Dear editor,

We would like to thank the reviewers for their additional in-depth review and are glad to read that the reviewers agree that our manuscript has much improved. We have addressed the remaining comments thoroughly and would be happy if the manuscript can now be considered for publication. Please find below our detailed response to the reviewers' comments. We would also like to mention, that the manuscript was much expanded due to the many corrections and new text and figures. Therefore, we decided to convert the manuscript as "standard format article" and not a short communication as also suggested by Dirk Scherler. In addition, we checked the journal guidelines, that says the "Brief communication" should be short (2–4 journal pages: https://www.the-cryosphere.net/about/manuscript_types.html)
We hope you agree with this decision.

All corrections and changes what we did in the manuscript are in yellow.

Best regards,

Levan Tielidze on behalf of all co-authors

Reply to Dr. Dirk Scherler's comments

The Reviewer comments are shown in black while author responses are subsequently provided in red

The revised version of Tielidze et al.'s contribution is much improved over the first submission. The authors have clarified the methodology, improved the analysis and streamlined the discussion.
My main comments are related to the discussion, which I think still needs some work. First, I think the order of the two chapters should be reversed. It makes more sense to me to that you first compare your results with those of others in order to discuss how your results are similar or different and how they combine to provide a more complete picture of debris-cover change in this region. Second, the chapter on supraglacial debris cover change is in fact more about the reasons of change and that should be stated explicitly, also in the chapter title. I think this is a very useful chapter to have, but I found some of the reasoning not well supported. Perhaps you could expand the discussion here by comparing your regions. If the regions are indeed different in topography and climate, you could provide

measurements (e.g., mean catchment slope, mean annual precipitation, etc.) and figures that support some of your arguments.

We thank you for offering constructive and thorough comments on our paper. Each concern is addressed below and in the manuscript, and we believe these changes have improved the clarity and quality of the paper.

First of all we would like to mention, that due to many corrections and new text/figures, the manuscript was much expanded. Therefore, we decided to convert it as the "standard format article".
We also took in to account your previous suggestion, that *"the paper should be a relevant contribution, but may be better published as a standard format paper, instead of a brief communication?"*

We also changed the term - "Caucasus Mountains" to the "Greater Caucasus" in the title. The "Caucasus Mountains" is a broad concept and consist of two separate mountain systems: the Greater Caucasus and the Lesser Caucasus. As the current study was conducted just in the Greater Caucasus the new title stands as the "**Supraglacial debris-cover changes in the Greater Caucasus**"

We have also taken care to address discussion section. First of all we changed the structure of the discussion and it starts from "5.1 Comparison with previous investigations" and continues to "5.2 Possible reasons of supraglacial debris-cover changes".
We also provided a new (edited) paragraph in order to improve the difference between the slopes:
"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."
Please see P11 L10-16 and P13 L1-4

In addition, we provided better evidence for the differences of supraglacial debris cover formations in the western, central and eastern sections/regions:
"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."
Please see P13 L5-18

Regarding to your comment: *"you could provide measurements (e.g., mean catchment slope, mean annual precipitation, etc.) and figures that support some of your arguments."* The manuscript and supplement overall contains 14 images, and we believe that this is quite enough for the one publication.

Specific comments
P1L37-39: The effect of debris thickness on melt rates has first been described by Östrem (1959): Geografiska Annaler, Vol. 41, No. 4 (1959), pp. 228-230.
Suggested reference has been added in the text. Please see P1 L41

P2L1-3: Here too, I think you could refer to earlier studies that document changes in debris cover. For example, Deline (2005; The Holocene 2005 15: 302 DOI: 10.1191/0959683605hl809rr) showed an increase of debris-cover for Mont Blanc glaciers, and Stokes et al. (2007) for the Caucasus.
Done, suggested references have been added in the text. Please see P2 L3

P2L18-21: In your discussion (P9L34-37), you mention the issue of nominal glaciers in the RGI classified as debris-covered in Scherler et al. (2018). Why not mention it here already? It would be a great motivation for your study to provide an improved estimate of supraglacial debris cover for the Caucasus. Holding back the information until the discussion makes no real sense, because your results are not instrumental in detecting this issue.
Special thank for this comment. We added our motivation here and overall this section stands as a:
"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."
Please see P2 L18-22

P2L29: It would be useful if you could mention in this chapter what fraction of all glaciers in the Caucasus you have analyzed in this study.
We provided appropriate sentence that making more clear what fraction of all glaciers we analyzed:
"Overall, this equals 49.5% and 32.6% of the Greater Caucasus total glacier area and number respectively."
Please see P3 L25-26

P2L30: "different climate conditions": Can you provide more details on how the climate differs in the studied regions? This may also help you in the discussion of why the regions differ in the rate of debris cover change.
The new format of the manuscript allowed us to provide more detail information not just about the climatic, but also orographic and current glaciation differences between the selected regions. Consequently, we provided the new paragraph - "**2 Study area**". We think that it makes the manuscript more comprehensive. In addition, it helps the reader to better understand the climatic and topographic differences between the selected regions:
"**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)."

Please see P2 L29-42 and P3 L1-17

P4L19-21: Is this sentence complete? Sounds like words are missing.

We corrected this sentence as:

"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%."

Please see P6 L24-25

P6L2-3: The bars: You write in the caption they reflect the ratio of clean ice to debris cover. Don't they rather reflect the percentage of debris cover?

We corrected this sentence as:

"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)."

Please see P8 L13-14

P6L11: "rate of supraglacial debris cover increase": Are these really rates? The units do not say so. Did you divide the percentage or area changes by the time period to come up with units %/yr or km^2/yr?

We calculated supraglacial debris cover increase and glacier area decrease rates for all selected regions and entire study area. All these calculations are included in the manuscript. For more clarifications, we provided new figure:

"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."

Please see P9 L7-8

P6L20-26: I wonder if you want to show a figure relating to this paragraph, either in the paper or in the supplementary material? The question is what information you take away from mentioning the big glaciers and how that ties in to your discussion.

We provided a new figure in the supplement, showing the Bezingi (debris covered) and Karaugom (debris free) glaciers comparison - Terminus retreat differences. This figure

supports our discussion that debris-covered glaciers may not be as sensitive to climate change as debris-free glaciers.
Please see Figure S2 in the supplement.

Also, if the numbers in parentheses are rates, make sure to provide the correct units.
We corrected all rate numbers as a (-6.3% or -0.22% yr^{-1}) and (-17.8% or -0.63 yr^{-1}).
Please see P8 L28 and P9 L2

P7L2-4: Is the upglacier enlargement of the debris cover not simply a consequence of the rise of the ELA and the enlargement of the ablation area at the cost of the accumulation area?
Indeed, all these events are closely related each other, but we do not provide the ELA measurement in this manuscript. We think it requires deep and complex analyses with more calculations. This could be an interesting topic of further research and separate investigation.

P7Figure 3: Why did you choose 5642 m as the upper limit of your y-axis? Also, some of the curves are truncated with this choice.
We choose this elevation as a highest point of the investigated region. Glaciers on Elbrus are situated in the altitudinal range of 2500 to 5642 m. The truncated curve caused by choosing of an altitudinal zones with 500 m ranges (e.g. 4000-4500, 4500-5000, 5000-5642). In case of choosing an altitudinal zones with 100 m ranges, this curve would be close to the y-axis. But we note that all curves on this figure are shown correctly.

P7L15: “appears”: Why appears? You have the data to quantify the attribution of the reduction in clean ice areas to retreat and debris-cover expansion.
We have changes this sentence and new sentence stands as: “This reduction was caused by both glacier retreat and an increase in total supraglacial debris cover (Table 2, Fig. 3-6).”
Please see P11 L34-35

P7L19-22: Can you provide more quantitative data to support your suggestion that the increase rate of debris cover during the 2000-2014 period was higher due to rock avalanches? The changes shown in Fig. 4 do not appear to be due to rock avalanches falling on glaciers.
We provided more calculation and quantitative data for some glaciers. Overall it stands: “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).”
Please see P11 L40-41 and P12 L1-4

In addition, we provided more suitable images in the supplement, showing SDC area increase after the rock avalanches in the second investigated period
Please see Figure S5 in the supplement

P7L23: Your explanation is not readily evident to me. Can you please explain in more detail? I would have guessed that steeper slopes would result in more debris cover (see discussion in Scherler et al., 2011, JGR, VOL. 116, F02019, doi:10.1029/2010JF001751).
We would like to clarify that we meant the "steep surface of the glacier" and not "steep slope". We provided new sentence here:
"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."
Please see P12 L10-14

P8L2: "increase rate": I believe you the rate was higher between 2000-2014 compared to before, but it is hard to read from Fig. 4. Perhaps add the rate to your table or add another table with rates?
Accepted. We calculated supraglacial debris cover increase and glacier area decrease rates not just for the Elbrus but also for all selected regions and entire study area. For more clarifications, we provided a new figure:
"**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."
Please see P9 L1-8

P8L6-8: This statement is not really evident to me. Looking at Fig. 4, I see both large and small increases in debris cover in all directions. You could provide a rose diagram to analyze how changes in the rate depend on orientation. Also, if you want to link the thinning with the expansion, you should show that these quantities correlate.
Accepted. For this discussion we provided new text and the appropriate image in the result section:
"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)."
Please see P8 L5-10
In addition, please see new figure: "**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."
Please see P10 L1-3

P8L16-18: Perhaps; but this statement may be too general. Glaciers in Fig. 4 that had already some debris cover in 1986 appear to have retreated less than others.
Agreed. We have modified this sentence to read: "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."
Please see P13 L30-32

P8L19-20: Why is the thermal resistance of the debris on Caucasus glaciers different from that on other glaciers? And why is it relevant for your discussion here?
The detailed comparison of thermal resistance between Caucasus and other mountain glaciers was described by Lambrecht et al. 2011 (see reference in the manuscript), discussing that it should be caused by local geology, different grain size distribution (air content) and water saturation, etc. We don't think it is basic to describe all these reasons in the Discussion here. Furthermore, it still requires more detail investigation, in order to better understand all these causes.
We include some results of thermal resistance measurement here, because the "**relatively higher thermal resistance**" makes debris-covered glaciers even less sensitive to climate change in the Caucasus than other mountainous regions. In addition, it is good consistent with our measurements that debris-covered glaciers characterized lower retreat (e.g. Bezingi) than high sensitive debris-free glacier (e.g. Karaugom).

P9L6: Changes in retreat rate between glaciers with different amounts of debris cover as well as different bed slopes have earlier been reported for Himalayan glaciers in Scherler et al. (2011, Nature Geoscience, DOI: 10.1038/NGEO1068).
Done. Suggested reference has been added accordingly P13 L41

P10L15: Sure you mean "gradually"?
Done. Suggested sentence has been changed accordingly P15 L7

Reply to Dr. Sam Herreid's comments

Reviewer comments are shown in black while author responses are subsequently provided in red.

I would like to applaud the authors, this revised version of the article is substantially improved. Below are minor comments with two specific points raised about overlap between this work and Tielidze and Wheate, 2018, and the ability to detect a debris cover change signal. After a consideration of the comments below, I would recommend publication of this article in The Cryosphere.

We are very grateful for this very positive feedback! And we thank you for the helpful comments, which have helped to improve the manuscript. We address all your comments below.

P1L31: Missing "per" year superscript "-1"

Done. Superscript has been added in the text. Please see P1 L29

P1L38: Add this citation along with Nicholson et al., 2018: Østrem, G., 1959. Ice melting under a thin layer of moraine, and the existence of ice cores in moraine ridges. Geografiska Annaler, 41(4), pp.228-230.

Done. Suggested reference has been added in the text. Please see P1 L41

P2L1: I think it's either "energy balance" or "mass balance" not "energy mass balance".

Done. Suggested sentence has been changed as a "mass balance". Please see P2 L2

P2L15: "Ice and snow melt in these mountains are major sources of runoff for populated places" Is this common knowledge or is there a citation for this?

Appropriate reference has been added in the text (Tielidze, 2017).

Tielidze L.: Introduction. In: Glaciers of Georgia. Geography of the Physical Environment. Springer, Cham, https://doi.org/10.1007/978-3-319-50571-8_1, 2017.

Please see P2 L15

P2L19: I think Scherler et al., 2018 "measured" that debris cover is abundant, not "suggest."

Done. Suggested sentence has been changed accordingly. Please see P2 L18

P2L20: more than 25% [of] glacier area

Done. Suggested sentence has been changed accordingly. Please see P2 L19

P2L21: Add citations for the earlier studies that indicate low relative supraglacial debris cover in the Greater Caucasus, or if already present in the three citations at the end of the sentence, move the relevant citations to the middle of the sentence so it is clear which reference is to which statement.

Done. Suggested sentence has been changed accordingly. Please see P2 L23-24

P2L33: For consistency with how you set up this list, give the ratio (130/0).

Done. Suggested sentence has been changed accordingly. Please see P3 L23

P2L34: northern/southern slope ratio is not given for the Elbrus massif and not divided by aspect in later analysis (although the eastern slopes are referenced). Please explain why or add this.

We have divided Elbrus glaciers according to different slopes:

"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"

Please see P3 L23-25

In addition, we added more results in the "Result" section:

"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)."

Please see P8 L6-10

In addition, please see new figure: "**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."

Please see P10 L1-3

Also, we added one more sentence in the "Discussion" section as a

Glaciers in the western slopes are affected by avalanches and thus are partially debris covered (Kutuzov, et al., 2019).

Please see P13 L21-22

P3L7: is 1986 to 2014 explicit or do you mean 1985/86 to 2013/14?

We meant 1985/86 to 2013/14 and this sentence has been changed accordingly.

Please see P7 L1

P3L10: It's not clear to me what work is new here and what is from Tielidze and Wheate, 2018. Looking at this earlier article, effort was taken to include debris cover. If you are using the same work then you do not need to describe the mapping methods in this article, simply cite your earlier work and present your new analysis of debris cover changes. If you have made changes to the earlier inventory, then I think a missing result is the difference between these glacier outlines and those of Tielidze and Wheate, 2018 for the subset regions considered here.

The inventory by Tielidze and Wheate (2018) is based only "manually mapped" outlines and does not contain any dataset (result) about the supraglacial debris cover distribution (except the only one Shkhelda Glacier - 43°100 N, 42°380 E).
Furthermore, we have not used a "semi-automated" mapping method (outlines) and any threshold values in the mentioned inventory. All selected glaciers were mapped just manually there.
In the current study, we only use these manually mapped glacier outlines from Tielidze and Wheate (2018), nothing else from there. And that's why the "manual mapping" method was not described here again.
All other works were performed for this new study as it is described in the methodology section.
Overall, this sentence stands as:
"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 measurement."
Please see P4 L1-2

P3L21-22: Manual improvements correcting for snow and shadows, does this step also include mapping debris cover?
This does not include mapping debris cover, although this step helped us to determine clean ice (semi-automated) outline correctly that allowed us to measure difference between entire glacier (manual outline from Tielidze and Wheate, 2018) and clean ice (semi-automated) outline properly or to calculate supraglacial debris cover area.
Thus, we have not done any corrections here.

P3L24: "Supraglacial debris cover was extracted and saved as a separate layer." You can remove this sentence, your readers know you did this implicitly.
Done. Suggested sentence has been deleted accordingly.

P4L16-17: "The accuracy is +/-30 m for debris and +/-15 m for clean ice" How did you derive this result? Is this an average value for all seven glaciers?
We clarified this sentence: "Based on all seven glacier measurements, the average accuracy was calculated as ±30 m for supraglacial debris cover and ±15 m for clean ice."
Please see P6 L21-22

P6L11: make it a little more clear that these results are no longer per your subregions. Something like "For all regions investigated in the Greater Caucasus mountains, the rate of supraglacial debris cover was different between northern and southern aspects."
Done. Suggested sentence has been changed accordingly. Please see P8 L16-17

P6L12: "debris-covered"
Done. Suggested sentence has been changed accordingly. Please see P8 L17

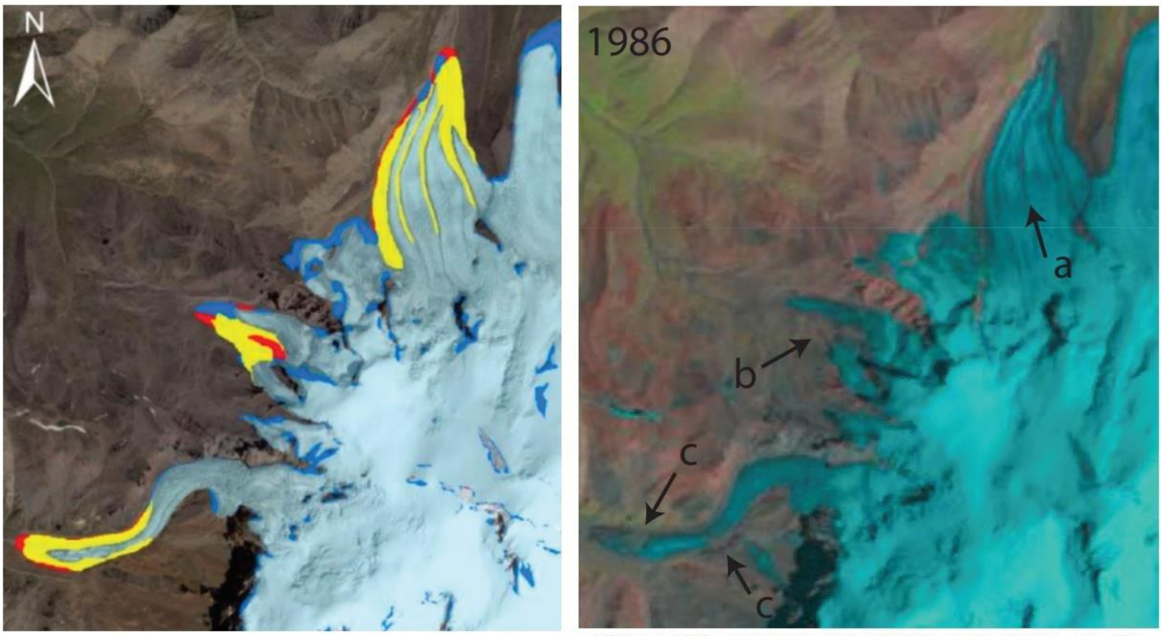
P6L22: missing superscript "-1"
Done. Suggested superscript has been added accordingly. Please see P8 L28

P6L23: (and P6L26): rewrite; something like "[..same period] with a terminus retreat of"
Done. Both suggested sentence have been changed accordingly. Please see P8 L29

P7L24: "northern slopes are less steep" do you mean the mountain slope above the glaciers? How would this couple with more debris cover? Can you take this one logic step further?
We meant the surface of the glacier. We clarified this sentence:
"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."
Please see P12 L10-14

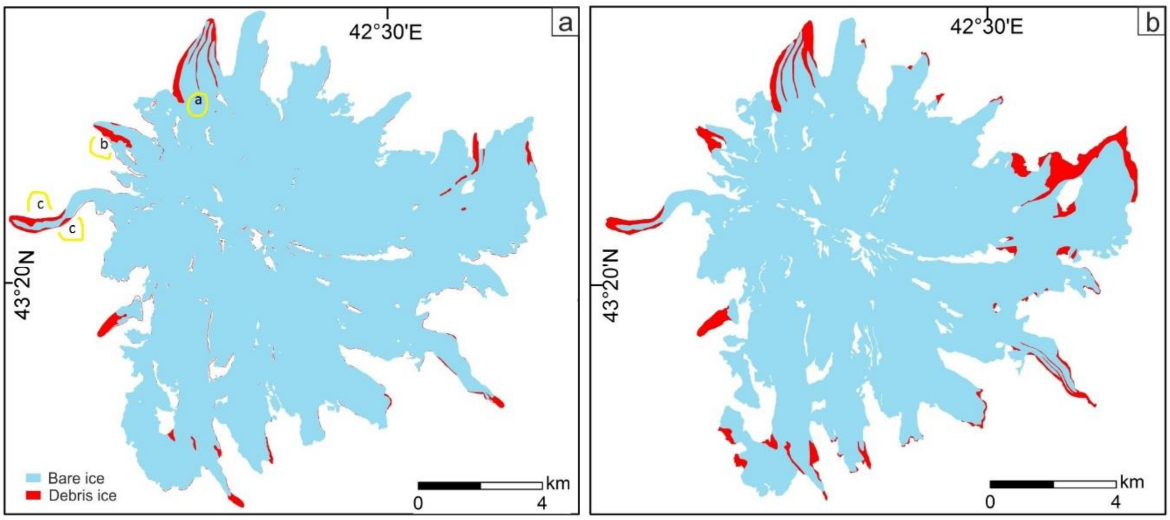
P8L2-3: "..although the total uncertainty is comparable to the obtained relative changes" I have a lot of respect for honest results that fall within suitable error bounds, however, there are clear changes between 1986 and 2014. Why was your method unable to confidently resolve this? In this discussion can you propose a method that might be more successful?
We clarify that this high error caused by using the buffer method for the small size of the supraglacial debris-covered outlines.
We clarify that this high error was caused by using the buffer method for the small size of the supraglacial debris-covered outlines.
The error is mostly inversely proportional to the length of the outline margin. So it depends strongly on the size of the outline. In this sense, the area error assessed by this study is rational because it accounts for the length of the SDC outline perimeter.
The more successful method could be multiple digitization that was excluded recently.
Overall we don't think that the "high error values" have vital importance in this case and have not done any changes here.

P8L3-4 "Comparison with semi-automated methods shows that debris cover may be considerably underestimated." First, it is unclear what you are referring to as the semi-automated method, if I follow correctly, this is the bare ice area that was subtracted from manual outlines to derive a debris cover so how could this dataset provide the comparison to make this statement? Beyond descriptive clarity, I'm inclined to agree with the general statement. I had a quick look on Earth Explorer and compared the image from 1986 against your Figure 4 (see attached figure). I added some arrows where Figure 4 misleadingly shows changes, e.g. an entirely new medial moraine network (labeled 'a'), area that is shown to gain debris cover but if this is the case then the glacier would have had to have grown not shrunk over the investigation period ('b'), and what looks like two rock avalanche deposits that are missed ('c'). I think it is a fine argument that these points are within your error bounds and I acknowledge that it is difficult to maintain consistent methods with debris-covered area change measurements because earlier sensors do not have the radiometric resolution that the later sensors do. However, the images do show true changes and it is the challenge of this line of research to be able to extract a meaningful signal.



LT05_L1TP_171030_19860806_20170217_01_T1

We would like to say special thanks for this comment here.
Apparently, we technically missed some debris-covered spots while making a new overlapping picture for the Elbrus massif. Please take in to account, this does not mean that we missed these areas while the calculating overall supraglacial debris cover area. For more clarification please see image below, from previous version of the manuscript (that was published in The Cryosphere Discussion) showing the SDC area changes between 1986 and 2014. All missed spots selected by you, are shown in the panel "a".
To double check please see: https://www.the-cryosphere-discuss.net/tc-2018-259/tc-2018-259-supplement.pdf



We have replaced a wrong version of the figure with new one. Please see P14 L1-3
In order to avoid any confusion, we made the "gif" file additionally showing clear differences between clean-ice and SDC in 1986- 2014.

The “gif” file is attached as a separate file in the supplement.

In addition, we have changed this sentence to: “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).”
Please see P13 L21-24

P8L5: “lake number and area”
Done. Suggested sentence has been changed accordingly. Please see P13 L23

P8L7: I do not follow the evidence for an increase of debris cover being explained by resurfacing of englacial debris. Is there a pattern in how the debris cover looks that would lead you to make this assumption?
Accepted. Indeed, this statement is probably speculative and was not supported by strong evidence. Text was revised:
“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).”
Please see P13 L24-26

P8L9: what boundaries in the subsurface are you looking for and why?
We meant that the GPR survey could be a good opportunity to recognising the ice under the SDC. We have changed this sentence and now stands as a:
“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).”
Please see P13 L26-29

P9L1: please make statements without ambiguities like “somewhat”
We use word “relatively” instead of “somewhat”. Overall, we changed the structure of this sentence to:
“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 m²/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 m²/W) (Lambrecht et al., 2011)”
Please see P13 L33-36

P9L6: end the sentence after “(2008)”, and I believe you meant to say Rowan et al. (2005) found similar model results.
Done. Suggested sentence has been changed accordingly. Please see P13 L40-41

P10L10: the list of detailed field measurements: “debris thickness, GPR, radiation” give a physical quantity, a geophysical tool and an emission of energy, please rewrite to list measurements.

Accepted and we provided new sentence here:

"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)."

Please see P14 L16-18 and P15 L1-2

Figure 2. This figure is very nice. Could you please add the error bounds? Also, the wording "clean ice to supraglacial debris cover [ratio]" should be reversed, the ordering implies numerator and denominator.

Done. Suggested figure and sentence have been changed accordingly. Please see P8 L12-14

Figure 4. I'm not questioning the area you show as clean ice in 1986 that is no longer clean ice in 2014 high on the massif, but area that is former glacier and now bedrock is distinctly different from a discussion of debris cover changes on a glacier's surface.

In order to better clarify, we provided new sentence below to Fig. 7: "Blue color shows retreat of clean ice parts."

Please see P14 L3

Figure S4: A figure showing a permafrost dataset with no real context or discussion seems out of the scope of this paper.

We have changed this figure. First of all we deleted "panel c" from the figure. We provided more suitable images in the supplement, showing SDC area increase after the rock avalanches in the second investigated period.

Please see P4 Figure S5 in the supplement.

Supraglacial debris-cover changes in the Greater Caucasus

Levan G. Tielidze[1,6,7], Tobias Bolch[2], Roger D. Wheate[3], Stanislav S. Kutuzov[4], Ivan I. Lavrentiev[4], Michael Zemp[5]

[1]Department of Geomorphology, Vakhushti Bagrationi Institute of Geography, Ivane Javakhishvili Tbilisi State University, 6 Tamarashvili st., 0177, Tbilisi, Georgia
[2]School of Geography and Sustainable Development, University of St Andrews, North Street, Irvine Building, St Andrews, KY16 9AL, Scotland, UK
[3]Natural Resources and Environmental Studies, University of Northern British Columbia, 3333 University Way, Prince George, V2N 4Z9, BC, Canada
[4]Department of Glaciology, Institute of Geography of the Russian Academy of Sciences, 29 Staromonetniy Pereulok, 119017, Moscow, Russia
[5]Department of Geography, University of Zurich, 190 Winterthurerstrasse, CH-8057, Zurich Switzerland
[6]Antarctic Research Centre, Victoria University of Wellington, PO Box 600, 6140, Wellington, New Zealand
[7]School of Geography Environment and Earth Sciences, Victoria University of Wellington, PO Box 600, 6140, Wellington, New Zealand

Correspondence to: Levan G. Tielidze (levan.tielidze@tsu.ge)

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.

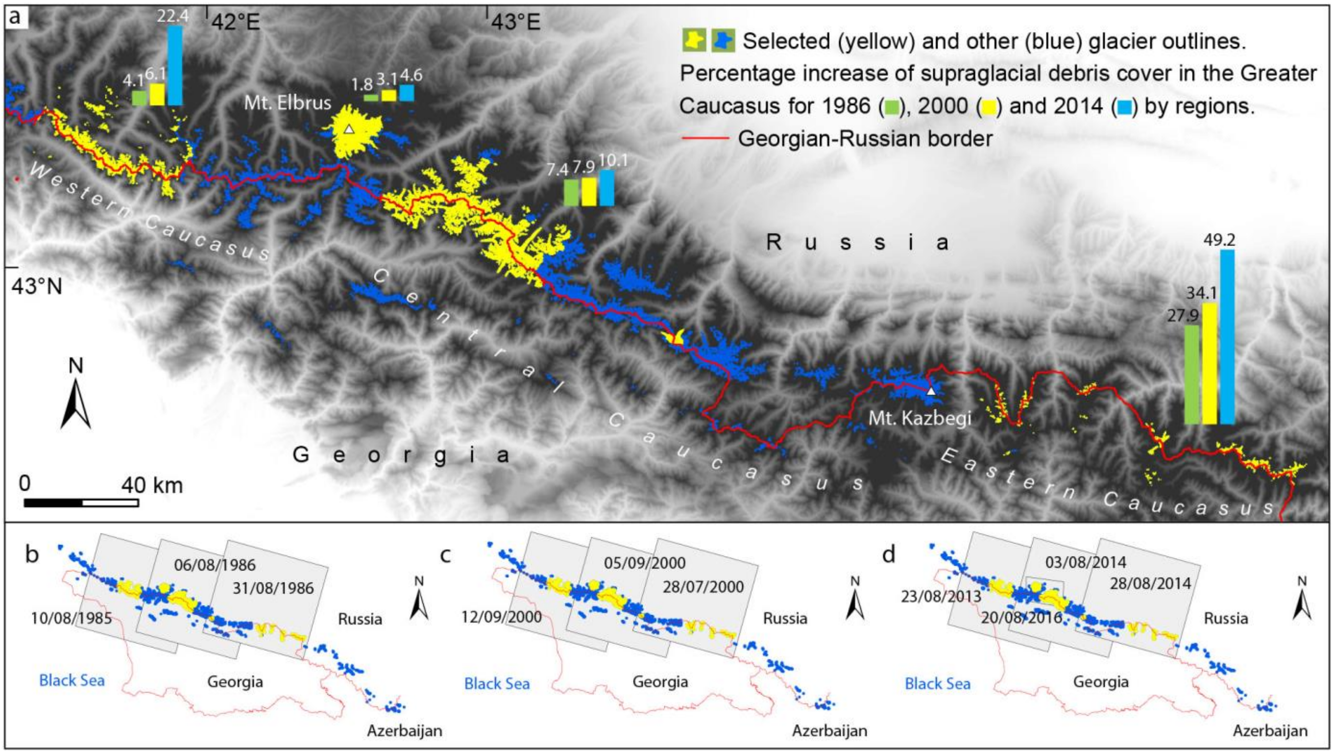


Figure 1. a – Investigated area and selected glaciers by regions. b – Three Landsat 5 TM satellite scenes 1985-1986. c – Three Landsat 7 ETM+ satellite scenes from 2000. d – Three Landsat 8 OLI satellite scenes from 2013-2014 and one (smaller) SPOT satellite scene from 2016.

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.

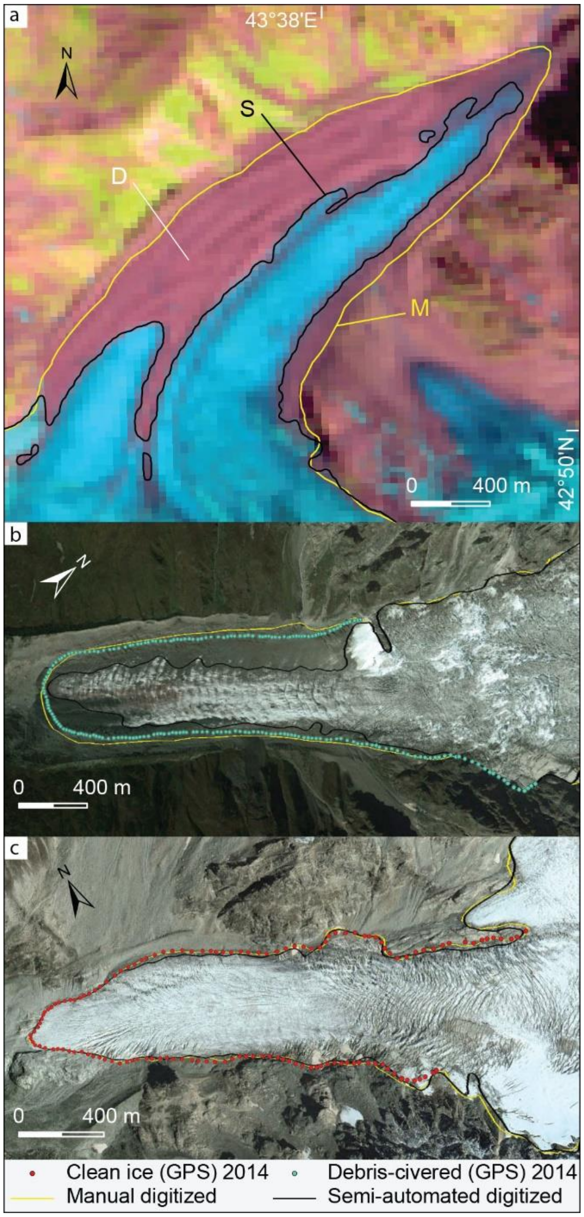


Figure 2. Mapping examples: a – supraglacial debris cover (D) assessment with comparison of different methods: manually (M) and semi-automated (S) (ratio TM 3/5 followed by manual improvement, threshold ≥2). Landsat image 06/08/1986 is used as the background. Examples of glacier outline accuracy assessment 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 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	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).

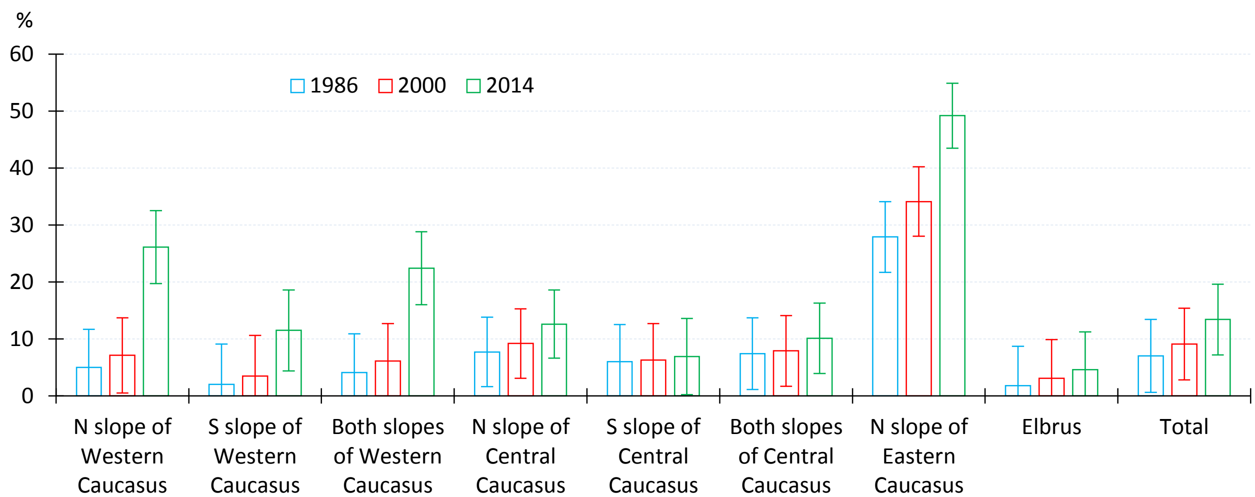


Figure 3. Percentage increase of supraglacial debris cover in the Greater Caucasus for 1986, 2000 and 2014 by different regions (glaciers are non-existent on southern slopes of the eastern Greater Caucasus).

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).

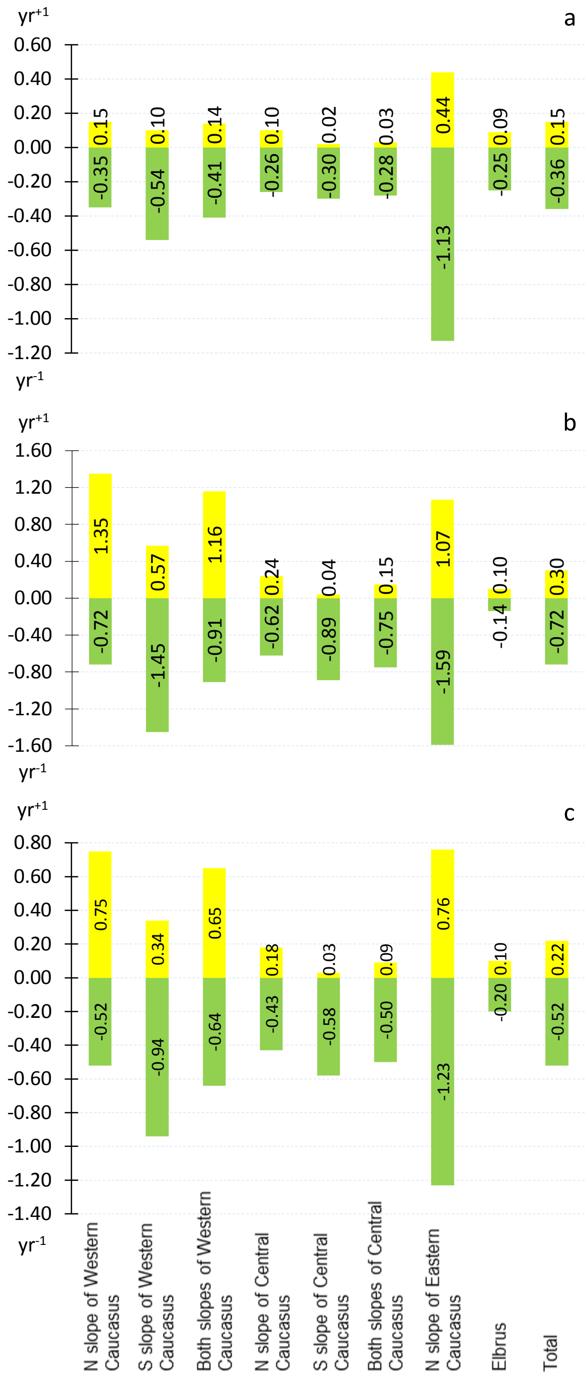


Figure 4. Supraglacial debris cover increase (yellow) and glacier area decrease (green) rates in the Greater Caucasus by slopes, sections and mountain massifs in 1986–2000, 2000–2014 and 1986–2014.

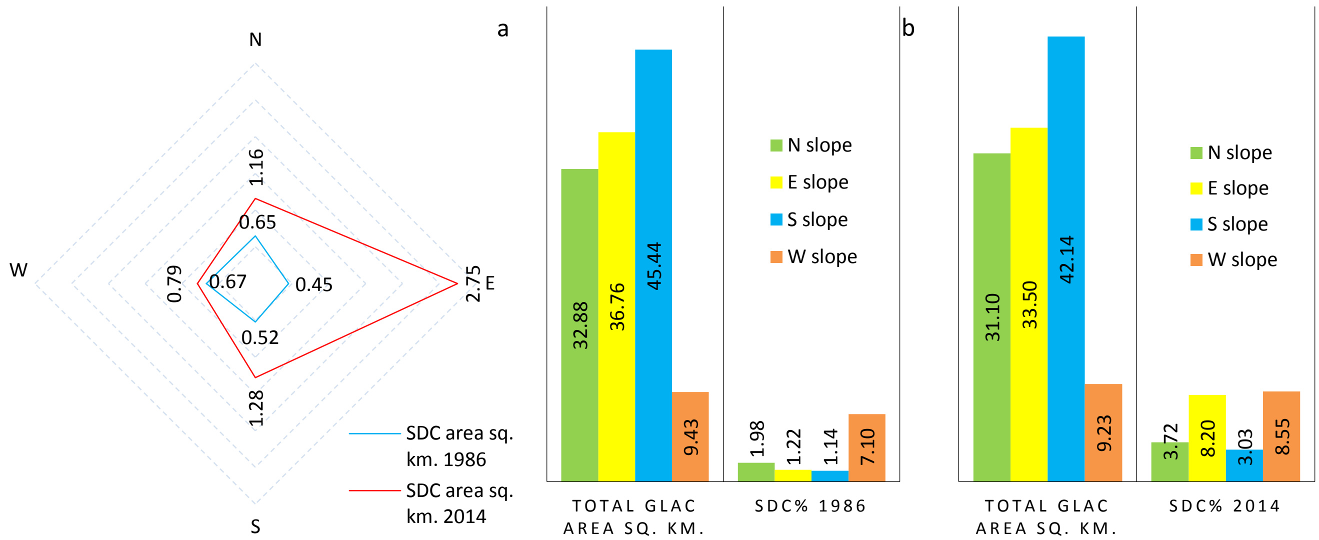


Figure 5. a – Supraglacial debris cover (SDC) area increase for the Elbrus slopes between 1986 and 2014. b and c – Total glacier area (km^2) and supraglacial debris cover percentage distribution between 1986 and 2014.

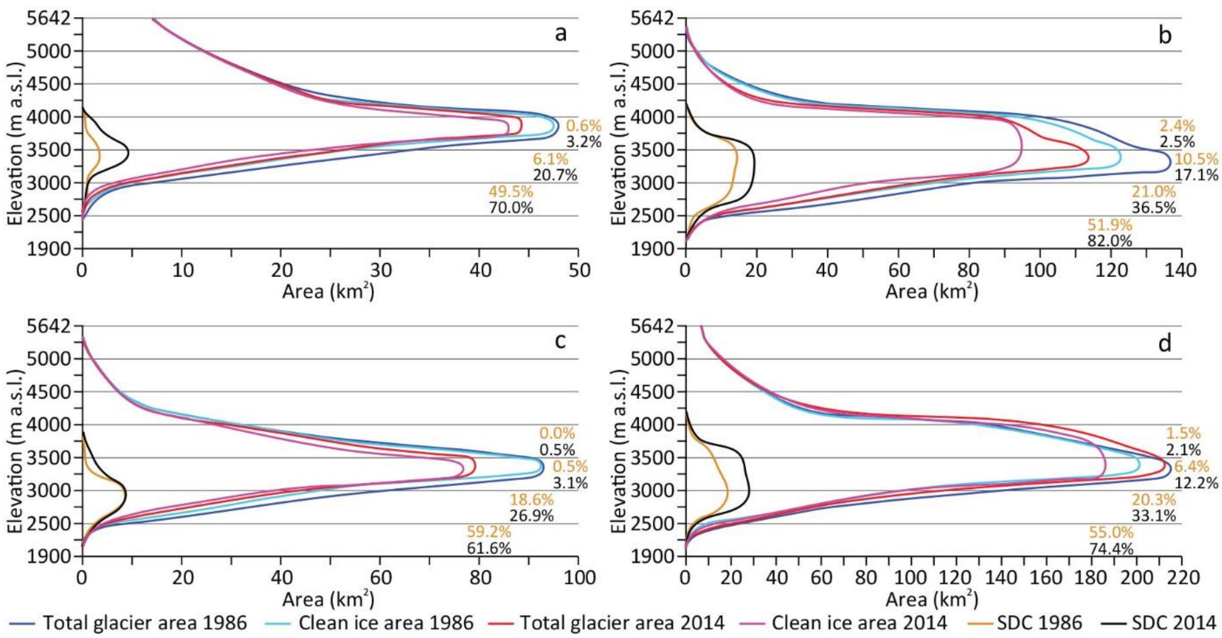


Figure 6. Hypsometry of supraglacial debris cover (SDC), clean ice and total glacier area, of the four study regions in 1986 and 2014. a – Elbrus, b – Northern Slope, c – Southern Slope, d – all selected glaciers. Supraglacial debris cover percentage is given according to the different elevation zones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

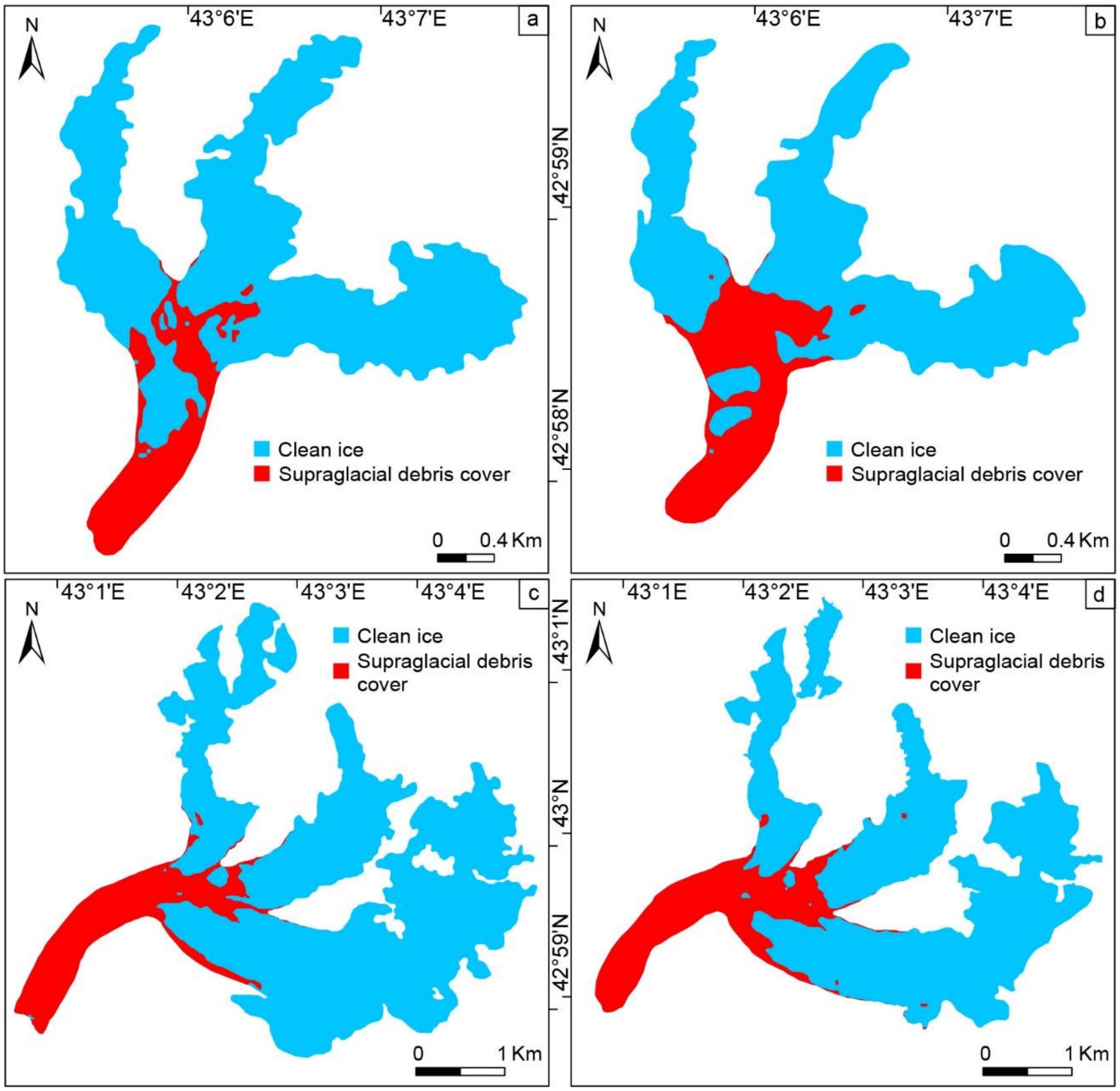


Figure 7. An example of the supraglacial debris cover up-glacier migration onto the Shkhara Glacier: a – 1986, b – 2014 and Khalde Glacier: c – 1986, d – 2014.

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 m²/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 m²/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).

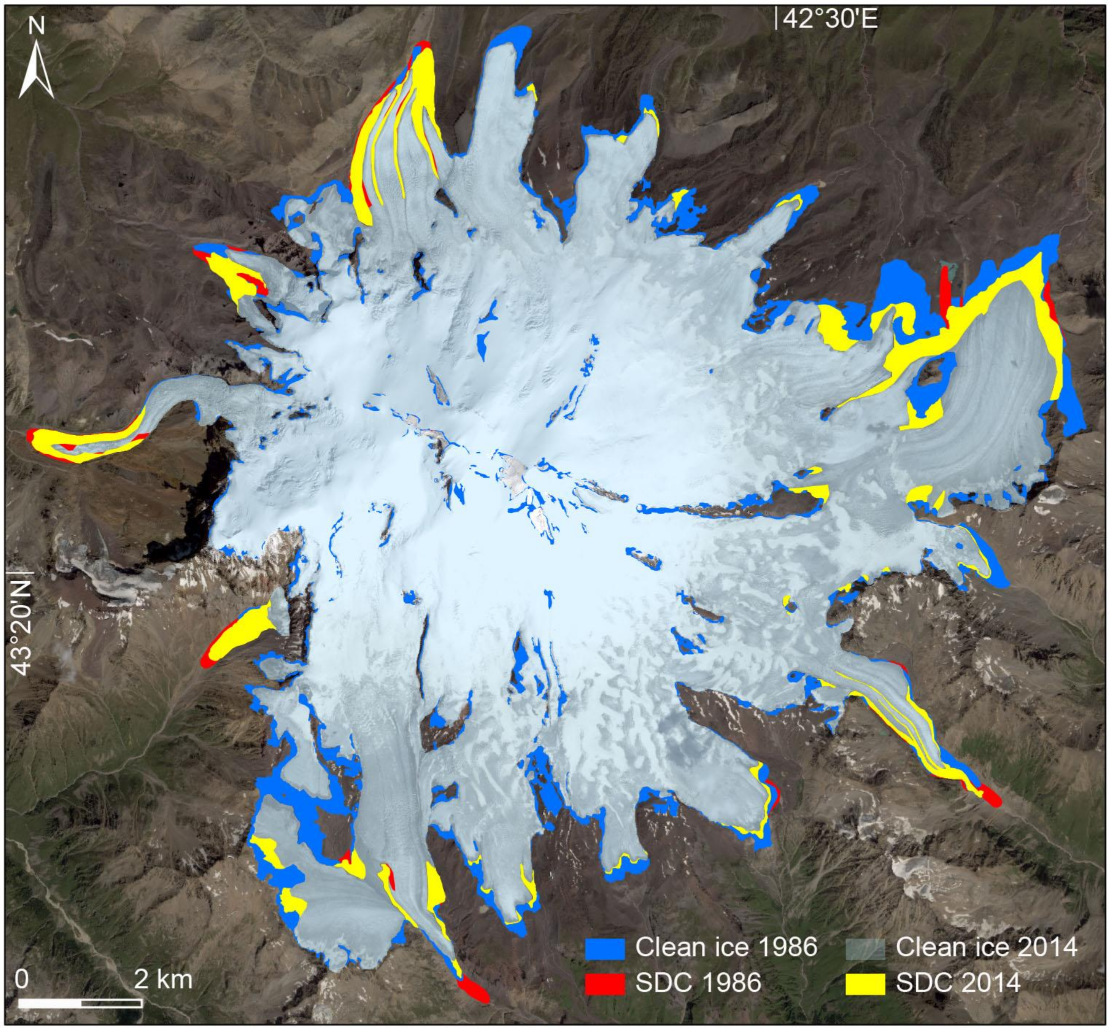


Figure 8. Supraglacial debris cover increase on the Elbrus Massif from 1986 to 2014. SPOT-7 image 20/08/2016 is used as the background. Blue color shows retreat of clean ice parts.

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.

Acknowledgements:

This work was supported by Shota Rustaveli National Science Foundation of Georgia (SRNSFG) [YS17_12]. We gratefully acknowledge the support of the editor, Etienne Berthier, and two reviewers, Dirk Scherler and Sam Herreid, for useful suggestions and detailed comments which clearly enhanced the quality of the paper. Special thanks to Shaun Eaves (Victoria University of Wellington) for proofreading the manuscript.

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.

References

Baraer, M., Mark, B. G., McKenzie, J. M., Condom, T., Bury, J., Huh, K. I., Portocarrero, C., Gomez, J., and Rathay, S.: Glacier recession and water resources in Peru's Cordillera Blanca. Journal of Glaciology, 58**,** 134-150, 2012.

Benn, D. I., and Evans, D. J. A.: Glaciers and Glaciation, Arnold, London, 1998.

Benn, D., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L., Quincey, D., Thompson, S., Toumi, R., and Wiseman, S.: Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. Earth-Science Reviews, 114**,** 156-174, 2012.

Bochud, M.: Tectonics of the Eastern Greater Caucasus in Azerbaijan. PhD Thesis, Faculty of Sciences of the University of Fribourg (Switzerland), 2011.

Bolch, T., Menounos, B., and Wheate, R.: Landsat-based inventory of glaciers in western Canada, 1985–2005, Remote Sens. Environ., 114, 127–137, doi:10.1016/j.rse.2009.08.015, 2010.

Deline, P.: Change in surface debris cover on Mont Blanc massif glaciers after the 'Little Ice Age' termination. The Holocene, 15(2), 302–309. https://doi.org/10.1191/0959683605hl809rr, 2005.

Deline, P., Gruber, S., Delaloye, R., Fischer, L., Geertsema, M., Giardino, M., Hasler, A., Kirkbride, M., Krautblatter, M., Magnin, F., McColl, S., Ravanel, L., and Schoeneich, P.: Chapter 15 - Ice Loss and

Slope Stability in High-Mountain Regions. In W. Haeberli, Colin Whiteman, John, F. Shroder (Eds.): Snow and Ice-Related Hazards, Risks and Disasters. Boston: Academic Press, pp. 521–561, https://doi.org/10.1016/B978-0-12-394849-6.00015-9, 2015.

Frey, H., Paul, F., and Strozzi, T.: Compilation of a glacier inventory for the western Himalayas from satellite data: methods, challenges, and results, Remote Sens. Environ., 124, 832–843, 2012.

Gobejishvili, R., Lomidze, N., and Tielidze, L.: Late Pleistocene (Wurmian) glaciations of the Caucasus, in: Quaternary Glaciations: Extent and Chronology, edited by: Ehlers, J., Gibbard, P. L., and Hughes, P. D., Elsevier, Amsterdam, 141–147, doi:10.1016/B978-0-444-53447-7.00012-X, 2011.

Glasser, N., Holt, T. O., Evans, Z. D., Davies, B. J., Pelto, M., and Harrison, S.: Recent spatial and temporal variations in debris cover on Patagonian glaciers. Geomorphology 273, 202-216. doi.org/10.1016/j.geomorph.2016.07.036, 2016.

Granshaw, F., D. and Fountain, A. G.: Glacier change (1958–1998) in the North Cascades National Park Complex, Washington, USA. J. Glaciol., 52(177), 251–256, doi: 10.3189/172756506781828782, 2006.

Haeberli, W., Bösch, H., Scherler, K., Østrem, G. and Wallén, C. C. (Eds.): World glacier inventory - status 1988. IAHS(ICSI)/UNEP/UNESCO, Nairobi. 1989.

Jiang, S., Nie, Y., Liu, Q., Wang, J., Liu, L., Hassan, J., Liu, X., and Xu, X.: Glacier Change, Supraglacial Debris Expansion and Glacial Lake Evolution in the Gyirong River Basin, Central Himalayas, between 1988 and 2015. Remote Sens. 10, 986. https://doi.org/10.3390/rs10070986. 2018.

Kirkbride, M. P. and C. R. Warren.: Tasman Glacier, New Zealand: 20th-century thinning and predicted calving retreat. Global Planet. Change, 22 (1–4), 11–28, 1999.

Kirkbride, M. P., Deline, P.: The formation of supraglacial debris covers by primary dispersal from transverse englacial debris bands. Earth Surf. Process. Landforms 38, 1779–1792. https://doi.org/10.1002/esp.3416. 2013.

Kozachek, A., Mikhalenko, V., Masson-Delmotte, V., Ekaykin, A., Ginot, P., Kutuzov, S., Legrand, M., Lipenkov, V., and Preunkert, S.: Large-scale drivers of Caucasus climate variability in meteorological records and Mt El'brus ice cores, Clim. Past, 13, 473–489, https://doi.org/10.5194/cp-13-473-2017, 2017.

Kutuzov S., Lavrentiev I., Smirnov A., Nosenko G. and Petrakov D.: Volume changes of Elbrus glaciers from 1997 to 2017, Front. Earth Sci. 7:153. doi:10.3389/feart.2019.00153.

Lambrecht, A., Mayer, C., Hagg, W., Popovnin, V., Rezepkin, A., Lomidze, N., and Svanadze, D.: A comparison of glacier melt on debris-covered glaciers in the northern and southern Caucasus, The Cryosphere, 5, 525-538, doi:10.5194/tc-5-525-2011, 2011.

Mattson, L. E.: The influence of a debris cover on the midsummer discharge of Dome Glacier, Canadian Rocky Mountains. IAHS Publ. 264 (Symposium in Seattle 2000 – DebrisCovered Glaciers), 25–33, 2000.

Mccarthy, M., Pritchard, H., Willis, I., and King, E.: Ground-penetrating radar measurements of debris thickness on Lirung Glacier, Nepal. Journal of Glaciology, 63(239), 543-555. doi:10.1017/jog.2017.18, 2017.

Mikhalenko, V., Sokratov, S., Kutuzov, S., Ginot, P., Legrand, M., Preunkert, S., Lavrentiev, I., Kozachek, A., Ekaykin, A., Faïn, X., Lim, S., Schotterer, U., Lipenkov, V., and Toropov, P.: Investigation of a deep ice core from the Elbrus western plateau, the Caucasus, Russia, The Cryosphere, 9, 2253-2270, doi:10.5194/tc-9-2253-2015, 2015.

Mölg, N., Bolch, T., Rastner, P., Strozzi, T., and Paul, F.: A consistent glacier inventory for Karakoram and Pamir derived from Landsat data: distribution of debris cover and mapping challenges, Earth Syst. 30 Sci. Data, 10, 1807-1827, https://doi.org/10.5194/essd-10-1807-2018, 2018.

Mölg, N., Bolch, T., Walter, A., and Vieli, A.: Unravelling the evolution of Zmuttgletscher and its debris cover since the end of the Little Ice Age, The Cryosphere, 13, 1889-1909, https://doi.org/10.5194/tc-13-1889-2019, 2019.

Nicholson, L. I., McCarthy, M., Pritchard, H. D., and Willis, I.: Supraglacial debris thickness variability: impact on ablation and relation to terrain properties, The Cryosphere, 12, 3719-3734, https://doi.org/10.5194/tc-12-3719-2018, 2018.

Östrem, G.: Ice Melting under a Thin Layer of Moraine, and the Existence of Ice Cores in Moraine Ridges. Geografiska Annaler, 41(4), 228-230, 1959.

Paul, F., Huggel, C., and Kaab, A.: Combining Satellite Multispectral Image Data and a Digital Elevation Model for Mapping Debris-Covered Glaciers. Remote Sensing of Environment 89: 510–518. doi:10.1016/j.rse.2003.11.007, 2004.

Paul, F. R., Barry, R. G., Cogley, J. G., Frey, H., Haeberli, W., Ohmura, A., Ommanney, C. S. L., Raup, B., Rivera, A., and Zemp, M.: Recommendations for the compilation of glacier inventory data from digital sources, Ann. Glaciol., 50, 119–126, 2009.

Paul, F., Barrand, N., Baumann, S., Berthier, E., Bolch, T., Casey, K., Frey, H., Joshi, S., Konovalov, V., Le Bris, R., Mölg, N., Nosenko, G., Nuth, C., Pope, A., Racoviteanu, A., Rastner, P., Raup, B., Scharrer, K., Steffen, S., and Winsvold, S.: On the accuracy of glacier outlines derived from remote-sensing data, Ann. Glaciol., 54, 171–182, doi:10.3189/2013AoG63A296, 2013.

Petrakov, D. A., Krylenko, I. V., Chernomorets, S. S., Tutubalina, O. V., Krylenko, I. N., and Shakhmina, M. S.: Debris flow hazard of glacial lakes in the Central Caucasus. Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Chen & Major, eds. Millpress, Netherlands, 2007.

Popovnin, V. V., and Rozova, A.: Influence of sub-debris thawing on ablation and runoff of the Djankuat Glacier in the Caucasus. Nord. Hydrol., 33, 75–94., 2002.

Popovnin, V. V., Rezepkin, A. A., and Tielidze, L. G.: Superficial moraine expansion on the Djankuat Glacier snout over the direct glaciological monitoring period, Earth Cryosphere, vol. XIX, No. 1, pp. 79–87, 2015.

Pratap, B., Dobhal, D., Mehta, M., and Bhambri, R.: Influence of debris cover and altitude on glacier surface melting: A case study on Dokriani Glacier, central Himalaya, India. Annals of Glaciology, 56(70), 9-16. doi:10.3189/2015AoG70A971, 2015.

Rau, F., Mauz, F., Vogt, S., Singh Khalsa, S. J., and Raup, B.: Illustrated GLIMS Glacier Classification Manual, Glacier Classification Guidance for the GLIMS Glacier Inventory. 2005. www.glims.org

Raup, B. H., Khalsa, S. J. S., Armstrong, R. L., Sneed, W. A., Hamilton, G. S., Paul, F., Cawkwell, F., Beedle, M. J., Menounos, B. P., Wheate, R. D., Rott, H., Shiyin, L., Xin, Li., Donghui, S., Guodong, C., Kargel, J. S., Larsen, C. F., Molnia, B. F., Kincaid, J. L., Klein, A., and Konovalov, V.: Quality in the GLIMS glacier database, in: Global Land Ice Measurements from Space, Springer Berlin Heidelberg, 163–182, doi:10.1007/978-3-54079818-7_7, 2014.

Rowan, A. V., Quincey, D. J., Egholm, D. L., and Glasser, N. F.: Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya. Earth Planet. Sci. Lett.430, 427–438. doi.org/10.1016/j.epsl.2015.09.00, 2015.

Scherler, D., Bookhagen, B., and Strecker, M. R.: Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nature Geoscience vol. 4, pp. 156-159. https://doi. 10.1038/NGEO1068, 2011.

Scherler, D., Wulf , H. and Gorelick, N.: Global assessment of supraglacial debris-cover extents. Geophysical Research Letters, 45. https://doi.org/10.1029/2018GL080158, 2018.

Stokes, C. R., Popovnin, V. V., Aleynikov, A., and Shahgedanova, M.: Recent glacier retreat in the Caucasus Mountains, Russia, and associated changes in supraglacial debris cover and supra/proglacial lake development, Ann. Glaciol., 46, 196–203, 2007.

Thompson, S., Benn, D., Mertes, J. And Luckman A.: Stagnation and mass loss on a Himalayan debris-covered glacier: processes, patterns and rates. Journal of Glaciology. Vol. 62, Issue 233. pp. 467-485, doi.org/10.1017/jog.2016.37, 2016.

Tielidze, L. G.: Glacier change over the last century, Caucasus Mountains, Georgia, observed from old topographical maps, Landsat and ASTER satellite imagery, The Cryosphere, 10, 713-725, doi.org/10.5194/tc-10-713-2016, 2016.

Tielidze L.: Introduction. In: Glaciers of Georgia. Geography of the Physical Environment. Springer, Cham, https://doi.org/10.1007/978-3-319-50571-8_1, 2017.

Tielidze, L. G. and Wheate, R. D.: The Greater Caucasus Glacier Inventory (Russia, Georgia and Azerbaijan), The Cryosphere, 12, 81-94, https://doi.org/10.5194/tc-12-81-2018, 2018.

Tielidze, L. G., Kumladze, R. M., Wheate, R. D., and Gamkrelidze, M.: The Devdoraki Glacier Catastrophes, Georgian Caucasus. Hungarian Geographical Bulletin, 68(1), 21-35. https://doi.org/10.15201/hungeobull.68.1.2, 2019a.

Tielidze L., Gobejishvili R., Javakhishvili A.: Eastern Greater Caucasus. In: Tielidze L. (eds) Geomorphology of Georgia. Geography of the Physical Environment. Springer, Cham. https://doi.org/10.1007/978-3-319-77764-1_10, 2019b.

Volodicheva, N.: The Caucasus, in: The Physical Geography of Northern Eurasia, edited by: Shahgedanova, M., 350–376, Oxford University Press, Oxford, 2002.

Zhang Y., Hirabayashi, Y., Fujita, K., Liu, S., and Liu, Q.: Heterogeneity in supraglacial debris thickness and its role in glacier mass changes of the Mount Gongga, Science China Earth Sciences 59, 170, doi:10.1007/s11430-015-5118-2, 2016.

Supplement of

Supraglacial debris-cover changes in the Greater Caucasus

Levan G. Tielidze et al.

Correspondence to: Levan G. Tielidze (levan.tielidze@tsu.ge)

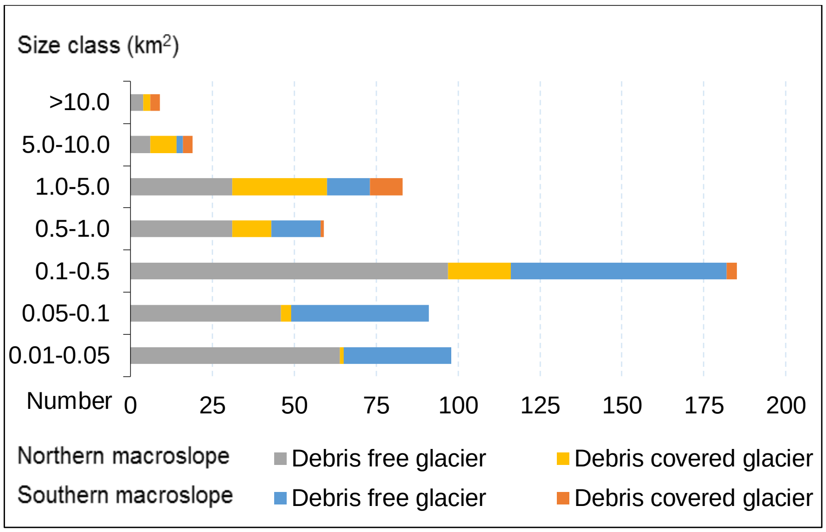


Figure S1. The Greater Caucasus glacier size classes with debris covered and debris free glaciers distributions for northern and southern slopes.

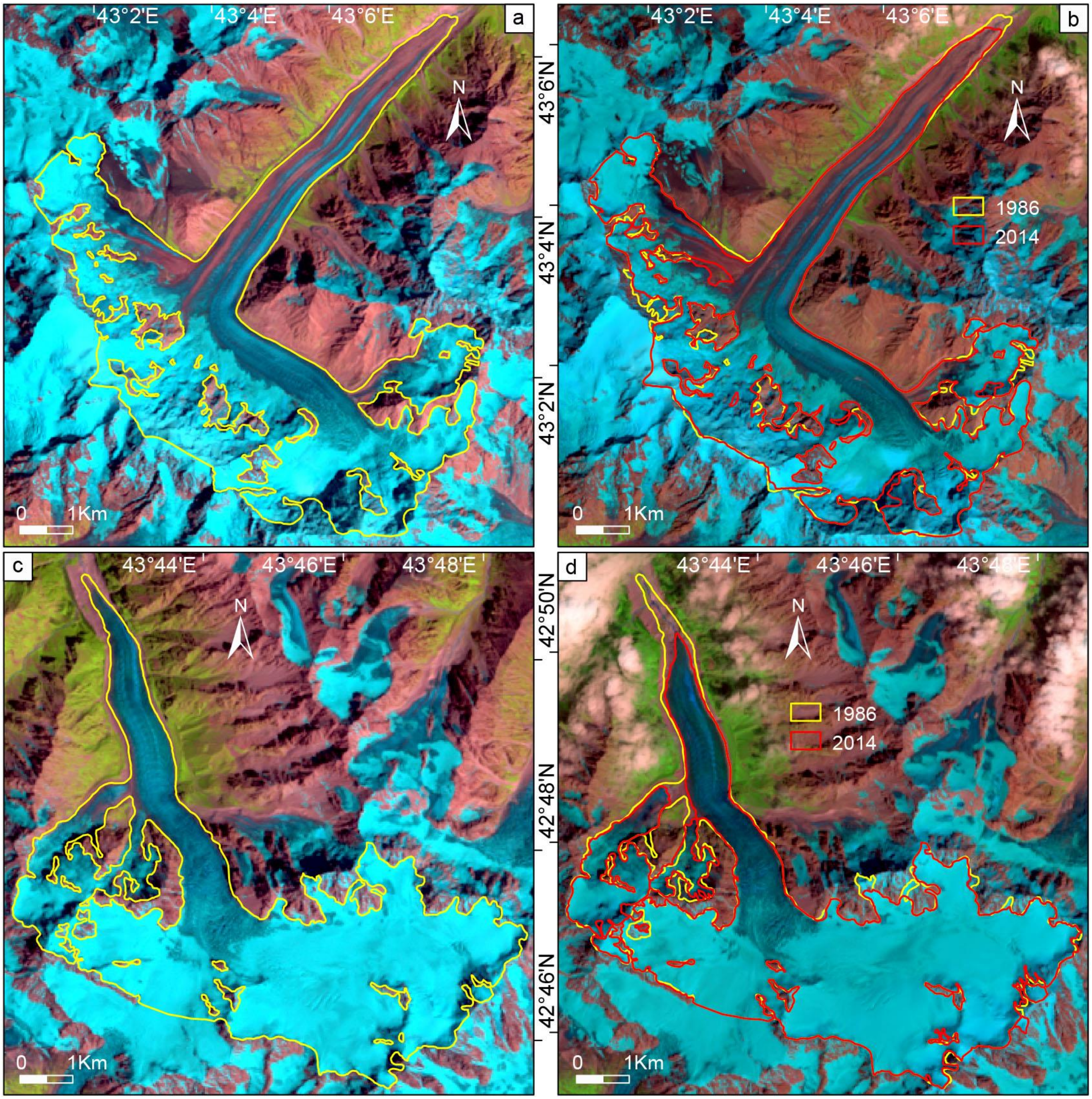


Figure S2. Debris-covered Bezingi Glacier retreat between 1986 (a) and 2014 (b); Debris-free Karaugom Glacier retreat between 1986 (c) and 2014 (d).

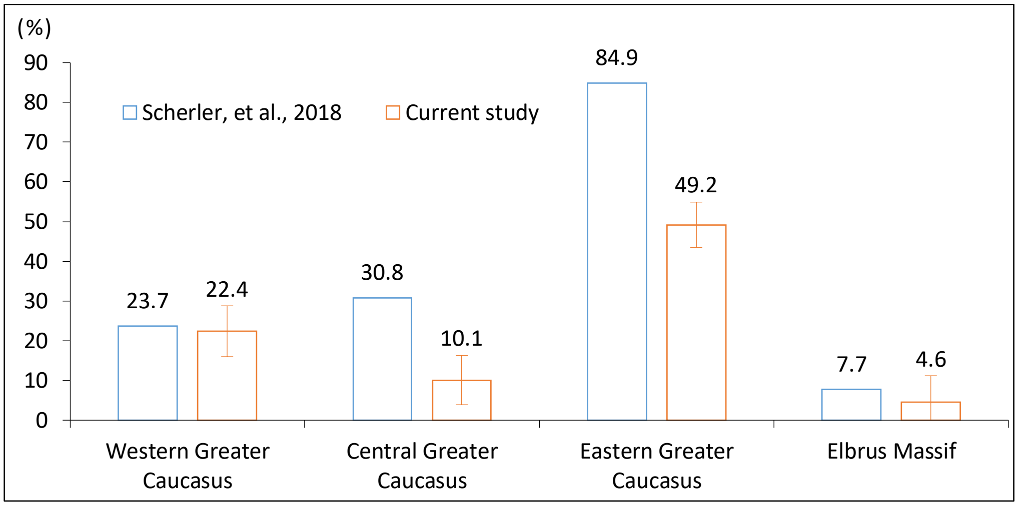


Figure S3. Relative supraglacial debris cover for the Western, Central, and Eastern Greater Caucasus as well as for Elbrus based on the current study and in comparison with Scherler et al. (2018).

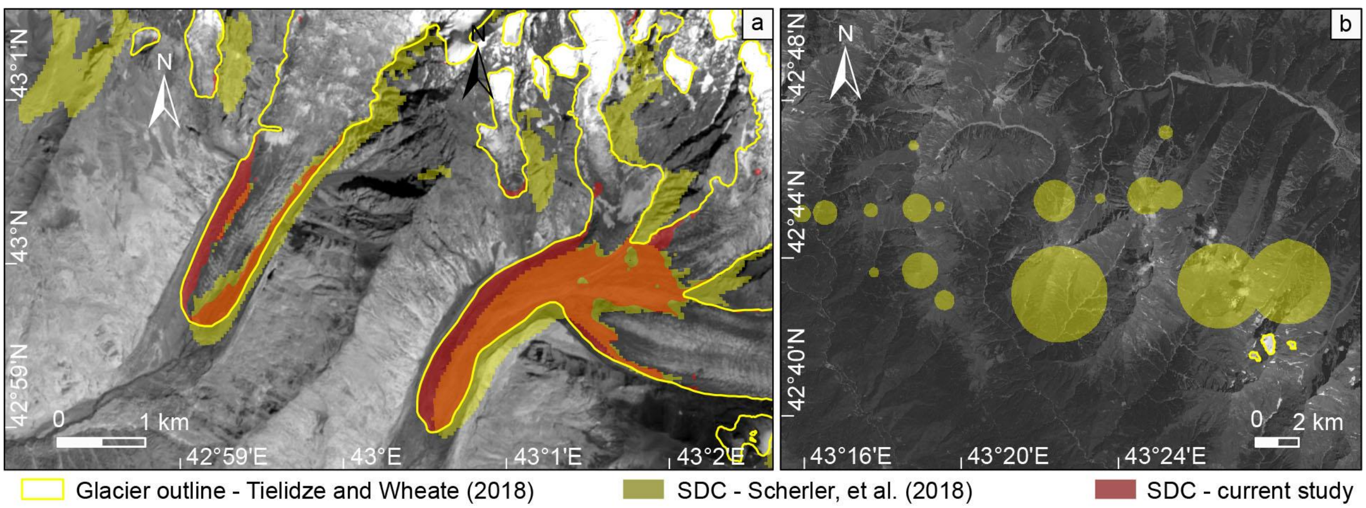


Figure S4. a - Comparison of supraglacial debris cover (SDC) assessment by Scherler, et al. (2018) (based on the RGI v6) and current study. b - An example of the RGI v6 nominal glaciers (circles). According to Scherler, et al. (2018), all nominal glaciers were classified as debris-covered. Landsat 8 (panchromatic band 8), 03/08/14 was used as background.

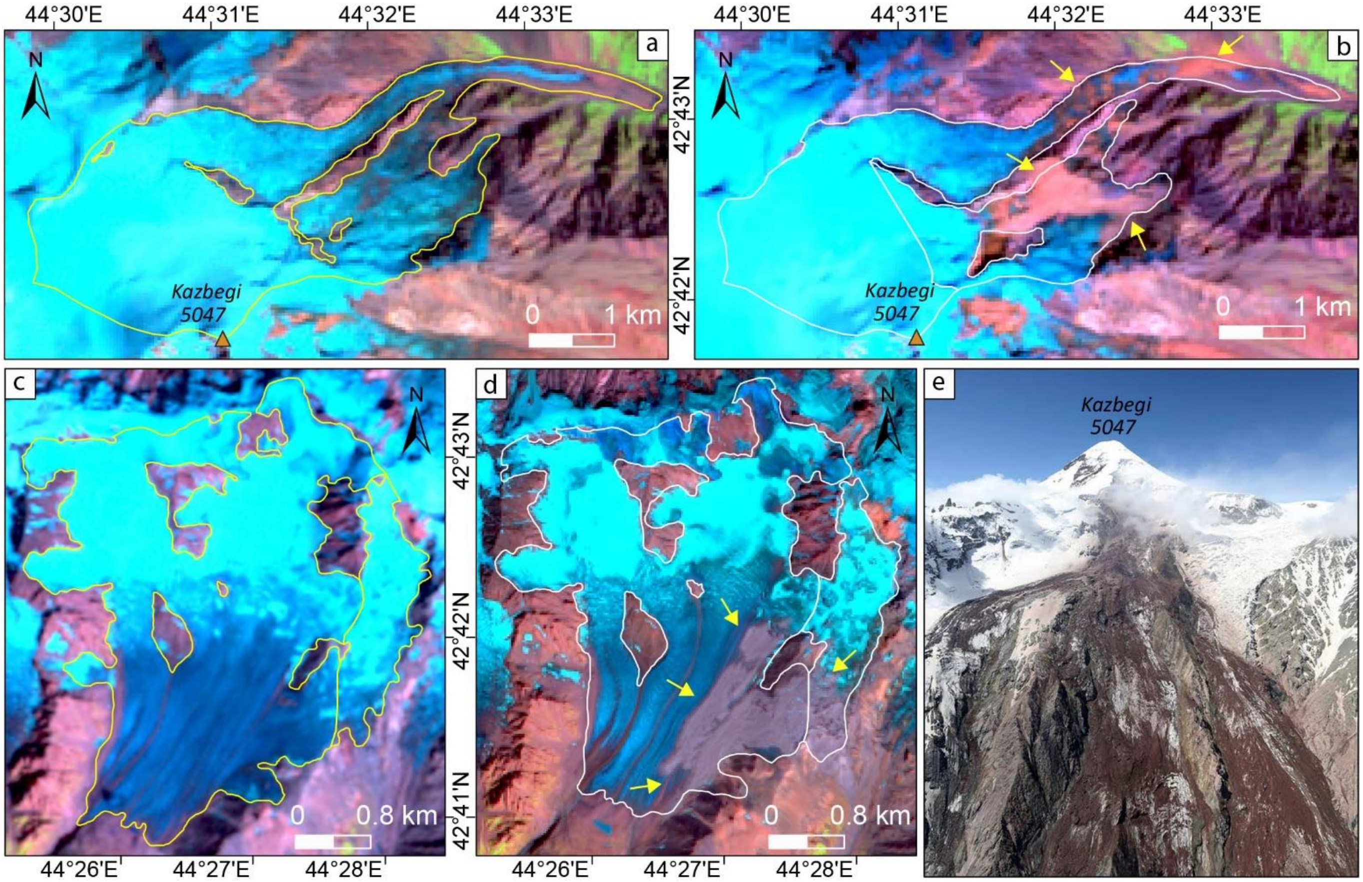


Figure S5. a – Devdoraki Glacier in 2000 (Landsat 7, 28/07/00); b – Devdoraki Glacier after rock-ice avalanche in 2014 (Landsat 8, 28/08/14). c – Suatisi Glacier in 2000 (Landsat 7, 28/07/00); d – Suatisi Glacier in 2014 (Landsat 8, 03/08/14). Yellow arrow shows increased supraglacial debris cover area. e – Devdoraki Glacier oblique image showing increased supraglacial debris cover area after rock-ice avalanche (18/04/14).

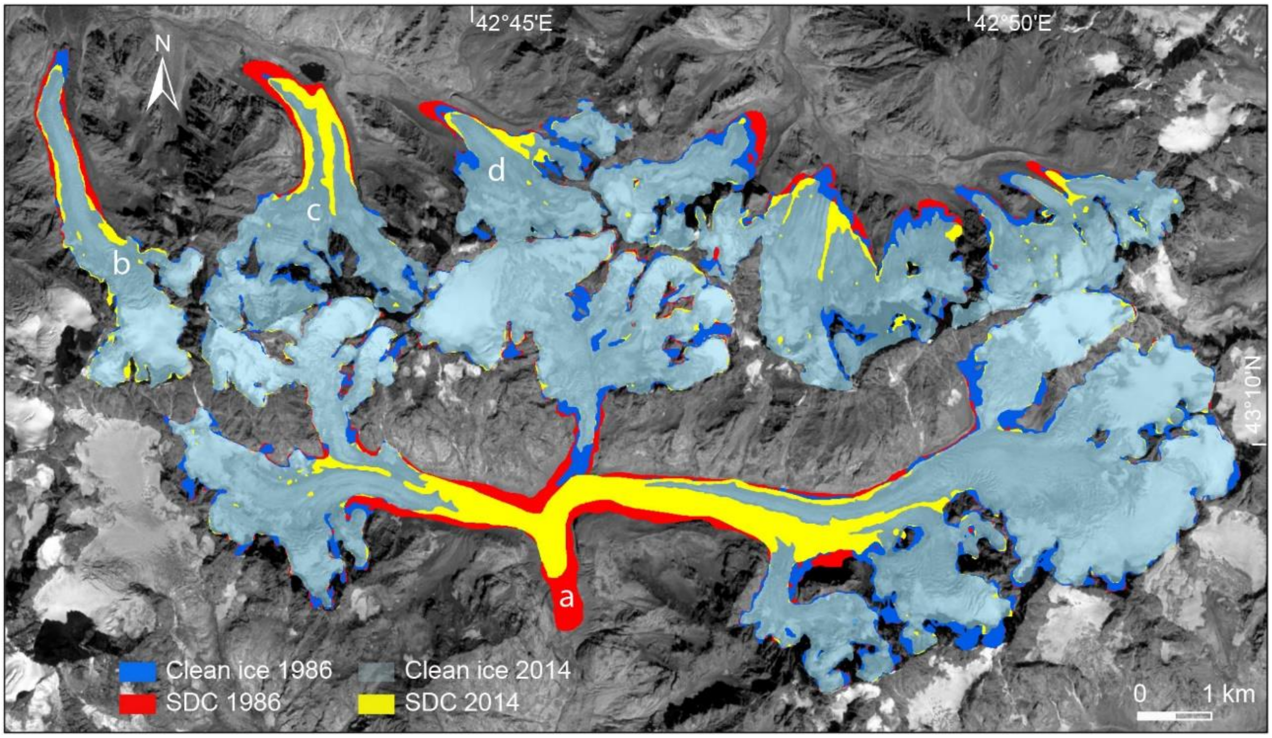


Figure S6. A comparison of supraglacial debris cover (SDC) and clean-ice area distribution in 1986-2014 for the southern (a – Lekhziri) and northern-facing (b – Kashkatash, c – Bashkara and d – Djankuat) glaciers. Landsat 8 (panchromatic band 8), 03/08/14 was used as background.