Glaciers change over the last century, Caucasus Mountains, Georgia, observed by the old topographical maps, Landsat and ASTER satellite imagery

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Abstract

The study of glaciers in the Caucasus began in the first quarter of the 18th century. The first data on glaciers can be found in the works of great Georgian scientist Vakhushti Bagrationi. After almost hundred years the foreign scientists began to describe the glaciers of Georgia. Information about the glaciers of Georgia can be found in the works of W. Abich, D. Freshfield, G. Radde, N. Dinik, I. Rashevskiy, A. Reinhardt etc. The first statistical information about the glaciers of Georgia are found in the catalog of the Caucasus glaciers compiled by K. Podozerskiy in 1911. Then, in 1960s the large-scale (1 : 25 000, 1 : 50 000) topographic maps were published, which were compiled in 1955–1960 on the basis of the airphotos. On the basis of the mentioned maps R. Gobejishvili gave quite detailed statistical information about the glaciers of Georgia. Then in 1975 the results of glaciers inventory of the former USSR was published, where the statistical information about the glaciers of Georgia was obtained on the basis of the almost same time (1955-1957) aerial images. Thus, complete statistical information on the glaciers of Georgia has not been published for about last half century. Data obtained by us by processing of the aerial images of Landsat and ASTER is the latest material, which is the best tool for identification of the change in the number and area of the glaciers of Georgia during the last one century. Our research has found that the area of the glaciers of Georgia has been reduced from 613.3±36.78 to 555.9±11.1 km^2 in the years of 1911–1960, while their number was increased from 515±46 to 786±39. As for the years of 1960–2014, in this period both the area and number of the glaciers were reduced respectively from 555.9±11.1 km^2 to 355.8 km^2 and from 786±39 to 637.

1 Introduction

The current global warming has already lasted for longer than 150 years. In the middle of the 19th century, the Little Ice Age had come to its end and everywhere mountain glaciers began to decrease (Solomina, 2000). Since the end of the 1950s until the middle of the 1970s, the glaciers were in a quasi-stationary state in most of the mountain areas in Eurasia (Dyurgerov, 2005). Now, the glaciers degrade in all mountain areas of Eurasia. This is reflected in the fact that small glaciers disappear, the termini retreat, the area and volume of glaciers decrease, their surfaces are covered with moraines and large spaces of dead ice are being formed. Compound glaciers are broken into simpler components. Estimations of these changes were published in a number of papers; however, the general picture of the modern Eurasian glaciers to the present moment is not complete. Permanent, regular and detailed observations of the glacier behaviors are necessary to be performed in different regions (Barry, 2006; Khromova et al., 2014). Among them Caucasus, where the glaciers are an important source of water for agricultural production in Georgia, and runoff in large glacially-fed rivers (Kodori, Enguri, Rioni, Tskhenistskali, Nenskra) supplies several hydroelectric power stations. Caucasian glaciers also play a role in water levels in the Caspian Sea, the largest endoreic body of water on Earth. Since the mid-1970s, lake levels have rise ~ 2 m, with major socio-economic impacts (Arpe et al., 2000) on bordering coastal nations. Future trends in glacier change are thus a topic of considerable interest to the region.

Most studies of the Caucasus have focused on glaciers draining the northern slopes of the range in Russia (e.g., Shahgedanova and others, 2005; Stokes and others, 2006; Shahgedanova and others, 2014) with fewer published works about glaciers on the south-facing slopes of the Caucasus. This article presents the percentage and quantitative changes in the number and area of the glaciers of Georgian Caucasus in the years of 1911–1960–2014, according to the individual river basins. The air temperature course of the Georgia's middle and high mountain weather stations has been studied. The river basins have been revealed, where there are the highest indices of the reduction in area and number of the glaciers and the reasons have been explained.

2 Study area

One region where mountain glaciers exist in Eurasia is the Caucasus Mountains, running west-northwest to east-southeast between the Black Sea and the Caspian Sea and separating southwestern Russia from Georgia (Volodicheva, 2002). The current number of glaciers is ~ 2000, with a total area of ~ 1100 km^2 and volume ~ 68 km^3 (Radicì et al., 2014). According to the morphological and morphometric characteristics the Greater Caucasus can be divided into three parts within Georgia – Western Caucasus, Central Caucasus and Eastern Caucasus (Maruashvili, 1971; Gobejishvli, 1995; Tielidze, 2014) (Fig. 1).

Western Caucasus region includes the part, which is located to the west of the Dalari Pass. It has a sublatitudinal direction in Georgia. The relief of its southern slope is characterized by complex orographic structure. The main watershed range is the highest morphological unit here. The Greater Caucasus branch-ranges: Gagra, Bzipi, Chkhalta (Abkhazeti) and Kodori, located in echelon, are also sharply distinguished morphologically and morphometrically (Geomorphology of Georgia, 1973).

Central Caucasus sector is the highest hypsometrically; it is characterized by a complex geological structure and is very interesting by glacial-geomorphological point of view because in the Pleistocene (Gobejishvili et al., 2011) and even today the main center of glaciation is located in the Central Caucasus. Its western boundary coincides with the Dalari pass and runs along the Enguri and Kodori Rivers' watershed (Kharikhra range), while its east boundary coincides with the Jvari Pass and then runs along the bottom of the river gorges of Tergi-Bidara-Mtiuleti's Aragvi (Maruashvili, 1971). In terms of the glaciers distribution, the several orographic units can be distinguished in the Central Caucasus: Svaneti, Samegrelo, Letchkhumi, Shoda-Kedela and Java ranges.

To *Eastern Caucasus* belongs the part of the Greater Caucasus range, which is located to the east of the Georgian Military Road (Jvari Pass). Both the southern and northern slopes of the Caucasus range get within the Georgia's boundaries. Eastern Caucasus is quite high hypsometrically: heights of its peaks – Kuro, Komito, Shani, Amgha, Tebulosmta and others exceed 4000 m. Though, because of the relatively dry climate and morphological features of the relief, the contemporary glaciers are more weakly represented in the Eastern Caucasus than in the hypsometrically lower Western Caucasus.

Caucasian thermal regime is mainly determined by its geographical location, solar radiation, subsurface feature, atmospheric circulation and relief. Therefore, the air temperature is characterized by high contrast (Tielidze, 2014).

In the territory of Georgia January is considered the coldest month, but in the high mountain regions (2700–2800 m) February is considered the coldest month. Stable frosty periods at a height of 2000–3000 m last from November to May, and above 3000 m – from early October through June (from October to July). The average January temperature is −6 and −8°C at a height of 2000 m and the temperature of the coldest month is −14 and −16°C at a height of 3600 m (Gobejishvili, 1995; Tielidze, 2014).

The average monthly temperature of the warmest month – August varies from +14 to +17°C at about 1500 m of altitude; and at the heights of 2800 and 3600 m it is respectively +7.6 and +3.4°C (Gobejishvili, 1995; Tielidze, 2014). Average multiannual air temperature ranges from +5.9°C (Mestia, 1906–2013) to −5.7°C (Kazbegi, 1907–2009).

3 Data sources and methods

3.1 Old topographical maps

The Glacier Inventory by K. I. Podozerskiy (PGI) is the first information about glacier numbers and areas in the Caucasus. This inventory, based on the ordnance survey in 1887–1910, was published in 1911 in Russia (Khromova et al., 2014). detailed analysis of the data showed that there are some defects in the shape of the glaciers of that time; particularly the inaccessible firn valleys of the valley glaciers are depicted incorrectly. Naturally, this fact will cause a slight error in the identification of precise areas of the glaciers of that time, but in reality there exist no other data about the mentioned period and these maps are the most reliable source for us (Tielidze et al., 2015a).

The old topographic maps were replaced with the new ones in 1960, when during the period of the former Soviet Union the 1 : 25 000 and 1 : 50 000 – scale maps were published with the depiction of quite precise contours of the glaciers of the Caucasus. R. Gobejishvili gave us new statistical information about the glaciers of Georgia (Gobejishvili, 1989; Tielidze et al., 2015a). These maps were compiled in 1955–1960 on the basis of the aerial images.

The Next inventory of the Caucasus glaciers is the result of a manual evaluation of various glacier parameters from the original aerial photographs and topographic maps

(The Catalog of Glaciers of the USSR, Vol. 8–9 1975) (Khromova et al., 2014), where the statistical information on glaciers of Georgia was obtained based on the same time (1955-1957) satellite images. There are some mistakes made in the mentioned catalog regarding data of number and area of the glaciers in some of the river basins (particular – Bzipi, Kelasuri, Khobistskali, Liakhvi, Aragvi and Tergi River basins), where the temporary snow spots and snow areas are considered as glaciers and therefore the number and area of the glaciers are incorrect. Given that this fact will cause a some error in the identification of precise areas of the glaciers of that time, we did not use mentioned catalog data in our research.

As we had the information of the last century only in printed form and not electronically. After maps scanning, we used standard transformation parameters (for both period maps 1911, 1960) to re-project the maps in Universal Transverse Mercator (UTM), zone 38-North on the WGS84 ellipsoid, to facilitate comparison with modern datasets (ArcGis 10.2.1 software).

3.2 Landsat and ASTER imagery and glacier area mapping

Many of the world's glaciers are in remote areas, meaning that land-based methods of measuring their changes are expensive and labour-intensive. Remote-sensing technologies have offered a solution to this problem (Kaab, 2002). Landsat L8 OLI/TIRS (Operational Land Imager and Thermal Infrared Sensor), with 30 m horizontal resolution available since February 2013, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) imagery with 15 m resolution available since January 2000, is a convenient tool for determine to glaciers area and number change. All above mentioned together with the old topographical maps allow us to identify the change in the number and area of the glaciers in the last century by a minimum error. All images (Landsat and ASTER) were acquired at the very end of the ablation season when glacier tongues were free of seasonal snow under cloud-free conditions and were suited for glacier mapping (Fig. 1), where the glacier margins were obscured by shadows from rocks and glacier cirque walls (Khromova et al., 2014). Landsat images were supplied by the US Geological Survey's Earth Resources Observation and Science (EROS) Center and downloaded using the EarthExplorer tool (http://earthexplorer.usgs.gov/). The images were orthorectified prior to distribution using the GTOPO30 elevation dataset. ASTER images were supplied by the National Aeronautic and Space Administration's (NASA) Earth Observing System Data and Information System (EOSDIS) and downloaded using the Reverb/ECHO tool (http://reverb.echo.nasa.gov/).

To promote mapping the glacier boundaries, we produced a color-composite scene for each acquisition date, using bands, for Landsat images – 7 (short-wave infrared), 5 (near infrared) and 3 (green); for ASTER images – 3N (Normal visible near-infrared) and 2 (visible near-infrared).

3.3 Glacier delineation error and analysis

We co-registered the images to one another using the 28 August 2014 Landsat image as a master; registration uncertainties are 1 pixel (30.0 m). For more accuracy, each glacier boundary was manually digitized. We calculated the total surface for each glacier (for individual river basin) according to Paul et al., (2009). The size of the smallest glacier mapped was 0.01 km^2.

Offsets between the images and the archival maps are also at the 1 pixel level based on an analysis of common features identifiable in each dataset. It should be noted that the topographic maps of 1960 are drawn by as much precision, that the delineation error for 1960 glaciers extents are just 3 %. As for the data of 1911, there are some gaps made, mostly in the firns of the Enguri and Rioni glaciers. In this case of the glaciers of that time the delineation error are 17 %.

Manual digitizing by an experienced analyst is usually more accurate than automated methods for glaciers with the debris cover (Raup and others, 2007), which is a major source of error in glacier mapping (Bhambri et al., 2011; Bolch et al., 2008), but in the Caucasus, supra-glacial debris cover has a smaller extent than in many glacierized regions, especially Asia (Stokes et al., 2007; Shahgedanova et al., 2014). For the precise determination of debris cover we have used our record data also. We have conducted field works almost in every glaciated areas during 2004-2014 and glaciers which are mostly covered by debris cover (Khalde, Lekhziri, Chalaati, Shkhara, Devdoraki, Zopkhito, Ushba et al.) were surveyed by GPS. which helped us to obtain even more accurate result.

3.4 Climatic data

In parallel with the dynamics of the glaciers it is important for us to identify the course of the air temperatures in the high mountain regions of Georgia during the almost same period. For this we used the middle and high mountain meteorological station of the Georgia. Their average monthly and mean annual air temperature records were used to characterize climatic variations in the Enguri (Mestia meteorological station data of 1906–2013, middle mountain −1441 m a.s.l.), Rioni (Mamisoni meteorological station data of 1907–1995, high mountain −2854 m a.s.l.) and Tergi (Jvari Pass meteorological station data of 1907–2009, high mountain 2395 m a.s.l. and Kazbegi meteorological station data of 1907–2009, high mountain −3653 m a.s.l.) River basins, on the southern and northern slope the Greater Caucasus (Fig. 1).

4 Results

4.1 Area and number change

Our research has found, that the area of the glaciers in Georgia was reduced by 9.3±6.0 % in 1911–1960, while their number was increased by 52.6±9.0 %. During this period, the increase in the number of the glaciers in parallel to the reduction in their area was caused by the fact that in the early 20th century total area of all of the compound-valley glaciers exceeded 200 km^2 (Tielidze, 2014). As a result of degradation of the mentioned glaciers the relatively small size simple valley type of glaciers occurred, as well as even smaller size cirque type of glaciers. Accordingly, the division of the glaciers caused the increase in the number of glaciers in the mentioned period.

As for the years of 1960–2014, in this period both the number and area of the glaciers were reduced respectively by 19.0±5.0 and 36.0±2.0 %. Such a sharp reduction in the number of glaciers is caused by the fact that in Georgia for the 60–70s of the 20th century the most of the glaciers were small cirque type of glaciers, which have disappeared completely in the last half century (Tielidze, 2014). Change of glaciers according to separate parts of the Caucasus range and river basins are following.

4.1.1 Western Caucasus

The Bzipi River gorge is the westernmost basin of the territory of Georgia, where the contemporary glaciers are represented (Tielidze, 2014). Except of Bzipi, the glaciers are represented in the basins of the rivers of Kelasuri and Kodori within the Western Caucasus. By the data of 1911 (K. Podozerskiy) there were 10 glaciers in the Bzipi basin with the area of 4.0 km^2. By the data of topographic maps of 1960 (R. Gobejishvili) there were 18 glaciers with the area of 7.2 km^2. According to the Landsat images of 2014 the number of the glaciers is 18, while the area 4.0 km^2 (Table 1). The Bzipi River basin is characterized by the cirque glaciers of small size of about 0.5 km^2.

K. Podozerskiy does not provide any kind of information about the Kelasuri River basin. By the data of 1960 there was only one glacier with the area of 0.7 km^2 in this basin. According to the data of 2014 the number of the glaciers is 1, while the area 0.1 km^2 (Table 1).

The major center of the contemporary glaciation on the southern slope of the Western Caucasus is located in the Kodori River basin, which extends from the Marukhi pass up to the Dalari pass. The height of the peaks located there exceeds 3800–4000 m. According to the data of 1911 there were 118 glaciers in the Kodori River basin with the area of 73.2 km^2. By the data of 1960 there were 160 glaciers with the area of 64.5 km^2. According to the data of 2014 there are 145 glaciers in this basin with the total area of 40.1 km^2 (Table 1).

In total, the glaciers area decreased by 33.0 km^2 (42.7 %) in the Western Caucasus during the last one century, while their number increased by 36 (28.1 %) in the same period (Figs. 2 and 3).

4.1.2 Central Caucasus

The Central Caucasus section is distinguished by the highest relief in the territory of Georgia, the height of the peaks located there exceeds 4500–5000 m. There are the river basins within the Central Caucasus such as the Enguri, Khobistskali, Rioni, Liakhvi and Aragvi.

Enguri River basin is the largest in Georgia according to the number and area of the contemporary glaciers. It exceeds all other basins taken together. Here can be found the largest glaciers of Georgia such as Lekhziri (23.3 km^2, by Landsat images 2014), southern and northern Tsaneri (12.6/11.5 km^2, by Landsat images 2014) and others (Tielidze, 2014). In 1911 there were 174 glaciers in the Enguri River basin with the total area of 333.0 km^2; according to the data of 1960 there were 299 glaciers with the area of 320.5 km^2, and by the data of 2014 there are 269 glaciers in this basin with the total area of 223.4 km^2 (Table 1).

No information is available about the glaciers of the Khobistskali River basin in the catalog of K. Podozerskiy. And there were 16 glaciers by the data of 1960 with the total area of 0.9 km^2. According to the data of 2014 there are 9 glaciers in this basin with the area of 0.5 km^2 (Table 1).

Another important center of the contemporary glaciation in Georgia is the Rioni River basin. The heights of the peaks located there exceed 4000 m. On the southern slope of the Caucasus the Rioni River basin is only behind the Enguri and Kodori River basins according to the number of the contemporary glaciers, and according to the area – it is only behind the Enguri River basin. According to the data of 1911 there were 85 glaciers in the Rioni River basin with the area of 78.1 km^2. According to the data of 1960 the number of the glaciers was 112 with the total area of 75.1 km^2. And by the data of 2014 there are 97 glaciers with the total area of 46.7 km^2 (Table 1). The largest glacier in the Rioni River basin is Kirtisho with the area of 4.4 km^2.

By relatively low hypsometrical location is distinguished the Liakhvi River basin, which is located to the east of the Rioni River basin. According to the data of 1911 there were 12 glaciers in the basin with the area of 5.1 km^2. There were 16 glaciers in the Liakhvi River basin with the total area of 4.0 km^2 according to the data of 1960. And according to the data of 2014 there are 10 glaciers in the Liakhvi River basin with the total area of 1.9 km^2 (Table 1).

The easternmost basin of the Central Caucasus, where the contemporary glaciers are presented, is the Aragvi River basin. According to the data of 1911 there were 3 glaciers with the total area of 2.2 km^2. According to the data of 1960 the area of all glaciers was 0.9 km^2. And by the data of 2014 the only one glacier (Abudelauri) is remained in the basin with the area of 0.3 km^2 (Table 1).

In total, the glaciers area decreased by 145.7 km^2 (34.8 %) in the Central Caucasus during the last one century, while their number increased by 112 (40.9 %) in the same period (Figs. 2 and 3).

4.1.3 Eastern Caucasus

In Georgia the Eastern Caucasus is represented both by southern and northern slopes. The basins of the rivers such as Tergi, Asa, Arghuni and Pirikita Alazani are located there. All of the river basins are distributed on the northern slopes of the Caucasus.

The Tergi River basin is a main glaciation center of the Eastern Caucasus. Some of the peaks' heights exceed 5000 m here (Mkinvartsveri/Kazbegi 5033 m). According to the number of glaciers the Tergi River basin is in the fourth place after Enguri, Kodori and Rioni and its share is 9.1 % in the total number of the glaciers of Georgia. It is also in the fourth place by the area after Enguri, Rioni and Kodori, and its share in the total area of the glaciers of Georgia is 10.0 %. By the data of 1911 there were 63 glaciers in the

Tergi River basin with the total area of 89.1 km^2. By the data of 1960 there were 99 glaciers with the total area of 67.2 km^2. And according to the data of 2014 there are 58 glaciers with the total area of 35.6 km^2 (Table 1).

The Asa River basin is located on the northern slope of the Greater Caucasus. Its name is Arkhotistskali in the territory of Georgia. Heights of some of the peaks in this region exceed 3700 m. By the data of 1911 there were 17 glaciers in the Asa River basin with the total area of 4.1 km^2. By the data of 1960 there were 9 glaciers in this basin with the total area of 2.6 km^2. And according to the data of 2014 there are 3 glaciers with a total area of 0.6 km^2 (Table 1).

The Arghuni River basin is located on the northern slope of the Greater Caucasus and it has the meridional direction. Although the hypsometric benchmarks of the relief are quite high, the contemporary glaciation is presented in small scales, and the glaciers are characterized by the small sizes. By the data of 1911 there were 10 glaciers in the Arghuni River basin with a total area of 5.4 km^2. By the data of 1960 there were 17 glaciers with the total area of 2.7 km^2. And according to the data of 2014 there are only 6 glaciers with the total area of 0.5 km^2 (Table 1).

Pirikita Alazani River basin is located on the northern slope of the Greater Caucasus and is of latitudinal direction. Here the individual peaks' height is over 3800–4000 m. According to the data of 1911 there were 23 glaciers there with the total area of 19.1 km^2. By the data of 1960 the glaciers were reduced in size and though the number of glaciers was increased up to 36, their area was reduced to 7.7 km^2. And according to the data of 2014 there are 20 glaciers in this basin with the total area of 2.4 km^2 (Table 1).

In total, the glaciers area decreased by 78.7 km^2 (66.8 %) in the Eastern Caucasus during the last one century, while their number decreased as well by 26 (23.0 %) in the same period. As we can see, as opposed to the Western and Central Caucasus the reduction in the total number of the glaciers are observed along with the reduction in their area in the Eastern Caucasus (Figs. 2 and 3).

4.2 Climatic variability

As for meteorological data, as we said, we also use the weather data in order to identify better the dynamics of the glaciers. Kazbegi high mountain weather station located in the Tergi River basin on the Mkinvartsveri (Kazbegi) massif (Fig. 1), much higher above sea level (3653 m) compared to the other weather stations in the Caucasus region, where the observation on air temperature starts from 1896. Exactly, the course of the mean annual air temperatures of the mentioned weather station is characterized by a sharply positive trend in the years of 1907–2009 (Fig. 4). Mean multiannual temperature of Kazbagi of the years of 1907–1960 is −5.8°C and for the years of 1961–2009 – −5.6°C. Accordingly, after the year of 1960 in Kazbegi meteorological station temperature increase by +0.2°C is observed (Table 2). The same is proven by the separate mean monthly temperature data, when for the cases of all twelve months the higher temperatures are recorded in the years of 1961–2009 than in the years of 1907–1960 (Fig. 5).

We selected the Jvari Pass meteorological station as the second representative station for the Tergi River basin, which is located to the south from the Kazbegi massif (on the Great Caucasus Watershed Range), approximately in 20 km from it, at an elevation of 2395 m a.s.l. (Fig. 1). The course of the mean annual air temperatures of the mentioned weather station is characterized by a sharply positive trend in the years of 1907–2009 (Fig. 4). Mean multiannual temperature of Jvari Pass of the years of 1907–1960 is −0.1°C and for the years of 1961–2009 – +0.2°C. Accordingly, after the year of 1960 in Jvari Pass meteorological station temperature increase by +0.3°C is observed (Table 2), which is the highest index in comparison with the rest of the stations. Almost the same is proven by the separate mean monthly temperature data, when in case of ten months out of twelve (except August and December) the higher temperatures are recorded in the years of 1961–2009 than in the years of 1907–1960 (Fig. 6).

Except of the dynamics of the glaciers in the Rioni River basin, it is also important to determine the air temperatures course within the almost same period. In this region the most favorable is the Mamisoni weather station located at a height of 2854 m in the Mamisoni pass (Fig. 1). We processed the air temperature data of 1907–1995 (Fig. 4). Figure shows that the mean annual air temperature trend in the years of 1907–1970 in Mamisoni is distinguished with the positive trend; but then seems that in the years of 1970–1988 the air temperature decreases, and the trend is again positive in the years of 1988–1995. In total, in Mamisoni, for the years of 1907–1960 and 1961–1995 taken separately, in both cases the mean annual air temperature amounts −2.2°C and unlike Kazbegi and Jvari Pass stations the mean annual air temperature increase is not observed after 1960 (Table 2). As for the mean monthly temperatures, in this case the March–August (6 months) temperatures of the years of 1961–1995 are relatively low than the data for the same months of the years of 1907–1960, while the September–February (the remaining 6 months) temperatures are relatively high (Fig. 7).

In order to identify the course of the air temperatures in the Enguri River basin, we processed the Mestia weather station data of the years of 1906–2013. The mentioned weather stations are located in Mestia, at a height of 1441 m a.s.l. (Fig. 1). The trend here is also clearly positive (Fig. 4). Mean multiannual temperature of Mestia of the years of 1906–1960 is +5.9°C; and for the years of 1961–2013 +6.0°C. Accordingly, after the year of 1960, in Mestia meteorological station temperature increase by +0.1°C is observed (Table 2). As for the mean monthly temperatures, in this case the temperatures of May–June, August–September and November separately of the years of 1961–2013, are relatively low than the data of the same months of the years of 1906–1960 and the data of December–April (five months) and separate data of October are relatively high. As for the July mean monthly temperature, it is unchanged during the both periods (Fig. 8).

To know the significance of air temperature trends we used Mann Kendall test analysis. Software used performing the statistical Mann-Kendall test is Addinsoft's XLSTAT 2015. According to them positive trend of mean annual temperature was detected as for whole observed period (1907-2009), as for separate ones (1907-1960, 1961-2009) for Kazbegi and Jvari pass weather stations. There was not trend for Mamisoni pass and for Mestia weather station positive trend is observed only for period 1961-2013.

5 Discussion

Our results are consistent with other studies of glacier changes in the Caucasus Mountains (e.g., Shahgedanova and others, 2014), although most previous studies have focused on the north-facing slope (Russian side). According to the Shahgedanova and others (2014), the Caucasus glaciers (In total, 478 glaciers) lost 4.7±2.1 % of their total area between 2000 and 2010/2012. The greatest loss was observed on the southern slope of the Caucasus Range, where glaciers lost 5.6±2.5 %. One consequence of this result is that Georgian glaciers are at higher risk of disappearance than north-facing glaciers in Russia.

According to our survey, over the past century, the largest reduction in the percentage of the area of the glaciers is observed in the *Eastern Caucasus*, in particular, in the Tergi River basin, where the area of the glaciers was reduced by 60.1 % in the years of 1911–2014. In parallel with the reduction of the glaciers the Jvari Pass and Kazbegi meteorological stations mean annual air temperature for years 1961–2009 was accordingly 0.3 and 0.2°C higher than the 1907–1960, that certainly is one of the accelerating factors of melting the glaciers. Also, melting of the glaciers in the Eastern Caucasus by such rate is stipulated not only by the climate conditions, but by the morphological peculiarities of the relief as well. The relief of some of the river basins is built by Jurassic sedimentary rocks, which suffer heavy denudation. That is why the Pleistocene glaciation forms, where the snow is well-kept and collected, and therefore, is one of the important conditions for the existence of glaciers, are poorly preserved there (Gobejishvili et al., 2011; Tielidze, 2014).

As it was mentioned above, the main glaciation center on the *Central Caucasus* is the Enguri and Rioni River basins. According to the materials available to us, the area of the glaciers in the Rioni River basin was reduced by only 3.8 % in the years of 1911–1960, while the area of the glaciers in the Enguri River basin was reduced only by 3.7 %. In our opinion, the mentioned data is not true, because, as it was mentioned above, certain glaciers in the Rioni and Enguri basins are difficult to access for the plane table surveying; therefore, the first topographical survey of the Caucasus was conducted, the firn contours of the mentioned glaciers were incorrectly depicted, and some small glaciers were completely omitted. The catalog of 1911 by K. Podozerskiy, which is compiled based on the mentioned maps, is distinguished by the certain defects. As in the same period of 1911–1960 in the Rioni and Enguri basins the number of the glaciers considerably increased, namely: in the Rioni basin more than 27 glaciers, in the Enguri basin more than 125 glaciers, it is natural that the number of the glaciers would not have been increased so sharply due to such a low rate of the reduction in the area of the glaciers. As for the period of 1960–2014, the areas of the glaciers in the Rioni and Enguri basins were decreased quite greatly, respectively by 37.8 and 32.8 %.

As for the *Western Caucasus* it should be noted that the Bzipi and Kelasuri River basin are the only two in Georgia, where the number of the glaciers has not been changed since 1960 (Table 1), one of the conditioning factors of which is a fact that in winter period falls more solid precipitation in the Western Caucasus (Abkhazeti sector) than in the Central and Eastern Caucasus (Kordzakhia, 1967; Gobejishvili, 1995), which is one of the necessary conditions for feeding and maintaining the glaciers.

6 Conclusions

As a result of our research we concluded, that the area of the glaciers of Georgia has been reduced from 613.3±36.78 to 555.9±11.1 km^2 in the years of 1911–1960, while their number was increased from 515±46 to 786±39. In the mentioned years the number of the glaciers has been increased in almost all of the river basins (with the exception of the Asa River basin), which was caused by the division of the large size of glaciers during their degradation.

In 1960–2014 the area of the glaciers has been reduced from from 555.9±11.1 km^2 to 355.8 km^2 and their number was reduced from 786±39 to 637 (Fig. 9). In 1960–2014 the simultaneous reduction in the number and area of the glaciers is caused due to the fact that for the years of 1960–1970 in Georgia dominated the small size of glaciers of cirque type, which have completely disappeared during the last half century. In total, the area of the glaciers of Georgia reduced by 42.0 % in the years of 1911–2014, while their number increased by 23.7 %.

As a result of the research it was identified that in the end of the 19th century and early 20th century, the largest glacier of Georgia was Tviberi (Fig. 10a). According to the topographical map of 1887 the glacier area was 49.0 km^2 and its tongue was ended at a height of 2030 m above sea level. Before 1960, the Kvitoldi glacier was separated from the Tviberi glacier's left side, which became an independent glacier (Fig. 10b2). In the topographical map of 1960 the area of the Tviberi was 24.7 km^2 and the glacier tongue was ended at the height of 2140 m a.s.l. (Fig. 10b1). In the Landsat image of 2014 can be well seen the Tviberi degradation after 1960, when the relatively small size simple valley type of glaciers and even smaller cirque type of glaciers were occurred (Tielidze et al., 2015b) (Fig. 10c). Tviberi glacier degradation is well seen in the images of 1884–2011 (Fig. 10d, e).

Finally, by the data of 2014 the largest glacier of Georgia is Lekhziri glacier, which is a compound-valley type and its area is 23.3 km^2. The second largest glacier is the southern Tsaneri with the area of 12.6 km^2. And the third place occupies the northern Tsaneri with the area of 11.5 km^2.

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References

Arpe, K., Bengtsson, L., Golitsyn, G., Mokhov, I., Semenov, V., and Sporyshev, P.: Connection between Caspian sea level variability and ENSO, Geophys. Res. Lett., 27, 2693–2696, 2000. Barry, R. G.: The status of research on glaciers and global glacier recession: a review, Prog. Phys. Geog., 30, 285–306, 2006.

Bhambri, R., Bolch, T., Chaujar, R. K., and Kulshreshtha S. C.: Glacier changes in the Garhwal Himalaya, India, from 1968 to 2006 based on remote sensing, J. Glaciol., 57, 543–556, 2011.

Bolch, T., Buchroithner, M. F., Pieczonka, T., and Kunert, A.: Planimetric and volumetric glacier changes in the Khumbu Himalaya 1962–2005 using Corona and ASTER data, J. Glaciol., 54, 562–600, 2008.

Catalog of Glaciers of the USSR: Katalog Lednitov USSR, vol. 8–9, Gidrometeoizdat, Leningrad, 1975 (in Russian).

Dyurgerov, M. B.: Glacier mass balance and regime data of measurements and analysis, Institute of Arctic Alpine Research (University of Colorado, Boulder) Occasional Paper No. 55, 268 pp., 2002.

Javakhishvili, A. (Ed.): Geomorphology of Georgia, Publ. “Metsniereba”, Tbilisi, 1973 (in Russian).

Gobejishvili, R. G.: Glaciers of Georgia, Monograph. Publ. “Metsniereba”, Tbilisi, 1989 (in Russian).

Gobejishvili, R. G.: Present day glaciers of georgia and evolution of glaciation in the mountains of eurasia in late pleistocene and holocene, Thesis for a Doctor’s Degree, Tbilisi, 320 pp., 1995 (in Georgian).

Gobejishvili, R., Lomidze, N., and Tielidze, L.: Late Pleistocene (Wurmian) glaciations of the Caucasus, in: Quaternary Glaciations: Extent and Chronology, edited by: Ehlers, J., Gibbard, P. L., and Hughes, P. D., Elsevier, Amsterdam, 141–147, doi:10.1016/B978-0-444-53447-7.00012-X, 2011.

Kaab, A.: Monitoring high-mountain terrain deformation from repeated air- and spaceborne optical data: examples using digital aerial imagery and ASTER data, ISPRS J. Photogramm., 57, 39–52, 2002.

Khromova, T., Nosenko, G., Kutuzov, S., Muravievand, A., and Chernova, L.: Glacier area changes in Northern Eurasia, Environ. Res. Lett., 9, 015003, doi:10.1088/1748-9326/9/1/015003, 2014.

Kordzakhia, R.: Enguri and Tskhenistskhali river basins climate features within the Svaneti, Acts of Georgian Geographical Society, Vol. IX–X, Tbilisi, 110–125, 1967 (in Georgian).

Maruashvili, L.: Physical Geography of Georgia, Monograph. Publ. “Metsniereba”, Tbilisi, 1971 (in Georgian).

Paul, F. R., Barry, R. G., Cogley, J. G., Frey, H., Haeberli, W., Ohmura, A., Ommanney, C. S. L., Raup, B., Rivera, A., and Zemp, M.: Recommendations for the compilation of glacier inventory data from digital sources, Ann. Glaciol., 50, 119–126, 2009.

Podozerskiy, K. I.: Ledniki Kavkazskogo Khrebta (Glaciers of the Caucasus Range): Zapiski Kavkazskogo otdela Russkogo Geograficheskogo Obshchestva, Publ. Zap. KORGO., Tiflis, 29, 1, 200 pp., 1911 (in Russian).

Radicì V., Bliss, A., Beedlow, A. C., Hock, R., Miles, E., and Cogley, J. G.: Regional and global projections of twenty-first century glacier mass changes in response to climate scenar- ios from global climate models, Clim. Dynam., 42, 37–58, doi:10.1007/s00382-013-1719-7, 2014.

Raup, B., A. Kaab, J. Kargel, M. P. Bishop, G. S. Hamilton, E. Lee, F. Rau, F. Paul, D. Soltesz, S. J. Singh Kalsa, M. Beedle & C. Helm.: Remote Sensing and GIS technology in the Global Land Ice Measurements from Space (GLIMS) Project. Computers and Geoscience, 33, 104-125, 2007.

Shahgedanova, M., Stokes, C. R., Gurney, S. D. and Popovnin V.: Interactions between mass balance, atmospheric circulation, and recent climate change on the Djankuat Glacier, Caucasus Mountains, Russia. Journal Of Geophysical Research, Vol. 110, D04108, doi:10.1029/2004JD005213, 2005.

Shahgedanova, M., Nosenko, G., Kutuzov, S., Rototaeva, O., and Khromova, T.: Deglaciation of the Caucasus Mountains, Russia/Georgia, in the 21st century observed with ASTER satellite imagery and aerial photography, The Cryosphere, 8, 2367–2379, doi:10.5194/tc-8-2367-2014, 2014.

Solomina, O. N.: Retreat of mountain glaciers of northern Eurasia since the Little Ice Age maximum, Ann. Glaciol., 31, 26–30, 2000.

Stokes, C. R., Gurney, S. D., Popovnin, V. and Shahgedanova M.: Late-20th-century changes in glacier extent in the Caucasus Mountains, Russia/Georgia Journal of Glaciology, Vol. 52 No. 176, 99-109, 2006.

Stokes, C. R., Popovnin, V. V., Aleynikov, A., and Shahgedanova, M.: Recent glacier retreat in the Caucasus Mountains, Russia, and associated changes in supraglacial debris cover and supra/proglacial lake development, Ann. Glaciol., 46, 196–203, 2007.

Tielidze, L. G.: Glaciers of Georgia, Monograph. Publ. “Color”, 254 pp., Tbilisi, 2014 (in Georgian).

Tielidze, L. G., Lomidze, N., and Asanidze, L.: Glaciers retreat and climate change effect during the last one century in the Mestiachala River Basin, Caucasus Mountains, Georgia, Earth Sci., 4, 72–79, doi:10.11648/j.earth.20150402.12, 2015a.

Tielidze, L. G., Kumladze, R., and Asanidze, L.: Glaciers reduction and climate change impact over the last one century in the Mulkhura River Basin, Caucasus Mountains, Georgia, Int. J. Geosci., 6, 465–472, doi:10.4236/ijg.2015.65036, 2015b.

Volodicheva, N.: The Caucasus. In Shahgedanova, M., ed. The physical geography of Northern Eurasia. Oxford, Oxford University Press, 350-376, 2002.

Table 1. The change in the area and number of the glaciers of Georgia in 1911–1960–2014 according to the individual river basins.

Basin Name	K. Podozerskiy, 1911		R. Gobejishvili, by the maps of 1960		Landsat and Aster Imagery, 2014	
	Number	Area, km^2	Number	Area, km^2	Number	Area, km^2
Bzipi	10	4.0	18	7.2	18	4.0
Kelasuri			1	0.7	1	0.1
Kodori	118	73.2	160	64.5	145	40.1
Enguri	174	333.0	299	320.5	269	223.4
Khobisckali			16	0.9	9	0.5
Rioni	85	78.1	112	75.1	97	46.7
Liakhvi	12	5.1	16	4.0	10	1.8
Aragvi	3	2.2	3	0.8	1	0.3
Tergi	63	89.1	99	67.2	58	35.6
Asa	17	4.1	9	2.6	3	0.6
Arghuni	10	5.4	17	2.7	6	0.4
Pirikita Alazani	23	19.1	36	9.7	20	2.4
Total	**515**	**613.3**	**786**	**555.9**	**637**	**355.8**

Table 2. Mean annual temperatures of Georgia's medium and high mountain meteorological stations.

Mestia		Mamisoni		Jvari Pass		Kazbegi	
Years	Mean annual ^0C	Years	Mean annual ^0C	Years	Mean annual ^0C	Years	Mean annual ^0C
1906-1960	+5.9	1907-1960	-2.2	1907-1960	-0.1	1907-1960	-5.8
1961-2013	+6.0	1961-1995	-2.2	1961-2009	+0.2	1961-2009	-5.6
Temperature increase +0.1		Temperature increase 0.0		Temperature increase +0.3		Temperature increase +0.2	

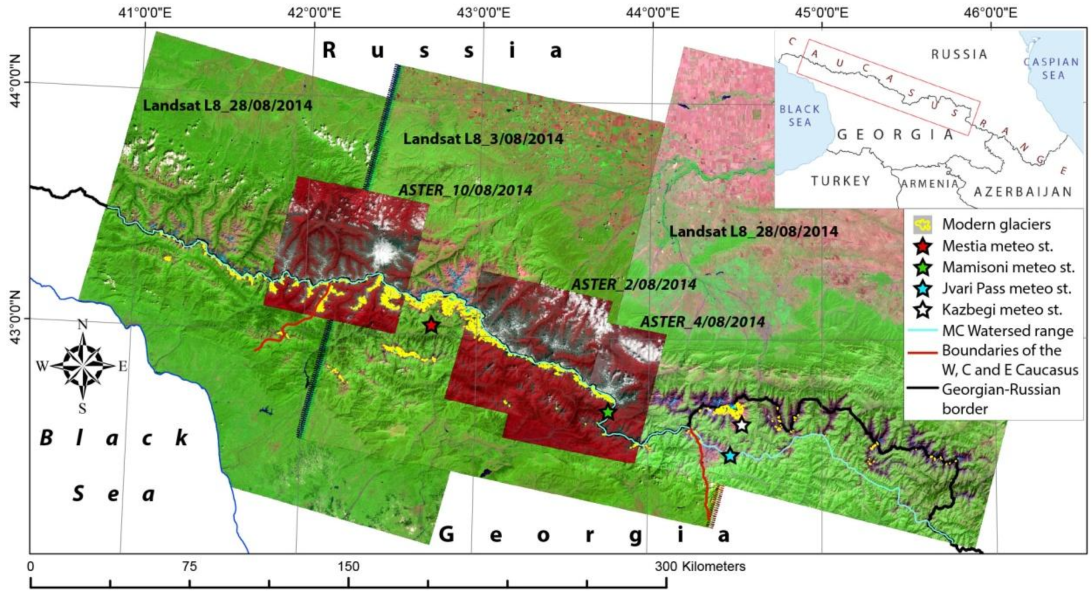


Figure 1. Georgian Caucasus glacier outlines (in yellow) derived from Landsat and ASTER imagery, and Georgia's mountain meteorological stations location.

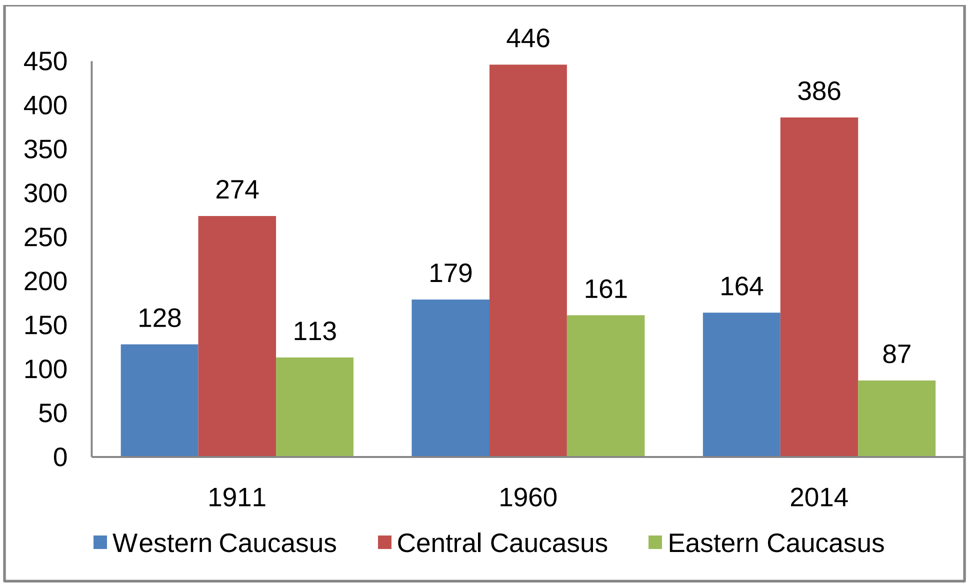


Figure 2. The change in the number of the Western, Central and Eastern Caucasus glaciers in 1911–1960–2014.

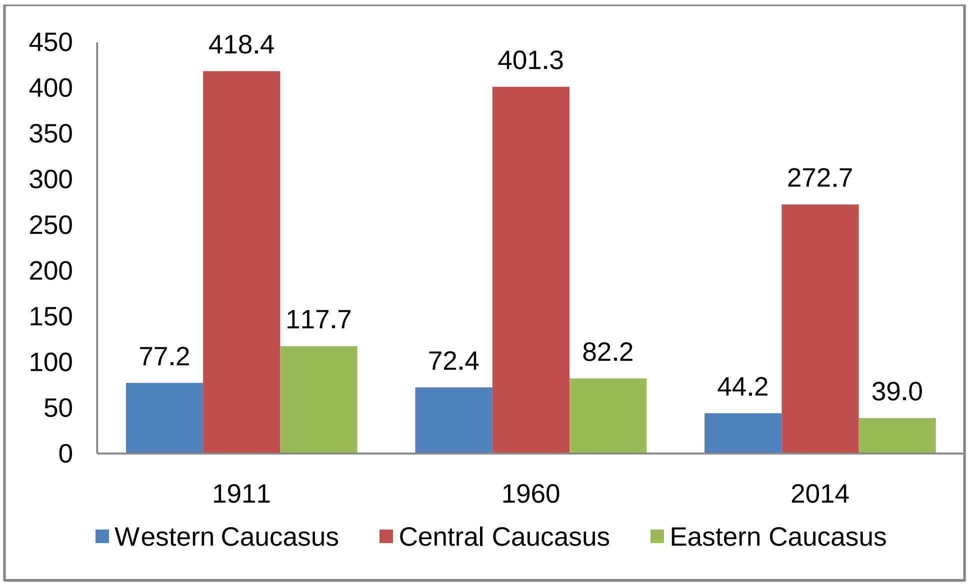


Figure 3. The change in the area (km^2) of the Western, Central and Eastern Caucasus glaciers in 1911–1960–2014.

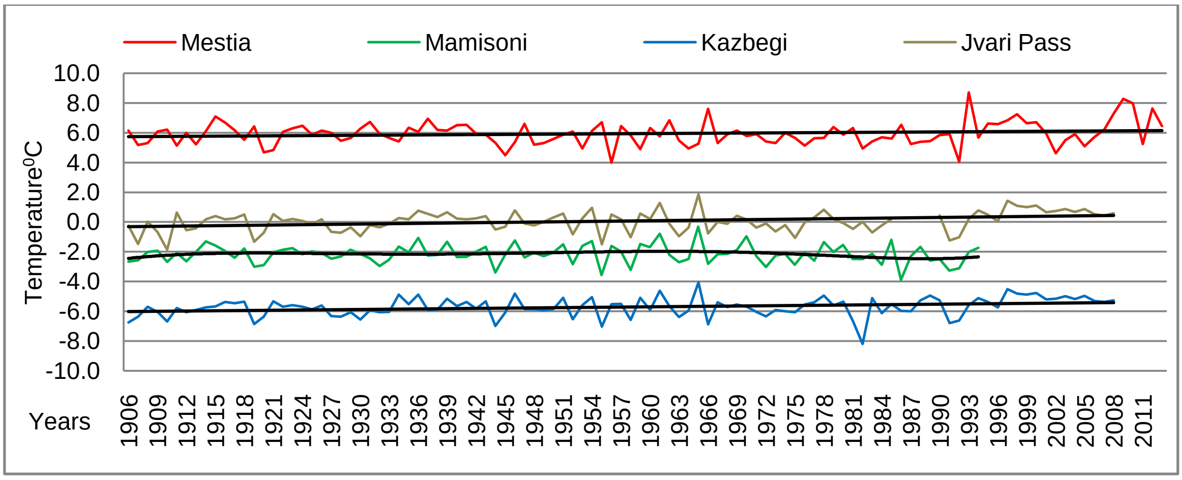
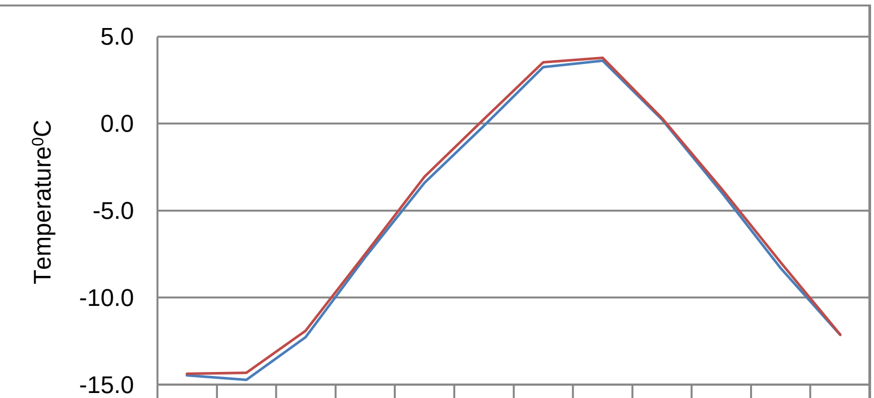
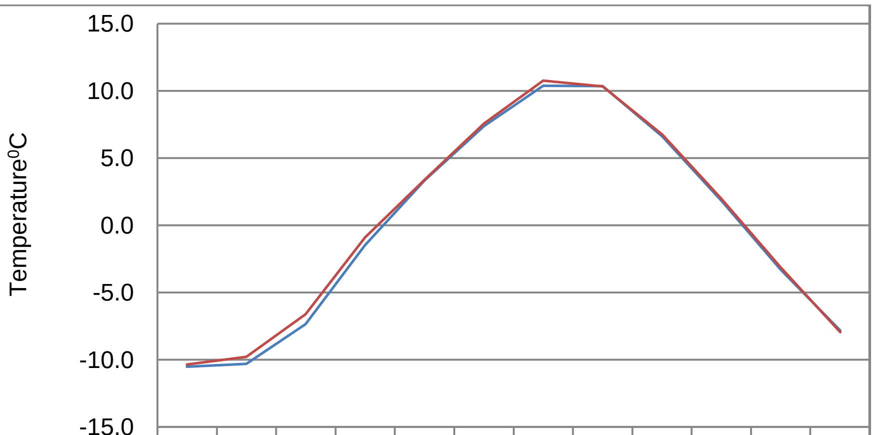


Figure 4. The course of the mean annual air temperatures in the Mestia, Mamisoni, Jvari Pass and Kazbegi meteorological stations over the last one century.



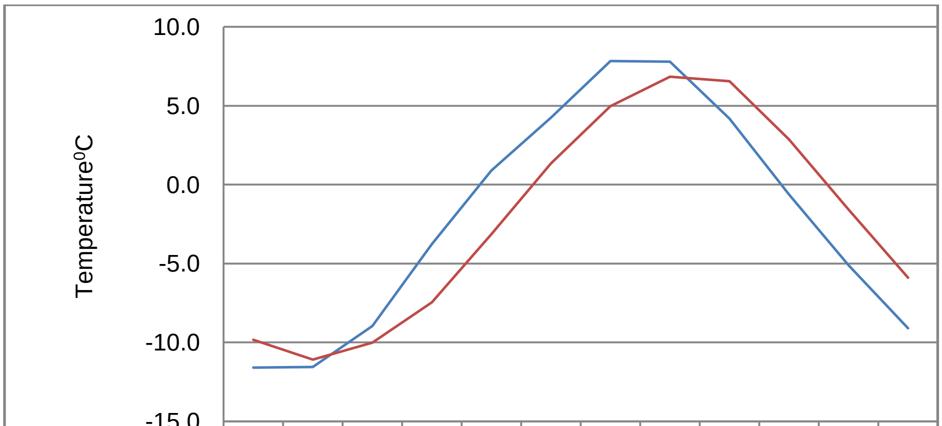
Months	1	2	3	4	5	6	7	8	9	10	11	12
1907-1960	-14.5	-14.7	-12.3	-7.7	-3.4	-0.1	3.2	3.6	0.2	-4.0	-8.3	-12.2
1961-2009	-14.4	-14.3	-11.9	-7.5	-3.1	0.3	3.5	3.8	0.3	-3.8	-8.0	-12.1

Figure 5. Mean monthly air temperature course of the Kazbegi meteorological station in the years of 1907–1960 and 1961–2009.



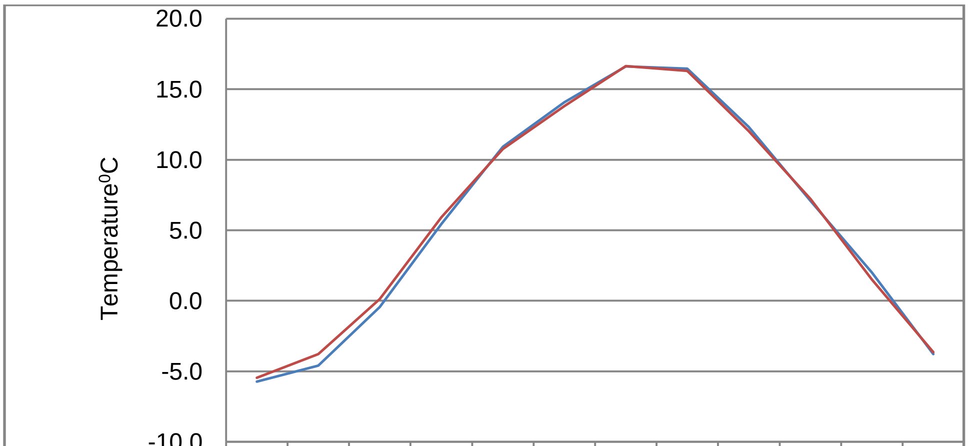
Months	1	2	3	4	5	6	7	8	9	10	11	12
1907-1960	-10.	-10.	-7.4	-1.5	3.3	7.4	10.4	10.3	6.6	1.8	-3.3	-7.8
1961-2009	-10.	-9.8	-6.6	-0.9	3.4	7.6	10.8	10.3	6.8	2.0	-3.1	-7.9

Figure 6. Mean monthly air temperature course of the Jvari Pass meteorological station in the years of 1907–1960 and 1961–2009.



Months	1	2	3	4	5	6	7	8	9	10	11	12
1907-1960	-11.6	-11.6	-9.0	-3.8	0.9	4.2	7.8	7.8	4.2	-0.6	-5.1	-9.1
1961-1995	-9.8	-11.1	-10.0	-7.5	-3.1	1.4	5.0	6.8	6.6	2.9	-1.6	-5.9

Figure 7. Mean monthly air temperature course of the Mamisoni meteorological station in the years of 1907–1960 and 1961–1995.



Months	1	2	3	4	5	6	7	8	9	10	11	12
1906-1960	-5.7	-4.6	-0.5	5.4	10.9	14.1	16.6	16.5	12.3	7.1	2.0	-3.8
1961-2013	-5.5	-3.8	0.1	5.9	10.8	13.8	16.6	16.3	12.0	7.2	1.5	-3.7

Figure 8. Mean monthly air temperature course of the Mestia meteorological station in the years of 1906–1960 and 1961–2013.

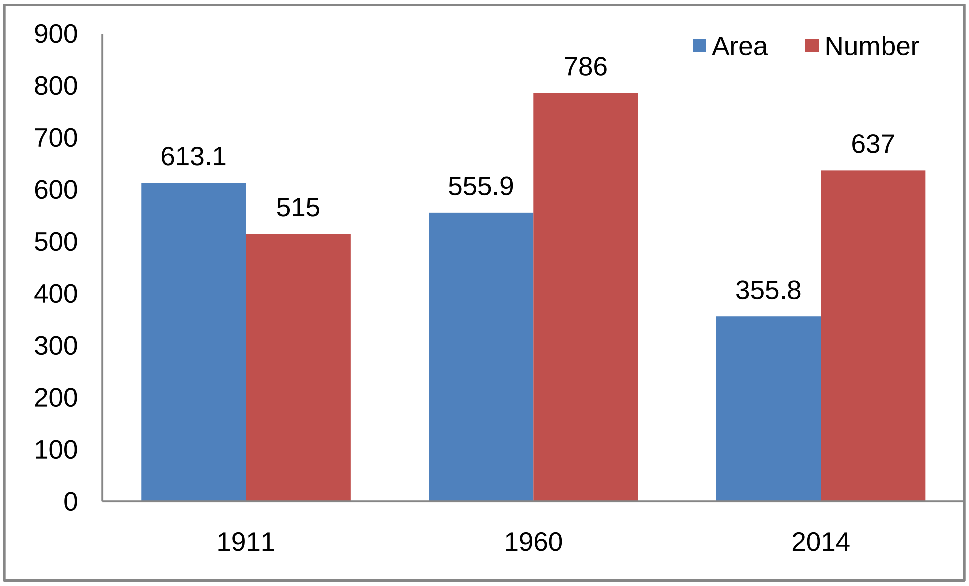


Figure 9. The change in the area (km^2) and number of the glaciers of Georgia in 1911–1960–2014.

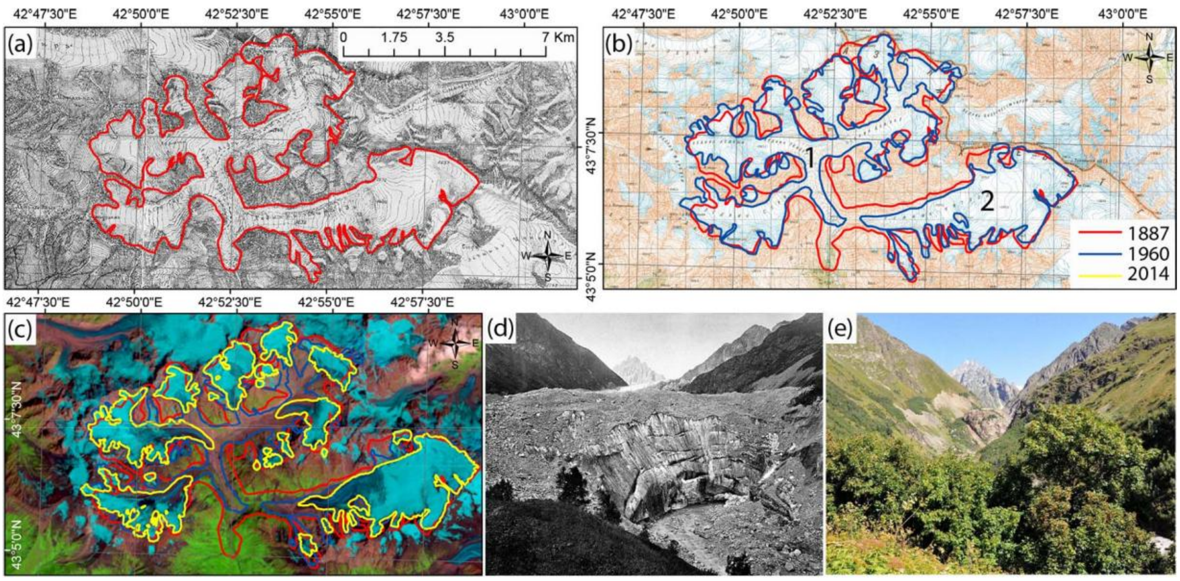


Figure 10. (a) Tviberi glacier, topographical map of 1887; **(b)** topographical map of 1960; (b1) Tviberi glacier; (b2) Kvitlodi glacier; **(c)** Landsat L8 imagery; **(d)** photo of 1884 (M. V. Dechy); **(e)** photo of 2011 (L. G. Tielidze).