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

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Abstract
Debris cover on glaciers can significantly alter melt, and hence, glacier mass balance and runoff. Debris coverage typically increases with shrinking glaciers. Here, we present data on debris cover and its changes for 559 glaciers located in different regions of the Greater Caucasus mountains based on 1986, 2000 and 2014 Landsat and SPOT images. Over this time period, the total glacier area decreased from 691.5 km^2 to 590.0 km^2 (0.52% yr^{-1}). Thereby, the debris covered area increased from ~11 to ~24% on the northern, and from ~4 to 10% on the southern slope between 1986 and 2014. Overall, we found ~18% debris cover for the year 2014. With the glacier shrinkage, debris-covered area and the number of debris-covered glaciers increased as a function of elevation, slope, aspect, glacier morphological type, Little Ice Age moraines, and lithology.

1 Introduction

Debris cover on the tongues of mountain glaciers affects melt rates: increasing rates of ablation in cases of thin supraglacial debris cover (SDC) (< a few cm), or decreasing ablation under thick SDC (Nicholson et al., 2018). The SDC is relevant not only from its impact on the glacier ablation but also because it is considered to be a significant part of an efficient 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)

For some regions where the local population is dependent on glacial meltwater for water supplies, exact evaluation of glacial hydrology is important to ensure the sustainable use of water resources (Baraer et al., 2012). The difficulty of such investigations is associated with poor knowledge of the large-scale

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spatial distribution of the thickness and properties of debris, since field measurements of the debris layer have practical difficulties on a large scale, and methods for satellite mapping of supraglacial debris 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), 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 mountian glaciers. The SDC becomes especially important in understanding the complex relation between climate change and glacier mass budget.

Europe's highest mountain system - the Greater Caucasus - contains over 2000 glaciers, with a total area of 1193±54 km^2 (Tielidze and Wheate, 2018). In the Greater Caucasus, SDC is an important control for ice ablation, as it is similarly in many other glacierised areas (Lambrecht et al., 2011) and has been identified as a key player 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. In fact, these areas show the highest percent of SDC worldwide, which contradicts earlier studies covering smaller regions or individual glaciers in the Greater Caucasus (Stokes et al., 2007; Lambrecht et al., 2011; Popovnin et al., 2015).

The purpose of this study is to provide the first regional assessment of the spatial distribution of SDC for four regions along the Greater Caucasus based on optical satellite data and recently published glacier inventories from 1986 and 2014 and to discuss the changes in SDC with respect to controlling factors and in the light of existing global and local studies.

2 Data and methods

2.1 Datasets

We have selected 559 glaciers in different regions representing different climate conditions and glacier characteristics - 223 glaciers in the western Greater Caucasus (145 - northern slope, 78 - southern slope); 285 glaciers in the central Greater Caucasus (173/112); and 130 glaciers only on the northern slope of the eastern Greater Caucasus (as glaciers are almost non-existent in the south). In addition, 21 glaciers on the Elbrus massif were selected as a largest glacier massif in the whole region (Fig. 1a-d). The size of the largest glacier selected was 37.5 km^{2}and the smallest 0.01 km^2.

Landsat 5 TM imagery from 1985/86 and Landsat 8 OLI imagery from 2013/14 (for details see Table S1) with manually mapped glacier outlines for the Greater Caucasus' latest glacier inventory (Tielidze and Wheate, 2018) were used in this study. In addition, Landsat 7 ETM+ imagery from 2000 were downloaded from the Earthexplorer website (http://earthexplorer.usgs.gov/) and glacier margins digitized manually. We also used high resolution (1.5 m) SPOT satellite image of 2016. SPOT image was orthorectified using ScanEx Image Processor software and SRTM DEM. The TM, ETM+, and OLI scenes served as a basis for glacier mapping while the SPOT image was used for corrections of debris-covered glacier areas on the eastern slopes of Elbrus.

All imagery was captured from the 28th of July to the 12th of September. Additionally, results of airborne Ground Penetrating Radar (GPR) survey conducted in 2013 and 2014 at Elbrus were included.

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-259
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Discussion started: 9 January 2019

The Cryosphere Discussions

The ASTER GDEM, vers. 2 (spatial resolution 30 m) was used to extract slope information. Reported vertical and horizontal accuracy of the GDEM are ~20 m and ~30 m, respectively (Frey, et al., 2012).

2.2 Comparison of manually to automatically derived glacier extents and uncertainty estimation

For the first step, we created image ratios using the Red and Short-wave infrared bands (OLI 4/6 or TM 3/5) to automatically identify clean-ice glaciers and converted the raster polygons into vector data for further processing; in the second step we visually identified and deleted misclassified polygons (e.g. snow, shadows); then we manually corrected the automated outlines as accurately as possible in order to assess subtle changes in the extent over time (e.g. the emergence of thin medial moraines may have been beyond the resolution of automated techniques). Finally a simple approach was used to assess the debris cover area, as the difference between the manual and semi-automated extents: SDC = Manual minus semi-automated extent areas to assess the SDC (Fig. 1e).

Key difficulties in identifying the SDC is unclear boundaries between SDC and moraines and debris in shadow. Relatively heavily debris-covered glacier tongues are often in contact with frontal or lateral moraines and it is difficult to distinguish. In such cases we used very high-resolution imagery available in Google Earth and GPS measurement data from different years. GPS readings were assumed to be within one-half pixel of true coordinates. In the cases where no clear boundary between SDC and moraines could be found, we followed a more conservative interpretation (Mölg, et al., 2018) that might have resulted in a potential underestimation of the debris-covered glacier area.

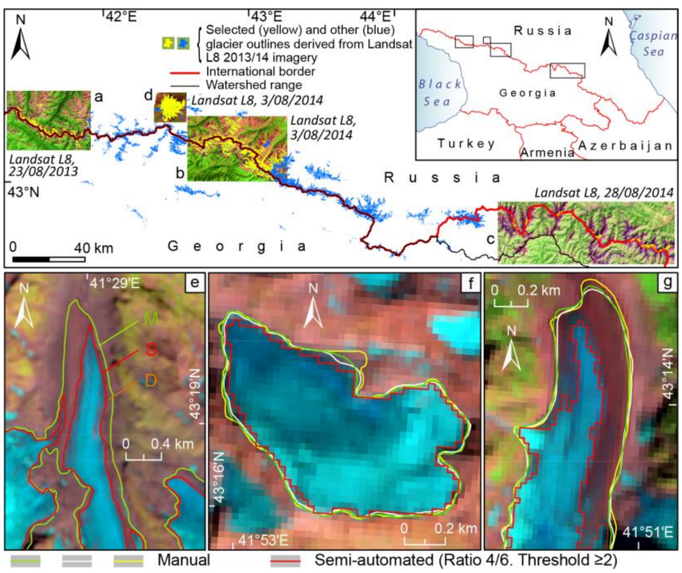

Figure 1. Investigated area and selected glaciers in sections a – western Greater Caucasus; b – central Greater Caucasus; c – eastern Greater Caucasus; d – the Elbrus. Mapping examples: e – debris cover (D) assessment with comparison of different methods: manually (M) and semi-automated (S) (ratio OLI 4/6 followed by manual improvement). Examples from the multiple digitisations for f – debris-free and g – debris-covered glaciers (bands 654 as RGB) using the OLI scene performed by different analysts (colored lines) based on a Landsat 8 OLI scene acquired 23/08/2013.

For uncertainty estimation, we used i) buffer (Granshaw and Fountain, 2006; Bolch et al., 2010) with different sizes for clean and debris-covered glacier parts; and ii) a sample of manually digitization (Paul, et al., 2013).

For the buffer method we applied an uncertainty of 1 pixel for clean-ice parts and 2 pixel for debris-covered parts and the uncertainty term was calculated as an average ratio between the original glacier areas and the areas with a buffer increment. This generated an average uncertainty of the mapped glacier area of ~4.2% for 1986, ~4.3% for 2000 and ~4.4% for 2014 for debris-free parts and ~6.6% for 1986, ~6.5% for 2000 and ~6.4% for 2014 for debris-covered parts.

The buffer width, however, is critical to the resultant uncertainty estimation (Guo et al., 2015); we also performed method (ii) to obtain a more realistic uncertainty estimate for the analysts participating in the outline correction. By three different operators we manually digitized six different size glaciers in the western, central and eastern Greater Caucasus (Fig. 1f, g). For debris covered glaciers, the Normalised Standard Deviation (NSD - based on delineations by multiple digitalization divided by the mean glacier area for all manual outlines) was 6.2% and the difference between the manually and automatically derived area was 12.3%. For debris-free glaciers the NSD was 5.9% and the difference between the manually and automatically derived area was 4.7%.

The GPR survey of 2014 has shown the existence of large debris covered parts of glacier tongues on the eastern slopes of the Elbrus massif which were previously not included in the glacier area (Shahgedanova et al., 2014). High resolution SPOT 7 imagery confirmed the complicated geomorphology and was used for additional corrections of the debris covered area. Accuracy assessment of debris-covered glacier outlines are challenging without more ground truthing (Frey et al., 2012) and local uncertainty values can be as high as five pixels or ±150 m (Paul et al. 2013). However given the large total glacier area of the Elbrus massif and a small relative SDC area, we used an error estimation of one pixel buffer (30 m).

3. Results

We found a significant increase of SDC area for all investigated glaciers from about 9±6.6% of the total glacier area in 1986, to 11±6.5% in 2000 and 18±6.4% in 2014 concomitant with a shrinkage of the total glacier area (Table 1). 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 (see Fig. S1).

On the northern slope of the western Greater Caucasus, debris cover area increased especially in the second investigated period (~7% to ~26%). The relative increase on the southern slope was similar but the overall SDC with ~12% only about half the value of the northern slope (Table 1).

The central Greater Caucasus contained the largest SDC in 1986 (~7%) but the increase was significantly lower than in the western and eastern sections over the last 30 years (from ~8% to ~13% on the northern and from ~6% to ~8% on the southern slope in 2014).

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 28% to 49%.

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 ~2% to ~6%).

The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-259
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The Cryosphere Discussions

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, 1985/86				Landsat 7, 2000				Landsat 8, 2013/14. SPOT 2016			
		Bare ice area km^2	Debris covered area			Bare ice area km^2	Debris covered area			Bare 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	87.1±1.9	15	4.6±0.11	5±6.6	80.8±1.8	21	6.2±0.13	7±.6.5	57.9±1.9	33	20.4±0.66	26±6.4
Southern slope (Kodori)	78	34.8±0.9	1	0.7±0.01	2±6.6	31.7±0.8	1	1.1±0.027	3±.6.5	23.1±0.7	3	3.0±0.09	12±6.4
Central Caucasus													
Northern slope (Baksan, Chegem, Cherek)	173	194.7±4.2	28	16.3±0.35	8±6.6	184.5±4.2	37	18.7±0.42	9±.6.5	161.9±4.1	42	23.4±0.59	13±6.4
Southern slope (Enguri)	112	168.1±2.9	15	10.7±0.18	6±6.6	160.5±2.9	15	10.8±0.19	7±.6.5	139.4±2.7	17	10.4±0.20	8±6.4
Eastern Caucasus													
Northern slope (Tergi headwaters, Sunja Right tributaries, Sulak)	130	35.4±1.5	54	13.7±0.58	28±6.6	27.2±1.1	56	14.1±0.57	34±.6.5	16.3±0.8	59	15.8±0.77	49±6.4
Elbrus massif	21	123.1±6.56	9	2.3±1.7	2±6.6	117.2±4.3	13	3.7±1.0	3±.6.5	112.4±3.8	18	6.0±1.5	6±6.4

* % of the total glacier area.

4 Discussion

4.1 SDC increase possible reasons

We have observed a clear increase in debris cover in all investigated regions which was more pronounced after 2000. Debris cover migrated up-glacier 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).

Glacier thinning and a warming atmosphere can lead to permafrost thawing and slope instability at higher altitudes (Stokes et al., 2007). Rock avalanches after 2000 on some glaciers, have dramatically increased SDC (see Fig. S2), which might be one of the reasons why the SDC increase rate was higher during the second period (2000-2014). Another main reason could be related to the thickness of the SDC, which increased (>70 cm) recently for some glaciers (Popovnin, et al., 2015) and ablation at the snout is greatly reduced by the presence of the thick SCD with melting focused on the debris-free ice on the slopes. In this case, the reduction of glaciers is mainly at the expense of clean ice. A good example is the northern slope of the western Greater Caucasus, where the total glacier area decrease was only 0.7% yr^{-1} between 2000 and 2014, while the clean ice decrease was 2% yr^{-1}.

One of the reasons why northern slopes are characterized with more debris than southern slopes could be associated not only with slope aspect, but also with lower slope inclination. Total glacier surface area on the southern slope includes 54.5% which are inclined 10-25°, while the northern slope has only 46.6% (see Fig. S3; S4). If local surface slope is too high, debris usually slides farther down until a gentler slope allows accumulation (Paul et al., 2004).

Another reason debris cover 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 debris. An example is Georgia's largest glacier Lekhziri and its northern counterparts (with the exception of the Bashkara Glacier) (see Fig. S5).

The Little Ice Age (LIA) moraine can affect the SDC increase on the glacier tongue, as debris often falls from lateral moraines onto the glacier surface (Popovnin et al., 2015; Pratar et al., 2015). The LIA moraines for the northern Caucasus valley glaciers are 2-3 times longer (e.g. Bezingi, Dikh-kotiu-bugoisy, Karaugom, etc.) and more well preserved than the southern.

Smaller percentage increase of the SDC on the central section in comparison to the western and eastern sections can be attributed to its high elevation and steep slopes. In the eastern Greater Caucasus, a large percentage of the debris cover is a result of the lithology, as some parts of the eastern Greater Caucasus are Jurassic sedimentary rocks (Gobejishvili et al., 2011; Tielidze, 2016), and therefore the process of mechanical weathering is more intense.

4.2 SDC change on the Elbrus massif

In the case of Elbrus, GPR measurements showed that a substantial amount of ice (20-40 m) may be present under debris cover on the eastern slope even though high resolution imagery and oblique photograph do not give any clear additional evidence (see Fig. S6). We have identified a more than doubling of DC areas for Elbrus glaciers in 1986-2014 with the highest increase rate in 2000-2014 (see Fig. S7), 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. These glaciers are characterized by high rates of retreat and great expansion in proglacial lake numbers and area (Petrakov et al., 2007). Detailed GPR survey may help to accurately identify debris covered glacier boundaries in this area.

4.3 Comparison of previous investigations

Our results are broadly consistent with previous research; 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). The debris layer became thicker by 70 cm and larger in some points near the terminus between 1983 and 2010, whereas the volume of the lithogenic matter over the whole glacier experienced a 141% increment. 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 found that large portion of selected glaciers in the Greater Caucasus are covered by SDC, but our values are clearly lower than the results of Scherler, et al. (2018) who calculated SDC of ~39% in the same area by 2015 (Fig. 2). These differences can be explained by i) The RGI v6 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. S8a); 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. S8b).

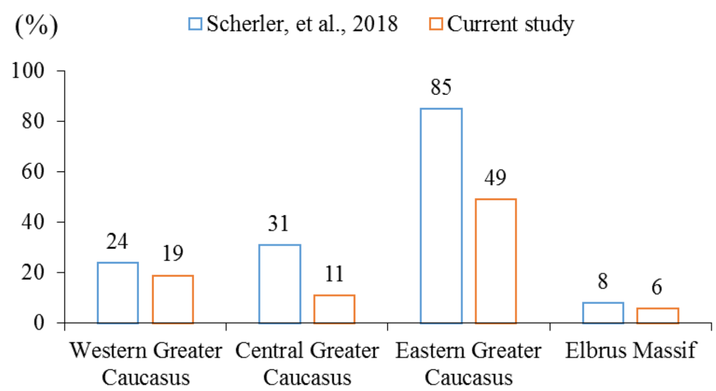

Figure 2. Percentage comparison of the SDC area according to the Western, Central, Eastern Greater Caucasus and the Elbrus massif by Scherler et al., 2018 and Current research.

5 Conclusions

Here we presented SCD change over the last 30 years in the Greater Caucasus region. We found that the overall glacier reduction by 15% was accompanied by a SDC increase of 50% between 1986 and 2014. Overall we measured SDC increase from ~9% to ~11% and ~18% 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 vital to maintain monitoring supraglacial and periglacial debris cover. The recent significant increase of the SDC area in this region may alter the glacier mass balance in different ways depending on a 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) to reduce uncertainties connected with SDC assessment and glacier mapping accuracy in this region.

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