Brief communication: Supraglacial debris-cover changes in the Caucasus Mountains

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Abstract

In spite of recently conducted glacier studies in the Greater Caucasus, knowledge about the coverage and characteristics of supraglacial debris cover is still 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 combine 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 from 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±4.1% or -0.52% yr) in contrast with an increase of debris cover from 7.0±6.4% or 48.3±3.1 km^2 in 1986 to 13.4±6.2% or 79.0±4.9 km^2 in 2014. Debris-free glacier characterized with higher area shrinkage and terminus retreat than the debris-covered glacier. Overall we have observed up-glacier migration of SDC during the investigated period.

1 Introduction

Supraglacial debris cover (SDC) on the tongues of mountain glaciers affects melt rates: increasing rates of ablation in cases of thin SDC (< a few cm), or decreasing ablation under thick SDC (Nicholson et al., 2018). SDC is relevant not only from its impact on glacier ablation but also because it is considered to be 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 and energy balances of the glacier. Several studies show an increase in debris-covered area with overall glacier shrinkage and mass loss (Kirkbride and Deline, 2013; Glasser et al., 2016).

For regions where the local population is dependent on glacial meltwater for water supplies, accurate 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 poor knowledge of the large-scale extent, thickness, and properties of the SDC. Field measurements of a debris layer has practical difficulties on a large scale, and methods for satellite mapping of supraglacial debris thickness remain in development (Zhang et al., 2016). Several studies have also reported debris cover's role 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 the SDC into account when assessing temporal change of mountain glaciers.

One of the world's highest mountain system - the Greater Caucasus - contains over 2000 glaciers, with a total area of 1193±54 km^2 (Tielidze and Wheate, 2018). These mountains, are the main source of runoff for the densely populated places and ice/snow melt is important for water production in many parts of the Caucasus region. In the Greater Caucasus, SDC is an important control for ice ablation, as it changes the melt regime (Lambrecht et al., 2011), and has been identified as a glacier-wide component in glacier mass balance (Popovnin and Rozova, 2002). Thus, correct delineation of SDC in the Greater Caucasus is important to correctly model future glacier development, as surface mass balance of ice under SDC is different from that of bare ice (Ragettli et al., 2016). A recent global study (Scherler, et al., 2018) suggests that SDC is abundant in the Caucasus and Middle East (more than 25% glacier area are covered by SDC) and that this region shows the highest percent of SDC worldwide. Earlier studies indicated smaller relative SDC in the Greater Caucasus but covering smaller regions or individual glaciers (Stokes et al., 2007; 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 SDC and related changes between 1986, 2000 and 2014 for the Greater Caucasus.

2 Data and methods

2.1 Datasets

We selected four regions representing different climate conditions (Stokes, 2011) and glacier characteristics (Tielidze and Wheate, 2018) with a total of 659 glaciers: 223 glaciers in the western Greater Caucasus (145 - northern slope, 78 - southern slope); 285 in the central Greater Caucasus (173/112); and 130 on the northern slope of the eastern Greater Caucasus (as glaciers are almost non-existent in the south). In addition, all 21 glaciers on Elbrus - the largest glacierised massif in the whole region were selected (Fig. 1a-d). 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 were calculated according to Paul et al. (2009).

A total of 9 Landsat images were used in this study (Table S1). 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). The images were downloaded from the Earthexplorer website (http://earthexplorer.usgs.gov/). We also used high resolution (1.5 m) SPOT satellite image from 2016. The SPOT image was orthorectified using ScanEx

Image Processor software and the SRTM DEM. The Landsat scenes served as a basis for SDC assessment while the SPOT image was used for corrections of SDC areas of Elbrus. All imagery was captured from the 28th of July to the 12th of September, when glacier tongues were free of seasonal snow under cloud-free conditions and, hence, suited for the SDC mapping.

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 SDC by five-hundred-meter elevation bands. We used these elevation bands to intersect our digitized debris-covered areas for 1986 to 2014, with the total area per elevation band summed.

Other datasets used in this study include the latest "Greater Caucasus Glacier Inventory" manually mapped data set (Tielidze and Wheate, 2018), high resolution images from Google Earth and GPS measurement.

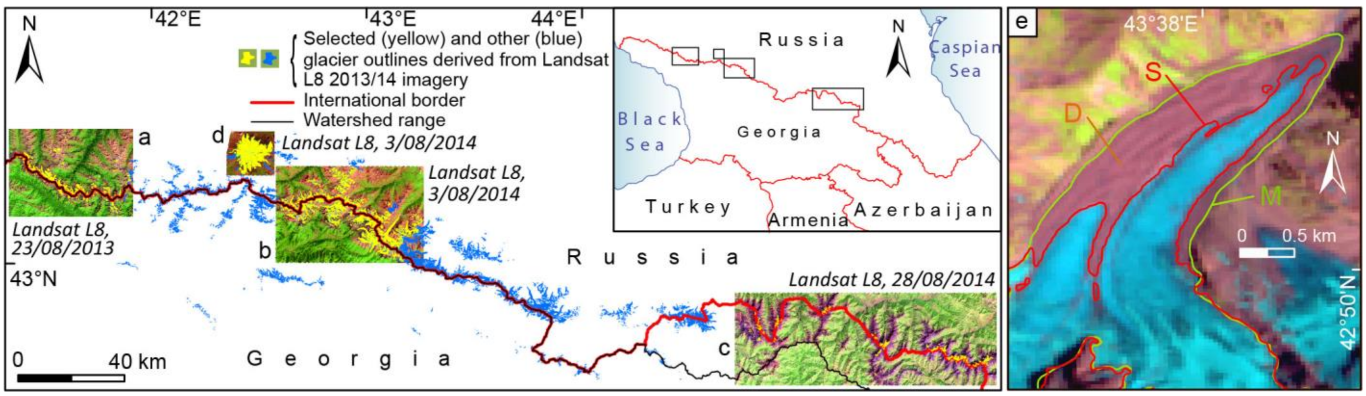

Figure 1. Investigated area and selected glaciers in regions a – western Greater Caucasus; b – central Greater Caucasus; c – eastern Greater Caucasus; d – the Elbrus massif. Mapping examples: e – debris cover (D) assessment with comparison of different methods: manually (M) and semi-automated (S) (ratio TM 3/5 followed by manual improvement. Threshold ≥2). Landsat image 06/08/1986 is used as the background.

2.2 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 SDC was classified as the residual between a semi-automatically derived clean-ice map and a manually improved glacier extent map (Paul et al., 2004) (Fig. 1e). SDC layers were extracted and saved as separate layers to generate the SDC data. To assess temporal change, we calculated the area of SDC for individual glaciers for the years 1986, 2000, and 2014.

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 (More than 10% and less than 50% of the glacier surface is debris covered); and iii) mostly debris-covered (More than 50% and less than 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 buffer with 15 m (1/2 pixel) (Bolch et al., 2010) and for debris-covered parts with 60 m (two pixel) (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 estimations for all Caucasus glaciers are described in previous studies (Tielidze, 2016; Tielidze and Wheate, 2018).

Upon delineation of SDC 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 SDC and ±3.4% for clean ice area.

For extra uncertainty assessment we used GPS (Garmin 62 Stc) measurement data which were obtained during field investigation in 2014. GPS data mainly included measurements of glacier margins (>1200 point measurements). These GPS measurements have horizontal accuracy from ±4 to ±10 m. In total seven glaciers (Ushba, Chalaati, Lekhziri, Adishi, Shkhara, Zopkhito, Kirtisho) were measured. Fig. S1 shows the results of comparison between GPS measurements and Landsat based SDC/clean ice outlines. The accuracy is ±30 m for SDC and ±15 m for clean ice.

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

3 Results

We found an absolute increase of SDC area 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 shrinkage of the total glacier area. This equates to a total increase in the proportion of SDC surface area from 7.0±6.4% in 1986, to 9.1±6.3% in 2000, and to 13.4±6.2% in 2014 (Table 1; Fig. 2). SDC was greatest in the glacier area classes 1.0-5.0 and 5.0-10.0 km^2 for both northern and southern slopes (Fig. S2). 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, SDC area increased, especially in the second investigated period (7.1±6.6% to 26.1±6.4%). The relative increase on the southern slope was similar but the overall SDC with 11.5±7.1% was only about half the value of the northern slope (Table 1; Fig. 2).

The central Greater Caucasus contained the largest SDC 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% on the northern and from 6.0±6.5% to 6.9±6.7% on the southern slope in 2014).

Table 1. Change of supraglacial debris cover and bare ice in the Greater Caucasus for 1986, 2000 and 2014 by regions and slopes.

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 km^2	Clean ice area km^2	Debris covered area			Total glacier area km^2	Clean ice area km^2	Debris covered area			Total glacier area km^2	Clean ice area km^2	Debris covered area		
				Glacier number	Area km^2	%*			Glacier number	Area km^2	%*			Glacier number	Area km^2	%*
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	130.4±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.

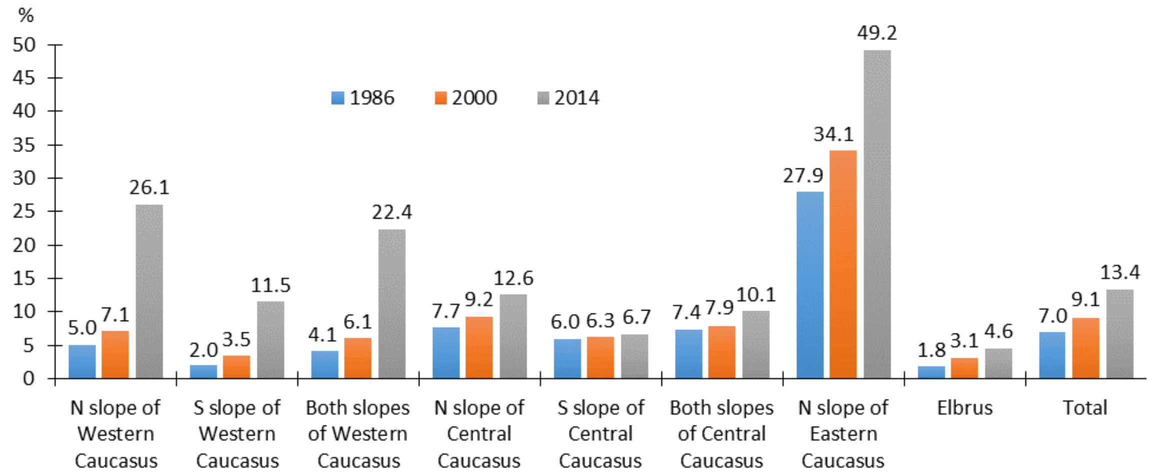

Figure 2. Increase of SDC in the Greater Caucasus for 1986, 2000 and 2014. The bars indicate clean ice to SDC ratios and are ordered by years (colours) and regions. For all regions (but Elbrus), the sub-regional results for the northern and southern sides of the main watershed (cf. Fig. S5) are also shown (glaciers are non-existent on southern slopes of the eastern Greater Caucasus).

The eastern Greater Caucasus is characterized with fewer glaciers but represents the largest percentage of debris cover. Over the last 30 years, SDC almost doubled from 27.9±6.2% to 49.2±5.7%.

The Elbrus massif contained the least percentage of debris cover in the whole investigated area but we found that SDC more than doubled between 1986 and 2014 (from 1.8±6.9% to 4.6±6.6%).

The increase rate was different from northern to southern slopes. Debris covered area increased from 7.7±6.2% or 36.9±2.3 km^2 to 15.4±6.1% or 65.6±4.0 km^2 on the northern (including Elbrus), and from 5.3±6.5% or 11.4±0.74 km^2 to 7.6±6.9% or 13.4±0.91 km^2 on the southern slope of the Greater Caucasus between 1986 and 2014.

Hypsometrical profiles show that the percentage proportion of SDC is abundantly distributed in 2500-3000 m zone for Elbrus and in 1900-2500 m zone for the other regions (Fig. 3). The SDC has doubled from 6.4% to 12.2% in 3000-3500 m zone for all selected glaciers in 1986-2014 (Fig. 3d). The proportion of SDC has increased in 3500-4000 m zone as well for all regions and selected glaciers during the investigated period.

SDC area for the largest Bezingi Glacier in the Greater Caucasus increased from 4.4±0.25 km^2 or 11.0±5.9% to 7.5±0.44 km^2 or 20.0±6.0% between 1986 and 2014 in contrast with a shrinkage of the total glacier area from 40.0±0.90 km^2 to 37.5±0.94 km^2 (-6.3% or -0.22% yr) during the same period and terminus retreat by ~374 m. Comparison with the debris-free Karaugom Glacier (third largest glacier of the Greater Caucasus), that is located the same region (northern slope of central Greater Caucasus) - shows almost triple the percentage area shrinkage from 29.2±0.62 km^2 to 24.0±0.44 (-17.8% or -0.63 yr) and terminus retreat by ~1366 m.

4 Discussion

4.1 Supra-glacial debris-cover changes

We have observed a clear increase in SDC in all investigated regions which was more pronounced after 2000. Based on our investigation SDC migrated up-glacier (Fig. 3, S3) 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).

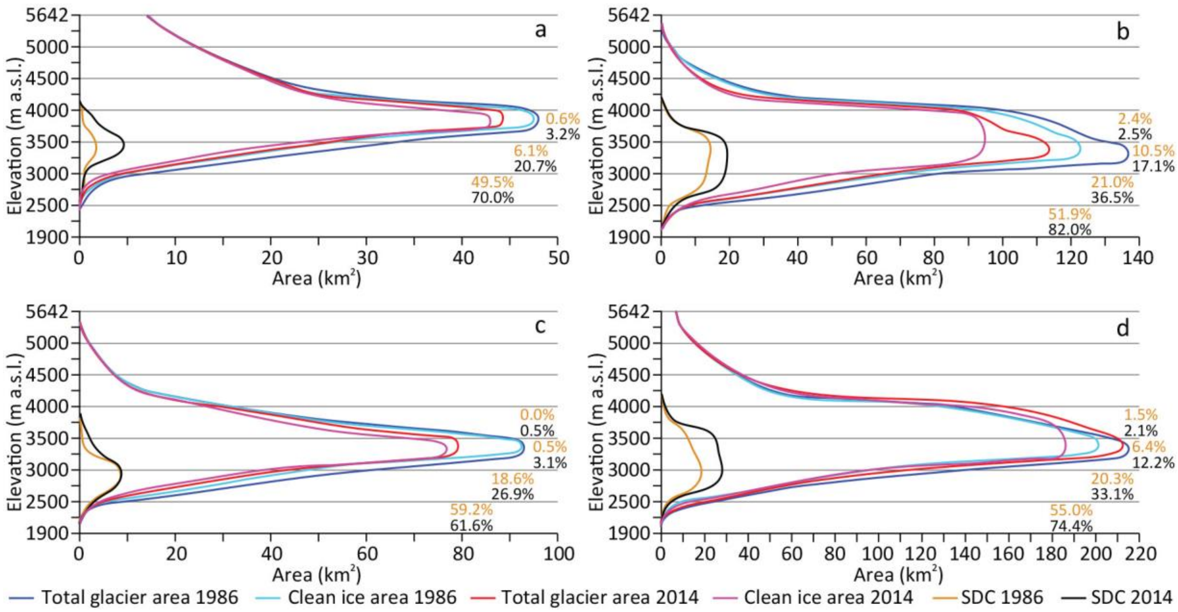

Figure 3. Hypsometry of SDC, clean ice and total glacier area, of the four study regions in 1986 and 2014. a – Elbrus, b – Northern Slope, c – Southern Slope, d – all selected glaciers. SDC percentage according to the different elevation zones in 1986 (brown digits) and 2014 (black digits).

The results presented in this study indicates that the clean ice area decreased by 18.7±4.1% between 1986 and 2014 (Table 1). This reduction appears to be attributable to both glacier retreat (Table 1) and an increase in SDC (Table 1, Fig. 2, 3). This is supported by field measurements on Djankuat glacier, which indicate that SDC area increased from 2% to 13% and become 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, have dramatically increased SDC (Fig. S4), which might be one of the reasons why the SDC increase rate was higher during the second period (2000-2014).

One possible reason that SDC occurs more on the northern slope than the southern, may be that the northern slopes are longer and more gradual than the southern. Most valley glacier tongues in the north are longer and at lower altitudes than the southern glaciers. But there are some areas where the northern slope is shorter and steeper, and here, the glaciers of the southern slope are characterized with relatively more SDC. An example is Georgia’s largest glacier Lekhziri and its northern counterparts (with the exception of the Bashkara Glacier) (Fig. S5).

Our results indicate more than doubling of SDC areas for Elbrus glaciers in 1986-2014 with the highest increase rate between 2000 and 2014 (Fig. 4), although the total uncertainty is comparable to the obtained relative changes. Comparison with the semi-automated methods shows that debris cover may be considerably underestimated. The glaciers on the eastern slope of Elbrus are characterized by high rates of retreat and great expansion in proglacial lake numbers and area (Petrakov et al., 2007). The most significant increase of SDC occurred on the eastern oriented glaciers of Elbrus that can be explained by the resurfacing on the englacial debris as a result of the glacier recession. In fact, these glaciers are characterized by the highest thinning rates in recent years (Kutuzov, et al., 2019). Detailed GPR survey may help to accurately identify debris covered glacier boundaries in this area.

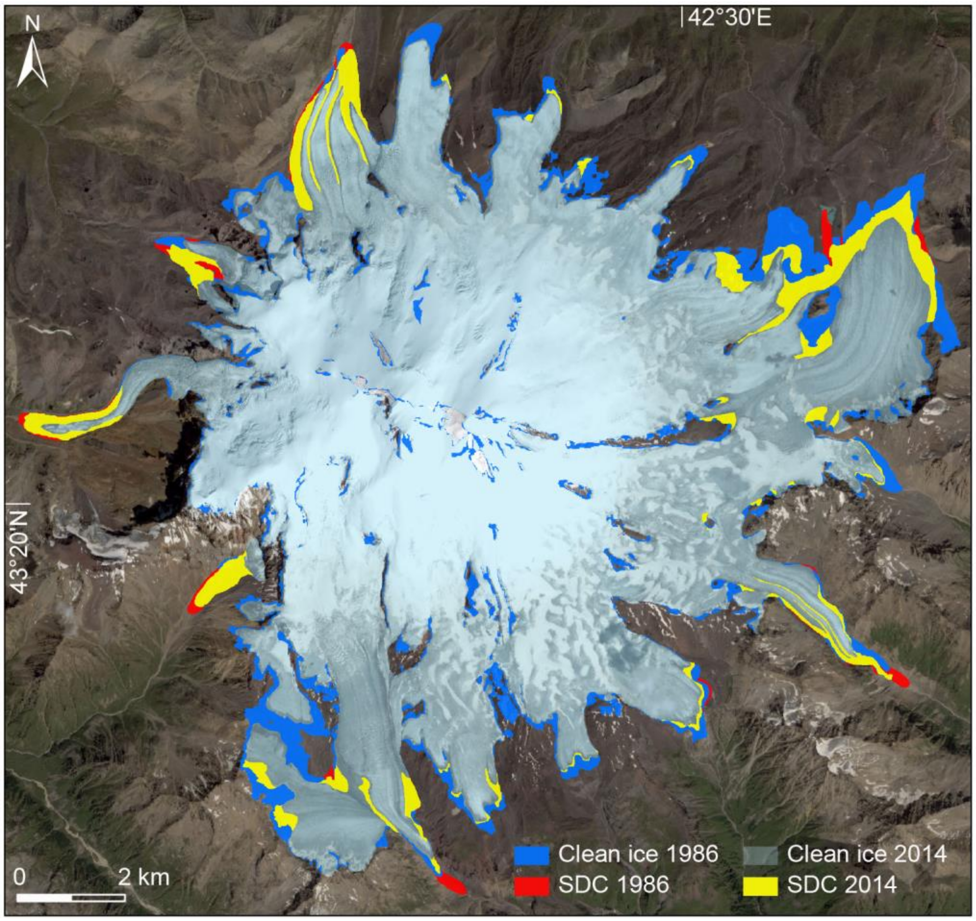

Figure 4. SDC increase on the Elbrus massif from 1986 to 2014. SPOT-7 image 20/08/2016 is used as the background.

The glaciers in the Greater Caucasus retreated continuously (Tielidze and Wheate, 2018), and possibly, the shielding effect of the increased SDC at the glacier surface is not enough to offset the retreat trend. The same result was concluded by Mölg et al. (2019) in the evolution of Zmuttgletscher Glacier, Swiss Alps. However, direct field measurement shows that thermal resistance of the SDC for some glaciers (Adyl-su and Zpkhito river basins) in the Greater Caucasus is somewhat higher than in other glacierised regions of the world (Lambrecht et al., 2011), preventing what would otherwise be an even more rapid retreat, as debris-covered glaciers may not be as sensitive to climate change as debris free glaciers (Mattson, 2000). This discussion is confirmed by our comparison of two largest debris-covered

(Bezingi) and debris-free (Karaugom) glaciers of the Greater Caucasus, where the debris-free glacier is characterized with higher area shrinkage and terminus retreat than the debris-covered glacier. Jiang et al. (2018) found the same result that the debris-covered glaciers in central Himalaya had retreated less than debris-free glaciers in the same region, and Rowan et al. (2015) found that debris-covered glaciers tend to recede more slowly than debris-free glaciers in the Himalaya because the supraglacial debris slows down the response of a glacier to atmospheric warming.

4.3 Comparison of previous investigations

Direct comparisons of SDC previous investigations in the Greater Caucasus are somewhat difficult, because most of them cover relatively small area (except the Scherler et al. 2018). However, our results are good agreement with other studies of SDC change in this region. For example, Stokes et al. (2007) calculated SDC general increase from 3% to 6% between 1985 and 2000 on several glaciers in the central Greater Caucasus. On individual glaciers, SDC ranges from just a few percent (e.g. Bzhedukh) to over 25% (e.g. Shkhelda). Popovnin et al. (2015), reported a SDC increase from 2% to 13% 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 in some points near the terminus between 1983 and 2010, the volume of the lithogenic matter over the whole glacier increased by about 140%. Lambrecht et al. (2011) estimated that the SDC distribution remained nearly constant at about 16% between 1971 and 1991 in the Adyl-su River basin (northern slope of the central Greater Caucasus). Between 1991 and 2006, the SDC started to increase noticeably reaching 23% within 15 years. For the Zopkhito River basin glaciers (southern slope of the central Greater Caucasus), SDC increase was lower in the same period (from 6.2% to 8.1%).

We extracted both SDC 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 large portion of selected glaciers in the Greater Caucasus are covered by SDC, but our values are clearly lower than the results by Scherler, et al. (2018) who calculated more than 30% of SDC in the same glaciers for 2015 (Fig. S7). These differences can be explained by i) The RGI v6 as 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. S7a); 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. S7b). We note that the scope of the study by Scherler et al. (2018) was an automatized global assessment of SDC from optical satellite data, without correcting any outlines in the RGI.

5 Conclusions

Here we presented SDC 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 SDC increase from 48.3±3.1 km^2 to 79.0±4.9 km^2 between 1986 and 2014. Overall we measured SDC increase from 7.0±6.4% to 9.1±6.3% and 13.4±6.2% based on all selected glaciers in 1986-2000-2014.

With the expected continuing of the increase of SDC in the Greater Caucasus region, it is meaningful to maintain monitoring of SDC, as it has an important control on glacier dynamics. The recent significant increase of the SDC 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, GPR, radiation) to reduce uncertainties connected with SDC assessment and glacier mapping accuracy in this region.

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