Author reply to reviewer and editor comments

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

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Dear referees and editor, I have took your remaining comments and once again very carefully checked my manuscript.

I appreciate the support and constructive reviews of editor and both referees.

Thank You.

My detail answers on the comments you can see below:

Anonymous Referee #1

C1	section on error estimation needs to be improved and uncertainty (±) presented with all results including parts of the Caucasus range, river basins and individual glaciers. Sections 4.1.1, 4.1.2, 4.1.3, 5 Discussion, 6 Conclusions, Table 1, fig.2,3,9.
R1	I agree and improved the manuscript accordingly. please see manuscript: Result section - pp. 5-8; Discussion section pp. 9-10; Table 1, 2 (p. 13).
C2	more careful verification of old maps and data sets is needed
R2	I agree. Please see "3.1 Old topographical maps" section, Line 137-141; "3.3 Glacier delineation error and analysis" section, Line 198-201; "5 Discussion" section, Line 411-421.

Anonymous Referee #2

C3	abstract first 10 sentences: These sentences show progress of study of glaciers in the Caucasus (review type?). There is need to present your study (brief significance, method, and results) in the abstract. I would suggest to re-write these sentences in 1-2 lines only.
R3	I agree. Please see Abstract section, Line 15-26
C4	Refer previous studies from the abstract in introduction (abstract first 10 sentences).
R4	I agree. Please see Introduction section, Line 44-54
C5	"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." This paragraph belong to methodology. So present this paragraph in method part instead of result section.

R5	I agree. Please see "3.4 Climatic data" section, Line 227-228
C6	Include uncertainties ± with each numbers (results and discussion).
R6	I agree and improved the manuscript accordingly. please see manuscript: Result section pp. 5-8; Discussion section pp. 9-10; Table 1, 2 (p. 13).
C7	Show results of Mann Kendall test analysis in table.
R7	I agree. Please see Table 4 (p. 14)
C8	Carefully English check is required.
R8	I agree. English has been checked with a 'native speaker'

Editor Comments:

C9	As already mentioned in my access review: The methodology must "be described more in detail including an assessment of the uncertainty. The link to the climate data should be improved. "You are addressing glacier area changes. These changes show, in contrast to mass balance measurements, a delayed signal to climate and hence, you should not relate the same periods to each other. Looking only at temperature is not enough. Include also precipitation analysis. Are the climate data checked for homogenization? (e.g. trends due to changes of instrumentation, outliers).
R9	I agree and improved the manuscript accordingly. Please see "3 Data sources and methods" section (pp. 3-5); "4.2 Climatic variability" section (p. 9) and Figure 6 (p. 18). As for the climate data homogenization: During 1906-2013 just two years - 1966 (for all meteo stations) and 1993 (just for Mestia) were abnormally warm and one single year (1983) was very cold for Kazbegi. These few events do not significantly affect the long term average. As for the precipitations: During 1965-1990 just two years - 1978 and 1986 were abnormally humid for Jvari meteo station and one single year (1985) for Mamisoni (1965-1993) and one single year (1993) for Mestia meteo station (1961 -2010). Few high precipitation mentioned years do not impact long term average values.
C10	As also already mentioned in my access review: "the current scientific knowledge should be better acknowledged and discussed with respect to the own results". It has improved but not enough.
R10	I agree. Please see "1 Introduction" section, Line 55-81 "5 Discussion" section, Line 422-440
C11	In addition: "The difference to your own published papers (even if not peer reviewed) must clearly be shown and figures and numbers shown there properly acknowledged and cited." There is another paper published: Tielidze, L. et al. (2015): Glaciers Amount and Extent Change in the Dolra River Basin in 1911-1960-2014 Years, Caucasus Mountains, Georgia Observed with Old Topographical Maps and Landsat Satellite Imagery American Journal of Climate Change, 4, 217-225. The results of these papers must be properly acknowledged. I have I already clearly asked you to do so.
R11	I agree. Please see "1 Introduction" section, Line 75-81. "4.1.4 The largest glaciers" section, Line 344, Line 351, 357, " References" section, Line 552-555

C12	I do not agree to simply omit the information about the Soviet glacier inventory. This data was frequently used. Provide more information (e.g. comparisons (e.g. quantify the differences between Dr. Gobejishvili's data) about the quality and then provide a clear rational to omit.
R12	I agree. Please see "3.1 Old topographical maps" section, Line 153-156; Table 1, 2 (p. 13)
C13	There are several statements, especially in the introduction which must be underlined by references, e.g. L. 47, 55, 56 (but not only there).
R13	I've changed all Introduction section, please see Line 31-84
C14	I am aware that you are not a native speaker. The English must be perfect, but there are many mistakes and awkward phrases.
R14	I agree. English has been checked with a 'native speaker'

Specific comments:

C15	L. 16. Omit "great". This is a scientific article.
R15	I agree. Please see Line 45
C16	L. 29, 31 and later. Substitute "our" us "or" we "by the singular form. You are the only author.
R16	I agree. Please see Line 155, 157, 160 and later
C17	L. 40: I do not agree. The clear and significant warming started later. Be more specific and provide a reference.
R17	I agree and didn't use this sentence
C18	L.45: This is also too general.
R18	I agree and didn't use this sentence
C19	L. 60-63. Bo more specific and provide more details. Include also the information about the Caucasus glaciers in GLIMS and RGI.
R19	I agree. Please see Line 55-81
C20	L. 77: Radici et al. 2014. Wrong reference. They used the RGI data according to my knowledge. Please be more specific and include the RGI version for this coverage.
R20	I agree. Please see Line 55-57, 528-530
C21	L. 106: Your dissertation is hardly accessible and most of the readers will not understand Georgian. I am sure this is not the only source this statement. Please include additional references here and later with your dissertation.
R21	I agree. Please see Line 110-117
C22	L. 134: "quite precise" Be more specific.
R22	I agree. Please see Line 142-145
C23	L. 139: Provide proper reference to the Soviet Glacier Inventory.
R23	I agree. Please see Line 153-156 and Table 1, 2 (p. 13)
C24	L. 148ff: Accuracy of the registration?
R24	Please see Line 158-160; 198-201
C25	L. 166: "minimum error" "at the very end", be more precise.
R25	I agree. Please see Line 172-177
C26	Which processing level of Landsat and Aster did you use? L1T? Also ASTER data? L. 188: Why did you co-register the L1T images. These should already been properly co-registred.
R26	Please see Line 179-181
C27	L. 196/198: How did you obtain these numbers?

R27	Please see Line 198-201
C28	L .230: How did you derive these uncertainties? I especially do not understand the uncertainty for the numbers.
R28	Please see Line 234-242 based on the Line 195-218
C29	Section "4.2 Climate variability": Avoid repetitions. More the information about the stations and data used to the Data section and concentrate here on the main trends.
R29	I agree. Please see Line 371-379
C30	L. 409-414: Move the info about the significance test and ow you performed it to the methods section as asked by one reviewer, but mention the results of the tests in the results section along with the respective stations and periods.
R30	I agree. Please see Line 227-228; 376-379; 382-383
C31	5. Discussion: As mentioned above: The discussion must be clearly improved. Provide more information about how your results relate to published ones for Caucasus and, maybe, also Eurasia.
R31	I agree. Please see Line 398-440
C32	L. 426: "higher risk of disappearance" I do not agree. The results are statistically hardly different. Moreover "Risk" is not the proper term here.
R32	I agree. Please see Line 431-433
C33	L. 441ff: Here, you mention that you question the quality of the 1911 data. It is good to discuss. But be more quantitative and provide then better argumentation why you keep the 1911 data.
R33	Please see Line 140-141; 418-421
C34	6. Conclusions You should not provide new results in the conclusions but draw the main conclusions form the study (glacier changes and rates, reliability of source data, remaining knowledge gaps etc.). Move 480ff to the results section. Was the map of 1887 mentioned before?
R34	I agree. Please see new Conclusions Line 445-454, also 337-366. As for the 1887 maps, please see Line 134-137;
C35	Figures 2, 3, and 8 are not needed. Include the information into Table 1 and include the uncertainty in this table.
R35	I agree. Please see Table 1 and 2 (p. 13)
C36	Figs 5-8 are also not very good. You may show one representative climate diagram (with precipitation) and the temperature and precipitation changes in a table.
R36	I agree. Please see Table 3 (p. 13) and Figure 6 (p. 18)
C37	Fig. 10 is nice. I suggest to include an additional figure showing the glacier changes instead. This is most important to know about the quality of the data ..
R37	I agree. Please see figure 3 (p. 16) and figure 4 (p. 17)

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 8.12±1.80% or 49.85±10.60 km^2 from 613.55±9.80 km^2 to 563.70±11.31 km^2 during 1911–1960, while the number of glaciers increased from 515 to 786. During 1960-2014, the total ice area decreased by 36.88±2.16% or by 207.90±9.78 km^2 from 563.70±11.31 km^2 to 355.80±8.25 km^2, while glacier numbers decreased from 786 to 637. In total, the area of Georgia glaciers reduced by 42.00±1.96% between 1911-2014. The Eastern Caucasus section had the highest retreat rate (67.28±2.01%) over this period, while the central part of Georgian Caucasus had the lowest change rate (34.58±1.83%), with the Western Caucasus intermediate at 42.82 ±2.68%.

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 etc. 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 (1:50000) 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 region, where the total glaciers number is ~ 1400, with a total area of ~ 1100 km^2 (±10%) (Pfeffer et al., 2014). Similar results were obtained from Landsat imagery by Nakano et al., (2013). GLIMS (www.glims.org) cite in excess of 1300 glaciers with a combined area of 1354 km^2. The difference is due to the omission of the smaller glaciers in the eastern sector of the Caucasus Mountains in this recent assessment (Shahgedanova et al., 2014). These inventories, executed by semi-automatic digitizing do not consider the separate Georgian Caucasus glaciers percentage 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 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).

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.

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, Letchkhumi, 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 Caucasus Mountains are characterised 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).

3 Data sources and methods

3.1 Old topographical maps

The compilation of the first reliable map of the Caucasus, at a scale of 1:420000 and depicting the largest glaciers, was completed by 1862. Topographic surveys of the Caucasus at a scale of 1:42000 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 causes some error in the identification of precise areas, but there exist no other data from this time; thus 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 1:50000 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 in The Catalog of Glaciers of the USSR, Vol. 8–9 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 are 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). Landsat L8 OLI (Operational Land Imager), since February 2013, and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) since January 2000, imagery 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 thickness of 12 metres (1:42000) and 15 metres (1:50000). 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. This generated an average uncertainty of the mapped glacier area of 2.3% for 2014 (satellite images), 2.0% for 1960 (topographical maps) and 1.59% for 1911 (Podozerskiy catalog).

(c) Manual digitizing by an experienced analyst is usually more accurate than automated methods for glaciers with 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 I have also used my 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.) surveyed by GPS. 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): 1. Mestia (1441 m a.s.l.); 2. Mamisoni (2854 m a.s.l.); 3. Jvari Pass (2395 m a.s.l.) and Kazbegi (3653 m a.s.l.). I used 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 8.12±1.80% or 49.85±10.60 km^2, reduced from 613.55±9.80 km^2 to 563.70±11.31 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 36.88±2.16 % or 207.90±9.78 km^2, from 563.70±11.31 km^2 to 355.80±8.25 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 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 4.03±0.085 km^2. From the 1960 maps there were 18 glaciers with an area of 9.90±0.20 km^2; the satellite images of 2014 also showed 18 glaciers, but with a reduced area 3.99±0.13 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 0.26±0.015 km^2, and similarly in 2014 with an area of 0.11±0.005 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 73.20±1.55 km^2. In 1960, 160 glaciers were mapped with an area of 63.73±1.63 km^2 and in 2014 there were 145 glaciers in this basin with a total area of 40.06±1.29 km^2 (Table 1).

In total, in the Western Caucasus, glacier area decreased by 4.32%±2.31% or by 3.34±1.69 km^2 in 1911-1960. Between 1960–2014, glacier area was reduced by 40.23±2.87 % or by 29.73±1.62 km^2 (Table 2).

4.1.2 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 333.03±4.57

km^2; in 1960, 299 glaciers were mapped with an area of 323.70±5.72 km^2, and in 2014 there are 269 glaciers with a total area of 223.39±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 1.12±0.07 km^2 and in 2014, nine glaciers had an area of 0.46±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 78.12±1.61 km^2. In 1960 the number of glaciers was 112 with total area 76.77±1.66 km^2. By 2014 there were 97 glaciers with total area of 46.65±1.15 km^2 (Table 1). The largest glacier in the Rioni River basin is Kirtisho with an area of 4.41±0.07 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 5.15±0.13 km^2, increasing to 16 in 1960 with total area of 4.27±0.13 km^2. In 2014 10 glaciers had a total area of 1.82±0.07 km^2 (Table 1).

In total, the glacier area decreased by 2.50±1.69% or 10.44±6.95 km^2 in 1911-1960 in the Central Caucasus. Between 1960–2014, glacier area was reduced by 32.90±2.01% or 133.54±4.87 km^2 (Table 2).

4.1.3 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 2.21±0.04 km^2, reduced in 1960 to 0.88±0.03 km^2. By 2014 only one glacier (Abudelauri) remained in the basin with an area of 0.31±0.015 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 89.12±1.22 km^2. By 1960 there were 99 glaciers with total area of 67.01±1.33 km^2, and in 2014 there were 58 glaciers with total area of 35.56±0.8 km^2 (Table 1). The largest glacier in the Tergi River basin is Eastern Suatisi with an area of 7.68±0.09 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 4.14±0.13 km^2. By 1960 there were nine glaciers with total area of 2.59±0.085 km^2 and in 2014 three glaciers with a total area of 0.54±0.025 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

5.43±0.12 km^2. By 1960 there were 17 glaciers with total area of 2.92±0.12 km^2 but in 2014 there were only six glaciers with total area of 0.43±0.025 km^2 (Table 1).

In 1911 the Pirikita Alazani River basin contained 23 glaciers with total area of 19.12±0.32 km^2. By 1960 the glaciers were reduced in size and although the number increased to 36, their area was reduced to 10.48±0.32 km^2. In 2014 there were 20 glaciers in this basin with total area of 2.42±0.11 km^2 (Table 1).

In total, the glacier area decreased by 30.11±1.90% or 36.14±1.87 km^2 in 1911-1960 in the Eastern Caucasus. Between 1960–2014, glacier area was reduced by 53.19±2.38% or 44.62±1.44 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 49.02±0.44 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 24.72±0.35 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 48.90±0.49 km^2 (Fig. 3). In 1960, the Tsaneri Glacier was still the compound-valley type glacier (without the Nageba Glacier) and its area was 28.28±0.25 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 40.84±0.34 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 35.96±0.43 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 of 2014 this contact split. This resulted in the northern Lekhziri (central flow) Glacier (6.27±0.10 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 23.26±0.35 km^2 terminating at 2320 meters a.s.l.. Lekhziri 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 12.60±0.18 km^2, ahead of the northern Tsaneri (Fig. 3c) third with 11.53±0.14 km^2.

4.2 Climatic variability

Commencing with the highest elevation station, mean annual air temperatures at the Kazbegi weather station show a 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).

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

In 1960–2014 the reduction in glacier area in Georgia was mostly caused by the disappearance of small cirque glaciers (≤2 km^2) which were predominant in 1960-70, in association with a warming temperature trend.

In addition, 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).

In 1960-2014 glacier area and numbers decreased least in the Western Caucasus. This results from more precipitation falling as winter snow in the Western Caucasus (Abkhazeti sector) than in the Central and Eastern Caucasus (Kordzakhia, 1967; Gobejishvili, 1995).

Between 1911-2014 the highest percentage reduction in glacier area from Georgia's four largest river basins (Enguri, Rioni, Kodori and Tergi) was observed in the Tergi River basin, where glacier area was reduced by 60.09±1.73 (0.58 % yr^{-1})%. The main glacier center in the Central Caucasus is the Enguri and Rioni River basins. However the glacier area in the Rioni River basin in 1911–1960 was reduced by only 2.50±2.11% and the Enguri River basin glaciers were reduced by 2.80±1.57%. This may be because the 1911 data contain certain deficiencies, as glaciers in the Rioni and Enguri River basins were difficult to access for plane table surveying. Therefore, when the first topographical survey of the Caucasus was conducted, glacier extents were incorrectly depicted, and some small glaciers were completely omitted. The 1911 catalog by Podozerskiy, which was compiled based on those maps, contains such defects, but represents the only available data for this period for future comparison of the Caucasus glaciers.

My results are consistent with other studies of glacier change in the Caucasus Mountains. Shahgedanova and others (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 and on Mt Elbrus in the Baksan River basin (Russia) while 71 are located on the southern slopes in the Enguri River basin (Georgia). They found that glaciers lost 4.9% of their area between 2001 and 2010. Glacier wastage was higher in the Enguri basin at 5.6% versus 4.3% in the Baksan basin glaciers. One consequence of this result is that Georgian glaciers are characterized by higher retreat rates, than north-facing glaciers in Russia.

Glacier reduction in the Caucasus Mountains appears to be slower than in 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 Ural mountains, where Khromova et al., (2014) reported 22.3% total glacier area loss between 1952 and 2004. In contrast Bolch (2007) reported average glacier ice coverage loss of more than 32% in northern Tien Shan between 1955 and 1999.

6 Conclusions

The Georgian Caucasus region experienced glacier area loss over the last century at an average annual rate of 0.40% with a higher rate in Eastern Caucasus than in the Central and Western sections. Glacier melt is faster for southern (Georgian) glaciers than northern (Russian) glaciers. A combination of 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.

Glaciers of the Georgian Caucasus Mountains are expected to continue their retreat as regional air temperatures continue to get warmer. This deglaciation will have important consequences for the management of water resources for agriculture and hydropower production.

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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	4.03±0.085	2.10	18	9.90±0.20	±2.07	16	7.8	18	3.99±0.13	±3.25
Kelasuri				1	0.26±0.015	±5.76	3	1.5	1	0.11±0.005	±4.54
Kodori	118	73.20±1.55	2.11	160	63.73±1.63	±2.55	141	60.0	145	40.06±1.29	±3.22
Enguri	174	333.03±4.57	1.37	299	323.70±5.72	±1.76	250	288.3	269	223.39±4.6	±2.05
Khobisckali				16	1.12±0.07	±6.25	7	1.6	9	0.46±0.03	±6.52
Rioni	85	78.12±1.61	2.06	112	76.77±1.66	±2.16	124	62.9	97	46.65±1.15	±2.47
Liakhvi	12	5.15±0.13	2.52	16	4.27±0.13	±3.04	22	6.6	10	1.82±0.07	±3.84
Aragvi	3	2.21±0.04	1.80	3	0.88±0.03	±3.40	6	1.6	1	0.31±0.015	±4.83
Tergi	63	89.12±1.22	1.37	99	67.01±1.33	±1.99	129	72.1	58	35.56±0.8	±2.24
Asa	17	4.14±0.13	3.14	9	2.59±0.085	±3.28	3	1.1	3	0.54±0.025	±4.62
Arghuni	10	5.43±0.12	2.20	17	2.92±0.12	±4.10	14	1.7	6	0.43±0.025	±5.81
Pirikita Alazani	23	19.12±0.32	1.67	36	10.48±0.32	±3.10	40	8.9	20	2.42±0.11	±4.54
Total	**515**	**613.55±9.80**	**1.59**	**786**	**563.70±11.31**	**±2.00**	**755**	**514.1**	**637**	**355.80±8.25**	**±2.32**

* 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	77.23±1.64	±2.12	179	73.89±1.85	±2.50	180	69.3	164	44.16±1.43	±3.24
Central	271	416.30±6.31	±1.51	443	405.86±7.59	±1.87	403	359.4	385	272.32±5.86	±2.15
Eastern	116	120.02±1.84	±1.53	164	83.88±1.90	±2.26	192	85.4	88	39.26±0.98	±2.50

Table 3. Mean monthly air temperatures (^{0}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

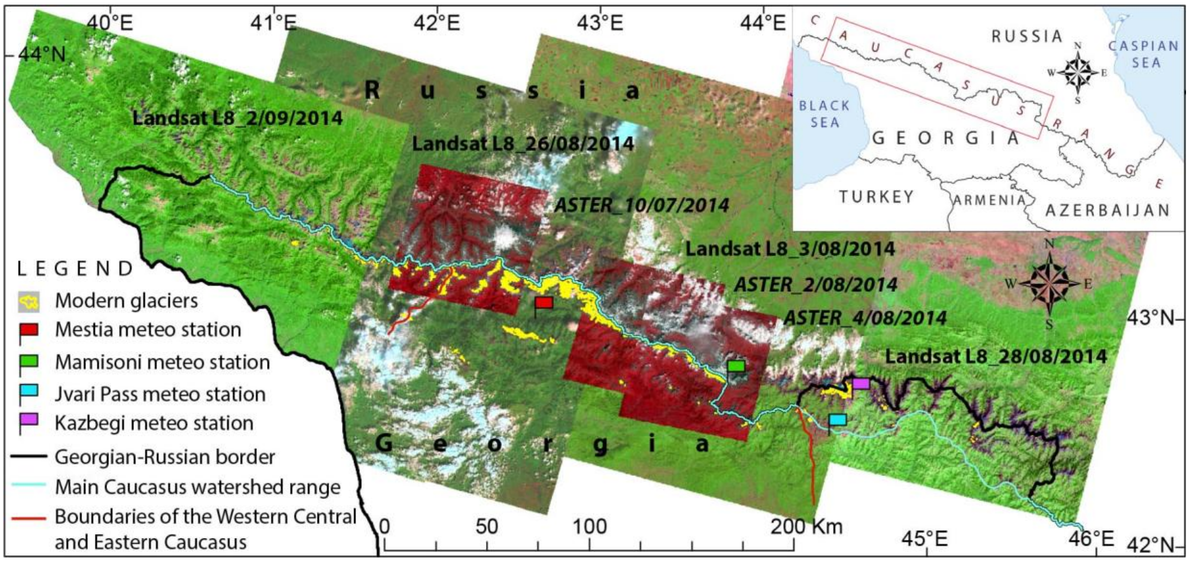

Figure 1. Georgian Caucasus glacier outlines (in yellow) derived from Landsat and ASTER imagery, and Georgia's mountain meteorological station locations.

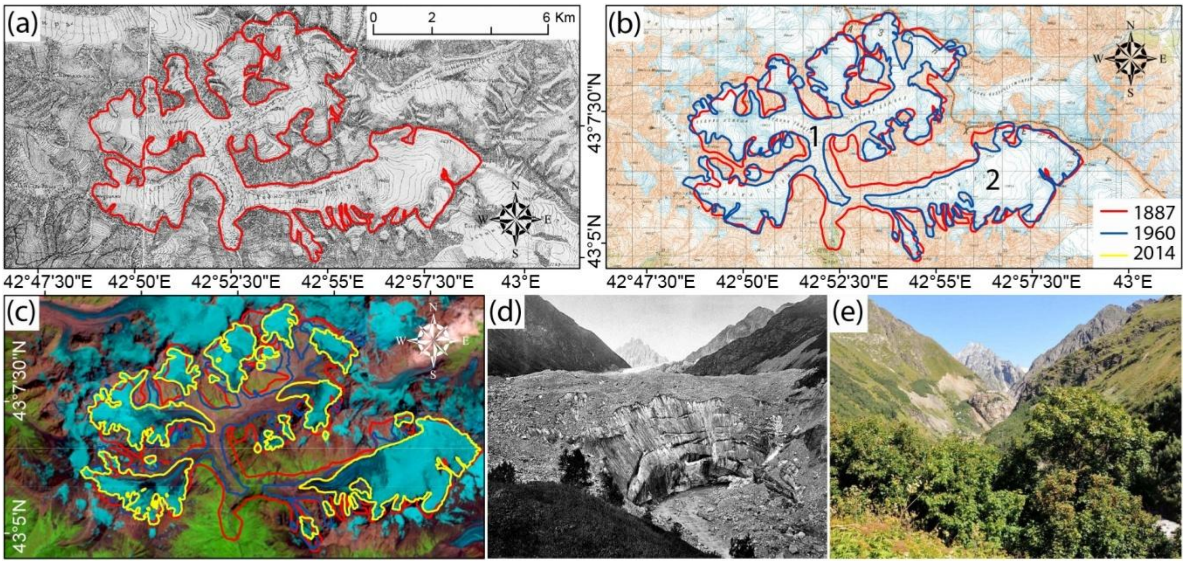

Figure 2. (a) Tviberi Glacier, topographical map 1887; **(b)** topographical map 1960, 1: Tviberi Glacier, 2: Kvitlodi Glacier; **(c)** Landsat L8 imagery; **(d)** Tviberi Glacier terminus in 1884 (photo by M. V. Dechy); **(e)** the same view in 2011 (photo by L. G. Tielidze).

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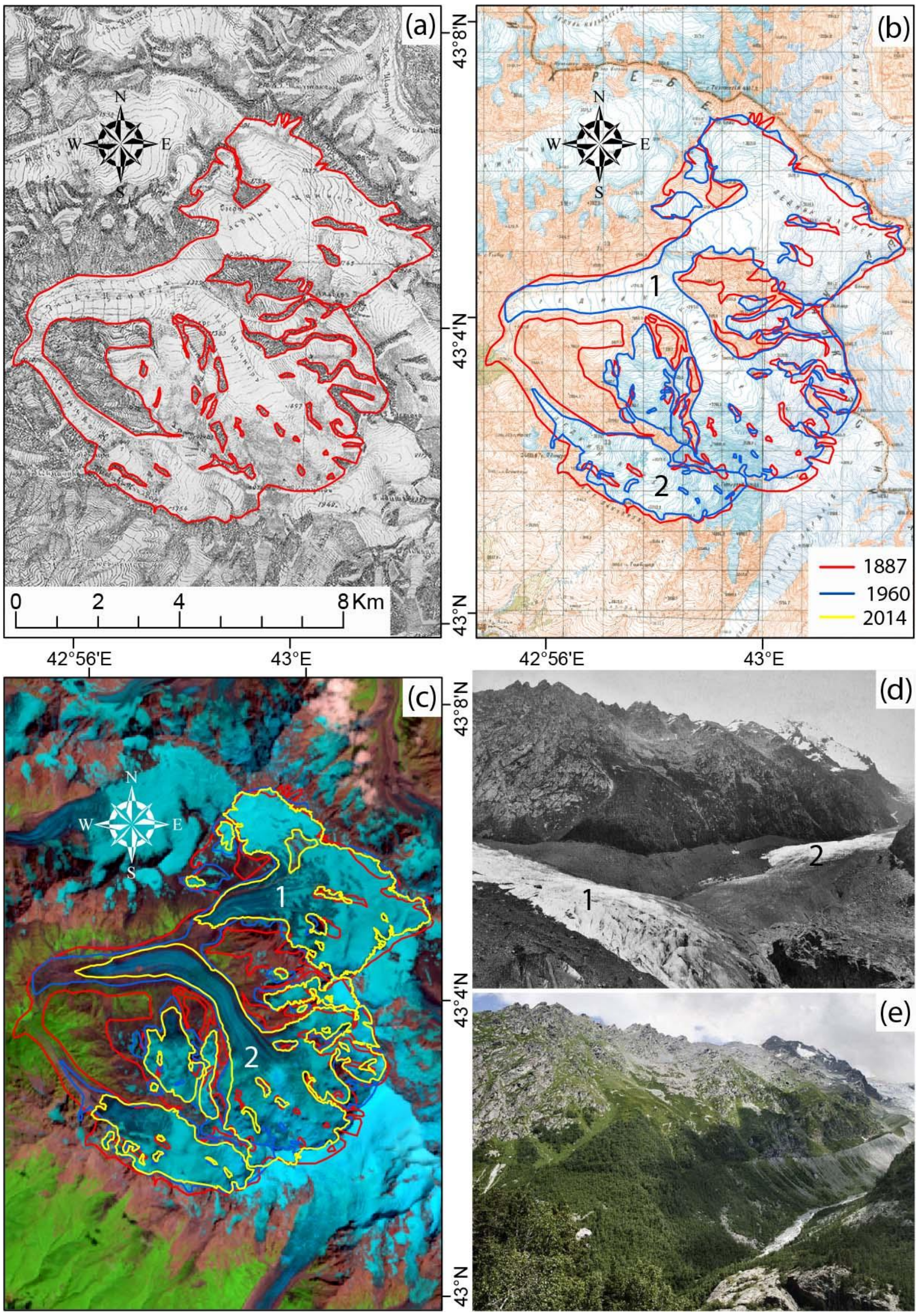

602 **Figure 3.** (a) Tsaneri Glacier, topographical map 1887; (b) topographical map 1960, 1 Tsaneri
603 Glacier, 2 Nageba Glacier; (c) Landsat L8 imagery, 1 Northern Tsaneri Glacier, 2 Southern Tsaneri
604 Glacier; (d) 1 Tsaneri and 2 Nageba glaciers confluence in 1884 (photo by M. V. Dechy); (e) the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

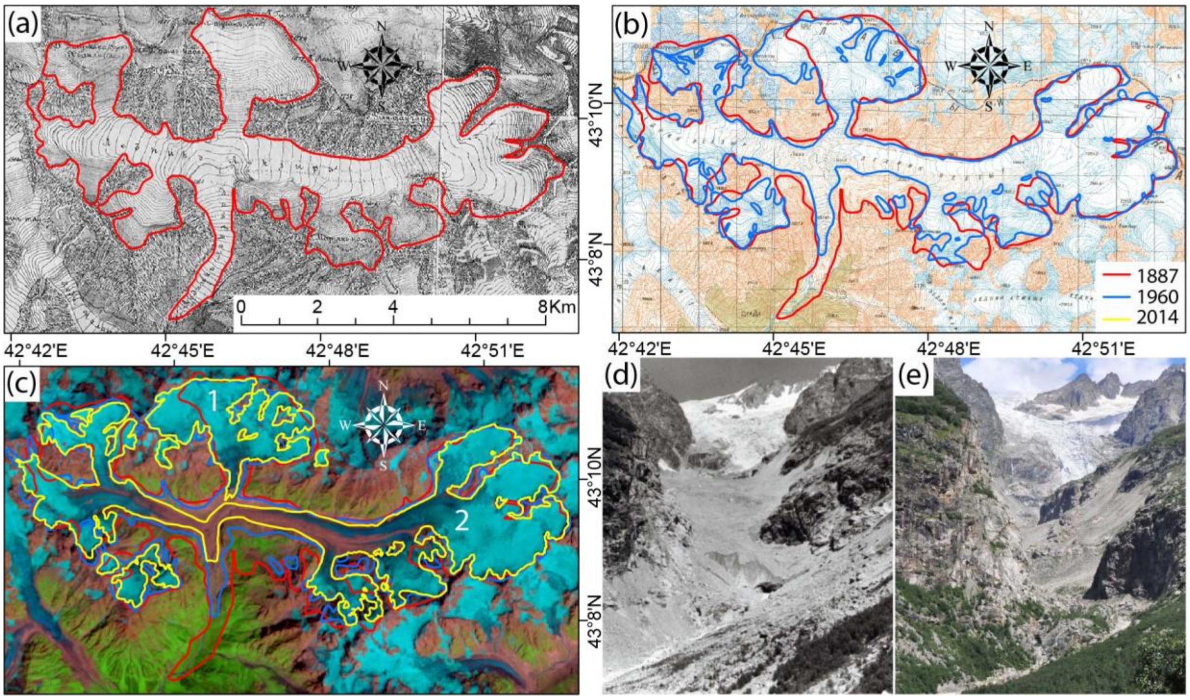

Figure 4. (a) Lekhziri Glacier, topographical map 1887; (b) topographical map 1960, (c) Landsat L8 imagery; 1: Northern Lekhziri (central flow), 2: Georgias largest glacier Lekhziri (consisting of two flows); (d) Lekhzi Glacier terminus in 1960 (photo by Sh. Inashvili); (e) the same view in 2011 (photo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

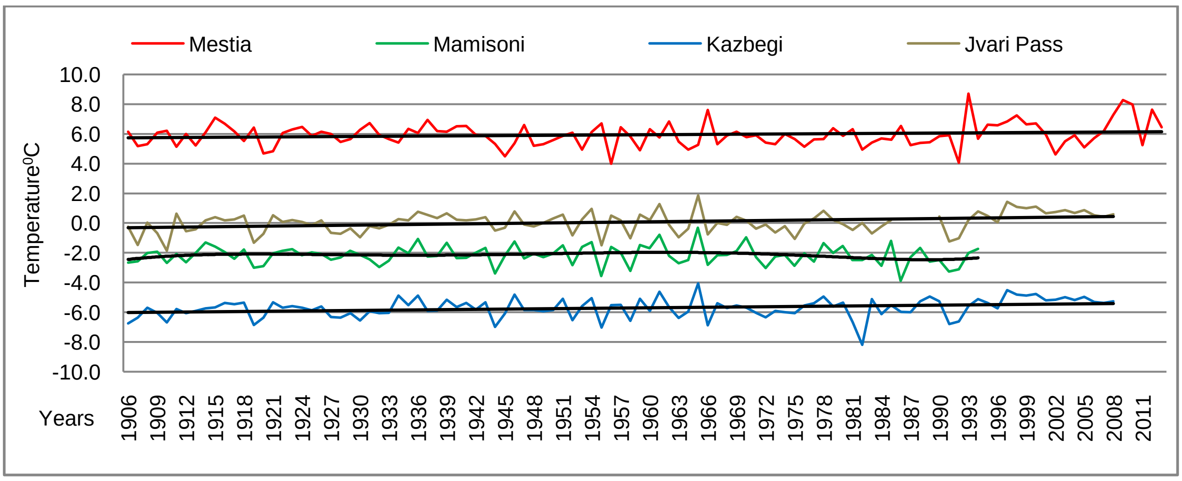

Figure 5. Mean annual air temperatures at the Mestia, Mamisoni, Jvari Pass and Kazbegi meteorological stations over the last century.

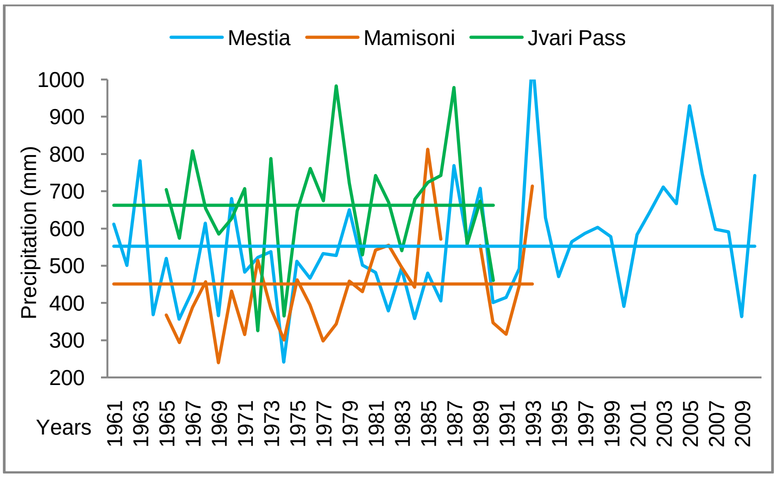

Figure 6. October–April precipitation for Mestia (1961-2010), Mamisoni (1965-1993) and Jvari Pass (1965-1990) meteorological stations. Horizontal lines show record averages for each station.