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

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Abstract

While there are a large number of glaciers in the Greater Caucasus, the region is not fully represented in modern glacier databases with previous incomplete inventories. Here, we present an expanded glacier inventory for this region over the 1960-1986-2014 period. Large scale topographic maps and satellite imagery (Landsat 5, Landsat 8 and ASTER) were used to conduct a remote sensing survey of glacier change in the Greater Caucasus mountains. Glacier margins were mapped manually and reveal that, in 1960, the mountains contained 2349 glaciers, with a total glacier surface area of 1674.9±35.2 km^2. By 1986, glacier surface area had decreased to 1482.1±32.2 km^2 (2209 glaciers), and by 2014, to 1193.2±27.0 km^2 (2020 glaciers). This represents a 28.8±2.2% (481±10.6 km^2) reduction in total glacier surface area between 1960 and 2014 and a marked acceleration in the rate of area loss since 1986. Analysis of possible controls suggest that the general decreases in both glacier area and number for the period 1960-2014 are directly due to general increase in temperature, especially in summer (June-July-August), although the response of individual glaciers was modulated by other factors, including glacier size, elevation, rock structure, exposition, morphological type and debris cover. This new glacier inventory can be used as a basis dataset for future studies including glacier change assessment.

1 Introduction

Glacier inventories provide the basis for further studies on mass balance and volume change, which are relevant for local hydrological issues as well as global calculation of sea level rise (Fischer et al., 2015). Changes in glacial extent are inseparably linked with climate affecting the mass balance of glaciers on a seasonal or annual time scale, shifting to changes in area over a ten-year time scale, depending on the response time of the glacier (Barry, 2006; Pelto, 2006). However, the response to climate is complicated by local orography and individual attributes of the glacier, such as slope, aspect and elevation. To better understand the effect of these properties on glacier area, it is necessary to track a large number of glaciers of various sizes and attributes over many decades (Tennant et al., 2012).

Despite interest in glacier change and subsequent research, the inventories of alpine glaciers have often been focused on a limited region due to data, time or other resources (Paul et al., 2002a, Konya et al., 2014). In cases where the study regions overlapped, differences in methodologies have led to discrepancies in the glacier extents (Paul, 2000, Paul et al., 2013). Consistent methodological inventories are necessary to support mountain glaciers research (Earl and Gardner, 2016).

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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). Glacier research is thus vitally important for the Caucasus region.

2 Study area

2.1 Orography and climate

The Caucasus mountains consist of two separate mountain systems: the highest and most extensive part - the Greater Caucasus 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 (5033 m) (Maruashvili, 1981). 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).

The central Caucasus main watershed extends from the Azau subrange (43^{0}15′N, 42^{0}24′E) to Mt. Zekari (42^{0}33′N, 43^{0}56′E); the length of ~150 km represents a part of the watershed boundaries of the Caspian Sea and the Black Sea (Fig. 1). The rivers of the Azov Sea basin (Kuban River and its tributaries) are separated from the rivers of the Black Sea basin (Mzimta, Bzipi, Kodori, Enguri) by the western section of the Greater Caucasus, while the eastern section separates Tergi (Terek), Sulak, Kusarchai and other rivers which join with the Caspian Sea from the north part of the Absheron peninsula via the rivers (Mtkvari (Kura), Sumgait and others), which flow to the Caspian Sea from the south of the same peninsula.

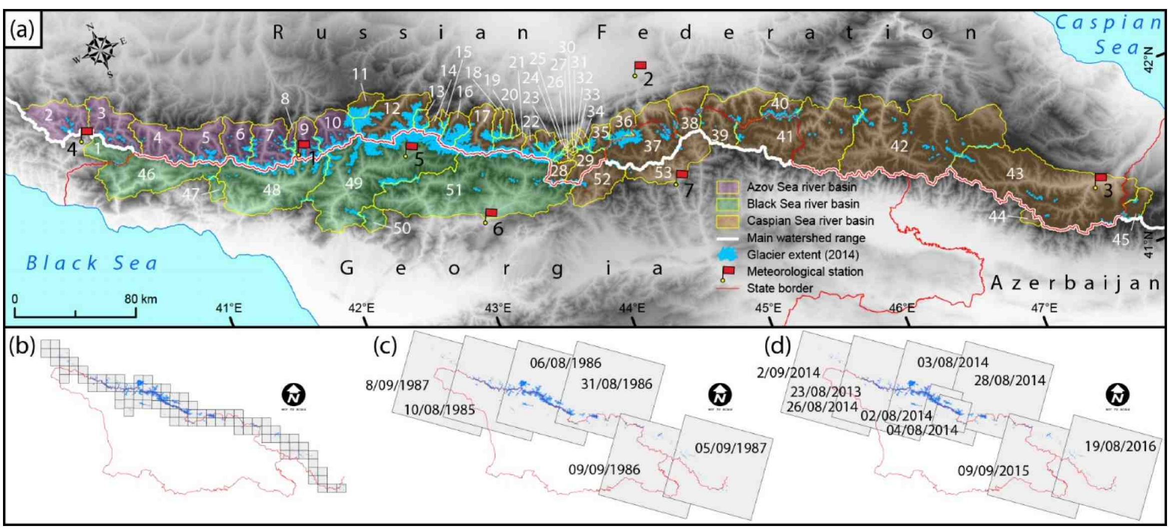

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Figure 1. (a) Distribution of the Greater Caucasus glaciers, by river basins, and location of meteorological stations. The numbers of the river basins are given in Table 2. (b) 1960s 1 : 50 000 scale map sheets (88) are based on aerial photographs 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.

The main watershed reaches its maximum height on the boundary of Svaneti and Kabardino-Balkaria – at the head of the Enguri River (Maruashvili, 1981). The ”Bezingi Wall” which is the highest part of the central watershed is represented by summits exceeding 5000 m: Shkhara 5203 m (43^{0}N, 42^{0}06′E), Janga 5058 m (43^{0}01′N, 43^{0}03′E), and Pushkin peak 5034 m (43^{0}N, 43^{0}04′E). The maximum height (Mt. Chanchakhi, 42^{0}44′N, 43^{0}47′E) in the headwaters of the Rioni River is 4462 m and 4046 m (Mt. Dombai-ulden, 43^{0}14′N, 41^{0}43′E) in the headwaters of the Kodori River. The ridge of the greater Caucasus from that point descends to the west, and it does not reach 3000 m until after Mt. Chugush (3238 m, 43^{0}47′N, 40^{0}12′E), located to the north-east of the resort town Sochi. To the east, the Caucasus range gradually decreases from the headwaters of the Rioni River. It remains below 4000 m east from Mamisoni Pass (42^{0}42′N, 43^{0}47′E) in its ~350 km length. Only in Azerbaijan, near the Dagestan border in the headwaters of the Turianchai River does it rise and reaches 4466 m at Mt. Bazardüzü (41^{0}13′N, 47^{0}51′E). Elevation sharply decreases further to the east reaching 3632 m (Mt. Babadağ, 41^{0}01′N, 48^{0}18′E) at Shamakhi and only 2209 m (Mt. Dibrar) north of Maraza village.

The Elbrus and The Kazbegi-Dzhimara massifs are distinguished by their significant glacier areas within the study area.

Elbrus, the highest summit of the Caucasus, has two peaks with eastern (5621 m 43^{0}20′N, 42^{0}27′E) and western (5642 m 43^{0}21′N, 42^{0}26′E) summits where the whole complex is covered by glaciers (Zolotarev and Kharkovets, 2012). Elbrus is an active volcano but only minor fumarole activity is currently observed (Laverov et al., 2005). Glaciers on Elbrus are situated in the altitudinal range of 2800 to 5642 m (Mikhalenko et al., 2015). The Elbrus valley glaciers, like other Caucasus glaciers, are affected by surge episodes (Kotlyakov et al., 2002); the associated rapid increases in ice flow rates can generate catastrophic detachments (Evans et al., 2009).

Mt. Kazbegi (5033 m 42^{0}41′N, 44^{0}31′E) is the sixth highest summit in the Caucasus, east of Mt. Dzhimara (4780 m 42^{0}43′N, 44^{0}24′E). Together, they form the Kazbegi-Dzhimara mountain massif (Kutuzov et al., 2016). Kazbegi is a dormant volcano with a two-headed cone and several side cones. The main cone erupted about 185,000±30,000 years ago, while the side cone of New Tkarsheti erupted about 6000 years ago (Chernyshev et al., 2002). Valley type glaciers Mydagrabyn, Maili, Kolka (Russia), Suatisi, Mna, Gergeti, Abano, Chachi, Devdoraki (Georgia) are on the slopes of the Kazbegi-Dzhimara massif and characterized by strong glacial hazards (Tielidze, 2016a).

As the greater Caucasus range is located on the boundary between temperate and subtropical climatic zones, the orientation and height of the range determines the contrasts between the northern and southern macroslopes: mean January and July temperatures at the meteorological stations in the north (Klukhorsky Pass, Vladikavkaz, Akhty) are 1-2^{0}C cooler than those in the south (Krasnaya Polyana, Mestia, Ambrolauri, Pasanauri). In the study region the minimum air temperature of -42^{0}C was measured in January 1983 in the Kazbegi high mountain meteorological station (3653 m). The average regional lapse rate was minimum in winter (2.3^{0}C per 1000 m) and maximum (5.2^{0}C per 1000 m) in summer (Kozachek et al., 2016).

Precipitation arrives from the west, in storm systems that replenish the waters of the Black Sea, driving the contrasts between the eastern and western of the southern macroslope, as well as between the well-watered Kolkheti Lowland and the northern slopes of the dryer Kuban Deppresion. The annual precipitation reaches 1160 mm a^{-1} at the Krasnaya Polyana meteorological station (539 m), while the lowest values occur in the eastern section (except the Akhty station) with annual precipitation of 240 mm a^{-1} in the Vladikavkaz (671 m) and 350 mm a^{-1} in the Pasanauri (1070 m) meteorological stations.

2.2 Glaciers

Little Ice Age (LIA) maximum positions have been dated to AD 1680, 1750 and 1850 in the Greater Caucasus Range (Volodicheva, 2002). The largest glaciers are located in the central Greater Caucasus including the glaciated massifs of Mt. Elbrus and Kazbegi-Dzhimara, where larger valley glaciers have individual areas of 3–36 km^2. Glacier melt in the Caucasus occurs mainly between June and August (JJA) (Shahgedanova et al., 2009).

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).

The altitude of the glacier equilibrium line (ELA), increases from 2500–2700 m in the Belaya, Laba, and Mzimta river basins in the west to 3700–3950 m in the Samur and Kusarchai basins in the eastern sector of the northern macroslope of the Caucasus (Mikhalenko et al., 2015). For the 1960s, ELA was determined to range from ~3030 m in the Bzipi River basin in the west to ~3480 m in the Pirikita Alazani River basin in the eastern section of the southern macroslope (Gobejishvili, 1995). The ELA is ~1000 m higher on the Elbrus slopes than the Enguri River basin glaciers 80 km southward (Mikhalenko et al., 2015). Analysis of the mass balance of Djankuat Glacier, a benchmark glacier selected by the World Glacier Monitoring Service with continued measurement since 1967, indicates that retreat is being driven by increased summer temperatures, with no compensating increase in winter precipitation (Shahgedanova et al., 2005).

2.3 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, 2016b); subsequently there were many early expeditions and glacier photographs 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 km^2 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, 2016b). 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 include some errors as temporary snowfields were misinterpreted as glaciers (Gobejishvili, 1995; Tielidze, 2016b) 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 glacier with total area 563.7 km^2 in the Georgian Caucasus. The current

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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 glacier inventories: Podozerskiy (1911), USSR glacier inventory (1967/1978) and the GLIMS database (2001/2004). Landsat and ASTER imagery from 1999/2004 were obtained for the latter covering over 90% of the glacierized area in the Caucasus. They found that glacier area decreased from the beginning to the middle of the 20th century by 24.7% and from the middle of the 20th century to the beginning of the 21th century by 17.7%. Elbrus glaciers lost 14.8% and 6.28% 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% for the first part of 20th century and 17.9% for the second part. In contrast, the south slope lost 12% and 28% respectively.

Lur'e and Panov (2014) examined northern Caucasus glacier variation for 1895-2011, finding glacier area decreased by 849 km^2 or by 52.6%. During this period, the average rate of glacier area reduction was 7.3 km^2/year, varying from 8.5 km^2/year in 1895–1970 to 5.2 km^2/year in 1971–2011. The most significant decrease was registered in the basins of Dagestan rivers (eastern Caucasus section); however they didn't describe their data sources for their glacier mapping.

The most recent glacier inventory, based on old topographic maps (1911/1960) and modern aerial imagery (Landsat/ASTER, 2014) was published by Tielidze (2016b), but compiled only for Georgian Caucasus glaciers, which reduced from 613.6±9.8 km^2 to 355.8±8.3 km^2 (0.4% 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.

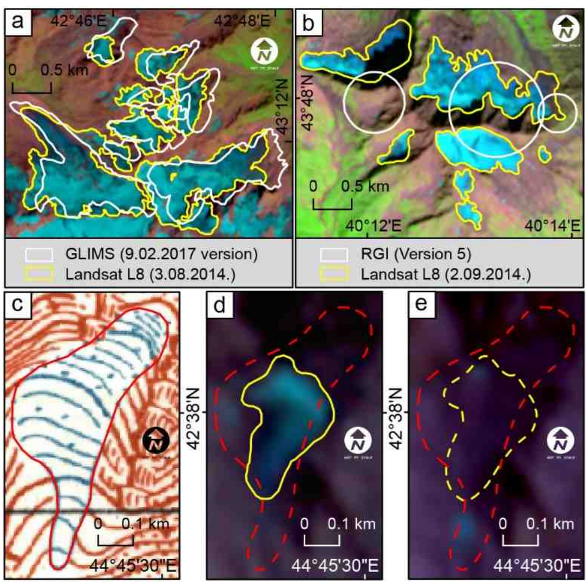

Figure 2. Comparison of glacier outlines from 2014, showing GLIMS (a) and RGI nominal glaciers (circles) (b). Examples of small glacier disappearance in the years of 1960 (c) - 1986 (Landsat 5, 31/08/1986.) (d) - 2014 (Landsat 8, 28/08/2014.) (e).

Other recent published works about the Caucasus, have mainly examined changes in glacier area for individual river basins or separate sections. Stokes et al. (2006, 2007) examining the central Caucasus determined that 94% of 113 selected glaciers retreated between 1985 and 2000; the largest glaciers (>10 km^2) and those located at lower elevations had retreated most dramatically. Shahgedanova et al. (2014) calculated 19.2 km^2 (4.7±2.1%) glacier area loss from 407.3±5.4 km^2 to 388.1±5.2 km^2 in the central and western Caucasus, between 1987-2010. Glacier changes for south macroslope Georgian glaciers between 1911-2014 in selected river basins, were reported by Tielidze et al. (2015a, 2015b, 2015c, 2015d).

The latest GLIMS database (9.02.2017 version, http://www.glims.org/download/) for the Caucasus (based on 2005–2007 ASTER imagery) identifies in excess of 1300 glaciers with a combined area of 1354 km^2 but with some inconsistent registration (Fig. 2a). The RGI database (http://www.glims.org/RGI/) incorporates nominal glaciers as circles in the eastern and western Caucasus sections (Fig. 2b) from the WGI-XF (Cogley, 2009); these are omitted from the GLIMS database There are no entries in the GLIMS book about the Caucasus glaciers (Kargel et al., 2014).

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 countries and river basins.

3 Methods

3.1 Data sources

We utilise increasingly accessible global satellite imagery and software (e.g. Gao and Liu, 2001; Raup et al., 2007) 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 visual 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 glacier termini because meltwater streams display as bright blue and contrast with the snout which casts an obvious shadow (Stokes at al., 2006). Manual delineation of debris-covered snouts is recommended by Paul et al. (2002b).

All images were acquired at the end of the ablation season, from 2 August to 9 September, when glacier tongues were 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.

Although, manual delineation or hand-digitization is time-consuming for a multi-temporal change analysis of a large area, such as an entire mountain range, this has been considered the most accurate method for mapping glaciers (DeBeer and Sharp, 2007; Albert, 2011; Stokes et al., 2013). Each glacier boundary was manually digitized and the total surface area calculated, with area >0.01 km^2 in accordance with Paul et al. (2009).

Large-scale topographic maps (1:50 000 scale) with a contour interval of 20 meters from (88) aerial photographs taken between 1950-1960 were used to compare glacier outlines (Fig. 1b). As these maps were only available in printed form, we scanned at 300 dpi with 5 m ground resolution and co-registered the maps using the 3 August 2014 Landsat image as a master (Tielidze, 2016b). Offsets between the images and the archival maps were within one pixel (15 m) based on an analysis of common features identifiable in each dataset. We reprojected 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 software). Together with aerial imagery, these older topographic maps allow us to identify changes in the number and area of glaciers over the last half century.

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

Date	Type of imagery	Region/Section	Resolution	Scene ID
10/08/1985	Landsat 5	W and C Greater Caucasus	30 m	LT51720301985222XXX04
06/08/1986	Landsat 5	C Greater Caucasus	30 m	LT51710301986218XXX02
31/08/1986	Landsat 5	C and E Greater Caucasus	30 m	LT51700301986243XXX03
09/09/1986	Landsat 5	E Greater Caucasus	30 m	LT51690311986252XXX03
05/09/1987	Landsat 5	E Greater Caucasus	30 m	LT51680311987248XXX03
08/09/1987	Landsat 5	W Greater Caucasus	30 m	LT51730301987251AAA04
23/08/2013	Landsat 8	W and C Greater Caucasus	15/30 m	LC81720302013235LGN00
03/08/2014	Landsat 8	C Greater Caucasus	15/30 m	LC81710302014215LGN00
26/08/2014	Landsat 8	W and C Greater Caucasus	15/30 m	LC81720302014238LGN00
28/08/2014	Landsat 8	C and E Greater Caucasus	15/30 m	LC81700302014240LGN00
02/09/2014	Landsat 8	W Greater Caucasus	15/30 m	LC81730302014245LGN00
09/09/2015	Landsat 8	E Greater Caucasus	15/30 m	LC81690312015252LGN00
19/08/2016	Landsat 8	E Greater Caucasus	15/30 m	LC81680312016232LGN00
02/08/2014	ASTER	C Greater Caucasus	15 m	AST_L1T_003080220140813 13_20150622105647_51181
04/08/2014	ASTER	C Greater Caucasus	15 m	AST_L1T_003080420140801 02_20150622114958_116303

3.2 Glacier delineation error and analysis

To estimate glacier uncertainty we calculated error terms using a buffer method similar to Granshaw and Fountain (2006) and Bolch et al. (2010) and adopted by Tielidze (2016b). The error term for the 1960 extents is based on a buffer incorporating the root-mean-square error (RMSEx,y) of the map rectification (15 m) and the digitizing error equal to half the width of a contour line (7.5 m).

Errors are 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 1986 Landsat 5 TM and ±15 m for 2014 Landsat 8 panchromatic and ASTER. Following Khromova et al. (2014), a buffer with a width of half of the RMSE was created along the glacier outlines and the error term was calculated as an average ratio between

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the original glacier areas and the areas with a buffer increment; for the 1986 images we used a buffer equal to half the resolution of the data (15m) and a similar buffer for the 2014 glacier extents. This generated an average uncertainty of the mapped glacier area of 2.3% for 2014, 2.2% for 1986 and 2.1% for 1960. Using the buffer method from Granshaw and Fountain (2006), these yield a total potential overall error of ±2.2 %. This suggests that our error term is probably conservative.

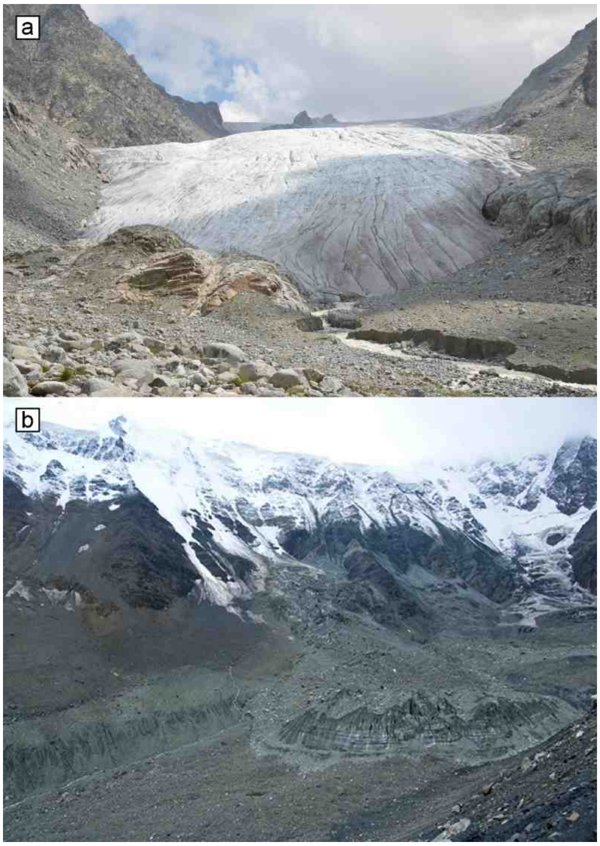

Figure 3. (a) Kirtisho Glacier terminus 2665 m a.s.l. ($42^0$50' N $43^0$34' E) in 2014, on the southern slope of the central Greater Caucasus (photo by L.G. Tielidze). Note the clearly identified boundaries of the glacier and to a limited extent the debris cover. (b) Kolka Glacier in 2014, northern slope of the Greater Caucasus (photo by V. Ivanov) and one of the most heavily debris-covered glaciers in the Caucasus.

In general, manual delineation is considered the most accurate method for debris-covered termini because of the difference in illumination at the glacier boundary (DeBeer and Sharp, 2007). Importantly, debris cover is not continuous on the snouts of many glaciers in the Greater Caucasus (Fig. 3a) and most glaciers of Mt. Elbrus (Shahgedanova et al., 2014). One of the most heavily debris-covered glaciers in the Caucasus is Kolka Glacier ($42^0$44' N, $44^0$26' E) where supra-glacial debris covers approximately 64% (Fig. 3b). To account for the error term due to debris cover, after Frey et al. (2012) and Shahgedanova et al. (2014) we increased the buffer size to two pixels (30 m) and error of mapping was calculated as ±8.8% which is the largest error in our database. We consider that these glaciers are not typical for the Caucasus region.

3.3 Climatic data

There are seven middle and high-altitude meteorological stations with ongoing observations in the study area (see Fig. 1 for their locations), Klukhorsky Pass (2037 m), Vladikavkaz (671 m), Akhty (1065 m) in the northern Greater Caucasus and Krasnaya Polyana (539 m), Mestia (1441 m), Ambrolauri (544 m) and Pasanauri (1070 m) in the southern Greater Caucasus. We examined the average monthly, mean annual and ablation season (JJA) air temperature records, along with accumulation season (October–April) precipitation. Temperature and precipitation data from these stations were available from 1960 to 2014, except the Klukhorsky Pass, Vladikavkaz, Akhty and Krasnaya Polyana stations, where the precipitation data are from 1966-2014. The primary goal was to assess long-term temperature and precipitation variability for association with glacier area change.

4 Results

4.1 Area and number change

The total ice area loss between 1960 and 1986 was 192.8±4.2 km^2 or 11.5±2.2%, while the number of glaciers reduced from 2349 to 2209 (Table 2). These results reflect that in the 1960–70s, there were many small cirque glaciers, which disappeared in the years 1960-1986 (Fig. 2c, d, e). Between 1986 and 2014, glacier area decreased by 288.9±6.4 km^2 or 19.5±2.3%, and glacier numbers from 2209 to 2020.

Glaciers in the northern Greater Caucasus lost 131.0±2.9 km^2 or 11.0±2.1% of their area (0.4% yr^{-1}) between 1960-1986, while the number of glaciers reduced from 1622 to 1523 (Table 3). Between 1986 and 2014, glacier area decreased by 189.7±4.2 km^2 or 18.0±2.2% (0.6% yr^{-1}) while the number of glaciers reduced from 1523 to 1391.

On the southern macroslope, glacier area decreased by 61.8±1.7 km^2 or 12.7±2.7% (0.5% 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±2.3 km^2 or 23.3±2.3% of their area (0.8% yr^{-1}) while the number of glaciers reduced from 686 to 629.

Overall, the differences between the two macroslopes were small. The greater loss was observed on the southern slope where glaciers lost 33.0±2.5% (0.6% yr^{-1}) over the last half century, while the northern slope glaciers lost 27.0±2.1% (0.5% yr^{-1}).

The eastern Caucasus section (Aragvi, Tergi headwaters, Sunja right (south-east) tributaries - Sulak, Samur, Agrichai and Kusarchai) experienced the highest glacier surface decrease, where the total ice area loss between 1960 and 2014 was 53.3±2.2% or 100.5±2.2 km^2.

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Table 2. The Greater Caucasus glacier number and area in 1960–1986–2014 by individual river basins.

Russian Caucasus			USSR Catalog 1967-1978		Topographic maps 1960			Landsat 5, 1985/86/87			Landsat 8, 2013/14/15/16 and ASTER 2014		
#	Main river basin	Tributary river basin	Number	Area km^2	Number	Area km^2	Uncertainty ±(%)	Number	Area km^2	Uncertainty ±(%)	Number	Area km^2	Uncertainty ±(%)
1	Mzimta		7	1.7	13	2.4±0.1	±4.2	13	2.3±0.1	±4.3	13	1.9±0.1	±5.3
2	Kuban	Belaya	29	7.6	39	7.6±0.2	±2.6	45	8.3±0.3	±3.6	50	6.6±0.2	±3.0
3		Malaya Laba	27	9.4	39	11.2±0.3	±2.7	45	8.4±0.3	±3.6	39	7.5±0.3	±4.0
4		Bolshaya Laba	21	5.8	30	7.1±0.2	±2.8	30	6.7±0.2	±3.0	29	4.5±0.1	±2.2
5		Bolshoy Zelenchuk	56	30.7	58	32.4±0.8	±2.5	65	33.8±0.9	±2.7	74	25.6±0.8	±3.1
6		Maliy Zelenchuk	28	26.3	37	30.3±0.6	±2.0	41	29.8±0.5	±1.7	46	24.6±0.6	±2.4
7		Teberda	85	61.0	99	63.6±1.4	±2.2	103	62.1±1.3	±2.1	100	53.7±1.3	±2.4
8		Daut	16	5.5	19	7.2±0.2	±2.8	22	6.1±0.2	±3.3	24	4.8±0.2	±4.2
9		Uchkulan	58	20.8	64	27.3±0.7	±2.6	65	22.7±0.7	±3.1	71	19.2±0.7	±3.6
10		Ullukam	88	52.9	107	65.2±1.6	±2.5	105	51.0±1.3	±2.5	95	42.5±1.1	±2.6
11	Malka		10	56.5	10	64.0±0.5	±0.8	11	57.5±0.4	±0.7	12	52.2±0.4	±0.8
12	Baksan		156	132.7	170	187.0±3.5	±1.9	162	169.8±3.2	±1.9	156	146.3±3.0	±2.1
13	Chegem	Bashil-Auzusu	28	26.9	39	34.6±0.7	±2.0	31	30.1±0.6	±2.0	30	25.3±0.5	±2.0
14		Gara-Auzusu	28	28.0	21	30.1±0.5	±1.7	19	29.3±0.6	±2.0	17	24.7±0.5	±2.0
15		Bulungu	9	3.2	8	6.6±0.1	±1.5	10	4.0±0.1	±2.5	9	2.9±0.1	±3.4
16	Cherek	Cherek-Bezingskiy	85	76.3	48	82.4±1.4	±1.7	40	81.1±1.3	±1.6	48	73.8±1.3	±1.8
17		Cherek-Balkarskiy	80	107.0	78	115.0±1.9	±1.7	79	113.0±1.9	±1.7	86	96.8±1.8	±1.9
18		Psigansy	17	15.0	13	15.2±0.3	±2.0	12	15.6±0.3	±1.9	13	12.8±0.3	±2.3
19	Urukh	Khanzidon	13	4.7	14	8.5±0.2	±2.4	15	8.4±0.2	±2.4	12	6.3±0.2	±3.2
20		Biliagikom	5	2.0	6	2.5±0.06	±2.4	4	2.1±0.1	±4.8	5	1.0±0.07	±7.0
21		Urukh headwaters	34	23.0	35	31.1±0.6	±1.9	33	30.3±0.7	±2.3	35	25.3±0.6	±2.4

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22		Karaugom	27	39.6	21	48.4±0.7	±1.4	23	45.7±0.7	±1.5	31	41.7±0.7	±1.7
23		Aigamuga	26	13.4	14	24.0±0.5	±2.1	17	17.4±0.3	±1.7	20	14.7±0.4	±2.7
24	Ardon	Tseyadon	29	15.0	22	21.4±0.4	±1.9	18	19.2±0.3	±1.6	20	16.8±0.3	±1.8
25		Sidan	1	0.05	1	0.08±0.005	±6.3	1	0.07±0.005	±7.1	1	0.03±0.02	±6.7
26		Vilsa	3	0.6	6	1.1±0.07	±6.4	5	1.0±0.08	±8.0	5	0.9±0.04	±4.4
27		Adaikom	5	4.7	9	7.0±0.2	±2.9	8	5.4±0.1	±1.9	7	4.6±0.1	±2.2
28		Mamikhdon	14	4.2	18	6.1±0.2	±3.3	15	4.9±0.2	±4.1	15	3.7±0.1	±2.7
29		Nar	11	2.9	28	6.5±0.2	±3.1	15	3.2±0.1	±3.1	11	1.6±0.04	±2.5
30		Gilvan	1	0.2	3	0.3±0.02	±6.7	1	0.05±0.04	±8.0	0	0	0
31		Kasaidon	2	0.19	2	0.5±0.03	±6.0	2	0.3±0.02	±6.7	2	0.2±0.01	±5.0
32		Labagkomdon	1	0.04	1	0.1±0.008	±8.0	1	0.1±0.008	±8.0	1	0.06±0.004	±6.7
33		Baddon	7	3.5	6	4.3±0.08	±1.9	8	3.5±0.3	±8.6	8	2.6±0.1	±3.8
34		Arkhondon	5	4.1	5	4.2±0.09	±2.1	4	4.0±0.3	±7.5	4	3.5±0.1	±2.9
35	Fiagdon		31	12.3	33	12.6±0.4	±3.2	29	8.8±0.3	±3.4	28	6.2±0.3	±4.8
36	Gizeldon		27	34.6	32	33.8±0.6	±1.8	30	31.0±0.6	±1.9	25	25.2±0.5	±2.0
37	Tergi headwaters		4	2.6	22	5.3±0.2	±3.8	27	4.8±0.2	±4.2	20	3.2±0.1	±3.1
38	Sunja right tributaries	Assa	7	2.7	7	3.3±0.1	±3.0	8	2.1±0.1	±4.8	6	1.3±0.04	±3.1
39		Arghuni	10	4.3	13	6.6±0.2	±3.0	9	5.7±0.1	±1.8	8	4.4±0.1	±2.3
40		Sharo Argun	34	17.6	37	24.6±1.2	±4.9	36	21.1±0.5	±2.4	32	15.7±0.4	±2.5
41	Sulak	Andiyskoye Koysu	7	12.3	22	15.3±0.4	±2.6	25	13.1±0.4	±3.1	16	9.2±0.2	±2.2
42		Avarskoye Koysu	88	23.5	105	28.0±0.9	±3.2	86	18.4±0.7	±3.8	34	5.9±0.2	±3.4
43	Samur		20	9.0	63	14.30±0.4	±2.8	49	10.2±0.4	±3.9	17	2.4±0.09	±3.8
Total, Russian Caucasus			1248	907.58	1417	1099.1±22.1	±2.0	1367	992.4±20.7	±2.1	1275	822.2±17.9	±2.2
Azerbaijan Caucasus													
44	Agrichai	Shinchai	0	0	2	0.1±0.008	±8.0	1	0.04±0.003	±7.5	1	0.03±0.002	±6.7
45	Kusarchai		8	3.2	24	6.0±0.2	±3.3	17	4.6±0.2	±4.3	15	0.8±0.07	±8.8
43	Samur		0	0	7	1.2±0.05	±4.2	7	1.1±0.04	±3.6	4	0.4±0.03	±7.5

Total, Azerbaijan Caucasus			8	3.2	33	7.3±0.3	±4.1	25	5.7±0.3	±5.3	20	1.2±0.1	±8.3
Georgian Caucasus													
46	Bzipi		16	7.8	26	9.5±0.3	±3.2	23	6.7±0.3	±4.5	19	3.2±0.2	±6.2
47	Kelasuri		3	1.5	3	1.4±0.06	±4.3	2	1.2±0.03	±2.5	2	0.9±0.03	±3.3
48	Kodori		141	60.0	179	65.1±1.8	±2.8	179	61.0±1.9	±3.1	161	42.2±1.4	±3.3
48	Enguri		250	288.3	317	324.7±6.2	±1.9	306	285.8±5.6	±2.0	289	225.3±4.6	±2.0
50	Khobistkali		7	1.6	20	1.2±0.1	±8.3	13	0.9±0.04	±4.4	11	0.6±0.04	±6.7
51	Rioni		124	62.9	141	78.3±1.9	±2.4	134	65.5±2.1	±3.2	120	50.9±1.3	±2.6
52	Liakhvi		22	6.6	19	4.5±0.1	±2.2	14	2.6±0.1	±3.8	12	2.0±0.08	±4.0
53	Aragvi		5	1.6	8	1.1±0.05	±4.5	1	0.5±0.04	±8.0	1	0.3±0.02	±6.7
37	Tergi headwaters		129	72.2	111	66.2±1.4	±2.1	89	50.8±1.2	±2.4	74	40.2±1.6	±4.0
38	Sunja right	Assa	3	1.1	12	2.6±0.1	±3.8	9	1.9±0.06	±3.2	4	0.8±0.05	±6.2
39	tributaries	Arghuni	14	1.7	19	3.0±0.1	±3.3	16	1.6±0.1	±6.3	12	0.8±0.07	±8.8
41	Sulak	Andiyskoye Koysu (Pirikita Alazani)	40	8.9	44	10.9±0.4	±3.7	31	5.5±0.2	±3.6	20	2.6±0.1	±3.8
Total, Georgian Caucasus			754	514.2	899	568.5±12.5	±2.2	817	484.0±11.2	±2.3	725	369.8±8.7	±2.4
Total, Greater Caucasus			**2002**	**1421.78**	**2349**	**1674.9±35.2**	**±2.1**	**2209**	**1482.1±32.2**	**±2.2**	**2020**	**1193.2±27.0**	**±2.3**

Table 3. The Northern and Southern Greater Caucasus glacier number and area change in 1960–1986–2014.

Regions (Slopes)	Topographic maps 1960			Landsat 5, 1985/86/87			Landsat 8, 2013/14/15/16 and ASTER 2014		
	Number	Area km^2	Uncertainty ±(%)	Number	Area km^2	Uncertainty ±(%)	Number	Area km^2	Uncertainty ±(%)
Northern Caucasus	1622	1186.5±24.4	±2.1	1523	1055.5±22.5	±2.1	1391	865.8±19.2	±2.2
Southern Caucasus	727	488.4±14.5	±3.0	686	426.6±9.7	±2.3	629	327.4±7.6	±2.3

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4.1.1 Elbrus and Kazbegi-Dzhimara massif

Glaciers located on Mt. Elbrus lost 9.9±0.1 km^2 or 7.3±1.1% (0.3% yr^{-1}) of their combined area between 1960 and 1986 and the same amount from 1986 to 2014 (Table 4; Fig. 4a). Overall, the relative loss was 14.7±1.2% between 1960 and 2014. Generally, the Elbrus glacier reduction rate is comparable with glacier area loss in the Greater Caucasus main watershed range despite the higher elevation and larger accumulation areas.

Among the large glaciers (> 10 km^2) the Dzhikiugankez Glacier experienced a high rate of reduction, as the most extensive glacier on the Elbrus massif (Table 4), the relative loss was 27.2±0.6% (0.5% yr^{-1}) between 1960-2014. The important relative losses for the Dzhikiugankez Glacier can be explained by the role of the post-volcanic activity, especially the influence of thermal and fluid flows in the north-eastern part of the Elbrus volcano (Masurenkov and Sobisevich, 2012; Holobâcă, 2016).

Table 4. Elbrus glacier number and area change in 1960–1986–2014. All glaciers are shown in Fig. 4a.

Elbrus glaciers			Topographic maps 1960		Landsat 5, 06/08/1986		Landsat 8, 03/08/2014/	
#	Name	WGI ID	Area km^2	Uncertainty ±(%)	Area km^2	Uncertainty ±(%)	Area km^2	Uncertainty ±(%)
1	Ulluchiran	SU4G08005001	12.87±0.13	±1.0	13.12±0.08	±0.6	12.68±0.09	±0.7
2	Karachaul	SU4G08005002	6.20±0.08	±1.3	6.22±0.06	±1.0	5.96±0.07	±1.2
3	Ullukol	SU4G08005003	6.42±0.08	±1.2	5.81±0.06	±1.0	5.45±0.06	±1.1
4	565a	SU4G08005004	0.97±0.02	±2.1	0.54±0.02	±3.7	0.13±0.01	±7.7
5	Mikelchiran	SU4G08005005	7.74±0.06	±0.8	7.09±0.06	±0.8	6.84±0.06	±0.9
6	Dzhikiugankez	SU4G08005006	28.41±0.12	±0.4	24.0±0.15	±0.6	20.68±0.16	±0.8
7	Irikchat	SU4G08005018	1.56±0.01	±0.6	1.29±0.03	±2.3	1.09±0.02	±1.8
8	Irik	SU4G08005020	12.56±0.14	±1.1	11.46±0.11	±1.0	10.95±0.11	±1.0
9	Terskol	SU4G08005026	9.83±0.16	±1.6	9.78±0.08	±0.8	9.45±0.07	±0.7
10	Garabashi	SU4G08005027	3.13±0.04	±1.3	2.75±0.04	±1.5	2.45±0.05	±2.0
11	Maliy Azau	SU4G08005028	10.08±0.08	±0.8	10.03±0.07	±0.7	9.41±0.09	±1.0
12	Bolshoy Azau	SU4G08005029	21.26±0.17	±0.8	20.47±0.16	±0.8	18.20±0.18	±1.0
13	311	SU4H08004311	0.57±0.02±	±3.5	0.51±0.02	±3.9	0.37±0.01	±2.7
14	312	SU4H08004312	0.25±0.01	±4.0	0.33±0.01	±3.0	0.26±0.01	±3.8
15	Ullukam	SU4H08004313	0.56±0.02	±3.6	0.72±0.02	±2.8	0.67±0.02	±3.0
16	313	SU4H08004313	1.08±0.03	±2.8	0.98±0.03	±3.1	0.98±0.03	±3.1
17	317	SU4H08004317	0.74±0.01	±1.4	0.76±0.02	±2.6	0.76±0.02	±2.6
18	Unnamed*	Unknown	0.65±0.02	±3.1	0.59±0.01	±1.7	0.52±0.02	±3.8
19	Kyukyurtlyu	SU4H08004318	5.69±0.1	±1.8	5.61±0.06	±1.1	5.54±0.07	±1.3
20	319	SU4H08004319	1.54±0.03	±1.9	0.98±0.03	±3.1	0.94±0.02	±2.1
21	Bityuktyube	SU4H08004320	2.40±0.05	±2.1	1.74±0.04	±2.3	1.65±0.03	±1.8
22	321	SU4H08004321	0.38±0.02	±5.3	0.21±0.01	±4.8	0.08±0.006	±8.0
Total			**134.89±1.42**	**±1.1**	**124.99±1.37**	**±1.1**	**115.06±1.34**	**1.2**

* Omitted in WGI database

Unlike the Elbrus, the size of the change varied dramatically from glacier to glacier on the Kazbegi-Dzhimara massif. The total ice area loss between1960-1986 was 6.1±0.1 km^2 or 9.0±2.0% (0.3% yr^{-1}) (Table 5; Fig. 4b). From 1986 to 2014 glacier area decreased by 8.3±0.2 km^2 or 13.4±2.2% (0.5% yr^{-1}). Overall, the relative loss was 21.2±2.2% between 1960 and 2014.

Among glaciers with area >5 km^2, the Devdoraki Glacier experienced a high rate of reduction between 1960-2014 (Table 5), with a relative loss of 38.8±1.4% (0.7% yr^{-1}). Among glaciers with area 2-5 km^2, the Kolka Glacier had the highest rate of loss of 50.4±7.1% (0.9% yr^{-1}). Kolka Glacier is well known for a strong rock-ice avalance and glacial mudflow in 2002 (Haeberli et al., 2004; Huggel et al., 2005; Petrakov et al., 2008).

Table 5. Kazbegi-Dzhimara massif glacier number and area change in 1960–1986–2014. All glaciers are shown in Fig. 3b.

Kazbegi-Dzhimara massif glaciers			Topographic maps 1960		Landsat 5, 06/08/1986		Landsat 8, 28/08/14/	
#	Name	WGI ID	Area km^2	Uncertainty ±(%)	Area km^2	Uncertainty ±(%)	Area km^2	Uncertainty ±(%)
1	Mydagrabyn	SU4G08010031	9.98±0.11	±1.1	9.73±0.12	±1.2	8.16±0.12	±1.5
2	Unnamed	Unknown	-**		-		0.16±0.01	±6.3
3	Kolka	SU4G08010039	5.06±0.35	±6.9	4.28±0.24	±5.6	2.51±0.22	±8.8
4	Unnamed	Unknown	-		-		0.75±0.02	±2.7
5	Unnamed	SU4G08010040	0.79±0.03	±3.8	0.73±0.02	±2.7	0.50±0.02	±3.8
6	Maili	SU4G08010041	7.29±0.07	±1.0	6.75±0.07	±1.0	6.57±0.06	±0.9
7	Unnamed	Unknown	-		-		0.05±0.004	±8.0
8	Unnamed	SU4G08010042	-		0.67±0.02	±3.0	0.44±0.01	±2.3
9	Chachi	SU4G08011046	2.61±0.03	±1.1	2.57±0.04	±1.6	1.85±0.04	±2.2
10	Unnamed	Unknown	-		-		0.08±0.006	±7.5
11	Unnamed	SU4G08011047	0.86±0.03	±3.5	0.52±0.02	±3.8	0.12±0.01	±8.3
12	Unnamed	Unknown	-		-		0.05±0.004	±8.0
13	Devdoraki	SU4G08011048	7.19±0.1	±1.4	6.96±0.1	±1.4	4.40±0.06	±1.4
14	Unnamed	Unknown	-		-		1.78±0.04	±2.2
15	Abano	SU4G08011049	1.96±0.04	±2.0	1.49±0.04	±2.7	1.33±0.05	±3.8
16	Unnamed	Unknown	-		-		0.03±0.002	±6.7
17	Unnamed	Unknown	0.58±0.02	±3.4	0.34±0.02	±5.9	0.1±0.002	±2.0
18	Gergeti	SU4G08011052	6.82±0.09	±1.3	6.26±0.1	±1.6	5.77±0.09	±1.6
19	None	SU4G08011056	0.49±0.02	±4.1	0.39±0.01	±2.6	0.36±0.01	±2.8
20	Denkara	SU4G08011057	1.33±0.02	±1.5	0.93±0.02	±2.1	0.31±0.01	±3.2
21	Unnamed	Unknown	0.49±0.02	±4.1	0.06±0.005	±8.3	0.03±0.002	±6.7
22	Unnamed	SU4G08011058	0.89±0.03	±3.4	0.63±0.02	±3.2	0.53±0.02	±3.8
23	Unnamed	SU4G08011059	1.12±0.02	±1.8	0.98±0.03	±3.1	0.75±0.03	±4.0
24	Mna	SU4G08011060	3.25±0.05	±1.5	2.89±0.06	±2.1	2.59±0.06	±2.3

25	Unnamed	SU4G08011061	1.57±0.02	±1.3	1.30±0.03	±2.3	1.44±0.02	±1.4
26	Suatisi Eastern	SU4G08011062	10.84±0.1	±0.9	9.87±0.12	±1.2	8.89±0.09	±1.0
27	Unnamed	Unknown	-		-		0.08±0.006	±7.5
28	Suatisi Central	SU4G08011063	2.62±0.05	±1.9	2.32±0.04	±1.7	2.07±0.04	±1.9
29	Unnamed	Unknown	-		0.29±0.02	±6.9	0.23±0.01	±4.3
30	Suatisi Western	SU4G08011064	2.49±0.04	±1.6	2.16±0.04	±1.9	1.55±0.03	±1.9
31	Unnamed	Unknown	-		-		0.12±0.01	±8.3
32	Unnamed	Unknown	-		-		0.18±0.01	±5.6
Total			**68.23±1.21**	**±1.8**	**62.12±1.36**	**±2.2**	**53.78±1.24**	**±2.3**

* Omitted in WGI database

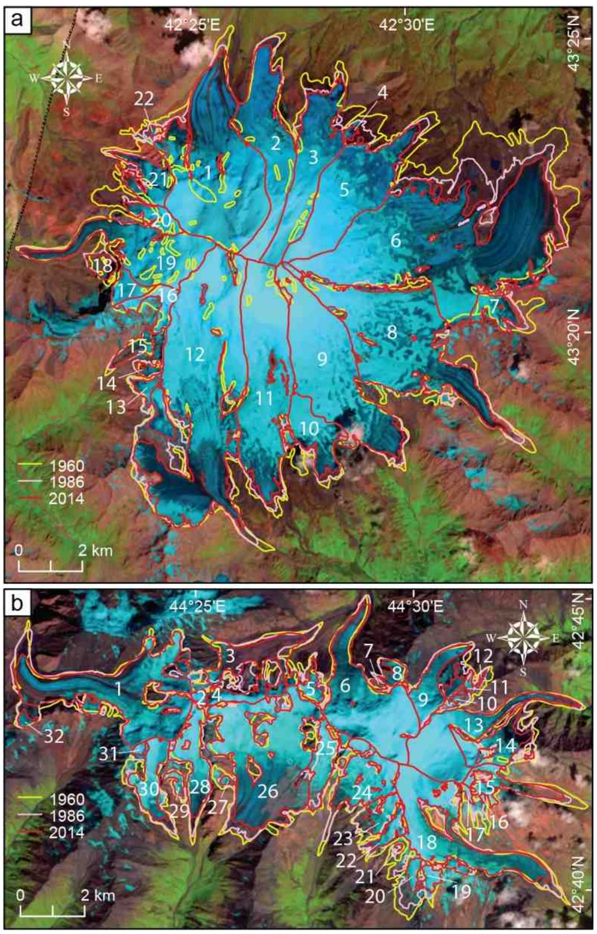

Figure 4. Changes in glacierized area of Elbrus and Kazbegi-Dzhimara massifs between 1960-1986-2014. See Tables 4 and 5 for the change statistics of individual glaciers. The 3/08/2014 and 28/08/2014 Landsat 8 images (Table 1) are used as background.

In comparison with the glaciers of Elbrus, there are several reasons for higher reduction of the glaciers of the Kazbegi-Dzhimara massif: a) the Kazbegi-Dzhimara massif is slightly lower hypsometrically, compared to Elbrus; many glaciological studies suggest that altitude is the most important independent variable and is a fundamental control of both temperature and precipitation (Evans, 1969; Flint, 1971; Price, 1981). Changes in altitude also indicated a generalized glacial retreat between the Elbrus and Kazbegi-Dzhimara glaciers; b) the slopes of Kazbegi-Dzhimara massif are more steeply angled, which is why the glaciers of this massif are characterized by frequent mechanical destruction and glacial avalanches, often with catastrophic effect; c) compared to Elbrus, the Kazbegi-Dzhimara massif is located about 1^0 to the south and by 2^0 to the east, where the climate is more continental and solid precipitation is relatively less compared to the north-west.

4.1.2 Glacier aspect and terminus retreat

Glaciers with north, northeast and northwest aspects are the most extensive, covering 286.0±6.1 km^2 (370 glaciers), 277.7±6.0 km^2 (443 glaciers) and 231.6±5.9 km^2 (483 glaciers) respectively, and combining for 66.7% of all glaciers (Fig. 5a, b). The south, southeast and southwest aspects cover 89.4±1.9 km^2 (145 glaciers), 132.7±2.4 km^2 (169 glaciers) and 85.0±1.7 km^2 (121 glaciers) respectively, and combine for 25.7% of all glaciers. The southern macroslope of the greater Caucasus is relatively shorter and steeper than the northern, providing one of the favorable conditions for the existence of large size glaciers in the north.

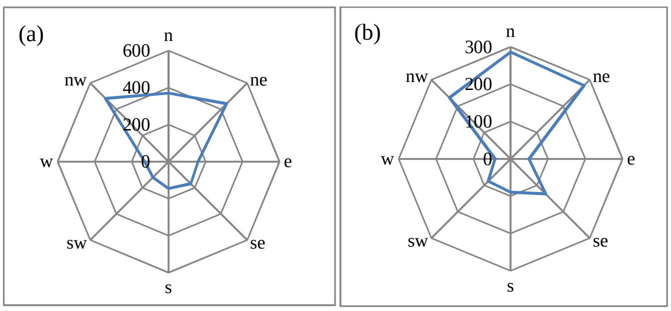

Figure 5. Glacier aspect – (a) number and (b) area.

We chose the 14 largest glaciers on the central Caucasus northern and southern macroslopes for measuring terminus retreat (Table 6; Fig. 6); each glacier area was >8.0 km^2. Across the region, terminus retreat mostly increased from the 1960-1986 period to 1986-2014. The highest recession rates of 48.8 m yr^{-1} were observed on the Karaugom Glacier northern macroslope, but 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}). The greatest total retreat was exhibited by the Lekhziri, the largest glacier on the southern macroslope, retreating 1595m at an average rate of 29.5 m yr^{-1}.

Of the 14 glaciers measured, 13 retreated between 1986 and 2014. Five glaciers showed less change between 1986-2014 than 1960-1986 (Bezingi, Lekhziri, Chalaati, Khalde and Shkhelda) and one glacier (Midjirgi) advanced (Table 6; Fig. 7). 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 Mizhirgi Glacier advanced between 1985 and 2000). The overall advance of Mizhirgi Glacier between 1985 and 2000 was around 110±25 m (Stokes et al., 2006). Microstadial moraines in front of Chalaati Glacier

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confirm ~20 m glacier advance during 1990-1993 (Gobejishvili, 1995; Gobejishvili et al., 2012). Records show that 1992 was the coldest between 1960-2014 (Fig. 7), but there is no clear geographical template which characterizes the advancing glaciers.

The compound-valley glacier of Chalaati (43.7^0N, 42.42^0E) has the lowest terminus position for the whole Caucasus region (1960 m a.s.l.), based on a 2014 GPS survey (Table 6) (Tielidze, 2016b). Overall, the valley glacier terminus positions are between 2200 and 3200 m., while cirque and hanging glaciers are at higher elevations, between 2800 and 3900 m. According to this current inventory, the Bezingi Glacier represents the largest single glacier in the Greater Caucasus.

Table 6. Characteristics of glaciers used for measuring terminus retreat. The average error terms are ±15 m.

Name	River basin	Area 1960	Uncertainty ±(%)	Area 1986	Uncertainty ±(%)	Area 2014	Uncertainty ±(%)	Terminus retreat 1960-1986		Terminus retreat 1986-2014		Terminus elevation m, 2014
								m	m yr^{-1}	m	m yr^{-1}	
Bezingi	Cherek-Bezingskiy	40.42±0.49	±1.2	39.98±0.45	±1.1	37.47±0.47	±1.3	519	19.7	374	13.4	2220
Dych-sy-Ailama	Cherek-Balkarskiy	39.49±0.49	±1.2	34.85±0.47	±1.3	27.53±0.39	±1.4	461	17.7	1094	39.1	2270
Karaugom	Karaugom	29.94±0.3	±1.0	29.17±0.31	±1.1	23.99±0.22	±0.9	164	6.3	1366	48.8	2125
Lekhziri	Enguri	35.80±0.45	±1.3	33.95±0.47	±1.4	23.76±0.36	±1.5	859	33.0	736	26.3	2345
Agashtan	Cherek-Balkarskiy	21.35±0.18	±0.8	20.39±0.16	±0.8	18.93±0.21	±1.1	368	14.2	587	21.0	2510
Midjirgi	Cherek-Bezingskiy	13.77±0.25	±1.8	13.90±0.24	±1.7	12.71±0.24	±1.9	808	31.1	+40	+1.4	2650
Tsaneri southern*	Enguri	28.26±0.26	±0.9	14.38±0.16	±1.1	12.31±0.16	±1.3	448	17.2	781	27.9	2525
Tseya	Tseyadon	14.03±0.21	±1.5	12.83±0.19	±1.5	11.87±0.18	±1.5	295	11.3	341	12.2	2360
Tsaneri northern	Enguri	0**	0	13.30±0.11	±0.8	11.28±0.11	±1.0	0	0	574	20.5	3000
Kvitlodi	Enguri	12.23±0.13	±1.1	11.65±0.12	±1.0	9.58±0.1	±1.0	598	23.0	883	31.5	2580
Adishi	Enguri	10.48±0.11	±1.0	10.34±0.1	±1.0	9.58±0.1	±1.0	124	4.8	390	13.9	2480
Challati	Enguri	12.71±0.18	±1.4	12.36±0.19	±1.5	9.24±0.14	±1.5	460	17.7	223	8.0	1960
Khalde	Enguri	11.87±0.19	±1.6	10.65±0.18	±1.7	8.59±0.13	±1.5	130	5.0	130	4.6	2545
Shkhelda	Baksan	13.61±0.24	±1.8	12.50±0.25	±2.0	8.28±0.16	±1.9	950	36.5	480	17.1	2400

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

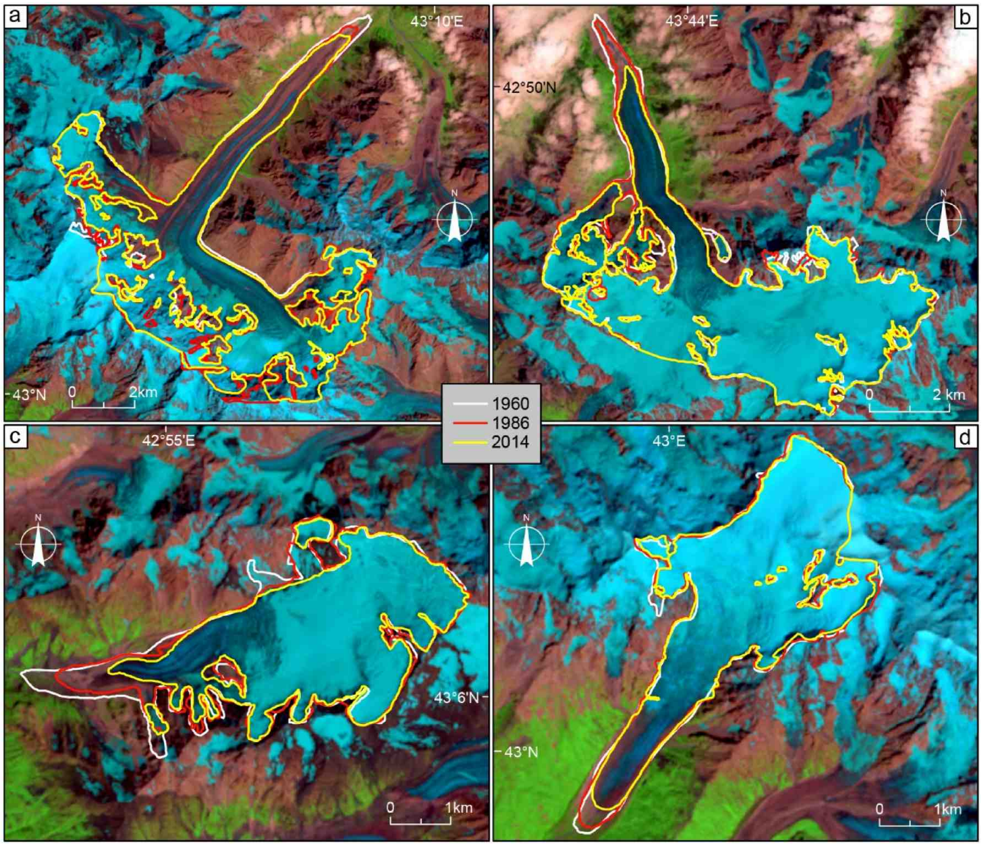

Figure 6. (a) Bezingi, (b) Karaugom, (c) Kvitlodi and (d) Adishi glaciers reduction in the years 1960-1986-2014. The 3/08/2014 Landsat 8 image (Table 1) is used as background.

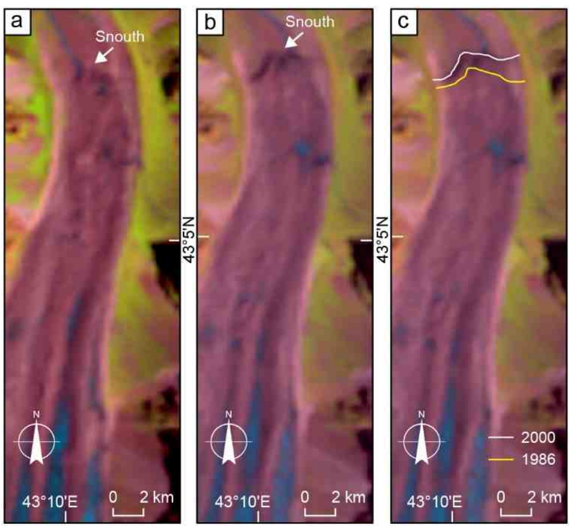

Figure 7. Mijirgi Glacier advance between 1986-2000. (a) Landsat 5 TM, 6/08/1986. (b) Landsat 5 TM, 12/08/2000. In 1986, the flow of meltwater comes from a different position at the terminus. (c) With the two snout comparison, it is visible that the snout has advanced.

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4.2 Climatic variability

There are strong positive mean annual and summer air temperatures linear trends at all meteorological stations for the period 1960-2014 (Fig. 8; Table 7). The highest mean annual air temperature increases were at Vladikavkaz.

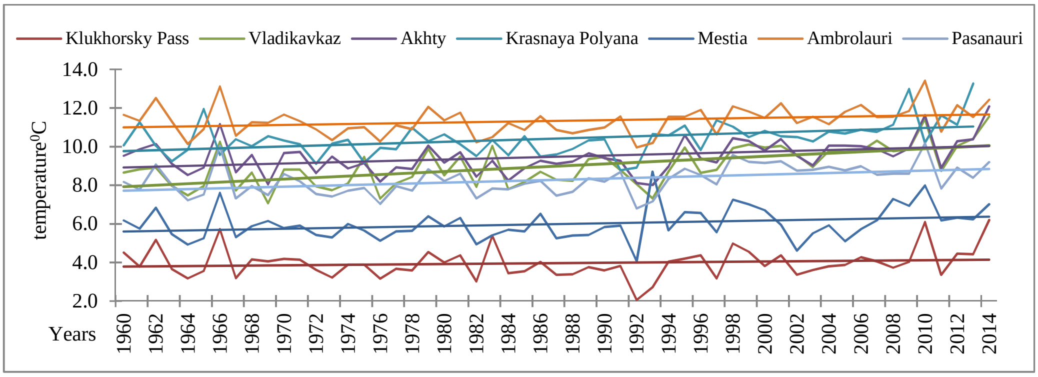

Figure 8. Mean annual air temperatures at the seven meteorological stations in the years 1960–2014.
teorological stations in the years 1960–2014.

Table 7. Mean monthly and JJA average monthly air temperatures (^{0}C) at the seven meteorological stations in 1960–1986 and 1987–2014.

Mean monthly air temperatures (^{0}C)				JJA average monthly temperatures (^{0}C)		
Meteo Station	**1960-1986**	**1987-2014**	**Increase**	**1960-1986**	**1987-2014**	**Increase**
Klukhorsky Pass	3.9	4.0	**0.1**	11.8	12.5	**0.7**
Vladikavkaz	8.5	9.4	**0.9**	18.7	19.9	**1.2**
Akhty	9.2	9.7	**0.5**	18.6	19.5	**0.9**
Krasnaya Polyana	10.1	10.6	**0.5**	18.6	19.7	**1.1**
Mestia	5.8	6.4	**0.4**	15.2	15.9	**0.7**
Ambrolauri	11.2	11.5	**0.3**	20.6	21.4	**0.8**
Pasanauri	8.0	8.6	**0.6**	17.3	18.3	**1.0**

The observed glacier recession is consistent with increasing air temperature of the ablation season (JJA) registered in both the northern and southern macroslopes (Fig. 9). The highest increase was recorded in the eastern Greater Caucasus, at Vladikavkaz station. The average JJA temperatures in 1960–1986 were 18.7^{0}C, versus 19.9^{0}C registered between 1986 and 2014 (Table 7). Increases are observed for all stations from 1960–1986 to 1987–2014.

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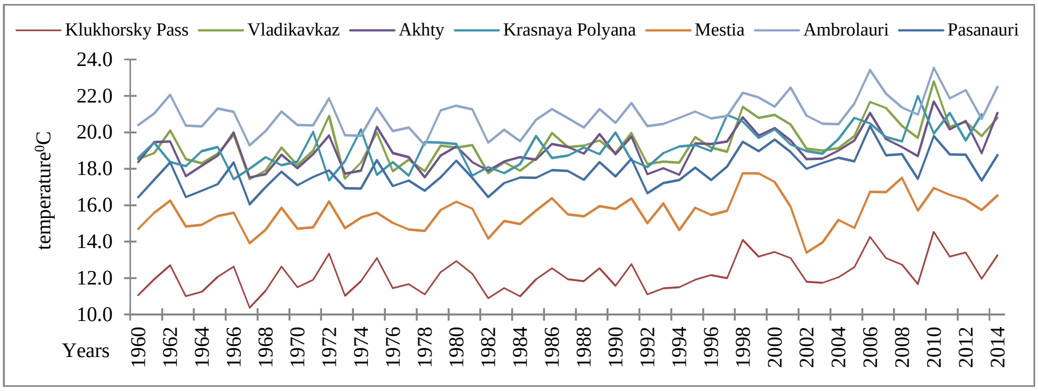

Figure 9. JJA temperature for the seven meteorological stations.

Increased precipitation in the accumulation season (October–April) was registered for all stations from 1960–1986 to 1987–2014 (Fig. 10; Table 8), but does not sufficiently offset impacts of the observed summer warming.

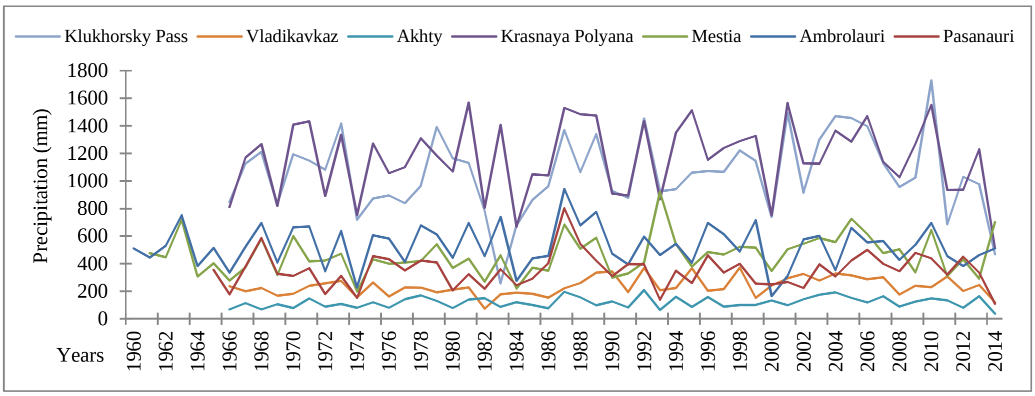

Figure 10. October–April precipitation for the seven meteorological stations.

Table 8. October-April average monthly precipitations (mm) at the seven meteorological stations in 1960/66–1986 and 1987–2014.

Meteo Station	**1960/66-1986**	**1987-2014**	**Increase (%)**
Klukhorsky Pass	970.0	1115.3	**15.0**
Vladikavkaz	200.8	262.6	**30.8**
Akhty	107.0	127.3	**19.0**
Krasnaya Polyana	1114.7	1205.5	**8.1**
Mestia	410.7	507.8	**23.6**
Ambrolauri	519.2	536.9	**3.4**
Pasanauri	329.7	367.8	**11.0**

5 Discussion

Shrinkage rates clearly show an increase from the northwest to the southeast of the Greater Caucasus. This spatial pattern is broadly consistent with patterns of area change reported earlier by Lur'e and Panov (2014); Shahgedova et al. (2014) and Tielidze (2016b). The higher glacier melt in the eastern Caucasus is conditioned not only by climate, but also by the morphological features 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).

The climate data suggest the loss of glacier surface area across the Greater Caucasus between the 1960s and 2014 mostly reflects influence of rising temperatures. Thus, temperature was the main control on the early glacial fluctuations of the 21st century in the Greater Caucasus, with the temperature rise leading to a marked decrease in glacier surface area, despite increase in precipitation during the accumulation season, (October-April). Nevertheless, the modest annual temperature increase over the last half century in the Greater Caucasus is lower than in some regions, for example, in the eastern Alps, where over the 20th century (1929-2011) temperatures have risen by ~1.8^{0}C (Zecchetto et al., 2016) at a rate about double the northern hemispheric average (Auer et al., 2007).

Similar rates of retreat have been found for glaciers in other mountain ranges. For example, in Kamchatka, Lynch et al. (2016) reported ~30% glacier area loss between 1950-2014. In the Kodar Mountains, Siberia, Stokes et al. (2013) document a 44% decrease in the area of exposed glacial ice between 1963 and 2010, with a 40% loss since 1995. Tennant et al. (2012) reported 40±5% (0.5±0.06% yr^{-1}) glacier area loss between 1919-2006 in the Canadian Rocky Mountains. Malmros et al. (2016) estimated overall loss in glacierized area of 30±3% from 1955 to 2013/14 in the Chilean and Argentinian Andes, though regional differences were noted.

Glacier reduction in the Caucasus Mountains appears to be slower in comparison with the European Alps. Fischer et al. (2014) reported 44%, or 1.2% yr^{-1} area loss, Swiss Alps for the 1973–2010, but this is for an area dominated by very small glaciers. The rate is slower in the Tibetan plateau, where Ye et al. (2017) document a 7.3±4.3% (0.2% yr^{-1}) decrease between 1970-2013. In the Tien Shan, Farinotti et al. (2015) found an 18±6% decrease in glacier surface area between 1961 and 2012. Winsvold et al. (2014) reported 11% reduction in Norway between 1947-2006.

We suggest the results of Khromova et al. (2009, 2014) - that the Caucasus glacier decrease was faster in the first half of 20th century than the second half, may be due to their use of the USSR catalog (1967-1978) for 1960s data. The USSR catalog presents over 250 km^2 less glacier area than our investigation, and over 50 km^2 less than Tielidze's (2016b) inventory for the Georgian Caucasus glaciers in the 1960s. Gobejishvili (1995) also refers to the USSR catalog data deficiencies.

The GLIMS glacier database (9.02.2017 version) contains inconsistent registration and there are a number of deficiencies to be remedied after this inventory, for example these river basins do 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 about one-third of the territory for the whole Greater Caucasus where modern glaciers are present. GLIMS (http://www.glims.org/maps/glims) represents the Caucasus as a Russian glacier region, which should be amended to a separate Caucasus region by individual countries (Russia/Georgia/Azerbaijan), as was done for Turkey or Iran, where glaciers are much smaller.

The RGI 5.0 version database similarly contains significant 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 km^2, we found an additional 40 glaciers with a total area of 3.5 km^2. 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.

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 1986 (Landsat 5) and 2014 (Landsat 8, ASTER) were used to map the 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 circue type glaciers) and uncertain glacier extents. Other sources of error for aerial imagery include seasonal snow, shadows, and debris cover, which can impede glacier mapping. Using the 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 0.4% yr^{-1} between 1960-1986 and 0.7% yr^{-1} between 1986-2014. Overall, the glacier loss was 0.5% yr^{-1} between 1960-2014.

b) Considering some errors in the 1911 catalog, we calculate that glacier area decreased from 1967.4 km^2 in 1911 to 1674.9 km^2 in 1960 or 14.9% (0.3% yr^{-1}). Overall this was 39.4% (0.4% yr^{-1}) between 1911-2014. Accordingly, we conclude that glacier area reduction accelerated between 1986-2014 in comparison with the 1960-1986 period and accelerated between 1960-2014 in comparison with the 1911-1960 period.

c) Glacier number and area changes indicate that glaciers in the eastern Greater Caucasus have retreated (1.0% yr^{-1}) more than in the central and western sections, and southern glaciers have retreated (0.6% yr^{-1}) more than northern glaciers between 1960-2014. The largest wastage in the eastern section is mostly in line with mean monthly and JJA temperature increases and the presence of Jurassic sedimentary rocks in this region. If the rapid decrease in the surface area of the glaciers on the eastern Greater Caucasus continues over the 21st century, many will disappear by 2100.

d) Glaciers of the Elbrus and Kazbegi-Dzhimara massifs lost a lower proportion of their area between 1960-2014, compared to glaciers located on the main watershed range, by 0.3% yr^{-1} and 0.4% yr^{-1} respectively.

e) The retreat of glacier termini accelerated between 1986-2014 in comparison with the 1960-1986 period.

A combination of several factors such as glacier size and elevation, as well as climatic aspects such as continentality in the eastern Caucasus and Black Sea influence in the western Caucasus, are related to the observed spatial trends in the glacier change analysis.

Future work, including aerial and satellite images with a higher resolution, may reduce these uncertainties. The inventory presented here will further enable focus on assessing changes in glaciers, debris cover, mass balance, total volume and hydrological modeling.

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