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Spatial and time dynamics of glaciers following the Little Ice Age on the southern slope of the Greater Caucasus

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A B S T R A C T

The article presents an analysis of the scale in space and time of degradation of some glaciers on the southern slope of Central CaucasusRidge following the Little Ice Age to modern times by the method of remote sensing of short distances. It also describes the opportunities and advantages of using this method as compared to the traditional methodology of Orthorectifying and mappingof aerial pictures. In the study, we used the historical and topographic maps of different periods, archived historical materials of aerial photographing, remote sensing and modern aerial imagestaken with an unmanned aerial vehicle (UAV) (Phantom 4pro) in 2017. The study, besides the traditional approach, is based on the new technique of UAV photography, creating a digital three-dimensional so called "point cloud" model and its use in calculations of various glacial-geomorphological parameters with photogrammetry software and geo-information systems (Pix4D, Global Mapper, ArcGIS). The article gives a detailed description of opportunities of the UAV survey in terms of high-mountainous relief and hampering factors. It was established that the glaciers were quantify following the Little Ice Age and the values of their retreat depend on the concrete types of glaciers and geographical factors.
The mentioned glaciers are typical for the soutern slope of the Caucasus Range and are located between mountain Elbrus and Mkinvartsveri arrays next to the watershed ranges. The analysis of dynamics evidences that in the study period, the retreat varies between 0.8 and 4.2 km.

Keywords: Little ice age, Glacier fluctuation, Moraine, Remote sensing, UAV unmanned aerial vehicle, GIS mapping.

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Introduction

For the last half a billion years, the climate on the earth has been characterized by an alternation of warm and cold periods. The reasons for such an alternation have been active volcanism, cyclical alternation of the earth's orbital location in the Solar system, changing composition of the atmosphere, shape of continents and ratio between the land and the ocean and a set of many other factors. The XX and XXI centuries in the history of the earth's climate are marked by a global change, with the anthropogenic activities playing a significant role. The impact of global warming is confirmed by now and it is demonstrated by a recent increase in the average temperature on earth by 0.6ºC [1]. Time period from 1990 to 2000 was distinguished by the highest temperature background for the last 150 years, since the onset of the instrumental measurements. The trend in global temperature has increased sharply in recent years and as compared to 1961-1990, an increase in the average temperature of the land reached 0.24-0.44ºC [2].

The ongoing climate change has a decisive influence on such an important component of the geographical layer as cryosphere, which is

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The ongoing climate change has a decisive influence on such an important component of the geographical layer as cryosphere, which is one of the forming elements of the earth climate and a good indicator of its changes both, in the global and regional aspects [3]. The basic impact taking place in parallel to the climate change is irreversible degradation of the glaciers in the mountainous systems for the last 200 years which is associated with the continuous increase ofglobal temperature since the LIA (Little Ice Age).It will lead to the reduction of the freshwater resources and hydropower potential of the rivers and supply of irrigation and drinking water systems and increase in the probability of periglacial risks associated with glaciers. The southern slope of Great Caucasus range and its adjacent ridges, has experienced a strong reduction in glaciation after the maximum glacier extent at the end of the LIA (≈1820-1850), like other mountainous regions, it have been marked by a significant abatement of glaciation [4].

The goal of the study is to provide a spatio-temporal analysis of the dynamics of the large valley glaciers of the central part of Great Caucasusand restoration of their geometrical changesof behavior from the Little Ice Age to modern times. This problem was solved by using a synthesis of traditional and modern methods and different techniques to observe the process, including an unmanned aerial vehicle, as well as different approaches to data processing, including 3D and Geographical Information Systems software, when combined with the glacial-geomorphological method, allows obtaining and swiftly processing much better qualitative and quantitative data. This methodology was used to calculate the morphometric properties of the glaciers, restore document the dynamics of their equilibrium line altitude and calculate a number of glaciological parameters.

It should be noted, that the method used by us to study the glaciers further provides important opportunities to calculate many such numerical values, cannot be calculated by using the traditional cartographic and geodetic methods or those of remote sensing.

Objectives and methods

Study Area

The study area covers the southern slope of Central Caucasus range. With its diversified climatic and relief conditions and compatibility between them and in respect of ongoing modern glaciation, Caucasus is an specific geographical situation on the Eurasian Continent, as a transient hearth of modern glaciation transient between the glaciations in the continental (the Pamirs, Tian Shan) and humid marine climate (the Alps). In addition, glaciers exist in different climate conditions, like humid (West Caucasus), moderately humid (Central Caucasus) and moderately dry continental (East Caucasus) climates with the diversity of the climatic-geographical conditions typical to Caucasus Ridge [5]. The main center of glaciation of them is in Central Caucasus, at 43.2^0-43.1^0; 42.7^0-44.4^0. Between mountains Elbrus and Mkinvartsveri, where the relief reaches the highest points (Mount Elbrus at 5642 m, Dikhtau at 5025 m, Shkhara 5203 m, Mkinvartsveri at 5047 m, with over 10 highest peaks over 5000 m altitude along the given section), its average height is 4100 m above sea level. The mean annual amount of precipitations is 3000 mm. In this region, while the amount of precipitations in the eastern part of the Ridge is 10 times less [6] The difference between the amount of precipitations on the southern and northern slopes of the Ridge is also large. Such a difference in climatic conditions results from the location of Caucasus Ridge on the border between the moderate and subtropical climatic zones [7]. In addition, Caucasus Ridge is under the influence of the warm and humid air masses of the Atlantic Ocean and Mediterranean sea on the one hand and of the continental air masses of Siberia, Central Asia and Iran mountainous regions. The most important role in the formation of the climate of Caucasus ranges played by the Black and Caspian Seas. In terms of such diversified climatic conditions, the character of the modern glaciation is also diverse both, on the northern slope of Caucasus Ridge and in the western, eastern and central parts of it. The principal regularities of the climatic conditions and modern glaciation are as follows: the amount of precipitations decreases from west to east and the influence of the continental air masses increases, and the equilibrium line altitude (ELA) of the glaciers increases to 2500-2700 m in West Caucasus, to 3200-3400 m in Central Caucasus and 3700-3950 m in East Caucasus.

Methods and materials

GIS and Areal Mapping methods

One of the most convenient means to gather, store, analyze and visualize the geo-spatial data of different themes and scales is – the geographical information systems (GIS) [8]. In combination with such methods, as remote sensing, unmanned one of the forming elements of the earth climate and a good indicator of its changes both, in the global and regional aspects [3]. The basic impact taking place in parallel to the climate change is irreversible degradation of the glaciers in the mountainous systems for the last 200 years which is associated with the continuous increase ofglobal temperature since the LIA (Little Ice Age).It will lead to the reduction of the freshwater resources and hydropower potential of the rivers and supply of irrigation and drinking water systems and increase in the probability of periglacial risks associated with glaciers. The southern slope of Great Caucasus range and its adjacent ridges, has experienced a strong reduction in glaciation after the maximum glacier extent at the end of the LIA (≈1820-1850), like other mountainous regions, it have been marked by a significant abatement of glaciation [4].

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Table 1. *Coverage of the areas photographed during the UAV flight*

Glacier and adjacent periglacial zone	UAV flay date	No. of aerial photos	Coverage area of an orthophotom^2	No. of points,10^6	Density of points per sq.m. X;Y;Z;	Orthophotoresolution, cm	≈ Scale
1. Adishi	25/08/2017	1143	5.86	110.1	38	8.3	1:300
2. Khalde	30/08/2017	989	4.8	98.8	36	9.1	1:350
3. Shkhara	27/08/2017	818	3.9	92.7	36	8.1	1:400
4. Zopkhito	08/09/2017	914	3.31	107.4	40	7.59	1:300

aerial vehicle, which has been extensively used in various fields recently and exploration of the study object. Unlike the traditional cartographic methods, it provides good opportunities to obtain highly accurate and thoroughly informative data, including 2D, 3D and 4D cartographic information. Data processing is fast and most of production processes can be automated [9-11]. At the first stage, a geo-database of the study glaciers was created and integrated in a single coordinate space (UTM WGS-84, Zone38).The digital data obtained from the observations of the glaciers and their periglacial zones with an aerial vehicle and electronic and paper versions of different periods and available archive material of remote sensing and cartography are included in this data base structure. For the sake of thorough data integration, digital elevation models were used: a) through the manual digitalization of contour lines of a 1:50000-scaled topographic map of the Soviet period and b) a detailed relief model acquired with the UAV. Modern information about the studied glaciers and other field observations were collected with an unmanned aerial vehicle (DJI Phantom4Pro) by using flight control and planning software (Pix4D) (See Tab.1).

The gained data were processed in theGlobal Mapperand Esri ArcGIS software. The aerial survey of the glacier tongues and periglacial zones referred in the table (see table 1)was done in August and September of 2017. The aerial survey needs a preliminary study of the study area and evaluation of its parameters. At the first stage of the flight planning, the relief of the territory was evaluated, the longitudinal and lateral profiles were drafted at the office by using topographic maps, digital relief models and other available internet sources (Google Earth, SRTM – Shuttle Radar Topography Mission 30m), what was necessary if considering the high degree of dissection of the relief of the area, short fields of vision and presence of barriers to avoid a collision of the drone with the surrounding slopes or other relief forms. The technical parameters of the UAV are limited: the maximum flight duration with one take-off is 30 minutes; in case of a slight wind, the duration of the battery operation reduces to ≈ 26-28 minutes. A drone also has some height limitations and it can operate at maximum 500 m from the takeoff point. It should also be noted, that a drone can be used maximum up to6000 m above sea level. By considering all the above-listed limitations, the survey area was divided into sections of ≈0.2km^2 (690×310 m) following the flight safety parameters (SFig. 1), and the coordinates of takeoff points and extreme points of the missions were identified for each zone to avoid the collision of the drone with the relief barriers.

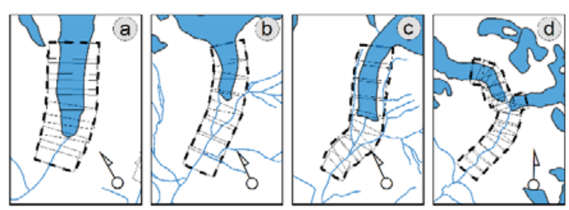

Fig. 1. *Plan of aerial survey of the glacial glacial zone of the glaciers and flight missions: a) Adishi, b) Shkhara, c) Khalde, d) Zopkhito*

The flight was done at 300 m flight level above take-off altitude from each takeoff point. In addition, it is important to ensure a continuous radio communication with the control panel. In order to gain highly accurate X;Y;Z coordinates of the study area (LAS Point Cloud Data), the coverage of the photographs is desirable to vary from 60 to 80%

during the flight. It is true that this will reduce the photographing area to ≈2,5 km^2, but it improves the data accuracy in a three-dimensional space. Coverage of even 0-10% is sufficient to generate an orthophotowith the image quality quite satisfactory for 2D GIS deciphering purposes.

Parametersof the glaciers and their calculation

A good indicator in the study of glaciers variation is the location of the glacier tongue above the sea level in altitude, time and space, variation of the glacier tongue and surface topography, formation of a moraine cover, its morphometry, etc. In the Little Ice Age period, the moraine extent of the same period was well preserved in the periglacial zone of some valley glaciers, and they can be used to restore the location of a glacier and various morphometric indicators of the relevant period. The advantage of the method lies in the possibility to swiftly obtain and calculate a number of accurate glacial-morphological parameters what is often impossible by using traditional deciphering of cartographic aerial photos or if possible, is a labor-consuming process. As for the study of the territory with the field geodetic apparatus, its use in the high mountains is quite limited and needs extensive labor. Two factors are important in this respect: a UAV is capable of producing maximum 1000 coordinate points (X;Y;Z) per square meter on the one hand and on the other hand, what is no less important, no matter how great the density of the survey of the territory and exploration of the topographic surface with the geodetic apparatus is, an aerial photo is impossible to produce. Following the processing of the data of UAV used by us during the field study (LAS point cloud data; X;Y;Z average density of 40 points/m^2) with high accuracy, many parameters of a glacier dynamics were made possible to decipher and calculate (Fig. 2). By manual digitalization and semi-automatic processing of the point cloud in Global Mapper software media, we restored the location of the glacier in the modern period and Little Ice Age period, calculated the location of the tongue above sea level in the Little Ice Age, indicators of the tongue retreat both, in length and height, designed a high-resolution and highly accurate relief model and its lateral and longitudinal profiles by using the modern methodology.

In the study of glaciers, alongside with the Geographical Information Systems, we used literary sources [4], [11], [12] and method of overlay of the cartographic maps (1890-1911. maps of the Russian Empire) and remote sensing archive materials. By comparing the old and modern data, we obtained numerical indicators, which thoroughly describe the glacier dynamics in the last 200 years.

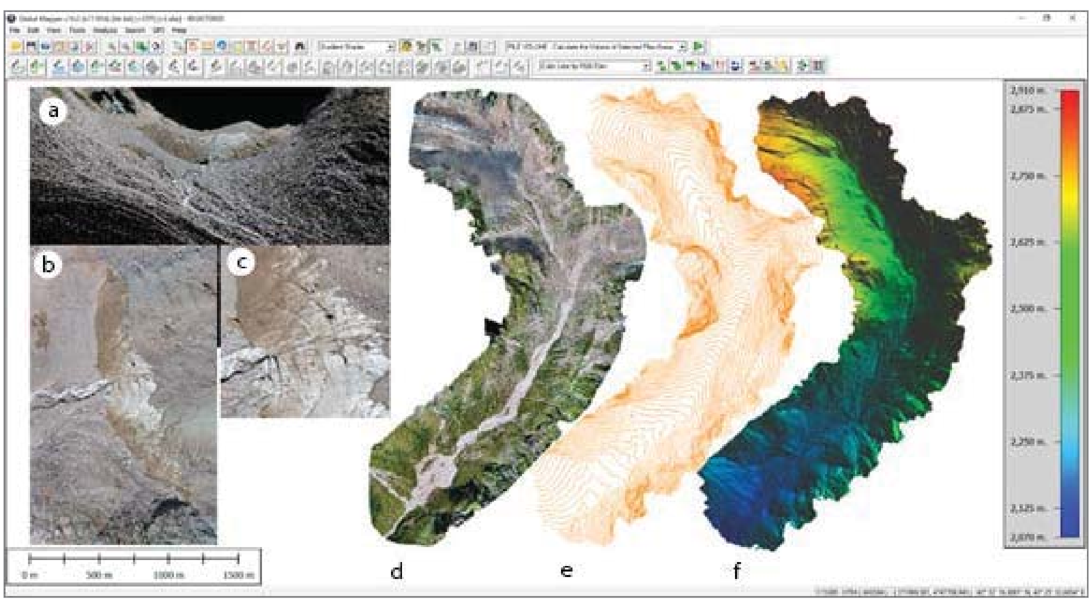

Fig. 2. *Glacier Zipkhito: a) LAS x; y; z point cloud data; b, c) glacier tongue, d) orthophoto, e) elevation contours with a 10 m spacing, f) digital relief model*

Results and analysis

The analysis of the gained results evidences that the glaciers on the southern slope of Caucasus rangeare in the phase of active diminution demonstrated by a significant tongue retreat, increased altitude above sea level and decreased thickness at the same time. The variation of the parameters is associated with the process of the glacier dynamics. As an example, we calculated the characteristic parameters and their variation forof 25 glaciers in the study from the Little Ice Age to modern times (Tab. 2).

Table 2. *Dynamics of the glacier tongues from LIA to modern period*

Glacier	Type of glacier	Tongue elevationin different periods, asl, m			Difference in the periods, m		Average annualelevation change, m/yr		Total elevation in 1820-2010-17	Retreat in 1820-2010-17
		I≈ 1820	II ≈ 1960	III ≈ 2010-2017	II ≈ 1960	III ≈ 2010-2017	II ≈ 1960	III ≈ 2010-2017		
Shkhara	Valley	2310.00	2490.00	2535.00	180.00	45.00	1.29	0.79	225.00	888.00
Guli	Valley	2580.00	2800.00	2920.00	220.00	120.00	1.57	2.11	340.00	1081.00
Ushba	Complex valley	2060.00	2380.00	2590.00	320.00	210.00	2.29	3.68	530.00	1243.00
Adishi	Valley	2270.00	2380.00	2415.00	110.00	35.00	0.79	0.61	145.00	1326.00
Kibisha	Cirque	3090.00	3190.00	3225.00	100.00	35.00	0.71	0.61	135.00	1359.00
Khalde	Valley	2330.00	2500.00	2525.00	170.00	25.00	1.21	0.44	195.00	1542.00
Boko	Valley	2285.00	2440.00	2637.00	155.00	197.00	1.11	3.46	352.00	1592.00
Nageba	Valley	2170.00	2413.00	2550.00	243.00	137.00	1.74	2.40	380.00	1600.00
Tbilisa	Valley	2540.00	2815.00	3010.00	275.00	195.00	1.96	3.42	470.00	1622.00
Marukhi	Valley	2340.00	2400.00	2561.00	60.00	161.00	0.43	2.82	221.00	1734.00
Buba	Valley	2400.00	2820.00	2950.00	420.00	130.00	3.00	2.28	550.00	1770.00
Kirtisho	Valley	2320.00	2425.00	2618.00	105.00	193.00	0.75	3.39	298.00	2007.00
Mna	Suspended valley	2660.00	2855.00	3050.00	195.00	195.00	1.39	3.42	390.00	2053.00
Shdavluri	Valley	2320.00	2640.00	2720.00	320.00	80.00	2.29	1.40	400.00	2178.00
Gergeti	Valley	2600.00	2930.00	3113.00	330.00	183.00	2.36	3.21	513.00	2187.00
Tsaneri	Complex valley	2060.00	2280.00	2376.00	220.00	96.00	1.57	1.68	316.00	2203.00
Koruldashi	Valley	2160.00	2480.00	2800.00	320.00	320.00	2.29	5.61	640.00	2249.00
Dolra	Valley	2370.00	2540.00	2932.00	170.00	392.00	1.21	6.88	562.00	2338.00
Namkvami	Valley	2460.00	2730.00	3023.00	270.00	293.00	1.93	5.14	563.00	2362.00
Laila	Complex valley	2100.00	2220.00	2620.00	120.00	400.00	0.86	7.02	520.00	2467.00
Zopkhito	Valley	2120.00	2480.00	2560.00	360.00	80.00	2.57	1.40	440.00	2603.00
Chalaati	Complex valley	1620.00	1800.00	1940.00	180.00	140.00	1.29	2.46	320.00	2646.00
Lekhziri	Complex valley	1780.00	1970.00	2224.00	190.00	254.00	1.36	4.46	444.00	3698.00
Tviberi	Complex valley	2031.00	2140.00	2428.00	109.00	288.00	0.78	5.05	397.00	4096.00
Kvishi	Complex valley	2300.00	2415.00	2780.00	115.00	365.00	0.82	6.40	480.00	4224.00
Average		**2291.0**	**2501.3**	**2684.1**	**210.3**	**182.8**	**1.5**	**3.2**	**393.0**	**2122.7**

One of the most important factors characterizing the variability of the glaciers is the variation of the altitude of the glacier tongues above sea level in time and space. We give the data about the tongue variations of 25 glaciers for three periods, starting the LIA (≈ 1820) to the middle of the XX century (≈1950-1960) and the most recent modern period. R. Gobejishvili [6] gives the altitudes of the tongues of the first and second periods above sea level. Aerospace photos and digital relief model (SRTM) of different periods (2010-2017) were used to obtain the contemporary data about the location of the glacier tongues and their altitudes.

The data analysis has made it clear that the glaciers continue active retreat in both most recent periods as compared to the first, LIA period. If during the LIA period, the location of the tongues of the considered glaciers above sea level was 2291 m on average, the similar data in the II period (1960s) were 2501 m and 2684 m in the III period (See Table 2). The total difference in elevation of the glacier tongues above sea level made 400 m.

The analysis of the table makes it clear that in the considered period, an average annual value of the glaciers elevation has increased from 1.5 to 3.2 m since 1960s caused by the current climate change and sustainable thermal balance variation established on earth. A larger retreat is seen with the complex types of valley glaciers. Most of the glaciers (88%) retreated within the range of 2-3 km (See Fig. 2). The response of complex valley glaciers and large glaciers to the current climate changes is particularly worthwhile. The value of their retreat is twice as much as an average value as a result of the glacier tongues descending to lower altitudes, their physical condition, mechanical destruction, water currents, exposition and influence of other factors. Average annual retreat of the considered glaciers is 10.7 m/yr, while this indicator for complex valley and large glaciers varies between 18 and 22 m/yr. There is no doubt that the degradation of the glaciers considered in the similar period did not take the same pace and included the periods of short pauses, but in the final run, the retreat of the glaciers took a high pace [13], [14]. It is true that there are certain differences fixed in the average values of retreat of glaciers, but in this case too, most of them (88%) retreated by 8-12 m on average (See Fig. 3).

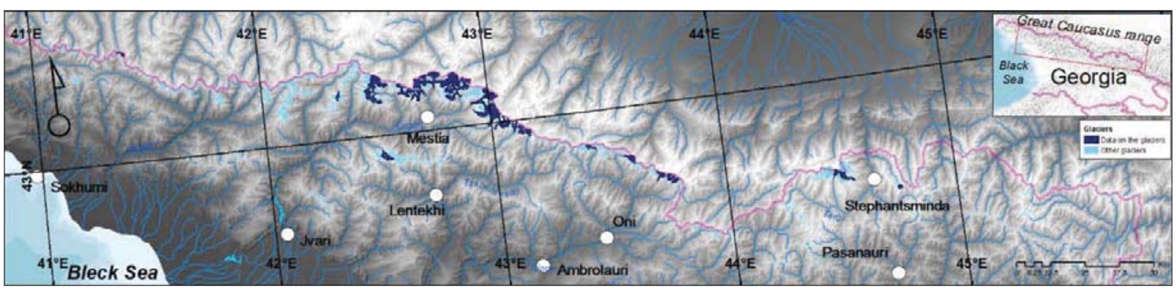

Fig. 3. *Plan of location of the glaciers*

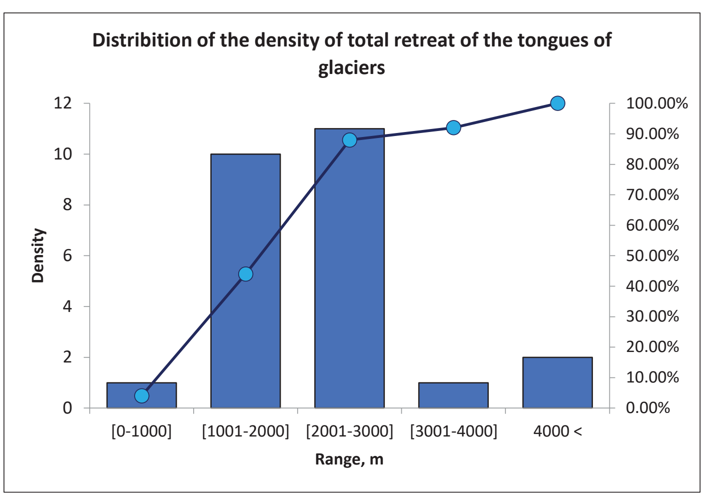

Fig. 4. *Distribution of the density of total retreat of the tongues of glaciers in ≈ 1820-2017*

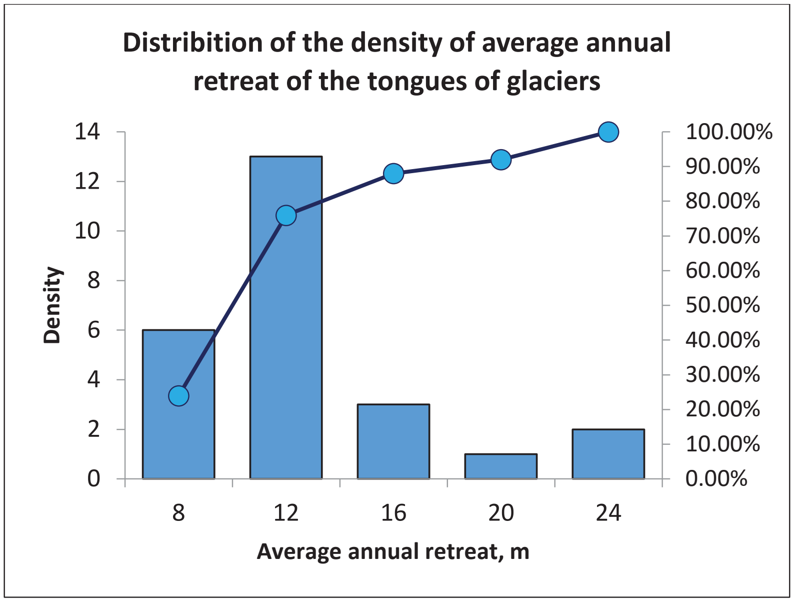

Fig. 5. . *Distribution of the density of average annual retreat of the tongues of glaciers in ≈ 1820-2017*

Conclusion

In the maximal phase of the Little Ice Age (≈1820), the glaciers were in the period of quite active irreversible degradation and melting evidenced by their gradual and swift retreat. Dynamics of melting of glaciers at southern slopes of the Greater Caucasus is in direct proportion with current climatic cycles, at that these processes are more noticeable at gorge-type glaciers. The reduction of the valley glaciers for the last 200years has exceeded 40% of the total area of the maximal phase and still takes an active course. If such trends continue without any changes, presumably the reduction of the large valley glaciers will reach 65% by 2100 what will presumably cause the disappearance of small karr glaciers. These processes lead to the increase inequality in the within-year distribution of a hydrological flow of the major rivers in the region and great amplitudes in different seasons. At that, increase in melting intensity predetermines the growth of intensity and frequency of glacial mudflow formation, since the glaciers with stable balance carry less risk of glacial mudflows and abrupt freshets.

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