QUANTIFICATION OF GLACIER FACIES AND ELA DELINEATION IN WESTERN HIMALAYAS USING SENTINEL-1 SAR DATA

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Abstract

Mapping of different glacier zones & identification of equilibrium line altitude are the important factors which determine the rate of advance/retreat of a glacier. In this paper, the potential of using free of charge multi-temporal Sentinel-1 SAR images for glacier zones mapping in the Chandra basin of Himachal Pradesh is investigated. The glaciers in this region are influenced by South Asian monsoons in the summer and westerlies in the winter. So, the location of the glaciers of this region makes them significant to select for the study. The images recorded in three different months (January, May & September) of year 2015 & 2016 were used. Support vector machines (SVM) algorithm was implemented on twenty-four glaciers to classify the different zones lying on the glaciated terrain. Google earth imagery and RGB composite was used to select training samples and validate the classification results. SVM performs well with an accuracy of more than 90% for both the year. Further, the changes in area covered by each zone has been analysed for two significant years and the position of ELA for two benchmark glaciers namely Bara shigri and Chota shigri glacier has been demarcated. Results achieved depicts that the accumulation is more in year 2016 and ablation is more in year 2015 for the study area, it may be because of surrounding climate.

1. Introduction

The Himalayas are one of the world's greatest glacier systems, with the potential of enormous water storage and known as the 'water tower of Asia'. Major rivers of Asia originated from these glaciers and they are the only source of fresh water for millions of people living in Indian sub-continent. So, these freshwater reservoir must be regularly observed and it is significant to know the different facets of these glaciers such as glacier mass balance, glacier dynamics and zones distribution. Glacier mass budget is the outcome of snow accumulated in the upper part of the glacier and the ablation is the lower fragment of the glacier. With the scarcity of ground-based information in these harsh terrains, satellite based information is the most sensible way to analyse and evaluate the changes taking place. In terms of all-weather and all-day capability, radar remote sensing outperforms other approaches such as optical and infra-red (Ulaby et al., 1986). The development of remote sensing tools over the past few decades has made glaciological investigations easier, which would have otherwise been a laborious task given the severe environment and weather circumstances.

Multi-temporal SAR data have great potential in mapping glacier facies which leads to the glacier mass balance estimation. The SAR backscatter signals from snow and ice are highly dependent on the snow density, liquid water content, grain size and surface roughness (Benson 1962; Partington 1998; Venkataraman and Singh 2009; Zhou and Zheng 2017). Since SAR backscatter largely depends on the moisture content and surface roughness, different snow types such as dry snow, wet snow, new snow, old snow, bare ice, debris-covered ice, etc. can be differentiated (Winsvold et al. 2018). The glacier zones identified by SAR is generally termed as radar glacier zones and composed of dry snow, percolation zone, wet snow zone, bare/glacial ice and debris cover. Limited studies have been carried out to map/identify the glacier facies/zones using SAR data in the Himalayan region (Kundu and Chakraborty, 2015; Sood, 2015; Thakur et al., 2017; Das et al., 2018; Pandey et al., 2020; Panwar and Singh, 2021).

2. Test Site and Data Used

The study was carried out for 24 glaciers of Chandra basin located in Lahaul–Spiti district of Himachal Pradesh indicated by blue color boundaries (Figure 1). Chandra is the sub-basin of Chenab basin, lying on the northern edge of Pir Panjal range of the Himalaya with an elevation range between 2400 m above sea level to 6400 m above sea level. The selected region is composed of large extent of debris cover. South Asian monsoons in the summer and westerlies in the winter have impact on the glaciers of these regions (Bookhagen & Burbank, 2010).

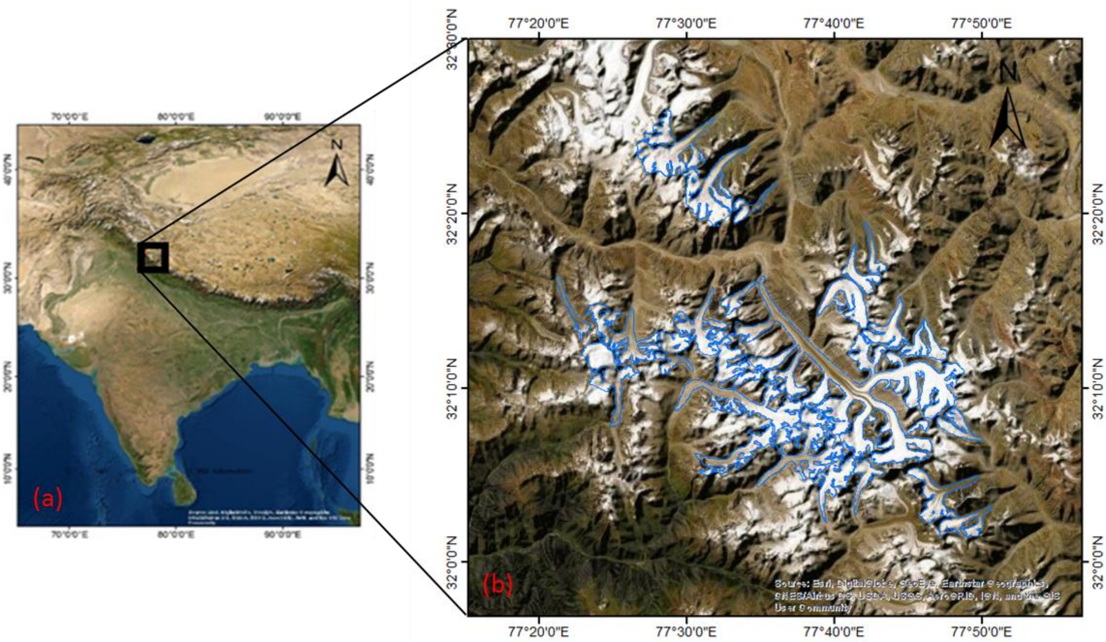


Figure 1: Overview of study area (a) India map (b) Glacier boundaries (blue color) selected for study obtained from base map, using ArcGIS 10.1

Table 1: Details of the data used in the study

Year	Date	Season	Orbit Direction
2015	30 January 2015	Winter	Ascending
	07 May 2015	Early Summer	
	03 September 2015	Late Summer	
2016	26 January 2016	Winter	Descending
	25 May 2016	Early Summer	
	22 September 2016	Late Summer	

Sentinel-1 SAR data was used to assess the glacier facies. Sentinel-1 mission of Copernicus Initiative of European Union was launched by European Space Agency (ESA) performing C-band SAR imaging, regardless of the weather, day and night conditions. For glacier facies mapping, three datasets from one year are required, each representing the winter, early summer and late summer season. Level-1 VV polarized GRD (Ground Range Detected) Sentinel-1 products of two consecutive year 2015 and 2016, were utilized for glacier facies mapping and ELA demarcation. Glacier topographical parameter i.e. elevation were obtained from the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) which is freely available covering over 80% of the globe.

3. Methodology

To identify different glacier facies, the methodology proposed by Partington (1998) has been implemented (Figure 2). This methodology involves the use of multi-temporal SAR data to generate the composite images using winter, early summer and late summer radar backscatter images. While winter image is passed thru blue band, early summer and late summer images are passed through red and green bands respectively and these images stacked to form a single three band (Partington, 1998). Generally, the late summer image define the maximum melting conditions and winter image defines the maximum freezing. Based on the temporal backscattering properties, different tonal variations on the glacier surface of the RGB composite represent different glacier zones. The intensity images of the study area obtained from Sentinel-1 SAR and SNAP software was used to pre-process data (ESA, 2020). The terrain correction was done using a digital elevation model and linear backscatter values were converted into decibels (dB). A composite image was generated for further classification process.

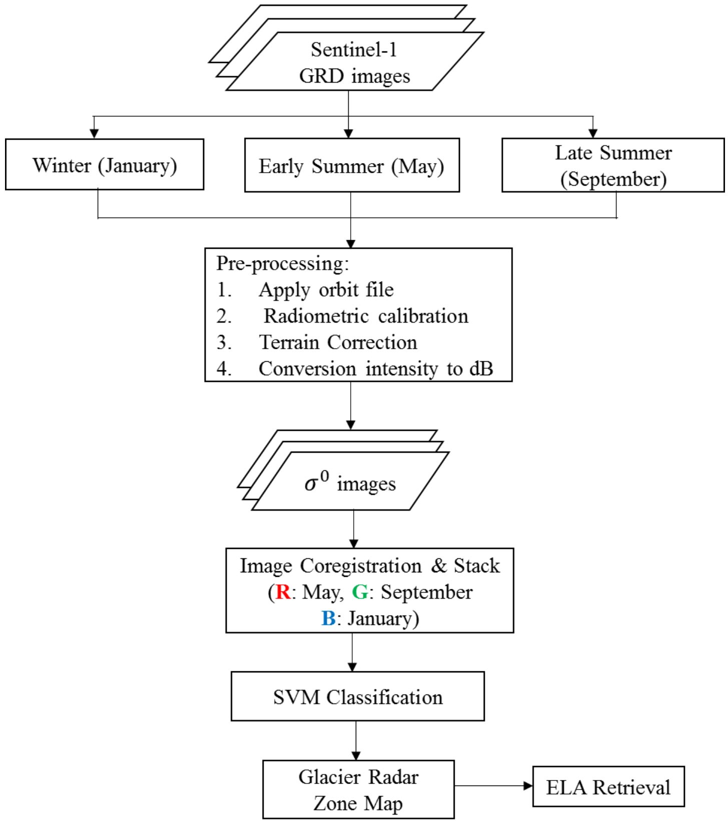
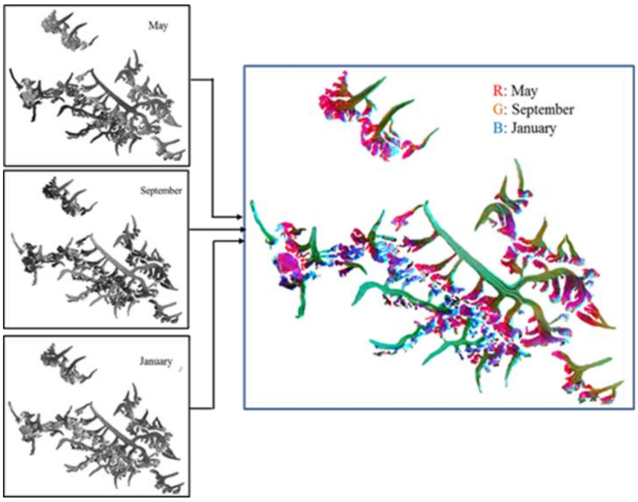


Figure 2: Overall methodology flowchart of the study

In this study, SVM is used for classification because of its efficient and robust nature (Camp-Valls et al., 2014). Since the approach used for classification is supervised in nature, so it requires the set of training data to be used for training the classifier. The reference and sample data was produced by creating the ROI polygons with the help of previously published studies and temporal backscatter characteristics. With the help of the RGB composite image (Figure 3), different radar zones are visualized clearly and training samples created. Apart from SVMs, other classifiers (supervised or unsupervised) may also be applied to classify different glacier facies. The confusion matrix based accuracy measurement was used to assess the classification accuracy (Cogalton 1991). The overall accuracy was used to indicate the accuracy of the classified images.

4. Results and Discussions

Classification of glacier zones was performed using Sentinel-1 datasets and multi-temporal SAR based method. Usually the glacier facies/zones comprises of dry snow and wet snow facies, percolation facies, debris cover and bare ice facies and distributed from higher to the lower elevation of glaciers. Generally, the glacier radar zones follows altitudinal pattern. SAR senses the dry snow facies as a dark region, because of the comparable size of the snow grain and C-band radar signal (Partington 1998). This zone has generally been absent in case of Himalayan region. Due to melting and freezing, the pipes like structures formed in percolation zone called ice pipes/ice lenses. These pipe like structures can produce a very high radar backscatter return and appears bright in SAR image in winter data. Generally, within the percolation/wet-snow facies we will expect to find three different zones at varying elevations.



Glacier Facies	Seasonal Characteristics: Winter (Blue)	Early Summer (Red)	Late Summer (Green)	Appearance in RGB Composite
Upper Percolation	Dry Snow	Dry Snow	Dry Snow melting	Greenish white
	High	High	Slightly higher	
Middle Percolation	Dry Snow	Dry snow melting	Melting Snow	Pink/Purple
	High	High	Low	
Wet Snow/Lower Percolation	Dry snow Melting	Firn exposed	Firn melting	Blue
	High	Low	Low	
Bare Ice	Snow melting/ ice exposed	Ice melting	Excessive Ice melting	Reddish/ Greenish black
	Low	Low	Low	
Debris cover	Debris	Debris	Debris	Light Greenish Grey

Figure 3: RGB composite for the year 2015 – generated by assigning blue to winter image, green to late summer image and red to early summer image, table for appearance of different glacier facies in RGB composite in different season

At the highest elevation (the upper percolation zone), there is no melting and consistently high backscatter observed for all three season. Further down (the middle percolation), melting occurs in the late-summer but not in the early-summer or winter and the backscatter will be uniformly high during winter and early summer and low in late summer. Finally, towards the lowest altitudes in the percolation/wet-snow zones (the lower percolation/wet snow), melting takes place in both early- and late-summer season, so the backscatter would be high in the winter and low in both summer season. In the lower part of glacier (called ablation zone), bare ice and debris cover zone are present. Higher temperature, along lower elevations, give rise to snow melting that causes variations in backscattering intensities of different glacier zones. As time proceeds from winter to early summer and the late summer, temperatures gradually increase giving rise to temporal variations along different glacier zones. Increase in liquid water content of snowpack, exposure of underlying ice layers subjected to change in scattering mechanisms from volume to surface scattering.

Classification was performed on two glaciers of the study area for a period of 2 years - 2015 and 2016. Support vector machines (SVMs) was used for classification with the help of radial basis kernel function. The classified outputs representing different glacier zones, are displayed in Figure 4. Classified map present five classes of glacier zones - Upper Percolation Zone (UPZ), Middle Percolation Zone (MPZ), Wet Snow Zone (WSZ), Debris Cover Zone (DCZ) and Bare Ice Zone (BIZ). The results from radar image analysis shows a general pattern of zones/facies distribution on the surface of selected glaciers in the Western Himalaya. The zones on the mountain glaciers follow an altitudinal pattern with the percolation zone (dry snow zone is absent in case of Himalayas) located at higher reaches followed by wet snow, bare ice and debris, respectively. The highest zone predominantly consists of percolation facies – upper percolation zone, middle percolation and wet snow facies. The dry snow facies were absent for the selected area.

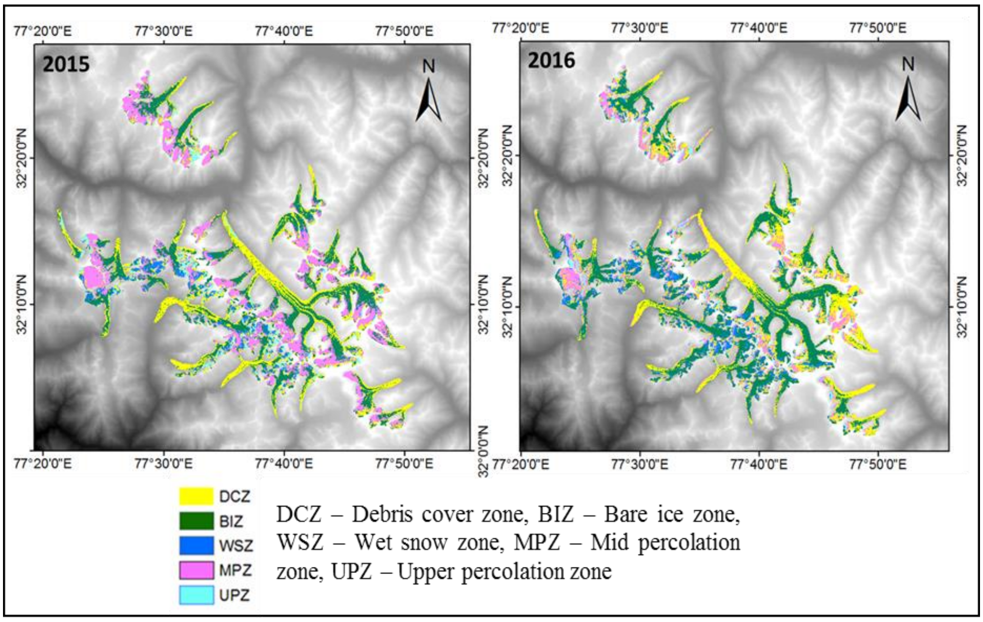


Figure 4: Classified maps using SVM

A glacier is totally dynamic in nature, so always there is difference in the areal extent of derived classes. The total area of accumulation zone is more in the year 2015 and lesser in 2016 collectively for all 24 glaciers. In Bara Shigri, the accumulation zone occupies roughly 41% in the year 2015 and about 32% in the year 2016. Rest is the ablation zone which is 59% in 2015 and 68% in the year 2016. From the classified maps, it can be seen debris cover is extensive over the Chota Shigri and Bara Shigri. Equilibrium line altitude (ELA) separates the accumulation zone from the ablation zone and works as a reliable indicator of glacier health (Kulkarni, 1992). The fluctuations in ELA gives an idea about the trends of the glacier i.e. advance or retreat. ELA is strongly influenced by surrounding climatic and temperate conditions.

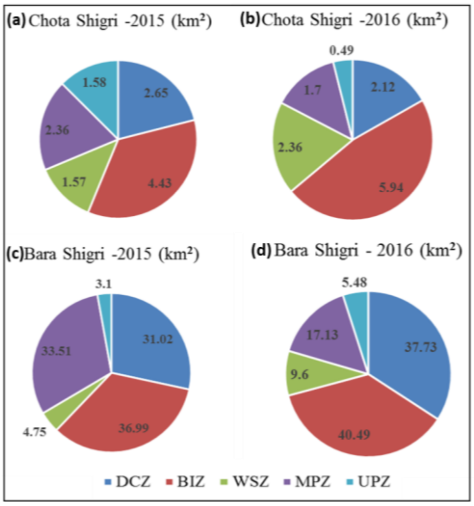


Figure 5: Facies Area changes for Chota Shigri and Bara Shigri glaciers

Due to warmer temperatures, ELA moves upwards in elevation which specifies the area covered by accumulation zone reduced and ablation area increases that indicates retreat of glacier health. On the contrary, over cold conditions, ELA moves downwards in altitude representing advancing health of the glacier and positive glacier mass balance. After classification of glacier zones, we were able to successfully delineate the equilibrium line altitude for glaciers in consideration for the years 2015 and 2016. ELA for both the year is manually demarcated and displayed in Figure 6 for Chota Shigri and Bara Shigri glacier. 2015 had ELA at the lowest for both the selected glaciers.

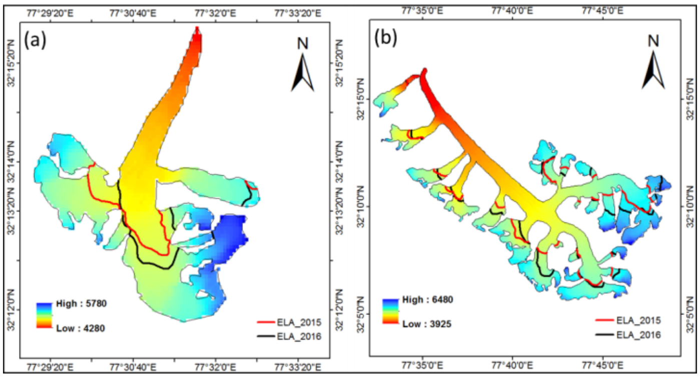


Figure 6: Illustration of change in ELA positions over (a) Chota Shigri (b) Bara Shigri glacier in the year 2015 and 2016

5. Conclusions

Multi-temporal SAR backscatter data of winter, early summer and late summer were used to make a RGB color composite to distinguish the different radar glacier facies in the Western Himalayas for two different years. Glacier zones distribution and ELA retrieval are important to understand the glacier mass balance and glacier dynamics. The efficacy of support vector machine for multi-temporal SAR data for delineating glacier features and manual ELA delineation has been revealed in this study for two consecutive years. SVM performs well with accuracy of more than 90% for both years. This study gives an idea how ELA and zones changes in two different years. The accumulation area is more and ELA is at the lowest in year 2015 for both Chota Shigri and Bara Shigri glaciers. Glacier zones classification and distribution of their area provides the link between the mass balance and the dynamics of glacier which further assist the monitoring of glaciers. Further, assessments over other regions of

Himalayas can also be done and analysis from satellite observations should be substantiated with field observations.

6. References

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