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Snow Cover Area Changes in the Changme Khangpu Basin during 2002-2019, North Sikkim Himalaya, India

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Abstract: The Himalayan region is characterised by snow-covered mountains and glacierised basins which directly or indirectly regulates many large to small rivers downstream. To simulate and forecast stream-flow in these glacierised basins, an accurate snow cover area (SCA) estimation is of utmost importance. The present study assesses the snow cover dynamics (monthly, annual and seasonal) in the Changme Khangpu Basin (CKB) for almost two decades, from 2002 to 2019. The spatial and temporal variations in the SCA have been estimated using Moderate Resolution Imaging Spectro-radiometer (MODIS) 8-day maximum composite snow cover products from Terra (MOD10A2). Further, the SCA change has been compared with a remotely sensed meteorological parameter like temperature. The result shows a decreasing trend in annual mean SCA of the basin in the last two decades and an increase in seasonal mean SCA in the ablation period (May, June, July, August and September), whereas a decrease in seasonal mean SCA in accumulation period has been observed. The seasonal change in SCA will help in estimating the availability of water in the region for the people residing downward in the valley.

Keywords: Himalayan glacierized basin; Snow cover area; Remote sensing; Eastern Himalaya.

Introduction

Snow covers around 40 percent of the Earth's land surface during Northern Hemisphere winter and significantly affects the albedo which is an important component of the earth's radiation balance, and therefore regulating earth's climate, water cycle and maintaining Cryospheric regime (Foster et al., 2003; Goose et al., 2010; Ming et al., 2014; Bolch et al., 2015; Hock et al., 2017). The Himalaya 'abode of snow' has many large rivers that originate from these glacierised basins. The seasonal changes in snow cover (during winter and summer) affect the flow of streams and rivers originating high in the Himalaya (Kumar et al., 2019). All the rivers originating from the higher Himalaya receive almost 40-50 % of annual snow and glacier melt run-off (Jeelani et al., 2012; Armstrong et al., 2019). Changes in the precipitation phase and increase in air temperature can lead to early snowmelt and can affect the stream runoff pattern (Kulkarni et al., 2002; Krishna, 2011; Lutz et al., 2014; Pratap et al., 2019).

The study of variations in snow cover and snowmelt run-off is a vital aspect that can be used for avalanche forecasting, environmental impact assessment, estimating the potential of mini and micro hydro-power plants and understand the water resource management (Immerzeel et al., 2009; Wang et al., 2010; Thayyen and Gergon, 2010; Chu, 2018). The snow cover estimation is also an important parameter for simulating and forecasting the daily stream-flow in snow-covered and glacierised basins, hence, accurate data on snow cover is of utmost importance (Mir et al., 2015a). The contribution of

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snow to different aspects shows that it is very useful for efficient series monitoring of seasonal snow in the Himalaya.

Despite the importance of snowmelt water contribution to the Himalayan rivers, its characteristics are less understood due to the complexities of the processes involved in snow hydrology and the lack of hydro-meteorological data in the high-altitudes (Miller et al., 2012). For instance, the seasonal snowline descends to an altitude of 2000 m in the western part of the Himalaya by February (Jain et al., 2010). As the snowmelt commences in March, the snow line starts receding upwards and by the end of June reaches an altitude of 5500 m (Gaddam et al., 2016; Pratap et al., 2019). In terms of snowmelt runoff estimation, SCA and temperature are important parameters of estimation and can be obtained from both- remote sensing data and meteorological data (Alam et al., 2011; Abudu et al., 2012). The MODIS products offer the best potential for snow mapping regularly with respect to the temporal and spatial resolutions; also in terms of accurate data availability (Hall and Riggs, 2007; Mir et al., 2015b).

Considering the importance of snow cover, the present study has been conducted for the assessment of SCA in the Changme Khangpu Basin (CKB) of North Sikkim in the Eastern Himalayan region.

Study Area

The Changme Khangpu Basin (CKB) in the Eastern Himalaya ranges from 1540 to 7000 m a.s.l, occupying an area of 792.2 km^2. About 70 % of the basin area is above the elevation of 3000 m a.s.l and shows a slope gradient not more than 45^o. In the present study, the basin includes 58 glaciers covering a total area of 70.68 km^2 with the lowest elevation of 4300 m a.s.l. The basin has many small streams originating from a single to a group of glaciers that finally merge to form Lachung *Chhu,* a major tributary of the Teesta River (Figure 1). The area receives cumulative annual rainfall between 347 mm and 2400 mm where the air temperature varies from 9^{o}C to 25^{o}C and -10^{o}C to 9^{o}C in summer and winter, respectively. The summer starts from May upto August while winter duration is from November to March in the region as the ablation and accumulation pattern in Sikkim is different as compared to other parts of Himalaya (Basnett et al., 2012). The precipitation received during winter is mostly as snowfall due to western disturbances. Snowmelt runoff is one of the primary inputs of river discharge and is the major source of water supply in these regions. Though seasonal snow cover has noticeably less volume of stored water as compared to glacier ice melt, it is also economically more important and a rich water resource downstream, which governs downstream erosion and provides ample amount of water for the generation of hydroelectric power in the Chungthang station (1550 m a.s.l) (Figure 1).

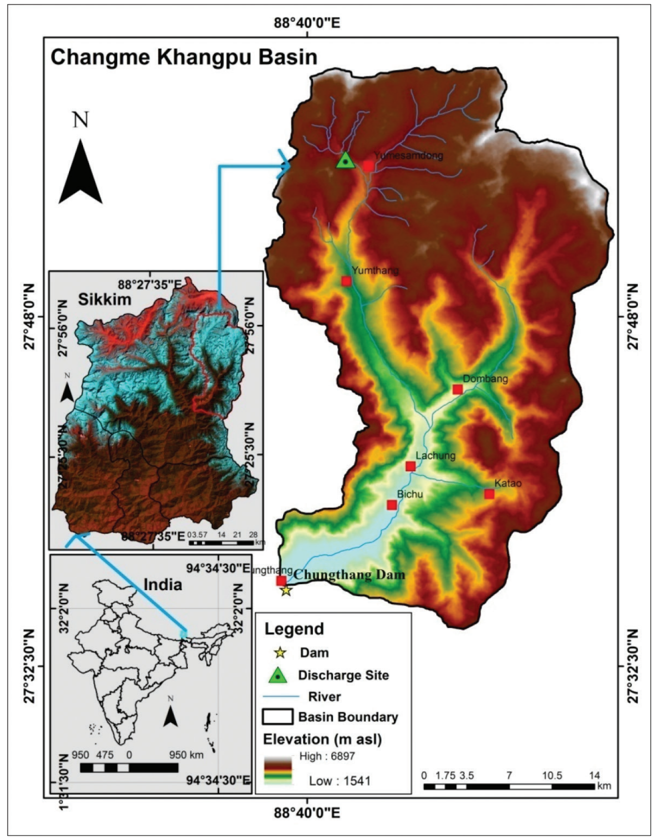

Figure 1: Location map of Changme Khangpu basin in Sikkim, India. Background generated using ASTER GDEM having 30 m resolution.

Data and Methodology

The data used for snow cover mapping is mainly the MODIS 8-day composite snow cover products from Terra (MOD10A2) and is an 8-day composite of MOD10A1 (daily snow product) to show maximum snow extent. MODIS snow cover products are generated using a global snow cover extraction algorithm available at a 500 m spatial resolution. The temporal resolution of MODIS varies as it gives the daily snow extent, 8-day composite, and the monthly snow extent as an end product. The snow products containing the tile number 'h25v06.006' were downloaded from the NSIDC website (https://n5eil01u.ecs.nsidc.org/MOST/MOD10A2.006/) for the period from 2002 to 2019.

The weather data was obtained using history+ from meteoblue.com, which is based on the local model for India having a resolution of 12x12 km^2 (https://www.meteoblue.com/en/historyplus). Since the weather stations' data are not available for the region, the data is obtained for two nearby stations namely—Lachung (2800 m a.s.l) and Yumesamdong base station (4800 m a.s.l).

The processing of snow data includes the re-projection of a total of 876 MODIS snow products from Sinusoidal projection to UTM projection, image rectification, resampling to 500 m and masking Area of Interest (AOI) in Arc Map 10.2. The pixel value of 200 represents snow pixels and was taken for the assessment of SCA in the said imageries. The average monthly mean SCA was estimated by taking the average value of SCA from different scenes of a particular month. Further, the monthly, seasonal, and annual snow cover extents for the year 2002-2019 was taken into consideration to understand the behaviour and changing patterns of snow cover in the basin. The seasons have been divided into two parts—the ablation (May-September: MJJAS) and accumulation seasons (November-March: NDJFM). The detailed flow-chart methodology for the estimation of SCA using MODIS is shown in Figure 2.

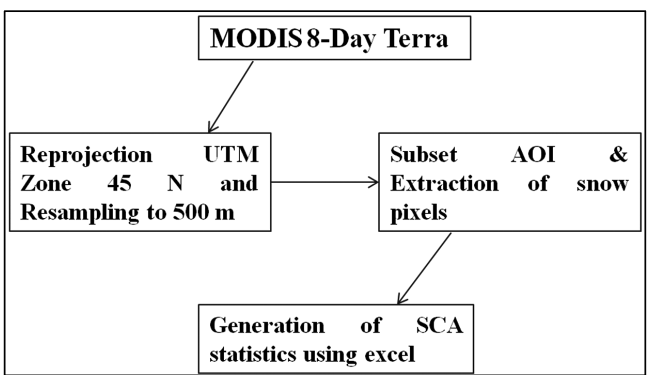

Figure 2: Methodology opted for the extraction of the SCA from MODIS 8-Day terra data.

Results and Discussions

CKB is characterised by glacierised and snow cover areas, where the snow and ice melt of the valley contribute significantly to the downstream river system. Two moisture sources viz. western disturbances (WD) and Indian summer monsoon (ISM) dominate during the winter and summer periods, respectively. The monthly distribution of SCA from 2002 to 2019 has been depicted in Figure 3.

The monthly snow cover between January and December for the study period of 18 years showed maximum snow cover extent in the month of February and March. The mean monthly SCA for 18 years (2002-2019) suggests that the snow cover reached its maximum in February (85.66 ± 12.98 %) (678.62 km^2) and minimum in July (35.52 ± 5.83 %) (281.42 km^2). The mean monthly snow depletion curve suggests that snow starts accumulating from October and keeps on increasing until the month of February-March (Figure 4a). From April onwards, it starts decreasing with the lowest snow cover area in June at 46.70 ± 5.23 %, July at 35.52 ± 5.83 % and August at 39.56 ± 6.52 %, respectively. The rate of SCA decline is linear from March onwards but it shows a slight crimp during June, where SCA depletion is flattened. Similarly, the SCA results show a small decline in November after a rapid increase in August to October (Figure 4a).

The annual time series plot shows a declining trend in the extent of SCA from 2002 to 2019 (Figure 4b). The highest SCA was observed in 2003, 538.39 ± 49.53 km^2 (67.46 ± 9 %) and lowest in 2017, 442.60 ± 42.25 km^2 (55.87 ± 7.1 %) (Table 1). In CKB, the mean annual SCA from 2002 to 2019 is estimated to be 62.08 % ± 10.15 %, (491.45 ± 90.01 km^2). The inter-annual variation in the trend line shows a negative trend of 3.81 ± 2.05 % in SCA from 2002 to 2019 (Figure 4c).

The seasonal snow cover extent in the basin is shown in Figure 5a. The SCA shows a declining trend in the accumulation period and an increasing trend in the ablation period for over 18 years. The estimated mean SCA was 75.26 ± 5.21% in the accumulation period, which is around 1.68 times higher than the mean SCA of the ablation period (44.78 ± 3.11%). The trend of snow cover anomaly from its mean value shows a decrease in the percentage of SCA in winters. It is important to mention that the anomaly of SCA in the month of December shows almost stable trend over the studied period (Figure 5b).

The relation between annual mean SCA and temperature for the 18 years (2002-2019) was also analysed and a negative correlation was observed suggesting that an increase in the average temperature leads to a decrease in SCA as shown in the snow depletion curve (Figure 6a, c). A gradual increase in temperature in the basin was found at the start of month of March and simultaneously, the decrease in SCA was also noticed. The SCA reached to a minimum in the month of July (35%) when the temperature reached its maximum of 18°C and 5°C at Lachung and Yumesamdong stations, respectively. The maximum

Figure 3: Monthly mean composite records of snow-covered areal extent in the Changme Khangpu basin from 2002 to 2019.

temperature was noticed in the month of July and fits well with the minimum extent of SCA in the same month. The temperature at Yumesamdong (4800 m a.s.l) is 1°C or below for most of the year, therefore, the SCA above the Yumesamdong is highest throughout the year.

The SCA has significantly decreased in the last few decades over the Himalayan region (Kulkarni et al., 2010; Gurung et al., 2011; Gaddam et al., 2018; Zhang et al., 2020). However, the SCA in the Upper Indus Basin (UIB) has shown an increasing trend in the last decades (Bilal et al., 2019; Hayat et al., 2019; Yaseen et al., 2020). The SCA in Sikkim including CKB has also been declined by 2.81 ± 2.02% (Basnett and Kulkarni, 2019). It is pertinent to mention that Sikkim receives maximum snowfall in the month of February, which is reflected in the present study as the maximum SCA in the Changme Khangpu basin was observed in the month of February and March (~85%), similar to eastern Himalayan basin of Bhutan (Gurung et al., 2011). However, the highest snow cover was observed

Table 1: Maximum and minimum snow-covered area from 2002 to 2019

Year	*Maximum SCA (%)*	*Month*	*Area (km²)*	*Minimum SCA (%)*	*Months*	*Area (km²)*
2002	88.9	March	704.69	40.1	August	318.31
2003	92.8	February	735.42	40.5	August	321.06
2004	89.0	January	705.75	37.7	August	298.88
2005	90.7	February	719.19	32.4	July	257.19
2006	89.5	March	709.00	34.2	July	271.38
2007	92.3	February	731.33	35.8	July	283.94
2008	91.2	February	722.96	31.5	July	249.63
2009	87.3	February	691.69	34.9	June	276.88
2010	87.7	February	694.81	32.4	August	256.75
2011	88.5	February	701.35	33.8	August	268.06
2012	88.9	January	704.31	39.3	August	311.81
2013	88.9	February	704.21	33.5	September	265.88
2014	88.6	February	702.35	31.5	July	250.00
2015	91.4	February	724.31	31.2	July	247.50
2016	85.5	January	677.38	23.5	July	186.44
2017	88.34	March	648.06	34.95	November	278.81
2018	89.8	February	711.48	24.0	July	190.17
2019	92.3	February	731.38	32.8	August	259.91

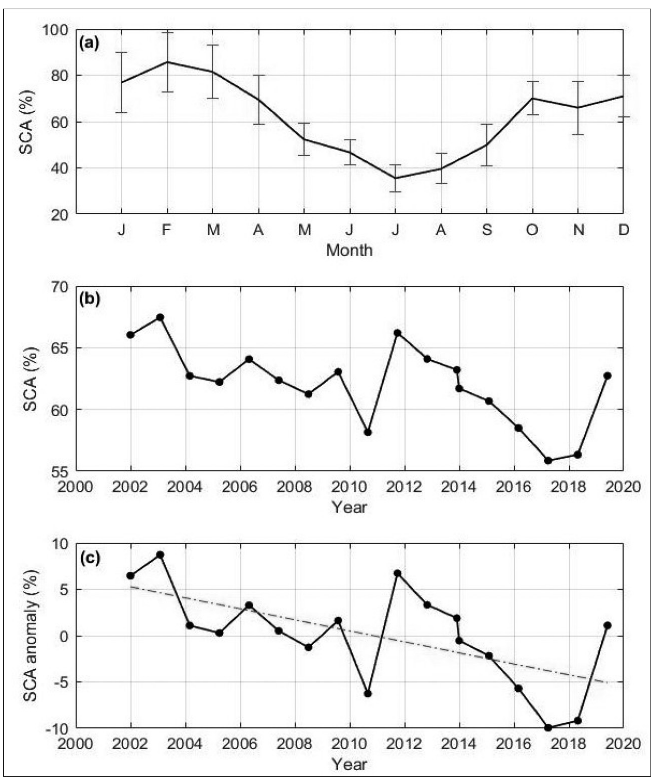

Figure 4: Snow cover area (SCA) during 2002-2019, (a) monthly mean SCA and error associated with the SCA estimation (b) mean annual SCA and (c) snow cover anomaly (%) and snow depletion curve.

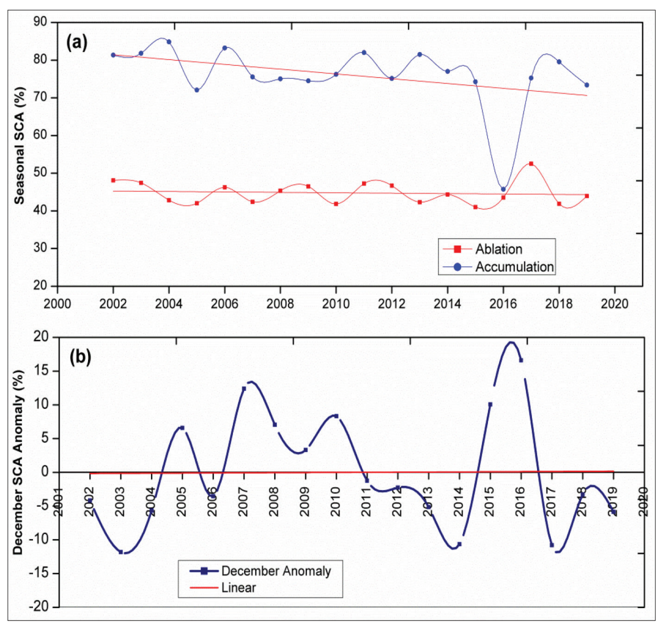

Figure 5: (a) Seasonal snow cover area (SCA) pattern in ablation period (MJJAS) and accumulation period (NDJFM) during 18 years, where winter SCA is three times higher than summer SCA. (b) Anomaly in areal extent of SC from its mean for the month of December (fall in winter snow cover on average, especially in the month of Nov, Jan, Feb and Mar).

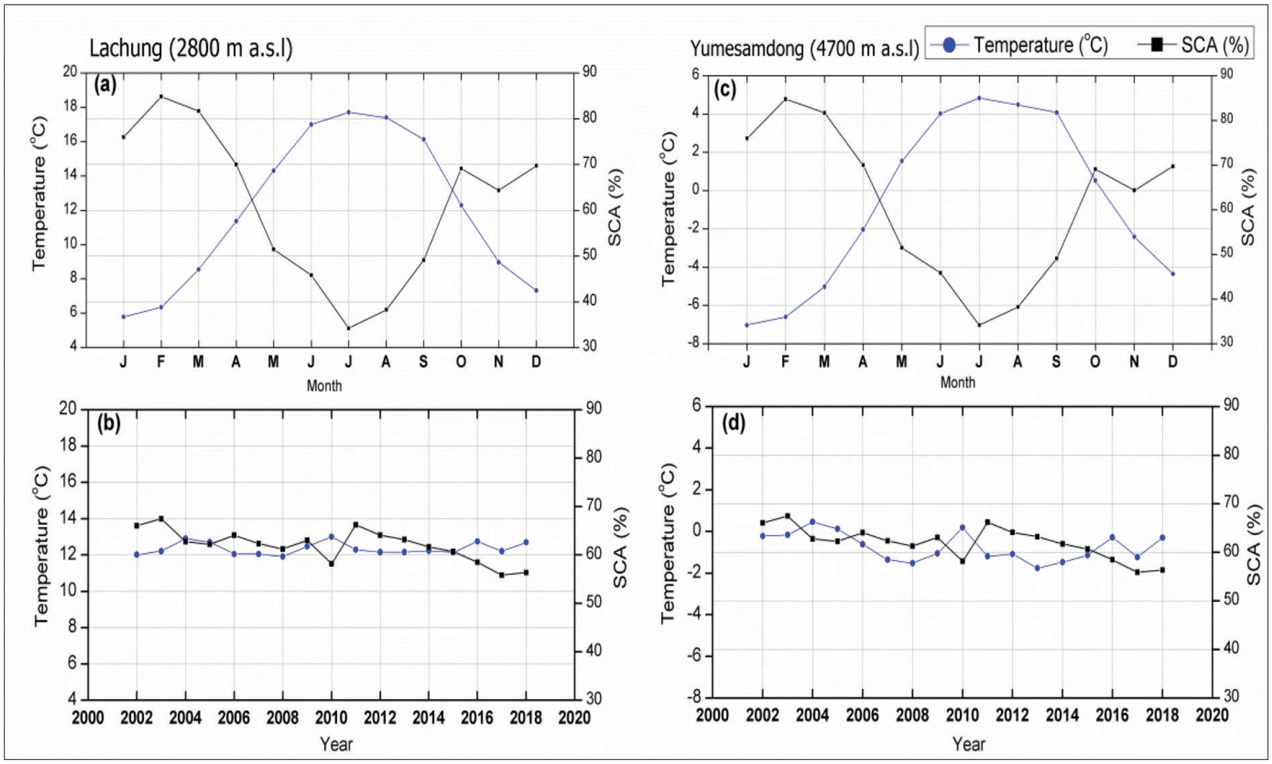

Figure 6: Relationship between SCA (%) and temperature (°C), (a-b) mean monthly and annual at Lachung (2800 m a.s.l) and (c-d) at Yumesamdong (4700 m a.s.l) for the period 2002-2018.

in the month of January in the Kashmir valley and Tibet regions (Negi et al., 2009) and in March for the Baspa basin in central Indian Himalaya, and west China (Dahe et al., 2006; Kaur et al., 2009). The western Himalaya receives more precipitation from western disturbances as compared to the central part (Bookhagen and Burbank, 2010; Dimri et al., 2015; Krishnan et al., 2018). These east-west SCA variations observed over the Himalaya may attribute to the upper air circulation and weather systems, which influence the timing of maximum snowfall occurrences across the Himalayas.

Conclusion

The annual SCA has declined in the last 18 years in CKB in the Sikkim Himalayan region. The maximum snow cover was observed in the month of February-March and minimum in the month of June-July. CKB is generally under the influence of western disturbances that may contribute to higher snow in the basin during the months of February-March. Whereas, in the western Himalaya, the SCA shows a declining trend from March onwards indicating the pattern of snow accumulation and ablation is different in the eastern and western Himalayas. The seasonal snow during winter (January to March) in the year 2017 was significantly less resulting lowest yearly mean SCA in this particular year. The study also suggests that SCA has witnessed a decreasing trend in accumulation season and increasing in ablation season during the studied period. The seasonal trend although shows considerable variability for both the accumulation and ablation periods, a significant decreasing trend was observed in all the winter months suggesting the decreased snowfall in the accumulation period, except in the month of December where a statistically stable trend was observed. Higher fluctuations in SCA were observed in the accumulation period because of the frequent snowfall and melting at lower altitudes. The maximum temperature observed in the month of July coincides well with the minimum extent of snow cover in the same month. The mean monthly SCA starts decreasing from April onwards with the increase in temperature in the region and contributes to snowmelt runoff till August. High temperatures in the month of July lead to the lowest SCA in the same month due to continuous melt at lower altitudes. Changes in climate or regional weather patterns (temperature and precipitation) may influence the timing of the winter snow season as well as the amount of snowfall that can ultimately affect the runoff in the Lachung River in the Basin. The variations in the snow-covered peaks observed over the Himalayas (Western, Central and

Eastern Himalaya) could be attributed to the upper air circulation and weather systems, which influences the timing of maximum snowfall occurrences across the different parts of Himalaya.

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