Supraglacial debris-cover changes in the Greater Caucasus

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Abstract

In spite of recent glacier studies in the Greater Caucasus, knowledge of supraglacial debris cover remains incomplete in this region. Here we present data of supraglacial debris cover for 659 glaciers across the Greater Caucasus based on Landsat and SPOT images from 1986, 2000, and 2014. We combined semi-automated methods for mapping the clean ice with manual digitization of debris-covered glacier parts and calculated supraglacial debris cover area as the residual between these two maps. Assessment of uncertainties were performed using the buffer method, high resolution Google Earth imagery, and GPS data for selected glaciers. From 1986 to 2014, the total glacier area decreased from 691.5±29.0 km^2 to 590.0±25.8 km^2 (-15.8±4.1% or -0.52% yr^{-1}) while the clean ice area reduced from 643.2±25.9 km^2 to 511.0±20.9 km^2 (-20.1±4.0% or -0.73% yr^{-1}) in contrast with an increase of supraglacial debris cover from 7.0±6.4% or 48.3±3.1 km^2 in 1986 to 13.4±6.2% (+0.22% yr^{+1}) or 79.0±4.9 km^2 in 2014. Debris-free glaciers exhibited higher area and length reductions than debris-covered glaciers. There are differences in the distribution of the supraglacial debris cover on the glaciers between northern and southern and between western, central and eastern Greater Caucasus. The observed increase of supraglacial debris cover is significantly stronger in the northern slopes. Overall we have observed up-glacier migration of supraglacial debris cover during the investigated period. The new supraglacial debris cover database created during the investigated period will be submitted to GLIMS, and can be used as a basis dataset for future studies.

1 Introduction

Supraglacial debris cover on mountain glaciers affects surface melt rates, increasing rates of ablation in cases of thin debris cover (< a few cm), or decreasing ablation under thick debris cover (Östrem, 1959; Nicholson et al., 2018). It is relevant not only from its impact on glacier ablation but also because it is an important part of the sediment transport system (supraglacial, englacial, and subglacial) in cold and high mountains, which ultimately affect the overall dynamics, and mass balance of the glaciers. Several studies show an increase in debris-covered area with overall glacier shrinkage and mass loss (Deline, 2005; Stokes et al., 2007, Kirkbride and Deline, 2013; Glasser et al., 2016).

For regions where the local population is dependent on glacial meltwater supply, detailed knowledge of glacial hydrology is important to ensure the sustainable use of water resources (Baraer et al., 2012). One difficulty of such investigations is associated with limited knowledge of the large-scale extent, thickness, and properties of the supraglacial debris cover. Field measurement of debris layers have practical difficulties on a large scale, and methods for estimating supraglacial debris thickness using remote sensing remain in development (Zhang et al., 2016). Several studies have also reported the role of debris cover in promoting the formation of supraglacial lakes (Thompson et al., 2016; Jiang et al., 2018), which are directly related to glacial hazards (Benn et al., 2012). Therefore, it is necessary to take supraglacial debris cover into account when assessing temporal change of mountain glaciers.

Ice and snow melt in the Greater Caucasus are major sources of runoff for populated places in many parts of the Caucasus region (Tielidze, 2017); supraglacial debris cover is an important control for ice ablation (Lambrecht et al., 2011), and a component in glacier mass balance (Popovnin and Rozova, 2002). Thus, correct delineation of supraglacial debris cover in the Greater Caucasus is vital to correctly model future glacier development. A recent global study (Scherler et al., 2018) measured that supraglacial debris cover is abundant in the Caucasus and Middle East (more than 25% of glacier area) and that this region shows the highest percent of supraglacial debris cover worldwide. However, Scherler et al. (2018) used the RGI v6 database with some inconsistent co-registration and nominal glaciers. That makes a good motivation for us to provide an improved estimate of supraglacial debris cover for this region. Earlier studies indicated lower relative supraglacial debris cover in the Greater Caucasus but extensive in smaller regions (Stokes et al., 2007) or individual glaciers (Lambrecht et al., 2011; Popovnin et al., 2015).

Based on a recently published glacier inventory (Tielidze and Wheate, 2018), we present the first regional assessment of the spatial distribution of supraglacial debris cover and related glacier changes between 1986, 2000 and 2014 for the Greater Caucasus.

2 Study area

The Greater Caucasus is one of the world's highest mountain systems, and the major mountain unit of the Caucasus region. The range stretches for about 1300 km from west-northwest to east-southeast, between the Taman Peninsula of the Black Sea and the Absheron Peninsula of the Caspian Sea. Using morphological and morphometric characteristics, the Greater Caucasus can be divided into three parts - Western, Central and Eastern. At the same time, the terms northern and southern Greater Caucasus are commonly used. The central Greater Caucasus is the highest part of the main watershed range represented by summits exceeding 5000 m: Dykh-Tau - 5205 m, Shkhara - 5203 m, Jangha - 5058 m, and Pushkin Peak - 5034 m. The western and eastern sections are relatively lower with highest summits of Mt. Dombai-ulgen (4046 m) and Mt. Bazardüzü (4466 m) respectively. Elbrus is the highest summit of the Greater Caucasus with two peaks - western (5642 m) and eastern (5621 m).

According to the recent inventory, this mountain range contains over 2000 glaciers with a total area of about 1200 km^2. The northern slopes of the Greater Caucasus contain more glaciers than the southern slopes (Tielidze and Wheate, 2018). The altitude of the glacier equilibrium line (ELA), increases from 2500–2700 m in the west to 3700-3950 m in the eastern sector of the northern slope of the Greater Caucasus (Mikhalenko et al., 2015). The ELA was determined to range from ~3030 m in the west to ~3480 m in the eastern section of the southern slope of the Greater Caucasus (Tielidze, 2016). The ELA is ~1000 m higher on the northern slopes of the Elbrus than the southern slopes of the central Greater Caucasus (Mikhalenko et al., 2015).

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 slopes. The mean annual temperatures at the northern slopes are usually 1-2°C cooler than those in the south (Tielidze and Wheate, 2018). The average regional lapse rate is minimum in winter (2.3°C per 1000 m) and maximum (5.2°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 slope, as well as between the southern and the northern slopes. Annual precipitation ranges between 2000-2500 mm in the west and declines to 800-1150 mm in the east on the northern slope of the Greater Caucasus. The central section of the southern slope receives over 2000 mm of precipitation while in the east, the annual total is 1000 mm. The south-western section of the region is very humid with annual precipitation about 3200 mm (Volodicheva, 2002; Mikhalenko et al., 2015).

3 Data and methods

3.1 Datasets

We selected 659 glaciers with total area of 590.0±25.8 km^2: 223 glaciers in the western Greater Caucasus (145 - northern slope, 78 - southern slope); 285 in the central Greater Caucasus (173/112); and 130 in the eastern Greater Caucasus (130/0, as glaciers are almost non-existent in the south). In addition, all 21 glaciers on Elbrus (5 - northern slope, 8 - southern slope, 5 - western slope, 3 - eastern slope) - the largest glacierised massif in the whole region - were selected (Fig. 1a). Overall, this equals 49.5% and 32.6% of the Greater Caucasus total glacier area and number respectively. The size of the largest glacier selected was 37.5 km^2 and the smallest – 0.01 km^2. The surface area for each glacier was calculated according to Paul et al. (2009).

A total of nine Landsat images were used in this study (Fig. 1 b-d; Table 1), downloaded from the Earthexplorer website (http://earthexplorer.usgs.gov/). These images with a spatial resolution of 30 m were acquired from Landsat Thematic Mapper (TM) (1985/86), Enhanced Thematic Mapper Plus (ETM+) (2000), and Landsat 8 Operational Land Imager (OLI) (2013/14). We also used a high resolution (1.5 m) SPOT satellite image from 2016, orthorectified using ScanEx Image Processor software and the SRTM DEM. The Landsat scenes served as a basis for supraglacial debris cover assessment while the SPOT image was used for corrections of supraglacial debris cover areas of Elbrus. All imagery was captured from the 28th of July to the 12th of September, when glacier tongues were mostly free of seasonal snow under cloud-free conditions.

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM, 30 m) version 2 (http://asterweb.jpl.nasa.gov/gdem.asp) was used to assess spatial change and calculate supraglacial debris cover by 500 m elevation bands. We used these elevation bands to intersect our digitized debris-covered areas for 1985/86 to 2013/14, with the total area per elevation band.

Other datasets used in this study include the “Greater Caucasus Glacier Inventory” manually mapped dataset (Tielidze and Wheate, 2018), high resolution images from Google Earth, and GPS measurements.

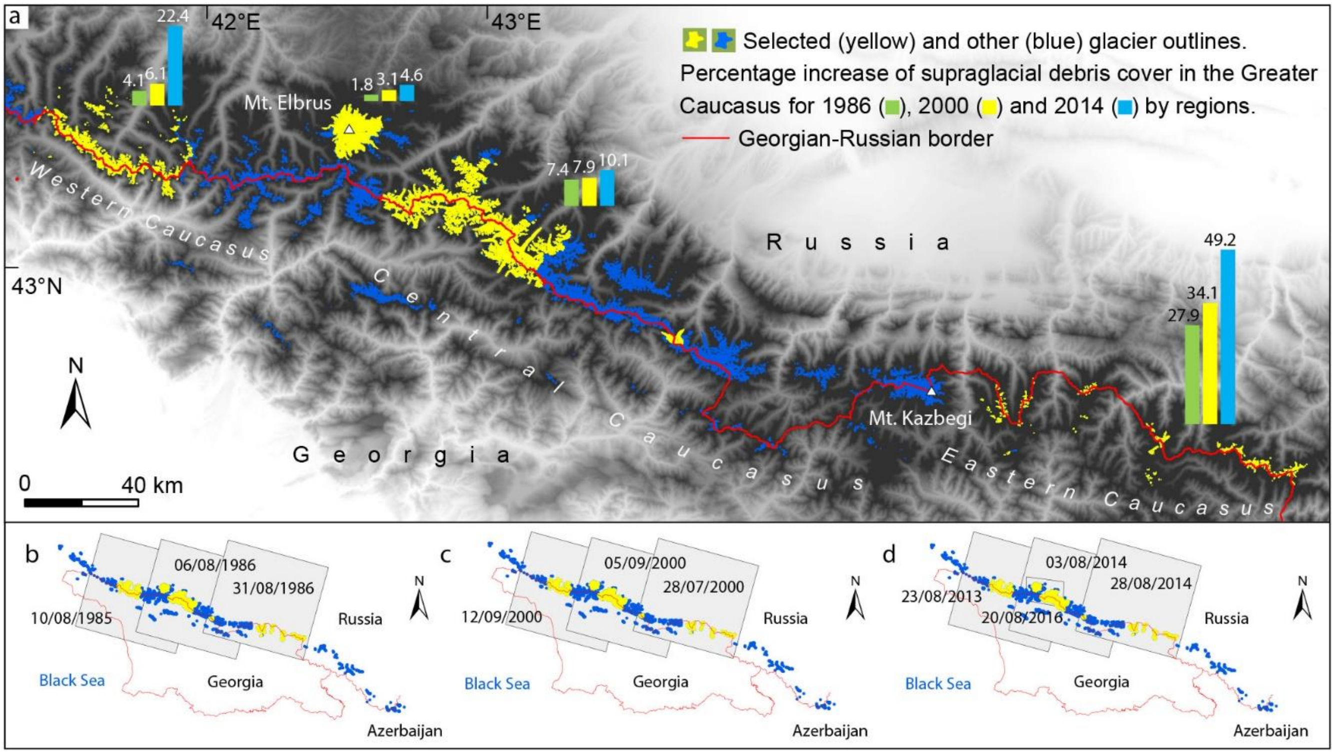

Figure 1. a – Investigated area and selected glaciers by regions. b – Three Landsat 5 TM satellite scenes 1985-1986. c – Three Landsat 7 ETM+ satellite scenes from 2000. d – Three Landsat 8 OLI satellite scenes from 2013-2014 and one (smaller) SPOT satellite scene from 2016.

Table 1. Satellite images used in this study.

Date	UTM zone	Sensor	Region/Section	Resolution	Scene ID
10/08/1985	37N	Landsat 5 TM	Western Greater Caucasus	30 m	LT51720301985222XXX04
06/08/1986	38N	Landsat 5 TM	Central Greater Caucasus	30 m	LT51710301986218XXX02
31/08/1986	38N	Landsat 5 TM	Eastern Greater Caucasus	30 m	LT51700301986243XXX03
12/09/2000	37N	Landsat 7 ETM+	Western Greater Caucasus	15/30 m	LE71720302000256SGS00
05/09/2000	38N	Landsat 7 ETM+	Central Greater Caucasus	15/30 m	LE71710302000249SGS00
28/07/2000	38N	Landsat 7 ETM+	Eastern Greater Caucasus	15/30 m	LE17003020000728SGS00
23/08/2013	37N	Landsat 8 OLI	Western Greater Caucasus	15/30 m	LC81720302013235LGN00
03/08/2014	38N	Landsat 8 OLI	Central Greater Caucasus	15/30 m	LC81710302014215LGN00
28/08/2014	38N	Landsat 8 OLI	Eastern Greater Caucasus	15/30 m	LC81700302014240LGN00
20/08/2016	37N	SPOT-7	Elbrus	1.5 m	DS_SPOT7201608200751063

3.2 Methods

The widely used band ratio segmentation method (RED/SWIR; Landsat OLI 4/6 or TM 3/5 with a threshold of ≥2.0) was used as the first step in delineating clean-ice outlines (Bolch et al., 2010; Paul et al., 2013), and then intensive manual improvements were performed (removed misclassified areas, e.g. snow, shadows). In the next step supraglacial debris cover was classified as the residual between a semiautomatically derived clean-ice map and a manually mapped (by Tielidze and Wheate, 2018) glacier extent map (Paul et al., 2004) (Fig. 2a). To assess temporal change, we calculated the area of supraglacial debris cover for individual glaciers for the years 1986, 2000, and 2014.

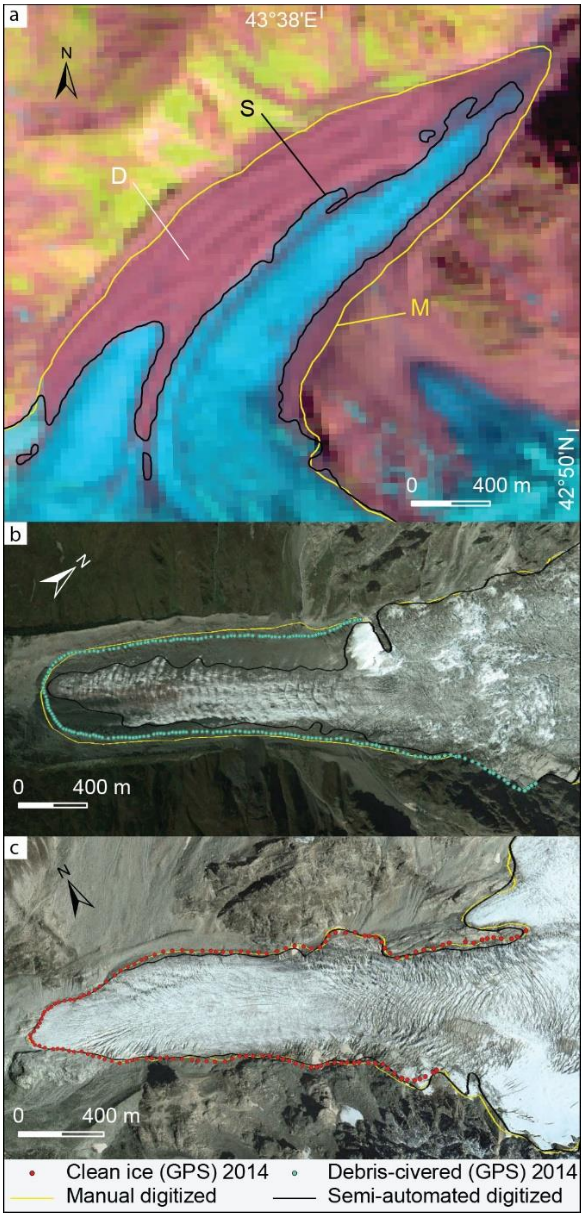

Figure 2. Mapping examples: a – supraglacial debris cover (D) assessment with comparison of different methods: manually (M) and semi-automated (S) (ratio TM 3/5 followed by manual improvement, threshold ≥2). Landsat image 06/08/1986 is used as the background. Examples of glacier outline accuracy assessment by GPS measurements: b – Adishi Glacier; c – Kirtisho Glacier. Google Earth imagery 19/09/2011 is used as the background.

We used Glacier Classification Guidance from the Global Land Ice Measurements from Space (GLIMS) for remote sensing observations (Rau et al., 2005) to define debris-free and debris-covered glaciers. According to this guideline we identified three different classes of glaciers: i) debris-free (almost no debris coverage on the glacier surface); ii) partly debris-covered (>10% and <50% of the glacier surface is debris covered); and iii) mostly debris-covered (>50% and <90% of the glacier surface is debris covered). The second and third classes of glaciers were defined as debris-covered glaciers in this study.

The buffer method (Granshaw and Fountain, 2006) was used for uncertainty estimation for both clean ice and debris-covered glacier parts. For clean ice we used a 15 m (1/2 pixel) buffer (Bolch et al., 2010) and for debris-covered parts 60 m (two pixels) (Frey et al., 2012). Following Mölg et al. (2018) we used the standard deviation of the uncertainty distribution for the estimate, as a normal distribution can be assumed for this type of mapping error. It is applied to glacier complexes excluding overlapping areas, as well as the border of clean and debris-covered ice of the same glacier. This generated an average uncertainty for the clean-ice/debris-covered parts of 4.0%/6.4% for 1986, 4.1%/6.3% for 2000, and 4.1%/6.2% for 2014. The uncertainty estimates for all Caucasus glaciers are described in previous studies (Tielidze, 2016; Tielidze and Wheate, 2018).

Upon delineation of supraglacial debris cover and clean ice areas, three randomly selected glacier outlines were corrected by review of exported polygons into Google Earth, which includes high resolution Quickbird images superimposed upon the SRTM3 topography (Raup, et al., 2014). They were then compared with outlines from nearly simultaneous Landsat 8 images. The area differences between the two sets of results were calculated as ±5.2% for supraglacial debris cover and ±3.4% for clean ice.

For extra uncertainty assessment we used GPS (Garmin 62stc) measurement data which included glacier margins (>1200 points) with horizontal accuracy from ±4 to ±10 m, obtained during field investigations in 2014. In total seven glaciers (Ushba, Chalaati, Lekhziri, Adishi, Shkhara, Zopkhito, Kirtisho) were surveyed. Fig. 2b-c shows the results of comparison between GPS measurements and Landsat based supraglacial debris cover/clean ice outlines. Based on all seven glacier measurements, the average accuracy was calculated as ±30 m for supraglacial debris cover and ±15 m for clean ice.

High resolution SPOT imagery was used for additional mapping of the debris covered area for Elbrus. The normalized standard deviation (NSD – based on delineations by two digitizations divided by the mean area) (Paul et al. 2013) between two datasets (Landsat and SPOT) was ±7.4%.

4 Results

We found an absolute increase of supraglacial debris cover for all investigated glaciers from 48.3±3.1 km^2 in 1986, to 54.6±3.4 km^2 in 2000 and 79.0±4.9 km^2 in 2014, in contrast with a reduction of the total glacier area. This equates to a total increase in the proportion of supraglacial debris cover surface area from 7.0±6.4% in 1986, to 9.1±6.3% (+0.15% yr^{+1}) in 2000, and to 13.4±6.2% (+0.30% yr^{+1}) in 2014 (Table 2; Fig. 3). Supraglacial debris cover was greatest in the glacier area classes 1.0-5.0 km^2 and 5.0-10.0 km^2 for both northern and southern slopes (Fig. S1). The number of debris-covered glaciers also increased from 122 in 1986, to 143 in 2000, and to 172 in 2014.

On the northern slope of the western Greater Caucasus, supraglacial debris cover area increased, especially in the second investigated period from 7.1±6.6% to 26.1±6.4% (+1.35% yr^{+1}). The increase rate on the southern slope was much lower in the same time (+0.57% yr^{+1}), and the overall supraglacial debris cover area (11.5±7.1%) was only about half the value of the northern slope (Table 2; Fig. 3, 4).

The central Greater Caucasus contained the largest supraglacial debris cover area in 1986 (6.9±6.3%) but the increase was significantly lower than in the western and eastern sections over the last 30 years - from 7.7±6.1% to 12.6±6.0% (+0.18% yr^{+1}) on the northern slope and 6.0±6.5% to 6.9±6.7% (+0.03% yr^{+1}) on the southern slope in 2014.

Table 2. Change of supraglacial debris cover and bare ice in the Greater Caucasus for 1985/86, 2000 and 2013/14 by regions and slopes. The error values are derived by a buffer approach.

Section and river basin	Selected glacier number	Landsat 5 TM, 1985/86					Landsat 7 ETM+, 2000					Landsat 8 OLI, 2013/14. SPOT 2016				
		Total glacier area km²	Clean ice area km²	Debris covered area			Total glacier area km²	Clean ice area km²	Debris covered area			Total glacier area km²	Clean ice area km²	Debris covered area		
				Glacier number	Area km²	%*			Glacier number	Area km²	%*			Glacier number	Area km²	%*
Western Caucasus																
Northern slope (Kuban)	145	91.7±3.4	87.1±3.1	15	4.6±0.31	5.0±6.7	87.2±3.4	80.8±3.0	21	6.2±0.41	7.1±6.6	78.3±3.4	57.9±2.1	33	20.4±1.3	26.1±6.4
Southern slope (Kodori)	78	35.5±1.7	34.8±1.6	1	0.7±0.05	2.0±7.1	32.8±1.6	31.7±1.5	1	1.1±0.078	3.5±7.1	26.1±1.3	23.1±1.1	3	3.0±0.21	11.5±7.1
Sum	**223**	**127.2±5.1**	**121.9±4.7**	**16**	**5.3±0.36**	**4.1±6.8**	**119.8±5.0**	**112.5±4.5**	**22**	**7.3±0.48**	**6.1±6.6**	**104.4±4.4**	**81.0±3.2**	**36**	**23.4±1.5**	**22.4±6.4**
Central Caucasus																
Northern slope (Baksan, Chegem, Cherek)	173	211.0±8.6	194.7±7.6	28	16.3±1.0	7.7±6.1	203.2±8.6	184.5±7.5	37	18.7±1.1	9.2±6.1	185.3±8.3	161.9±6.9	42	23.4±1.4	12.6±6.0
Southern slope (Enguri)	112	178.8±7.4	168.1±6.7	15	10.7±0.69	6.0±6.5	171.3±7.3	160.5±6.6	15	10.8±0.69	6.3±6.4	149.8±6.6	139.4±5.9	17	10.4±0.70	6.9±6.7
Sum	**285**	**389.8±15.0**	**362.8±14.4**	**43**	**27.0±1.7**	**7.4±6.3**	**374.5±15.9**	**345.0±14.1**	**52**	**29.5±1.8**	**7.9±6.2**	**335.1±14.9**	**301.3±12.8**	**59**	**33.8±2.1**	**10.1±6.2**
Eastern Caucasus																
Northern slope (Tergi headwaters, Sunja Right tributaries, Sulak)	**130**	**49.1±2.5**	**35.4±1.7**	**54**	**13.7±0.84**	**27.9±6.2**	**41.3±2.5**	**27.2±1.6**	**56**	**14.1±0.86**	**34.1±.6.1**	**32.1±2.0**	**16.3±1.1**	**59**	**15.8±0.90**	**49.2±5.7**
Elbrus Massif	21	125.4±5.3	123.1±5.1	9	2.3±0.16	1.8±6.9	120.9±4.6	117.2±4.3	13	3.7±0.25	3.1±6.8	118.4±4.2	112.4±3.8	18	6.0±0.4	4.6±6.6
All selected glaciers	**659**	**691.5±29.0**	**643.2±25.9**	**122**	**48.3±3.1**	**7.0±6.4**	**656.5±27.9**	**601.9±24.5**	**143**	**54.6±3.4**	**9.1±6.3**	**590.0±25.8**	**511.0±20.9**	**172**	**79.0±4.9**	**13.4±6.2**

* % of the total glacier area.

The eastern Greater Caucasus contains fewer glaciers but represents the largest percentage of supraglacial debris cover. Over the last 30 years, it almost doubled from 27.9±6.2% to 49.2±5.7% (+0.76% yr^{+1}).

The Elbrus Massif contained the least percentage of supraglacial debris cover in all our study regions, but it more than doubled between 1986 and 2014 (from 1.8±6.9% to 4.6±6.6% or +0.10% yr^{+1}). Supraglacial debris cover distribution according to the different slopes of the Elbrus was not homogenous. The increase rate was highest on the eastern slope from 1.22% to 8.20% or +0.25% yr^{+1} between 1986 and 2014, while the western slope had lowest increase rate from 7.10% to 8.55% or +0.05% yr^{+1}. In the same time, glacier area decrease was lowest on the western slope from 9.43 km^2 to 9.23 km^2 or -0.08% yr^{-1} and highest on the eastern slope from 36.76 km^2 to 33.50 km^2 or -0.31% yr^{-1} (Fig. 5a-c).

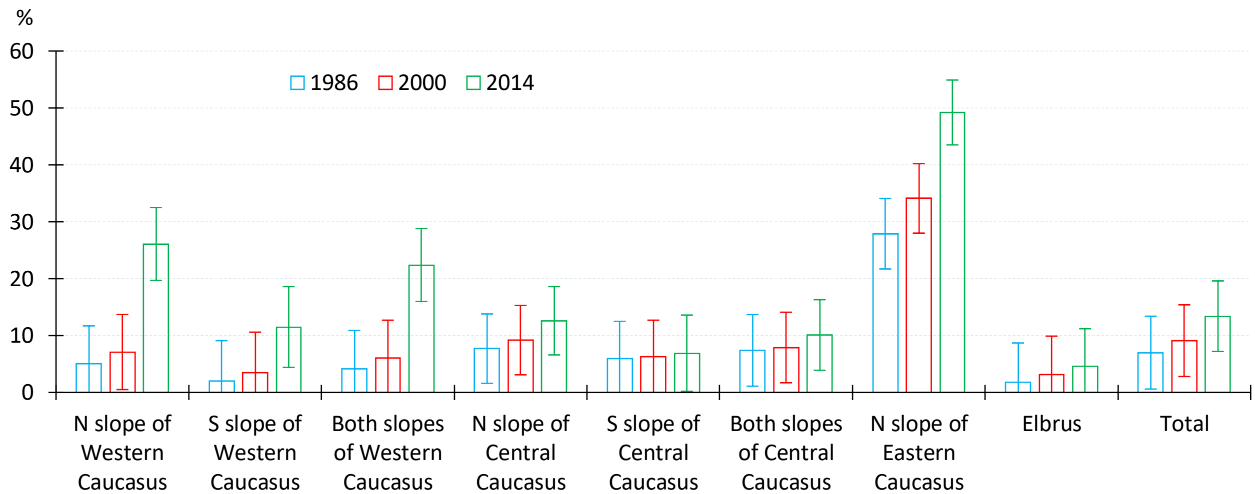

Figure 3. Percentage increase of supraglacial debris cover in the Greater Caucasus for 1986, 2000 and 2014 by different regions (glaciers are non-existent on southern slopes of the eastern Greater Caucasus).

For all regions investigated in the Greater Caucasus the rate of increase in supraglacial debris cover varied between northern and southern aspects. Debris-covered area increased from 7.7±6.2% or 36.9±2.3 km^2 to 15.4±6.1% (+0.28% yr^{+1}) or 65.6±4.0 km^2 on the northern slope (including Elbrus), and from 5.3±6.5% or 11.4±0.74 km^2 to 7.6±6.9% (+0.08% yr^{+1}) or 13.4±0.91 km^2 on the southern slope of the Greater Caucasus between 1986 and 2014.

Hypsometric profiles show that supraglacial debris cover is most commonly found in the 2500-3000 m zone for Elbrus and the 1900-2500 m zone for the other regions (Fig. 6). The supraglacial debris cover has doubled from 6.4% to 12.2% (+0.21% yr^{+1}) in 3000-3500 m zone for all selected glaciers in 1986-2014 (Fig. 6d), and has increased in the 3500-4000 m zone for all regions and selected glaciers during the investigated period.

Supraglacial debris cover area for (the largest) Bezingi Glacier in the Greater Caucasus increased from 4.4±0.3 km^2 or 11.0±5.9% to 7.5±0.4 km^2 or 20.0±6.0% (+0.32% yr^{+1}) between 1986 and 2014 in contrast with a reduction of the total glacier area from 40.0±0.9 km^2 to 37.5±0.9 km^2 (-6.3% or -0.22% yr^{-1}) during the same period with a terminus retreat of ~374 m. Comparison with the debris-free Karaugom Glacier (third largest glacier of the Greater Caucasus), located in the same region (northern slope of central Greater

Caucasus), shows that the area reduction was almost three times greater than the debris-covered Bezingi Glacier: from 29.2±0.6 km^2 to 24.0±0.4 (-17.8% or -0.63 yr^{-1}) with a terminus retreat of ~1366 m (Fig. S2).

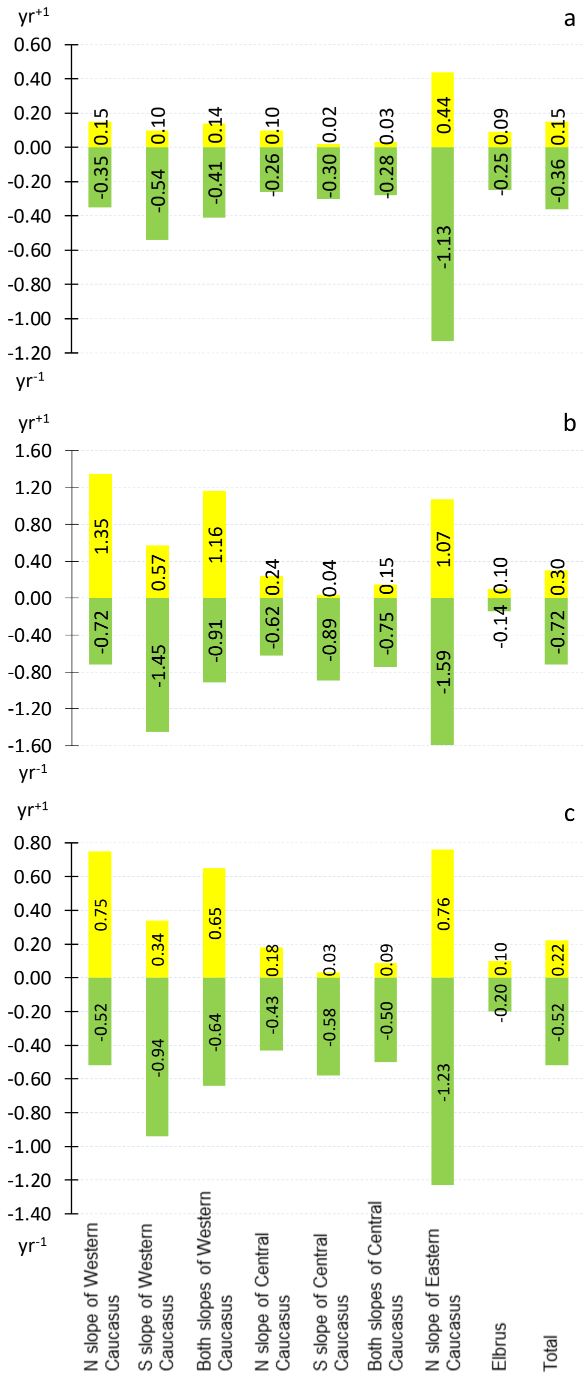

Figure 4. Supraglacial debris cover increase (yellow) and glacier area decrease (green) rates in the Greater Caucasus by slopes, sections and mountain massifs in 1986–2000, 2000–2014 and 1986–2014.

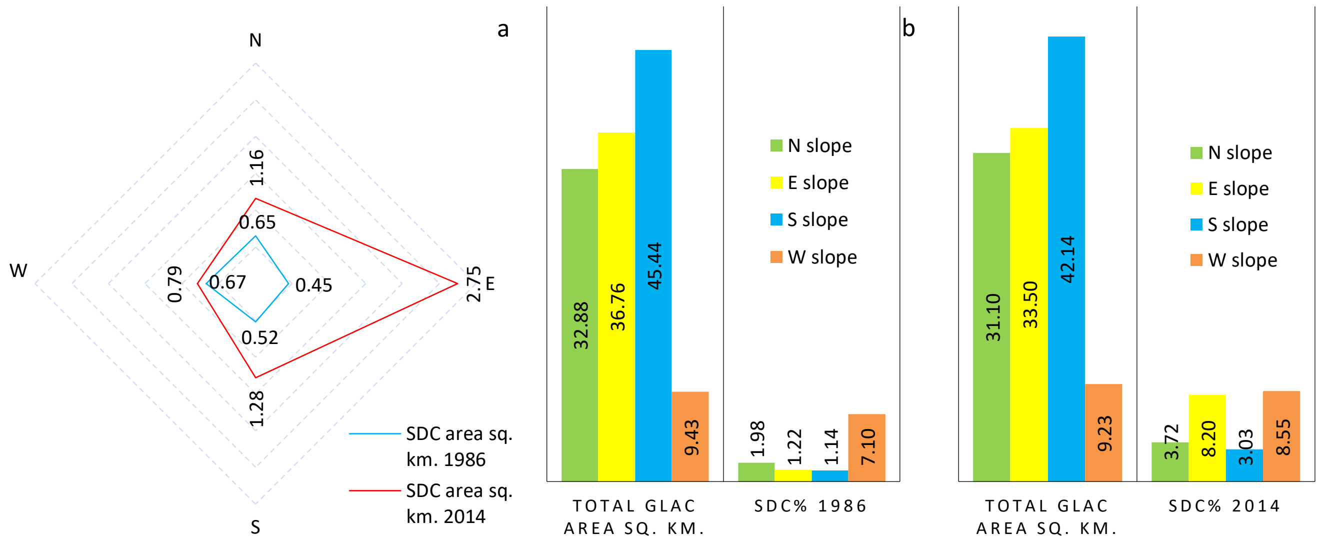

Figure 5. a – Supraglacial debris cover (SDC) area increase for the Elbrus slopes between 1986 and 2014. b and c – Total glacier area (km^2) and supraglacial debris cover percentage distribution between 1986 and 2014.

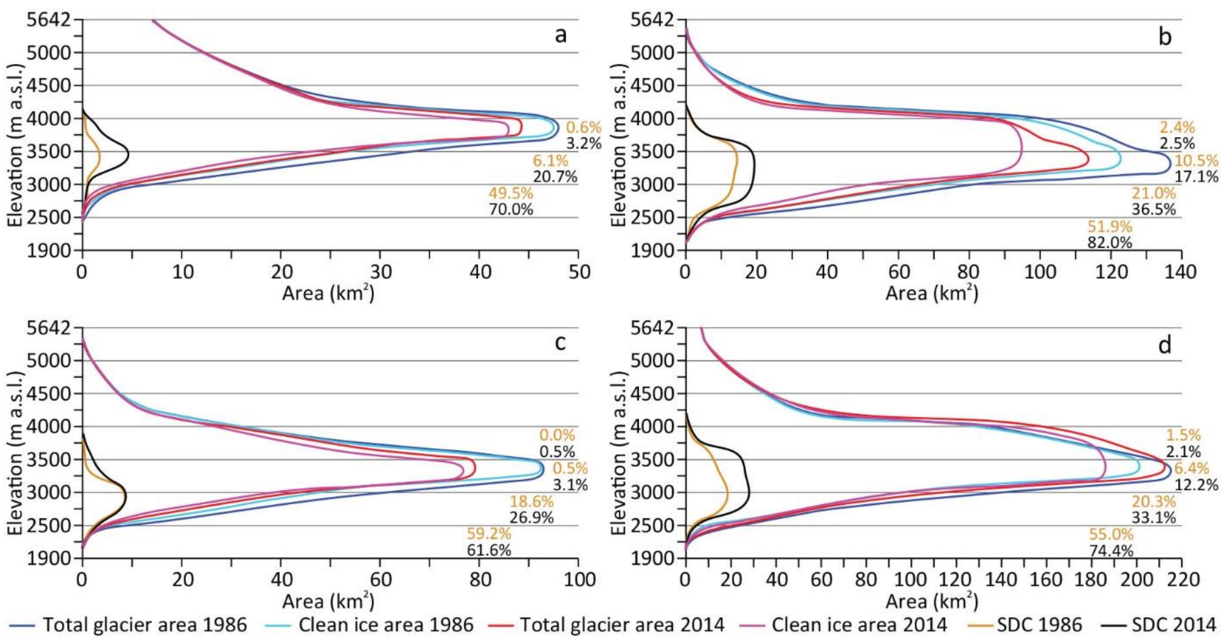

Figure 6. Hypsometry of supraglacial debris cover (SDC), clean ice and total glacier area, of the four study regions in 1986 and 2014. a – Elbrus, b – Northern Slope, c – Southern Slope, d – all selected glaciers. Supraglacial debris cover percentage is given according to the different elevation zones in 1986 (brown digits) and 2014 (black digits).

5 Discussion

5.1 Comparison with previous investigations

Direct comparisons of supraglacial debris cover with previous investigations in the Greater Caucasus are difficult, because most of them cover only a relatively small area (except Scherler et al. 2018). However, our results are in good agreement with other studies of supraglacial debris cover change in this region. For example, Stokes et al. (2007) calculated that supraglacial debris cover generally increased by 3%-6% (+0.20% yr^{+1}) between 1985 and 2000 on several glaciers in the central Greater Caucasus. On individual glaciers, supraglacial debris cover ranges from just a few percent (e.g. Bzhedukh) to over 25% (e.g. Shkhelda). Popovnin et al. (2015), reported a supraglacial debris cover increase from 2% to 13% (+0.23% yr^{+1}) between 1968-2010 based on direct field monitoring for the Djankuat Glacier (northern slope of the central Greater Caucasus). The debris layer became thicker and larger at some points near the terminus between 1983 and 2010, and the volume of the lithogenic matter over the whole glacier increased by ~140%. Lambrecht et al. (2011) estimated that the supraglacial debris cover distribution remained nearly constant at ~16% between 1971 and 1991 in the Adyl-su River basin (northern slope of the central Greater Caucasus). Between 1991 and 2006, the supraglacial debris cover started to increase noticeably reaching 23% (+0.46% yr^{+1}) within 15 years. For the Zopkhito River basin glaciers (southern slope of the central Greater Caucasus), supraglacial debris cover increase was lower in the same period (from 6.2% to 8.1% or +0.12% yr^{+1}).

We extracted both supraglacial debris cover and clean-ice outlines from Scherler et al. (2018) for our glacier sample to compare these results of our regional study with those from the global study. We found that a large portion of selected glaciers in the Greater Caucasus are covered by supraglacial debris cover, but our values are clearly lower than the results of Scherler, et al. (2018) who calculated more than 30% of supraglacial debris cover in the same glaciers for 2015 (Fig. S3). These differences can mostly be explained by i) the RGI v6 used by Scherler, et al. (2018), is characterized by some inconsistent co-registration for the Greater Caucasus region which probably stems from the use of improper orthorectified satellite imagery in contrast to the improved orthorectification of the Landsat L1T data (Fig. S4a); and ii) the RGI v6 contains nominal glaciers (i.e. ellipses around glacier label points) for the Greater Caucasus region which originate from the use of the world glacier inventory (WGI, Haeberli, et al., 1989) to fill gaps with no data for earlier versions of the RGI. According to Scherler, et al. (2018), all nominal glaciers were classified as debris covered (Fig. S4b). We note that the scope of the study by Scherler et al. (2018) was an automatized global assessment of supraglacial debris cover from optical satellite data, without correcting any outlines in the RGI.

5.2 Possible reasons for supraglacial debris-cover changes

We observed a clear increase in supraglacial debris cover in all investigated regions, which became more pronounced after 2000. Based on our investigation, the upper limit of supraglacial debris cover migrated up-glacier (Fig. 6, 7) as a response to glacier retreat thinning and reduced mass flux, as described by Stokes et al. (2007) and defined as 'backwasting' by Benn and Evans (1998). A similar pattern of up-glacier migration has also been detected on Tasman Glacier, New Zealand (Kirkbride and Warren, 1999), and on Zmuttgletscher Glacier, Swiss Alps (Mölg et al., 2019).

The results presented in this study indicate that the clean ice area for all selected glaciers decreased by -20.1±4.0% or -0.73% yr^{-1} between 1986 and 2014 (Table 2). This reduction was caused by both glacier retreat and an increase in total supraglacial debris cover (Table 2, Fig. 3-6). This finding is supported by field measurements on Djankuat Glacier, which indicate that supraglacial debris cover area increased from 2% to 13% (+0.23% yr^{+1}) and became thicker between 1968 and 2010 during glacier retreat (Popovnin et al., 2015).

Glacier thinning and a warming atmosphere can lead to permafrost thawing and slope instability at higher altitudes (Deline et al., 2015). Rock avalanches after 2000 on some glaciers in the Greater Caucasus (particularly in the eastern section), have strongly increased supraglacial debris cover (Tielidze, et al., 2019a). Supraglacial debris cover area increased from 2.1±6.1% to 17.6±5.7% or +1.09% yr^{+1} for the Suatisi Glacier and from 5.9±6.0% to 19.1±5.6% or +0.94% yr^{+1} for the Devdoraki Glacier between 2000 and 2014 (Fig. S5). This might be one of the reasons why the increase rate was higher during the second period (2000-2014).

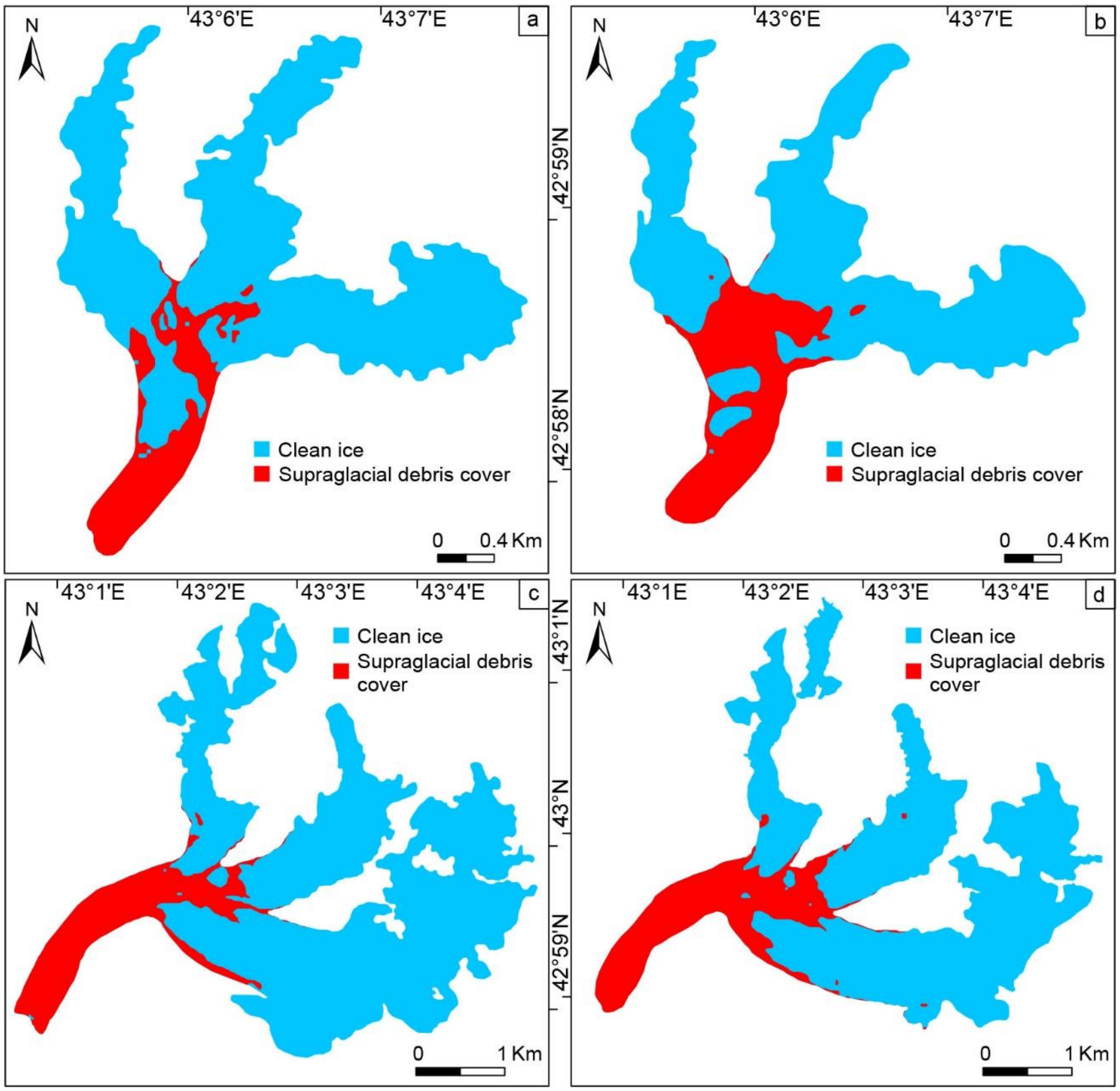

Figure 7. An example of the supraglacial debris cover up-glacier migration onto the Shkhara Glacier: a – 1986, b – 2014 and Khalde Glacier: c – 1986, d – 2014.

Our investigation shows also that the supraglacial debris cover increases more quickly in the northern slopes of the Greater Caucasus than in the southern. Due to the climatic (more radiation input on the southern side) and orographic conditions, glaciers on the southern slopes have relatively smaller size compared to their northern equivalents, although smaller glaciers exist as well in high cirques. Glacier surfaces on the northern slopes are less steep than the south. Most valley glacier tongues in the north are longer and reach lower altitudes than the southern-facing glaciers. But there are some exceptions, where the northern-facing glaciers are shorter and steeper, and here, the glaciers of the southern slope are characterized with relatively more supraglacial debris cover. An example is Georgia's largest glacier Lekhziri and its northern counterparts, with the exception of the Bashkara Glacier (Fig. S6). This conclusion is supported by Lambrecht et al. (2011) who observed increase of supraglacial debris cover more rapidly in the northern slopes, than the southern.

The variation of supraglacial debris cover area in the eastern, central and western Greater Caucasus could mostly be conditioned by climate, lithology and morphological peculiarities of the relief. Some river basins in the eastern Greater Caucasus are built on Jurassic sedimentary rocks, which suffer consistent denudation (Gobejishvili et al., 2011; Bochud, 2011) suitable for supraglacial debris cover formation. Furthermore, high erodability of the rocks may be a major reason why rock glaciers are widespread in the eastern Greater Caucasus (Tielidze, et al., 2019b). The relief of the central Greater Caucasus is mainly constructed from Proterozoic and Lower Paleozoic plagiogranites, plagiogneisses, quartz diorites and crystalline slates, which present poor conditions for the formation of rock avalanches in this area. In addition, the central Greater Caucasus is the highest section of the main watershed range and glacier surfaces are relatively steeper making less favourable conditions for supraglacial debris cover accumulation. The western Greater Caucasus is hypsometrically lower with less steep glaciers. This section is distinguished with the highest glacier reduction after the eastern Greater Caucasus and it is possible that thinning glaciers rapidly become debris-covered over the ablation area (Pratap, et al., 2015). This might be confirmed by detailed field measurements and could be part of a separate investigation.

Our results indicate more than doubling of supraglacial debris cover area for Elbrus glaciers in 1986-2014 with the highest increase rate between 2000 and 2014 (Fig. 4, 8), although the total uncertainty is comparable to the obtained relative changes. Glaciers in the western slope of Elbrus are affected by avalanches and thus are partially debris covered (Kutuzov, et al., 2019). Glaciers on the eastern slope are characterized by high rates of retreat and great expansion in proglacial lake number and area (Petrakov et al., 2007). The most significant increase of supraglacial debris cover occurred on the eastern oriented glaciers of Elbrus, where glaciers are characterized by the highest thinning rates in recent years (Kutuzov, et al., 2019). Detailed Ground-Penetrating Radar (GPR) survey may help to more accurately identify supraglacial debris cover extent in this area (e.g. unpublished GPR measurements by S. Kutuzov and I. Lavretiev showed that ~30 m of ice may be present under the previously considered ice-free area on the eastern slope of Elbrus).

The glaciers in the Greater Caucasus have retreated continuously since 1960 (Tielidze and Wheate, 2018), suggesting that the shielding effect of increased supraglacial debris cover at the glacier surface may only partly offset the retreat trend. The same result was concluded by Mölg et al. (2019) in the evolution of Zmuttgletscher Glacier, Swiss Alps. Direct field measurements show that thermal resistance of the <20 cm supraglacial debris cover for some glaciers (e.g. Djankuat and Zpkhito) in the Greater Caucasus is relatively higher (0.07-0.15°C and 0.05-0.08°C m^2/W) than in other glacierised regions of the world (e.g. Baltoro, Karakoram 0.02-0.07°C and Maliy Aktru, Altay 0.02-0.09°C m^2/W) (Lambrecht et al., 2011), preventing what would otherwise be a more rapid retreat, as debris-covered glaciers may not be as sensitive to climate change as debris-free glaciers (Mattson, 2000). This process is consistent with our observations of the largest debris-covered (Bezingi) and debris-free (Karaugom) glaciers of the Greater Caucasus, where the latter is characterized with higher area shrinkage and terminus retreat. Numerous authors have found similar model results in the Himalaya (e.g. Scherler et al., 2011; Rowan et al., 2015; Jiang et al., 2018).

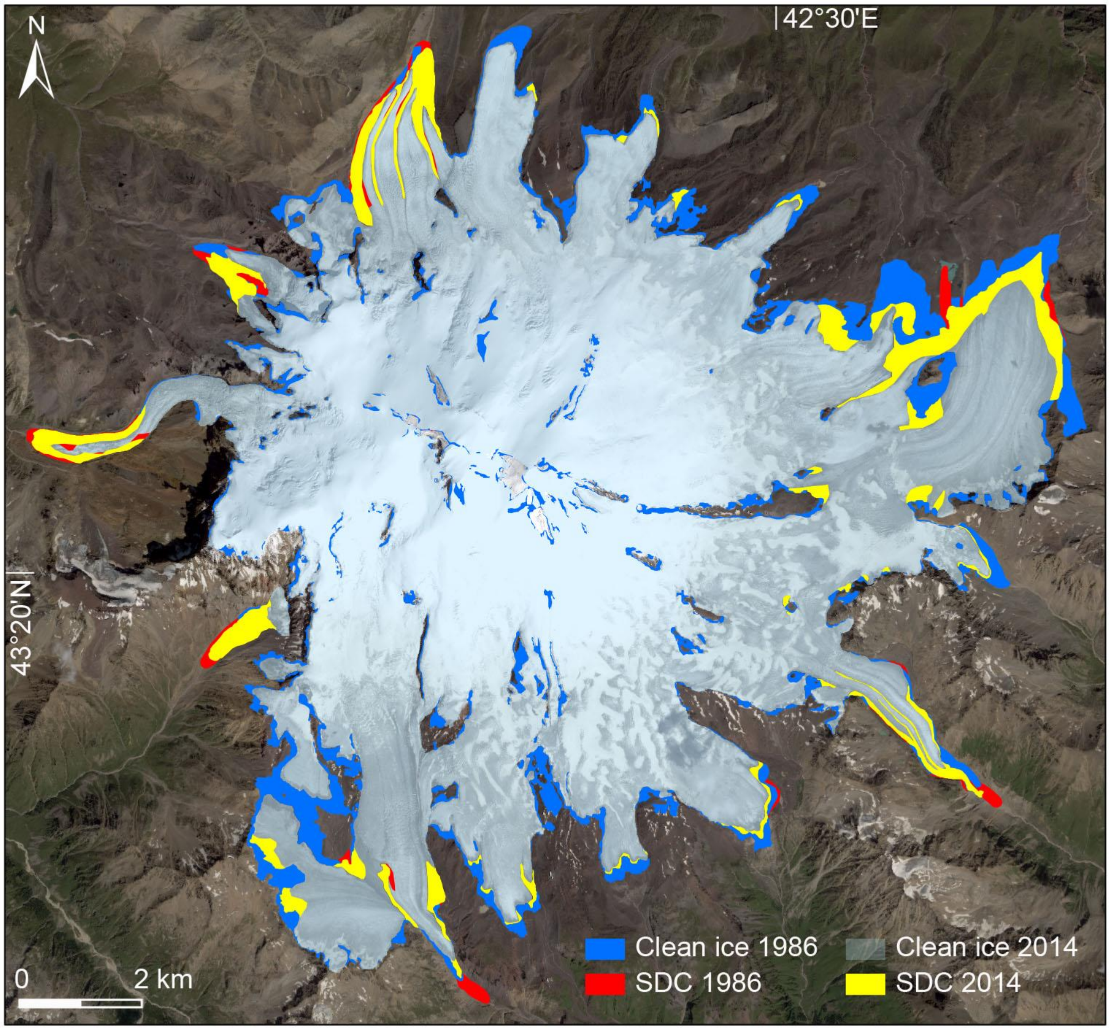

Figure 8. Supraglacial debris cover increase on the Elbrus Massif from 1986 to 2014. SPOT-7 image 20/08/2016 is used as the background. Blue color shows retreat of clean ice parts.

6 Conclusions

We have presented supraglacial debris cover change over the last 30 years in the Greater Caucasus region. We found that the overall glacier reduction by 15±4.1% was accompanied by supraglacial debris cover increase from 48.3±3.1 km^2 to 79.0±4.9 km^2 between 1986 and 2014. Overall we measured supraglacial debris cover increase from 7.0±6.4% to 9.1±6.3% and 13.4±6.2% based on all selected glaciers in the years 1986 to 2000 and to 2014.

Given the increasing degree of supraglacial debris cover in the Greater Caucasus region, it is worthwhile to maintain its monitoring, as it constitutes an important control on glacier response to climate change. The recent significant increase of the supraglacial debris cover area in this region may alter the glacier mass balance in different ways depending on debris thickness and properties. Such feedbacks can affect future glacier evolution and should be considered in glacier modeling.

Future work should focus on using high resolution aerial/satellite imagery and more detailed field measurements. e.g. debris thickness measurement by Ground-Penetrating Radar using a Sensors and Software pulseEKKO 1000, with 225, 450, 900 and 1200 MHz antennas (Mccarthy, et al., 2017), or incoming and reflected solar radiation; long-wave terrestrial and returned radiation by Kipp & Zonen CRN1 net radiometer (Lambrecht, et al., 2011). This will reduce uncertainties connected with supraglacial debris cover assessment and glacier mapping accuracy in this region.

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Information about the Supplement
Supraglacial debris-cover changes in the Greater Caucasus includes the glacier size classes with debris covered and debris free glaciers distributions for northern and southern slopes (Fig. 1); Comparison of Debris-covered (Bezingi) and Debris-free (Karaugom) glaciers retreat between 1986 and 2014 (Fig. 2); Relative supraglacial debris cover for the Western, Central, and Eastern Greater Caucasus as well as for Elbrus based on the current study and in comparison with Scherler et al. (2018) (Figs. 3-4); Increased supraglacial debris cover area for the Devdoraki and Suatisi glaciers before and after rock-ice avalanches (Fig. 5); A comparison of supraglacial debris cover and clean-ice area distribution in 1986-2014 for the southern and northern-facing glaciers (Fig. 6).

Supplement. The supplement related to this article is available online at: https://doi.org/…..

Competing interests. The authors declare that they have no conflict of interest.

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