

Response letter for reviewer and editor comments

“The Greater Caucasus Glacier Inventory (Russia/Georgia/Azerbaijan)” by L. G. Tielidze and R. D. Wheate

<http://www.the-cryosphere-discuss.net/tc-2017-48/>

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Dear referee and editor,

We very much appreciate your comments concerning our manuscript. Those comments are valuable and helpful for improving our manuscript. We tried our best to follow all comments and made revision and answers carefully. All corrections are marked in **yellow** in the revised manuscript.

Please see detail answers on the comments below.

Thank you

A) Many of the tables presenting data of individual glaciers have been moved to the supplement. This is fine. On the other hand the paper itself contains aggregate figures (Fig. 4, 5, 6, 8, 10) of glacier statistics and changes that do not reveal any numbers. As these are also not listed in the supplement, the related values should be added in tabular form to the paper (Figs.5 and 6d) and in the supplement (Figs. 4, 6abc, 8, 10).

We have changed and added some figures/tables: Fig. 4; Table 3 in the manuscript and Table 5-6; Fig. 3-12 in the supplement.

B) The analysis is currently restricted to the presentation of area changes (Figs. 4 and 6) and some selected glacier statistics in the form of bar charts and plots (Figs. 5, 7 and 8). Overlay of glacier outlines is visualized in the supplement (Figs. 1, 2, 14). To put some ‘meat to the bone’ I would like to see some further plots and analysis of the data. Suggestions include (see also Specific comments):

- a) Glacier aspect vs. mean elevation, maybe with colour-coded dots distinguishing between the northern and southern macro slope (as Fig. 8c)*
- b) A map showing the spatial distribution of mean elevation (using colour-coded circles) for all glaciers larger than a certain threshold (maybe $> 1 \text{ km}^2$).*
- c) A map, plot or table showing the change in mid-point or mean elevation from the 1960s inventory to the most recent one. Plotting this against the change in minimum elevation could be very interesting as well.*
- d) A scatter plot showing glacier size vs. minimum and maximum elevation (dots in different colours and/or small symbols).*
- e) A scatter plot showing glacier size vs. relative change in area, maybe colour-coded for different regions and symbol coded for the two periods 1960-1986 and 1986-2014.*
- f) A scatter plot showing length changes vs. original length (this could end up in the supplement if results show a limited correlation).*

Please see new figures/tables: Fig. 8c; Table 3; Fig. 7b.

C) The discussion section is currently looking at area change rates and differences to the RGI/GLIMS databases. This is fine but it should be extended, also considering the new plots suggested above. I thus suggest introducing three or four subheadings: 5.1 Glacier inventory parameters, 5.2 Glacier changes, 5.3 Comparison to GLIMS and the RGI, 5.4 Accuracy con-

<i>siderations (this can also be part of 5.2). The discussion should then focus on commenting on and evaluating the results rather than repeating the data. This might include interesting local differences, the large-scale variability and comparison to other studies, at best from the Alps that have at least similar characteristics (east-west and north-south gradients, similar mean elevation and glacier types).</i>
We agree. Please see new Discussion section P 12-13.
Specific comments
P1
<i>L19: aspect and height; what about slope?</i>
We add slope data P1 L19; P9 Table 3; P12 Fig. 9.
<i>L19-22: Simplify sentences, they have too many commas.</i>
We have changed this, removing some commas.
<i>L23: The area results for the three inventories are fine but what about adding some further key characteristics and changes, e.g. mean size and elevation for the southern/northern slope, change in mean elevation from 1960 to 2014, and aspect dependence of elevation (if present)? See also General comments.</i>
We agree, please see P9 Table 3.
<i>L24: 'The new glacier inventory will be ...'</i>
We have changed this sentence P1 L25.
<i>L30: Bliss et al. 2014 is maybe more a global scale hydrological study rather than a global sea-level study. Maybe move this one upward and add here Radic and Hock 2013 and/or Huss and Hock 2015?</i>
We have added new reference P1 L32.
<i>L40: 'with ten thousands of people'?</i>
We have changed this P1 L43.
P2
<i>L1 I fully agree with you that this should be changed but it is just a matter of an email to Bruce Raup and than it is done. It is thus a rather short-lived statement and the reader might wonder why you have not already addressed this issue. It is much better to write here positively that the former wrong assignment of the greater Caucasus to one country has now been amended and split into three of them (R/G/A).</i>
We have changed this sentence P1 L25-27.
<i>L6: This also sounds like complaining. In fact, nobody volunteered to write something so it is not covered (as many other regions). The GLIMS book never intended to be spatially complete as it lives from their contributors. So maybe remove this statement or write more precisely: 'As no-body volunteered to write a section about the Glaciers in the Caucasus for the GLIMS book (Kargel et al. 2014), the region is missing in this compilation.' or something similar.</i>
We have changed this sentence P2 L6-8.
<i>L7/8: To avoid brackets, maybe write 'Our inventory has 6.5% less glacier area than ... and 7.3% more than ...'</i>
We have changed this sentence P2 L5-6.
<i>L10: I suggest writing: 'Caucasus region based on manual delineation of glaciers from multi-temporal satellite images, and ...'</i>
We agree P2 L10.
P3
<i>L6-9: This sounds a bit like mass balance observations are also providing temperature and precipitation time series. Please add one more sentence to clarify.</i>
We decided to delete this sentence as it was more connected mass balance and less glacier inventory.
<i>L14: 'photographs covering the time period 1875-1906 ...'</i>
We agree P3 L12.
<i>L28: with a total area of 563.7 ...</i>

We agree P3 L27.
<i>L37: maybe add: 'indicating a contrasting slow-down/increase of the loss rate on the north-ern/southern slopes.'</i>
We agree P3 L37.
<i>P4</i>
<i>L25: And for glaciers without a melt water stream or a very lateral location of it?</i>
We have changed this sentence P4 L24-25.
<i>L33: interval of 20 m from</i>
We agree P4 L33.
<i>L36: 'georectified' you mean orthorectified (with a DEM) or geocoded?</i>
Georectified is the correct word as we didn't use a DEM.
<i>P5</i>
<i>L1: not for deriving the mean slope? This is a very good indicator for mean ice thickness.</i>
We have add slope data P9 Table 3; P12 Fig. 9.
<i>L5: Table formatting is maybe not required but I would align all heading row text centre, all cell body text (columns 2, 3, 5) left and cell body numbers right. As the path-row is visually difficult to ex- tract from the given scene ID, I suggest adding a further column Path-Row (with entries only for Landsat and maybe ASTER).</i>
We agree and changed table P5 Table 5.
<i>L7: Actually both, the buffer method and the multiple digitizing only provide uncertainty (or precision), error (or accuracy) can only be determined by a comparison to appropriate reference data. So I suggest merging sections 3.2 and 3.3 to one section 'Uncertainty assessment' and start with a sentence saying that you have determined uncertainty with two independent methods. Than start with the buffer method (as it is the more simple one) before you describe the multiple digitizing. When you also want to include the accuracy assessment performed with the Garmin GPS, name this section 'Uncertainty and accuracy assessment'. Then introduce the latter and also present results of it as these are currently missing. I see black dots in Fig. 2 c/d but it is not described in the caption what they mean (please add). Regarding Fig. 2, please make the a b c d panel marks much larger (factor 4) than they are now. Also be consistent with the syntax: Either use (a) (b) as in Figs. 1 and 8 or just a b as here.</i>
We agree, please see the new "3.2 Glacier uncertainty and accuracy assessment" section P5-7.
<i>L17/18: Maybe write: 'To determine the precision of the digitizing, we manually digitized fifteen differently sized glaciers independently five times in the western ...'? (it is not really the error that is determined by the method but the variability of the interpretation. So roughly this is the analysts precision.</i>
We have changed this sentence P6 L6-7
<i>L28/9: 'covered heavily by debris'</i>
We changed this sentence P6 L25
<i>P6</i>
<i>L6: It is difficult to see anything on Fig 2c. I suggest replacing it with another close-up view.</i>
We have changed this figure, please see P6 Figure 2.
<i>L9: As mentioned above, please merge this section with 3.2.</i>
We agree, please see the new "3.2 Glacier uncertainty and accuracy assessment" section P5-7.
<i>L16/17: You might consider to also referring here to your own results shown in Figs. 2a and b. They clearly reveal a $\pm 1/2$ pixel buffer for clean ice and a ± 1 or 2 pixel buffer for debris-covered ice.</i>
We have added our results here P5 L20.
<i>L20: 30 m (with a space in-between)</i>
We have changed this P5 L20.
<i>P7</i>
<i>L6: I suggest showing a close-up of the debris-covered part.</i>
We agree, please see P7 Figure 3d.

P8
<i>Tables 2 and 3: I think these two tables can be safely merged.</i>
We agree, please see P8 Table 2.
<i>Figure 4: I suggest adding minor tick marks on the y-axis (step 0.1) and repeat them on the opposite site</i>
We have changed this figure, please see P8 Figure 4.
<i>L15: experienced the highest relative glacier area loss</i>
We agree, please see P8 L20.
<i>L17/18: This might be correct but it comes a bit of a sudden and is difficult to verify without knowing further details. So maybe move it to the discussion and add some details about the cited study there. The problem is that you cite here a study that has been published before this study but you link the results of this study to it. So I wonder how the cited study could have known the results presented here?</i>
We have decided to delete this sentence, as it was a bit confusing.
<i>L21: I would not introduce a subheading 4.1.1 when there is no 4.1.2. Maybe rename 4.1 to 'Glacier changes for the entire study region' and 4.1.2 to '4.2 Glacier changes in the ... massif?'</i>
We agree, please see P7 L11; P8 L27.
P9
<i>L24 (Fig. 5): I think this figure is fine in general but I would change a few things: remove the 'Mean area ...' text line, add some minor tick marks for both y-axes (left and right), use more distinct colours (or shades of grey?) for the bars and triangles (green is difficult to distinguish from cyan), and in particular change the colour of the 1960 triangle to something else (black?). As it is very difficult to extract any numbers from the graph, please also provide a table listing all numbers (can be in an Appendix).</i>
We agree, please see new figure P9 Figure 5.
<i>L30: resulting from the disintegration of ... (retreat is change in terminus position).</i>
We have changed this P10 L6.
<i>L34: As Fig. 6 is only an aggregate figure, would it be possible to add a scatter plot showing the individual values, maybe symbol coded for the two periods (1960-1986 and 1986-2014) and colour coded for northern/southern slopes? This would also depict the local variability.</i>
This is an insightful suggestion, but we were reluctant to add another 'similar' figure to those already in the paper. The north-south values are already shown in figures 4,7-9 and table 3.
P10
<i>L2: Please add the equidistance of the elevation bands used. Currently it looks like 250 m? In this case please use 50 m to avoid the blocky appearance of the graph.</i>
We agree and changed figure, please see P11 Figure 7a.
<i>L9 (Fig. 7): Can you please add some minor tick marks on both axes. With 50 m elevation bins please also use major gridlines for the y-axis.</i>
We have changed this figure according your comment, please see new figure P11 Figure 7a.
<i>L9: Please consider adding a scatter plot (as Fig. 7b) showing glacier size vs. minimum and maximum elevation (colour coded in the same plot)</i>
We agree and have added new figure, please see P11 Figure 7b.
P11
<i>L3 (Fig. 8): Please use capital letters for the cardinal directions (N, NE, E, etc.)</i>
We agree and changed these figures, please see P11 Figure 8a-c
<i>L3: Please add a scatter plot (as Fig. 8b) showing aspect vs. mean or mid-point elevation of glaciers</i>
We have added new figure, please see P11 Figure 8c.
<i>L3: If there is some interesting variability, please show a map with colour-coded circles representing glacier mean (or mid-point) elevation for all glaciers larger 0.5 or 1 km².</i>
We have added new table for glacier mean and minimum elevation P9 Table3

<i>L5: When analysing length changes, wouldn't it be more sensible to sort glaciers for length classes? I ask because there is often a certain relationship between initial glacier length and length change. You can check this by creating a scatter plot initial length vs. (absolute) length change. If there is a relation, I suggest showing also this plot.</i>
We reviewed this, but did not find a significant relationship between glacier length and change worth showing in this paper.
<i>L6/7: 'length change': I think you mean 'retreat rates' here?</i>
We have changed this P12 L6.
<i>L28: Discussion section: The two topics presented in the discussion section are fine. However, I think ones the additional plots are shown some further discussion on the achieved results should be presented. This should also add some science (or give some 'meat to the bone') to this data-driven contribution.</i>
We agree, please see new Discussion section P12-14.
<i>L36: than from 1957-2000</i>
We have changed this P13 L1.
<i>L37ff: Interpretation of shrinkage rates: as mentioned in my previous review, I would really restrict the higher loss rates in regions with smaller glaciers to their size and nothing else (please add the related scatterplot as suggested above). All other representations require knowledge about changes that you do not have. I repeat: Glaciers are where they are because climate is at it is. So climatic conditions itself do not have any impact on area change rates. What you need to show for your statements is that climate CHANGE was different in different regions and elevations. For the eastern Caucasus this means that climate has dried (less precipitation) at the elevation of glaciers whereas at the same time the larger accumulation areas of the glaciers in the central Caucasus have received more precipitation. Similarly, to get increased glacier loss at lower elevations you must show that temperatures have increased more at these elevations than higher up. As no proof is given for any of these trends, you cannot claim that these are the reasons.</i>
We decided to delete this sentence and added new text P13 L1-5.
<i>P12 L21/2: I assume these differences have a sign? Can you please add which ones are larger and smaller?</i>
We have added exact numbers P14 L12-13.
<i>L26 (Fig. 10): I think there is not much to see when absolute area differences are plotted like this. Better use a plot style like in Fig, 6 with bars and positive/negative differences. Maybe these display even better when presented as relative rather than absolute differences</i>
We have changed this figure, please see P14 Figure 11
<i>P13 L8/9: Is this shown somewhere (map overestimation of snowfields and the related correction with Corona images? I suggest adding this, as it would have some relevance beyond this study. Increasing the consistency in the interpretation of glacier outlines is still a major issue for glacier inventories so a practical example would be very helpful.</i>
We have added new figure for this, please see P6 Figure 2d-e
<i>L20/1: 0.7% is quite strong but it is only half of the rate in the Alps. For this not further elaborated statement I would maybe add a citation from one of the global scale studies presenting volume changes per RGI region until 2100.</i>
We have added to the text: Huss and Hock, please see P15 L7-8.

The Greater Caucasus Glacier Inventory (Russia/Georgia/Azerbaijan)

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Abstract

There have been numerous studies of glaciers in the Greater Caucasus, but none that have generated a modern glacier database across the whole range. Here, we present an updated and expanded glacier inventory over the three 1960-1986-2014 time periods covering the entire Greater Caucasus. Large scale topographic maps and satellite imagery (Corona, Landsat 5, Landsat 8 and ASTER) were used to conduct a remote sensing survey of glacier change and the 30 m resolution ASTER GDEM to determine the aspect, slope and height distribution of glaciers. Glacier margins were mapped manually and reveal that in 1960, the mountains contained 2349 glaciers with a total glacier surface area of $1674.9 \pm 70.4 \text{ km}^2$. By 1986, glacier surface area had decreased to $1482.1 \pm 64.4 \text{ km}^2$ (2209 glaciers), and by 2014 to $1193.2 \pm 54.0 \text{ km}^2$ (2020 glaciers). This represents a $28.8 \pm 4.4\%$ ($481 \pm 21.2 \text{ km}^2$) or $0.53\% \text{ yr}^{-1}$ reduction in total glacier surface area between 1960 and 2014 and an increase in the rate of area loss since 1986 ($0.69\% \text{ yr}^{-1}$), compared to 1960-1986 ($0.44\% \text{ yr}^{-1}$). Glacier mean size decreased from $0.70\text{-}0.66\text{-}0.57 \text{ km}^2$ between 1960-1986-2014. This new glacier inventory data have been submitted to GLIMS, and can be used as a basis dataset for future studies. The GLIMS former assignment of the greater Caucasus to one country has now been amended and split into three (Russian-Georgia-Azerbaijan).

1 Introduction

Glacier inventories provide the basis for further studies on mass balance and volume change, which are relevant for local to regional-scale hydrological studies (Huss, 2012; Fischer et al., 2015), and to global calculation of sea level change (Gardner et al., 2013; Radic and Hock, 2014). In addition, glacier inventories are invaluable data sets for revealing the characteristics of glacier distribution and for upscaling measurements from selected locations to entire mountain ranges (Nagai et al., 2016).

In a high mountain system such as the Greater Caucasus, glaciers are an important source of water for agricultural production, and runoff supplies several hydroelectric power stations. Most rivers originate in the mountains and the melting of glaciers/snow are important component inputs in terms of water supply and for recreational opportunities (Tielidze, 2017). However glacier hazards are relatively common in this region leading to major loss of life. On September 20 2002, for example, Kolka Glacier (North Ossetia) initiated a catastrophic ice-debris flow killing over 100 people (Evans et al., 2009), and on May 17 2014, Devdoraki Glacier (Georgia) caused a rock-ice avalanche and glacial mudflow killing nine people (Tielidze, 2017). The Greater Caucasus glaciers also have economic importance as a major tourist attraction e.g. Svaneti, Racha and Kazbegi regions in Georgia, with thousands of visitors each year (Georgian National Tourism Administration, 2017).

The GLIMS database (9.02.2017) for the Greater Caucasus identified in excess of 1295 glaciers with a combined area of 1111.8 km² but with some inconsistent registration. The RGI5 database identifies in excess of 1638 glaciers with a combined area of 1276.9 km² and incorporates nominal glaciers as circles in the eastern and western Caucasus sections (i.e. no outline extents) from the WGI-XF (Cogley, 2009); these are omitted from the GLIMS database. Our inventory has 6.5% less glacier area than the RGI database and 7.3% more than the GLIMS database. As nobody volunteered to write a section about the glaciers in the Caucasus for the GLIMS book (Kargel et al., 2014), the region is missing in this compilation.

Thus, the objectives of this paper are to construct an updated glacier inventory for the Greater Caucasus region based on manual delineation of glaciers from multi-temporal satellite images, and especially to fill the gap in the eastern Greater Caucasus.

2 Study Area

The Caucasus mountains consist of two separate mountain systems: the Greater Caucasus (the higher and more extensive part) extends for ~1300 km from northwest to southeast between the Black and Caspian seas, while the Lesser Caucasus, approximately 100 km to the south is characterized by relatively lower elevations. The Greater and Lesser Caucasus are connected by the Likhi range, which represents the watershed between the Black and Caspian seas.

The Greater Caucasus can be divided into western, central and eastern sections based on morphology divided by the mountains Elbrus (5642 m) and Kazbegi (5047 m) (Maruashvili, 1981) (Fig. 1). At the same time, the terms Northern and Southern Caucasus are frequently used to refer to the corresponding macroslopes of the Greater Caucasus range (Solomina et al., 2016).

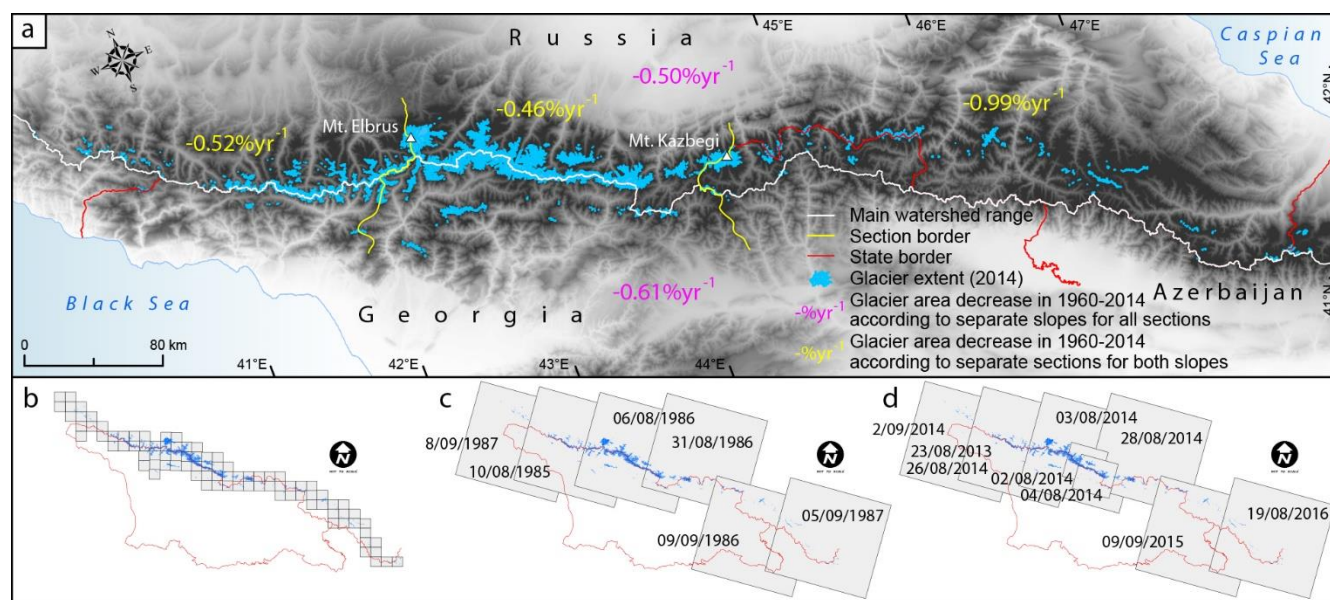


Figure 1. a - Distribution of the Greater Caucasus glaciers, b - 1960s 1:50 000 scale map sheets (88) are based on aerial photographs 1950-1960. c - Six Landsat 5 TM satellite scenes 1985-1987. d - Seven Landsat 8 OLI satellite scenes from 2013 to 2016 and two (smaller) ASTER satellite scenes from 2014.

Glacier retreat started from the Little Ice Age (LIA) maximum positions in the northern Caucasus from the late 1840s, with minor readvances in the 1860s-1880s and readvances or steady states in the 20th century (1910s, 1920s and 1970s-1980s) (Solomina, et al., 2016).

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). Direct field monitoring reveals evident debris expansion for some glaciers (e.g. Djankuat) from 2% to 13% between 1968-2010 (Popovnin et al., 2015). Glacier retreat appears to be associated with expansion of supraglacial debris cover and ice-contact/proglacial lakes, which may increase the likelihood of glacier-related hazards and debris flows (Stokes et al., 2007). Debris cover is more common in the north than in the south (Lambrecht et al., 2011, Tielidze et al., 2017).

2.1 Previous studies

The study of glaciers in the Caucasus began in the first quarter of the 18th century, in the works of Georgian scientist Vakhushti Bagrationi (Tielidze, 2016); subsequently there were many early expeditions and glacier photographs covering the time period 1875-1906 (Solomina et al., 2016). Studies focused on glacier mapping, began when Podozerskiy (1911) published the first inventory of the Caucasus glaciers, based on large scale military topographical maps (1:42 000) from 1881-1910, identifying 1329 glaciers, with total area 1967.4 km² in the Greater Caucasus (Kotlyakov et al., 2015). Detailed analysis of these early data showed some defects in the depicted shape of the glaciers and in particular those in inaccessible valley glaciers (Tielidze, 2016). Reinhardt (1916, 1936) noted Podozerskiy's errors in compiling a new catalog for some glacial basins of the Greater Caucasus region (Tielidze, 2017).

The next inventory of the Caucasus glaciers (Catalog of Glaciers of the USSR, The Caucasus, 1967-1978), assessed glacier parameters from ~1950-1960 aerial photographs. This includes some errors as temporary snowfields were misinterpreted as glaciers (Gobejishvili, 1995; Tielidze, 2016) and the catalog datasets contained glacier parameters but not outlines. As the USSR catalog and 1960s large-scale (1:50 000) topographic maps were based on the same aerial photographs, we have used both datasets in this article for a more comprehensive comparison.

Gobejishvili (1995) documented further statistical information about the glaciers of Georgia based on the same 1960s topographic maps, reporting there were 786 glaciers with a total area of 563.7 km² in the Georgian Caucasus. The current investigation revealed that he missed some small glaciers, particularly in the Bzipi, Kodori, Rioni, Enguri and Tergi river basins.

Khromova et al. (2009, 2014) used manually digitized results to estimate changes of more than 1200 glaciers in the Caucasus between three periods - 1911-1957-2000. They found that glacier area decreased from 1911-1957 by 24.7% (0.52% yr⁻¹) and from 1957-2000 by 17.7% (0.41% yr⁻¹). Elbrus glaciers lost 14.8% (0.31% yr⁻¹) and 6.3% (0.14% yr⁻¹) respectively for the two time periods. However, there was a difference between north and south slopes of the Caucasus. Glacier area change on the north slope was 30% (0.63% yr⁻¹) for the first part of the 20th century and 17.9% for the second part (0.41% yr⁻¹). In contrast, the south slope lost 12% (0.25% yr⁻¹) and 28% respectively (0.65% yr⁻¹) indicating a contrasting slow-down/increase of the loss rate on the northern/southern slopes.

Lur'e and Panov (2014) examined northern Caucasus glacier variation for 1895-2011, finding glacier area decreased by 849 km² (52.6%). During this period, the average rate of glacier area reduction was 0.45%yr⁻¹, varying from 0.52%yr⁻¹ in 1895-1970 to 0.32%yr⁻¹ in 1971-2011. The most significant decrease was registered in the basins of Dagestan rivers (eastern Caucasus section); however, they didn't describe the data sources for their glacier mapping.

The most recent glacier inventory, based on old topographic maps (1911/1960) and modern satellite imagery (Landsat/ASTER, 2014) was published by Tielidze (2016), but compiled only for Georgian Caucasus glaciers, which reduced from 613.6±9.8 km² to 355.8±8.3 km² (0.37% yr⁻¹) between 1911-

2014, while glacier numbers increased from 515 to 637. The current investigation has revealed, that some small glaciers were omitted as Tielidze used Gobejishvili's (1995) glacier database.

Other recent published works about the Caucasus, have mainly examined changes in glacier area and length for individual river basins or separate sections. Stokes et al. (2006; 2007) determined that 94% of 113 selected glaciers in the central Caucasus retreated between 1985 and 2000; the largest glaciers ($>10 \text{ km}^2$) had retreated at twice the rate ($\sim 12 \text{ m yr}^{-1}$) as the smallest ($<1 \text{ km}^2$) glaciers ($\sim 6 \text{ m yr}^{-1}$). Shahgedanova et al. (2014) calculated $4.7 \pm 2.1\%$ or $0.20\% \text{ yr}^{-1}$ glacier area loss from $407.3 \pm 5.4 \text{ km}^2$ to $388.1 \pm 5.2 \text{ km}^2$ in the central and western Greater Caucasus, between 1987-2010.

In this article, we present the percentage and quantitative changes in the number and area of glaciers for the whole Greater Caucasus in the years 1960-1986-2014, by individual slopes, sections, countries and river basins.

3 Methods

3.1 Data sources

We utilise increasingly accessible global satellite imagery (Wulder et al., 2012; 2016; Pope et al., 2014) to investigate glacier area and number change in the Greater Caucasus between 1960-1986-2014. Changes in glacier extent in the Greater Caucasus between 1986 and 2014 were determined through analysis of images from Landsat 5 Thematic Mapper (TM), Landsat 8 Operational Land Imager (OLI), and the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Table 1). Georeferenced images were downloaded using the Earthexplorer (<http://earthexplorer.usgs.gov/>) and Reverb/ECHO tools (<http://reverb.echo.nasa.gov/>).

We used the Landsat 8 panchromatic band, along with a color-composite scene for each acquisition date, combining shortwave-infrared, near-infrared, and red for Landsat, and near-infrared, red and green for ASTER images. These false-colour composite images can accurately show many glacier termini where meltwater streams display as bright blue and contrast with the snout which casts an obvious shadow (Stokes et al., 2006). This contrast remains apparent even with significant glacier retreat.

All images were acquired at the end of the ablation season, ranging from 2 August to 9 September, when glaciers were mostly free of seasonal snow under cloud-free conditions, but with some glacier margins obscured by shadows from rock faces and glacier cirque walls. In total, six Landsat 5 (TM) scenes were used for 1985/86/87, with seven Landsat 8 (OLI) for 2013/14/15/16 and two ASTER scenes used for 2014 (Fig. 1c, d; Table 1). The latter were used primarily to complete coverage from isolated cloud cover in the Landsat scenes.

Large-scale topographic maps (88 sheets, 1:50 000 scale) with a contour interval of 20 m from several hundred aerial photographs taken between 1950-1960 were used to evaluate glacier outlines (Fig. 1b). Corona images, dating from 1964 were obtained from the Earthexplorer website (<http://earthexplorer.usgs.gov/>) and two were georectified for comparison with map extents. As the maps were only available in printed form, we scanned at 300 dpi with 5 m ground resolution and with the Corona imagery co-registered using the 3 August 2014 Landsat image as a master (Tielidze, 2016). Offsets between the images and the Corona/archival maps were within one pixel (15 m) based on an analysis of common features identifiable in each dataset. We reprojected Corona imagery and maps to Universal Transverse Mercator (UTM), zones 37/38-north on the WGS84 ellipsoid, to facilitate comparison with modern image datasets (ArcGIS 10.2.1). Together with Landsat imagery, these older topographic maps and Corona imagery enabled us to identify changes in the number and area of glaciers over the last half century.

The 30 m resolution ASTER Global DEM (GDEM, 2011) was used to determine the aspect, slope and height distribution of glaciers, downloaded from NASA LPDAAC Collections (<http://earthexplorer.usgs.gov/>).

We detected the glacier length by measurement of changes in the central flowline (Paul and Svoboda, 2009). This method uses the maximum length along the central flowline in different years, input that is required for glacier inventories.

Table 1. List of satellite images scenes used in this study.

Date	Resolution	Path	Row	Type of imagery	Region/Section	Scene ID
25/08/1964	2 m	-	-	Corona	C Greater Caucasus	DS1115-2154DF071_d
25/08/1964	2 m	-	-	Corona	E Greater Caucasus	DS1115-2154DA082_c
10/08/1985	30 m	172	030	Landsat 5	W and C Greater Caucasus	LT51720301985222XXX04
06/08/1986	30 m	171	030	Landsat 5	C Greater Caucasus	LT51710301986218XXX02
31/08/1986	30 m	170	030	Landsat 5	C and E Greater Caucasus	LT51700301986243XXX03
09/09/1986	30 m	169	031	Landsat 5	E Greater Caucasus	LT51690311986252XXX03
05/09/1987	30 m	168	031	Landsat 5	E Greater Caucasus	LT51680311987248XXX03
08/09/1987	30 m	173	030	Landsat 5	W Greater Caucasus	LT51730301987251AAA04
23/08/2013	15/30 m	172	030	Landsat 8	W and C Greater Caucasus	LC81720302013235LGN00
03/08/2014	15/30 m	171	030	Landsat 8	C Greater Caucasus	LC81710302014215LGN00
26/08/2014	15/30 m	172	030	Landsat 8	W and C Greater Caucasus	LC81720302014238LGN00
28/08/2014	15/30 m	170	030	Landsat 8	C and E Greater Caucasus	LC81700302014240LGN00
02/09/2014	15/30 m	173	030	Landsat 8	W Greater Caucasus	LC81730302014245LGN00
09/09/2015	15/30 m	169	031	Landsat 8	E Greater Caucasus	LC81690312015252LGN00
19/08/2016	15/30 m	168	031	Landsat 8	E Greater Caucasus	LC81680312016232LGN00
02/08/2014	15 m	171	030	ASTER	C Greater Caucasus	AST_L1T_00308022014081313_20150622105647_51181
04/08/2014	15 m	170	030	ASTER	C Greater Caucasus	AST_L1T_00308042014080102_20150622114958_116303

3.2 Glacier uncertainty and accuracy assessment

We have determined uncertainty with two independent methods (buffer and multiple digitization). We used a buffer method similar to Granshaw and Fountain (2006) and Bolch et al. (2010) and adopted by Tielidze (2016). The uncertainty term for the 1960 extents is based on a buffer incorporating the root-mean-square error (RMSE_{x,y}) of the map rectification (15 m) and the digitizing uncertainty equal to the width of a contour line (15 m).

Uncertainty is introduced by the resolution of the satellite image in terms of what can be seen, and the contrast between the glacier and adjacent terrain (Stokes et al., 2013). For debris-free glacier ice that is not obscured by clouds, DeBeer and Sharp (2007) suggested that line placement uncertainty is unlikely to be larger than the resolution of the imagery, i.e. ± 30 m for Landsat 5 TM and Landsat 8 OLI. This can be seen in figure 2, along with a ± 1 or 2 pixel buffer for debris-covered ice. A buffer with a width of one RMSE was created along the glacier outlines and the uncertainty term was calculated as an average ratio between the original glacier areas and the areas with a buffer increment; for the 1986 images we used a buffer equal to the resolution of the data (30 m) and a similar buffer for the 2014 glacier extents. This generated an average uncertainty of the mapped glacier area of 4.6% for 2014, 4.4% for 1986 and 4.2% for 1960. Using the buffer method from Granshaw and Fountain (2006), these yield a total potential overall error of $\pm 4.4\%$.

For 1986/2014 imagery we digitised the outlines of both debris-covered and debris-free ice and tested a number of well-known semi-automated techniques (band ratio TM3/TM5 and OLI4/OLI6, ratio thresholds range ≥ 2.0) (Paul and Kaab, 2005; Andreassen et al., 2008; Bolch et al., 2010) to extract glacier outlines and compare with manually generated outlines (Fig. 2).

Generally, for debris-free glaciers, automated delineation using the spectral ratio is more consistent and reproducible than manual delineation. These techniques are relatively useful for large sample sizes and/or large glaciers where manual delineation would be time-consuming (e.g. Central Greater Caucasus), but their value can be limited by areas of glacier with supraglacial debris (e.g. Western and Eastern Greater Caucasus) (Paul et al., 2013).

Following Paul et al. (2013) to determine the precision of the digitizing, we manually digitized fifteen differently sized glaciers independently five times in the western, central and eastern Greater Caucasus to estimate 1986 and 2014 glacier area error. For debris covered glaciers (Fig. 2a), the Normalised Standard Deviation (NSD - based on delineations by multiple digitalization divided by the mean glacier area for all outlines) was 6.9% and the difference between the manually and automatically derived area was 13.41%. For debris-free glaciers (Fig. 2b, c) the NSD was 5.7% and difference between the manually and automatically derived area was 4.9%.

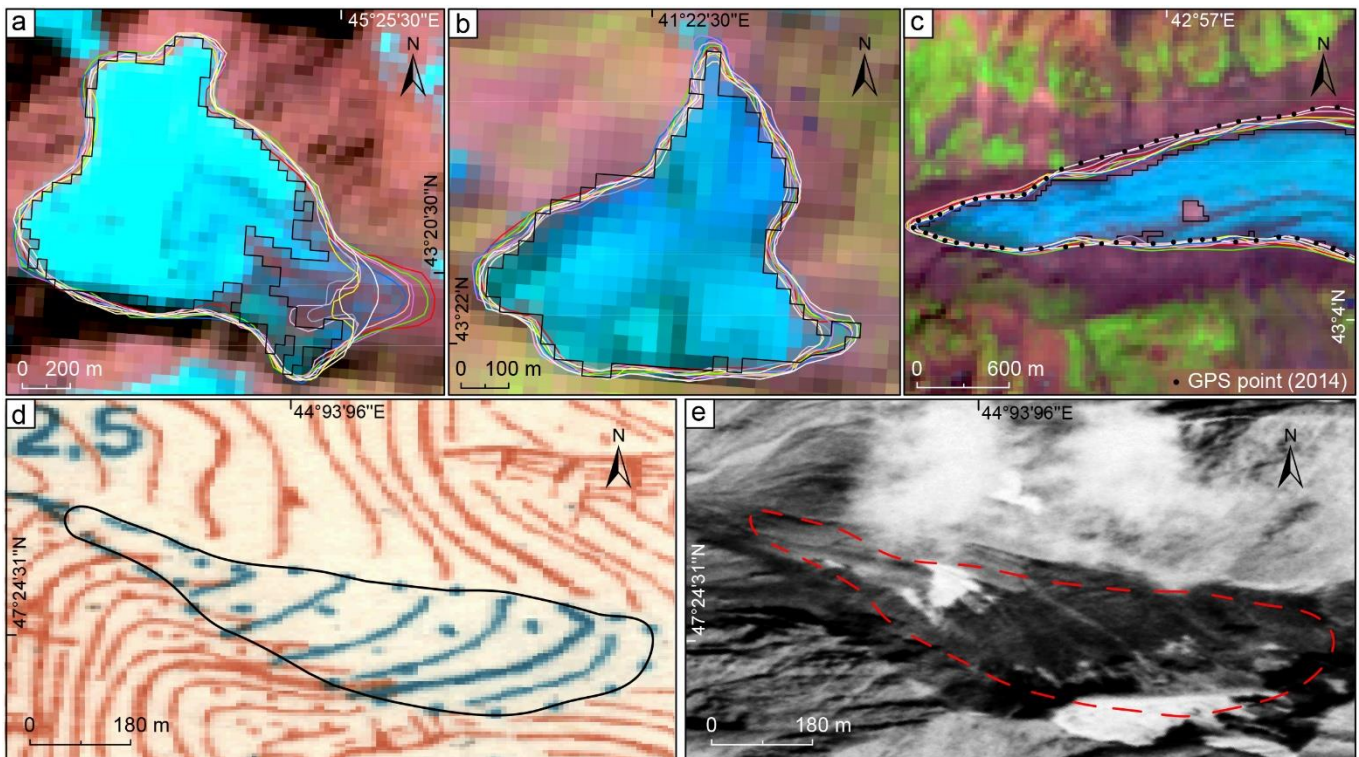


Figure 2. a-c Examples from the multiple digitizations of glaciers (bands 654 as RGB) using the OLI scene performed by different analysts (coloured lines). Black outlines refer to the automatically derived extents (4/6 ratio); pixel size is 30 m. d – Error in the 1960 map included mapped snow for small cirque type glacier; e – same place 1964 Corona imagery.

To estimate 1960s glacier area error we digitized multiple (3) times three different size glaciers (<2km², 2-5 km², >5 km²) in the central and eastern Greater Caucasus using topographic maps and two Corona imagery (Fig. 3a-c). For 1960 topographic map glaciers, NSD was 0.4% and for Corona 5.9%. Between the maps and Corona imagery NSD was 4.8%.

Importantly, debris cover is not continuous on the snouts of many glaciers in the Greater Caucasus and most glaciers of Mt. Elbrus (Shahgedanova et al., 2014; Tielidze et al., 2017), but there are some glaciers covered by heavy debris. One of the most debris-covered we digitized in the Caucasus is Skhelda Glacier (8.28±0.65 km²) (43°10'N, 42°38'E), where supra-glacial debris covers approximately 35% (Fig. 3d). To account for the error term due to debris cover, after Frey et al. (2012) we increased the buffer size to two pixels (30 m) and error of mapping was calculated as ±7.9% which is the largest error

in our database. In addition, for more accuracy assessment we used GPS (GARMIN 62stc) measurement data 2011-2016 for some glaciers (Fig. 2c; 3d), where GPS readings were assumed to be within one half pixel of true coordinates.

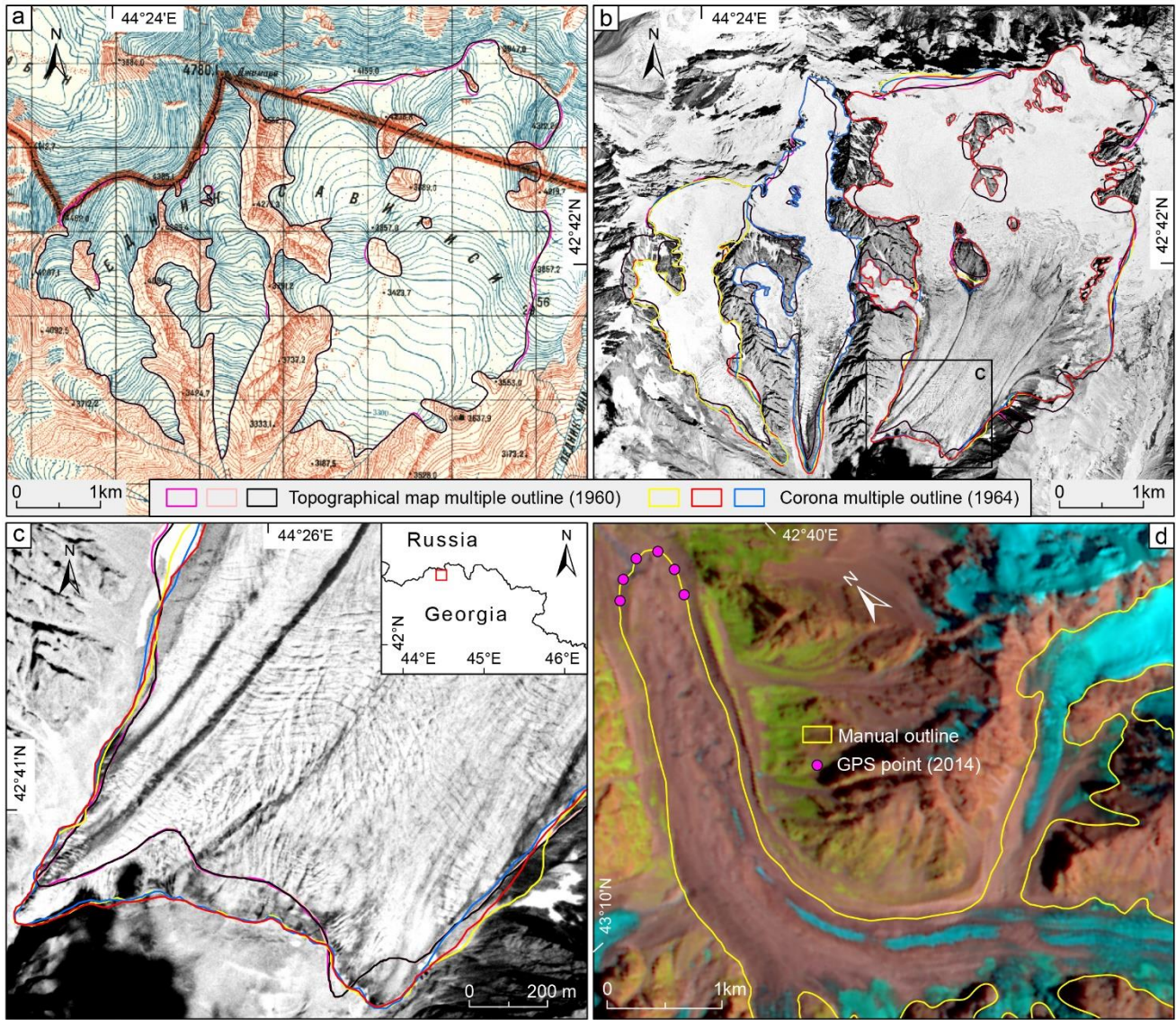


Figure 3. a-c Examples from the multiple digitizations of glaciers using the 1960s topographic map and 1964 Corona imagery performed by different analysts (coloured lines). d – Shkhelda Glacier, one of the heavily debris covered glaciers in the Greater Caucasus. The 23/08/2014 Landsat 8 image (Table 1) is used as background.

4 Results

4.1 Glacier changes for the entire study region

The total ice area loss between 1960 and 1986 was $192.8 \pm 8.4 \text{ km}^2$ or $11.5 \pm 4.4\%$ ($0.44\% \text{ yr}^{-1}$), while the number of glaciers reduced from 2349 to 2209. Between 1986 and 2014, glacier area decreased by $288.9 \pm 12.8 \text{ km}^2$ or $19.5 \pm 4.6\%$ ($0.69\% \text{ yr}^{-1}$), and glacier numbers from 2209 to 2020.

Glaciers in the northern Greater Caucasus lost $131.0 \pm 5.8 \text{ km}^2$ or $11.0 \pm 4.2\%$ of their area ($0.42\% \text{ yr}^{-1}$) between 1960-1986, while the number of glaciers reduced from 1622 to 1523. Between 1986 and 2014, glacier area decreased by $189.7 \pm 8.4 \text{ km}^2$ or $18.0 \pm 4.4\%$ ($0.64\% \text{ yr}^{-1}$) while the number of glaciers reduced

from 1523 to 1391. Glacier mean size decreased from 0.73-0.69-0.62 km² in the northern Greater Caucasus between 1960-1986-2014.

On the southern macroslope, glacier area decreased by 61.8±3.4 km² or 12.7±5.4% (0.48% yr⁻¹) between 1960-1986, while the number of glaciers reduced from 727 to 686. Between 1986 and 2014, glacier area decreased by 99.2±4.6 km² or 23.3±4.6% of their area (0.83% yr⁻¹) while the number of glaciers reduced from 686 to 629. Glacier mean size decreased from 0.67-0.62-0.52 km² between 1960-1986-2014.

Overall, the differences between the two macroslopes were small. The greater loss was observed on the southern slope where glaciers lost 33.0±5.0% (0.61% yr⁻¹) over the last half century, while the northern slope glaciers lost 27.0±4.2% (0.50% yr⁻¹) (Table 2; Fig. 4).

Table 2. The Greater Caucasus glacier number and area change according the different slopes and sections in 1960-1986-2014.

Slope/ Section	Topographic maps 1960		Landsat 5, 1985/86/87		Landsat 8, 2013/14/15/16 and ASTER 2014		Decrease 1960-1986 % yr ⁻¹	Decrease 1986-2014 % yr ⁻¹	Decrease 1960-2014 % yr ⁻¹
	Number	Area km ²	Number	Area km ²	Number	Area km ²			
Northern	1622	1186.5±48.8	1523	1055.5±45.0	1391	865.8±38.4	0.42	0.64	0.50
Southern	727	488.4±29.0	686	426.6±19.4	629	327.4±15.2	0.48	0.83	0.61
Western	713	330.2±16.6	738	300.3±16.0	723	237.3±13.8	0.34	0.74	0.52
Central	1140	1156.0±43.2	1060	1040.5±40.0	1033	867.8±35.0	0.38	0.59	0.46
Eastern	496	188.7±10.0	411	141.6±7.8	264	88.0±5.0	0.96	1.35	0.98

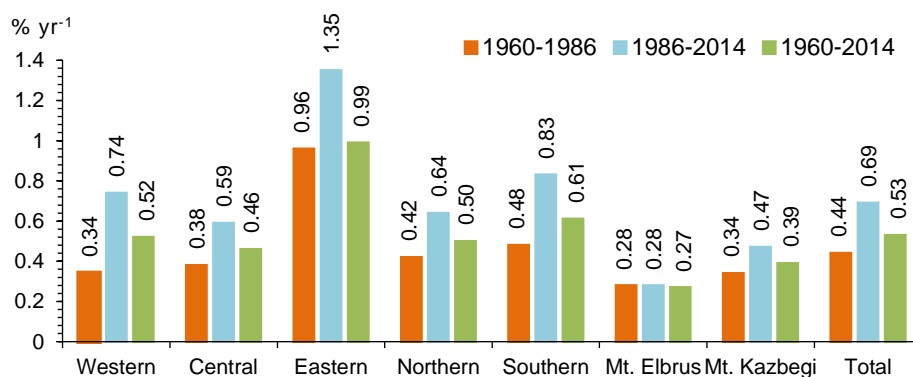


Figure 4. Greater Caucasus glacier area decrease by slopes, sections and mountain massifs in 1960-1986-2014.

The eastern Caucasus section (Aragvi, Terji headwaters, Sunja right (south-east) tributaries - Sulak, Samur, Agrichai and Kusarchai) experienced the highest relative glacier area loss, where the total ice area loss between 1960 and 2014 was 53.3±4.4% (0.98% yr⁻¹) or 100.5±4.4 km² (Table 2; Fig. 4). Glacier area and number change by individual river basins and countries are given in the Supplement (Table 1, 2).

Glacier mean elevation for the northern macroslope changed from 3458-3477-3506 m asl between 1960-1986-2014, and minimum elevation changed 1939-1964-1997. For the southern macroslope mean elevation changed from 3246-3278-3320 m asl and minimum 1875-1908-1960 in same time. Detailed glacier parameters changes according to different slopes and sections are shown in Table 3.

4.2 Glacier changes on the Elbrus and Kazbegi-Dzhimara massif

Glaciers located on Mt. Elbrus lost 9.9±0.2 km² or 7.3±2.2% (0.28% yr⁻¹) of their combined area between 1960 and 1986 and the same amount from 1986 to 2014. Overall, the relative loss was 14.7±2.4% (0.27% yr⁻¹) between 1960 and 2014.

Among the large glaciers (>10 km²) the Dzhikiugankez Glacier experienced a high rate of reduction, as the most extensive glacier on the Elbrus massif, the relative loss was 27.2±1.2% (0.50% yr⁻¹) between 1960-2014. The important relative losses for the Dzhikiugankez Glacier can be explained by the role of post-volcanic activity, especially the influence of thermal and fluid flows in the north-eastern part of the Elbrus volcano (Masurenkov and Sobisevich, 2012; Holobăcă, 2016).

Table 3. Topographic parameters for glaciers 1960-1986-2014.

Slope/ Section	Minimum elevation a.s.l.			Median elevation a.s.l.			Mean glacier size km ²			slope ^a		
	1960	1986	2014	1960	1986	2014	1960	1986	2014	1960	1986	2014
Northern	1939	1964	1997	3458	3477	3506	0.73	0.69	0.62	23.22	22.83	22.21
Southern	1875	1908	1960	3246	3278	3320	0.67	0.62	0.52	22.78	22.19	21.16
Western	1786	1803	1891	3064	3071	3092	0.46	0.40	0.32	24.47	24.08	23.86
Central	1865	1879	1964	3453	3489	3527	1.01	0.98	0.84	22.30	22.02	21.17
Eastern	2279	2305	2332	3633	3681	3737	0.38	0.34	0.33	25.66	24.78	23.91

Unlike the Elbrus, the size of the change varied dramatically from glacier to glacier on the Kazbegi-Dzhimara massif. The total ice area loss between 1960-1986 was 6.1±0.2 km² or 9.0±4.0% (0.34% yr⁻¹). From 1986 to 2014 glacier area decreased by 8.3±0.4 km² or 13.4±4.4% (0.47% yr⁻¹). Overall, the relative loss was 21.2±4.4% (0.39% yr⁻¹) between 1960 and 2014 (Fig. 4).

Among glaciers with area 2-5 km², the Devdoraki Glacier experienced a high rate of reduction between 1960-2014, with a relative loss of 38.8±2.8% (1.4% yr⁻¹). We do not include Kolka Glacier in a statistical analysis, as it was almost removed by its strong rock-ice avalanche in 2002 (Haeberli et al., 2004; Huggel et al., 2005; Petrakov et al., 2008). Elbrus and Kazbegi-Dzhimara glaciers area and number change are given in the Supplement (Table 3-4; Fig. 1-2).

4.2 Glacier characteristics

The greatest area is occupied by glaciers in the size class 1.0-5.0 km² across all three time periods. (Fig. 5; in the Supplement Table 5). The largest glaciers are located in the central Greater Caucasus where valley glaciers have individual areas of 5-37 km². The total area of glaciers in the central section is more than triple that in western Caucasus, which in turn is almost triple the glacier area in the eastern section, even though the eastern section is higher than the western (Table 3). For 1960 there were 22 glaciers with individual area >10 km² and for 2014 there are just 13 in the Central Greater Caucasus. There are no glaciers of >10 km² area in the eastern and western Greater Caucasus.

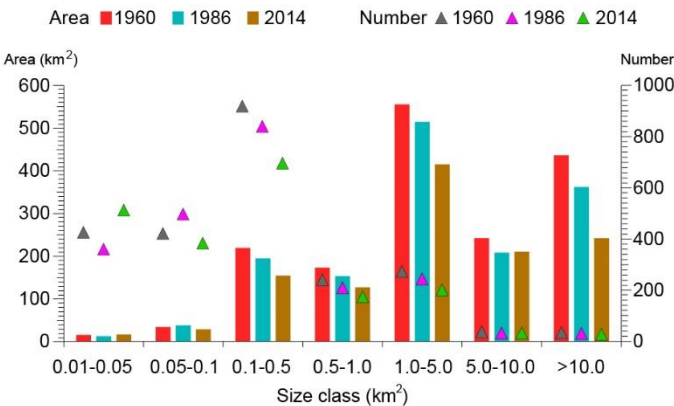


Figure 5. Cumulative glacier area and number values for seven size classes in the Greater Caucasus in 1960-1986-2014.

During the 1986-2014 period the number of smallest glaciers ($0.01-0.05 \text{ km}^2$) have increased in the western and central Caucasus ($1.15\% \text{ yr}^{-1}$) at the expense of relatively larger glaciers. Glacier area change by individual sections are shown in Fig. 6a-c, and in the Supplement Table 6.

Glacier area reduction varies between the individual sections of the Caucasus, with the highest increase in the number of glaciers in the smallest category ($<0.05 \text{ km}^2$) in the western section, resulting from the disintegration of larger glaciers. Glaciers of $0.1-10.0 \text{ km}^2$ showed the smallest decrease in the central Greater Caucasus, with the largest in the eastern Caucasus. The largest glaciers with $>10 \text{ km}^2$ area all in the central Caucasus showed the greatest overall loss ($0.82\% \text{ yr}^{-1}$) (Fig. 6d). The Greater Caucasus cumulative glacier area and number values for seven size classes glacier in 1960-1986-2014 by individual sections and slopes are given in the Supplement (Figs. 3-12).

Most of the glacier area in the Greater Caucasus occurs between 3000 m and 4000 m a.s.l. (857.6 km^2), and glaciers in the northern and southern slopes are distributed mainly in the same altitudinal range. The valley glacier terminus positions are between 1900 and 3200 m., whereas cirque and hanging glaciers are at higher elevations, between 2800 and 4500 m. The distribution of glacier area with elevation is depicted in figure 7a-b.

Glaciers with north, northeast and northwest aspects are the most extensive in the Greater Caucasus, covering $286.0 \pm 12.2 \text{ km}^2$ (370 glaciers), $277.7 \pm 12.0 \text{ km}^2$ (443 glaciers) and $231.6 \pm 11.8 \text{ km}^2$ (483 glaciers) respectively, and combining for 66.7% of all glaciers (Fig. 8a, b). The south, southeast and southwest aspects cover $89.4 \pm 3.8 \text{ km}^2$ (145 glaciers), $132.7 \pm 4.8 \text{ km}^2$ (169 glaciers) and $85.0 \pm 3.4 \text{ km}^2$ (121 glaciers) respectively, and combine for 25.7% of all glaciers. The southern macroslope of the greater Caucasus is relatively shorter than the northern, providing more favourable conditions for the existence of large size glaciers in the north.

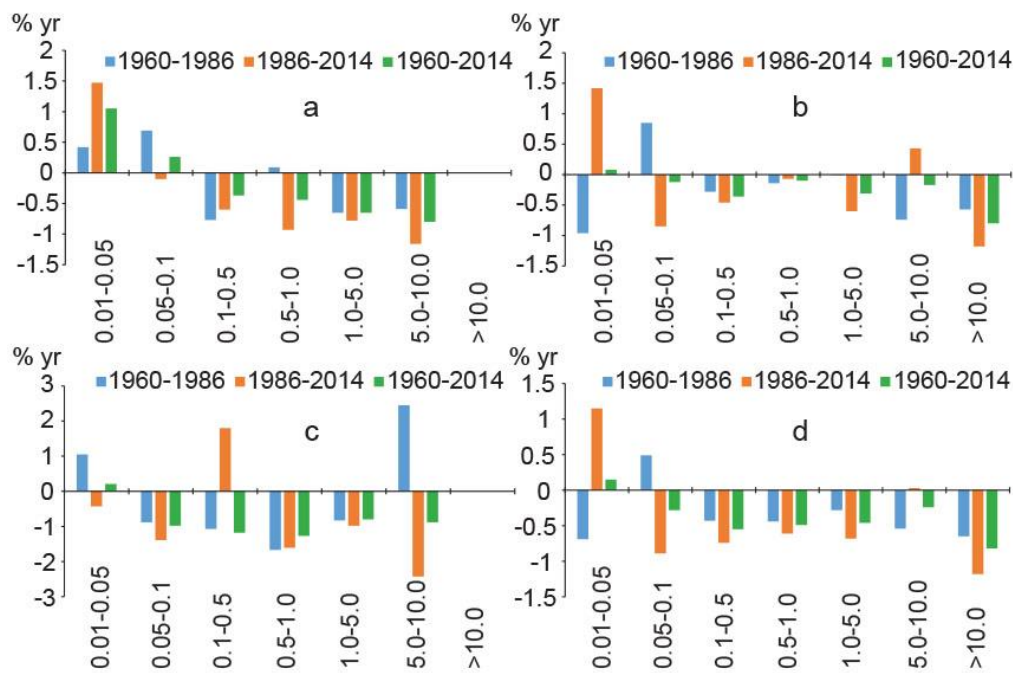


Figure 6. a – Area change for the seven size classes glacier in the western, b – central, c – eastern sections and d – entire Greater Caucasus in 1960-1986-2014.

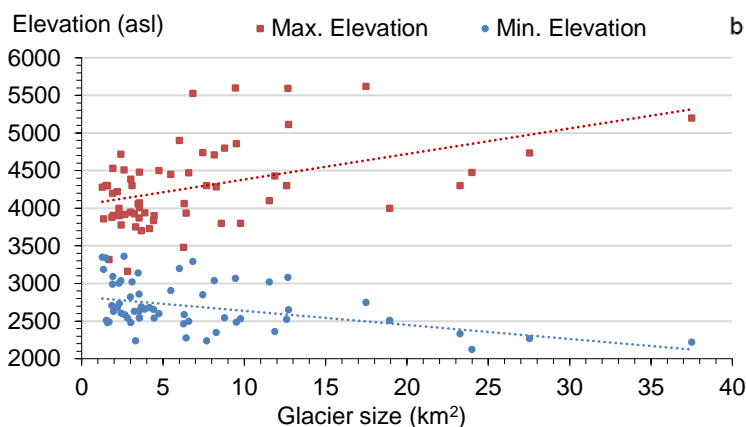
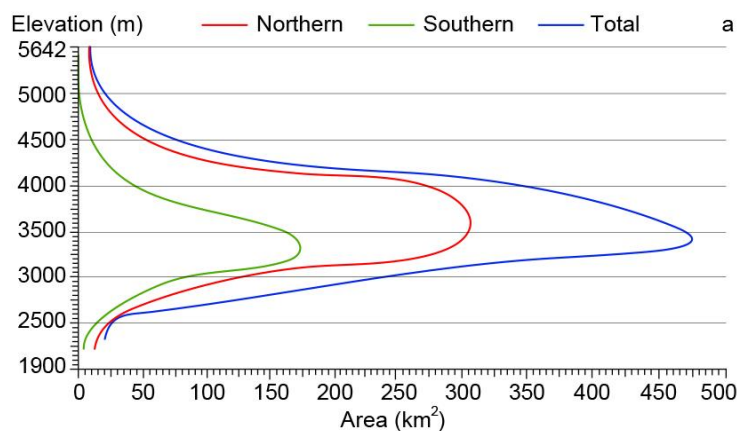


Figure 7. a - Distribution of glacier area with elevation for northern, southern and both slopes in the Greater Caucasus. **b -** Scatter plot showing glacier size vs minimum and maximum elevation

5

Glaciers with south aspects located on the northern slope are the most elevated in the Greater Caucasus. For the southern slope, southwest aspects are more elevated and for the entire mountain range - southeast aspects (Fig. 8c).

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The slopes with 10-15° gradient are most common for both northern and southern Greater Caucasus glaciers (Fig. 9).

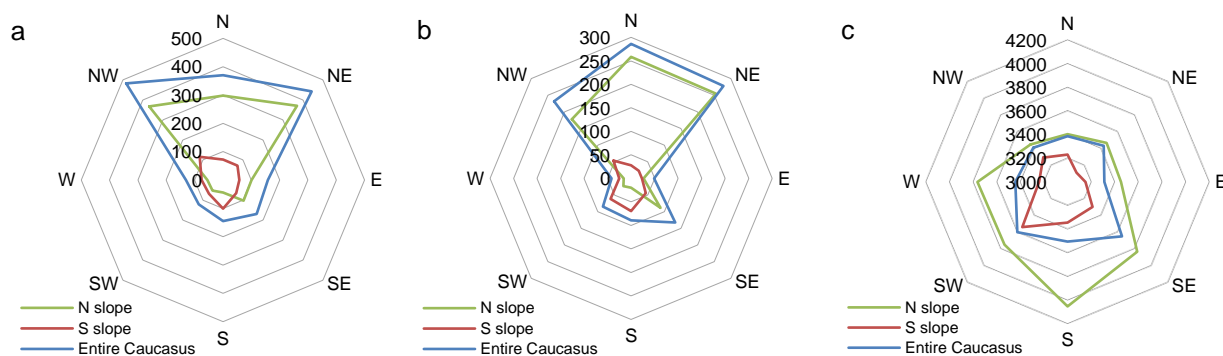


Figure 8. Proportion of glacier aspect by: a – number, b – area (km²) and c – aspect vs mean elevation (asl).

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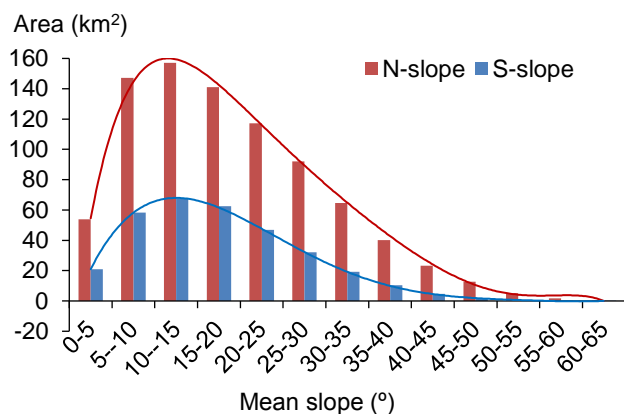


Figure 9. Greater Caucasus, mean slope vs glacier area for northern and southern macroslopes.

4.3 Glacier length change

- 5 We chose 30 glaciers in four size classes ($<1 \text{ km}^2$; $1-5 \text{ km}^2$; $5-10 \text{ km}^2$; $>10 \text{ km}^2$) in the western, central and eastern Caucasus macroslopes for sampling **retreat rates**. Across the region, **retreat rates** mostly increased from the 1960-1986 period to 1986-2014. The highest retreat rates of 48.8 m yr^{-1} were observed on the Karaugom Glacier northern macroslope in 1986-2014, while the Shkhelda Glacier experienced double the retreat rate between 1960-1986 (36.5 m yr^{-1}) than in 1986-2014 (17.1 m yr^{-1}).
- 10 The greatest total retreat was exhibited by the Lekhziri, the largest glacier on the southern macroslope, retreating 1595 m at an average rate of 29.5 m yr^{-1} in 1960-2014.

Of the 30 glaciers measured, 29 retreated between 1986 and 2014. Thirteen glaciers showed less change between 1986-2014 than 1960-1986, and one glacier (Midjirgi) advanced. These results correlate well with detailed field measurement of the snout position of Chalaati Glacier (Gobejishvili, 1995; Gobejishvili et al., 2012) and are in agreement with sporadic field measurement and anecdotal evidence from other glaciers (e.g. field investigation confirms that Midjirgi Glacier advanced between 1985 and 2000). The overall advance of Mizhirgi Glacier between 1985 and 2000 was around $110 \pm 25 \text{ m}$ (Stokes et al., 2006). Microstadial moraines in front of Chalaati Glacier confirm $\sim 20 \text{ m}$ glacier advance during 1990-1993 (Gobejishvili, 1995; Gobejishvili et al., 2012), but there is no clear geographical template which characterizes the advancing glaciers.

Overall, the largest glaciers ($>10 \text{ km}^2$) on average retreated $\sim 21.2 \text{ m yr}^{-1}$ between 1960-2014; glaciers with area $5-10 \text{ km}^2$ retreated $\sim 15.6 \text{ m yr}^{-1}$; glaciers between $1-5 \text{ km}^2$ retreated $\sim 12.0 \text{ m yr}^{-1}$ and glaciers between $<1 \text{ km}^2$ - retreated $\sim 7.8 \text{ m yr}^{-1}$.

According to this current inventory, the Bezingi Glacier represents the largest single glacier ($37.47 \pm 0.94 \text{ km}^2$) in the Greater Caucasus. Characteristics of glaciers used for measuring length change are given in the Supplement (Table 7; Fig. 13, 14).

5 Discussion

5.1 Glacier inventory parameters

- 30 Considering some errors in the 1911 catalog (Tielidze, 2016), we calculate that glacier area decreased from 1677.4 km^2 in 1911 to 1674.9 km^2 in 1960 or 14.9% ($0.30\% \text{ yr}^{-1}$). Overall this was 39.4% ($0.34\% \text{ yr}^{-1}$) between 1911-2014. Thus, we consider that glacier area reduction increased between 1986-2014 in comparison with the 1960-1986 period and between 1960-2014 in comparison with the 1911-1960 period. Therefore, our results contrast with those of Lur'e and Panov (2014) - where the northern Caucasus glacier decrease was faster between 1895-1970 ($0.52\% \text{ yr}^{-1}$) than in 1971-2011 ($0.32\% \text{ yr}^{-1}$) and Khromova et al. (2009) - where the Caucasus glacier decrease was faster between 1911-1957

(0.52% yr⁻¹) than from 1957-2000 (0.41% yr⁻¹). Glacier distribution and change during the investigation period are characterized by obvious regional differences (Fig. 4). These may be related to the different topography, aspect and climatic settings of glaciers of different size, as well as climate change.

Our results also showed that eastern Greater Caucasus glaciers are shrinking faster than those in the western and central areas; the smaller size of glaciers there may be the reason for this phenomenon. The Elbrus glacier area rate of loss is lower than in the Greater Caucasus main watershed range due to the higher elevation and larger accumulation areas.

5.2 Glacier changes

One of the important steps in utilizing our glacier inventory data is to understand spatial patterns in glacier characteristics across the region. Our study area displays region-wide consistency in glacier characteristics, notably glacier area, elevation and topography across the five subregions based on the ~2000 glacier data (Table 3).

Comparisons between glacier size and surface area fluctuations suggest that smaller glaciers, though losing the least surface area, actually lost a greater proportion of their total area. Approximately 28.37% (0.52% yr⁻¹) of the glacier area that disappeared was from glaciers 0.1-1.0 km² in size between 1960-2014. Compared with similar size glaciers in the surrounding regions, e.g. the Swiss Alps, rate of glacial shrinkage was twice as high (1.13% yr⁻¹ between 1973-2010) (Fischer et al., 2014). Similar trends, with small glaciers showing a propensity to shrink rapidly, have been found in numerous regions globally (Tennant et al., 2012; Stokes et al., 2013; Racoviteanu et al., 2015). This is considered a result of the greater volume-to-area and perimeter-to-area ratios of smaller glaciers – meaning they respond rapidly to a given ablation rate (Granshaw and Fountain, 2006; Tennant et al., 2012). Small glaciers are particularly sensitive to climate change. Their number will increase in the future (especially in the central Greater Caucasus) as the larger glaciers shrink and disaggregate.

Unlike the small glaciers, the largest glaciers (>10 km²) are disappearing more rapidly in the Caucasus (0.82% yr⁻¹) than the Alps (0.60% yr⁻¹) (Fischer et al., 2014).

Glacier slope may also play a significant role in determining glacier area change (Table 3), i.e., the steeper the glacier, the larger the area loss observed in our study. The same tendency was observed in the Himalaya (Salerno et al., 2008; Racoviteanu et al., 2015).

We note that direct comparison of such numbers can be critical for various reasons, such as diverse sample size or size class distribution of the investigated glaciers, different subregional to local climate conditions, various length and onset of observation periods, etc..

5.3 Comparison to GLIMS and the RGI

The GLIMS glacier database (9.02.2017 version) contained a number of deficiencies which have been remedied after this inventory, for example these river basins did not contain any glacier outlines: Belaya, Malaya Laba, Mzimba in the western Caucasus; Khobistskali in the central Caucasus; Aragvi, Assa, Arghuni, Sharo Argun, Andiyskoye Koysu, Avarskoye Koysu, Samur, Agrichai and Kusarchai in the eastern Caucasus. These constitute more than one half of the territory for the whole Greater Caucasus where modern glaciers are present (Fig. 10a). The GLIMS outlines also involve inconsistent registration, which appears to be associated with the use of ASTER imagery (Fig. 10b) (Khromova, 2009).

The RGI 5.0 version database similarly contains errors, especially in the central Caucasus section. For example in the Samegrelo, Lechkhumi and Shoda-Kedela sub-ranges, where the RGI database contains 39 nominal glaciers (circles representing areas), with a total area of 40.2 km², we found an additional 40 glaciers with a total area of 3.5 km². In addition, almost the whole eastern Caucasus section

(except the Tergi headwaters) and some parts of the western Caucasus section (Belaya, Malaya Laba and Mzimba river basins) are represented by nominal glaciers (Fig. 10c).

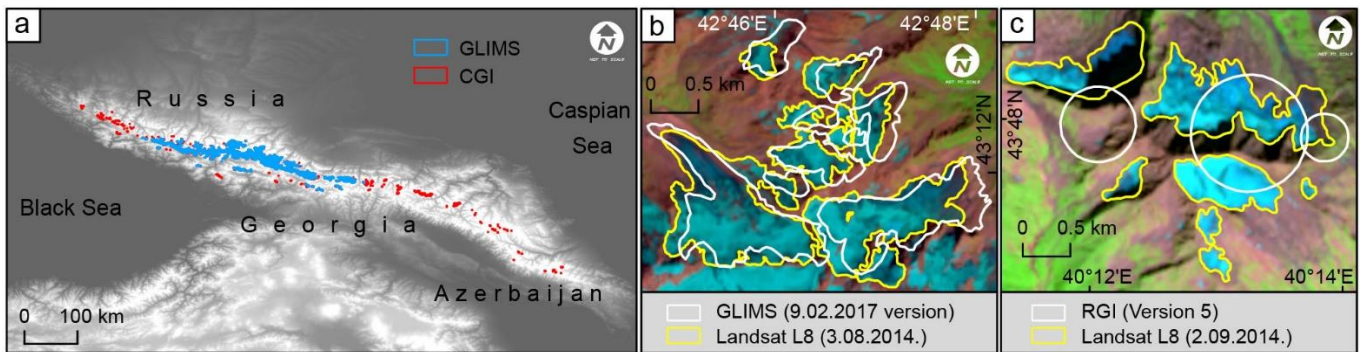


Figure 10. a – Comparison of the GLIMS with the new Caucasus Glacier Inventory (CGI). b – The GLIMS outlines inconsistent registration example. c – Glacier outlines from 2014, showing the RGI nominal glaciers (circles).

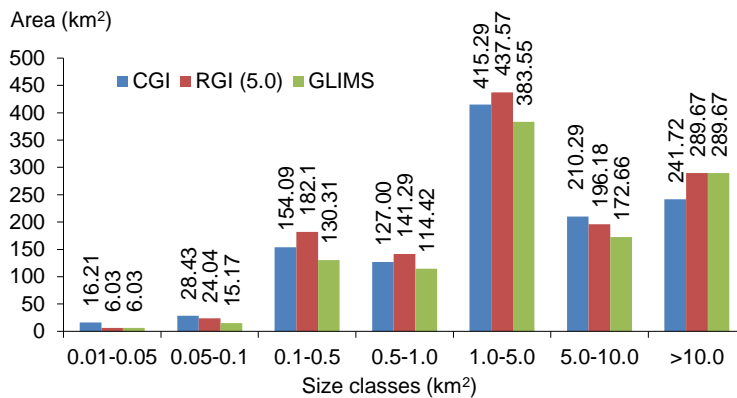


Figure 11. Glacier area comparison for seven classes glacier in the Greater Caucasus according to the RGI (5), GLIMS and new Caucasus Glacier Inventory (CGI).

Overall, glacier area difference was 165.1 km² between the RGI (1276.9 km²) and GLIMS (1111.8 km²), 83.7 km² between the RGI and new Caucasus Glacier Inventory (CGI) (1193.2±54.0 km²) and 81.4 km² between the GLIMS and CGI (Fig. 11).

6 Conclusions

We present a glacier change analysis including multi-temporal data sets covering the entire Greater Caucasus for the first time. Manual digitisation from 1960s large scale (1:50 000) topographic maps and satellite imagery from 1964 (Corona), 1986 (Landsat 5) and 2014 (Landsat 8, ASTER) were used to map glacier surface area. We expect that this inventory substantially improves existing knowledge for this region.

The main errors occur from data quality. Errors in the 1960s maps included mapped snow patches (especially for small cirque type glaciers) and uncertain glacier extents, which could be verified using available Corona 1964 satellite imagery (Fig. 2d-e). Other sources of error for aerial imagery include seasonal snow, shadows, and debris cover, which can impede glacier mapping. Using GPS field data, debris cover error can be resolved for some glaciers; while incorrect identification of seasonal snow generally affects small glaciers more than larger complexes, these do not make up a large percentage of the total area.

The main study findings can be summarised as follows:

a) The Greater Caucasus region experienced glacier area loss at an average annual rate 0.44% yr⁻¹ between 1960-1986 and 0.69% yr⁻¹ between 1986-2014. Overall, the glacier loss was 0.53% yr⁻¹ between 1960-2014.

b) Glacier number and area changes indicate that glaciers in the eastern Greater Caucasus have decreased (0.98% yr⁻¹) more than in the central (0.46% yr⁻¹) and western (0.52% yr⁻¹) sections, and southern glaciers have retreated (0.61% yr⁻¹) more than northern (0.50 % yr⁻¹) glaciers between 1960-2014. Although this rate is exceeded in other world mountain ranges (Huss and Hock, 2015), if the decrease in the surface area of glaciers in the eastern Greater Caucasus continues over the 21st century, many will disappear by 2100.

c) Glaciers of the Elbrus and Kazbegi-Dzhimara massifs lost a lower proportion of their area between 1960-2014, compared to glaciers located in the main watershed range, by 0.27% yr⁻¹ and 0.39% yr⁻¹ respectively.

The inventory presented here will further enable focus on assessing changes in glaciers, debris cover, mass balance, total volume and hydrological modeling.

7 Data availability

The data described in this article are available for public download at <http://www.glims.org/download/>

Supplement

This Greater Caucasus Glacier Inventory includes: the number and area change in 1960-1986-2014 by individual river basins and countries (Tables 1-2). Elbrus and Kazbegi-Dzhimara massif glacier number and area change in 1960-1986-2014 (Table 3-4; Fig. 1-2); cumulative glacier area and number values for seven size classes in 1960-1986-2014 for the northern, southern, western, central and eastern Greater Caucasus (Table 5; Fig. 3-12); Area change for the seven size classes glacier in the western, central, eastern sections and entire Greater Caucasus in 1960-1986-2014 (Table 6); characteristics of glaciers used for measuring length change (Table 7).

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Supplement

The Greater Caucasus Glacier Inventory (Russia/Georgia/Azerbaijan)

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Table 1. The Greater Caucasus glacier number and area in 1960-1986-2014 by individual river basins.

Main river basin	Tributary river basin	USSR Catalog 1967-1978		Topographic maps 1960		Landsat 5, 1985/86/87		Landsat 8, 2013/14/15/16 and ASTER 2014		Area change		
		Number	Area km ²	Number	Area km ²	Number	Area km ²	Number	Area km ²	1960- 1986	1986- 2014	1960- 2014
										% yr ⁻¹	% yr ⁻¹	% yr ⁻¹
Mzimta		7	1.7	13	2.4±0.2	13	2.3±0.2	13	1.9±0.2	-0.16	-0.62	-0.38
Kuban	Belaya	29	7.6	39	7.6±0.4	45	8.3±0.6	50	6.6±0.4	+0.35	-0.73	-0.24
	Malaya Laba	27	9.4	39	11.2±0.6	45	8.4±0.6	39	7.5±0.6	-0.96	-0.38	-0.61
	Bolshaya Laba	21	5.8	30	7.1±0.4	30	6.7±0.4	29	4.5±0.2	-0.21	-1.17	-0.67
	Bolshoy Zelenchuk	56	30.7	58	32.4±1.6	65	33.8±1.8	74	25.6±1.6	+0.16	-0.86	-0.38
	Maliy Zelenchuk	28	26.3	37	30.3±1.2	41	29.8±1.0	46	24.6±1.2	-0.06	-0.67	-0.34
	Teberda	85	61.0	99	63.6±2.8	103	62.1±2.6	100	53.7±2.6	-0.09	-0.48	-0.28

	Daut	16	5.5	19	7.2±0.4	22	6.1±0.4	24	4.8±0.4	-0.58	-0.76	-0.61
	Uchkulan	58	20.8	64	27.3±1.4	65	22.7±1.4	71	19.2±1.4	-0.64	-0.55	-0.54
	Ullukam	88	52.9	107	65.2±3.2	105	51.0±2.6	95	42.5±2.2	-0.83	-0.59	-0.64
Malka		10	56.5	10	64.0±1.0	11	57.5±0.8	12	52.2±0.8	-0.39	-0.32	-0.34
Baksan		156	132.7	170	187.0±7.0	162	169.8±6.4	156	146.3±6.0	-0.35	-0.49	-0.40
Chegem	Bashil-Auzusu	28	26.9	39	34.6±1.4	31	30.1±1.2	30	25.3±1.0	-0.50	-0.56	-0.49
	Gara-Auzusu	28	28.0	21	30.1±1.0	19	29.3±1.2	17	24.7±1.0	-0.10	-0.56	-0.33
	Bulungu	9	3.2	8	6.6±0.2	10	4.0±0.2	9	2.9±0.2	-1.51	-0.98	-1.03
Cherek	Cherek-Bezingskiy	85	76.3	48	82.4±2.8	40	81.1±2.6	48	73.8±2.6	-0.06	-0.32	-0.19
	Cherek-Balkarskiy	80	107.0	78	115.0±3.8	79	113.0±3.8	86	96.8±3.6	-0.06	-0.51	-0.29
	Psigansy	17	15.0	13	15.2±0.6	12	15.6±0.6	13	12.8±0.6	+0.10	-0.64	-0.29
Urukh	Khanzidon	13	4.7	14	8.5±0.4	15	8.4±0.4	12	6.3±0.4	-0.04	-0.89	-0.47
	Biliagikom	5	2.0	6	2.5±0.1	4	2.1±0.2	5	1.0±0.1	-0.61	-1.87	-1.11
	Urukh headwaters	34	23.0	35	31.1±1.2	33	30.3±1.4	35	25.3±1.2	-0.09	-0.58	-0.34
	Karaugom	27	39.6	21	48.4±1.4	23	45.7±1.4	31	41.7±1.4	-0.21	-0.31	-0.25
	Aigamuga	26	13.4	14	24.0±1.0	17	17.4±0.6	20	14.7±0.8	-1.05	-0.55	-0.71
Ardon	Tseyadon	29	15.0	22	21.4±0.8	18	19.2±0.6	20	16.8±0.6	-0.39	-0.44	-0.39
	Sidan	1	0.05	1	0.08±0.01	1	0.07±0.01	1	0.03±0.04	-0.48	-2.04	-1.15
	Vilsa	3	0.6	6	1.1±0.1	5	1.0±0.2	5	0.9±0.08	-0.34	-0.35	-0.33
	Adaikom	5	4.7	9	7.0±0.4	8	5.4±0.2	7	4.6±0.2	-0.87	-0.52	-0.63
	Mamikhdon	14	4.2	18	6.1±0.4	15	4.9±0.4	15	3.7±0.2	-0.75	-0.87	-0.72
	Nar	11	2.9	28	6.5±0.4	15	3.2±0.2	11	1.6±0.08	-1.95	-1.78	-1.39
	Gilvan	1	0.2	3	0.3±0.04	1	0.05±0.08	0	0	-3.20	0	0
	Kasaidon	2	0.19	2	0.5±0.06	2	0.3±0.04	2	0.2±0.02	-1.53	-1.19	-1.11
	Labagkomdon	1	0.04	1	0.1±0.016	1	0.1±0.016	1	0.06±0.008	0.00	-1.42	-0.07
	Baddon	7	3.5	6	4.3±0.2	8	3.5±0.6	8	2.6±0.2	-0.71	-0.91	-0.73
	Arkhandon	5	4.1	5	4.2±0.2	4	4.0±0.6	4	3.5±0.2	-0.18	-0.44	-0.30
Fiagdon		31	12.3	33	12.6±0.8	29	8.8±0.6	28	6.2±0.6	-1.15	-1.05	-0.94
Gizeldon		27	34.6	32	33.8±1.2	30	31.0±1.2	25	25.2±1.0	-0.31	-0.66	-0.47
Tergi headwaters		133	74.8	133	71.5±3.2	116	55.6±2.8	94	43.4±3.4	-0.85	-0.78	-0.72
Sunja right tributaries	Assa	10	3.8	19	5.9±0.4	17	4.0±0.4	10	2.1±0.2	-1.23	-1.69	-1.19
	Arghuni	24	6.0	32	9.6±0.6	25	7.3±0.4	20	5.2±0.4	-0.92	-1.02	-0.84

	Sharo Argun	34	17.6	37	24.6±2.4	36	21.1±1.0	32	15.7±0.8	-0.54	-0.91	-0.66
Sulak	Andiyskoye Koysu	47	21.2	66	26.2±1.6	56	18.6±1.2	36	11.8±0.6	-1.11	-1.30	-1.01
	Avarskoye Koysu	88	23.5	105	28.0±1.8	86	18.4±1.4	34	5.9±0.4	-1.31	-2.42	-1.46
Samur		20	9.0	70	15.5±1.0	56	11.3±1.0	21	2.8±0.2	-1.04	-2.68	-1.51
Agrichai	Shinchai	0	0	2	0.1±0.016	1	0.04±0.006	1	0.03±0.004	-2.30	-0.89	-1.29
Kusarchai		8	3.2	24	6.0±0.4	17	4.6±0.2	15	0.8±0.1	-0.89	-2.95	-2.13
Bzipi		16	7.8	26	9.5±0.5	23	6.7±0.6	19	3.2±0.4	-1.13	-1.86	-1.22
Kelasuri		3	1.5	3	1.4±0.1	2	1.2±0.06	2	0.9±0.06	-0.54	-0.89	-0.66
Kodori		141	60.0	179	65.1±3.6	179	61.0±3.8	161	42.2±2.8	-0.24	-1.10	-0.65
Enguri		250	288.3	317	324.7±12.4	306	285.8±11.2	289	225.3±9.2	-0.46	-0.75	-0.56
Khobistkali		7	1.6	20	1.2±0.2	13	0.9±0.08	11	0.6±0.08	-0.96	-1.19	-0.92
Rioni		124	62.9	141	78.3±3.8	134	65.5±4.2	120	50.9±2.6	-0.62	-0.79	-0.64
Liakhvi		22	6.6	19	4.5±0.2	14	2.6±0.2	12	2.0±0.2	-1.62	-0.82	-1.02
Aragvi		5	1.6	8	1.1±0.1	1	0.5±0.08	1	0.3±0.04	-2.09	-1.42	-1.34
Total, Greater Caucasus		2002	1421.78	2349	1674.9±70.4	2209	1482.1±64.4	2020	1193.2±54.0	-0.44	-0.69	-0.53

Table 2. The Greater Caucasus glacier number and area change in 1960-1986-2014 by countries.

Countries	Topographic maps 1960		Landsat 5, 1985/86/87		Landsat 8, 2013/14/15/16 and ASTER 2014		Decrease 1960-1986 % yr ⁻¹	Decrease 1986-2014 % yr ⁻¹	Decrease 1960-2014 % yr ⁻¹
	Number	Area km ²	Number	Area km ²	Number	Area km ²			
Russia	1417	1099.1±44.2	1367	992.4±41.4	1275	822.2±35.8	0.37	0.61	0.46
Georgia	899	568.5±25.0	817	484.0±22.4	725	369.8±17.4	0.57	0.84	0.64
Azerbaijan	33	7.3±0.6	25	5.7±0.6	20	1.2±0.2	0.84	2.81	1.54

Table 3. Elbrus glacier number and area change in 1960-1986-2014. All glaciers are shown in Fig. 1.

Elbrus glaciers			Topographic maps 1960	Landsat 5, 06/08/1986	Landsat 8, 03/08/2014/	Area change		
#	Name	WGI ID	Area km ²	Area km ²	Area km ²	1960-1986 % yr ⁻¹	1986-2014 % yr ⁻¹	1960-2014 % yr ⁻¹
1	Ulluchiran	SU4G08005001	12.87±0.26	13.12±0.16	12.68±0.18	+0.07	-0.11	-0.02
2	Karachaul	SU4G08005002	6.20±0.16	6.22±0.12	5.96±0.14	+0.01	-0.14	-0.07
3	Ullukol	SU4G08005003	6.42±0.16	5.81±0.12	5.45±0.12	-0.36	-0.22	-0.28
4	565a	SU4G08005004	0.97±0.04	0.54±0.04	0.13±0.02	-1.70	-2.71	-1.60
5	Mikelchiran	SU4G08005005	7.74±0.12	7.09±0.12	6.84±0.12	-0.32	-0.12	-0.21
6	Dzhikiugankez	SU4G08005006	28.41±0.24	24.0±0.3	20.68±0.32	-0.59	-0.53	-0.50
7	Irikchat	SU4G08005018	1.56±0.02	1.29±0.06	1.09±0.04	-0.66	-0.55	-0.55
8	Irik	SU4G08005020	12.56±0.28	11.46±0.22	10.95±0.22	-0.33	-0.15	-0.23
9	Terskol	SU4G08005026	9.83±0.32	9.78±0.16	9.45±0.14	-0.01	-0.12	-0.07
10	Garabashi	SU4G08005027	3.13±0.08	2.75±0.08	2.45±0.1	-0.46	-0.38	-0.40
11	Maliy Azau	SU4G08005028	10.08±0.16	10.03±0.14	9.41±0.18	-0.01	-0.22	-0.12
12	Bolshoy Azau	SU4G08005029	21.26±0.34	20.47±0.32	18.20±0.36	-0.14	-0.39	-0.26
13	311	SU4H08004311	0.57±0.04	0.51±0.04	0.37±0.02	-0.40	-0.98	-0.64
14	312	SU4H08004312	0.25±0.02	0.33±0.02	0.26±0.02	+1.23	-0.75	-0.07
15	Ullukam	SU4H08004313	0.56±0.04	0.72±0.04	0.67±0.04	+1.09	-0.24	-0.36
16	313	SU4H08004313	1.08±0.06	0.98±0.06	0.98±0.06	-0.35	0	-0.17
17	317	SU4H08004317	0.74±0.02	0.76±0.04	0.76±0.04	+0.10	0	+0.05
18	Unnamed*	Unknown	0.65±0.04	0.59±0.02	0.52±0.04	-0.35	-0.42	-0.37
19	Kyukyurtlyu	SU4H08004318	5.69±0.2	5.61±0.12	5.54±0.14	-0.05	-0.04	-0.04
20	319	SU4H08004319	1.54±0.06	0.98±0.06	0.94±0.04	-1.39	-0.14	-0.72
21	Bityukyube	SU4H08004320	2.40±0.1	1.74±0.08	1.65±0.06	-1.05	-0.18	-0.57
22	321	SU4H08004321	0.38±0.04	0.21±0.02	0.08±0.012	-1.72	-2.21	-1.46
Total			134.89±2.84	124.99±2.74	115.06±2.68	-0.28	-0.28	-0.27

* Omitted in WGI database

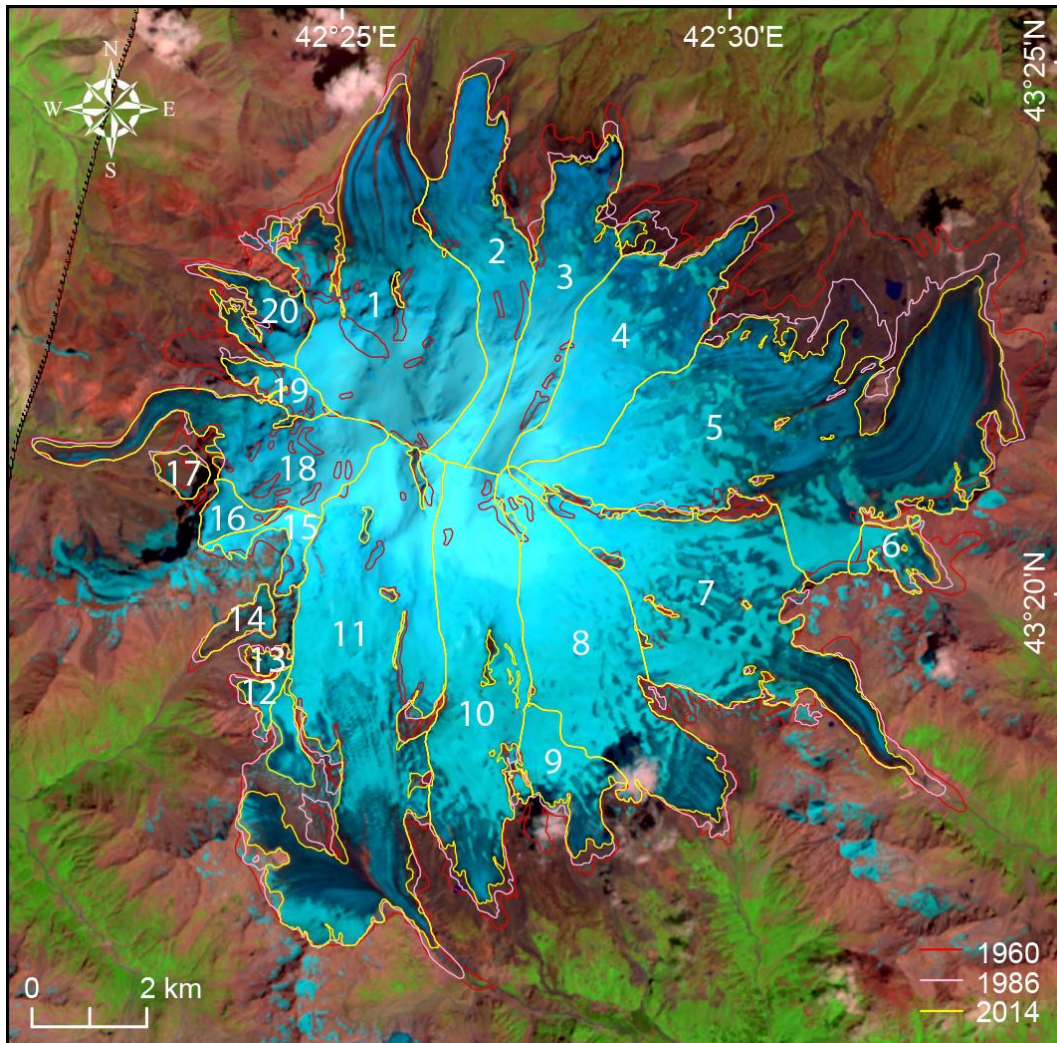


Figure 1. Changes in glacierized area of Elbrus between 1960-1986-2014.

See [Table 3](#) for the change statistics of individual glaciers. The 03/08/2014 Landsat 8 image is used as background.

Table 4. Kazbegi-Dzhimara massif glacier number and area change in 1960-1986-2014. All glaciers are shown in Fig. 2.

Kazbegi-Dzhimara massif glaciers			Topographic maps 1960	Landsat 5, 06/08/1986	Landsat 8, 28/08/14/	Area change		
#	Name	WGI ID	Area km ²	Area km ²	Area km ²	1960-1986 % yr ⁻¹	1986-2014 % yr ⁻¹	1960-2014 % yr ⁻¹
1	Mydagrabyn	SU4G08010031	9.98±0.22	9.73±0.24	8.16±0.24	-0.09	-0.57	-0.33
2	Unnamed*	Unknown	-	-	0.16±0.02	0	0	0
3	Kolka	SU4G08010039	5.06±0.7	4.28±0.48	2.51±0.44	-0.59	-1.47	-0.91
4	Unnamed	Unknown	-	-	0.75±0.04	0	0	0
5	Unnamed	SU4G08010040	0.79±0.06	0.73±0.04	0.50±0.04	-0.29	-1.12	-0.68
6	Maili	SU4G08010041	7.29±0.14	6.75±0.14	6.57±0.12	-0.28	-0.09	-0.18
7	Unnamed	Unknown	-	-	0.05±0.008	0	0	0
8	Unnamed	SU4G08010042	-	0.67±0.04	0.44±0.02	0	-1.22	0
9	Chachi	SU4G08011046	2.61±0.06	2.57±0.08	1.85±0.08	-0.05	-1.00	-0.53
10	Unnamed	Unknown	-	-	0.08±0.012	0	0	0
11	Unnamed	SU4G08011047	0.86±0.06	0.52±0.04	0.12±0.02	-1.52	-2.74	-1.59
12	Unnamed	Unknown	-	-	0.05±0.008	0	0	0
13	Devdoraki	SU4G08011048	7.19±0.2	6.96±0.2	4.40±0.12	-0.12	-1.31	-0.71
14	Unnamed	Unknown	-	-	1.78±0.08	0	0	0
15	Abano	SU4G08011049	1.96±0.08	1.49±0.08	1.33±0.1	-0.92	-0.38	-0.60
16	Unnamed	Unknown	-	-	0.03±0.004	0	0	0
17	Unnamed	Unknown	0.58±0.04	0.34±0.04	0.1±0.004	-1.59	-2.52	-1.53
18	Gergeti	SU4G08011052	6.82±0.18	6.26±0.2	5.77±0.18	-0.31	-0.27	-0.28
19	None	SU4G08011056	0.49±0.04	0.39±0.02	0.36±0.02	-0.78	-0.27	-0.49
20	Denkara	SU4G08011057	1.33±0.04	0.93±0.04	0.31±0.02	-1.15	-2.38	-1.42
21	Unnamed	Unknown	0.49±0.04	0.06±0.01	0.03±0.004	-3.37	-1.78	-1.73
22	Unnamed	SU4G08011058	0.89±0.06	0.63±0.04	0.53±0.04	-1.12	-0.56	-0.74
23	Unnamed	SU4G08011059	1.12±0.04	0.98±0.06	0.75±0.06	-0.48	-0.83	-0.61
24	Mna	SU4G08011060	3.25±0.1	2.89±0.12	2.59±0.12	-0.42	-0.37	-0.37
25	Unnamed	SU4G08011061	1.57±0.04	1.30±0.06	1.44±0.04	-0.66	+0.38	-0.15
26	Suatisi Eastern	SU4G08011062	10.84±0.2	9.87±0.24	8.89±0.18	-0.34	-0.35	-0.33

27	Unnamed	Unknown	-	-	0.08±0.012	0	0	0
28	Suatisi Central	SU4G08011063	2.62±0.1	2.32±0.08	2.07±0.08	-0.44	-0.38	-0.39
29	Unnamed	Unknown	-	0.29±0.04	0.23±0.02	0	-0.73	0
30	Suatisi Western	SU4G08011064	2.49±0.08	2.16±0.08	1.55±0.06	-0.51	-1.00	-0.70
31	Unnamed	Unknown	-	-	0.12±0.02	0	0	0
32	Unnamed	Unknown	-	-	0.18±0.02	0	0	0
Total			68.23±2.42	62.12±2.72	53.78±2.48	-0.34	-0.47	-0.39

* Omitted in WGI database

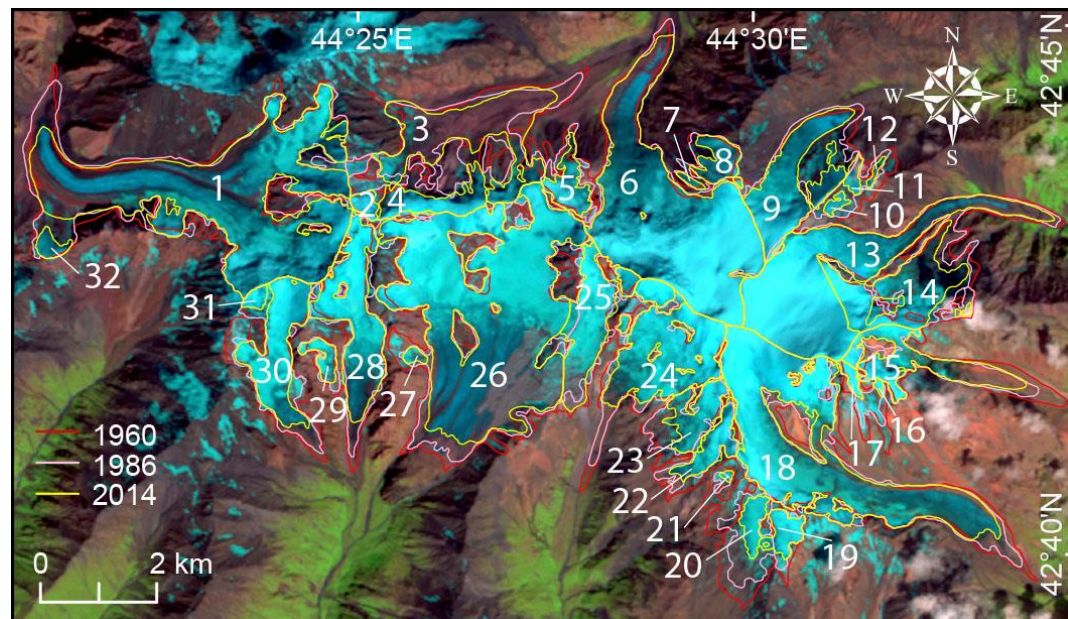


Figure 2. Changes in glacierized area of Kazbegi-Dzhimara massifs between 1960-1986-2014. See **Table 4** for the change statistics of individual glaciers. The 28/08/2014 Landsat 8 **image is** used as background.

Table 5. Cumulative glacier area and number change for seven size classes in the Greater Caucasus in 1960-1986-2014.

Size class (km ²)	Area			Number		
	1960	1986	2014	1960	1986	2014
0.01-0.05	14.95	12.26	16.21	431	364	516
0.05-0.1	33.70	38	28.43	427	502	388
0.1-0.5	219.18	194.42	154.09	918	839	695
0.5-1.0	173.27	153.38	127.00	241	209	175
1.0-5.0	555.28	514.46	415.29	275	246	204
5.0-10.0	242.12	208.08	210.29	35	29	29
>10.0	436.28	361.68	241.72	22	20	13

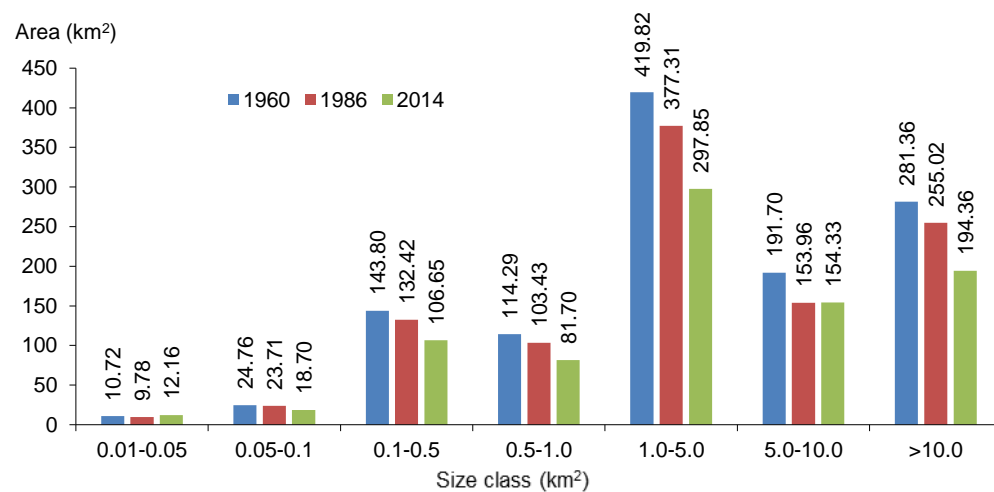


Figure 3. Cumulative glacier area values for seven size classes in 1960-1986-2014 for the northern Greater Caucasus.

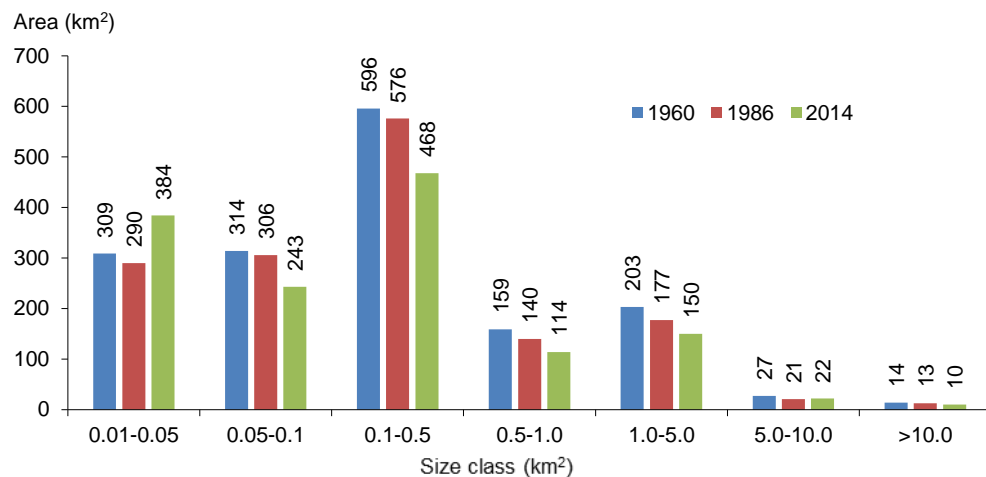


Figure 4. Cumulative glacier number values for seven size classes in 1960-1986-2014 for the northern Greater Caucasus.

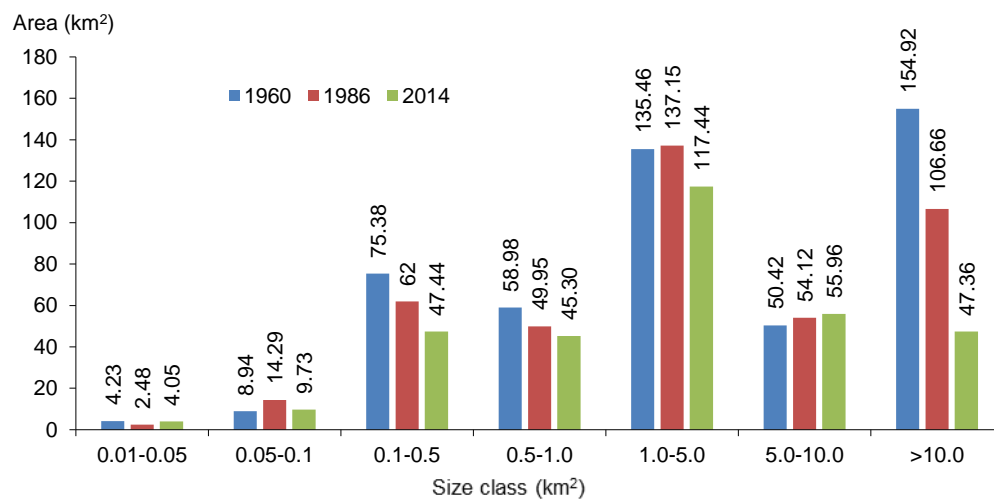


Figure 5. Cumulative glacier area values for seven size classes in 1960-1986-2014 for the southern Greater Caucasus.

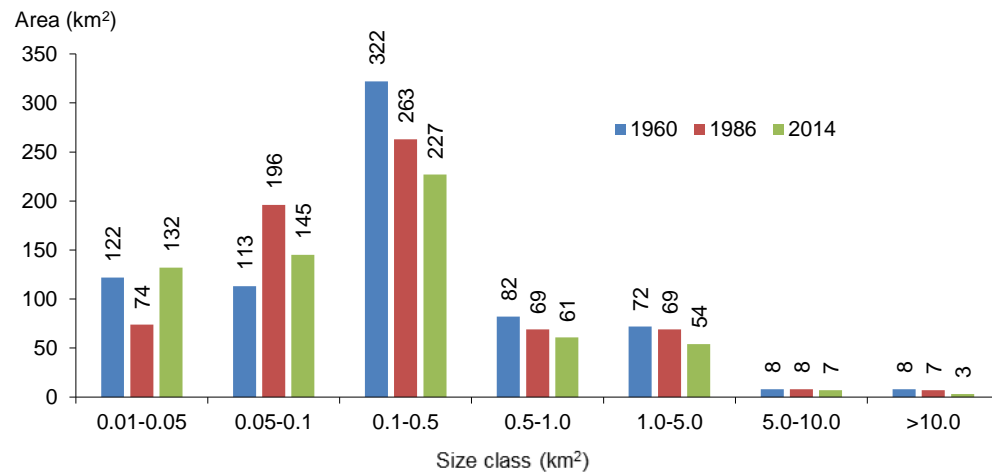


Figure 6. Cumulative glacier number values for seven size classes in 1960-1986-2014 for the southern Greater Caucasus.

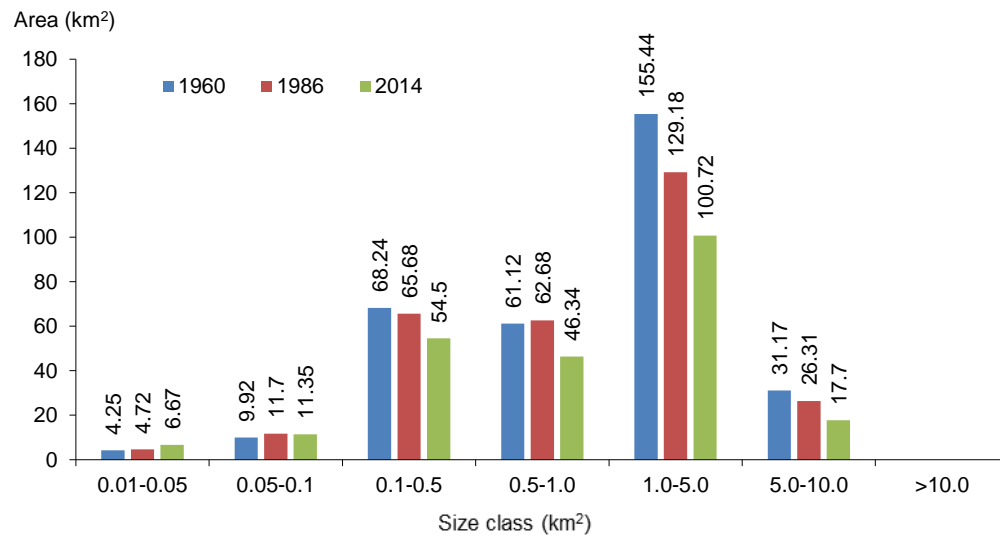


Figure 7. Cumulative glacier area values for seven size classes in 1960-1986-2014 for western Greater Caucasus.

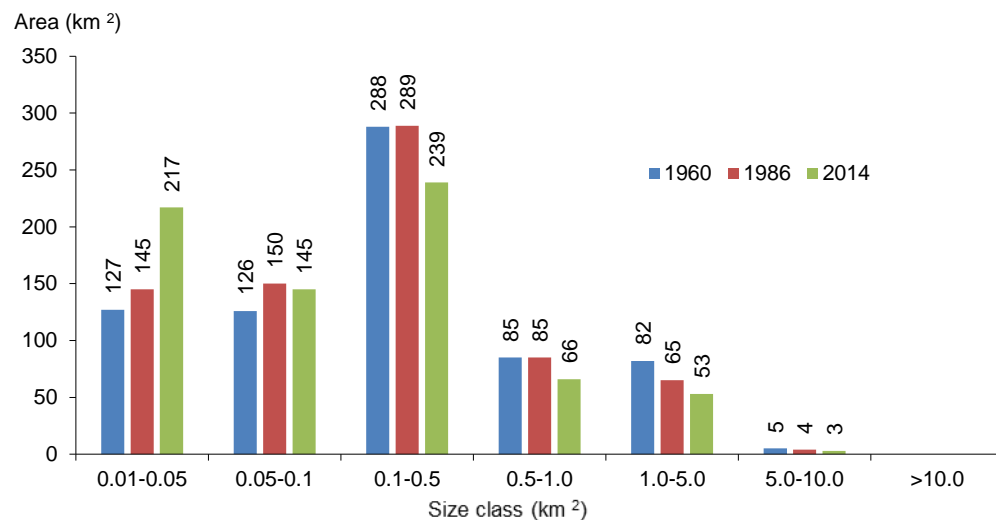


Figure 8. Cumulative glacier number values for seven size classes in 1960-1986-2014 for the western Greater Caucasus.

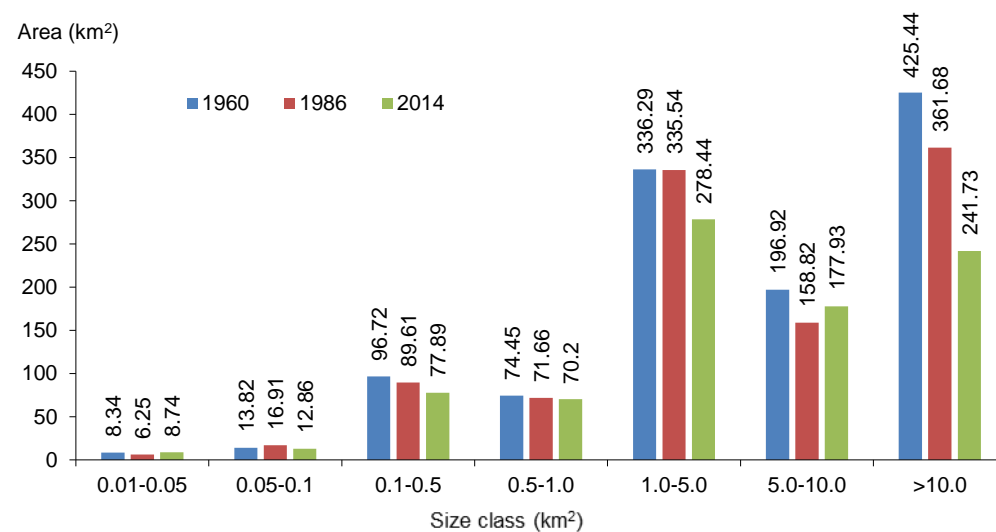


Figure 9. Cumulative glacier area values for seven size classes in 1960-1986-2014 for central Greater Caucasus.

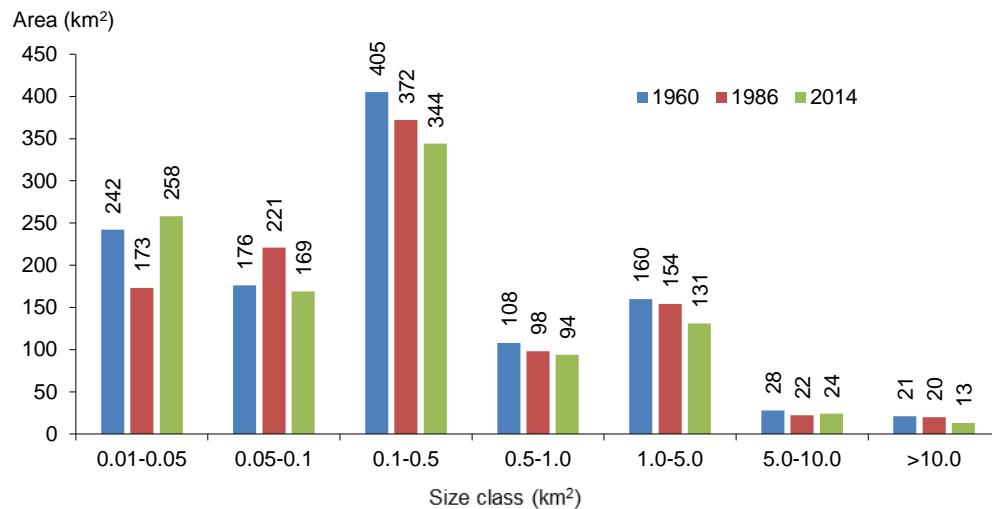


Figure 10. Cumulative glacier number values for seven size classes in 1960-1986-2014 for the central Greater Caucasus.

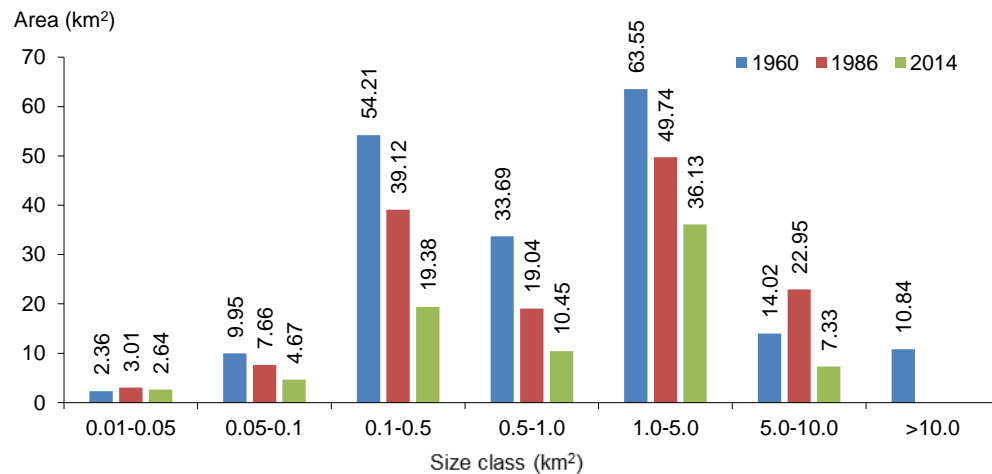


Figure 11. Cumulative glacier area values for seven size classes in 1960-1986-2014 for eastern Greater Caucasus.

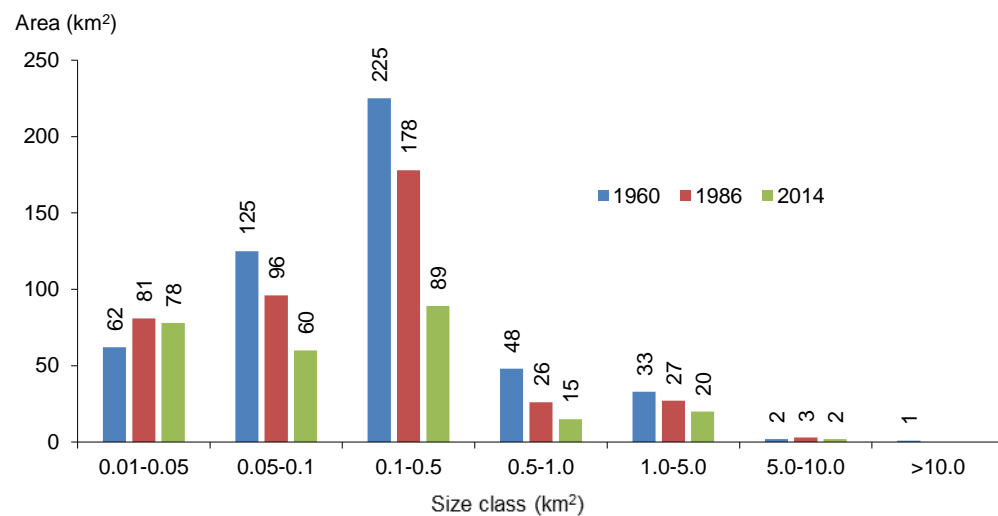


Figure 12. Cumulative glacier number values for seven size classes in 1960-1986-2014 for the eastern Greater Caucasus.

Table 6. y% Area change for the seven size classes glacier in the western, central, eastern sections and entire Greater Caucasus in 1960-1986-2014.

Western Caucasus				Central Caucasus			Eastern Caucasus			Entire Greater Caucasus		
Size class (km²)	1960-1986 y%	1986-2014 y%	1960-2014 y%	1960-1986 y%	1986-2014 y%	1960-2014 y%	1960-1986 y%	1986-2014 y%	1960-2014 y%	1960-1986 y%	1986-2014 y%	1960-2014 y%
0.01-0.05	0.42	1.47	1.05	-0.96	1.42	0.08	1.05	-0.43	0.21	-0.69	1.15	0.15
0.05-0.1	0.69	-0.1	0.26	0.85	-0.85	-0.12	-0.88	-1.39	-0.98	0.49	-0.89	-0.28
0.1-0.5	-0.77	-0.6	-0.37	-0.28	-0.46	-0.36	-1.07	1.8	-1.18	-0.43	-0.74	-0.55
0.5-1.0	0.09	-0.93	-0.44	-0.14	-0.07	-0.1	-1.67	-1.61	-1.27	-0.44	-0.61	-0.49
1.0-5.0	-0.65	-0.78	-0.65	-0.008	-0.6	-0.31	-0.83	-0.98	-0.8	-0.28	-0.68	-0.46
5.0-10.0	-0.59	-1.16	-0.8	-0.74	0.43	-0.17	2.45	-2.43	-0.88	-0.54	0.03	-0.24
>10.0	-	-	-	-0.57	-1.18	-0.8	-	-	-	-0.65	-1.18	-0.82

Table 7. Characteristics of glaciers used for measuring length change. The average error terms are ± 15 m.

Name/WGI ID	River basin	Area 1960	Area 1986	Area 2014	1960-1986 % yr ¹	1986-2014 % yr ¹	1960-2014 % yr ¹	Length change 1960-1986		Length change 1986-2014		Length change 1960-2014	
								m	m yr ¹	m	m yr ¹	m	m yr ¹
Glaciers with >10 km ² area													
Bezingi	Cherek-Bezingskiy	40.42±0.98	39.98±0.9	37.47±0.94	-0.04	-0.22	-0.13	-519	-19.7	-374	-13.4	-893	-16.5
Dych-sy-Ailama	Cherek-Balkarskiy	39.49±0.98	34.85±0.94	27.53±0.78	-0.45	-0.75	-0.56	-461	-17.7	-1094	-39.1	-1555	-28.8
Karaugom	Karaugom	29.94±0.6	29.17±0.62	23.99±0.44	-0.09	-0.63	-0.36	-164	-6.3	-1366	-48.8	-1530	-28.3
Lekhziri	Enguri	35.80±0.9	33.95±0.94	23.76±0.72	-0.19	-1.07	-0.62	-859	-33.0	-736	-26.3	-1595	-29.5
Agashtan	Cherek-Balkarskiy	21.35±0.36	20.39±0.32	18.93±0.44	-0.17	-0.25	-0.20	-368	-14.2	-587	-21.0	-955	-17.7
Midjirgi	Cherek-Bezingskiy	13.77±0.5	13.90±0.48	12.71±0.48	+0.03	-0.30	-0.14	-808	-31.1	+40	+1.4	-768	-14.2
Tsaneri southern*	Enguri	28.26±0.52	14.38±0.32	12.31±0.32	-0.21	-0.51	-1.04	-448	-17.2	-781	-27.9	-1229	-22.8
Tseya	Tseyadon	14.03±0.42	12.83±0.38	11.87±0.36	-0.32	-0.26	-0.28	-295	-11.3	-341	-12.2	-636	-11.8
Tsaneri northern	Enguri	-**	13.30±0.22	11.28±0.22	-0.58	-0.54	-	-	-	-574	-20.5	-	-
Glaciers with 5-10 km ² area													
Kvitlodi	Enguri	12.23±0.26	11.65±0.24	9.58±0.2	-0.18	-0.63	-0.40	-598	-23.0	-883	-31.5	-1481	-27.4
Adishi	Enguri	10.48±0.22	10.34±0.2	9.58±0.2	-0.05	-0.26	-0.15	-124	-4.8	-390	-13.9	-514	-9.5
Challaati	Enguri	12.71±0.36	12.36±0.38	9.24±0.28	-0.10	-0.90	-0.50	-460	-17.7	-223	-8.0	-683	-12.6
Khalde	Enguri	11.87±0.38	10.65±0.36	8.59±0.26	-0.39	-0.69	-0.51	-130	-5.0	-130	-4.6	-260	-4.8
Shkhelda	Baksan	13.61±0.48	12.50±0.50	8.28±0.65	-0.31	-1.20	-0.72	-950	-36.5	-480	-17.1	-1430	-26.5
Bashil	Chegem	8.16±0.19	7.91±0.19	7.34±0.19	-0.11	-0.25	-0.18	-230	-8.8	-530	-18.9	-760	-14.1
Dolra	Enguri	7.95±0.21	6.44±0.16	5.36±0.12	-0.73	-0.59	-0.60	-595	-22.9	-160	-5.7	-755	-14.0
Glaciers with 1-5 km ² area													
Boko	Rioni	5.07±0.12	4.71±0.12	4.62±0.11	-0.27	-0.07	-0.16	-287	-11.0	-436	-15.6	-723	-13.4
Mostotsete	Urukh Headwaters	4.27±0.14	3.58±0.012	3.23±0.13	-0.62	-0.34	-0.45	-105	-4.0	-135	4.8	-240	-4.4
Marukh northern	Malii Zelenchuk	3.25±0.08	3.30±0.08	2.82±0.07	+0.05	-0.51	-0.24	-255	-9.8	-240	-8.6	-495	-9.2
Chungurjar	Ullukam	3.13±0.09	2.11±0.07	1.88±0.07	-1.25	-0.39	-0.74	-490	-18.8	-405	-14.4	-895	-16.6
Tbilisa	Riorni	2.90±0.10	2.21±0.09	1.91±0.08	-0.91	-0.48	-0.63	-186	7.2	-354	-12.6	-540	-10.0
Sakeni	Kodori	2.47±0.07	2.39±0.08	1.99±0.05	-0.12	-0.59	-0.35	-560	-21.5	-275	-9.8	-835	-15.5
Abano	Tergi	1.96±0.09	1.49±0.09	1.33±0.09	-0.92	-0.38	-0.60	-550	-21.2	-240	-8.6	-790	-14.6
Glaciers with <1 km ² area													

SU5T09106388	Rioni	0.86±0.05	0.73±0.04	0.69±0.03	-0.58	-0.20	-0.36	-360	-13.8	-70	-2.5	-430	-8.0
***	Sharo Argun	0.90±0.05	0.77±0.04	0.55±0.03	-0.55	-1.02	-0.72	-65	-2.5	-270	-9.6	-335	-6.2
SU4G08011072	Tergi	0.62±0.03	0.55±0.03	0.42±0.02	-0.43	-0.84	-0.60	-60	-2.3	-310	-11.1	-370	-6.9
***	Andiiskoe Koisu	0.63±0.04	0.43±0.03	0.29±0.02	-1.22	-1.16	-0.99	-243	-9.3	-245	-8.8	-588	-10.9
SU4G08007139	Cherek-Balkarskiy	0.36±0.03	0.37±0.03	0.26±0.02	+0.10	-1.06	-0.51	-189	-7.3	-210	-7.5	-399	-7.4
SU4G08011083	Tergi	0.99±0.04	0.55±0.03	0.15±0.01	-1.70	-2.59	-1.57	-234	-9.0	-470	-16.8	-704	-13.0
SU5T09105282	Enguri	0.19±0.02	0.13±0.01	0.10±0.005	-1.21	-0.82	-0.87	-60	-2.3	-60	-2.1	-120	-2.2

*, ** Until the 1980s the Southern and Northern Tsaneri were merged as one compound-valley type glacier. Their division likely happened in 1980-1985.

*** Omitted in WGI database.

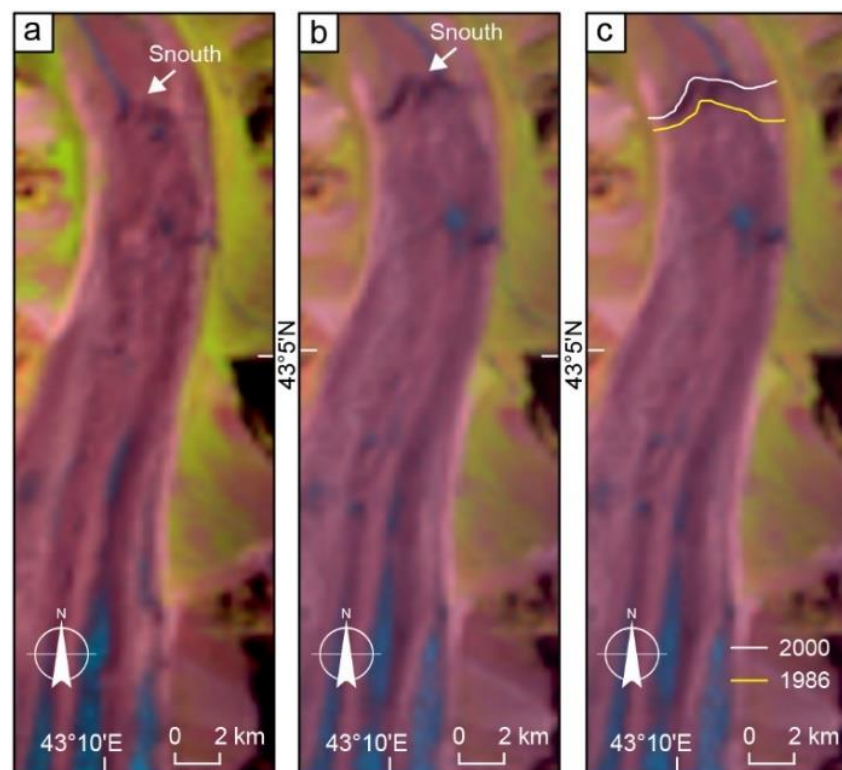


Figure 13. Midjirgi Glacier advance between 1986-2000. (a) Landsat 5 TM, 6/08/1986. (b) Landsat 5 TM, 12/08/2000.

In 1986, the meltwater flow comes from a different position at the terminus. (c) With the snout comparison, it is visible that the snout has advanced.

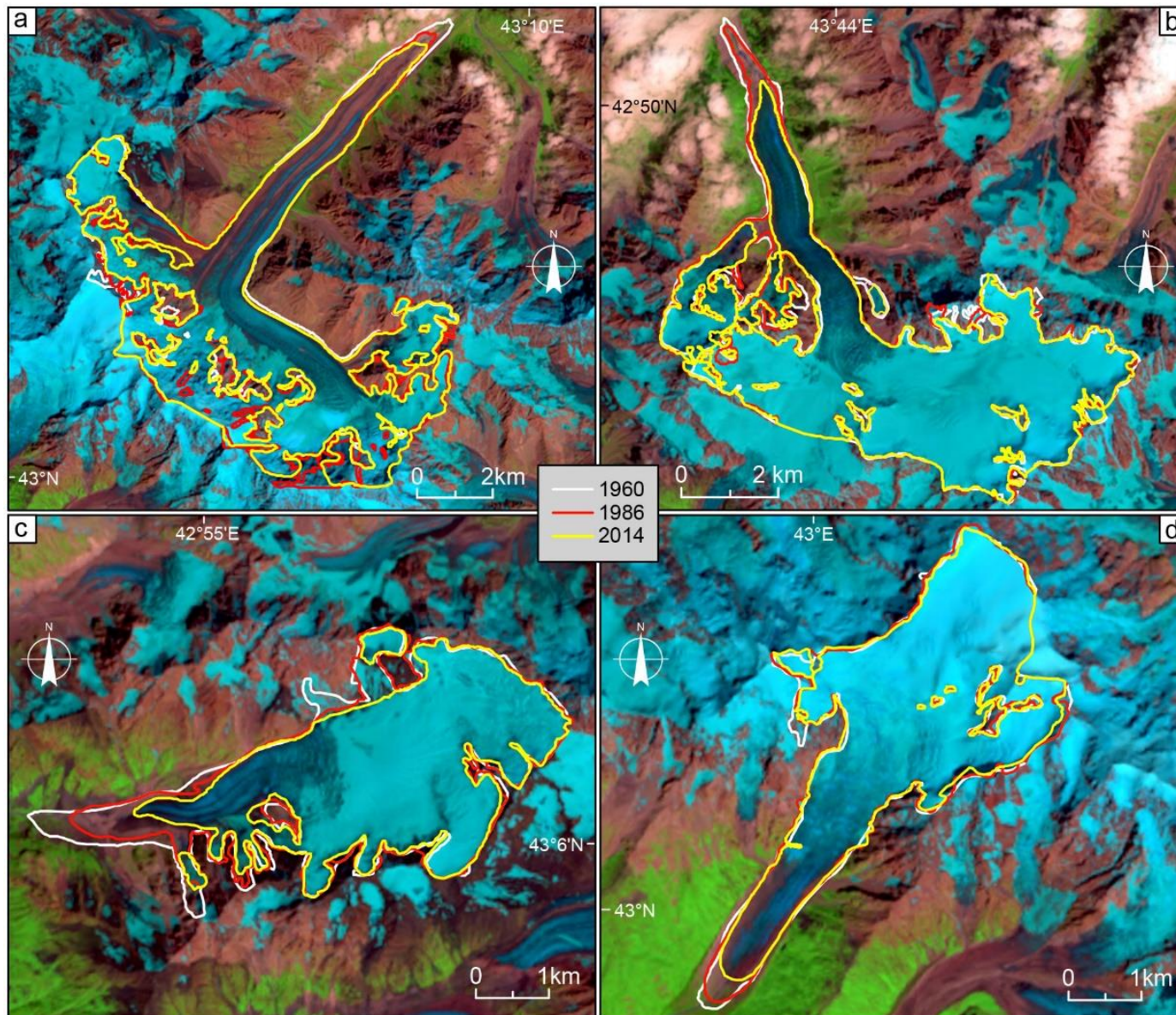


Figure 14. (a) Bezingi, (b) Karaugom, (c) Kvitlodi and (d) Adishi glaciers reduction in the years 1960-1986-2014. The 03/08/2014 Landsat 8 image (Table 1) is used as background.