

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.,
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Dear Dr. Sam Herreid,

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**.

General Comments

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 problems of the first version of the manuscript. Considering this, we provided a new chapter of methodology, with a more detail description. Several figures were added/deleted as well.

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 have added new text and figures in order to approve the SDC up-glacier migration. Please see P6 L15-19, P7 L6-10, Fig. S3 (P2).

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. 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.

<p>We excluded multiple digitization method in this version of manuscript. There is not yet an ideal method for estimating mapping errors for debris-covered glaciers, even though many attempts have been made from various studies. The buffer method is widely used and adopted for mapping errors of debris-covered/debris-free glaciers by many scientists (Bolch et al., 2010; Frey et al., 2012; Mölg et al., 2018, and many others. See these references in the main manuscript), that's why we decided to use the buffer method in this study. The uncertainty for debris-covered and debris-free glaciers was calculated separately based on this two different data-set (outlines).</p>
<p>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).</p>
<p>We agree that it was somewhat confusing and considering this we provided a new description (including the threshold values) of all steps of the methodology. We deleted all extra figures e.g. ice thickness measurements, etc.</p>
<p>Specific comments <i>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.</i> <i>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.</i> <i>P1L25: I think "-0.52% yr⁻¹"</i> <i>P1L25: Is glacier area change a result from this work or a result from previously published work?</i> <i>P1L25: This is not a "Thereby" statement.</i> <i>P1L25-26: northern and southern slopes of what? Unclear if reading only the abstract.</i> <i>P1L26-28: The last sentence of the abstract is unclear, unsupported in the text and should be removed.</i></p>
<p>We have completely changed an abstract text, please see new version P1 L24-34</p>
<p><i>P1L34: considered to be significant by whom?</i> <i>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.</i></p>
<p>We have changed this sentence, please see P1 L39-40</p>
<p><i>P1L39: "exact evaluation," do you mean precise or accurate?</i></p>
<p>We have changed this sentence, please see P2 L4-6</p>
<p><i>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).</i></p>
<p>We meant the thickness of debris, please see P1 L7-9</p>
<p><i>P2L4: "Several studies" but cite one, add "e.g." or other citations.</i></p>
<p>We added the second reference here, please see P2 L9-10</p>
<p><i>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.</i></p>
<p>We have deleted this sentence</p>
<p><i>P2L9-10: add a citation for how we know SDC is an important control for ice ablation.</i></p>
<p>We have changed this sentence, please see P2 L16-18</p>
<p><i>P2L14: What does "SDC is abundant" mean? Make this statement in objective relative terms or merge with next sentence on P2L15.</i></p>

<i>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?</i>
We have changed this sentence, please see P2 L20-22
<i>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.</i>
We have changed this sentence, please see P2 L25-27
<i>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?</i>
We have changed this sentence, please see P2 L31-32
<i>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? P2L37: Again, it is unclear if mapping glaciers is an objective of this study.</i>
We have changed this paragraph, please see P2 L38-42
<i>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)?</i>
We have changed this paragraph, please see P3 L3-4
<i>P2L40: This is not a sufficient explanation of GPR data acquisition and processing and these data have not been motivated in the introduction.</i>
We have excluded GPR data in this study
<i>P3L1: How do these stated errors effect this study?</i>
We have changed this paragraph, please see P3 L5-9
<i>P3L4: This is a very confusing title and I’m not so sure if there is a comparison described in this section.</i>
We have changed the title, please see P3 L20
<i>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. P3L6: I believe you identified “clean-ice”, not “clean-ice glaciers.” P3L6-7: I don’t think it is useful to the reader to know about data formats (raster polygons and vector data) 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? P3L8: “as accurately as possible” this is not meaningfully to the reader, please be more specific. 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. 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</i>

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 Käab. "Combining satellite multispectral image data and a digital elevation model for mapping debris-covered glaciers." *Remote sensing of Environment* 89.4 (2004): 510-518.

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.

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.

P4L2: Do you mean buffer distances when you say “sizes”

P4L2: “a sample of manually digitization” corrected to “manual digitization” needs a few more details to link to uncertainty estimation.

P4L4: Use meters rather than pixel for units.

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?

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.

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.

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

<p><i>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.</i></p> <p><i>P4L22-24: I don't find this argument for using a 30 m buffer to sound.</i></p>
<p>We improved methodology chapter and provided new text, please see P3 L21-34 and P 4L1-24</p>
<p><i>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.</i></p> <p><i>P4L28: I do not think it is established that debris area changes are concomitant with glacier area change.</i></p>
<p>We have changed this sentence, please see P4 L27-30</p>
<p><i>P4L32: If you have solved for errors numerically, why are you using a tilde here? (comment extends also to the abstract).</i></p>
<p>We deleted all tildes in the manuscript</p>
<p><i>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.</i></p>
<p>We provided new figures showing 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 L5-10) showing SDC vertical distributions, that approves SDC increase in upper elevations. Please see the appropriate text as well, P6 L15-19</p>
<p><i>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."</i></p>
<p>We provided new Fig. S4 (in supplement) showing SDC increase after rock avalanche</p>
<p><i>P5L14: "...recently for some glaciers" I believe the reference you cite considers one glacier not several.</i></p> <p><i>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.</i></p> <p><i>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?</i></p> <p><i>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.</i></p> <p><i>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.</i></p> <p><i>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</i></p>

<i>following the classical definition of a glacier. P6L17: "DC" not defined.</i>
We deleted all these sentences and instead of this, we provided the new text and figures, please see P7 L12-28, P8 L1-20, and P9 L1-6
<i>P6L38-41: Are you sure there are not other reasons for a difference between Scherler et al., 2018 and the two points you describe?</i>
As we mentioned, those two are the main reasons for the difference
<i>P7L10-13: A 50% increase in debris cover is not reported in your results. Please clarify how this value is calculated.</i>
We agree and changed this sentence, please see P9 L38-41
<i>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.</i>
We agree and changed Table 1, please see P5 L1-2
<i>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.</i>
We changed Fig. 1, please see P3 L14
<i>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?</i>
We moved the Fig.2 in the supplement as Fig. S6. Using this figure we just show the percentage differences of SDC between of these two study results. More reasons of these two results are shown in Fig. S7
<i>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 km² land surfaces as independent glaciers? I would be interested to see some of these glaciers along with a satellite image and their debris maps.</i>
We provided an appropriate text about the debris-covered and debris-free glacier definitions, please see P3 L28-34, and glacier size classification P2 L37
<i>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.</i>
We agree, and deleted this figure
<i>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.</i>
We agree and deleted this figure
<i>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.</i>
We have changes this image, please see Fig. S5, P3 L6
<i>Figure S6: Panels b and c showing ice thickness measurements have no established relevance to this article. I would suggest removing this figure.</i>
We agree and deleted this figure
<i>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:</i>

<p>Glasser, Neil F., et al. "Recent spatial and temporal variations in debris cover on Patagonian glaciers." <i>Geomorphology</i> 273 (2016): 202-216.</p> <p>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." <i>Journal of Glaciology</i> 61.227 (2015): 524-536.</p>
<p>We agree and changed the old figure with the new, please see Fig. 4, P8 L9-11</p> <p><i>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.</i></p>
<p>We agree and changed the old figure with the new, please see Fig. 4, P8 L9-11</p> <p>Technical corrections</p> <p><i>P1L30: I think "SDC" should be defined at the first mention of debris cover.</i></p>
<p>We agree, please see P1 L37</p> <p><i>P1L33: Remove "the" before "SDC" and "glacier ablation."</i></p>
<p>We agree, please see P1 L39</p> <p><i>P1L37: Add "summarized in Kirkbride and.."</i></p>
<p>There is no reason to add "summarized"</p> <p><i>P1L40: "The difficulty. . ." I would say "One difficulty.."</i></p>
<p>We agree, please see P2 L6</p> <p><i>P2L1: Use SDC consistently if defined, e.g. here: "properties of debris"</i></p>
<p>We agree, please see P2 L7</p> <p><i>P2L1: Change to "of a debris layer has"</i></p>
<p>We agree, please see P2 L7</p> <p><i>P2L10: Change "as it is similarity in" to "as it is similar to"</i></p>
<p>We changes this sentence, please see P2 L16-17</p> <p><i>P2L10: Comma after citation</i></p>
<p>We agree, please see P2 L17</p> <p><i>P2L11: Consider changing "key player" to "glacier-wide component"</i></p>
<p>We agree, please see P2 L17</p> <p><i>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.</i></p>
<p>We deleted earlier sentence and disagree to delete here as well</p> <p><i>P2L19: Change to "and a recently"</i></p>
<p>We changed this sentence, please see P2 L25-27</p> <p><i>P2L29: Change to "as the largest"</i></p>
<p>We changed this sentence, please see P2 L35-36</p> <p><i>P2L31-33: Awkward sentence, please break into two</i></p>
<p>We agree and changed this sentence, please see P2 L38-40</p> <p><i>P2L35: "imagery from 2016. The SPOT" not clear if one or several images were used</i></p>
<p>We changed this sentence, please see P2 L42</p> <p><i>P3L14: I would remove "Relatively heavily"</i></p> <p><i>P3L15: add "..to distinguish the glacier boundary" or "glacier terminus"</i></p> <p><i>P3L18: change to "..might result in a potential.."</i></p> <p><i>P4L1: change to "i) a buffer method"</i></p> <p><i>P4L2 "manual"</i></p> <p><i>P4L9: correct English in this sentence</i></p> <p><i>P4L13: end parenthesis after NSD</i></p> <p><i>P6L5: please add "Glacier" after named glaciers, here and throughout the article (or "glaciers" after a list)</i></p>
<p>We deleted all these sentences</p> <p><i>P6L30: This is not a "whereas" statement.</i></p>
<p>We agree, please see P9 L17</p>

P6L30: "increment" should be "increase."

We changed this sentence, please see P9 L17

P7L14: "vital" seems like too strong of language to me.

We agree and changed this sentence, please see P10 L1