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Morphology and Exposure Studies in the Autonomous Republic of Abkhazia (West Georgia) on the Background of Modern Climate Change

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Abstract: The degradation of glaciers is one of the most obvious signals of climate change in the current period of Earth's history. Modern glaciation is unevenly distributed between different regions of the Earth and some river basins. Glaciers in Georgia are spread over the Great Caucasus Range, concentrated in the basins of the Enguri, Rion, Kodori, Tergi and other rivers, where there are mountain peaks of 3500 m and higher. The study of the melting of glaciers due to the ongoing climate change is extremely important to clarify natural events of a glacial nature, to ensure the rise of the sea level and the safety of the population living in the coastal zone, to determine the change in glacial water runoff and to assess the risks related to the melting of glaciers in general, to develop adaptation strategies and mitigation measures to the melting of glaciers. In the article, the glaciers of the Autonomous Republic of Abkhazia (hereafter "Abkhazia") and their characteristics are studied. High-resolution satellite remote sensing (SRS) is the only way to study the current state of glaciers in the Autonomous Republic of Abkhazia, because on the one hand, there is no local glaciology school, and on the other hand, the current political situation does not allow conducting expeditions and studying glaciers in field conditions. The objective of the article is to study the morphology and exposure of these glaciers and snowfields based on the data from the catalogue of the former USSR (hereafter "catalogue") which is called initial data and is obtained from more than one century of observations and is issued between 1960 -1975 and satellite data, at several time points, namely 2010 and 2015 that are derived from high-resolution (30 m) LANDSAT satellite data, and the latest 2020 data are processed from satellite MODIS (1.5 m resolution). Complexly using the best international practices, processed SRS data and several SRS databases, historical data and expert knowledge define the reliability of received data. It should be noted that the authors had to overcome several difficulties and ambiguities in the data to discuss the problem relevantly.

Keywords: Glaciers of Abkhazia, Morphology, Exposure, Climate change.

1. INTRODUCTION

The degradation of glaciers is one of the most obvious signals of climate change in the current period of Earth's history (Bates et al., 2008; Tignor et al., 2018; Gaudio & Gobbi, 2022). The study of the melting of glaciers due to the ongoing climate change is extremely important to clarify natural events of a glacial nature, to ensure the rise of the sea level and the safety of the population living in the coastal zone, to determine the change in glacial water runoff and to assess the risks related to the melting of glaciers in general (Kordzakhia et al., 2015), to develop adaptation strategies and mitigation measures to the melting of glaciers. Mountain glaciers are an important source of fresh water, which is used for population, agriculture, energy and industrial needs.

High-resolution satellite remote sensing (SRS) is the only way to study the current state of glaciers in the Autonomous Republic of Abkhazia, because on the one hand, there is no local glaciology school, and on the other hand, the current political situation does not allow conducting expeditions and studying glaciers in field conditions.

2. METHODOLOGY, DATA, RESULTS

The study of the degradation of glaciers is very important in the background of modern climate change (Kordzakhia et al., 2019). One of the important problems is the research of Glaciers is the study of changes in morphology and exposure (Matnazarov et al., 2022). In the present work morphology and exposure of Abkhazian glaciers based on the data of the catalogue of the former USSR (hereinafter "Catalogue") [Maruashvili et al., 1975] and satellite data from 2010, 2015 and 2020 are made. The glaciers' characteristics determination is realized based on international best practices using satellite remote sensing (SRS), historical data (catalogue including topographic maps), expert knowledge and satellite databases of 2010, 2015, and 2020 (Gobejishvili & Kotliakov, 2006; Kordzakhia et al., 2020).

Data on all the characteristics of glaciers in dynamics, which are given in the catalogue are determined by using SRS data, namely Landsat satellite images (resolution 15–30 m) and GIS (geo-information systems) technologies. These data are: morphological type, general exposure, maximum length, area, minimum height, maximum height, firn line height, and ablation area of the glaciers. The changes in these characteristics for the mentioned dates are due to the current climate change.

The paper presents the results on the morphology and exposure of Abkhazian glaciers in the last decade using catalogue and SRS data. In the early studies, where we compared the data of the catalogue with the data of only one term (2015) of the SRS, no attention was paid to the study of this issue. As it turned out, comparing the characteristics of all four periods of observation of glaciers and discussing their dynamics is important, because due to current climate change, glaciers are degrading, small glaciers are separating, which leads to a change in their morphology. It is important to determine the exposure of the changed glaciers, which determines the rate of their melting.

The morphological types of mountain glaciers are: kar, valley and hanging types (Kordzakhia et al., 2015).

As for the exposure of glaciers, we have the following designations as in the catalogue: West - W, East - E, South - S; Southwest - SW; Southeast - SE, North - N; North-west - NW; Northeast - NE.

Three glacial basins are presented in Abkhazia and in total, they amount to 136 glaciers. The distribution of morphological types of glaciers of Abkhazia are:

- In r. Bzibi glacial basin (13 glaciers in total) seven glaciers were located on the southern slope of the main ridge and Bzibi ridge, and 6 glaciers were on the northern slope;
- In r. Kelasuri glacial basin (3 glaciers in total) three glaciers are located on the northern slope of the Bzibi ridge;
- In r. Kodori glacial basin (120 glaciers in total) there was one glacier on the northern slope of the Chkhalta ridge of the r. Amtkeli glacial basin and one more on the northern slope of Chkhalta ridge, 43 glaciers are located r. Chkhalta glacial basin and on the southern slopes of the main ridge; there are 7 glaciers in r. Khetskvar glacial basin, two glaciers in Gentsvishi glacial basin, one glacier in r.Klisch glacial basin, 23 glaciers in r. Gvandra Basin.

Morphology of Abkhazian Glaciers: The distribution of morphological types of Abkhazian glacial basins for catalogue data and according to the SRS info for four data is presented in Table 1.

Table 1. Distribution of morphological types of Abkhazian Glaciers according to the Catalogue (a) and the SRS data of 2010 (b), 2015 (c), 2020 (d).

Glacial basin		a. According to catalogue							
		The morphological types							
		Kar		Kar - valley		Valley		Hanging	
		quantity	area	quantity	area	quantity	area	quantity	area
1	Bzibi	11	5,5	0	0	1	1,3	1	0,3
2	Kelasuri	3	1,5	0	0	0	0	0	0
3	kodori	97	45,0	3	4,5	14	16,8	6	2,8
	Total	111	52	3	4,5	15	18,1	7	3,1

Table 1. (continued)

Glacial basin		b. According to SRS 2010							
		The morphological types							
		Kar		Kar - valley		Valley		Hanging	
		quantity	area	quantity	area	quantity	area	quantity	area
1	Bzibi	12	3,6	0	0	1	0,9	2	0,4
2	Kelasuri	2	0,9	0	0	0	0	0	0
3	kodori	99	28,0	4	5,6	15	11,4	29	4,9
	Total	113	32,5	4	5,6	16	12,3	31	5,3

Glacial basin		c. According to SRS 2015							
		The morphological types							
		Kar		Kar - valley		Valley		Hanging	
		quantity	area	quantity	area	quantity	area	quantity	area
1	Bzibi	8	2,1	0	0	1	0,8	1	0,2
2	Kelasuri	1	0,7	0	0	0	0	0	0
3	kodori	85	22,7	4	5,4	15	9,8	20	4,1
	Total	94	25,5	4	5,4	16	10,6	21	4,3

Glacial basin		d. According to SRS 2020							
		The morphological types							
		Kar		Kar - valley		Valley		Hanging	
		quantity	area	quantity	area	quantity	area	quantity	area
1	Bzibi	8	1,6	0	0	1	0,8	1	0,2
2	Kelasuri	1	0,6	0	0	0	0	0	0
3	kodori	74	18,0	4	4,9	15	7,8	17	3,4
	Total	83	20,2	4	4,9	16	8,6	18	3,6

As can be seen from the table, the glaciers of Abkhazia have karuli, gorge, karuli-valley and hanging morphologies. According to the catalogue, there is the largest number of kar glaciers, a total of 111. According to the data from 2010, 2015 and 2020, glaciers are degrading and dividing, small glaciers are separating. A kar glacier can be divided into two or three kar-type glaciers, one or two hanging type glaciers, and one or more snowfields. An example of this is No. 117 kar type medium glacier, which by 2010 was divided into 3 kar type glaciers, 1 hanging type small glacier and six snowfields. By 2015, only one kar-type small glacier and six snowfields remained from this glacier, and by 2020 - one kar- type small glacier and five snowfields.

A valley-type glacier generally retains its morphology, although it can be divided into valley and hanging type glaciers, as well as one or more snowfields. The kar-valley type glacier maintains its morphology in all three periods, although the occupied area decreases consistently. A hanging type glacier maintains its morphology, only its area decreases over time and sometimes it turns into a snowfield or disappears.

It should be noted that all snowfields are of kar or hanging type morphology. It is interesting to present Table 2, where it is visible that according to the satellite data of 2010, 60 snowfields were formed and none of the glaciers disappeared; by 2015, 77 snowfields were formed and 36 glaciers disappeared and by 2020, 103 snowfields were formed and 47 glaciers disappeared. Thus, since 2010, the number of snowfields and disappearing glaciers has been increasing intensively.

Table 2. Distribution of Snowfields and Fully Melted Glaciers of the Autonomous Republic of Abkhazia according to Glacial Basins according to the SRS data of 2010 (I), 2015 (II), 2020 (III).

Glacial basin		Snowfields			Fully melted glaciers		
		I	II	III	I	II	III
1	Bzibi	3	15	16	0	0	0
2	Kelasuri	1	2	2	0	0	0
3	Kodori	56	60	85	0	36	47
	Total	60	77	103	0	36	47

The valley type glaciers number is 15 according to the catalogue and their total area is 18.1 km^2. One of them, namely glacier No. 122, which according to the catalogue is an average glacier with an area of 1.4 km^2, is of the valley type, and according to the data of SRS in 2010 it was divided into two small glaciers of the valley type with areas of 0.4 and 0.3 km^2. In 2015, the area of each of them decreases and becomes 0.3 and 0.2 km^2, respectively. According to the SRS of 2020, both of them were divided into a small glacier and a snowfield of less than 0.1 km^2 area. Thus, the number of valley-type glaciers increased by 1 in 2010 and remained the same in 2015 and 2020. The total area of valley-type glaciers decrease over the years: 2010 - 12.3 km^2, 2015 - 10.6 km^2, 2020 - 8.6 km^2.

The number of hanging-type glaciers in Abkhazia is the smallest according to the catalogue. There is a total of 1 glacier in the Bzibi glacial basin, no hanging glacier in the Kelasuri glacial basin and 6 in the Kodori glacial basin valley. By 2010, a hanging-type glacier separated from Kar-type glacier No. 5 in the Bzibi glacial basin, thus the number of hanging glaciers became 2, however, in the following years, this glacier turned into a snowfield. By 2010, the number of hanging glaciers in the Kodori glacial basin was 29. In the following years, the number decreased in 2015 – to 20 and in 2020 – to 17.

Under the influence of current climate change, the increase in the number of kar and hanging glaciers by 2010 is due to the division of glaciers and the separation of small glaciers. This process continues further, but since 2010 their number has been consistently decreasing.

It should be noted that the number of the valley and kar-valley type glaciers remain unchanged, which is due to their morphological features, although the areas occupied by them are also consistently decreasing compared to 2010.

Since 2010, the area occupied by all morphological types of glaciers in Abkhazia has been decreasing, which is undoubtedly related to the current climate change.

General exposure of Abkhazian glaciers: The initial data on the general exposure of the Abkhazian glaciers was taken from the catalogue, and the general exposure of the glaciers in 2010, 2015 and 2020 was determined using the Google Earth program, where the direction and exposure of the valleys of the slopes can be seen. The contours of the glaciers of the mentioned years were included in the program, according to which the exposure of the slopes was determined. Also, the mentioned data was checked in Arc Map (Arc Gis) using specially designed Arc Toolbox tools. The method provides for the so-called Digital Elevation Model (DEM) of the terrain of Georgia. Processing with DEM is carried out in such a way as to obtain a map of the exposure of the slopes of Georgia. During processing, the DEM of the terrain of Georgia with a resolution of 20x20 was used (Figure 1).

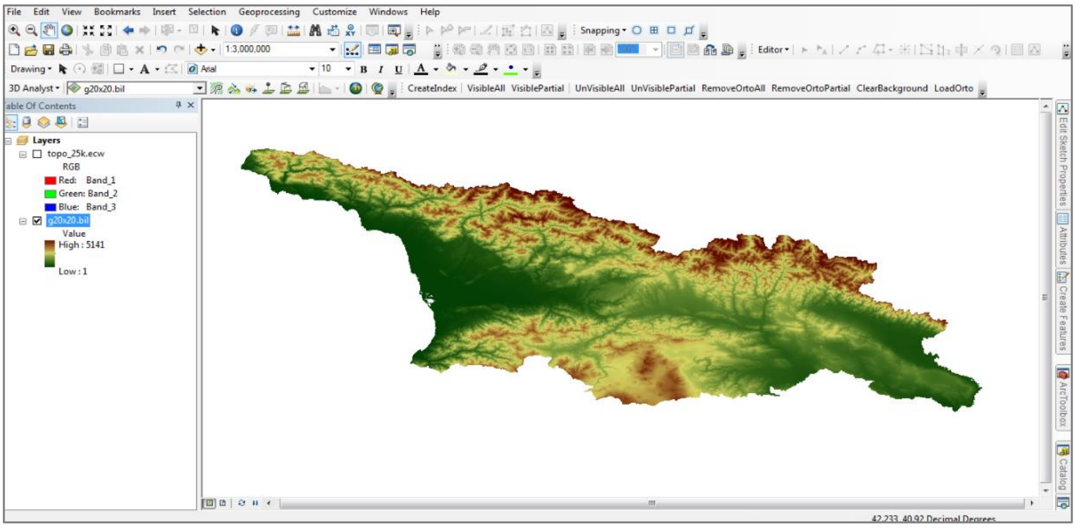

Figure 1. Digital elevation model of the terrain of Georgia with a resolution of 20x20.

Figure 2 shows the exposure map of the slopes of Georgia.

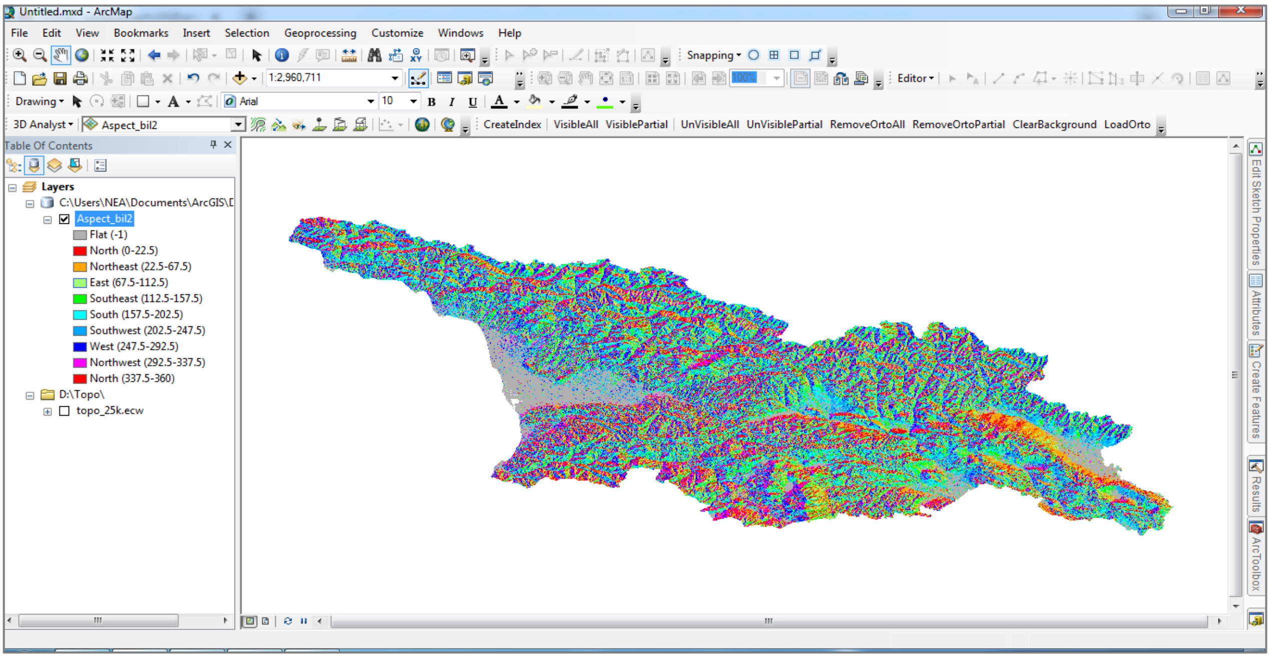

Figure 2. The exposure map of the slopes of Georgia. The image legend indicates conditional signs of the slope exposure by colour: N exposure is shown in red, NE - in orange, E - in light green, SE - in green, S- in blue, SW - in light blue, W - in yellow Blue, SW - with violet.

The contours of the research glaciers (according to years) were included in the image and their exposure was determined. For example, we have the image of the contours of glaciers №118, №119 and №120 on the slope exposure map of 2015 (Figure 3).

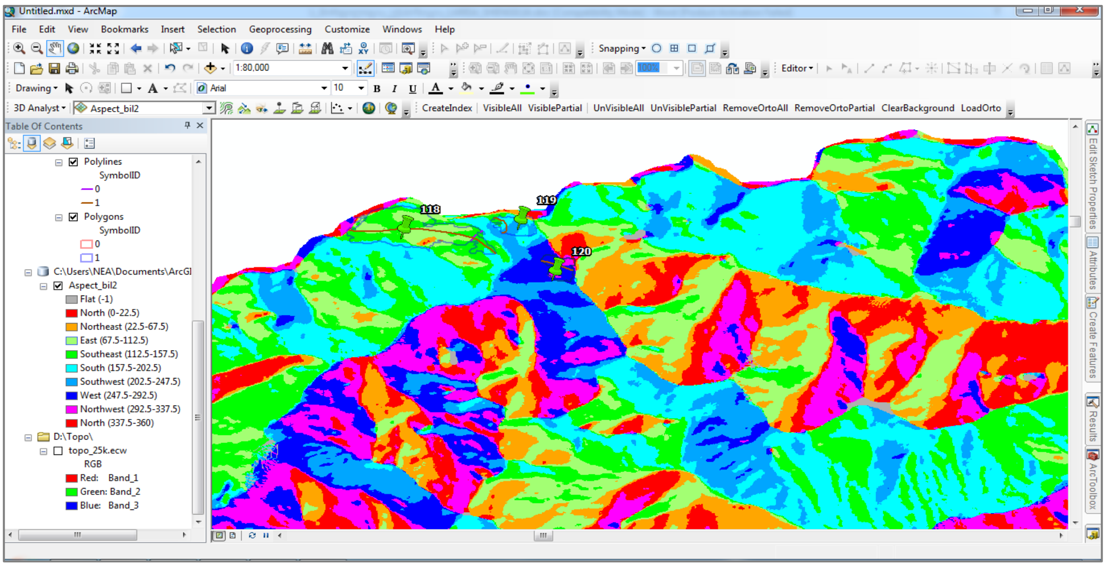

Figure 3. Contours of glaciers №118, №119 and №120 of 2015 on the exposure map of the slopes of Georgia.

In Figure 3 The contours of the research glaciers (according to years) were included in the image and their exposure was determined. For example, we have the image of the contours of glaciers №118, №119 and №120 on the slope exposure map of 2015 (Figure 3).

The contour of glacier №118 is in green, №119 – blue-sky, and №120 - blue, therefore the exposure of glacier №118 is SE, №119 - S, and №120 - W.

In the Figure 4 the contours of glaciers №118, №119 and №120 according to the Landsat 7 ETM+ sensor image of September 6, 2015 are shown.

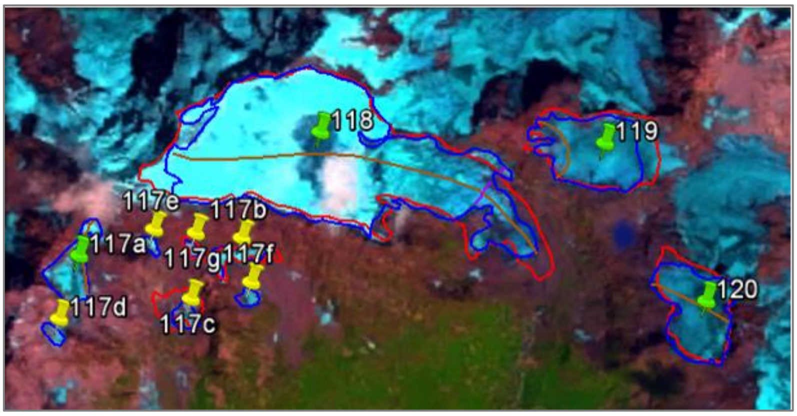

Figure 4. The contours of glaciers №118, №119 and №120 according to the Landsat 7 ETM+ sensor image of September 6, 2015.

In Figure 3, the contour of glacier№118 is green, №119 – sky-blue, and №120 - blue, therefore the exposure of glacier №118 is SE, №119 - S, and №120 - W.

The mentioned method has been tested and accepted in the world. Its use practically eliminates errors during the study of glacier exposure.

The study of the exposure of glaciers is of great importance in the issue of melting glaciers. For the research, we compiled a table of the distribution of the general exposure of glaciers according to the glacial basins of Abkhazia, for four dates (Table 3). Analysis of this table shows that the predominant direction of the general exposure of the Abkhazian glaciers both in the catalogue and in all three dates of SRS data is the NW and W directions. Naturally, these directions coincide with the direction of the invasion of air masses from Abkhazia to Georgia, which leads to the development of synoptic processes in the mountainous regions of Abkhazia, which are associated with the arrival of heavy precipitations.

Table 3. Distribution of general exposure of glaciers of Abkhazia according to catalogue (a) and SRS data from 2010 (b), 2015 (c), 2020 (d).

Glacial Basin		a. Catalogue Data															
		N		S		W		E		W		NE		SW		SE	
		quantity	area	quantity	area	quantity	area	quantity	area	quantity	area	quantity	area	quantity	area	quantity	area
1	**Bzibi**	6	2,7	0	0	3	2,6	0	0	0	0	0	0	4	1,8	0	0
2	**Kelasuri**	0	0	0	0	0	0	0	0	0	0	3	1,5	0	0	0	0
3	**Kodori**	11	4,5	20	13,8	23	9,9	14	8,6	25	14,2	9	8,0	7	3,1	11	8,8
	Total	17	7,2	20	13,8	26	12,5	14	8,6	25	14,2	11	9,5	11	4,9	11	8,8

Table 3. (continued)

		b. SRS Data from 2010															
Glacial Basin		**N**		**S**		**W**		**E**		**NW**		**NE**		**SW**		**SE**	
		quantity	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**
1	**Bzibi**	6	1,6	0	0	4	1,7	0	0	1	0,1	0	0	4	1,5	0	0
2	**Kelasuri**	0	0	0	0	0	0	0	0	0	0	2	0,9	0	0	0	0
3	**Kodori**	12	2,7	17	8,8	25	6,2	13	6,3	28	10,1	17	5,4	12	2,9	23	8,0
	Total	18	4,3	17	8,8	29	7,9	13	6,3	29	10,2	19	6,3	16	4,4	23	8,0

		c. SRS Data from 2015															
Glacial Basin		**N**		**S**		**W**		**E**		**NW**		**NE**		**SW**		**SE**	
		quantity	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**
1	**Bzibi**	2	0,9	0	0	1	0,2	0	0	0	0	1	0,1	4	1.1	0	0
2	**Kelasuri**	0	0	0	0	0	0	0	0	0	0	1	0,7	0	0	0	0
3	**Kodori**	12	1,9	15	7,8	19	5,2	12	5,4	25	8,6	16	4,5	10	2,5	15	6,1
	Total	14	2,8	15	7,8	20	5,4	12	5,4	25	8,6	18	5,3	14	3.6	15	6,1

		d. SRS Data from 2015															
Glacial Basin		**N**		**S**		**W**		**E**		**NW**		**NE**		**SW**		**SE**	
		quantity	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**	**quantity**	**area**
1	**Bzibi**	1	0,8	0	0	4	1,0	0	0	0	0	1	0,1	4	0,6	0	0
2	**Kelasuri**	0	0	0	0	0	0	0	0	0	0	1	0,6	0	0	0	0
3	**Kodori**	10	1,1	13	6,6	16	4,0	11	4,5	27	7,4	12	3,5	10	2,1	11	4,9
	Total	11	1,9	13	6,6	20	5.0	11	4,5	27	7,4	14	4,2	14	2,7	11	4,9

It is also important to note that among the snowfields formed as a result of the degradation of glaciers due to climate change, the number of northern exposure snowfields increased the most by 2020, from 8 in 2010 to 23 in 2020, i.e., an increase of 65%. The snowfields of western exposure increased by 61%, and those of south-eastern exposure - by 54% (see Table 4).

Table 4. Distribution of snowfields of Abkhazia according to general exposure and SRS data from 2010 (1), 2015 (2), 2020 (3).

Glacial Basin		**N**			**S**			**W**			**E**			**NW**			**NE**			**SW**			**SE**		
		1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
1	**Bzibi**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3	3	3	-	-	-	-	-	-
2	**Kelasuri**	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	2	2	-	-	-	-	-	-
3	**Kodori**	8	15	23	3	5	4	7	11	18	5	5	8	10	10	10	8	8	10	2	3	5	13	15	20
	Total	8	15	23	3	5	4	7	11	18	5	5	8	10	10	10	12	13	15	2	3	5	13	15	20

3. CONCLUSION

Under the influence of current climate change, the increase in the number of closed and hanging glaciers by 2010 is due to the division of glaciers and the separation of small glaciers. This process continues further, but since 2010, their number has been steadily decreasing.

The number of the Valley and Karuli-valley type glaciers remains unchanged, which is due to their morphological features, although the areas occupied by them are also consistently decreasing compared to 2010. Since 2010, the area occupied by all morphological types of glaciers is decreasing, which is directly related to the current climate change.

The predominant direction of the general exposure of Abkhazian glaciers, both in the catalogue and in all three periods, is the northwest and west direction. Naturally, these directions coincide with the direction of the invasion of air masses from Abkhazia to Georgia, which leads to the development of synoptic processes in the mountainous regions of Abkhazia, which are associated with the arrival of large precipitations.

According to the data of all four periods in Abkhazia, there are more glaciers in the northern exposure (N, NW, NE) than in the southern exposure (S, SW, SE) and the territories occupied by them are also larger. This is an important conclusion because, in all other glacial basins of West Georgia, the picture is the opposite. As a result of the ongoing climate change impact on these glaciers, the areas of Abkhazian glaciers have been consistently decreasing since 2010 compared to catalogue data for glaciers of all exposures.

Of the snowfields formed as a result of the degradation of glaciers due to climate change, the number of snowfields with northern exposure increased the most by 2020.

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