Author reply to editor comments

“Glaciers change over the last century, Caucasus Mountains, Georgia, observed from old topographical maps, Landsat and ASTER satellite imagery” by L. G. Tielidze

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Dear editor,
Thank you so much for your comments. I did one more editing you requested me. My detail answers on the comments you can see below:

General comments:

C1	You must provide more information about possible inhomogeneity in the climate data. I do not meant extreme values but outliers due to wrong notes or trends due to changes of instrumentation etc .. Please see e.g., Begert, M., Schlegel, T., & Kirchhofer, W. (2005). Homogeneous Temperature and Precipitation Series of Switzerland from 1864 to 2000. International Journal of Climatology, 25, 65-80. I am aware that you likely can not avoid adjust some inhomogeneities, but you must as least do the best you can and mention is drawbacks in the manuscript, similar you wrote in the reply but be more quantitative (what does "don not significantly affect the trend "mean). Include this info in 3.4.
R1	Please see L 263-267. I have checked the climate data as best I can with the information I have been given. I believe the data were collected without any bias or changes over the ~100 years. In recent years, the some manual stations have been replaced by automatic weather stations, but these do not affect the data presented in this article. It is beyond the scope of this article to perform the types of analysis done by Begert et al.
C2	Use only one decimal digit instead of two when presenting numbers (e.g. 36.9 ± 2.2 instead of 36.88 ± 2.16).
R2	I agree. Please see all presenting numbers.
C3	Provide more information about the glaciers (esp. ELA) either in the section about the study region (in general form) and at the beginning of the results section (when analysing the own data see below).
R3	I agree and improved the manuscript accordingly. Please see L 125-133. It was not feasible to establish ELA from the available ASTER/Landsat imagery for 2014, but this would be a logical continuation of this work in a future study.
C4	It would be good if you would include more results of the inventory since it is the first recent one for entire Georgia, e.g. clearly state the current glacierized area in Georgia, more topographic information (min, max elevation, aspect, mean elevation). Is there any trend of the ELA / mean elevation present which can e.g. be related to climate (e.g. continentality etc.)? This is not much work but will clearly increase the impact of your paper. Just a suggestion, feel free to consider or not.
R4	I agree and improved the manuscript accordingly. Please see L 96-103; 125-133; 151-157;

	408-426.
C5	The discussion is still the weakest part. Do not present new results but put your results into perspective. Discuss e.g. better the observed temperature trends with respect to the literature. 0.2 ° warming in 100 years seems to be quite low. The first two statements (L. 398-404) must be better underlined by data. There are also regions where smaller cirque glaciers were quite stable due to specific topographic locations (e.g. there is one publication about the small glaciers in the Canadian Rockies). The info about the uncertainty of the 1911 data should be presented in the data section and the effect on the data a bit more detailed in the discussion.
R5	I agree and improved the manuscript accordingly. Please see new Discussion section L 463-532; 170-172.
C6	The conclusions are still weak and too general. You have much more conclusions you can draw (regional differences, suitability of the maps). I do not really like the separation in countries. Climate and glaciers do not know countries. Are not there south facing glaciers in the Russian territory and vice versa? Are there also differences in glacier size? The last two sentences should either be discussed before and underlined with relevant literature or omitted.
R6	I agree and improved the manuscript accordingly. Please see new Conclusions section L 535-553; 96-99.

More specific comments:

C7	L. 55-59: Good that you mention now GLIMS and RGI. However, you need to be more specific about the source of the data for this region (see RGI technical reports, and GLIMS metadata and include the RGI version (s) (as already requested)
R7	I agree and improved the manuscript accordingly. please see L 56-69; 475-481.
C8	L. 148: Include the reference for the original inventory, not only Khomova et al. 2014.
R8	I agree, please see L 181.
C9	L. 206: Provide a rational for the 7.5m. You may mention in this section the general uncertainty of glacier outlines of maps. You approach is valid but more theoretical.
R9	I agree, please see L 237-240.
C10	L. 224: Why only data from the accumulation season? Maybe there is also some summer snowfall. But it is better to use only the accumulation season than the annual data and do not separate the seasons.
R10	Dear editor, I am bit confused from your comment. Do you suggest me to use annual precipitation and not accumulation? or accumulation season data is good and I have to correct just Fig. 6. In my opinion it is more suitable to use accumulation season only as it is a standard. e.g. Shahgedanova et al. (2014) used just accumulation season data for the deglaciation research in the Caucasus.
C11	L434ff: Good that you include now comparisons to some other studies. This should slightly be extended.
R11	I agree, please see L 518-532.
C12	L. 439: You do not need to refer to my own study about Northern Tien Shan. It is specific and my numbers are probably too high due to some errors in the data from the soviet glacier inventory. You may keep as I used this inventory but the uncertainty should be mentioned. I think it is better to quote Sorg et al. (2012), Nat. Clim. Change when you want to refer to the Tien Shan.
R12	I agree, please see L 522-526.
C13	Fig. 5: Include the info about the black line in the figure.

R13	I agree, please see P. 20, Fig. 5.
C14	Fig. 6: The horizontal lines are a bit confusing as you show above the trends with solid lines, I would omit as the differences can also be seen without the line.
R14	I agree, please see P. 21, Fig. 6.

All correction and change what I did is the red color.

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

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Abstract

Changes in the area and number of glaciers in the Georgian Caucasus mountains were examined over the last century, by comparing recent Landsat and ASTER images (2014) with older topographical maps (1911, 1960) along with middle and high mountain meteorological stations data. Total glacier area decreased by 8.1±1.8% (0.2±0.04% yr^{-1}) or by 49.9±10.6 km^2 from 613.6±9.8 km^2 to 563.7±11.3 km^2 during 1911–1960, while the number of glaciers increased from 515 to 786. During 1960-2014, the total ice area decreased by 36.9±2.2% (0.7±0.04% yr^{-1}) or by 207.9±9.8 km^2 from 563.7±11.3 km^2 to 355.8±8.3 km^2, while glacier numbers decreased from 786 to 637. In total, the area of Georgia glaciers reduced by 42.0±2.0% (0.4±0.02% yr^{-1}) between 1911-2014. The Eastern Caucasus section had the highest retreat rate of 67.3±2.0% (0.7±0.02% yr^{-1}) over this period, while the central part of Georgian Caucasus had the lowest 34.6±1.8% (0.3±0.01% yr^{-1}), with the Western Caucasus intermediate at 42.8±2.7% (0.4±0.03% yr^{-1}).

1 Introduction

Alpine glaciers are an important component of the global hydrologic cycle. Glaciers can help to regulate streamflow in regions where water is stored during colder periods of the year and later released as melt water runoff during warm dry conditions (Beniston, 2003; Earl and Gardner, 2016). Alpine glaciers also provide proxy information on regional and global climate where other long-term records may not exist, as changes in glacier mass and/or extent can reflect changes in temperature and/or precipitation (e.g. Oerlemans and Fortuin, 1992; Meier et al., 2007). Regular and detailed observations of alpine glacier behavior are necessary in regions such as the Georgian Caucasus, where the glaciers are an important source of water for agricultural production, and runoff in large glacially-fed rivers (Kodori, Enguri, Rioni, Tskhenistskali, Nenskra) supply hydroelectric power stations. In addition, glacier outburst floods and related debris flows are a significant hazard in Georgia and in the Caucasus. Thus, future trends in glacier change are of considerable interest to the region.

The study of glaciers in the Caucasus began in the first quarter of the 18th century, in the works of Georgian scientist Vakhushti Bagrationi, followed by foreign scientists a century later. e.g. W. Abich, D. Freshfield, G. Radde, N. Dinik, I. Rashevskiy, A. Reinhardt. Data on the glaciers of Georgia are found in the catalog of the Caucasus glaciers compiled by Podozerskiy (1911). Subsequently, in the 1960s large-scale (1:50,000) topographic maps were published and compiled from aerial photographs taken 1955-1960. Based on these maps, Gobejishvili (1989, 1995) documented further statistical information about the glaciers of Georgia. The glacier inventory of the former USSR was published in 1975, where data on the glaciers of Georgia were obtained from (1955-1957) aerial images. Thus, complete statistical information on the glaciers of Georgia has not been published for about 50 years.

While the glaciers of the Caucasus are much larger than those of the Middle East, the Randolph Glacier Inventory (RGI), presents these together as one main region (Pfeffer et al., 2014). In the RGI version 3.2, the Greater Caucasus region database contains 1303 glaciers, with a total area of 1100.7 km^2. Although this version omitted glaciers in the Eastern Caucasus section (Shahgedanova et al., 2014), these omissions have been partly rectified by adding nominal glaciers from the WGI-XF (Cogley, 2009). The 339 added glaciers, with date ranges 1965–1976, cover 155 km^2 and include some in the Central Caucasus section (in the Svaneti and Lechkhumi sub-ranges in the Georgian Caucasus) and in the Lesser Caucasus in Armenia (GLIMS Technical Report, 2015). After these corrections, the RGI 4.0 and 5.0 version databases contain 1637 glaciers, with total area of 1255.6 km^2. The GLIMS database (www.glims.org) identifies (based on 2005-2007 ASTER imagery) in excess of 1300 glaciers with a combined area of 1354 km^2. These previous inventories, executed by semi-automatic digitizing also do not consider the separate Georgian Caucasus glaciers composition.

Most recent studies of the Caucasus have focused on the northern slopes of the range in Russia which contain limited information about Georgian glaciers. For example, Stokes et al. (2006) examined changes in termini positions of 113 glaciers in the Central Caucasus between 1985 and 2000 using Landsat imagery. From this assessment, they reported a total loss of bare ice area of about 10%. Shahgedanova et al. (2014) examined two objectives: (i) to quantify changes in glacier area in the central and western sectors of the Caucasus Mountains between 1999/2001 and 2010/2012 using ASTER and panchromatic Landsat imagery, and (ii) to assess changes in glacier retreat rates from 1987-2010 using aerial photographs and ASTER imagery for a sub-sample of valley glaciers. From this assessment (total 498 glaciers), they inferred a total loss of ice area of 4.7±2.1% or 19.2±8.7 km^2 from 407.3±5.4 km^2 to 388.1±5.2 km^2.

Recent published works about glaciers on the south-facing slopes of the Caucasus, have examined changes in glacier area for river basins in the Georgian Caucasus between 1911-2014 using old topographical maps and modern aerial images. These studies inferred a total loss of ice area ~ 30.1% (from 48.5 km^2 to 33.9 km^2) in Dolra River basin (Tielidze et al., 2015a), ~ 38.8% (from 100.0 km^2 to ~ 61.2 km^2) in Mulkhura River basin (Tielidze et al., (2015b); and ~ 20.1% (from 55.2 km^2 to 44.1 km^2) in Mestiachala River basin (Tielidze et al., 2015c).

This article presents the percentage and quantitative changes in the number and area of glaciers for all Georgian Caucasus in the years 1911–1960–2014, by individual river basins.

2 Study area

According to the conditions of relief, the northern slope of the Caucasus is more favorable for formation of glaciers than the southern one. This is contributed by high hypsometry and extremely partitioned slopes, gorges and depressions, represented by wide cirques of Wurm period. The high mountainous relief of the Greater Caucasus is favorable for the continuing existence of glaciers in Georgia. The Greater Caucasus mountain range extends along the northern territory of Georgia for about 750 km. The Georgian glaciers are concentrated mostly in the southern watersheds, as well as in the sub-ranges of the Greater Caucasus and Kazbegi massif (Tielidze, 2016). According to morphological and morphometric characteristics, the Greater Caucasus can be divided into three parts within Georgia – Western, Central and Eastern Caucasus (Maruashvili, 1971; Gobejishvli, 1995) (Fig. 1).

The *Western Caucasus* is located to the west of the Dalari Pass, and includes four main sub-ranges: Gagra, Bzipi, Chkhalta (Abkhazeti) and Kodori. These are lower in elevation than the Central and Eastern Caucasus, with just one peak (Dombai-ulgen) exceeding 4000 m and several peaks between 3800–4000 m. However the Western section receives more abundant precipitation than the Central and Eastern Caucasus.

The *Central Caucasus* is the highest in elevation and the main center of glaciation in the Caucasus. Its western boundary is Dalari Pass and runs along the Enguri and Kodori rivers' watersheds (Kharikhra range), while its east boundary coincides with the Jvari Pass and then runs along the bottom of the river gorges of Tergi-Bidara and Mtiuleti's Aragvi (Maruashvili, 1971). In terms of the glacier distribution, orographic units can be distinguished in the Central Caucasus: Svaneti, Samegrelo, Lechkhumi, Shoda-Kedela and Java ranges.

The *Eastern Caucasus* is located to the east of the Georgian Military Road (Jvari Pass). Both the southern and northern slopes of the Caucasus range lie within Georgia's boundaries. Eastern Caucasus has the high average elevation with many peaks e.g. Kuro, Komito, Shani, Amgha, Tebulosmta, exceeding 4000 m. However, because of the relatively dry climate and geomorphological features, there are fewer glaciers in the Eastern Caucasus than in the lower Western Caucasus.

The location of the Equilibrium Line Altitude (ELA) for the river basins in the Georgian Caucasus was first determined by A. Reinhardt (1916) based on the 1880-1910 topographical maps (1:40,000 scale) and field-desk research. He determined ELA in 17 main and tributary river basins, with ELA mean elevation at ~3090 m a.s.l.. Using the 1955-1960 original aerial imagery, 1:50,000 scale topographical maps (1960) and several years of field-desk research, R. Gobejishvili (1995) calculated the ELA (1960) in 10 main and 18 tributary river basins at ~3260 m a.s.l., with the highest ELA values (~3500 m a.s.l.) in the river basins of the Eastern Georgian Caucasus, where there is lower annual snow precipitation.

The Caucasus Mountains are characterized by strong longitudinal gradients that produce a maritime climate in the west and a more continental climate in the east. Westernmost areas typically receive around three to four times more precipitation than eastern areas (Horvath and Field, 1975). The southern slopes also experience higher temperatures and precipitation, which can be up to 3,000-4,000 mm annually in the southwest (Volodicheva, 2002). Much of this precipitation falls as snow, especially on windward slopes of the western Greater Caucasus, which are subjected to moist air masses from the Black Sea (Stokes, 2011).

January is usually the coldest month in Georgia, but in the high mountain regions (2700–2800 m) February is often the coldest month. Stable frosty periods at a height of 2000–3000 m last from November to May, and above 3000 m from October to July. The average January temperature is −8^{0}C at a height of 2000 m and the coldest month is −16^{0}C at a height of 3600 m (Gobejishvili, 1995). The average monthly temperature of the warmest month – August, varies from +14 to +17^{0}C at about 1500 m of altitude, falling to +7.6 and +3.4^{0}C respectively at 2800 and 3600 m (Gobejishvili, 1995). Average multiannual air temperature ranges from +5.9^{0}C (Mestia, 1906–2013) to −5.7^{0}C (Kazbegi, 1907–2009).

The snow cover is unevenly distributed in the Greater Caucasus Range; snowfall in the Western Caucasus is greater and snow cover lasts for a longer period than in the Eastern Caucasus. The average snow cover in the Eastern Caucasus is ~110 days at ~1500 m a.s.l., ~145 days at ~2000 m a.s.l. and ~195 days at ~2500 m a.s.l.. In the Western Caucasus snow cover extends for ~135, 182 and 222 days respectively. In the Eastern Caucasus the average depth of snow cover is ~21-40 cm at ~1500-2000 meters elevation, and more than 100 cm at ~2000-2500 meters (Gobejishvili, 1995; Tielidze, 2016).

3 Data sources and methods

3.1 Old topographical maps

The compilation of the first reliable map of the Caucasus, at a scale of 1:420,000 and depicting the largest glaciers, was completed by 1862. Topographic surveys of the Caucasus at a scale of 1:42,000 were accomplished 50 years later (1880-1910). Having analyzed these maps, Podozerskiy (1911) published the first inventory of Caucasus glaciers (Kotlyakov et al., 2010). Detailed analysis of these early data showed some defects in the shape of the glaciers and in particular the inaccessible valley glaciers were depicted incorrectly. This caused some error in the identification of precise areas, such as in the Enguri and Rioni River basins, which were difficult to access for plane table surveying. However as no other data exist from this time, these maps are the most reliable source for this research to establish century-long trend glacier changes (Tielidze et al., 2015c).

The oldest topographic maps were replaced in 1960, under the former Soviet Union with 1:50,000 scale topographical maps from 1955–1960 aerial images. Based on these, Gobejishvili (1989) generated new statistical information on the glaciers of Georgia.

The next inventory of the Caucasus glaciers was the result of a manual evaluation of selected glacier parameters from the original aerial photographs and topographic maps (Catalog of Glaciers of the USSR, 1975; Khromova et al., 2014), where information on Georgia was obtained from the same (1955-1957) aerial photographs. There are some mistakes in the catalog regarding number and area of the glaciers in some river basins (particularly the Bzipi, Kelasuri, Khobisckali, Liakhvi, Aragvi and Tergi), where temporary snow fields were considered as glaciers (Gobejishvili, 1995). The USSR Catalog datasets contain tables with glacier parameters but not glacier outlines. As the

USSR and Gobejishvili's inventories were based on the same aerial photographs, I have used both datasets in this article for a more comprehensive comparison.

As this information was only available in printed form, I scanned and co-registered the maps and images using the August 3 2014 Landsat image as a master. Offsets between the images and the archival maps were within one pixel (15 m) based on an analysis of common features identifiable in each dataset. I reprojected both maps (1911, 1960) to Universal Transverse Mercator (UTM), zone 38-North on the WGS84 ellipsoid, to facilitate comparison with modern image 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, such 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). Satellite imagery - Landsat L8 OLI (Operational Land Imager), since February 2013, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), since January 2000, with 15/30 m resolution provide convenient tools for glacier analysis. Together with old topographical maps, these allow us to identify changes in the number and area of glaciers over the last century. Most of the images (Landsat and ASTER) were acquired at the end of the ablation season, from August 2 to September 2 (except for one ASTER image, on 10 July), when glacier tongues were free of seasonal snow under cloud-free conditions and suited for glacier mapping (Fig. 1), but with some glacier margins obscured by shadows from rock faces and glacier cirque walls (Khromova et al., 2014). Landsat (level L1T) georeferenced 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/). ASTER (level L1T) 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/)

I used the Landsat 8 panchromatic band, along with a color-composite scene for each acquisition date, for Landsat images – bands 7 (short-wave infrared), 5 (near infrared) and 3 (green); for ASTER images – bands 3 (near-infrared), 2 (red) and 1 (green). Each glacier boundary was manually digitized and the total surface area for each glacier calculated according to Paul et al., (2009). The size of the smallest glacier mapped was 0.01 km^2.

3.3 Glacier delineation error and analysis

For the Georgian Caucasus glaciers I calculated three error terms resulting from (a) co-registration of old maps and satellite images, (b) glacier area error and (c) debris cover assessment.

(a) Offsets between the images and archival maps are within 1 image pixel (15 m). Glacier outlines on the old topographic maps (1911, 1960) correspond to a line thickness of 12 metres (1:42,000) and 15 metres (1:50,000). Using the buffer method from Granshaw and Fountain (2006), these yield a total potential error of ±1.64%.

(b) The glacier area error is mostly inversely proportional to the length of the glacier margin (Pfeffer et al., 2014). Applying glacier buffers account for the length of the glacier perimeter, while the buffer width, is critical to the resultant glacier area error (Guo et al., 2015). I estimated uncertainty by the buffer method suggested by Bolch et al. (2010) and Granshaw and Fountain (2006) with a buffer size 7.5 m for all aerial images and maps, based on the 15 m image pixel size, and map uncertainty in the absence of stated historical accuracies. This generated an average uncertainty of the mapped glacier area of 2.3% for 2014 (satellite images), 2.0% for 1960 (topographical maps) and 1.6% for 1911 (Podozerskiy catalog).

(c) Manual digitizing by an experienced analyst is usually more accurate than automated methods for glaciers with debris cover (Raup et al., 2007), which is a major source of error in glacier mapping (Bhambri et al., 2011; Bolch et al., 2008) 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). One of the most heavily debris-covered glaciers in the Georgian Caucasus is Khalde Glacier (42.596^{0}N, 43.22^{0}E) where supra-glacial debris covers 23%. For the precise determination of debris cover I also used my GPS field data collected in most glaciated areas during 2004-2014 including those with highest debris cover (Khalde, Lekhziri, Chalaati, Shkhara, Devdoraki, Zopkhito, Ushba et al.). Thus the error associated with debris-covered glaciers was considered to be negligible.

3.4 Climatic data

I examined the average monthly and mean annual air temperature records, along with accumulation season (October–April) precipitation from middle and high mountain meteorological stations of Georgia to characterize climatic variations since 1907 (see figure 1 for their locations): Mestia (1441 m a.s.l.); Mamisoni (2854 m a.s.l.), Jvari Pass (2395 m a.s.l.) and Kazbegi (3653 m a.s.l.).

The primary goal was to assess long-term temperature and precipitation variability for association with glacier area change. As high-quality homogenization and in-depth analysis is an extended labour-intensive process (Begert, et al., 2005), I relied on the Mann-Kendall test in Addinsoft's XLSTAT 2015 for the significance of air temperature and precipitation trends.

4 Results

4.1 Area and number change

The total ice area loss between 1911–1960 was 8.1±1.8% or 49.9±10.6 km^2, reduced from 613.6±9.8 km^2 to 563.7±11.3 km^2, while the number of glaciers increased from 515 to 786. These results reflect that in the early 20th century, compound-valley glaciers exceeded 200 km^2 (Tielidze, 2014), and these degraded into relatively smaller simple valley glaciers and even smaller cirque glaciers.

Between 1960–2014, glacier area decreased by 36.9±2.2% or 207.9±9.8 km^2, from 563.7±11.3 km^2 to 355.8±8.3 km^2 and glacier numbers from 786 to 637. These occurred because in the 1960–70s, many glaciers were small cirque glaciers, which disappeared completely in the last half century (Tielidze, 2014). Glacier changes according to divisions of the Caucasus range and river basins are described below.

4.1.1 The Western Caucasus

The Bzipi River Gorge is the westernmost basin in Georgia containing glaciers, generally small cirque glaciers about 0.5 km^2 in area, (Tielidze, 2014) with glaciers also in the basins of the Kelasuri and Kodori rivers.

Podozerskiy (1911) indicates there were 10 glaciers in the Bzipi basin with an area of 4.0±0.01 km^2. From the 1960 maps there were 18 glaciers with an area of 9.9±0.2 km^2; the satellite images of 2014 also showed 18 glaciers, but with a reduced area 4.0±0.1 km^2 (Table 1).

Podozerskiy does not provide any information on the Kelasuri River basin. In 1960 there was only one glacier mapped with an area of 0.3±0.02 km^2, and similarly in 2014 with an area of 0.1±0.01 km^2 (Table 1).

The majority of contemporary glaciers on the southern slopes of the Western Caucasus are located in the Kodori River basin, which extends from the Marukhi Pass to the Dalari Pass, including several peaks between 3800–4000 m. The 1911 data indicate 118 glaciers in the Kodori River basin with an area of 73.2±1.6 km^2. In 1960, 160 glaciers were mapped with an area of 63.7±1.6 km^2 and in 2014 there were 145 glaciers in this basin with a total area of 40.1±1.3 km^2 (Table 1).

In total, in the Western Caucasus, glacier area decreased by 4.3±2.3% or by 3.3±1.7 km^2 in 1911-1960. Between 1960–2014, glacier area was reduced by 40.2±2.3% or by 29.7±1.6 km^2 (Table 2).

4.1.2 The Central Caucasus

The Central Caucasus section is distinguished by the highest relief in Georgia, where five peaks exceed 5000 m. River basins include the Enguri, Khobistskali, Rioni and Liakhvi.

The Enguri River basin has the largest number and area of contemporary glaciers exceeding all other basins combined. These include the largest glaciers in Georgia such as the Lekhziri, Southern and Northern Tsaneri (Tielidze et al., 2015c; 2015b). In 1911 there were 174 glaciers in the Enguri River basin with a total area of 333.0±4.6 km^2; in 1960, 299 glaciers were mapped with an area of 323.7±5.7 km^2, and in 2014 there are 269 glaciers with a total area of 223.4±4.6 km^2 (Table 1).

No information is available about the glaciers of the Khobistskali River basin in the catalog of Podozerskiy, but in 1960, there were 16 glaciers with a total area of 1.1±0.1 km^2 and in 2014, nine glaciers had an area of 0.5±0.03 km^2 (Table 1).

Another important center of glaciation in Georgia is the Rioni River basin with peaks above 4000 m. On the southern slope of the Caucasus, the Rioni River basin is third behind the Enguri and Kodori River basins in the number of contemporary glaciers, and in area it is only behind the Enguri River basin. In 1911 there were 85 glaciers in the Rioni River basin with an area of 78.1±1.6 km^2. In 1960 the number of glaciers was 112 with total area 76.8±1.7 km^2. By 2014 there were 97 glaciers with total area of 46.7±1.2 km^2 (Table 1). The largest glacier in the Rioni River basin is Kirtisho with an area of 4.4±0.1 km^2.

The Liakhvi River basin, is the easternmost basin of the Central Caucasus. In 1911 there were 12 glaciers in the basin with an area of 5.2±0.1 km^2, increasing to 16 in 1960 with total area of 4.3±0.1 km^2. In 2014 10 glaciers had a total area of 1.8±0.1 km^2 (Table 1).

In total, the glacier area decreased by 2.5±1.7% or 10.4±7.0 km^2 in 1911-1960 in the Central Caucasus. Between 1960–2014, glacier area was reduced by 32.9±2.0% or 133.5±4.9 km^2 (Table 2).

4.1.3 The Eastern Caucasus

In Georgia the Eastern Caucasus is represented both by some southern and the majority northern slopes, in the basins of the Aragvi, Tergi, Asa, Arghuni and Pirikita Alazani rivers.

The westernmost basin of the Eastern Caucasus, is the Aragvi River basin. In 1911 there were three glaciers with a total area of 2.2±0.04 km^2, reduced in 1960 to 0.9±0.03 km^2. By 2014 only one glacier (Abudelauri) remained in the basin with an area of 0.3±0.02 km^2 (Table 1).

The Tergi River basin is the main glaciation center of the Eastern Caucasus with several peaks above 4500 m and one above 5000m (Mkinvartsveri/Kazbegi). The number and area of glaciers in the Tergi River basin are below only Enguri, Kodori and Rioni with ~9.1% of the total number of the glaciers of Georgia, and 10% by area. In 1911 there were 63 glaciers in the Tergi River basin with total area of 89.1±1.2 km^2. By 1960 there were 99 glaciers with total area of 67.0±1.3 km^2, and in 2014 there were 58 glaciers with total area of 35.6±1.0 km^2 (Table 1). The largest glacier in the Tergi River basin is Eastern Suatisi with an area of 7.7±0.1 km^2.

The Asa River basin is located on the northern slopes of the Greater Caucasus, with peaks above 3700 m. In 1911 there were 17 glaciers with total area of 4.1±0.1 km^2. By 1960 there were nine glaciers with total area of 2.6±0.01 km^2 and in 2014 three glaciers with a total area of 0.5±0.03 km^2 (Table 1).

The Arghuni River basin is also located on the northern slope of the Greater Caucasus. In 1911 there were 10 glaciers in the Arghuni River basin with a total area of 5.4±0.1 km^2. By 1960 there were 17 glaciers with total area of 2.9±0.1 km^2 but in 2014 there were only six glaciers with total area of 0.4±0.03 km^2 (Table 1).

In 1911 the Pirikita Alazani River basin contained 23 glaciers with total area of 19.1±0.3 km^2. By 1960 the glaciers were reduced in size and although the number increased to 36, their area was reduced to 10.5±0.3 km^2. In 2014 there were 20 glaciers in this basin with total area of 2.4±0.1 km^2 (Table 1).

In total, the glacier area decreased by 30.1±1.9% or 36.1±1.9 km^2 in 1911-1960 in the Eastern Caucasus. Between 1960–2014, glacier area was reduced by 53.2±2.4% or 44.6±1.4 km^2 (Table 2).

4.1.4 The largest glaciers

The largest glacier at the end of the 19th century and early 20th century in Georgia was Tviberi Glacier (Fig. 2a). According to the topographical map of 1887 the glacier area was 49.0±0.4 km^2 terminating at a height of 2030 m above sea level. Before 1960, the Kvitoldi glacier separated from the Tviberi Glacier's east side, and became an independent glacier (Fig. 2b). In the 1960 topographical map the area of the Tviberi was 24.7±0.4 km^2 and the glacier tongue ended at 2140 m a.s.l. (Fig. 2b). The Landsat 2014 image shows the Tviberi degradation after 1960, when the smaller simple valley glaciers and even smaller cirque glaciers developed (Tielidze et al., 2015b) (Fig. 2c). Tviberi Glacier degradation is evident in the photographic images of 1884–2011 (Fig. 2d, e).

The compound-valley glacier Tsaneri (with the Nageba Glacier) was the second largest glacier in Georgia according to the topographical map of 1887 with an area of 48.9±0.5 km^2 (Fig. 3). In 1960, the Tsaneri Glacier was still the compound-valley type glacier (without the Nageba Glacier) and its area was 28.3±0.3 km^2 (Tielidze et al., 2015b) (Fig. 3b). The glacier is now in the form of two disconnected glaciers - Northern Tsaneri and Southern Tsaneri (Fig. 3c, d, e).

The third largest glacier in Georgia at the end of the 19th century was Lekhziri Glacier with an area of 40.8±0.3 km^2. Lekhziri was a compound-valley glacier at this time (cross-shaped) terminating at a height of 1730 meters a.s.l. (Fig. 4a). In 1960 the glacier area was 36.0±0.4 km^2 terminating at 1970 meters a.s.l. (Fig. 4b). This area reduction was mainly caused by the shortening of its tongue (Tielidze et al., 2015c). Visual observation during an expedition to the glacier in 2011, showed that the central flow of the glacier had weak contact with the two main flows and on the Landsat 2014 image this contact split. This resulted in the Northern Lekhziri (central flow) Glacier (6.3±0.1 km^2) and Lekhziri Glacier (consisting of two flows) forming the largest glacier in Georgia (compound-valley type) (Fig. 4c). In 2014 the area of the Lekhziri Glacier was 23.3±0.4 km^2 terminating at 2320 meters a.s.l.. Glacier degradation is clearly visible in the photographic images of 1960–2011 (Fig. 4d, e). The second largest glacier in Georgia is the Southern Tsaneri (Fig. 3c) with area 12.6±0.2 km^2, ahead of the Northern Tsaneri (Fig. 3c) third with 11.5±0.1 km^2.

4.1.5 Glacier morphology, aspect and terminus position

Valley glaciers cover the largest area - 161.6±2.7 km^2 (69 glaciers, mean area 2.3 km^2) in Georgia. The second and the third most common are compound-valley (seven glaciers covering 55.0±1.7 km^2, mean area 7.9 km^2) and cirque types (289 glaciers with a total area of 40.9±1.8 km^2, mean area 0.14 km^2). Cirque glaciers are the most numerous, followed by hanging glaciers (123 covering 16.4±0.8 km^2) and cirque-valley glaciers (74 with an area of 4.9±0.1 km^2).

Glaciers with south and southwest aspects are the most extensive, covering 72.8±1.6 km^2 (104 glaciers), - and 72.4±1.4 km^2 (71 glaciers) respectively, and combining for 41% of all glaciers. In contrast, those facing north, northeast and east account for only 22.5% of the total. These reflect the geographic location of Georgia relative to the Caucasus Mountains.

The terminus positions of the morphological glacier types generally increase in elevation from west to east in the Georgian Caucasus. The compound-valley glacier of Chalaati (43.7^{0}N, 42.42^{0}E) has the lowest terminus position for the whole Caucasus region (1960 m a.s.l.), based on a 2014 GPS survey. Overall, the valley glacier terminus positions are between 2200-3000 m a.s.l., while cirque and hanging glaciers are at the highest elevations, between 2800-3600.

4.2 Climatic variability

Commencing with the highest elevation station, mean annual air temperatures at the Kazbegi weather station show a slight positive trend in the years 1907–2009, rising by 0.2^{0}C from 1907–1960 to 1961–2009 (Fig. 5). The same is seen in the mean monthly temperature data for all twelve months (Table 3). The Jvari Pass weather station has the highest increase (0.3^{0}C) in mean annual air temperatures from 1907–1960 to 1961–2009 although it is not consistent for every month (Table 3). The Mann Kendall statistical test, indicates a positive trend of mean annual temperature was detected for the whole observed period (1907-2009), and also for 1907-1960, and 1961-2009, for both the Kazbegi and Jvari Pass weather stations (Table 4).

The Mamisoni station shows no significant trend for 1907-1995 (Fig. 5) and monthly means are cooler between March-August (Table 3). The warming trend is positive for the Mestia weather station, the lowest elevation location (Fig. 5), although it is only statistically significant for the period 1961-2013 (Table 4). Mean monthly temperatures were warmer compared with the earlier period 1906-1960 in the autumn/winter (October-April), but cooler in spring/summer (May-September).

During 1906-2013 just two years - 1966 (for all meteorological stations) and 1993 (just for Mestia) were abnormally warm and one single year (1983) was very cold for Kazbegi. Mestia's 1993 warm temperature caused unusually high December mean temperature (3.6^{0}C), compared to the mean multiannual December temperature (-3.7^{0}C). In January 1983 the absolute minimum temperature (-42^{0}C) was recorded in Georgia, at Kazbegi station, where the January mean temperature was -22.4^{0}C, compared to the mean multiannual January temperature (-14.4^{0}C).

An increase in the accumulation season (October-April) precipitation similar to that found by Shahgedanova et al. (2014), and statistically significant at 95% confidence level, was registered at both Mestia and Mamisoni meteorological stations in their most recent 1985–2010 and 1981-1993 periods, when average precipitation of 608.5 and 527.1 mm exceeded their 1961–1985 and 1965-1980 averages of 495.7 and 380.0 mm by 22.7 and 38.7% respectively (Fig. 6). By contrast, the accumulation season precipitation increased by only 3.6% at Jvari Pass in 1981–1990 (677.9 mm) in comparison with 1965–1980 (653.6mm).

5 Discussion

The modest annual temperature increase over the last century in the Georgian Caucasus is lower than in many regions, for example, in the Alps, where over the 20th century temperatures have risen by about 2^0C at a rate about twice as large as the northern-hemispheric average (Auer et al., 2007). This observed warming was relatively homogeneous over the Alpine region but was particularly pronounced from 1980 onwards with annual mean warming rates of about 0.5^0C per decade (EEA, 2009; Gobiet, et al., 2014). The response time of a glacier to a change in climate depends on its size, attributes, and topography (Tennant, et al., 2012), and is not immediate. However it appears that the Alpine glaciers average annual retreat rate over the last half century is about twice that of Georgian Caucasus glaciers (Fischer et al., 2014).

My analysis shows that the RGI 4.0 and 5.0 version databases contain many errors, especially in the Western/Eastern Caucasus section and Samegrelo, Lechkhumi and Shoda-Kedela sub-ranges, where many polygons are mapped incorrectly, and thus glacierized area appears to have increased. In the GLIMS database, the opposite has occurred as smaller glaciers have been omitted in the Samegrelo, Lechkhumi sub-ranges (Central Caucasus section) and the Tergi, Asa, Arghuni and Pirikita Alazani (Eastern Caucasus section) river basins such that the mapped glacierized area has decreased.

In 1960–2014 the reduction in glacier area in Georgia was mostly caused by the disappearance of small cirque glaciers (≤1.0 km^2) which were predominant in 1960-70, in association with a modest warming temperature trend. Between 1960-2014 glacier area and numbers decreased least in the Western Caucasus. This results from more precipitation falling there as winter snow (in the Abkhazeti sector) compared to the Central and Eastern Caucasus (Kordzakhia, 1967; Gobejishvili, 1995). Thus glacier area (0.6 km^2 average area) in the Bzipi River basin (Western Caucasus) decreased 59.6±2.7% between 1960-2014 but glacier numbers were unchanged. This was also observed in the Canadian Rocky mountains where small cirque glaciers (0.5 km^2) decreased only in size by 52% between 1881-1991 (Lawby, et al., 1995). The greater glacier melt in the Eastern Caucasus is conditioned not only by climate, but also by the morphological peculiarities of the relief. Some of the river basins are built on Jurassic sedimentary rocks, which suffer consistent denudation, detrimental to glacier preservation (Gobejishvili et al., 2011).

Between 1911-2014 the highest percentage glacier loss from Georgia's four largest river basins (Enguri, Rioni, Kodori and Tergi) was observed in the Tergi River basin, where glacier area decreased by 60.1±1.7% (0.6±0.01% yr^{-1}). The glacier area in the Rioni River basin in 1911–1960 was reduced by only 2.5±2.1% and the Enguri River basin glaciers by 2.8±1.6%. This reflects the deficiencies in the 1911 catalog data, but source represents the only available data for this period for future comparison of the Caucasus glaciers.

I compared my results to those of Shahgedanova et al. (2014) for the northern slopes, where the most heavily debris-covered glacier was Donguz-Orun (43.231^{0}N, 42.512^{0}E) and supra-glacial debris covers approximately 70%. Generally in the Caucasus, south facing glaciers are characterized by less debris cover then those with northern aspects.

Direct comparisons with other inventories in the Caucasus are difficult, because most of them cover relatively short and recent periods. However, my results are consistent with other studies of glacier change in the Caucasus Mountains. For example, Shahgedanova et al. (2014), suggest that glaciers located on the southern slopes of the Central Caucasus range may have lost a higher proportion of their area than glaciers in northern regions of the Caucasus (5.6±2.5 km^2) between 2000 and 2010/2012. The valley glaciers lost an even higher proportion (7.4%). Khromova et al., (2014) mapped outlines of 179 glaciers, of which 108 glaciers are located on the northern slopes of the Greater Caucasus while 71 are located on the southern slopes. They found that glaciers lost 4.9% of their area between 2001 and 2010. Glacier wastage was higher in the southern slopes at 5.6% versus 4.3% in the northern slopes glaciers.

Glacier reduction in the Caucasus Mountains appears to be slower than some regions such as the European Alps. Fischer et al., (2014) reported 33% (1.1% yr^{-1}) and 11% (1.3% yr^{-1}) reduction for the eastern Swiss Alps for the 1973–2003 and 2003–2009 periods respectively; but it appears to be faster than in the Altai mountains, where Khromova et al., (2014) reported 16.4% (0.3% yr^{-1}) glacier area loss between 1952 and 2004. Sorg et al., (2012) reported average glacier ice loss of 0.3% a^{-1} in Tien Shan over the last half century. The strongest annual area shrinkage rates were found in the outer ranges (0.4 to 0.8% a^{-1}), whereas smaller rates were reported for glaciers in the inner (0.2 to 0.4% a^{-1}) and eastern ranges (0.1 to 0.3% a^{-1}). The overall range of annual area changes was similar to those for the Himalaya–Karakorum region, which represent the southern margin of the Asian high mountains complex (0.1 to 0.7% a^{-1}) (Bolch, et al., 2012). The Georgian Caucasus inventory data parallels results in the Canadian Rocky Mountains, where Tennant et al., (2012) reported 40±5% (0.5±0.06% yr^{-1}) glacier area loss between 1919-2006, and in the Cordillera Blanca mountains (Peru), where Racoviteanu et al., (2008) estimated overall loss in glacierized area of 22.4% (0.7% yr^{-1}) from 1970 to 2003.

6 Conclusions

I used Podozerskiy's 1911 catalog, 1960 maps data and recent (2014) Landsat and ASTER imagery to determine area change of glaciers in the Georgian Caucasus mountains. The main uncertainties and errors arise from 1911 data quality, specifically glacier firn area extent boundaries. Despite these errors, the 1911 Podozerskiy's catalog is still a useful source of information on early 20th century glacier extents and elevations. Over long periods, glacier changes are significantly larger than the errors in the maps. Other sources of error in the most recent datasets include debris cover, which hinder glacier delineation, but by using GPS field data these can be resolved.

The Georgian Caucasus region experienced glacier area loss over the last century at an average annual rate of 0.4% with a higher rate in Eastern Caucasus than in the Central and Western sections. Glacier melt is faster for southern glaciers than northern glaciers. A combination of topographic factors including glacier geometry and elevation, as well as climatic aspects such as southern aspect and higher radiation input, are related to the observed spatial trends in the glacier change analysis. Extending the attributes considered in this study, future research should further focus on attributes related to glacier type and source of nourishment (e.g. outlet, cirque, avalanche-fed, and debris-covered glaciers), in order to better understand how these factors influence glacier change.

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

Basin Name	Podozerskiy's 1911 Catalog			Topographic maps 1960			*The USSR Catalog of 1975		Landsat and ASTER Imagery, 2014		
	Number	Area, km^2	uncertainty (%)	Number	Area, km^2	uncertainty (%)	Number	Area, km^2	Number	Area, km^2	uncertainty (%)
Bzipi	10	4.0±0.01	±2.1	18	9.9±0.2	±2.1	16	7.8	18	4.0±0.1	±3.3
Kelasuri				1	0.3±0.02	±5.8	3	1.5	1	0.1±0.01	±4.5
Kodori	118	73.2±1.6	±2.1	160	63.7±1.6	±2.6	141	60.0	145	40.1±1.3	±3.2
Enguri	174	333.0±4.6	±1.4	299	323.7±5.7	±1.8	250	288.3	269	223.4±4.6	±2.1
Khobisckali				16	1.1±0.1	±6.3	7	1.6	9	0.5±0.03	±6.5
Rioni	85	78.1±1.6	±2.1	112	76.8±1.7	±2.2	124	62.9	97	46.7±1.2	±2.5
Liakhvi	12	5.2±0.1	±2.5	16	4.3±0.1	±3.0	22	6.6	10	1.8±0.1	±3.8
Aragvi	3	2.2±0.04	±1.8	3	0.9±0.03	±3.4	6	1.6	1	0.3±0.02	±4.8
Tergi	63	89.1±1.2	±1.4	99	67.0±1.3	±2.0	129	72.1	58	35.6±1.0	±2.2
Asa	17	4.1±0.1	±3.1	9	2.6±0.01	±3.3	3	1.1	3	0.5±0.03	±4.6
Arghuni	10	5.4±0.1	±2.2	17	2.9±0.1	±4.1	14	1.7	6	0.4±0.03	±5.8
Pirikita Alazani	23	19.1±0.3	±1.7	36	10.5±0.3	±3.1	40	8.9	20	2.4±0.1	±4.5
Total	**515**	**613.6±9.8**	**±1.6**	**786**	**563.7±11.3**	**±2.0**	**755**	**514.1**	**637**	**355.8±8.3**	**±2.3**

* The USSR Catalog data sets contain tables with glacier parameters and do not have glacier outlines.

Table 2. The change in the area and number of glaciers of Western, Central and Eastern Georgian Caucasus in 1911-1960-2014.

Georgian Caucasus Sections	Podozerskiy's 1911 Catalog			Topographic maps of 1960			The USSR Catalog of 1975		Landsat and ASTER Imagery, 2014		
	Number	Area, km^2	uncertainty (%)	Number	Area, km^2	uncertainty (%)	Number	Area, km^2	Number	Area, km^2	uncertainty (%)
Western	128	77.2±1.6	±2.1	179	73.9±1.9	±2.5	180	69.3	164	44.2±1.4	±3.2
Central	271	416.3±6.3	±1.5	443	405.9±7.6	±1.9	403	359.4	385	272.3±5.9	±2.2
Eastern	116	120.0±1.8	±1.5	164	83.9±1.9	±2.3	192	85.4	88	39.3±1.0	±2.5

Table 3. Mean monthly air temperatures (^{o}C) at the Mestia, Mamisoni, Jvari Pass and Kazbegi meteorological stations in the years of 1906/1907–1960 and 1961–2009/2013.

Meteo Station	**Year/Month**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	Mean annual
Mestia	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	5.9
Mestia	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	6.0
Mamisoni	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	-2.2
Mamisoni	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	-2.2
Jvari Pass	1907-1960	-10.5	-10.3	-7.4	-1.5	3.3	7.4	10.4	10.3	6.6	1.8	-3.3	-7.8	-0.1
Jvari Pass	1961-2009	-10.4	-9.8	-6.6	-0.9	3.4	7.6	10.8	10.3	6.8	2.0	-3.1	-7.9	0.2
Kazbegi	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	-5.8
Kazbegi	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	-5.6

Table 4. Results of the Mann-Kendall test for temperature data for the weather stations of Georgia in the years of (1907-2009)-(1907-1960)-(1961-2009). Statistically significant results are in bold.

Mann Kendall test (1907-2009)					
Meteo stations	Mann Kendall Statistic (S)	Kendall's tau	Var (S)	p-value (one-tailed)	alpha
Jvari pass	1042	0.1984	123151	**0.0015**	0.05
Kazbegi	1242	0.2365	123147	**0.0002**	0.05
Mamisoni	-174	-0.0444	79625	0.7301	0.05
Mestia	302	0.0533	137993	**0.2089**	0.05
Mann Kendall test (1907-1960)					
Meteo stations	Mann Kendall Statistic (S)	Kendall's tau	Var (S)	p-value (one-tailed)	alpha
Jvari pass	256	0.1790	17965	**0.0286**	0.05
Kazbegi	228	0.1594	17966	**0.0452**	0.05
Mamisoni	109	0.0762	17967	0.2102	0.05
Mestia	-44	-0.0308	17966	0.6258	0.05
Mann Kendall test (1961-2009)					
Meteo stations	Mann Kendall Statistic (S)	Kendall's tau	Var (S)	p-value (one-tailed)	alpha
Jvari pass	342	0.2908	13458	**0.0016**	0.05
Kazbegi h/m	321	0.2731	13457	**0.0029**	0.05
Mamisoni pass	-85	-0.1429	4958	0.8835	0.05
Mestia	288	0.2090	16995	**0.0139**	0.05

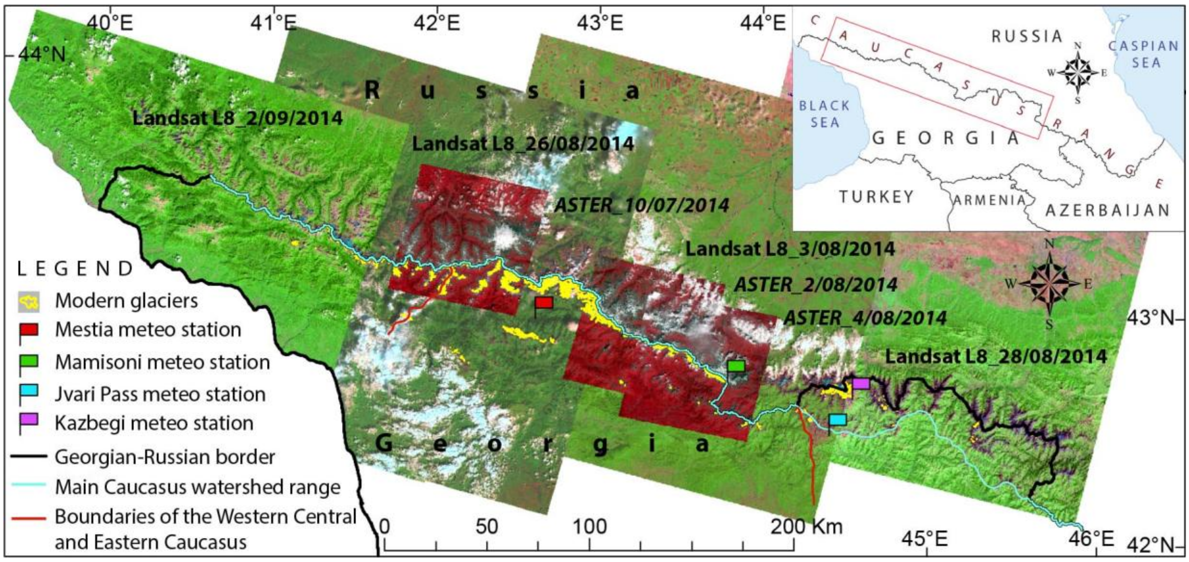

Figure 1. Georgian Caucasus glacier outlines (in yellow) derived from Landsat and ASTER imagery, and Georgia's mountain meteorological station locations.

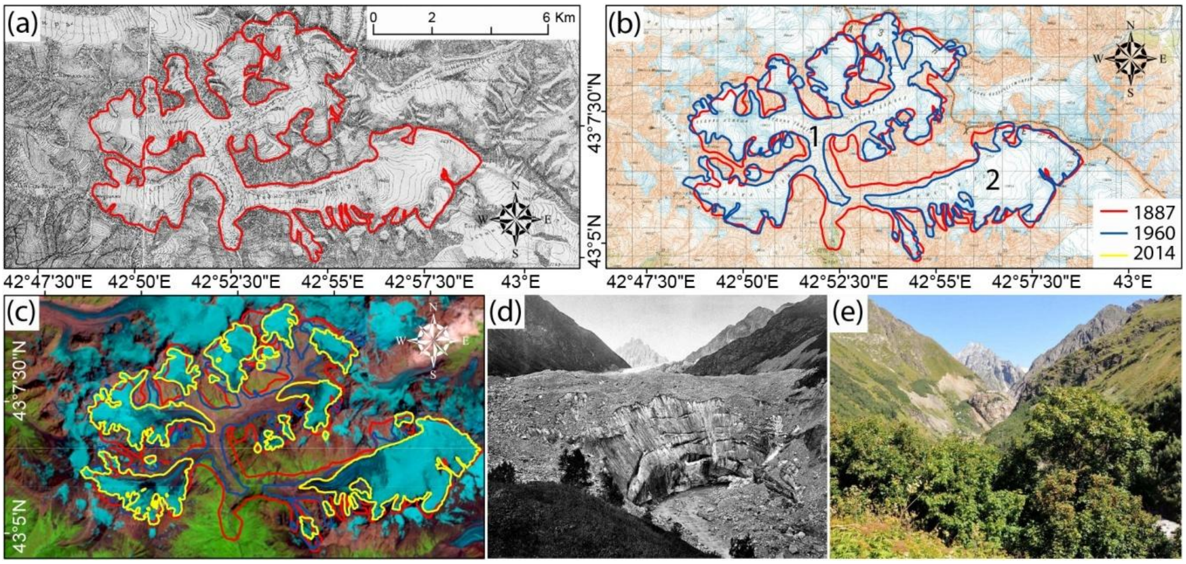

Figure 2. (a) Tviberi Glacier, topographical map 1887; **(b)** topographical map 1960, 1: Tviberi Glacier, 2: Kvitlodi Glacier; **(c)** Landsat L8 imagery; **(d)** Tviberi Glacier terminus in 1884 (photo by M. V. Dechy); **(e)** the same view in 2011 (photo by L. G. Tielidze).

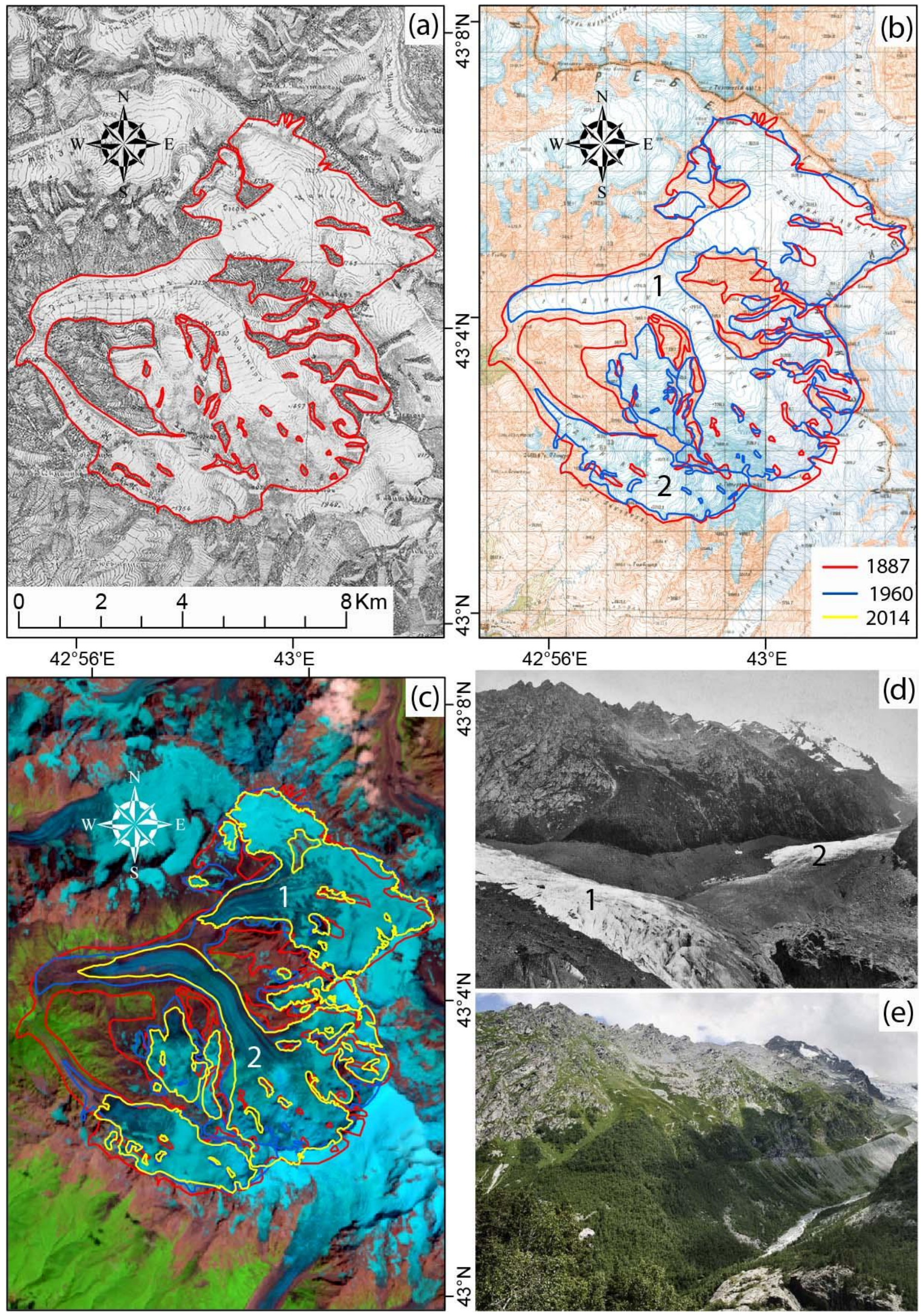

Figure 3. (a) Tsaneri Glacier, topographical map 1887; (b) topographical map 1960, 1 Tsaneri Glacier, 2 Nageba Glacier; (c) Landsat L8 imagery, 1 Northern Tsaneri Glacier, 2 Southern Tsaneri Glacier; (d) 1 Tsaneri and 2 Nageba glaciers confluence in 1884 (photo by M. V. Dechy); (e) the same view in 2011 (photo by F. Ventura).

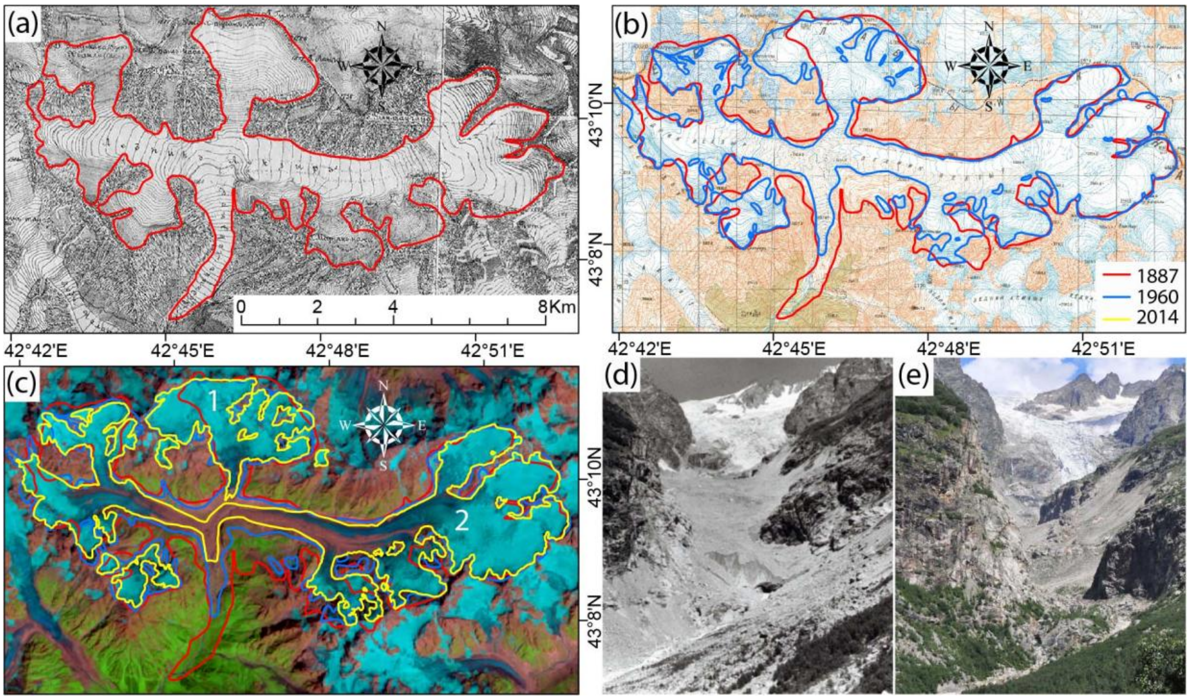

Figure 4. (a) Lekhziri Glacier, topographical map 1887; (b) topographical map 1960, (c) Landsat L8 imagery; 1: Northern Lekhziri (central flow), 2: Georgia's largest glacier Lekhziri (consisting of two flows); (d) Lekhzi Glacier terminus in 1960 (photo by Sh. Inashvili); (e) the same view in 2011 (photo by L. G. Tielidze).

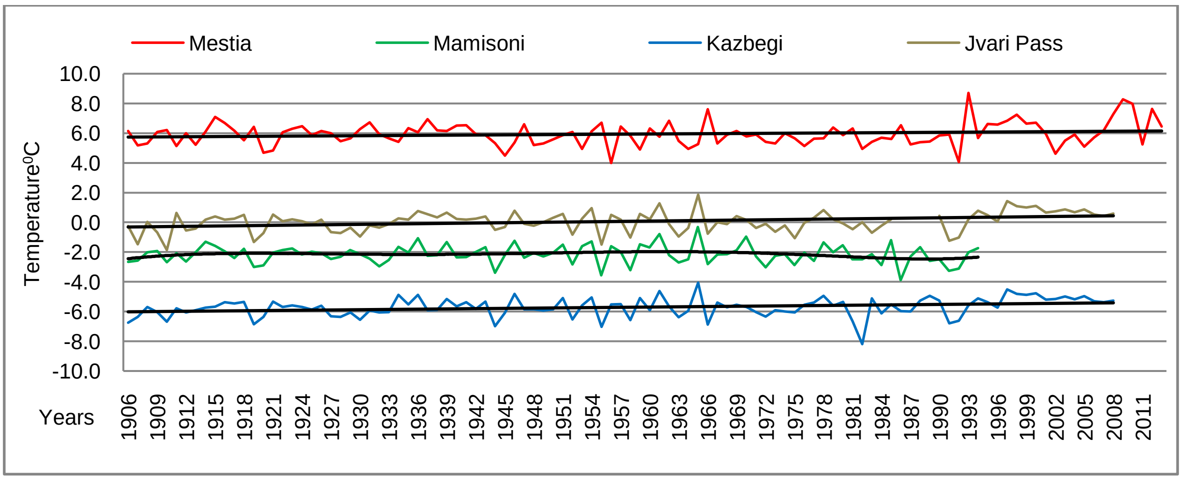

Figure 5. Mean annual air temperatures at the Mestia, Mamisoni, Jvari Pass and Kazbegi meteorological stations over the last century. The black line is the trend showing a temperature course with time.

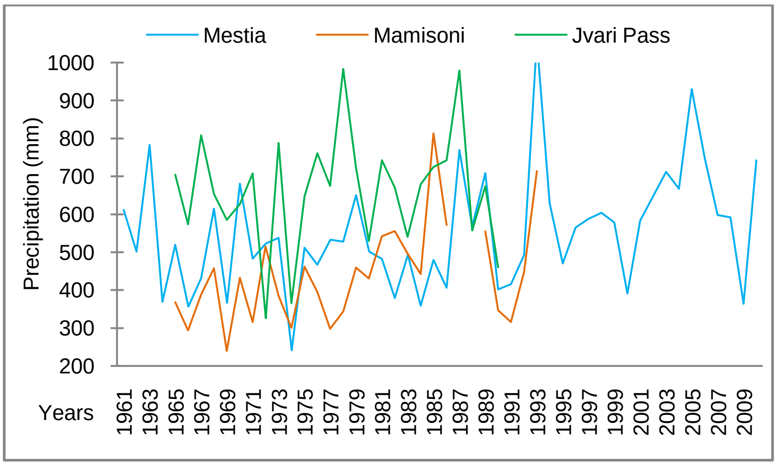

Figure 6. October–April precipitation for Mestia (1961-2010), Mamisoni (1965-1993) and Jvari Pass (1965-1990) meteorological stations.