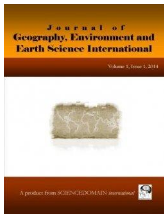

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Mass Balance of the Himalayan Glaciers and Their Regional Variations

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Authors' contributions

This work was carried out in collaboration between the two authors. Author SD developed classification algorithm with a guidance from author MC. Authors SD and MC analyzed the results and performed the statistical analysis. Author SD managed the literature searches and wrote the first draft of the manuscript. Both authors managed the analyses of the study and read to approve the final manuscript.

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ABSTRACT

Aim: Popular methods of glacial mass balance studies are time consuming, laborious and therefore, not repetitive at yearly manner. A compact, user-friendly classification algorithm has been applied to estimate Equilibrium Line Altitude (ELA) and mass balance of mountain or valley glaciers at yearly basis using Synthetic Aperture Radar (SAR) data for a period of 2012 to 2015. Cloud cover over the glacier catchment areas was studied to identify major seasons of precipitation over the study areas. The results were also compared to study the regional characteristics of the glaciers.

Study Area: The proposed module was used to analyze data over three Himalayan glaciers, namely, Durung Drung, Gangorti and Zemu. Chhota Shigri glacier was also studied with these three glaciers to understand the regional variations of the Himalayan glaciers.

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Methodology: The classification algorithm was fixed for all glaciers and also independent from season, therefore, required least user intervention. The conditional loop based logics, consist of linear equations, classified glaciated region in different physical zones. Purely backscatter based classification result produced error by mixing zones due to overlapped signatures. Altitude thresholds of accumulation zones were employed to segregate the mixing in next level. The method required calibrated ortho-rectified sigma naught dual-pol SAR imagery as primary input. The glaciated area should be provided as Area of Interest (AOI). A Digital Elevation Model (DEM) file is required for altitude threshold. The output classes are saved in separate files with Boolean values. Optical data were used to estimate cloud coverage over the catchments of the glaciers.

Results: Average mass balance of the selected glaciers is estimated as - 0.44 m w.e.a^{-1} during the study period. The mass balance of the glaciers are comparatively studied with variation in melting seasons, duration of melting periods, on set and cease of melting for each glacier to understand the regional pattern of mass loss.

Conclusion: Co and cross polarized SAR data are employed to derived debris size; however, cross polarized SAR backscattering has better correlation with debris size. The accuracy of the result derived from the developed method is ± 50 mm. Collection of field data on the surface topography is difficult for Mountain glaciers, especially over Himalaya. Use of satellite data can generate detailed information of glacier surface which will be further help to understand role of debris in glacier mass balance.

Keywords: Synthetic Aperture Radar (SAR); snow line; Firn line; ELA; mass balance; cloud cover.

1. INTRODUCTION

The Himalayan glaciated region accompanying the other neighboring glaciated regions, like, Karakoram, Hindukush and Central Asian mountain range, forms the largest glaciated region outside the poles. The major agricultural regions of Asia depend on the perennial rivers originated from the snow-melt runoff of this glaciated region. Therefore, the health of the Himalayan and other neighboring glaciated regions are of a major concern for the glaciologists to understand the impact of the climate change over these regions. In last few decades, advancement of the remote sensing techniques, promote glaciological studies which are, otherwise, a tedious job because of the harsh environment and climatic conditions. Various research works published on estimation of mass balances of the Himalayan glaciers explain the glaciers are losing mass, however, their rate of losses are debatable. The mass balance rates of the Chhota Shigri glacier of the Himachal Himalaya differently reported by a variety of study methods [1-6]. This variability is more prominent for the glaciers of one glaciated basin to others [7-9]. The fact of loosing mass of the Himalayan glaciers is quite established, however, in contrast, the glaciers of the Karakoram region are advancing due to a positive mass balance [8,10,11]. Statistically significant increase in winter and summer precipitation have been observed since 1961, which indicate winter warming and summer cooling and increase in the summer cloudiness and storms. This contributes to the positive mass balance [10,12]. Most of the mass balance studies are objected to study one or two glaciers at a time and the methods involved in estimation are also repetitive for each different glacier and hence, time-consuming which may restrict selection of study areas.

Here, this research work has been objected to estimate mass balance of four Himalayan glaciers, distributed through west to east, using a single geo-informatics tool which reduces processing time and also subjectivity of the users. The output classified SAR images provide information like snowline, firnline, on set and cease of melting season. The second level products generated from this information are Equilibrium Line Altitude (ELA) and mass balance. The Himalayan glaciers found at different basins from west to east are studied using C band Synthetic Aperture Radar (SAR) data during 2012 to 2015. Use of C band (5.35 GHz) SAR makes the study independent of the atmospheric conditions (cloud cover) and solar illumination (day and night), unlike, optical data. Application of a tool to estimate mass balances of different glaciers will also allow a comparative study of the mass balance values of the selected glaciers.

2. STUDY AREA

The Study areas are selected considering factors, like, differences in latitudes and longitudes, location of the glaciers on the ridgeline and amount of rainfall (summer and winter). Four Himalayan glaciers are selected from west to east (Fig. 1). The geographical positions of the glaciers show the longitudinal difference of the glaciers is more than 10 degrees and 6 degrees in latitude. The differences in precipitation amounts are also prominent over these regions [13]. The ridgelines of the Himalaya, oriented in east - west direction, controls amount of rainfall by creating orographic effect over the south-east monsoonal wind. During summer monsoon, the southern sides of the ridges get more precipitation than lee side. It is opposite for winter precipitation. Based on these differences the study areas are selected. The glaciers are distributed from west to east in different micro-climatic regions.

From the extreme western part of the Himalaya, the Durung Drung (DD) glacier of Jammu and Kashmir State is selected. The length of the glacier is 25 km. and having 70 sq. km of total glaciated area. The catchment of the glacier is of 125 sq. km. The Chhota Shigri (CS) glacier of Himachal Pradesh is situated on the south-eastern side of the DD glacier. The 9 km. long glacier is situated at the transition zone of two precipitation regimes [14] covering an area of 14 sq.km. and catchment area of 32 sq. km. The summer Asian monsoon and winter mid-latitude westerlies are prevalent over the glacial valley. The mass balance study of the glacier is done by Das and Chakraborty [6] previously. The glacier is now studied for clode cover pattern with other glaciers to understand the difference in regional pattern. In the Garhwal Himalaya, the Gangotri (GG) glacier is selected as another study area and is located at south-eastern side of the DD glacier. The glacier is second largest glacier of the Himalayan region, having a length of 30 km. The snout of the glacier is located at 4000 m a.s.l [15]. 138 sq. km. extended glaciated area is supported by 435 sq. km. glacier catchment area. Both the monsoonal and mid-latitude westerly precipitations influence the amount of precipitation [13]. In the eastern Himalaya, the Zemu (ZM) glacier (25 km long, 78 sq. km. glaciated area, which is originated from eastern flank of Kanchenjangha peak, is studied as the fourth study area. 207 sq. km extended catchment area of the ZM glaciated area is dominated by monsoonal precipitation. In the eastern region, around 80% of the mass is added by monsoonal precipitation [16].

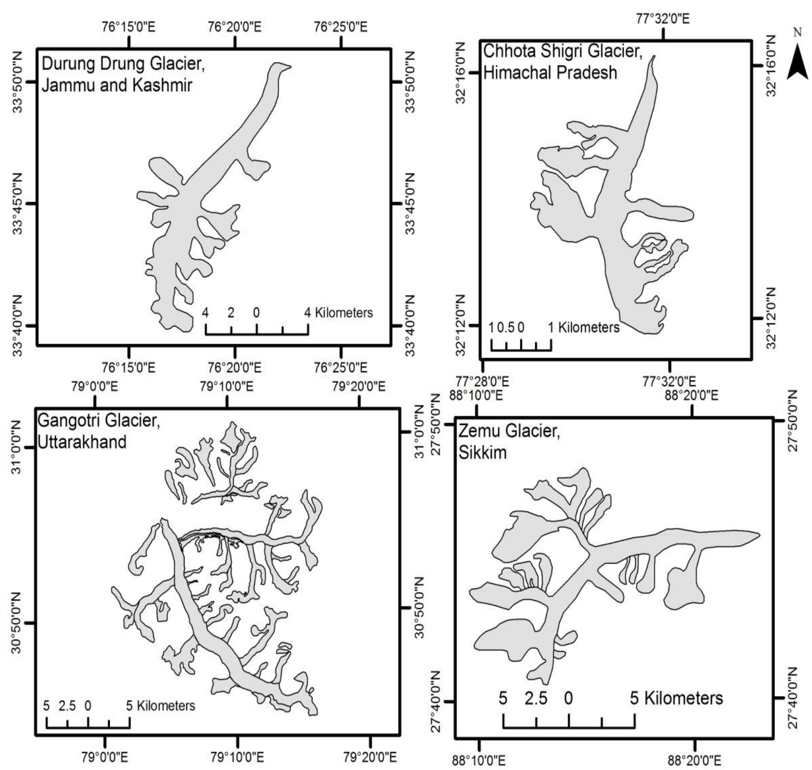

Fig. 1. Location map of the study areas; namely, a) Durung Drung (DD), b) Chhota Shigri (CS), c) Gangotri (GG) and d) Zemu (ZM)

3. DATA AND METHODOLOGY

The Data of Synthetic Aperture Radar (SAR) sensor acquired in 5.35 GHz frequency (C band) were used as the primary input for monitoring the mass balances of the glaciers. A set of eighty nine dual polarimetric SAR scenes (HH and HV) of Medium Resolution SAR mode (MRS; 24 m resolution) of Radar Imaging SATellite-1 (RISAT-1) were collected over a period of 2012 - 2015 covering both ablation and accumulation seasons. The data, having nominal incidence angle of 37°, were geometrically corrected against the Digital Elevation Models to minimize the geometric errors (layover and foreshortening) generated due to the side looking properties of SAR over the glaciated regions. A description of the data used for the study is given in Table 1.

The Speckle filtering and backscattering sigma naught calibration were the major pre-processing steps before classifying the images. Equation (1) was used for calibrating filtered scenes to backscattering sigma naught values. A linear rule based classification algorithm developed by Kundu and Chakraborty [17] had been applied to classify the glacial zones of the glaciers. The overall accuracy and kappa coefficient of the classification model is 94.80 and 0.924 respectively. The inputs to the classification step were SAR data (filtered, calibrated ortho-rectified), glacier boundary (vector file, .shp format) to generate mask and DEM for providing altitude thresholds to separate out the classes having overlapped backscattering signatures. The output results contained different backscattering classes based on the surface roughness, moisture content and subsurface properties (during winter season only).

$$\sigma_o(\text{in dB}) = 20\ \log10(X) - \kappa_{dB} + 10\ \log10(\sin\theta_{local}/\sin\theta_{centre}), \quad (1)$$

Where, X= amplitude value, κ_{dB} = Calibration constant, θ_{local} = local incidence angle at a pixel, θ_{centre} = nominal incidence angle at the scene centre.

The glacial facies, identified from the SAR data, were Debris Covered Ice Zone (DCIZ), Bare Ice Zone (BIZ) in the ablation zone and Superimposed Ice Zone (SIZ), Wet Snow Zone (WSZ), Partially Wet Snow Zone (WSZ2) and Seasonal Frozen Percolation Zone (Seasonal FPZ) in the accumulation zone. The snowline was considered as the lower altitude extent of the WSZ. Temporal changes of the snowline altitudes throughout the four years were derived from the classification results. The moisture content within the snow pack absorbs part of the incident radar energy and a large portion of it scatters in forward direction by specular reflection due to the concentration of water molecules at top surface of the snow pack. The WSZ, therefore, appears as the darkest zone over the glacier. The classification output during the ablation season provides distribution of the WSZs over the glaciers. The lower extents of the zone were identified and overlaid with DEM to extract the mean snowline altitudes. The highest snowline altitude at the end of ablation period (middle of August to middle of September months) is considered as the Equilibrium Line Altitude (ELA) of a particular glacier for a particular year. If data during this time period is not available, then the firn line altitude at the starting of the accumulation season of the same year is considered as the ELA for the glacier [6].

The compacted snow at the end of ablation season develops firn (density 0.5 kg m^{-3}). The granular snow acts as strong scatterers of the radar beam. This produces high backscattering and the firn zone appears bright in the SAR images. The zone is identified as the "Seasonal Frozen Percolation Zone" having a signature

Table 1. Description of the data used for identifying glacial facies to derive mass balance

Data Type	Satellite/Sensor	Remarks
C band SAR dual-pol (HH, HV)	RISAT-1 MRS mode	Resolution: spatial 25 m, 18 pixel spacing, temporal 25 days, nominal incidence: 37°
Optical data	Resourcesat-2 AWiFS, Landsat 7/8	AWIFS spatial resolution: 56 m x 56 m; Spectral band used: SWIR, NIR and Red.
Digital Elevation Model	SRTM DEM	Spatial resolution 30 m x 30 m
Glacier boundary as .shp format (vector file)	SRTM DEM	Developed from DEM and derivatives of DEM, i.e., slope and profile curvature (Chakraborty, Panigrahy and Kundu 2014)

similarity with the 'Frozen Percolation Zone' during the winter season [17]. The lower extent of the seasonal FPZ has been marked from the classified outputs and mean altitudes of the firn lines were derived similarly as done for the snow line altitudes.

The mass balance values (mb) were calculated from the ELAs by using an empirical method [18]. Before estimation, Accumulation Area Ratio (AAR), against each ELA for each glacier, was derived and used as an input in the empirical equation (2) where r^2 is 0.8 (Fig. 2).

$$Mb\ (m\ w.e.) = (243.01 \times AAR - 120.187)/100 \quad (2)$$

The cloud free optical satellite images of Resourcesat-2 AWiFS (Advanced Wide Field Sensor) and Landsat 7/8 were collected to identify snowlines of the glaciers during the four-year study period. The derived snowlines are overlaid on DEM to extract the mean altitudes of the lines for each date. The optical data were also used to find out the percentage area of the glacier basins under cloud cover for the year 2014 (Fig. 3). The percentage area under cloud cover provides information on precipitation pattern and concentration over the glaciated basins from east to west. Red, Near Infra-red and Short wave Infra-red bands of the optical data (SWIR) were used to classify the cloud over glacier catchment area. Maximum Likelihood classification without null class is employed to classify the image pixel in two category, i.e., cloud and non-cloud classes. Use of SWIR band reduces classification error by mixing of the signatures from snow and cloud. Error of the classification results increases in the presence of the ice clouds. However, the pattern of the cloud cover helps to reduce the mixing.

4. RESULTS AND DISCUSSION

4.1 Temporal Monitoring of Snowline and Firn Line Altitudes

The snow lines of the three Himalayan glaciers were identified from the classified SAR data of the ablation seasons. The optical data were also used independently to derive the snowlines. During the peak melting season, the snowline derived from two type of data set is closest (around 15 m). The difference increases as the melting rate decreases with the on-set of the accumulation season. Dryness in the snowpack allows radar beam to penetrate through the snow and interact with subsurface layers of the glaciers. During the starting of the summer season, a little increase in the temperature cause melting and changes radar backscattering returns. The optical data are unable to detect this moisture variation in the snow packs. Fig. 4 shows the temporal variability of the snowline altitudes of the four glaciers. Over the DD glacier, melting starts from the month of June, whereas, the same has been observed during the month of April for the ZM glacier of the eastern Himalaya. The average onset of the melting period is experienced during the month of May.

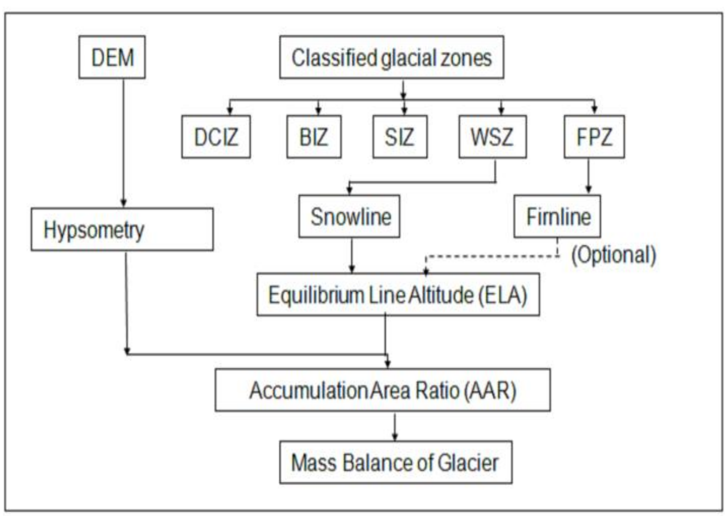

Fig. 2. Methodology followed to derive snowline, firnline, Equilibrium Line Altitude (ELA), Accumulation Area Ratio (AAR) and mass balance

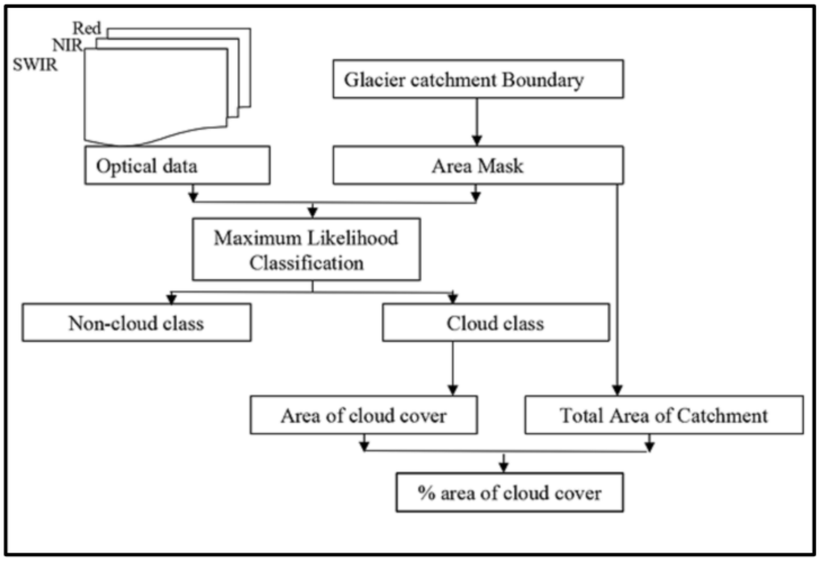

Fig. 3. Methodology of cloud cover classification and derivation of percentage cloud cover area over glacier catchment

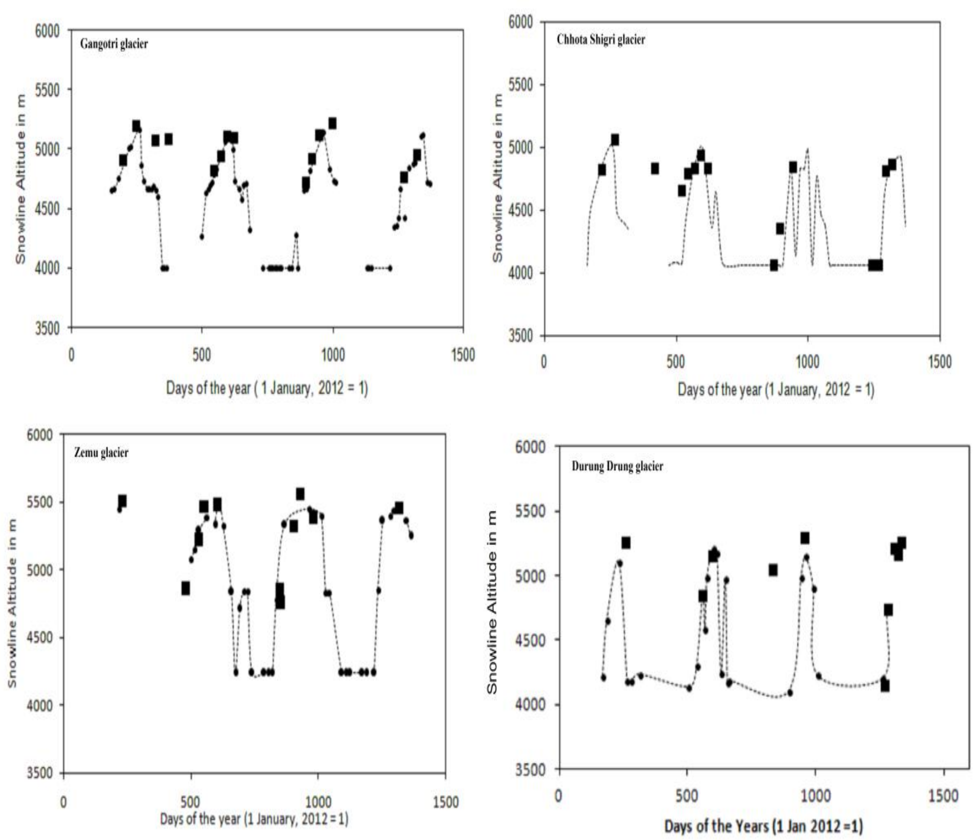

Fig. 4. Snowline altitudes derived from SAR data are represented by black squares. Dotted line with black circle is showing temporal changes in snowline altitudes identified by optical data. The graph includes snowline altitudes for four consecutive years from 2012 to 2015

Fig. 5 shows the altitudes of the firn lines. Variability of altitude is not significant for the firn lines throughout the accumulation seasons. Yearly variation in the mean firn line altitude is also negligible. The altitudes of the firn lines during the onset of the accumulation season are closest to the altitudes of snow lines at the end of the ablation season of any particular year. The lowest limit of the firn zone defines the extent of the accumulation zone of a glacier. However, SAR also detects old firn layers and mixes with the newer one and appears almost at the similar altitude each year. Therefore, identification of the ELA from the firn line altitude during peak winter season can introduce error in the result. In long term study, extent of the firn zone, however, reveals advancement or retreat of the glacier. The average firn line altitude of the ZM glacier is around 5400 m whereas; the other three glaciers have firn lines at 4900 - 5000 m altitude range.

4.2 Estimation of Mass Balance from ELA Derived from SAR Data

The ELAs of the three glaciers are derived from the highest snowline altitudes identified from the SAR derived classification outputs. Table 2 gives the ELAs of the three glaciers for the period of 2012 - 2015. The mass balance values are calculated from the ELAs by using the empirical method [18]. Table 3 is giving the mass balance values of the all these glaciers during 2012 - 2015. Mass balance of the Chhota Shigri (CS) glacier for the same period of time has been added in the table to get a complete database to understand regional variations.

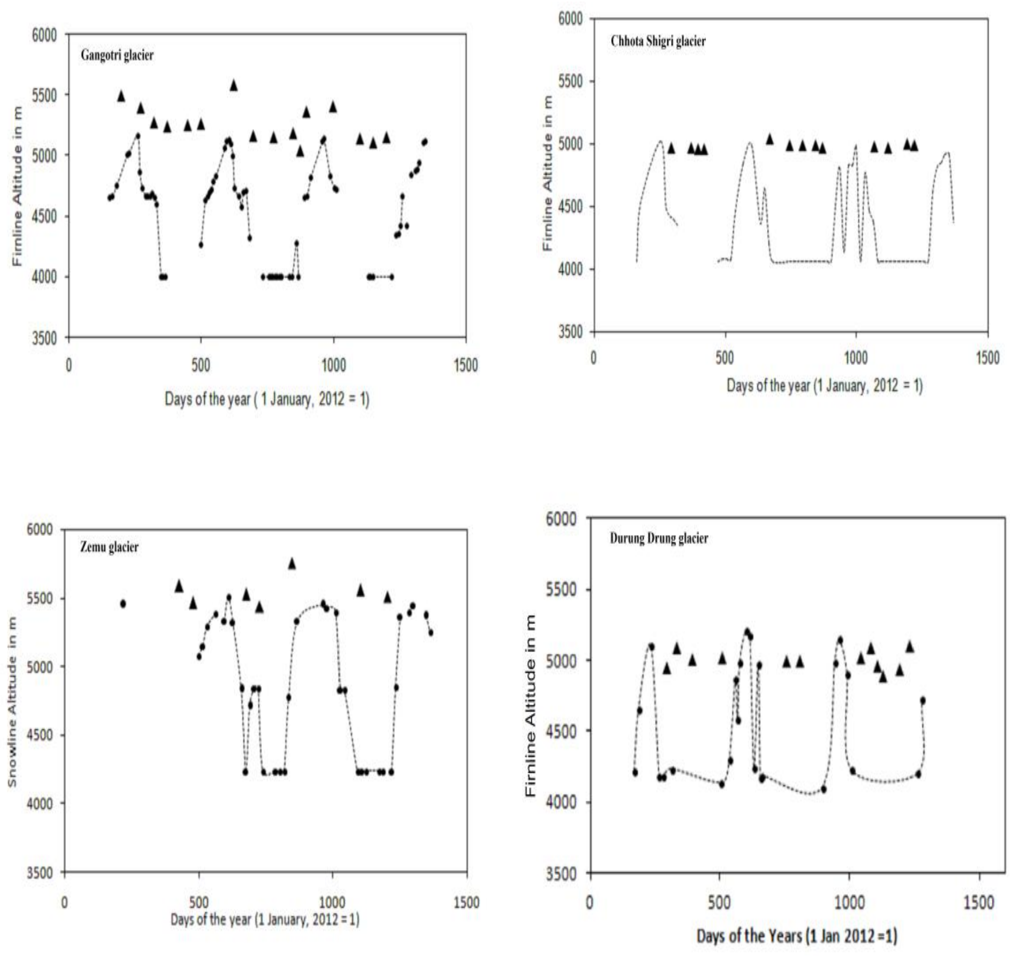

Fig. 5. The Firn line altitudes of the four glaciers for four consecutive years from 2012 to 2015 are shown in black triangles. The black dotted lines with black circles represent snowline altitudes of the four glaciers derived from optical data

Table 2. ELA (in m) of the glaciers derived from the highest snowline altitudes estimated from the temporal analysis of SAR data for the period of 2012 to 2015. Highlighted altitudes are derived from firn line during onset if accumulation season

Year	Durung Drung (DD)	Chhota Shigri (CS) [6]	Gangotri (GG)	Zemu (ZM)
2012	5257	5028	5194	5517
2013	5151	5019	5103	5479
2014	5173	4973	5114	5385
2015	5251	4913	5118	5465

Table 3. Mass balances (in m w.e. a^{-1}) of four glaciers are derived from the ELA estimated from the SAR data

Year	Durung Drung (DD)	Chhota Shigri (CS) [6]	Gangotri (GG)	Zemu (ZM)
2012	-0.31	-0.65	-0.69	-0.66
2013	-0.12	-0.59	-0.51	-0.63
2014	-0.16	-0.25	-0.53	-0.52
2015	-0.3	-0.03	-0.54	-0.61

In comparison to the central and eastern Himalayan glaciers, i.e., the GG and ZM, the western Himalayan glacier, the DD glacier, has better mass balance (Fig. 6). The similar result has been represented by Bahuguna et al. [19].

4.3 Effect of Weather Parameters over the Region Wise Differences in Mass Balance

The relationship between mass balance and regional variation in climate are not yet established firmly because of the insufficiency in weather and other ancillary data over the high altitude Himalayan regions. The GG and ZM glaciers are situated at southern side of 30° N latitude and the DD and CS glaciers are situated at north of it. Therefore, according to the latitudinal differences, glaciers are distributed in two major climatic regions, i.e., tropical hot & humid and mid-latitude alpine climatic zones. Throughout the longitudinal extension of the Himalaya, precipitation varies from east to west according to the orographic monsoonal precipitation. The meteorological weather stations are located at much lower altitudes compared with the terminal altitudes of the glaciers. Automated weather stations are installed near some of the selected glaciers in recent times; however, data on the variation in the weather parameters through the complete stretch of the Himalaya are not available. Therefore, analysis on the cloud cover concentration has been studied over the catchment areas of these selected glaciers. The probability of precipitation (solid/liquid form) is high at the presence of the cloud cover. It has been assumed that if the rate of cloud cover was high within a span of one year, the area would have received higher amount of precipitation over the catchment area.

Fig. 7 shows the percentage of the cloud cover area over the four glacier catchments for the year 2014. The occurrence of complete cloud cover over the catchment area (100%) is highest in the DD glacier for this selected year which decreased gradually over the other three glaciers from west to east. The number of days under the cloud cover is also high for the DD glacier. A higher occurrence of the cloud cover over the glacier catchment implies a higher probability of precipitation throughout the year. Precipitation at the high altitude mostly occurs in solid form which adds mass to the glacier. Situated in the rain shadow side of the Himalayan range and opposite aspect with the monsoonal air flow the GG glacier catchment has least percentage of cloud cover. The ZM glacier has maximum numbers of days of cloud cover which has around 50% coverage of the catchment area. Occurrence of the cloud cover is highly concentrated over the ZM glacier during the ablation season. During the winter season, the glacier has minimum cloud cover which implies minimum mass accumulation to the glacier during the accumulation season. Therefore, for the ZM glacier, major accumulation season coincides with the summer precipitation due to the south-west monsoon.

The DD glacier has very short melting period and the snowline altitude attains its maxima during the cloud free window at the end of the ablation season (Figs. 4 and 7). The snowline altitude starts to decrease with the appearance of the cloud which usually precipitates solid mass over the glacier and brings the snowline to the lower altitude from the month of October. The similar pattern is also observed for the other glaciers. However, differences are observed in the duration of the melting periods. The melting period of the ZM glacier is more than 200 days in a year which is the highest among the study areas. Table 4 has summarized the major ablation and accumulation seasons and the numbers of day's glaciers are exposed for melting. Obvious differences have been observed in the ablation and accumulation patterns. Variation in the accumulation rate, during the major accumulation season, affects the mass balance rates within the glaciers.

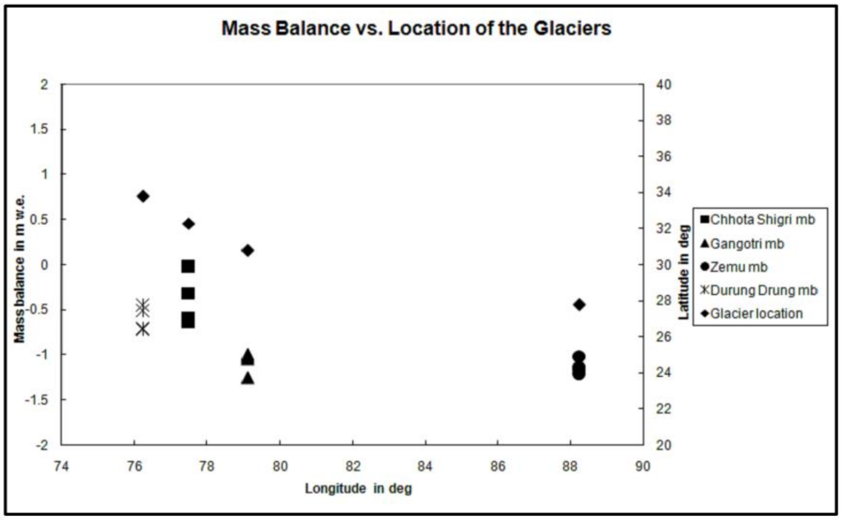

Fig. 6. Variation on annual mass balance figures (mb in m w.e.) compared with changes in geographical distributions. The star marks are showing geographical location (Lat/long) of the glaciers. Mass balance figures of four glaciers are when plotted against longitudinal positions the figures show that eastern and central Himalayan glaciers, i.e., Zemu and Gangotri have higher rate of loosing mass as compared to western Himalayan glaciers

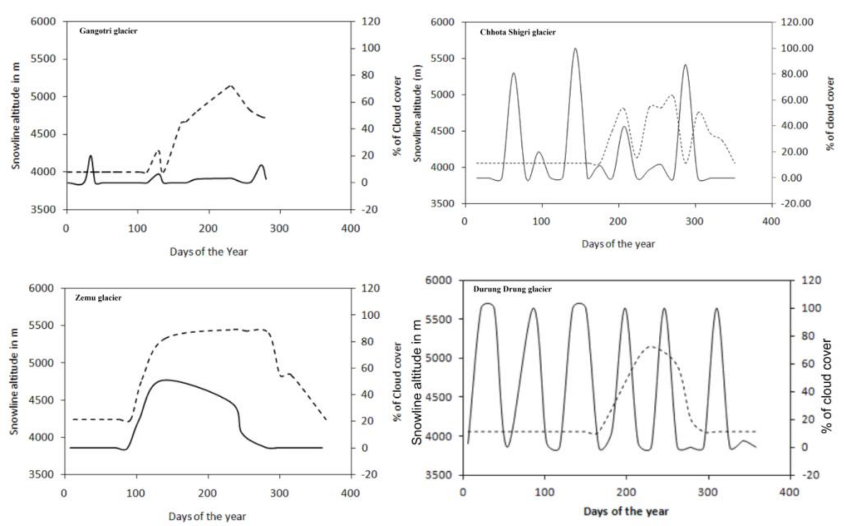

Fig. 7. Percentage catchment area under cloud cover has been alanysed for the year 2014 over four study areas, i.e., Gangotri (GG), b) Chhota Shigri (CS), c) Durung Drung (DD) and d) Zemu (ZM) glaciers (clockwise from top left). The graph shows major season of precipitation over the glacier catchments

Table 4. Major ablation and accumulation seasons derived from snowlines and cloud cover patterns of the four glaciers (DD = Durung Drung; CS = Chhota Shigri; GG = Gangotri; ZM = Zemu)

Name of Glaciers	Major ablation season	Major accumulation season	Melting period in days
DD	Middle of June - End of August	Starting of September - Middle of June	75
CS	Middle of May - End of August	Middle of September - Middle of May	100
GG	Starting of May - End of August	Middle of September - End of April	120
ZM	Starting of April - End of September	Starting of October - End of March*	200

**Very low rate of winter accumulation comparing with other three glaciers; precipitation takes place during summer also*

5. CONCLUSION

The use of SAR data for estimating mass balances of glaciers facilitates regular monitoring. Monitoring of mass balance data for the high altitude Himalayan glaciers at yearly basis can provide a complete glacier inventory which is still limited by the using either optical remote sensing data or field in-situ data. The years 2014 and 2015 have better mass balance for all of the four glaciers than the previous two years. The mean of mass balances of the glaciers during the study period is - 0.44 m w.e.a^{-1}. The individual mass balance figure varies significantly from west to east part of the Himalaya. Average yearly mass balance of the Durung Drung and Chhota Shigri glaciers, situated at western part of the Himalaya are - 0.22 and - 0.38 m w.e.a^{-1}, whereas, the Gangotri and Zemu glaciers are losing mass at an average rate of 0.56 and 0.60 m w.e.a^{-1}. This study also shows variations in the cloud cover over the study areas. The Durung Drung glacier of the western Himalaya has highest occurrence of cloud throughout the year which also helps to accumulate more solid precipitation over the glacier and improves mass balance. In contrast to the western glaciers, the cloud cover over the Zemu glacier is concentrated, especially, during the summer season. The Zemu glacier has very low amount of cloud cover during the winter time which accumulates small amount of solid mass. Lower rate of winter mass accumulation and high rate of summer precipitation may be the cause of more negative mass balance in the eastern Himalayan glaciers. However, the effects of cloud cover and precipitation over the glaciers require a detailed study over the high altitude Himalayan region. Use of the SAR data to estimate mass balance of the Himalayan glaciers increases scope to generate large amount of data in glacier inventory yearly. Regular yearly monitoring of the Himalayan glaciers can provide a better understanding on the effect of sub-tropical humid climate over the high altitude mountain glaciers and their dynamics which differ from glaciers of the polar region.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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