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DELINEATION RADAR ZONES OF GLACIERS IN THE ALA-ARCHA VALLEY OF KYRGYZ REPUBLIC

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ABSTRACT:
Glaciers are a critical source of freshwater, especially during the lean season. Globally, the glaciers are losing their mass balance rapidly under the influence of climate change. In view of this, the regular study of these glaciers is very vital. However, field-based studies of most of the glaciers is a daunting task. On the contrary, emerging geospatial technology may play an important role in the studies of glaciers. The equilibrium line altitude (ELA) of the glaciers has been considered an essential indicator of climate change. There are numerous methods to delineate the equilibrium line of a glacier; however, each has its own merits and demerits. In the present study, the synthetic aperture radar (SAR) remote sensing-based approach has been used for identifying the ELA of glaciers in the Ala-Archa River catchment of Kyrgyzstan from 2015 – 2019. Initially, the glacier radar zoneswereemapped using the Sentinel-1 SAR datasets of each year under consideration. It was found that mainly the middle percolation, lower percolation, and bare-ice zones along with debris cover-ice are present in the glaciers. It was observed that the percolation refreeze zone covers approximately 40%, and the Bare-Ice zone covers 48% of the total area. Considering the boundary of lower percolation and bare-ice zone as ELA, the ELA of each glacier in each year was estimated. The lowest ELA of 3462 m was observed in 2018, whereas the highest (4309 m) was recorded in 2019. It was noticed that the trend of ELA is consistently increased from 3839.25 m in 2015 up to in 3868.29 m 2019. The temporal analysis of glacier radar zone estimation and ELA may help in studying the impact of climate change on glacier retreat and mass balance change. It can be concluded that geospatial techniques can make the glacier change studies possible without field survey. However, to validate the results of the study, field observations are a must.

Key-words: *Glacier, Radar zone, Ala-Archa river valley, SAR imagery, Sentinel-1.*

1. INTRODUCTION

The cryosphere is one of the geographical spheres of the Earth, which is characterized by the presence of ice (Dostovalov and Kudryavtsev, 1967). Glaciers are formed as a result of the accumulation and transformation of solid precipitations. However, both these parameters are largely affected by climate change. Most of the glaciers over the globe are showing negative mass balance, and their Equilibrium Line Altitude (ELA) is shifting upwards, or glaciers are treating continuously (Beniston et al. 2018; Das and Chakraborty 2019). It is predicted that most of the glaciers in the High Mountain Asia region may lose their mass balance of approximately 64 ±5% by the end of the century (Hock et al., 2019).

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As glaciers are one of the major freshwater sources, the runoff from them is especially important in summer and early autumn when the water demand is high and the flowis minimal (Bolch2015). Therefore, their mass loss may impact water resources availability in the region. It is to be noted that the ELA has been considered as one of the critical parameters of climate change impact. Further, the glacier area below the ELA may be considered as ablation and the area above it as accumulation. The ratio of accumulation area and the total area is known as the area accumulation ratio (AAR) (Meier, 1962). It is again an important parameter for glacier mass balance studies. The accumulation area ratio has a significant effect on the retreat or advance of the glacier (Brahmbhatt et al., 2014), because both parameters are highly affected by air temperature and precipitation.

On the contrary, these are located in high altitudes or rugged terrain; therefore, their study through physical field surveys or visits is a daunting task. Geospatial technology has emerged as an effective tool in mapping and monitoring these glaciers at regular intervals throughout the year (Garg et al., 2021). Initially, the optical remote sensing data were extensively used for glacier mapping. Glacier mapping helps to generate snow line, consequently equilibrium linealtitude, accumulation area ratio. The equilibrium line is usually considered as the snow line at the end of the glacier melt season. A clear relationship exists between its position and the annual mass balance (Meier at all., 1962). By continuing the same survey for several years, temporal changes of such mentioned elements can be generated. Most glacier dynamics researches and glacier mapping in Kyrgyzstan are based on optical images (Aizen et all., 2007; Shabunin 2018). The optical remote sensing data has constraints with respect to the presence of clouds, due to which glaciers may not be visible during a large period of time in a year.

However, with the advent of synthetic aperture radar (SAR) technology, it is now possible to study the glaciers anytime in a year. Radar surveying has a number of advantages and features compared to optical and infrared sensors (Mouginot et al., 2017; Brancato et al., 2020; Mohajeraniet al., 2021):

- Meteorological independence: mostly the microwave frequencies remains unaffected by cloud cover or aerosols
- Independence from light conditions: Observation process during dark time is possible
- High accuracy in measuring geometric features of the target
- Possibility of making 3D models and mapping
- Ability to obtain physical parameters such as dielectric constant and structure

SAR has now become the most suitable technique in cryosphere monitoring and observation. The technology has been utilized for the determination of dry and wet snow/ice, glacier radar zone mapping, glacier surface velocity, etc. extensively. The main goal of this research was to map different glacier radar zones for better estimation of ELA. Earlier, the optical data of the end of the ablation period was generally used for the purpose; however, during this time, the probability of cloud in the images is high. Therefore, the ELA retrieval after or before this time period may be erroneous. Further, the ELA is usually identified in these images based on visual interpretation. The accuracy of the identified ELA again depends upon the capabilities of the observer. The researchers have also proposed hypsometric or geodetic approaches for the ELA with the use of a digital elevation model (DEM). However, the availability of DEM with high Spatio-temporal resolution and accuracy is further a constraint in such analysis. However, the SAR data may have different backscattering in different seasons, attributing to snow/ice conditions. Exploiting the backscattering mechanism in different seasons, researchers have identified distinct glacier radar zone. It is considered that the boundary of the bare ice zone and the adjacent wet snow or percolation-refreeze zone is generally called an actual transient snow line. Therefore, the present study is performed in virtue of Sentinel-1 SAR datasets. Sentinel-1 is the Copernicus Program satellite which was developed by European Space Agency (ESA). C-band sensors of Sentinel-1A satellites have 10 m resolution and swath up to 400 km along with the temporal resolution of 12 days.The glaciers in Ala-Archa River Basin are considered for the present study. The basin water is the main source to the capital city of Kyrgyzstan, i.e., Bishkek and arable lands of Chui valley.

2. STUDY AREA

The high elevation of the Tien Shan mountains (JengishChokusu Peak 7439 m and 4895 m in Kyrgyz Ala-Too range) allows forming permanent ice, snow, and firn in high altitudes. The Ala-Archa river catchment remains one of the most glacierized zones, as it is surrounded bythe highest and central part of the Kyrgyz Ala-Too mountain range in the northern Kyrgyz Republic. The basin is located between 42°15'00" – 43°15'00" N latitude and 74°15'00" – 75°00'00" E longitude as shown in **Fig. 1**. Glaciers occupy 29.8 km² between the elevation range from 4716 to 3271 m (Zholdoshbekov 2020).The Kyrgyz Ala-Too (Kyrgyz Range) represents the north-western part of the Tien Shan mountain system. Kyrgyz Ala-Too is the second most extensive mountain range after the Kakshaal range in Tien Shan. It extends in a longitudinal direction over 454 km (Atlas of Kyrgyz SSR, 1987).It is separated from other parts of the Tien Shan Mountains from the east side with Boom (Boam) canyon, from the south side with Kochkor, Suusamyr, and Talas intermountain depressions. As Voda et al. (2019) pointed out, the morphometric characteristics of the river basin are very important. It can be seen that the slopes are asymmetrical;on the southern side, it is short and steep, whereas on the northern slope gentle and long. The northern slope is fractured with deep (1000-1500) valleys such as Ala-Archa in the meridional direction. Altitudes range from 630 m on the Ala-Archa river mouth to 4895 m on BatyshAlamudun peak, the highest point of the Kyrgyz Ala-Too range.The lower part of the Ala-Archa river basin contains part of Chui valley. The total area of the catchment is 270 km².

According to data of hydrometeorolgical sevice of Kyrgyz Republic the mean annual discharge of the Ala-Arch ariver is 4.69 m³/sec (Kashka-Suu river mouth). The Ala-Archa river contributes the water from glacier and snowmelt water (Water resources of USSR 1973). Water from the Ala-Archariveris used for irrigation using drainage canals andthe Ala-Archa reservoir. In the mountainous part of the catchment, a national park was established in 1976 with the same name.

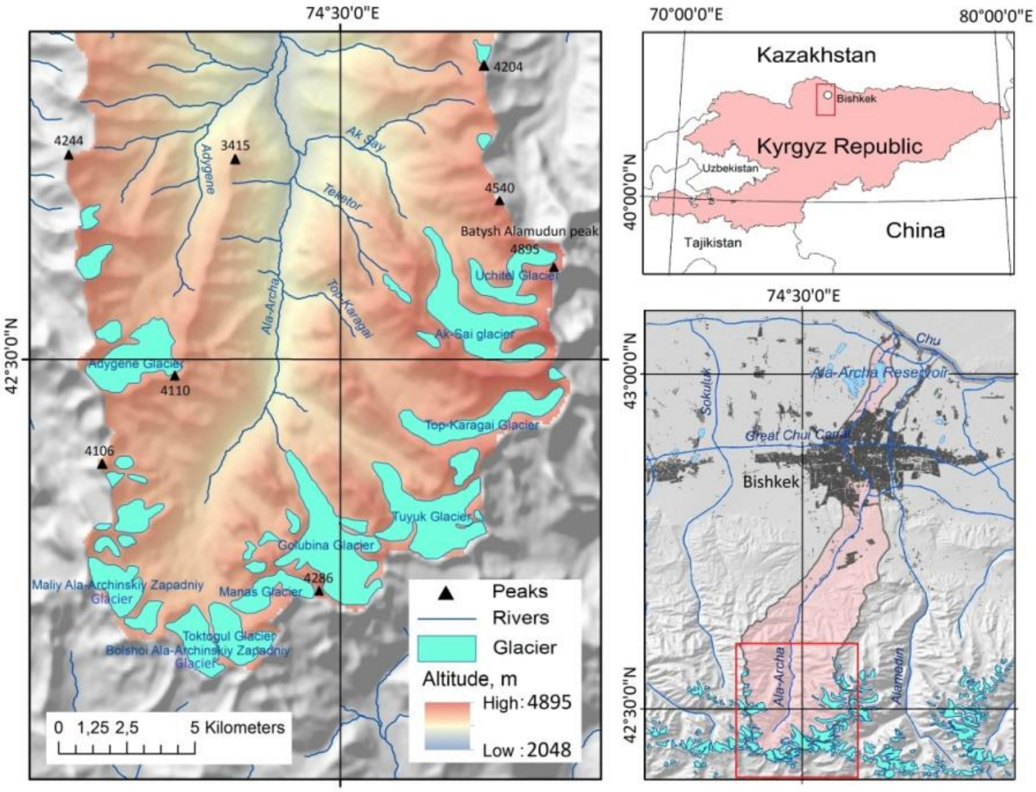

Fig. 1. The location oftheAla-Archariver catchmentand its glaciers inthe Kyrgyz Republic (SRTM DEM utilized for physical map, topography shade generation and RGI for distribution of glaciers).

3. DATA AND METHODS

Variation in glacier's ELA is an important indicator of climate change impact (Thakur et al., 2016; Gupta et al., 2018).Therefore, the identification of ELA with higher accuracy is critical in such studies. Generally, the optical remote sensing data has been used for the delineation of ELA. However, the data suffer from the availability of cloud-free data during and of ablation period. On the other hand, the geodetic methods require a high-resolution DEM dataset for the year of analysis. Considering the limitations of optical remote sensing data and DEMs, in the present study, SAR data-based technique has been adopted, as shown in **Fig. 2**. The temporal Sentinel-1 C-band VV Polarization SAR datasets for the years 2015-2019 were utilized (details are provided in **Table 1**). Cross-polarization (VH or HV) gives information based largely on volume scattering, whereas co-polarized signals (HH or VV) are large contributions from surface scattering (Massom and Lubin, 2006). According to Fu et al. (2020), the cross-polarization is practically comparable to the co-polarization having an absolute value lower than 6 dB.

Our interest was to retrieve surface backscatter;in this study, images with VV polarization were utilized. The data was initially pre-processed for orbit, radiometric and geometric corrections. Co-registration is applied using external DEM, i.e., SRTM 90 m. After taking the subset of the area of interest,the geometric correction was completed. After geometric correction due to side-looking characteristics of SAR image, some distortions could be formed. Layover shadows can be reached 3% among glacier areas in the current research area. Finally, the intensity values were converted into dB.Then, theRGB composite of the SAR data of three different seasons was generated for each year under consideration. In the northern slope of the Kyrgyz Ala-Too range, the peak of dry snow occurs at the end of January and the start of February, wet snow in May, and the peak of glacier melting at the end of August. The different tonal variations in the backscattering of composite images represent different glacier radar zones (Mahagaonkar, 2019). Therefore, the images from spring (wet snow facies may occur), summer (peak of glacier melting), and winter (peak of dry snow accumulation) seasons, when glacier surface remains in different backscatter conditions, were used. The spring image was used in Red, summer in Green, and winter for the Blue channel to generate RGB composite.

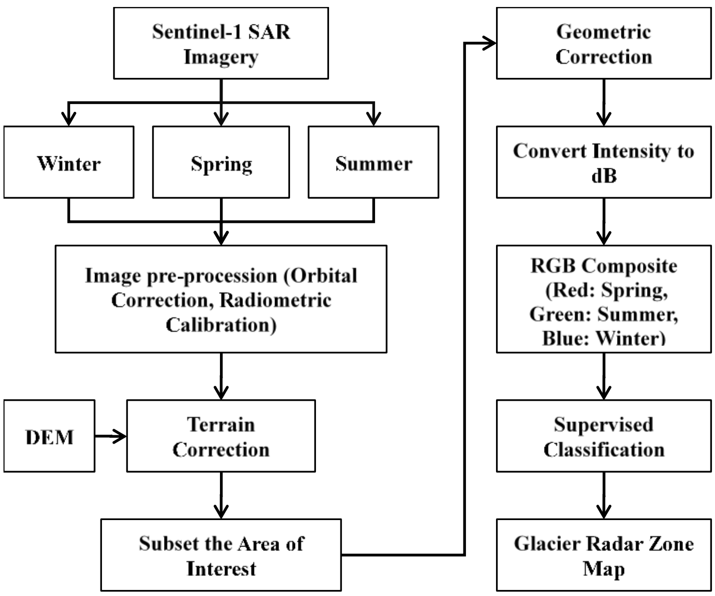

Fig. 2. Methodological flowchart for classification glacier zones by using multi-temporal Sentinel-1 SAR data.

Table 1.

List of C-band Sentinel-1 datasets used for glacier radar zone estimation.

Mission	Product type	Beam mode	Orbit	Orbit type	Polarization	Date
S1A	GRDH	IW	4124	A	VV	11.01.2015
S1A	GRDH	IW	5699	A	VV	29.04.2015
S1A	GRDH	IW	7449	A	VV	27.08.2015
S1A	GRDH	IW	9724	A	VV	30.01.2016
S1A	GRDH	IW	11124	A	VV	05.05.2016
S1A	GRDH	IW	12874	A	VV	02.09.2016
S1A	GRDH	IW	15149	A	VV	05.02.2017
S1A	GRDH	IW	16374	A	VV	30.04.2017
S1A	GRDH	IW	18124	A	VV	28.08.2017
S1A	GRDH	IW	20224	A	VV	19.01.2018
S1A	GRDH	IW	21799	A	VV	07.05.2018
S1A	GRDH	IW	23549	A	VV	04.09.2018
S1A	GRDH	IW	25627	A	VV	25.01.2019
S1A	GRDH	IW	27027	A	VV	01.05.2019
S1A	GRDH	IW	28777	A	VV	29.08.2019

S1A: Sentinel-1 A; GRDH: Ground Range Detected High Resolution; IW: Interferometric Wide (IW) swath; A: orbit type represents ascending pass; VV: Vertical-Vertical polarization.

The entire analysis till this step was carried out in SNAP software. In the RGB image, the debris-covered area would appear bright due to high scattering in all seasons, bare ice – greenish, low percolation zone as blue/purple, and middle percolation zone with pink/magenta color. A bare ice zone represents the ablation zone of the glacier. An ablation zone is also characterized by the presence of a surface water flow of melted ice. If crevasses are more and denser, the surface flows may decrease. Clean water and pure ice have a low dielectric constant. Therefore, signals in the microwave region will penetrate into pure ice thickness up to 10 meters (Woodhouse, 2006). Due to the high percolation of microwaves, the bare ice zone appears dark in RGB of the SAR images.

Percolation zones: After the co-registration process, we can see in RGB image three high, middle, and low percolation zones. Low percolation takes place in dry snow, which has less liquid content and high porosity. This phenomenon can be observed at high altitudes with an annual temperature is about -25^{o}C. During the snowmelt, due to excessive water content, backscattering may decrease. In RGB image middle percolation zone appears in pink or purple, low percolation area in blue color. In the case of icefalls and dense crevasses, backscatter increases due to specular reflectance due to high surface roughness. Debris-covered ice can be classified as different glacier zone due to different physical properties. Ice surface moraine, which is represented by debris cover, closes direct sun radiation and delays ice melting. Due to high reflectivity by the low dielectric constant and surface roughness, debris covers appear from SAR imagery with light and grey light color.Further details on glacier radar zones may be found at Partington (1998); Rau et al. (2000).

For better extraction of glacier radar zone, the Support Vector Machine (SVM) classification technique was used. This algorithm is suitable for classifying complex and noisy images. It separates the classes with a decision surface that maximizes the margin between the classes (SVM Tutorial, 2020).The literature suggested that the algorithm is most suitable for snow cover classification (Tsai et al., 2019; Alifu et al., 2020). For classification, signature sets were chosen according to backscattering characteristics and represented by the colors of each zone in the RGB image. SVM classification was performed in ENVI software. The following parameters were chosen for the classification: Kernel Type as Radial Basis Function, γ = 0.33, and the Penalty Parameter as 100. Glaciers of Ala-Archa valley are classified in the following classes based on backscattering phenomena: debris-covered ice; bare ice; low and middle percolation zones. In the classified image, the debris-covered area was represented with yellow color, bare ice–brown, low percolation zone with blue, and middle percolation zone as pink color. It is worth noting that it is hard to distinguish the shadow region which appears after geometric correction and debris-covered areadue to the high backscattering of both in SAR composite.However, shadowareas can be differentiated by terrain correction using SNAP software. Generally, the line demarcating the bare-ice and lower percolation/wet-ice zone is considered as ELA. In this way, the ELA of each year for each glacier of Ala-Archa valley was identified. The identified ELA was then overlaid on the ALOS PALSAR 12.5 m DEM to determine the elevation in each year. The change in elevation would suggest the impact of climate change.

4. RESULTS

The flow in the Ala-Archa River is very vital for Bishkek, the capital of the Kyrgyz Republic. It mainly depends on the melting of snow or glaciers in the valley. However, most of the glaciers are showing negative balance across the globe under changing climate. The ELA of a glacier is being considered one of the primary indicators of climate change. Thereare a number of techniques to estimate the ELA of a glacier; each has its own advantages and disadvantages. For the present analysis, SAR based technique has been used. Initially, the glacier radar zones of all the glaciers falling in Ala-Archa River valley were mapped using the Sentinel-1 SAR data for 2015-2019.

4.1. Glacier Radar Zone classification

The SAR images of different seasons in each year were stacked to generate an RGB composite, as mentioned in the Method Section. As the liquid water content of a glacier changes due to season, the glacier surface features would reflect different tonal variations. For the example, the SAR images of the different season and RBG composite of the year 2019 is shown in **Fig. 3**. The tonal variation (as discussed in the Method section for each zone) of the backscatter values in the composite was then used for the identification of glacier radar zones.

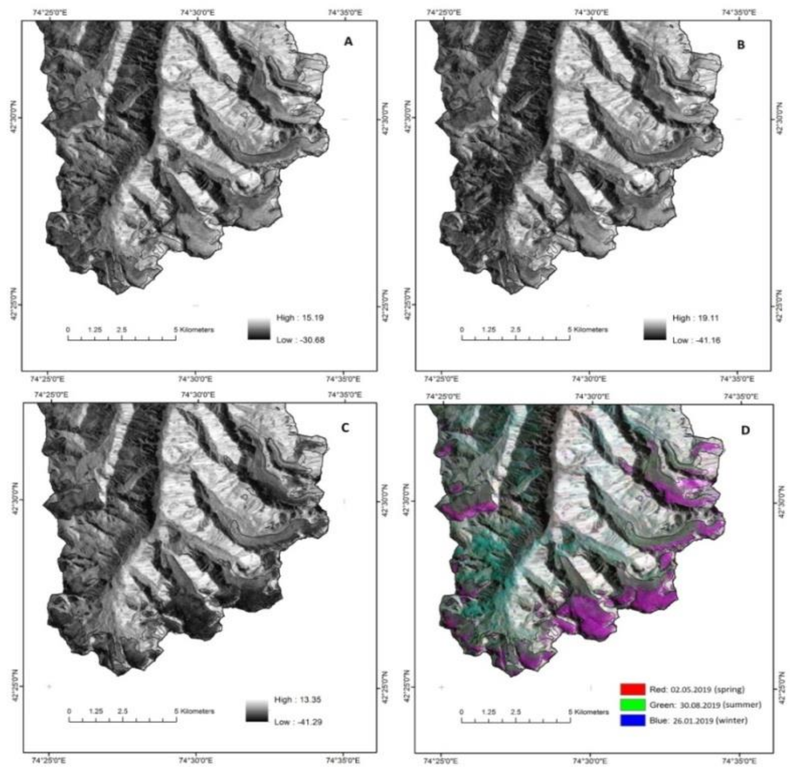

Fig. 3. Backscatter intensity images with VV polarization for A) 26.01.2019, B) 02.05.2019, C) 30.08.2019, and D) RGB composite image created by using multi-temporal backscatter images.

The glaciers of Ala-Archa valley showed three distinct zones bare ice, low and medium percolation, and debris-covered ice. Further, the change in ablation and accumulation zones over time can be verified by temporal variations of glacier radar zones.

To assess the area under each zone, the RGB composites of each year under consideration were classified using the SVM method, as discussed earlier. The results of classified glacier radar zones are provided in **Fig. 4**. The temporal changes in each zone area are provided in **Table 2**. Share of middle percolation zone estimated around 40% from the glacier area. It has the maximum area in Golubina and Tuyuk glaciers, as seenin **Fig. 4**. Ablation zone has the greatest area in Adygine, Top-Karagai, Maliy Ala-Archinskiy Zapadniy, Bolshoi Ala-Archinskiy Zapadniy glaciers.

The highest variability of glacier zones is observed in small glaciers. In some years, small glaciers overlay under almost the same glacier zone, and this statement can be rapidly changed next year. Here the accumulation zone, which comprises low and middle percolation areas, occupies 37.3% in 2015, 43.64% in 2017, 43.54% in 2018, and 44.94 in 2019 from the total area of the glacier. It can be seen that the accumulation zone area has increased by around 8.54% in the observed years. The debris-covered zone was keeping around 10% of the total area during the study period. The bare ice zone represents the ablation zone. It can be seen that the bare-ice zone maintains an area of around 48% throughout except for the year 2019.

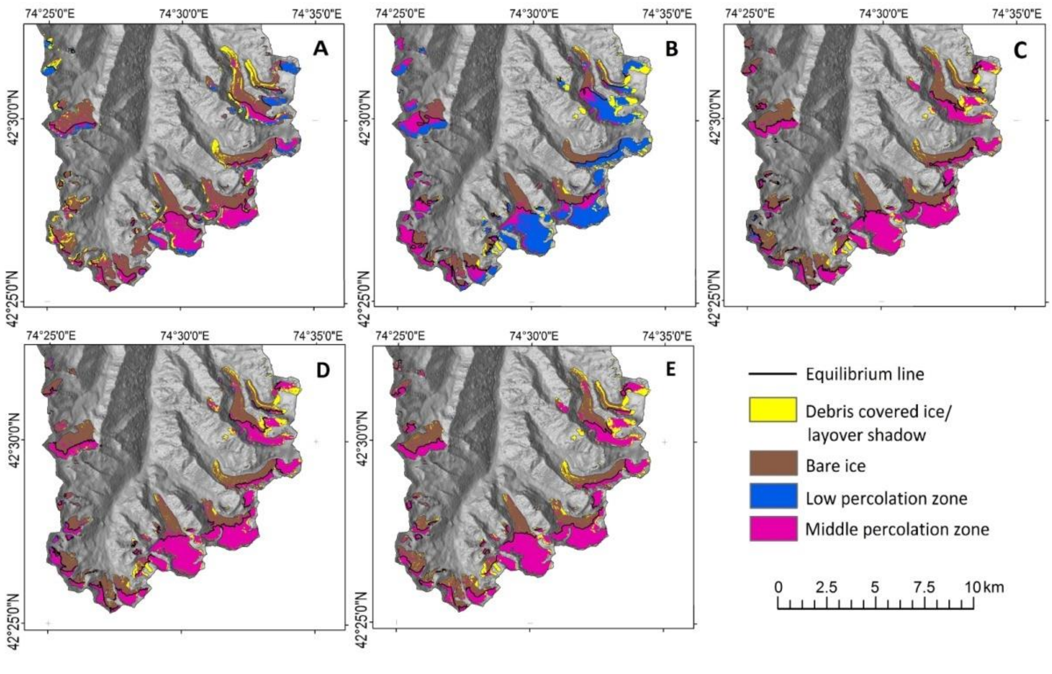

Fig. 4. Classified maps of Ala-Archa valley glacier for A) 2015, B) 2016, C) 2017, D) 2018 and E)2019. Hill shaded map on the background generated by using ALOS PALSAR DEM.

Table 2.

Annual changes of glacier radar zones in Ala-Archa valley (in %).

Glacier faces	2015	2016	2017	2018	2019
Debris covered ice	14.39	10.76	8.47	9.76	12.96
Bare ice	48.29	27.28	48.18	46.70	42.09
Middle percolation	28.37	22.89	41.78	41.97	43.88
Low percolation	8.93	39.05	1.86	1.57	1.06

4.2. ELA Analysis

The boundary between the bare ice zone and low percolation area is generally identified as the equilibrium line. Overlaying the equilibrium line over the DEM,one can generate ELA. For ELA calculation ALOS PALSAR DEM was utilized as mentioned in the previous section. The mean value of ELA was found to be 3853.4 m. According to Aizen et al., (1997) the ELA of the Ala-Archa glaciers was 3848 m. The lowest value of ELA 3462 m was observed in 2018. The highest elevation of the snow line was recorded in 2019 (4309 m). The lowest elevation of ELA was observed in 2019 was 3662 m which was close to the mean ELA (**Table 3**).

The high variation of minimum and maximum values of ELA can be explained due to the location of an ablation zone in a higher elevation (**Fig. 4**). The wind blows snow cover, and ice can be bared in high elevation zones. Also, due to different expositions, ELA gives high-altitude ranges. The trend of ELA for each glacier is shown in **Fig. 5**. Most of the small glaciers are coming in the ablation zone. The linear trend of ELA increased from 3839.25 m in 2015 to 3868.3 m in 2019 **(Fig. 5).** The variation observed in the shift of ELA or change in glacier radar zones is mainly attributing to climatic conditions around the glaciers.

Table 3.

The statistics of ELA of the glaciers in the Ala-ArchaBasin.

Assessment year	ELA (in m)		
	Minimum	Maximum	Mean
2015	3588	4302	3892.09
2016	3499	4095	3762.31
2017	3963	4256	3865.96
2018	3462	4261	3880.34
2019	3662	4309	3869.37

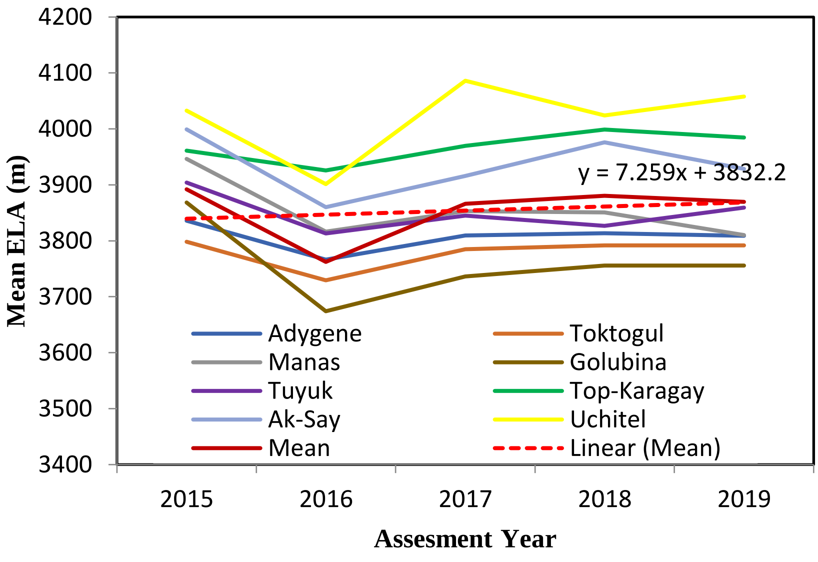

Fig. 5. ELA of large glaciers 2015-2019.

The analysis showed that the area of the Bare-Ice zone is reducing and the Percolation zone is increasing. This means more accumulation has been taken place. It is recommended that the findings must be validated with the field observations. As the position of ELA is driven by climatic factors, further, the meteorological data on precipitation and temperature must be analyzed. To detect the trend in ELA, long-term remote sensing data should be analyzed along with climatic data. With the analysis of 5 years of data, it can't be said that glaciers are generally retreating or advancing.

5. DISCUSSION AND CONCLUSIONS

It is generally agreed that SAR imageries are one of the most convenient tools in glacier radar zone mapping (Fu et al., 2020;Huang et al., 2013; Akbari et al., 2013; Zhou and Zheng, 2017). Cloud-free images make the SAR applications indispensable in glacier studies. The evidence suggests increasing the implementation of SAR data in different glacier studies (radar zone; dray or wet ice; surface velocity; etc.) in the Tian Shan region. Therefore, the methodologies of glacier investigations and their local seasonal specifics can be created. The same kinds of manuals are prominent for the Himalayan and Alpine regions.

The objective of this work was to map radar zones and concomitant parameters estimation of the glaciers in Ala-Archa valley using the Sentinel-1 SAR datasets. The 12-day repeat cycle of the Sentinel-1 product is quite suitable, as an analysis requires season data. Glaciers of Ala-Archa valley are classified into 4 glacier radar zones, namely bare ice, low and middle percolated zones, and debris-covered areas. A high percolation zone is not observed in this study area. Accompanying parameters like trends of ELA, AAR are improving glacier retreat tendency.

The line demarcating the bare ice and lower percolation zones are termed the ELA. A general upward shift in ELA was found; in some large glaciers (Manas, Tuyuk, Ak-Sai), ELA was showing a downward shift as well. It was noticed that the mean ELA has come down by around 23 m from 2015 to 2019.

Research limitations contain several important points:

- Side-looking view geometry increases overlay shadow area, especially in mountainous terrain. In this situation, overlay shadow limitation can be prevented by using imagery with another track.
- Equilibrium line is provided strongly between bare ice and middle, low percolation zones. In some cases, this approach gives ambiguous value. The high amplitude of ELA is caused not only by exposition (solar angle), here also wind speed and direction is important due to exposing the ice by blowing the snowpack. Due to the instability of wind direction and speed in mountainous terrain, it is hard to estimate the occurrence of wind-bared zones.

Those points are suggested to improve the quality of the work:

- The obtained data about disposition and elevation of equilibrium line, which obtained from glacier radar zone mapping, can be utilized in glacier mass balance estimation.
- In order to better understand trends in glacier dynamics, the observation time scale should be extended.
- Same research should be provided to the entire Kyrgyz Ala-Too mountain range.
- Climatic and other products of ground observations should be implemented to validate the findings.
- In-depth analysis of the results and their causes is required.

REFERENCES

Aizen V., Aizen E., Kuzmichonok V.A. (2007) Glaciers and hydrological changes in the Tien Shan: Simulation and prediction. *Environmental Reearch. Lett*ters, 2 (4) 045019, DOI: 10.1088/1748-9326/2/4/045019.

Aizen V.B., Aizen E.M. (1997) Hydrological cycles on the north and south peripheries of mountain-glacier basins of central Asia *J.Hydrol.Proc*. 11 451-69.

Akbari, V., Doulgeris, A.P.& Eltoft, T. (2013) Monitoring glacier changes using multitemporal multipolarization SAR images. *IEEE Trans. Geosci. Remote Sens.*, 52, 3729–3741.

Alifu, H., Vuillaume, J-F, Johnson, B.A.&Hirabayashi, Y. (2020) Machine-learning classification of debris-covered glaciers using a combination of Sentinel-1/-2 (SAR/optical), Landsat 8 (thermal) and digital elevation data. *Geomorphology*, 369, 2020,107365

Atlas of Kyrgyz, SSR (1987)*Main Administration of Geodesy and Cartography of the USSR*. Atlas (in Russian)

Beniston M, Farinotti D, Stoffel M et al (2018) The European mountain cryosphere: a review of its current state, trends, and future challenges. *The Cryosphere*, 12, 759-794. https://dx.doi.org/10.5194/tc-12-759-2018.

Bolch T. (2015) Glacier area and mass balance changes since 1964 in the Ala Archa Valley, Kyrgyz Ala-Too, northern Tien Shan. *Ice and Snow*, 129(1), 28-39.

Brahmbhatt, R., Nainwal, H.& Kulkarni, A. (2014) Impact of accumulation area ratio (AAR) on glacial change: few examples of Jammu & Kashmir. *Journal of Geomatics*, 8(1), 61-65.

Brancato, V. *et al.*(2020) Grounding line retreat of Denman Glacier, East Antarctica, measured with COSMO-SkyMed radar interferometry data. *Geophys. Res. Lett.* 47, e2019GL086291.

Das, S. & Chakraborty, M. (2019) Mass balance of ChhotaShigri Glacier using dual-polarised C band SAR data. *Remote Sensing Applications: Society and Environment*, 13, 150-157.

Dostovalov B.N.&Kudryavtsev V.A. (1967) *Obsheemerzlotovedenie* [General geocryology]. Moscow: Publishing house of Moscow university.

Fu, W., Li, X., Wang, M.& Liang, L. (2020) Delineation of Radar Glacier Zones in the Antarctic Peninsula Using Polarimetric SAR. *Water*, *12*, 2620. https://doi.org/10.3390/w12092620.

Garg, V., Kudekar, A.R., Thakur, P.K. et al. (2021). Glacier Change Studies under Changing Climate Using Geospatial Tools and Techniques. *J Indian Soc Remote Sens,* https://doi.org/10.1007/s12524-021-01388-5

Gupta, S.K., Negru, R.&Voda, M. (2018). The Indian Himalaya's unique attributes: Hemkund Sahib and The Valley of Flowers. *GeographiaTechnica*, 13 (2), 62-73.

Hock, R., Rasul, G., Adler, C.*et al.* (2019) *High Mountain Areas*. In: Pörtner H-O et al (eds) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. In press.

Huang, L., Li, Z.& Tian, B. (2013) Monitoring glacier zones and snow/firn line changes in the Qinghai–Tibetan Plateau using C-band SAR imagery. *Remote Sens. Environ*., 137, 17–30.

Mahagaonkar, A.V. (2019)*Glacier Surface Velocity Estimation & Faces Classification using InSAR and Multi-Temporal SAR Techniques in Indian Himalaya*, Enschede, The Netherlands.

Massom, R.&Lubin, D. (2006)*Polar Remote Sensing*: Volume II: Ice Sheets. Springer-Verlag, Berlin.

Meier, M. F. & Post, A. S. (1962) Recent variations in mass net budgets of glaciers in western North America. *International Association of Scientific Hydrology Publication 58 (Symposium at Obergurgl 1962 –2014; Variations of Glaciers)*, 63–77.

Meier, M. F. (1962)Proposed definitions for glacier mass budget terms. *Journal of Glaciol*ogy, 4 (33), 252–263.

Mohajerani, Y., Jeong, S., Scheuchl, B. *et al.*(2021) Automatic delineation of glacier grounding lines in differential interferometric synthetic-aperture radar data using deep learning. *Sci Rep*11, 4992, https://doi.org/10.1038/s41598-021-84309-3.

Mouginot, J., Rignot, E., Scheuchl, B. & Millan, R. (2017) Comprehensive annual ice sheet velocity mapping using Landsat-8, Sentinel-1, and Radarsat-2 data. *Remote Sens.*, 9, 364.

Partington, K. G. (1998) Discrimination of glacier faciès using multi-temporal SAR data. *Journal of Glaciology*, 44(146), 42–53.

Rau, F., Braun, M., Friedrich, M., Weber, F., &Goßmann, H. (2000) Radar glacier zones and their boundries as indicators of glacier mass balance and climatic variability. *EarselEProceedings*, 1, 317–327.

Shabunin A. G. (2018) The Catalogue of Claciers of Kyrgyzstan, *Central Asian Institute for Applied Geosciences (CAIAG).*

SVM Tutorials (2020) Harris Geospatial Solutions, Inc.[Online]. Available from: https://www.l3harrisgeospatial.com/docs/backgroundsvmgeneral.html. [Accessed September 2020].

Thakur, P.K., Aggarwal, S.P., Gunasekaran, A.&Sood, S. (2016) Estimation of Snow Cover Area, Snow Physical Properties and Glacier Classification in Parts of Western Himalayas Using C-Band SAR Data, *Journal of the Indian Society of Remote Sensing*, 45, 525-539. DOI: 10.1007/s12524-016-0609-y.

Tsai, Y-LS., Dietz, A., Oppelt, N.& Kuenzer, C. (2019). Remote Sensing of Snow Cover Using Spaceborne SAR: A Review. *Remote Sensing*, 11(12), 1456. https://doi.org/10.3390/rs11121456

Vieli, A. & Payne, A. J. (2005) Assessing the ability of numerical ice sheet models to simulate grounding line migration, *Journal of Geophysical Research*, 110(F1). doi:10.1029/2004jf000202.

Voda, M., Sarpe, C.A.& Voda, A.I. (2019) Romanian river basins lag time analysis. The SCS-CN versus RNS comparative approach developed for small watersheds. *Water Resources Management*, 32 (14).

Water resources of USSR (1973) Issyk-Kul lake, Chu, Talas and Tarim River Basin. Volume 14 Central Asia, issue 2, *Gidrometeoizdat*, Saint-Petersburg, USSR, 55-58p.

Woodhouse, I.H. (2006) Introduction to Microwave Remote Sensing, *CRC Press, Taylor & Francis Group.*

Zholdoshbekov, E. (2020) Glacier Dynamics studies OF Ala-Archa valley of Kyrgyz Republic using Geospatial Data. Post Graduate Diploma in Remote Sensing & Geographic Information System project thesis of Centre of Space Science and Technology Education in Asia and the Pacific (CSSTEAP) (Affiliated to the United Nations), Dehradun., India, 29.

Zhou, C.X.& Zheng, L. (2017) Mapping radar glacier zones and dry snow line in the Antarctic Peninsula using Sentinel-1 images. *Remote Sens*., 9, 1171.