26	38785.82	22807.48	30531.12	34579.58	35737.66
Feb	16982.72	29422.62	31040.29	39514.15	35554.13	36030.03	29002.43	26884.07	37151.19	39631.14	40394.47
Mar	38933.93	36264.01	39506.43	33845.88	31532.29	36052.57	38579.74	38177.26	40246.57	24388.23	35353.21
Apr	34667.81	33456.92	30741.05	31294.44	32756.91	31187.54	35154.44	29524.58	33178.93	37777.14	30709.50
May	29363.59	21125.42	23581.97	22221.04	27426.08	27418.57	26901.88	28832.74	29345.56	28832.74	31227.04
Jun	21673.66	12188.10	13193.57	12328.49	19580.95	20978.59	16899.43	19586.75	17650.95	20944.03	23055.20
July	14440.52	9398.62	8284.75	7002.81	11569.03	13066.49	10662.31	11449.25	10608.22	13879.83	14663.33
Aug	10194.36	7558.99	7441.57	8848.45	10614.01	10429.19	12742.78	7793.40	6545.80	10055.69	8997.42
Sept	10126.74	10231.71	9973.04	13699.95	22093.96	12645.76	10483.50	8995.06	7704.10	8156.81	10103.55
Oct	16772.36	12933.40	20711.13	20711.13	20759.00	19912.17	12144.10	16308.91	13149.99	13016.90	20041.82
Nov	14361.52	20367.46	12700.71	23800.07	34039.50	24109.82	16307.40	15639.39	20943.17	19464.60	27337.21
Dec	13753.83	36271.52	24158.55	27890.82	32981.23	22410.37	19006.31	29030.44	21719.59	18312.96	27928.60

sq km).

In the year 2008 (Figure 8) the SCA has increased gradually from January (18114.40 sq km) to February (39514.15 sq km) where it is maximum and starts decreasing from March month (33845.88 sq km) in April (31294.44 sq km) May (22221.04 sq km), June (12328.49 sq km), July (7002.81 sq km) where it is minimum and from August (8848.45 sq km) it is increasing in September (13699.95 sq km) October (13699.95 sq km), November (23800.07 sq km) till December month (27890.82 sq km).

In 2009 (Figure 9) has increased gradually from January (34313.40 sq km) to February (35554.13 sq km) where it is maximum and starts decreasing from March month (31532.29 sq km) in April (32756.91sq km) May (27426.08 sq km), June (19580.95 sq km), July (11569.03 sq km) and until August (10614.01sq km) where it is minimum and it decreases from September (22093.96 sq km) to October (20759.00 sq km) and increases in November (34039.50 sq km) and again decreases in December month (32981.23 sq km).

In 2010 (Figure 9) the SCA has increased gradually from January (32132.26 sq km) to February (36030.03 sq km) and

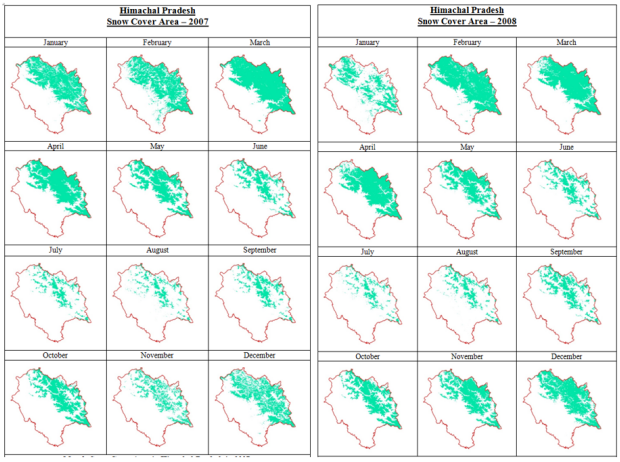

Fig. 8. Snow Cover Area in Himachal Pradesh (2007 and 2008)

March (36052.57 sq km)where it is maximum and starts decreasing in April (31187.54 sq km) May (27418.57sq km),

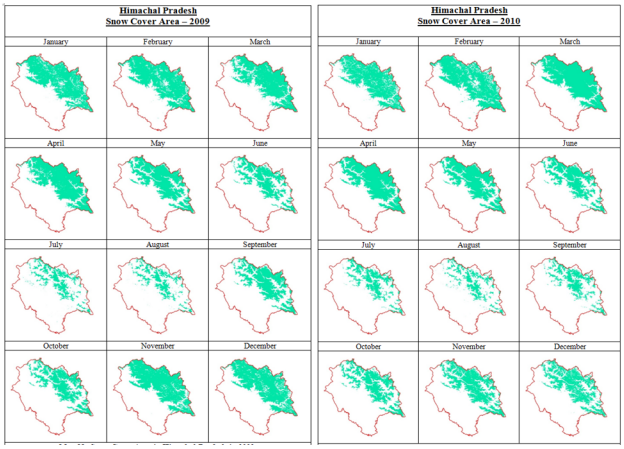

Fig. 9. Snow Cover Area in Himachal Pradesh (2009 and 2010)

June (20978.59 sq km), July (13066.49 sq km) and until August (10429.19 km) where it is minimum and it increases from September (12645.76 sq km) to October (19912.17 sq km) and increases in November (24109.82 sq km) and again decreases in December month (22410.37sq km).

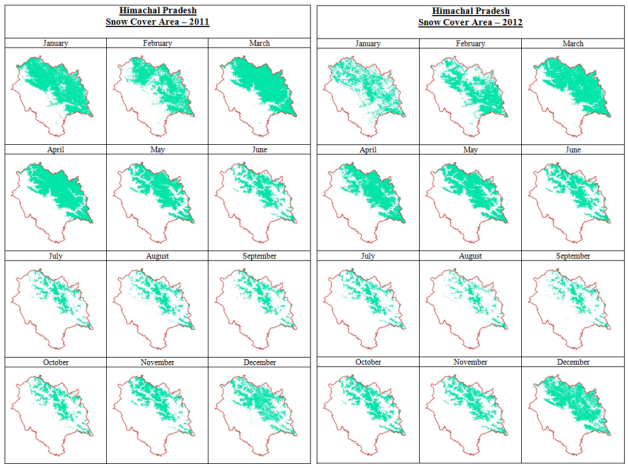

Fig. 10. Snow Cover Area in Himachal Pradesh (2011 and 2012)

In 2011 (Figure 10) shows that the SCA has decreased from January (38785.82 sq km) to February (13514.70 sq km) and increased in March (38579.74 sq km) where it is maximum and starts decreasing in April (35154.44 sq km) May (26901.88 km), June (16899.43 sq km), July (10662.31 sq km) and increases slightly in August (12742.78 sq km) and again decreased in September (10483.50 sq km) where it is minimum, it increases from October (12144.10 sq km), November (16307.40 sq km) December month (19006.31sq km).

In 2012 (Figure 10) the SCA has increased from January (22807.48 sq km) to February (26884.07 sq km) and in March (38177.26 sq km) where it is maximum and starts decreasing in April (29524.58 sq km) May (28832.74 sq km), June (19586.75 sq km), July (11449.25 sq km) and August (7793.40 sq km) where it is minimum and again increases in September (8995.06 sq km) October (16308.91 sq km), November (16307.40 sq km) till December month (29030.44 sq km).

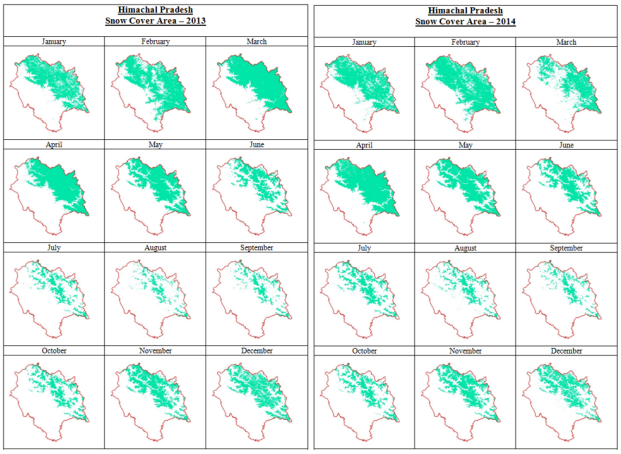

Fig. 11. Snow Cover Area in Himachal Pradesh (2013 and 2014)

In 2013 (Figure 11) the SCA has increased from January (30531.12 sq km) to February (37151.19 sq km) and in March (40246.57sq km) where it is maximum and starts decreasing in April (33178.93 sq km) May (29345.56 sq km), June (17650.95 sq km), July (10608.2 sq km) and August (6545.80 sq km) where it is minimum and again increases in September (7704.10 sq km) October (13149.99 sq km), November (20943.17 sq km) till December (21719.59 sq km) months.

In 2014 (Figure 11) the SCA has increased from January (34579.58 sq km) to February (39631.14 sq km) where it is maximum and decreases in March (24388.23 sq km) and increased slightly in April (37777.14 sq km) and decreases from May (28832.74 sq km), June (20944.03 sq km), July (13879.83 sq km) and August (10055.69 sq km) and in September (8156.81sq km) where it is minimum and starts increasing in October (13016.90 sq km) and November (19464.60 sq km) and decreased again in December (18312.96 sq km) months.

And in 2015 (Figure 12) the SCA has increased from January (35737.66 sq km) to February (40394.47 sq km) where it is maximum and starts melting in March (35353.21 sq km) and, April (30709.50 sq km) May (31227.04 sq km), June (23055.20 sq km), July (14663.33 sq km) and until August (8997.42 sq km) where it is minimum and again increases in September (10103.55 sq km) October (20041.82

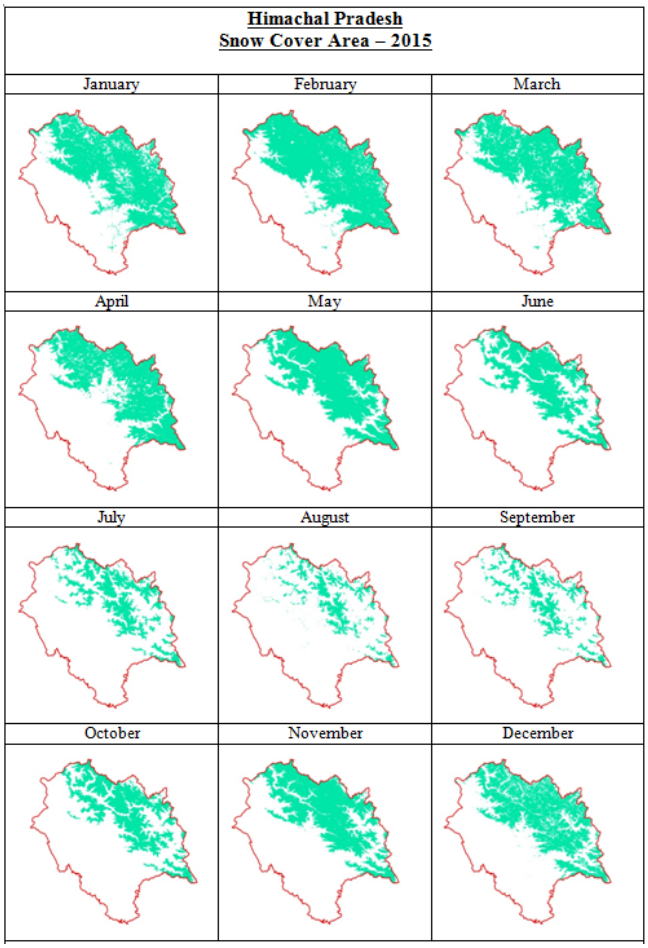

Fig. 12. Snow Cover Area in Himachal Pradesh (2015)

sq km), November (27337.21sq km) till December month (27928.60 sq km).

Snow Cover Area Variation Analysis with Elevation

In the present study the minimum and maximum elevation at which the snow cover area was observed during January 2005 to December 2015 is identified. As shown in (Figure 13) in 2005 the minimum elevation (782m) at which SCA observed was in the month of January. Then from January the snow starts melting at lower elevation and can be observed at maximum elevations in September (3526m). Similarly in 2006 also the minimum elevation at which SCA recorded was in January (469m) and at maximum elevation it observed was at in September (3529m).

But in 2007 the minimum elevation (1192m) at which SCA was recorded was in the month of February unlike the previous years of 2005 and 2006 and maximum elevation (3156m) at which it observed was same like previous years in September. Again in 2008 following the same trend the

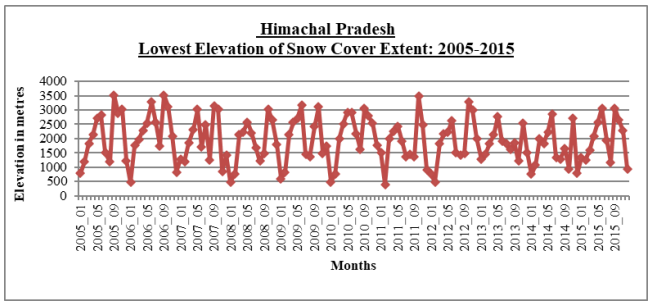

Fig. 13. LowestElevation Snow Cover extent has reached in Himachal Pradesh (2005 to 2015)

minimum elevation (483m) at which SCA seen was in January and but the maximum elevation (3030m) SCA reached was in October month unlike previous years. In 2009 year little variation observed SCA at the minimum elevation (593m) in January and but it was seen at maximum elevation (3161m) in June. Similarly in 2010 the minimum elevation (477m) at which SCA has been recorded in the month of January and maximum elevation (3070m) in September. In 2011 minimum elevation (395m) SCA has reached was in February, which is the lowest elevation SCA reached in all eleven years time period. And the SCA observed at maximum elevation (3495m) in October. In 2012 also minimum elevation (479 m). SCA reached was in February and maximum elevation (3283m) October. But in 2013 the trend observed was a entirely different it reached minimum elevation (1216 m) in the month of October and maximum elevation (2779 m) in the month of May. For the year 2014 minimum elevation (752m) SCA reached in January and the snow melts and goes up to maximum upper elevation (2860m) areas in June. And in 2015 it reached minimum elevation (939m) in the month of December and maximum elevation (3060 m) in September.

Conclusion

The general trend observed is the SCA is increasing from January to March and from March it starts decreasing till August and again from September to December it increases. The study reveals that the SCA was maximum in March and minimum in the month of August for most of the years, but in some the maximum SCA varied between January and March, and minimum between July and September. The Maximum SCA is recorded in 2013 in the month of March i.e. 40246.57 sq km in this whole eleven year time period from 2005 to 2015 and the minimum snow cover was also observed in the same year 2013 September which is estimated to be 6545.80 sq km. And the general trend observed for SCA with elevation is, it is in lower elevations mostly in the month of January and the snow starts melting and vanishing from the lower elevations till June and August. And later the snow starts accumulating and again slowly comes down to lower areas till the month of

Table 6. Lowest Elevation of Snow Cover reached in Himachal Pradesh (2005-2015)

Elevation in Metres											
Years / Months	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Jan	782	469	1274	483	593	477	1498	751	1274	752	1331
Feb	1201	1765	1192	771	822	749	395	479	1459	1076	1253
Mar	1826	1962	1839	2136	2138	1988	1988	1830	1837	1988	1593
Apr	2136	2284	2311	2226	2562	2525	2264	2159	2138	1824	2090
May	2710	2548	3015	2570	2720	2924	2423	2229	2779	2229	2562
Jun	2813	3281	1695	2197	3161	2916	1895	2632	1898	2860	3063
July	1519	2560	2484	1686	1439	2173	1363	1498	1818	1327	1943
Aug	1181	1748	1251	1220	1361	1619	1461	1424	1614	1287	1170
Sept	3526	3529	3156	1484	2413	3070	1376	1480	1859	1640	3060
Oct	2897	3120	3030	3030	3108	2797	3495	3283	1216	956	2644
Nov	3018	2086	853	2655	1487	2540	2472	2993	2534	2722	2278
Dec	1224	831	1408	1781	1730	1773	911	2006	1494	783	939

December. The snow cover has reached a minimum elevation of 395 m in the 2011 in the month of February, which was the minimum elevation it has reached in the overall eleven years time period. It can be concluded that the areas above this elevation are always covered with snow.

The results derived from the spatial temporal analysis of SCA in Himachal Pradesh, can be used in several research and developmental activities in the region. This information may be useful as inputs along with other data of Himachal Pradesh like temperature, Precipitation and can be used for climate change analysis, water management, and hydropower generation and in planning of many other developmental activities in Himachal Pradesh.

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