

## **Review of the study by Tielidze and Wheate**

### **General comments**

The study by Tielidze and Wheate is presenting the results of a glacier inventory comparison for the years 1960-1986-2014 over the entire Caucasus. The authors provide a detailed overview on previous studies in the region, shortcomings of existing datasets in GLIMS/RGI, glacier sizes through time for individual river catchments and glaciers, data on cumulative glacier length change and climatic trends. Whereas I highly welcome the effort of the authors to improve on the currently available datasets for the region (in terms of consistency and spatial coverage), I am not quite sure if the study can pass scientifically. To me the material presented looks more like a data report with some limited (and partly questionable) analysis. Indeed, there is also a problem with the five more or less identical publications by the first author, each covering different river-catchments (Tielidze et al. 2015a, b, c, d) of the study region (like salami slices) or the larger part of Georgia (Tielidze 2016) and each study is presenting the datasets in the same style with limited scientific analysis. In effect, this study adds further numbers for a region previously not covered by the author but basically that's it.

With three complete glacier inventories of a larger mountain range at hand I think the authors missed the opportunity to provide a convincing scientific analysis of the data obtained. Please have a look at recent studies by Davies and Glasser (2012), Guo et al. (2015), Paul and Mölg (2014), Winsvold et al. (2014), Fischer et al. (2015), Kienholz et al. (2015), or Ojha et al. (2016) to see what is missing. Instead, I have the impression that the study is blown-up with unused details about the investigated region (e.g. the entire page 3) but important details are not given (e.g. what is the ELA on P4/L14, on which glaciers have values been measured to provide this trend analysis?). Similarly, Tables 2, 4 and 5 now cover 5 pages of text but should be presented in the Appendix. It is neither motivated why the river basins have been selected, nor why this information is important at this level of detail (e.g. input for subsequent hydrological modelling? Moreover, much space is taken in the tables for presenting uncertainties (in km<sup>2</sup> and %) for each glacier/catchment, but the area changes itself (in km<sup>2</sup> and %) are not presented (although the related results are discussed in much detail incl. the abstract). Thereby, the uncertainty values are only determined with the (statistical) buffer method. So what can we learn from all these numbers? Instead of the 350 individual values I would have liked to see one number that is related to the uncertainty of the digitizing by the analyst, e.g. based on the independent multiple digitization of a couple of glaciers. I think for completely manually digitized inventories such an assessment is mandatory.

As parts of the text have been described in previous studies or is not really required in the context of this study, I think the 'data report' presented here can be easily turned into a nice scientific paper when replacing the text that is not required with an extended analysis of the results as shown in the studies cited above.

### **Specific comments**

In the following I list all comments, large and small. Some are repetitive.

P1

L18/19: 'marked acceleration': This is not obvious from the presented numbers. Please add relative change rates per year for both periods (with two decimals!)

L22: 'can be used': have/will the outlines and inventory data be submitted to GLIMS? If yes, please add so that it is clear they are accessible.

L27: The Fischer et al. (2015) study is maybe not so relevant for global sea level rise. I suggest writing ‘for local to regional-scale hydrological studies (Fischer et al. 2015, Huss 2012), to global calculation of sea level change (Bliss et al. 2014, Gardner et al. 2013).

L27: ‘glacial extent’: Please write ‘glacier extent’ when referring to contemporary glaciers.

L27-31: I do not understand this sentence, please rewrite. Please note (this still goes wrong in many studies), there is no direct link between climate change and change in glacier area. Changes in area result from the combined interaction of surface lowering (which is a result of glacier mass balance) and ice thickness distribution. So for the same climatic forcing (at the same elevation) area changes can be very large when the ice is thin or small when the ice is thick. This has little to do with response times or the geometric adjustment of a glacier on the decadal time scale.

L31/2: When it is important, why has it not been done here?

L32: Tracking only the area changes over many decades might not help much. A good understanding also requires to have surface elevation changes and ice thickness distribution.

L34: Maybe the cited studies are not the best examples. Recently published glacier inventories often cover entire mountain ranges with thousands to ten-thousands of glaciers (e.g. for Alaska, Greenland, the Alps, or the Greater Himalaya).

L35: Instead of citing here Paul (2000), I suggest citing much larger and more recent studies that investigated differences between inventories (e.g. Nuimura et al. 2015 or Nagai et al. 2016).

L36: I think this sentence needs to have a connection to the sentence before (e.g. ‘However, consistent methodological inventories are necessary to correctly perform change assessment and other glaciological research ...’). Unfortunately, this point is not taken up again to motivate (or even justify) the inventory presented here (see next point).

## P2

L7: Yes, glacier research certainly is. But why is it required to have yet another inventory of the region? Apart from several general statements, the introduction makes no attempt to motivate what is presented afterwards. When readers should also read the rest of the text, it must be clearly explained in the introduction what the research gaps are (for this region) and how this study is addressing them and presenting at the same time a never seen before analysis of the new dataset that has only become possible now. There is now a large opportunity to do so, so please do it!

L20ff: I think the text before is fine to introduce the study region. But from here until P3/L28 I suggest removing the text as the contents (descriptions of mountains and their height/location) is not used later in the text and digitally available for most of us.

P25 (Fig. 1): I am not convinced that the presentation of area changes in sub-catchments (Table 2) is really required. If the authors agree that they are not required, I would remove the catchment numbers here (but please provide them as a separate shape file with the dataset) and show instead where the glaciers depicted in Figs. 2 to 7 are located.

## P3

L29ff: Some climatic background is certainly fine, but how does the information provided here help me to understand the results of the inventory, e.g. for what purpose do I need to know the minimum and maximum lapse rates or the minimum air temperature in 1983? What I want to know is mean summer or annual temperature and precipitation at the mean elevation of glaciers.

## P4

L5/6: LIA history: I suggest adding here the study by Solomina et al. (2016).

L6: glaciated => glacierized

L14ff: Where does the ELA come from? ELA is related to glacier mass balance and the gradients provided here suggest that many glaciers with mass balance measurements have been used to derive it (which ones?). Note: snow lines or glacier mean elevation  $\neq$  ELA.

L20: Please use 'retreat/advance' only when reference is made to changes in length. For mass balance one can use mass loss/gain.

L39: 786 glaciers

P5

L12/13: Please give area changes always in % as absolute values are incomparable. Moreover, a comparison of area change over periods of different length should always provide the rate (i.e. per cent per year).

L20: Fig. 2d/e: Please do some contrast enhancement here, there is not much to see.

P6

L3/4: 'retreated most dramatically': What does this mean? Is it really retreat (length change) or area change? Please provide values for such statements.

L6: Here are all the salami-slices I referred to in the general comments. Please use this publication to make some progress in the analysis. There is no need to do the same paper again and again.

L17: These references are ok but maybe somewhat out-dated? What about Wulder et al. (2012 / 2016) or Pope et al. (2014)?

L26: 'cast an obvious shadow': The problem with retreating glaciers is that their terminus does no longer 'cast an obvious shadow' and that most glaciers in the world are in retreat. So what has been done when their terminus is barely visible?

L26: manual delineation: this is correct but for clean ice automated mapping is superior (consistent and reproducible), at least in the absence of seasonal snow

L28: Not only glacier tongues need to be free of seasonal snow, the entire glacier should be.

L34: 'the most accurate method': this is certainly correct for debris-covered glaciers, but for clean ice automated mapping has the same accuracy (and outlines are consistent, not generalized and reproducible; all important assets these days).

L37: of 20 metres from 88 aerial (remove brackets)

P7

L12: I assume this should read 'To estimate uncertainty of glacier area'? Please check carefully the difference between uncertainty (of a measurement) and error (difference to a reference dataset). These are different. For example (L14), the 'digitizing error' should likely read 'digitizing uncertainty'.

L14: Please clarify how the map rectification could have an impact on the derived glacier area when considering this as an 'error term'. As far as I know, geolocation uncertainty is only an issue when directly calculated from different datasets (e.g. cumulative length changes using digital intersection). Location errors should not impact on the derived area.

L16: I think all these are not errors but uncertainties.

L18: You can see in Paul et al. (2013) how line-placing uncertainty for manual digitizing looks like. It is indeed +/-1 pixel (and worse for higher resolution imagery due to increasing generalization). A more realistic result can thus be achieved when using a +/-1 pixel buffer (and +/-2 pixels for debris-covered glaciers).

P8

L4: conservative: It is foremost just a statistical value with probably little relation to the analysts work. I would thus strongly recommend to perform a multiple (3-5 times) digitizing experiment with a couple (about 10) of differently sized glaciers (with debris and clean). This should be done for all three datasets (map, TM, ASTER) and provide a more realistic estimate of the uncertainty.

L5: Figs. 3a and b should be shown side by side. It might also be helpful to mark the boundary of Kolka Glacier in Fig. 3b as the 64% debris cover mentioned in L15 cannot be seen.

L11: This seems to be a repetition from P6/L34.

L13: 'one of the most': Why not presenting a hypsographic analysis showing where the debris is?

L14: Why not adding that Kolka has rebuild from ice avalanches from the surrounding steep rock walls after being completely removed from its bed by the 2002 avalanche? This might help to explain why it is such a special case.

L17: 'not typical': why? I think the Caucasus has quite a lot of debris-covered glaciers, in particular the larger ones.

P9

L8: As mentioned above, there is no direct link between glacier area change and climate. When climate data are analysed for the same time period you have to analyse mass balance data, only these provide a direct and undelayed response to the governing atmospheric conditions. Also for a general trend analysis the forcing has to consider glacier response times. Understanding glacier area changes for 1960 to 1986 might thus require looking at climatic conditions from 1930-1960 (for an assumed 30 year response time). But even this might only allow explaining general trends in \*length\* changes as area changes are also driven by the ice thickness distribution. I think it is ok to say that glaciers have lost area since the 1960s because temperatures have increased, but that's it.

L13/15 and elsewhere: please always provide relative area change rates (per year) to have comparable values. And please always give two decimals! The rounded values in L17, 19, 20, 22, and 24 are not accurate enough (see example below).

L27: 'highest glacier surface decrease': What is this? Absolute loss, relative change, change rate? Please be precise.

P10-12 (Table 2): Please rethink if this Table makes any sense. I suggest removing it completely and refer to the digital datasets for such assessments. If it should stay, move it to the Appendix and better justify why these numbers per tributary river basin are required. There is currently no further use of them. Instead of providing (statistical) uncertainties for each basin, please consider adding absolute/relative area changes. This could also be visualized graphically for all regions (using a multi-segmented bar chart) or in dependence of elevation. Please also note that numbers should be aligned right rather than left.

P12 (Table 3): Please add the area changes for the two periods (at least the relative ones) including change rates per year.

P13 and 14/15 (Tables 4 and 5): as for Table 3, please add the area change (at least in per cent) when the caption says the table is presenting area changes. Please also right adjust all numbers and check if the provided uncertainty values are necessary.

P14 (L7): As mentioned above, Kolka Glacier was basically removed from its bed in 2002 and regenerated afterwards (but not yet to its full size). Due to this special behaviour the glacier should be removed from all statistical analysis.

P14 (L10): ... shown in Fig. 4b.

P15: Please consider using a bold font for the numbers in Fig. 4, they are partly difficult to see.

P16

L1-9: I suggest removing this highly speculative reasoning from the results section. It should also not be in the discussion as the statements are strange. For example, point c) indicates that the authors might not be fully aware how glaciers work. Why should geographic location (or altitude in a) have something to do with shrinkage rates? Glaciers are where they are because climate is as it is. As long as they have an accumulation area, it does not matter if climate is more continental or drier. They might be larger or smaller depending on mountain elevation and possibilities to accumulate snow but they will not shrink slower or faster due to their location. The only thing that would matter is when there are strong regional differences in climate change (such as locally increased precipitation). Please note that the most important control of locally averaged glacier area change rates is likely the size class distribution of the glaciers (please add), as relative area changes in general increase towards smaller glaciers (please add the related scatter plot). So area loss rates are normally higher where glaciers are smaller. For this reason only rates for glaciers in the same size class should be compared.

L4: Why citing here studies that are 35-50 years old?

L10: I would show the general characteristics of the glaciers in the study region before the changes are analysed. Please also add the size class distribution (by number and area) for different macro-regions.

L23: 'recession rates' is fine for area changes, but please use 'retreat rates' when referring to length changes.

L24: 26 and 28 years is quite a long period. Can it be excluded for all glaciers in the sample that advance phases in-between reduced the long-term mean value (see P17/L1)?

P17

L5: I think 'while' relates to time, it should thus be 'whereas' here.

L7 (Table 6): As for Table 3 and please align numbers right. To avoid confusion, I would not use terminus retreat but length change. Values should then be negative for retreat and positive for advance. What should terminus elevation tell us? Please consider providing glacier length here as there might be a relation between the two.

P18: Maybe the visibility of the scale bars can be improved?

P19/20 (Figs. 8 to 10, Tables 7 and 8)

As I think climate data cannot be directly related to area changes (see above), I do not need to have any of the figures and tables presented here. This also roots in the unreflected presentation of the data. They are shown but why? In particular the mean annual values presented in Fig. 8 and Table 7. What is their relation to the observed glacier changes? As a small point, I assume 'Mean monthly air temperature' is 'Mean annual air temperature' (and please right adjust all numbers)? As a comment to the graphics, I would recommend adding major tick marks also at the opposite site of each axis along with additional minor tick marks (one year / one degree step), temperature on the y-axis should be capitalized, and a space inserted before the °C (and please do not use a zero in superscript for the ° sign, this is a special symbol). It is also unclear to me why the trend lines are shown in Fig. 8 but not in Fig. 9, despite trends being much stronger for the summer months (according to Table 7)? Overall, it would be sufficient for me to just mention in the text that JJA temperatures (T) increased by about 0.7 to 1.2 degrees for the various climate stations. By also presenting the trends in precipitation (P) with increases from 10 to 30% it might be required to shortly explain how much P increase is required to compensate a 1

°C increase in summer T. This might require performing a sensitivity study with a mass balance model. Just arguing that this increase was not sufficient because glaciers are in retreat (P21, L9) is not an explanation (in particular considering that some glaciers did not retreat). Bottom line, I would remove this entire climatic analysis as it gives rise to numerous questions that are not easy to solve, the relation with area changes is very weak, and there is actually no real analysis of these datasets.

L12/13: Why are mean annual values shown in Fig. 8 and Table 7 when the relation is only with JJA T? And what does 'consistent' mean? In particular, the mean annual values of Fig. 7 say little about related glacier changes.

P21

L2: 'clearly show': Where? There is neither a scatter plot of area change rates nor a figure illustrating this.

L4/5: See comments above: Stronger relative changes in regions with smaller glaciers occur because smaller glaciers show a larger decline in the mean (please check and add a related scatter plot). There is no need to introduce 'Jurassic sedimentary rocks' as an explanation.

L7-13: Please remove; this analysis makes no sense in my opinion (as described above). By concluding from 'suggests ... mostly reflects influence of rising temperatures' that 'temperature was the main control on the early glacial fluctuations of the 21st century ...' is strange. How can something that 'reflects an influence' be converted in the next sentence to the main control on the fluctuations? And why early 21 century, the 1960-1986 period should be the late 21st century? And why glacier fluctuations? Temperature is in general the variable being responsible for the long-term trends whereas fluctuations (retreat and advance on top of a general trend) are driven by shorter-term variability in precipitation. I stop here but the reminder of this section is also not good (e.g. what have the eastern Alps T trend over the 1929-2011 period to do with the Caucasus variability?).

L14-24: I think the comparison of area change rates does not work in this way. I do not understand why a comparison is performed with glaciers in Kamchatka, the Kodar mountains, the Canadian Rocky Mts. or the Andes? How do they relate to the study region? Or have they been selected because of the roughly similar 50-60 year period? What about intermediate advances during this period? Can they be excluded for all regions?

L17/22: Please give two decimals for the average rate of change per year. Over a 50-year period 0.5% per year can be anything from 22.5 to 27.5%.

L22: I would argue that compared to the Caucasus the glaciers in the Alps are comparably large. But I also notice that you here consider the effect of larger relative area losses for smaller glaciers. So the question is why this has not been considered before (L4/5)?

L24: Please always add a mean value per year. When periods differ, please also explain why they can be compared nevertheless.

L27: I do not understand this comparison. There could only be an underestimation when the 1960s UGI has an underestimation of glacier area in comparison to the 1911 PGI inventory. Has it? Compared to the more recent inventories the effect should be vice versa. I do also not understand why Khromova (2014) is saying that glacier decrease was faster in the first half of the 20th century, 24.7% in 70 years is much less than 17% in 40 years?

L30-33: Is it required to list here all river basins? Maybe it is more meaningful to write the total and percentage of area that has been missed?

L34: I fully agree on this, the country must be correctly stated in the attribute table. Apart from this, in the RGI Caucasus is only one first-order region.

L36ff: I would have liked to see these issues more prominently covered in the introduction as they provide a very good motivation to perform this study.

P22

L9-11: It would have been nice to see some of these issues illustrated in the study, also to improve consistency in interpretation by the science community. Maybe one or two examples can be added in the revised version?

L15/16: Again, please give two decimals for change rates per year.

L21: have retreated => have decreased in size (reserve advance/retreat for length changes).

L23/4: see comments above, I am sure that lithology does not play a role here.

L25: This might be correct, but there is not much evidence for this statement in the text before. Have area/volume change scenarios been calculated? Or maybe refer to one of the global scale studies that have done this.

L29-31: This conclusion is also not really based on a careful elaboration in the manuscript. Please also consider ice thickness distribution and glacier size as key factors impacting on area change rates. If values are compared across the region, please only compare glaciers in the same size class.

L32: 'may reduce these uncertainties': Which uncertainties? Please name them before.

### **Additional References**

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