Dear Dr. Etienne Berthier,

We appreciate your help for the constructive comments which have significantly improved the quality of our manuscript. We have made our best effort to revise the manuscript based on your and the referee’s comments and suggestions.
In addition, we have expanded and made more detail comments in the response letters.
Please see the new response letters and the revised manuscript below.

All corrections and changes what we did in the manuscript are in yellow (first revision) and green (second revision).

# Authors reply to Dr. Dirk Scherler's comments

## "Brief communication: Supraglacial debris-cover changes in the Caucasus Mountains" by L. G. Tielidze, et al.

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

Dear Dr. Dirk Scherler,

First of all, we thank you for your careful reading of the paper and for the constructive review. In the following pages, we provide point-by-point responses following every comment.

All corrections and changes what we did in the text are in yellow (first revision) and green (second revision).

| |
|---|
| **General comments**<br>This contribution presents satellite imagery derived changes in supraglacial debris cover in the Caucasus Mountains between 1986, 2000, and 2014, based on Landsat and Spot imagery. The paper presents interesting data although I find some of the methodology unclear. The analysis of the data could be extended to support, or refute, some of the inferences in the discussion, which is sometimes rather speculative. When addressing these issues, the paper should be a relevant contribution, but may be better published as a standard format paper, instead of a brief communication? |
| We agree that the methodology section was confusing in the previous version of the manuscript, and therefore, we are presenting more comprehensive methodology here. The analysis of the data has also been expanded. Please find the new methodology section P3 L18-34; P4 L1-21.<br><br>It is true, that because of the many corrections and new text/figures, the manuscript was slightly expanded but we decided to keep it as a brief communication, which is better suited to its scope and length. We think that the standard format article should be much more thorough, in-depth study that could contain more detailed data. |
| **Main comments**<br>The description of the methods takes up a considerable fraction of the entire paper, but there still is some information missing. I had the biggest difficulties to understand how the GPR data was used. Hardly any information is given about it, but it appears to be relevant for "correcting" the debris covered area on the Elbrus Massif. If the GPR data was used in this study, I think the authors should provide much more information about the data and the results. At present, I've only seen one figure in the supplementary material (Figure S6). How reliable are the GPR measurements? Is there room for interpretation or was it all straight forward? I don't question the observations; I would just like to see more of the data the authors collected. |
| As the GPR data caused some awkwardness, we have excluded it in the current version of the manuscript. We agree that it required much more explanation and methodology |

definitions.

We note that, the removal has no impact of the overall results/message of the paper, since it was a more separate topic and not the main part of the manuscript. In addition it applied only to the Elbrus Massif and not the whole Caucasus.

Overall, I found the discussion quite confusing. It starts with a chapter on possible reasons for the observed SDC increase, but this chapter also addresses the question of spatial differences in SDC, without any temporal aspect. The authors mention many potential reasons for either spatial differences or temporal changes (and I think many of them are truly meaningful), but they remain speculative. I see potential to address some of these reasons with the current data, but that would require additional analysis. For example, the authors suggest that rock avalanches after 2000 may be one of the reasons why SDC increased more during the period 2000-2014 and they provide examples in the supplementary material. Wouldn't it be possible to quantify these in order to assess their relevance? From the supplementary figure, it wasn't clear to me if all of the rock avalanches were deposited in the ablation zone. If not, some of them may be gone again when buried under snow and ice in a few years. The authors also suggest that topographic differences between northern and southern slopes are responsible for spatial differences in debris cover. Instead of opposing just the two regions, wouldn't it make sense to analyze the glaciers and their topographic setting for testing this idea? If true, there should be a correlation between the topographic reason and the observed difference. There exist other inferences or statements ("Little Ice Age moraine can affect the SDC increase on the glacier tongue, as debris often falls from lateral moraines onto the glacier surface"; "in the eastern Greater Caucasus, a large percentage of the debris cover is a result of the lithology") that should be better backed up by observations, for example, from the spatial distribution of debris cover and its increase on the glacier surfaces.

We provided a new version of the Discussion with many corrections and new texts. We tried our best to avoid any speculations.

Overall we provided two sub-titles in Discussion section:

**4.1 Supraglacial debris-cover changes**

- Here we provided SDC percentage distribution by different elevation zones to justify the up-glacier migration Fig. 3; and added one more image in the supplement (Fig. S3).

- We also discussed that, dramatic increase of the SDC after 2000 could be caused by the rock avalanches related to permafrost. We gave an example of the Devdoraki Glacier – Fig. S4 and added a new related reference (Tielidze et al., 2019).

- In addition, we added one more relevant figure in supplement (Fig. S5) in order to better understand topographic differences between northern and southern slopes related to SDC different distribution.
More detailed analysis regarding the topographic differences for the Greater Caucasus glaciers, has been already Published in Tielidze et al., 2018 (see reference list in the manuscript).

- In case of Elbrus, we discuss that the significant increase of SDC can be related to resurfacing of the englacial debris as a result of glacier recession (specifically in the eastern slopes).

In the second subtitle **(4.2 Comparison with previous investigations)** we compared our results with previous studies in local and regional scale.

The comparison with previous estimates of debris cover in the Caucasus Mountains is useful and worth reporting. However, when comparing results with the values reported in our recent paper (Scherler et al., 2018), it should be explicitly stated that the scope of our study was a different one. We attempted an automatized global assessment, knowing and discussing the issues of erroneous glacier outlines in the RGI and we explicitly stated that we did not correct any outlines in the RGI. In other words, we did not pretend to get the debris cover correct, if the RGI outlines are not correct. This is an important point that should be acknowledged to avoid making a straw man argument! It is also not clear to me how the data of Figure 2 was put together. Were only those glaciers compared that were analyzed in both studies? And what about the circular glaciers? Overall, I find Figure 2 not relevant. More relevant would be the comparison of the clean ice-debris cover boundary between our and this study, as in our automatized mapping, we were relying on a single threshold value for the entire Earth.

We certainly do not question work by Scherler et al. (2018) and we mentioned (end of the Discussion) that the goal of your study was an automatized global assessment of SDC from optical satellite data, without correcting any outlines in the RGI. The big difference between these two results is just caused by RGI inconsistent outlines (that we mentioned before as well, e.g. Tielidze and Wheate, 2018).
But, in fact, the work by Scherler et al. (2018) is only one work including the SDC data-set for entire Greater Caucasus and we think that comparison of these two studies and highlighting the resultant overestimation caused by erroneous RGI outlines is important. Therefore, we decided to leave previous Fig. 2 but moved it in the supplement as Fig. S6.

In addition, we provided an explanation of how we compared these two data-set – "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." Please see P9 L24-25.

We also provided a new figure in the supplement (Fig. S7) showing the differences between current study and study by Scherler et al. (2018)/RGI outlines.

**Specific comments**

*P1L24: "Thereby": I don't see the causal connection to the foregone sentence*

*P1L26- 28: It would be good if you could provide an explanation, or your favorite explanation, why this is the case.*

We agree. We rewrote the abstract taken your comments into account. Please see P1 L24-34

*P2L2: "supraglacial debris thickness"*

Corrected as suggested, please see P2 L8

*P2L8: "Europe": Nothing important, but I'm wondering if all of the Caucasus Mountains and thus all of the glaciers and their area are part of Europe?*

Since there are several definitions about the location of the Greater Caucasus, we just mentioned it as a "one of the world's highest mountain systems".

| |
|---|
| Please see P2 L13 |
| *P2L10: Delete "similarly"* |
| We agree and deleted this word, please see P2 L16 |
| *P2L15: How does it contradict earlier studies? Please specify.* |
| We have changed this sentence, please see P2 L20-22 |
| *P2L25: What determined your selection of glaciers? Does this mean there exist glaciers that you did not consider? Please clarify* |
| We have changed this sentence and added appropriate citations, as follows: "We selected four regions representing different climate conditions (Stokes, 2011) and glacier characteristics (Tielidze and Wheate, 2018) with a total of 659 glaciers:"<br>Please see P2 L30-31 |
| *P2L29: "a largest" -> "the largest"* |
| Corrected as suggested, please see L2 L34 |
| *P2L39: "Additionally, . . ." -> Please specify how you included what kind of GPR results in which way. Also give references if it is published. If it is not published, I think you need to provide much more information on the GPR data.* |
| As the GPR data caused some awkwardness, we excluded it in the current version of the manuscript. We think that it required much more explanation and methodology definitions.<br>We note that, the removal has no impact of the overall results/message of the paper, since it was a separate topic and not the main part of the manuscript. |
| *P3L1: ASTER GDEM asks for a certain way of acknowledgement that is missing.* |
| We agree and an appropriate link was added P3 L5 |
| *P3L5: What threshold value did you use to distinguish between ice and debris?* |
| We used threshold value ≥2.0. This information was now added in the manuscript, please see P3 L20 |
| *P3L13: "SDC is" -> "SDC are"* |
| We deleted this sentence, so this comment is not relevant anymore. |
| *P3L14: Delete "Relatively"* |
| We agree and deleted this word |
| *P3L16: Again, it is unclear how you used GPR data (see comment above).* |
| As the GPR data caused some awkwardness, we excluded it in the current version of the manuscript. We think that it required much more explanation and methodology definitions.<br>We note that, the removal has no impact of the overall results/message of the paper, since it was a separate topic and not the main part of the manuscript. |
| *Figure 1: I think this figure should be larger – but maybe that's just due to the formatting of the PDF* |
| We have changed Fig. 1, please see P3 L12 |
| *P3L22: "sections" -> "regions"* |
| Improved as suggested, please see P3 L13 |
| *P3L23: "Elbrus Massif"* |
| Corrected as suggested, please see P3 L14 |
| *P4L9: Delete "however" & "critical to" -> "critical for"*<br>*P4L10: "performed" -> "used" & Why is method 2 giving you a more realistic uncertainty estimate?* |
| We used Google Earth software/images instead of the multiple digitization for uncertainty |

| |
|---|
| estimation as a second method. The main reason for this decision was the high-resolution imagery from Google Earth that allowed us much precise uncertainty estimation. Thus, we deleted this paragraph and provided a new one. Please see P4 L7-11 |
| *P4L19: How is the geomorphology complicated?* |
| We deleted this sentence because the differences in geomorphology of these parts have no impact on the debris-covered glaciers in this area |
| *P4L31: "debris cover" -> "SDC" & comma after "increased"* |
| Corrected as suggested, please see P4 L31 |
| *P5L8: "Debris cover migrated up-glacier" -> I haven't seen any data on the spatial distribution of the SDC. If you have, it would be worth showing it.* |
| We approved this sentence by providing the new text (P6 L15-19) and images (P7 Fig. 3). In the supplement P2 L12-14; Fig. S3, showing the up-glacier migration evidence. |
| *P5L10-P6L11: This chapter sounds more like results. Also see the main comments above.* |
| We have changed this chapter, please see specific comments how exactly we improved it.<br>**4.1 Supraglacial debris-cover changes**<br>- Here we provided SDC percentage distribution by different elevation zones to justify the up-glacier migration Fig. 3; and added one more image in the supplement (Fig. S3).<br><br>- We also discussed that, dramatic increase of the SDC after 2000 could be caused by the rock avalanches related to permafrost. We gave an example of the Devdoraki Glacier – Fig. S4 and added a new related reference (Tielidze et al., 2019).<br><br>- In addition, we added one more relevant figure in supplement (Fig. S5) in order to better understand SDC different distribution between northern and southern slopes related to topographic differences.<br>More detailed analysis regarding the topographic differences for the Greater Caucasus glaciers, has been already Published in Tielidze et al., 2018 (see reference list in the manuscript).<br><br>- In case of Elbrus, we discussed that the significant increase of SDC can be related to resurfacing of the englacial debris as a result of glacier recession (specifically in the eastern slopes).<br><br>- In addition, we discussed that shielding effect is not enough to offset the retreat trend in the Greater Caucasus.<br>Overall, please see new version of the chapter from P6 L28 to P9 L6 |
| *P6L14: Regarding the GPR results, see main comments above.* |
| As the GPR data caused some awkwardness, we excluded it in the current version of the manuscript. We think that it required much more explanation and methodology definitions.<br>We note that, the removal has no impact of the overall results/message of the paper, since it was a separate topic and not the main part of the manuscript. |
| *P6L25: Not clear how the cited studies and this one are broadly consistent. In that there is an increase? It appears difficult to compare a regional study with individual glacier studies. Perhaps compare results from this studies with previous ones by limiting to those glaciers that are in common?* |

We have changed this sentence, and mentioned that our result is in good agreement with general picture of other studies in this region, resulting the SDC increase in recent decades. Although, in the beginning of this chapter we also stated that direct comparisons of our study with previous investigations are difficult because most of them cover only a relatively small area.
Please see new version of these sentences P9 L9-11

*P6L31: “141% increment”?*

We have corrected this sentence”
“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%.”
Please see P9 L17-18

*P6L36-P7L3: See main comments above.*

Since the work by Scherler et al. (2018) is only one work including the SDC data-set for entire Greater Caucasus we think that comparison of these two studies and highlighting the resultant overestimation caused by erroneous RGI outlines is important.
Thus, we provided an explanation of how we compared these two data-set – “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.” Please see P9 L24-25.

We also provided a new figure in the supplement (Fig. S7) showing the clear differences between current study and study by Scherler et al. (2018)/RGI outlines.

Once again we emphasize that we do not question work by Scherler et al. (2018), and this is clearly state in the manuscript where we mentioned that the goal of study by Scherler et al. (2018) was an automatized global assessment of SDC from optical satellite data, without correcting any outlines in the RGI. The big difference between these two results is just caused by RGI inconsistent outlines.
Please see P9 L35-37.

Overall, we have changed this paragraph, please see new version P9 L24-37

*P7L10: SCD -> SDC*

Corrected, please see P9 L40

*P7L15: “periglacial debris cover”: this term comes surprising and it’s unclear how this conclusion came about. Also, why is the monitoring “vital”?*

We have changed this sentence as following: “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”.
Please see P10 L4-5

*P7L16: Delete “a”*

Deleted, please see P10 L7

# Authors reply to Dr. Sam Herreid's comments

## "Brief communication: Supraglacial debris-cover changes in the Caucasus Mountains" by L. G. Tielidze, et al.

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

Dear Dr. San Herried,

Thank you very much for your detail comments which we help to increase the quality of our manuscript. Please find in the following a point-by-point reply to your review.

All corrections and changes what we did in the text are in yellow (first revision) and green (second revision).

| |
|---|
| **General Comments**<br>This paper presents changes in glacier and debris-covered area for several subregions in the Greater Caucasus mountains. The results are accompanied by an error analysis that uses two approaches to quantify mapping error. This work is relevant both by expanding the spatial domain over which debris-covered area changes are measured and by providing a comparison against larger, global scale debris cover mapping efforts. Overall, I think there are methodological deficiencies that need to be addressed, figures that need to be both added and removed and a general improvement in the clarity of the writing. |
| We agree that methodological deficiencies were one of the main issues of the first version of the manuscript. Considering this, we provided a new chapter of methodology, with a more detailed description.<br><br>- In the beginning we described the clean-ice outline delineating process with widely used band ratio segmentation method (RED/SWIR; Landsat OLI 4/6 or TM 3/5 with a threshold of ≥2.0) and intensive manual improvements (removed misclassified areas, e.g. snow, shadows). In the end of the first paragraph, we mentioned our approach that "the supraglacial debris cover was classified as the residual between a semi-automatically derived clean-ice map and a manually improved glacier extent map", similar to the Paul et al. (2004). Supraglacial debris cover was extracted and saved as separate layers.<br><br>- Based on Global Land Ice Measurements from Space (GLIMS) Glacier Classification Guidance (Rau et al., 2005), we gave a more explanation in order to better understand the definitions of debris-covered and debris-free glaciers.<br><br>- for uncertainty estimation we used:<br>1. The buffer method;<br>For clean ice we used a 15 m (1/2 pixel) buffer (Bolch et al., 2010) |

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| For debris-covered parts 60 m (two pixels) (Frey et al., 2012)<br>2. High resolution Google Earth imagery;<br>3. GPS measurement data which >1200 points<br><br>- regarding to all these changes several figures were added/deleted as well. e.g.<br>Fig. 2. Showing the increase of supraglacial debris cover according to the all selected regions and entire Greater Caucasus for 1986, 2000 and 2014.<br>Fig. 3. Showing the hypsometrical distribution of supraglacial debris cover, clean ice and total glacier area in 1986 and 2014.<br>Fig. 4. Showing the hypsometrical debris cover increase on the Elbrus Massif from 1986 to 2014.<br>Fig. S1. Showing the examples of glacier outline accuracy assessment by GPS measurements.<br>Fig. S3. Showing the example of the supraglacial debris cover up-glacier migration onto the Khalde Glacier.<br>Fig. S4. Showing the example of the supraglacial debris cover increase onto the Devdoraki Glacier after rock-ice avalanche in 2014. Possible related to permafrost.<br>Fig. S5. Showing the comparison of supraglacial debris cover and clean-ice area distribution between the southern and northern slopes.<br><br>- Figure. 1 e, f, g, and Figure S2, S3, S4, S5, S6, S7, were deleted. |
| A key component of any study investigating debris-covered area change is a consistent and meaningful spatial domain. Transient snowfall (possible at any time of year) can cover debris resulting in an underestimation of debris cover that is actually present in a glaciers ablation zone. If a later map of debris cover is generated from an image with a higher snowline, a false debris-covered area change signal will be measured, even in a setting where the position of the equilibrium line is stable. In order to eliminate these errors, a spatial domain can be set at the aggregate lowest minimum snowline from all of the images used to map debris cover. Tracking of the up-glacier migration of debris cover in a phase of glacier shrinkage will require additional attention/data/criteria. If the debris-covered area changes mapped in this study were well below snowline, then showing this will negate the concern. If mapped debris-cover shared a boundary with snow rather than ice or firn, I do not think debris area change measurements can be trusted without more information. |
| We provided new figures that shows up-glacier migration, please see Fig. S3 (in supplement), where the SDC is well below to the snow line. In addition, we provided a new Fig. 3 (please see P7) that shows SDC vertical distributions, that approves SDC increase in upper elevations.<br>We also mentioned that the similar pattern of up-glacier migration was detected on Tasman Glacier, New Zealand (Kirkbride and Warren, 1999), and on Zmuttgletscher Glacier, Swiss Alps (Mölg et al., 2019).<br>Please see P7 L1-12 |
| One of the two approaches used in this study to estimate mapping errors is a buffer method which I do not think is sufficiently supported to meaningfully quantify error. I would like to see some evidence supporting the two buffer distances that were selected.<br>Further, it is unclear in the results presented with error bounds which approach they are derived from or if the two approaches are in some way combined. It seems feasible to use the |

detailed manual error assessment at six glaciers to calibrate a more meaningful buffer approach applied to the entire study area, but I do not believe this was done.

- For more evidence of error assessment we used not just the buffer method but also Google Earth images. According to the buffer method the uncertainty was ~4.1% for clean-ice and ~6.3% for debris-covered ice, while the according to the high resolution Google Earth images it was ~3.4% and ~5.2% respectively. A comparison of these two approaches show a good agreement.

In addition the buffer method is widely used and adopted for mapping errors of debris-covered/debris-free glaciers in many studies (e.g. Frey et al., 2012; Shahgedanova et al., 2014; Khromova, et al., 2014; etc.), that allow us to use it in current study.

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.

Shahgedanova, M., Nosenko, G., Kutuzov, S., Rototaeva, O., and Khromova, T.: Deglaciation of the Caucasus Mountains, Russia/Georgia, in the 21st century observed with ASTER satellite imagery and aerial photography, The Cryosphere, 8, 2367–2379, https://doi.org/10.5194/tc-8-2367-2014, 2014.

Khromova, T., Nosenko, G., Kutuzov, S., Muravievand, A., and Chernova, L.: Glacier area changes in Northern Eurasia, Environ. Res. Lett., 9, 015003, doi:10.1088/1748-9326/9/1/015003, 2014.

- In in the results the error bounds are derived from buffer method. Please see P5 L2

- Since we used high-resolution imagery from Google Earth that allowed us more precise uncertainty estimation than multiple digitization, we excluded it as a second method.

- Even though many attempts have been made from various studies, there is not yet an ideal method for estimating mapping errors for debris-covered glaciers. Thus, any method that used in a various studies can be critical with many reasons.

- Overall, please see new paragraphs from P3 L32 to P4 L11

An example of where article clarity could be improved is in the description of the debris cover mapping methods. The methods section is somewhat confusing to follow, yet follows the widely used approach of finding the residual of bare-ice area classified with a band ratio threshold and manual debris cover outlines. The threshold(s) used should also be stated for future studies that might want to repeat/continue this work. An additional focusing of the article is needed to address/remove results and figures that are not supported with motivation in the introduction or methods (e.g. ice thickness measurements).

We agree that it was somewhat confusing. Considering this we provided a new description (including the threshold values) of all steps of the methodology. We deleted all extra figures that were not related to new version of the manuscript. Overall, the new methodology section follows as:

- In the beginning we described the clean-ice outline delineating process with widely used band ratio segmentation method (RED/SWIR; Landsat OLI 4/6 or TM 3/5 with a threshold of ≥2.0) and intensive manual improvements (removed misclassified areas, e.g. snow, shadows). In the end of the first paragraph, we mentioned our approach that “the supraglacial debris cover was classified as the residual between a semi-automatically derived clean-ice map and a manually improved glacier extent map", similar to the Paul et al. (2004). Supraglacial debris cover was extracted and saved as separate layers.

- Based on Global Land Ice Measurements from Space (GLIMS) Glacier Classification Guidance (Rau et al., 2005), we gave a more explanation in order to better understand the definitions of debris-covered and debris-free glaciers.

- for uncertainty estimation we used:
1. The buffer method;
For clean ice we used a 15 m (1/2 pixel) buffer (Bolch et al., 2010)
For debris-covered parts 60 m (two pixels) (Frey et al., 2012)
2. High resolution Google Earth imagery;
3. GPS measurement data which >1200 points

**Specific comments**

*P1L20-21: Is it a fact that debris coverage typically increases with shrinking glaciers? I would think this is more of a hypothesis that studies like this will either support or reject.*

*P1L23: "throughout" or "across" rather than "different regions" might give more information to the reader, better still would be the fraction of the total glacier area that you consider.*

*P1L25: I think "-0.52% yrˆ-1"*

*P1L25: Is glacier area change a result from this work or a result from previously published work?*

*P1L25: This is not a "Thereby" statement.*

*P1L25-26: northern and southern slopes of what? Unclear if reading only the abstract.*

*P1L26-28: The last sentence of the abstract is unclear, unsupported in the text and should be removed.*

We completely rewrote the abstract taking these comments into account. Please see new version P1 L24-34

*P1L34: considered to be significant by whom?*

*P1L34: Isn't the debris cover generally a passive element in a sediment transport system? The sediment is of course a significant part of a sediment transport system, but its role in the efficiency isn't clear to me.*

We have changed this sentence as follows: "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 energy mass balance of the glaciers."
Please see P1 L39-40

*P1L39: "exact evaluation," do you mean precise or accurate?*

We have changed this sentence as follows: "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)."
Please see P2 L4-5

*P2L2-3: "methods for satellite mapping of supraglacial debris remain in development (Zhang et al., 2016)" Do you mean debris thickness, debris-covered area or both? This statement might need additional reference(s).*

We meant the thickness of debris, and changed this sentence as follows: “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)”.
Please see P1 L7-9

*P2L4: “Several studies” but cite one, add “e.g.” or other citations.*

We added the second reference here: “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),”
Please see P2 L9-10

*P2L6-7: This sentence should be restructured to make clear SDC is one of the complexities in the relation between climate and glacier mass budget.*

We simplified this sentence as follows: "Therefore, it is necessary to take supraglacial debris cover into account when assessing temporal change of mountain glaciers."
Please see P2 L11-12

*P2L9-10: add a citation for how we know SDC is an important control for ice ablation.*

We have changed this sentence as suggested: “In the Greater Caucasus, 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).”
Please see P2 L15-17

*P2L14: What does “SDC is abundant” mean? Make this statement in objective relative terms or merge with next sentence on P2L15.*

We specified this sentence as follows: “A recent global study (Scherler et al., 2018) suggests that supraglacial debris cover is abundant in the Caucasus and Middle East (more than 25% glacier area) and that this region shows the highest percent of supraglacial debris cover worldwide.”
Please see P2 L18-21

*P2L15: Can you please specifically state the contradiction? Did earlier studies claim the Caucasus and Middle East region did not have the highest percent debris coverage worldwide?*

We have changed these sentences as follows: “Earlier studies indicated lower relative supraglacial debris cover in the Greater Caucasus but extensive in smaller regions or individual glaciers (Stokes et al., 2007; Lambrecht et al., 2011; Popovnin et al., 2015).”
Please see P2 L21-23

*P2L18-19: This might not need to be changed but what a “region” is isn’t very clear.*
*P2L18-21: This once sentence paragraph needs to be rewritten, further, I don’t think a discussion of controlling factors is adequately discussed to be mentioned here. “in light of” isn’t clear scientific language and partly suggests there might be some global context when really a global product is sampled to match your spatial domain.*

We rewrote this paragraph as suggested:
“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.”
Please see P2 L24-26

*P2L25: Did you select these glaciers individually or did you select whole regions?*

| |
|---|
| *P2L25: could you add a citation or a sentence and a citation describing what differences in climate conditions we can have in mind while reading this article?* |
| We changed this sentence and cited appropriately: “We selected four regions representing different climate conditions (Stokes, 2011) and glacier characteristics (Tielidze and Wheate, 2018) with a total of 659 glaciers:”<br>Please see P2 L30-31 |
| *P2L34-35: “glacier margins digitized manually” I am confused, I thought the glacier outlines are taken from Tielidze and Wheate, 2018. Could you please make it very clear what data exist previously, what work was done for this study, and if the quality/data timing was not sufficient in earlier work, what alterations were made?* |
| We changed and specified this sentence as follows: “Other datasets used in this study include the “Greater Caucasus Glacier Inventory” manually mapped dataset (Tielidze and Wheate, 2018)”.<br>Please see P3 L9-10 |
| *P2L37: Again, it is unclear if mapping glaciers is an objective of this study.* |
| We corrected this sentence as follows: “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.”<br>Please see P2 L42 - P3 L1 |
| *P2L39: “All imagery was captured from the 28th of July to the 12th of September.” Why? This sentence is unclear and unrelated to the following sentence. My guess is that this the argument used for not considering seasonal snowline (see main comment above)?* |
| We explained this question: ”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.”<br>Please see P3 L2-3 |
| *P2L40: This is not a sufficient explanation of GPR data acquisition and processing and these data have not been motivated in the introduction.* |
| As the GPR data caused some awkwardness, we excluded it in the current version of the manuscript. We think that it required much more explanation and methodology definitions.<br>We note that, the removal has no impact of the overall results/message of the paper, since it was a separate topic and not the main part of the manuscript. |
| *P3L4: This is a very confusing title and I’m not so sure if there is a comparison described in this section.* |
| We have changed the title to simply “Methods”, please see P3 L18 |

| |
|---|
| *P3L5-12: The framework of written "steps" is ineffective here. For example the "then" on P3L8 implies a 3rd step but is not called as such. I think there are more than two clear steps and therefore suggest restructuring the presentation of information.*<br>*P3L6: I believe you identified "clean-ice", not "clean-ice glaciers."*<br>*P3L6-7: I don't think it is useful to the reader to know about data formats (raster polygons and vector data)*<br>*P3L7: I think it is better to say "removed misclassified area" rather than "deleted misclassified polygons" If a polygon was half correct would you still delete it? It was unclear in earlier sections that mapping glaciers was an objective of this study, it seemed like that task was complete and now the debris cover would be found as a residual from identifying bare ice only. Does this mean that Tielidze and Wheate, 2018 did not consider debris cover and therefore significantly underestimated glacier area?*<br>*P3L8: "as accurately as possible" this is not meaningfully to the reader, please be more specific.*<br>*P3L9: can you please clarify what you are assessing here? Did you classify thin medial moraines as debris covered instead of bare ice? I applaud this effort to consider medial moraines below the detection limit but a drawback of this is your end results become more difficult to reproduce in future comparison studies.*<br>*P3L10-12: This sentence is a bit awkward and confusing when really you are applying a very common technique used to map debris cover. A more simplistic description is "debris cover is classified as the residual between an automatically derived bareice map and a manually generated glacier extent map." With a citation usually to: Paul, Frank, Christian Huggel, and Andreas Kääb. "Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers." Remote sensing of Environment 89.4 (2004): 510-518.* |
| All these questions are related to the first paragraph of old version of manuscript. We have completely changed and provided new paragraph with more clear steps.<br><br>- In the beginning we described the clean-ice outline delineating process with widely used band ratio segmentation method (RED/SWIR; Landsat OLI 4/6 or TM 3/5 with a threshold of ≥2.0) and intensive manual improvements (removed misclassified areas, e.g. snow, shadows). Then, we mentioned our approach that "the supraglacial debris cover was classified as the residual between a semi-automatically derived clean-ice map and a manually improved glacier extent map", similar to the Paul et al. (2004). In the end of the first paragraph, we also mentioned that supraglacial debris cover was extracted and saved as separate layers and calculated the area of supraglacial debris cover for individual glaciers<br><br>Overall, please see new version of the paragraph P3 L19-25 |
| *P3L13: The difficult boundaries are not clearly explained. You list SDC, moraines and debris in shadow, in my opinion there should be no boundaries between these three. Do you mean moraines off the glacier? The writing of this list is also awkward.B* |
| We deleted this sentence because it is no longer associated with this paragraph. This does not affect the content of the methodology section. |
| *P3L15: I would be interested to know if the glacier edge picked from very high resolution agreed (independently) with your GPS measurements. In other words, Between Landsat derived outlines and field measurements, how much aid is heightened resolution?* |

*P3L16-17: This GPS data sounds very useful for validation of this work but if you are going to present it you will need to describe the sensor, field and processing methods, time of acquisition and location. Are you referring to the one point in Figure S4? Can you convince us readers that being in the field actually enables locating the terminus position better than high resolution imagery? I think for some glaciers this is true but for others it is so unclear that an aerial perspective is the best for outlining a glacier's edge.*

*P3L16: One-half pixel is not a helpful unit of measurement, please present in meters and describe how this error "[was] assumed."*

*P3L17-19: Cases of uncertainty are very nice for the reader if they are shown in an example. E.g. in your Figure 1 it would help us understand the limitations you encountered to have one of the examples be at a location of uncertainty. This may also help inspire future work to solve the difficulties faced here.*

All these questions are related to old version of GPS measurement. In this contents we provided new data and more explanation of GPS measurement. In addition we provided new image (Fig. S1) showing an examples of glacier outline accuracy assessment by GPS measurements.

- 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. S1 shows the results of comparison between GPS measurements and Landsat based supraglacial debris cover /clean ice outlines. The accuracy is ±30 m for supraglacial debris cover and ±15 m for clean ice.

Please see P4 L12-17 and P1 Fig. S1 in supplement

*P4L2: "a sample of manually digitization" corrected to "manual digitization" news a few more details to link to uncertainty estimation.*

We deleted this sentence because it is no longer associated with this paragraph. This does not affect the content of the methodology section.

*P4L4: Use meters rather than pixel for units.*

Corrected as suggested, please see P3 L33-34

*P4L4: How did you pick these buffer values? At P4L22 you cite an article reporting "five pixels" of error, does this article also support your using 2? Or 1?*

For clean-ice we used buffer values from Bolch et al., (2010) and for debris-covered ice, from Freay et al., (2012), We corrected these sentences as follows: "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)."
Corrected as suggested, please see P3 L32-34

*P4L5-6: "an average ratio between the original glacier areas and the areas with a buffer increment." It is unclear what is meant by original. This is also stated as a singular average, are you considering debris and bare ice separately? Do you include bare-ice/debris boundaries internal to the glacier? If so are you double counting error at these locations?*

*P4L7: I don't think the percentage error should be a function of area. I also would anticipate errors to be larger for earlier sensors and improve with the higher radiometric resolution of Landsat 8.*

We deleted this sentence because it is no longer associated with this paragraph. This does not affect the content of the methodology section.

*P4L10: If a method does not produce realistic results, as stated, you should not include it! This is anyhow an interpretation that belongs in the discussion. The two methods also have various strengths and weaknesses, there is an advantage to an error estimate that considers the whole area rather than six glaciers only. However, I do not see much value in the buffer method error estimates.*

*P4L9-16: It's not clear if we are only talking about the outline of the glacier or the outline of the glacier and the outline of the debris. Also here you establish an unspecified classification "debris covered glacier." What is a debris covered glacier? What criteria did you make this classification on? Was it an automated or manual classification? Is there a physical or processed based motivation for this Boolean classification? A figure showing examples of the error analysis should be at least in the SI.*

- In this case we gave priority to buffer method rather than multiple digitization, as we had an advantage to estimate uncertainty by using this. Considering this we replaced the multiple digitizations by Google Earth imagery that allowed us more precise uncertainty estimation. According to the buffer method the uncertainty was ~4.1% for clean-ice and ~6.3% for debris-covered ice, while the according to the high resolution Google Earth images it was ~3.4% and ~5.2% respectively. A comparison of these two approaches show a good agreement.

Please see P4 L7-11

- Regarding to the debris-covered glacier definition. Based on Global Land Ice Measurements from Space (GLIMS) Glacier Classification Guidance (Rau et al., 2005), we gave a more explanation in order to better understand the definitions of debris-covered and debris-free glaciers.

Please see P3 L26-31

*P4L17-19: The GPR data looks very interesting but it is not appropriately developed in this article. It is unclear if this is new work done for this paper or existing work presented in a different publication. If it is new and being presented here first there needs to be motivation in the introduction, methods and stand-alone results. If citing existing work, I don't think it is necessary to have Figure S6, and each statement regarding GPR work should be appropriately cited. A GPR trace that shows an ice thickness of zero off glacier that transitions to a non-zero ice thickness under debris is very interesting and relevant for glacier and debris mapping, however, as it is now, Figure S6 is beyond the scope of this article.*

As the GPR data caused some awkwardness, we excluded it in the current version of the manuscript. We think that it required much more explanation and methodology definitions.
We note that, the removal has no impact of the overall results/message of the paper, since it was a separate topic and not the main part of the manuscript.

*P4L27: Please clarify what you mean by "a significant increase." Do you mean within statistical significance there is a change (this would be the most meaningful use of the word) or do you mean you consider the amount of increase to be significant based on some unstated prior understanding? Considering your upper estimate for 1986 (12.6% debris-covered) and your lower estimate for 2014 (11.6 debris-covered), your results imply a decrease in SDC. Considering this, your results do not show a significant change.*

*P4L28: I do not think it is established that debris area changes are concomitant with glacier area change.*

We changed this sentence as follows: "We found an absolute increase of supraglacial debris cover for all investigated glaciers from 48.3±3.1 km2 in 1986, to 54.6±3.4 km2 in 2000 and 79.0±4.9 km2 in 2014, in contrast with a reduction of the total glacier area."
Please see P4 L24-27

*P4L32: If you have solved for errors numerically, why are you using a tilde here? (comment extends also to the abstract).*

We deleted all tildes in the manuscript

*P5L8: The up-glacier migration is not shown in any figures or presented in the results, please include this along with evidence that is not due to seasonal snow variability. Showing that all mapped debris cover is well below the seasonal snow line is sufficient. If, however, the debris cover extends to the seasonal snowline convincing the reader the signal is up-glacier migration will become more difficult but it is essential to make any statement about up-glacier migration of mapped debris cover.*

We provided new figures that shows up-glacier migration, please see Fig. S3 (in supplement), where the SDC is well below to the snow line. In addition, we provided a new Fig. 3 (please see P7) showing SDC vertical distributions, that approves SDC increase in upper elevations. Please see the appropriate text as well, P6 L15-19

*P5L12 (and Figure S2): A image showing the glacier before and after rock avalanche deposits would make this point much more clear. I would like to see some quantification of "dramatically increased SDC" or it is not adding information. Mapping and quantifying the area of SDC from rock avalanches would add a nice additional dimension to this* *article without requiring much extra work and might help you address the title of this section "SDC increase possible reasons" which should be rewritten as "Possible reasons for an increase in SDC."*

We provided new Fig. S4 (in supplement) showing SDC increase after rock avalanche

*P5L14: "..recently for some glaciers" I believe the reference you cite considers one glacier not several.*

*P5L16: "the reduction of glaciers is mainly at the expense of clean ice" This is both unclear and possibly not correct. Are you talking about changes in x,y or z? Please defend this statement if you elect to keep it here.*

*P5L22-23: Does local mean at an ice cliff scale or do you mean rocks are sliding down large portions of a glacier? At what glacier slope do you think rocks are able to accumulate?*

*P6L4-6: this information on lateral moraines either needs to be cited or the measurements be motivated in the introduction, described in the methods and presented in the results.*

*P6L8-9: Can you please offer support to the statement that "a large percentage of the debris cover is a result of the lithology" What percentage? A glacier surrounded by highly erosive rock at a very low angle might not generate any debris cover.*

*P6L14: In the framework of glaciology, 20-40 m of ice is not "substantial". 20-40 m of ice is likely not deforming internally and could be stagnant rendering it not part of a glacier following the classical definition of a glacier.*

*P6L17: "DC" not defined.*

We think that all these sentences were more confusing, rather than relevant to the manuscript. Considering this, we deleted all these sentences and instead of, we provided the new text and figures.

- In the beginning of the Discussion section we mentioned that supraglacial debris cover increase process became more pronounced after 2000. The up-glacier migration of the upper limit of supraglacial debris cover could be 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). We also mentioned that the similar pattern of up-glacier migration was detected on Tasman Glacier, New Zealand (Kirkbride and Warren, 1999), and on Zmuttgletscher Glacier, Swiss Alps (Mölg et al., 2019).
Please see P7 L1-12

- In the second paragraph, we discussed that the reduction of the clean glacier area (18.7±4.1% between 1986 and 2014) appears to be attributable to both glacier retreat and an increase in total supraglacial debris cover. In addition, we mentioned that this finding is supported by field measurements on Djankuat Glacier, which indicate that supraglacial debris cover area increased from 2% to 13% and become thicker between 1968 and 2010 during glacier retreat (Popovnin et al., 2015).
Please see P7 L14-18

- In the next paragraph, we expressed our opinion that the rock avalanches happened after 2000 on some glaciers could be related to permafrost. We provided Figure S4 that shows the SDC increase onto the Devdoraki Glacier before and after rock-ice avalanche.
Please see P7 L19-22

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| - In case of Elbrus, the most significant increase of supraglacial debris cover occurred on the eastern oriented glaciers of Elbrus, can be explained by resurfacing of the englacial debris as a result of glacier recession. In fact, these glaciers are characterized by the highest thinning rates in recent years (Kutuzov, et al., 2019).<br>Please see P8 L6-9<br><br>- In the last paragraph of Discussion, we mentioned that the shielding effect of the increased supraglacial debris cover at the glacier surface in the Greater Caucasus is not enough to offset the retreat trend, but preventing by more rapid retreat trend.<br>Please see P8 L16-20; P9 L1-6 |
| *P6L38-41: Are you sure there are not other reasons for a difference between Scherler et al., 2018 and the two points you describe?* |
| As we mentioned, these differences can mostly be explained by these two main reasons. |
| *P7L10-13: A 50% increase in debris cover is not reported in your results. Please clarify how this value is calculated.* |
| We provided more results in Table 1 (P 5), where we show the sum of debris-covered, clean-ice and total glacier area by individual sections of the study area. Also we provided a new figure (Fig. 2. P6) that is related the results of this study.<br>In addition we changed first sentence of the Conclusion section.<br>Please see P9 L41; P10 L1-3 |
| *Table 1: For future work that might want to cite this article, it might be convenient for additional rows that give the sum of all of these sub-regions. I believe these are also the values you cite in the article. I also would suggest showing the changes in a time series plot with error bars.* |
| We agree and changed Table 1, please see P5 L1-2. In addition we created the new Fig. 2 showing the supraglacial debris cover change according to the different years. |
| *Figure 1: e,f and g need to be shown in the upper (unlabeled) panel of this figure. This is may be personal preference, but I think the top panel could be a stand-alone location figure with panels e,f,g being their own figure or coupled to a Figure similar to Figure S7.* |
| We changed Fig. 1, please see P3 L12 |
| *Figure 2: According to the text all of the differences between your results and Scherler et al., 2018 is datum shifts and erroneously classified nominal glacier ellipses. Do these sources really explain all of the differences shown in this figure?* |
| We moved the Fig.2 in the supplement as Fig. S6. Using this figure we show the percentage differences of SDC between these two study results; specific examples are clearly shown in Fig. S7 |
| *Figure S1: How did you define debris covered and debris free glaciers? I think this classification should be shown in Figure 1 or elsewhere so it is clear for future work what was considered "debris-covered." What glacier criteria did you apply to classify 0.01-0.05 kmˆ2 land surfaces as independent glaciers? I would be interested to see some of these glaciers along with a satellite image and their debris maps.* |
| - We used Global Land Ice Measurements from Space (GLIMS) Glacier Classification Guidance (Rau et al., 2005), in order to better understand the definitions of debris-covered and debris-free glaciers.<br>Please see P3 L26-31, |

| |
|---|
| For glacier size classification and surface are calculation we used Paul et al., (2009) (see in the reference list).<br>Please see P2 L36 |
| *Figure S2: This figure does not provide much if any information to the article and does not fit the scope of the work that was done.* |
| We agree, and this figure was deleted |
| *Figure S4: It is not clear what is meant by "semi-automated." The whole approach to mapping debris cover could be called semi-automated, but what non-automated work went into the classification of bare ice alone? The trace of the longitudinal profile needs to be shown in a or b. Dashed line in a and b should probably be defined.* |
| We deleted this figure because it is no longer associated with this manuscript. |
| *Figure S5: Rather than what is essentially a repeated figure S4 in a different location, I would like to see more of the changes. Oblique photography is nice, but here does not offer much information.* |
| We have changed this image that clearly shows supraglacial debris cover and clean-ice area distribution in 1986-2014 for the southern and northern-facing glaciers.<br>Please see Fig. S5 (P3 L6 in supplement). |
| *Figure S6: Panels b and c showing ice thickness measurements have no established relevance to this article. I would suggest removing this figure.* |
| We deleted this figure, since we excluded GPR measurement. See comments above. |
| *Figure S7: I think an altered and expanded upon version of this figure is the key figure of this work and should be in the main article. Changes in glacier area and debris covered area are somewhat difficult to see side by side, I would recommend taking an overlap/transparency approach similar to the following two articles for visually showing changes in glacier and debris-covered areas:*<br>Glasser, Neil F., et al. "Recent spatial and temporal variations in debris cover on Patagonian glaciers." Geomorphology 273 (2016): 202-216.<br>Herreid, Sam, et al. "Satellite observations show no net change in the percentage of supraglacial debris-covered area in northern Pakistan from 1977 to 2014." Journal of Glaciology61.227 (2015): 524-536. |
| We agree and this figure was replaced by new one, please see P8 L12 (Fig. 4) |
| *Figure S8: It is confusing to discuss "Debris cover outline[s]" as well as "Bare ice outline[s]" as you are using different words to reference effectively the same thing.* |
| We replaced this figure by new one, please see Fig. S7 (P4 L9 in supplement) |
| **Technical corrections**<br>*P1L30: I think "SDC" should be defined at the first mention of debris cover.* |
| We spelt out "supraglacial debris cover" everywhere |
| *P1L33: Remove "the" before "SDC" and "glacier ablation."* |
| We changed this sentence, please see P1 L39 |
| *P1L37: Add "summarized in Kirkbride and.."* |
| Rather than add "summarized", we also cited Glasser et al., (2016) P2 L3 |
| *P1L40: "The difficulty. . ." I would say "One difficulty.."* |
| Done, please see P2 L6 |
| *P2L1: Use SDC consistently if defined, e.g. here: "properties of debris"* |
| We spelt out "supraglacial debris cover" everywhere |

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| *P2L1: Change to "of a debris layer has"* |
| We changed this sentence, please see P2 L7-8 |
| *P2L10: Change "as it is similarity in" to "as it is similar to"* |
| We changed this sentence, please see P2 L16-17 |
| *P2L10: Comma after citation* |
| Done, please see P2 L16 |
| *P2L11: Consider changing "key player" to "glacier-wide component"* |
| We changed this sentence, please see P2 L16-17 |
| *P2L12-13: "as surface mass balance. . .is different from that of bare ice" this has already been established earlier in your introduction and I don't think it needs to be restated.* |
| We changed this sentence, please see P2 L17-18 |
| *P2L19: Change to "and a recently"* |
| We changed this sentence, please see P2 L24-26 |
| *P2L29: Change to "as the largest"* |
| We changed this sentence, please see P2 L34-35 |
| *P2L31-33: Awkward sentence, please break into two* |
| Done, please see P2 L37-40 |
| *P2L35: "imagery from 2016. The SPOT" not clear if one or several images were used* |
| We changed this sentence, please see P3 L1 |
| *P3L14: I would remove "Relatively heavily"*<br>*P3L15: add "..to distinguish the glacier boundary" or "glacier terminus"*<br>*P3L18: change to "..might result in a potential.."*<br>*P4L1: change to "i) a buffer method"*<br>*P4L2 "manual"*<br>*P4L9: correct English in this sentence*<br>*P4L13: end parenthesis after NSD*<br>*P6L5: please add "Glacier" after named glaciers, here and throughout the article (or "glaciers" after a list)* |
| We deleted all these sentences because they are no longer associated with this manuscript. |
| *P6L30: This is not a "whereas" statement.* |
| Done, please see P9 L17 |
| *P6L30: "increment" should be "increase."* |
| Done, please see P9 L18 |
| *P7L14: "vital" seems like too strong of language to me.* |
| We changed by "worthwhile", please see P10 L5 |

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

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**Abstract**

In spite of recent glacier studies in the Greater Caucasus, knowledge of supraglacial debris cover remains incomplete in this region. Here we present data of supraglacial debris cover for 659 glaciers across the Greater Caucasus based on Landsat and SPOT images from 1986, 2000, and 2014. We combined semi-automated methods for mapping the clean ice with manual digitization of debris-covered glacier parts and calculated supraglacial debris cover area as the residual between these two maps. Assessment of uncertainties were performed using the buffer method, high resolution Google Earth imagery, and GPS data for selected glaciers. From 1986 to 2014, the total glacier area decreased from 691.5±29.0 km$^2$ to 590.0±25.8 km$^2$ (-15±4.1% or -0.52% yr) 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% or 79.0±4.9 km$^2$ in 2014. Debris-free glaciers exhibited higher area and length reductions than debris-covered glaciers. Overall we have observed up-glacier migration of supraglacial debris cover during the investigated period.

## 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 (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 energy mass balance of the glaciers. Several studies show an increase in debris-covered area with overall glacier shrinkage and mass loss (Kirkbride and Deline, 2013; Glasser et al., 2016).

For regions where the local population is dependent on glacial meltwater 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.

The Greater Caucasus is one of the world's highest mountain systems, containing over 2000 glaciers with a total area of 1193±54 $km^2$ (Tielidze and Wheate, 2018). Ice and snow melt in these mountains are major sources of runoff for populated places in many parts of the Caucasus region. In the Greater Caucasus, 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) suggests that supraglacial debris cover is abundant in the Caucasus and Middle East (more than 25% glacier area) and that this region shows the highest percent of supraglacial debris cover worldwide. Earlier studies indicated lower relative supraglacial debris cover in the Greater Caucasus but extensive in smaller regions or individual glaciers (Stokes et al., 2007; Lambrecht et al., 2011; Popovnin et al., 2015).

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

## 2 Data and methods

### 2.1 Datasets

We selected four regions representing different climate conditions (Stokes, 2011) and glacier characteristics (Tielidze and Wheate, 2018) with a total of 659 glaciers: 223 glaciers in the western Greater Caucasus (145 - northern slope, 78 - southern slope); 285 in the central Greater Caucasus (173/112); and 130 on the northern slope of the eastern Greater Caucasus (as glaciers are almost non-existent in the south). In addition, all 21 glaciers on Elbrus - the largest glacierised massif in the whole region - were selected (Fig. 1a-d). The size of the largest glacier selected was 37.5 $km^2$ and the smallest 0.01 $km^2$. The surface area for each glacier was calculated according to Paul et al. (2009).

A total of nine Landsat images were used in this study (Table S1), 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 1986 to 2014, 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 measurement.

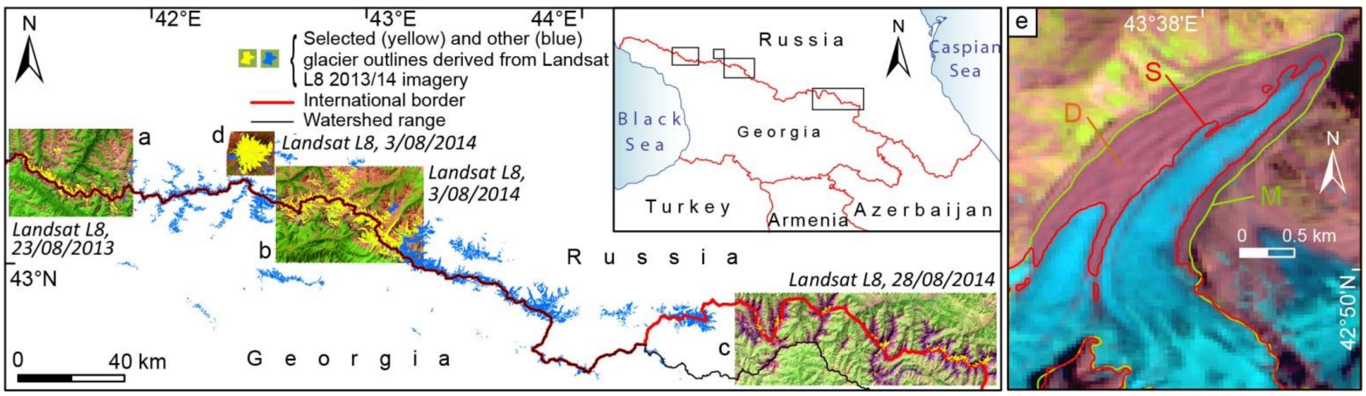


**Figure 1.** Investigated area and selected glaciers in regions a – western Greater Caucasus; b – central Greater Caucasus; c – eastern Greater Caucasus; d – the Elbrus Massif. Mapping examples: e – debris cover (D) assessment with comparison of different methods: manually (M) and semi-automated (S)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

## 2.2 Methods

The widely used band ratio segmentation method (RED/SWIR; Landsat OLI 4/6 or TM 3/5 with a threshold of ≥2.0) was used as the first step in delineating clean-ice outlines (Bolch et al., 2010; Paul et al., 2013), and then intensive manual improvements were performed (removed misclassified areas, e.g. snow, shadows). In the next step supraglacial debris cover was classified as the residual between a semi-automatically derived clean-ice map and a manually improved glacier extent map (Paul et al., 2004) (Fig. 1e). Supraglacial debris cover was extracted and saved as separate layers. To assess temporal change, we calculated the area of supraglacial debris cover for individual glaciers for the years 1986, 2000, and 2014.

We used Glacier Classification Guidance from the Global Land Ice Measurements from Space (GLIMS) for remote sensing observations (Rau et al., 2005) to define debris-free and debris-covered glaciers. According to this guideline we identified three different classes of glaciers: i) debris-free (almost no debris coverage on the glacier surface); ii) partly debris-covered (>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. S1 shows the results of comparison between GPS measurements and Landsat based supraglacial debris cover /clean ice outlines. The accuracy is ±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. Comparison of Landsat and SPOT data set the normalized standard deviation (NSD – based on delineations by two digitizations divided by the mean area) (Paul et al. 2013) as ±7.4% between these two datasets.

## 3 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% in 2000, and to 13.4±6.2% in 2014 (Table 1; Fig. 2). 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. S2). The number of debris-covered glaciers also increased from 122 in 1986, to 143 in 2000, and to 172 in 2014.

On the northern slope of the western Greater Caucasus, supraglacial debris cover area increased, especially in the second investigated period (7.1±6.6% to 26.1±6.4%). The relative increase on the southern slope was similar but the overall supraglacial debris cover area (11.5±7.1%) was only about half the value of the northern slope (Table 1; Fig. 2).

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

**Table 1.** Change of supraglacial debris cover and bare ice in the Greater Caucasus for 1986, 2000 and 2014 by regions and slopes. The error values are derived by 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 | 130.4±4.2 | 112.4±3.8 | 18 | 6.0±0.4 | 4.6±6.6 |
| **All selected glaciers** | **659** | **691.5±29.0** | **643.2±25.9** | **122** | **48.3±3.1** | **7.0±6.4** | **656.5±27.9** | **601.9±24.5** | **143** | **54.6±3.4** | **9.1±6.3** | **590.0±25.8** | **511.0±20.9** | **172** | **79.0±4.9** | **13.4±6.2** |

* % of the total glacier area.

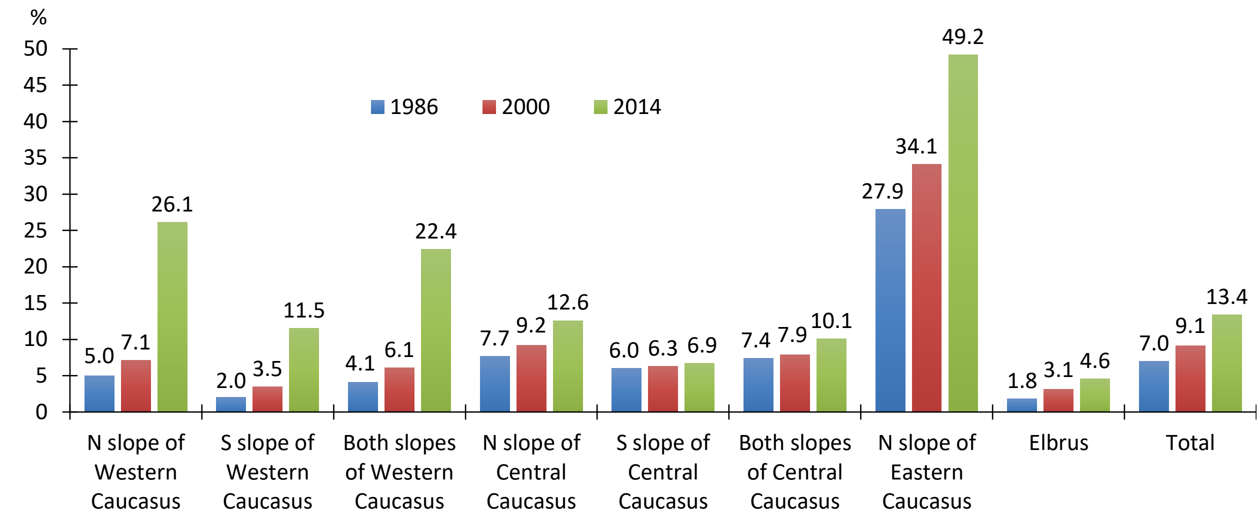


**Figure 2.** Increase of supraglacial debris cover in the Greater Caucasus for 1986, 2000 and 2014. The bars indicate clean ice to supraglacial debris cover ratios and are ordered by years (colours) and regions. For all regions (except Elbrus), the sub-regional results for the northern and southern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

The eastern Greater Caucasus 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%.

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%).

The rate of supraglacial debris cover increase was different 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% 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% 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. 3). The supraglacial debris cover has doubled from 6.4% to 12.2% in 3000-3500 m zone for all selected glaciers in 1986-2014 (Fig. 3d), 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% 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) during the same period and terminus retreat by ~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) and terminus retreat by ~1366 m.

## 4 Discussion

### 4.1 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. 3, S3) as a response to glacier retreat thinning and reduced mass flux, as described by Stokes et al. (2007) and defined as 'backwasting' by Benn and Evans (1998). A similar pattern of up-glacier migration has also been detected on Tasman Glacier, New Zealand (Kirkbride and Warren, 1999), and on Zmuttgletscher Glacier, Swiss Alps (Mölg et al., 2019).

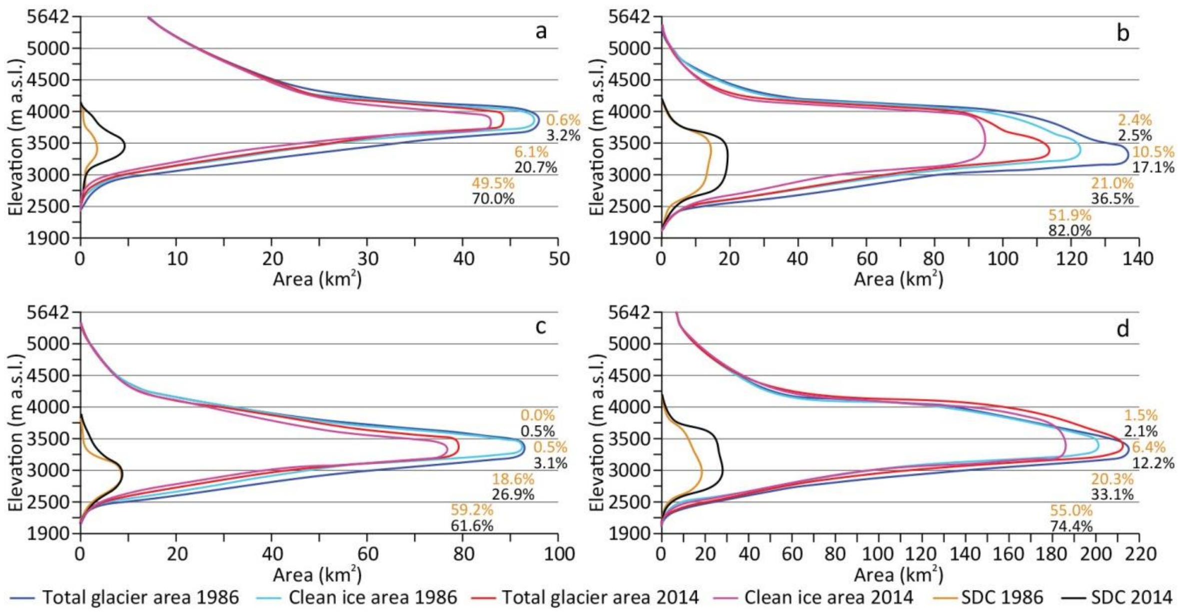


**Figure 3.** Hypsometry of supraglacial debris cover (SDC), clean ice and total glacier area, of the four study regions in 1986 and 2014. a – Elbrus, b – Northern Slope, c – Southern Slope, d – all selected glaciers. SDC percentage is given according to the different elevation zones in 1986 (brown digits)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

The results presented in this study indicate that the clean ice area for all selected glaciers decreased by 18.7±4.1% between 1986 and 2014 (Table 1). This reduction appears to be attributable to both glacier retreat and an increase in total supraglacial debris cover (Table 1, Fig. 2, 3). This finding is supported by field measurements on Djankuat Glacier, which indicate that supraglacial debris cover area increased from 2% to 13% and become thicker between 1968 and 2010 during glacier retreat (Popovnin et al., 2015).

Glacier thinning and a warming atmosphere can lead to permafrost thawing and slope instability at higher altitudes (Deline et al., 2015). Rock avalanches after 2000 on some glaciers in the Greater Caucasus, have dramatically increased supraglacial debris cover (Fig. S4) (Tielidze, et al., 2019), which might be one of the reasons why the increase rate was higher during the second period (2000-2014).

One possible reason that supraglacial debris cover occurs more on the northern slope than the southern, may be that the northern slopes are less steep than the south-facing slopes. Most valley glacier tongues in the north are longer and reach lower altitudes than the southern-facing 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 supraglacial debris cover. An example is Georgia's largest glacier Lekhziri and its northern counterparts, with the exception of the Bashkara Glacier (Fig. S5).

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

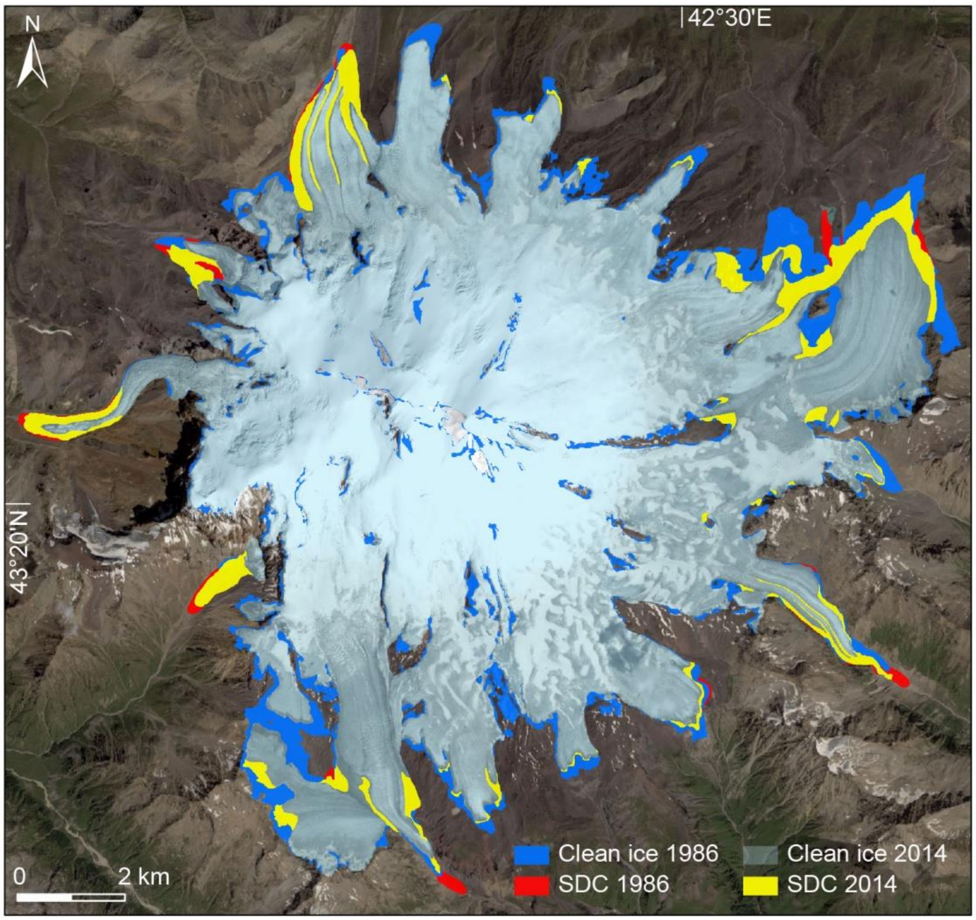


**Figure 4.** Supraglacial debris cover increase on the Elbrus Massif from 1986 to 2014. SPOT-7 image 20/08/2016 is used as the background.

The glaciers in the Greater Caucasus have retreated continuously since 1960 (Tielidze and Wheate, 2018), suggesting that the shielding effect of the increased supraglacial debris cover at the glacier surface is not enough to offset the retreat trend. The same result was concluded by Mölg et al. (2019) in the evolution of Zmuttgletscher Glacier, Swiss Alps. However, direct field measurements show that thermal resistance of the supraglacial debris cover for some glaciers (Adyl-su and Zpkhito river basins) in the

Greater Caucasus is somewhat higher than in other glacierised regions of the world (Lambrecht et al., 2011), preventing what would otherwise be 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. Jiang et al. (2018) and Rowan et al. (2015) found similar results in the Himalaya.

### 4.2 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% 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% 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% 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%).

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 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. S7). 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. S7a); and ii) the RGI v6 contains nominal glaciers (i.e. ellipses around glacier label points) for the Greater Caucasus region which originate from the use of the world glacier inventory (WGI, Haeberli, et al., 1989) to fill gaps with no data for earlier versions of the RGI. According to Scherler, et al. (2018), all nominal glaciers were classified as debris covered (Fig. S7b). We note that the scope of the study by Scherler et al. (2018) was an automatized global assessment of supraglacial debris cover from optical satellite data, without correcting any outlines in the RGI.

## 5 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, GPR, radiation) to reduce uncertainties connected with supraglacial debris cover assessment and glacier mapping accuracy in this region.

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*Supplement of*

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

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**Table S1.** 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 |

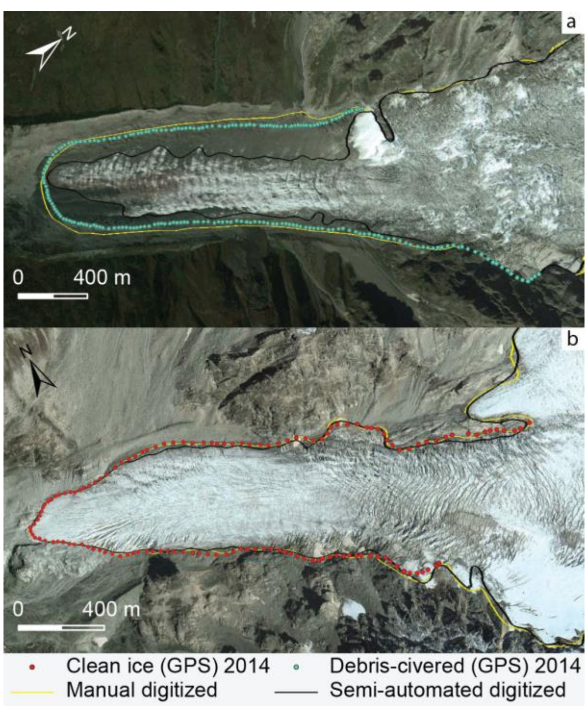


**Figure S1.** Examples of glacier outline accuracy assessment by GPS measurements: a – Adishi Glacier; b – Kirtisho Glacier. Google Earth imagery 19/09/11.

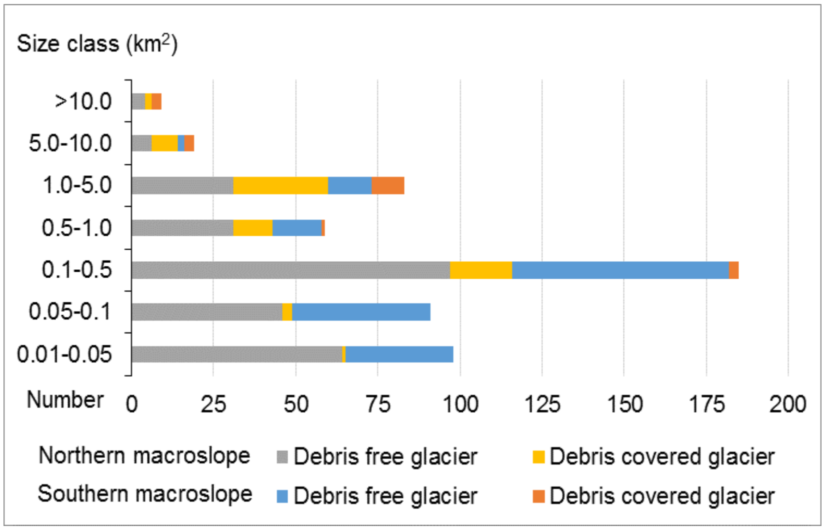


**Figure S2.** The Greater Caucasus glacier size classes with debris covered and debris free glaciers distributions for northern and southern slopes.

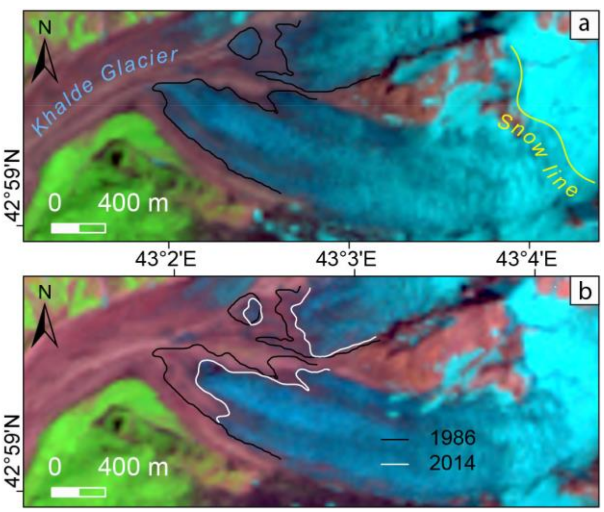


**Figure S3.** An example of the supraglacial debris cover up-glacier migration onto the Khalde Glacier. a – 1986 (Landsat 5, 06/08/86). b – 2014 (Landsat 8, 03/08/14).

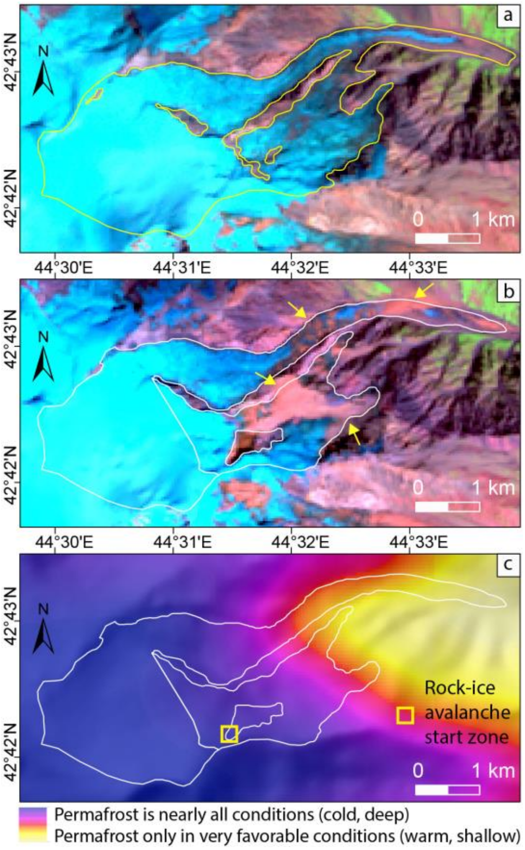


**Figure S4.** a – Devdoraki Glacier in 2000 (Landsat 7, 30/08/00); b – Devdoraki Glacier after rock-ice avalanche in 2014 (Landsat 8, 28/08/14). Yellow arrow shows increased supraglacial debris cover area. c – Devdoraki Glacier on the permafrost zonation index map (Gruber, 2012).

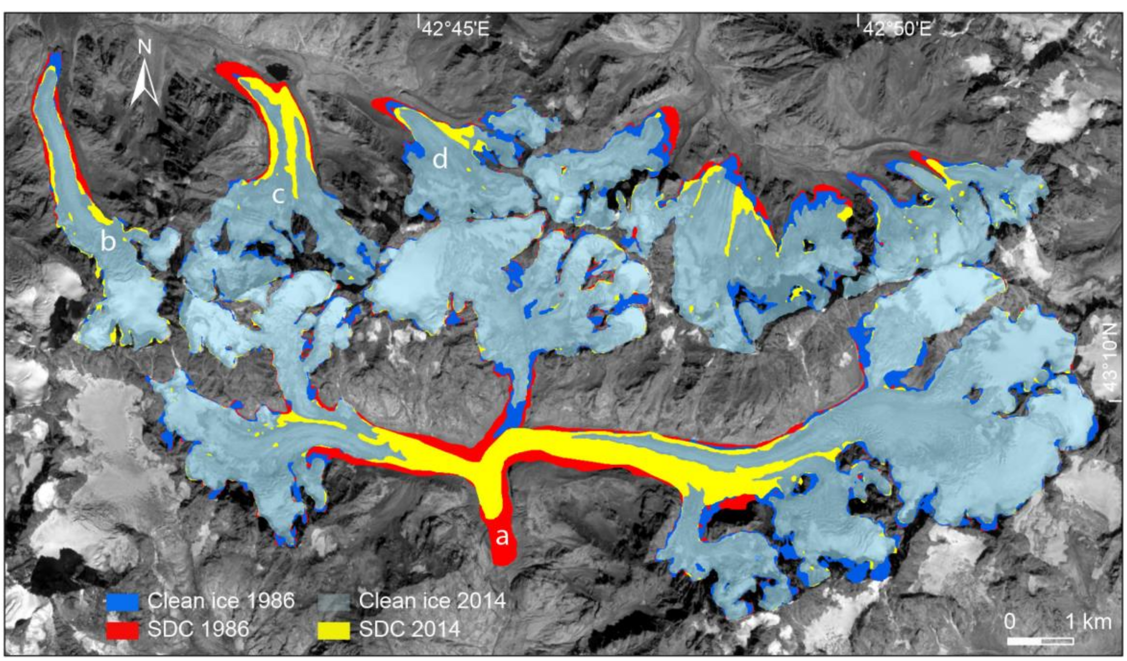


**Figure S5.** A comparison of supraglacial debris cover (SDC) and clean-ice area distribution in 1986-2014 for the southern (a – Lekhziri) and northern-facing (b – Kashkatash, c – Bashkara and d – Djankuat) glaciers. Landsat 8 (panchromatic band 8), 03/08/14 was used as background.

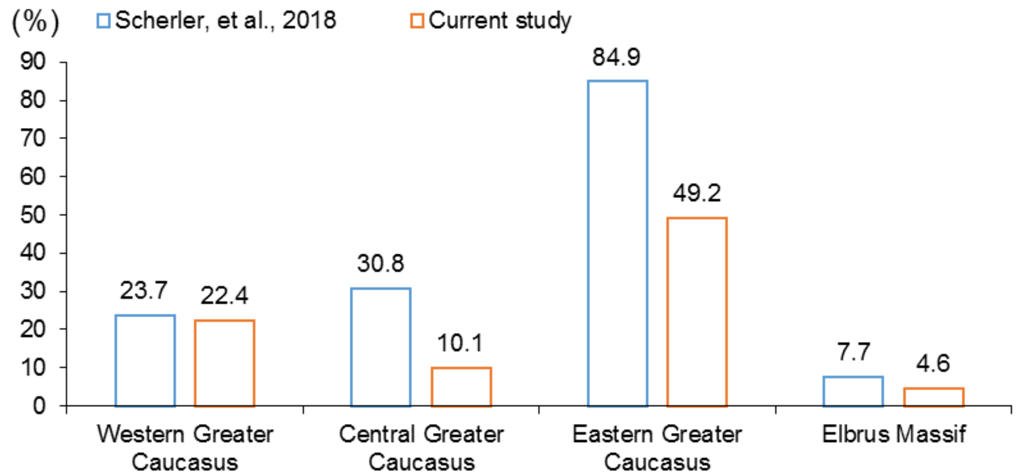


**Figure S6.** Relative supraglacial debris cover for the Western, Central, and Eastern Greater Caucasus as well as for Elbrus based on the current study (brown) and in comparison with Scherler et al. (2018).

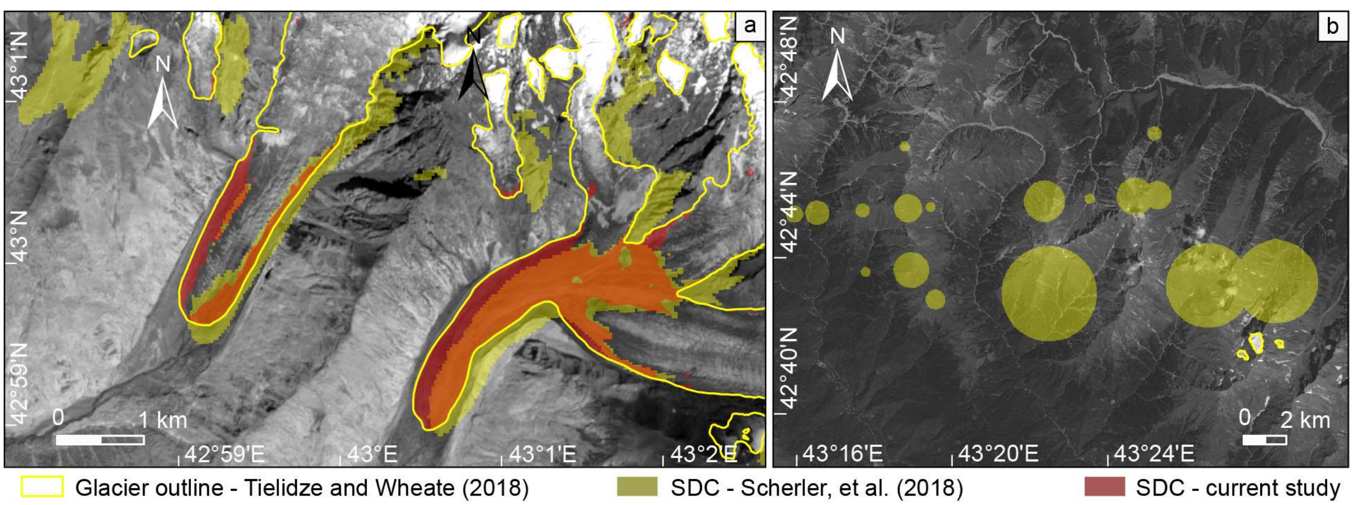


**Figure S7.** a - Comparison of supraglacial debris cover (SDC) assessment by Scherler, et al. (2018) (based the RGI v6) and current study. b - An example of the RGI v6 nominal glaciers (circles). According to Scherler, et al. (2018), all nominal glaciers were classified as debris-covered. Landsat 8 (panchromatic band 8), 03/08/14 was used as background.