



## Reply on RC1

Shakil Ahmad Romshoo et al.

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Author comment on "Evaluation of the global and regional glacier inventories and assessment of glacier elevation changes over the north-western Himalaya" by Shakil Ahmad Romshoo et al., Earth Syst. Sci. Data Discuss., <https://doi.org/10.5194/essd-2021-28-AC1>, 2021

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### Reviewer #1

**General Comment:** The authors present a new glacier inventory for north-western Himalaya, which is mainly based on manual glacier mapping using different data sources. They compared the new inventory with existing inventories and figured out limitations and differences of the individual inventories. Additionally, the authors used InSAR DEMs to compute glacier elevation changes between 2000 and 2012 of the study area.

The paper is well structured but the sections regarding the glacier elevation/mass change computations are very unclear and confusing. The authors are talking about mass balances but never provide any mass balance values. There are many flaws in the respective sections. Thus, I would suggest to remove the elevation/mass change computation sections completely, since the main focus of the paper is the evaluation of the glacier inventories.

Moreover, the results sections are too long and can be strongly condensed by focusing on tables and graphs.

**Response:** We express our gratitude to the reviewer for the elaborative and useful section-wise and line-by-line detailed review of the manuscript. We have responded point-by-point to all the comments and suggestions of the reviewer. The concerns of the reviewer regarding elevation change have been addressed entirely to the best of our ability and knowledge. The valuable comments and suggestions provided by the reviewer have greatly helped to improve the contents and quality of the manuscript.

Furthermore, we agree with the reviewer that the manuscript is focused on the evaluation of the glacier inventories, however, we believe that the elevation change information of the three basins will add value to the database, providing, in addition to the glacier inventory, a quick overview of the glacier elevation and mass changes of the glaciers in the database. As such we find merit in retaining the elevation change section while addressing the concerns of the reviewer about elevation change estimation. The point-by-point response to the detailed comments and suggestions raised by the reviewer is provided as follows:

**Comment #1:** At many places it is unclear, if the authors talk about mean/media values of certain variables (e.g. elevation, slope ...) or pixel wise values. A more precise wording is needed throughout the paper. (see details below).

**Response:** We have used the mean value of the topographic variables, obtained by averaging single-cell elevation, slope and aspect values from the DEM. This has been specified in the revised manuscript.

**Comment #2:** The computation of several "uncertainty" values is unclear. Please provide formulas (see details below)

**Response:** Clarification/correction provided wherever suggested in the revised manuscript. A detailed response is provided against each specific comment below.

**Comment #3:** The computation of the average aspect values is unclear and might be buggy (see details below)

**Response:** As mentioned in the manuscript, the aspect was calculated by averaging the aspect value of DEM cells within the extents of each glacier. However, the aspect has been now recalculated in the revised manuscript as specified in the RGI technical document. The aspect sines and cosines of each of the glacier's DEM grid cells were summed and the mean aspect was calculated as the arctangent of the quotient of the two sums. The calculated values of aspect were transformed to the eight cardinal directions (N, NE, E, SE, S, SW, W, and NW) with each cardinal direction having range of 45 degrees, half to each side.

**Comment #4:** The comparison of the different glacier inventories is OK but can be certainly extended. It would be interesting to compute the the overlap ratio  $r_{ov}$  also for e.g. DC, clean and shadowed glaciers to evaluate the difference between the inventories.

**Response:** Agreed, that the overlap ratio of different glacier classes will be more useful, however, it is pertinent to mention that the debris covered portions of the glaciers, particularly in the ICIMOD inventory, have been excluded from the glacier extents as such the same glacier classified as debris-covered in the KUGI gets classified as "clean" (as the debris covered area is excluded) in ICIMOD for example, thereby making it a bit difficult to find true overlap ratios.

**Comment #5:** It is also unclear, if the topographic parameters of the other inventories were taken from the inventory meta data or computed by the authors. The used DEMs might differ. Thus, it would be more meaningful to use a consistent source for topographic information before doing the comparison.

**Response:** Since the source DEMs for topographic information in the existing inventories are different, the topographic parameters for the KUGI and other inventories, evaluated in this study, were derived from the ASTER GDEM2, which is now specified in the revised manuscript.

**Comment #6:** Once, the paper is revised it should be properly proof read. I am not a native speaker, but I got the feeling that the English can be improved. Many sentences are quite complicated and unclear or maybe got just grammatical errors.

**Response:** Thanks for the suggestion, we have checked and revised the manuscript for any grammatical errors. We have revised and rephrased a few complex sentences in the revised manuscript for more clarity and better understanding. As suggested, we shall get the revised manuscript check by an English language editor/faculty in the University.

Detailed comments (\* significant issues):

**Comment #7:** L31: delete "for the study area"

**Response:** The phrase "for the study area" has been deleted from the revised manuscript as suggested.

**Comment #8:** l35: by "a" Digital...

**Response:** As suggested, the Digital Elevation Model has been prefixed by the letter "a" in the revised manuscript.

**Comment #9:** l37: to glacier areas...

**Response:** As suggested "area" replaced by "areas" in the revised manuscript.

**Comment #10:** L40: are you talking about the mean or median glacier elevation?

**Response:** It is the mean glacier elevation and has been specified in the revised manuscript.

**Comment #11:** L44: whats the meaning of the "R" values. Completely unclear.

**Response:** The overlap ratio of individual glaciers is represented by " $r_{ov}$ " whereas, the "R" ( $R_A^B$ ) has been used to represent the average overlapping ratio of the base and target glacier inventories (overlap ratio averaged for all the glaciers in a particular inventory combination e.g, KUGI-RGI for individual basins). This has been described under the methodology section in the revised manuscript.

**Comment #12:** L48: 2000 an 2012

**Response:** The typo has been corrected as "...2000 and 2012" in the revised manuscript

**Comment #13:** L71: what about Brun et al. 2017

**Response:** The references has been incorporated in the revised manuscript.

**Comment #14:** L97 and following: please list here more recent publications

**Response:** More recent publications suggested in the "general comments" and several other relevant publications suggested by other reviewers have been incorporated in the revised manuscript.

**Comment #15:** l104: please list some of the variables

**Response:** The variables include glacier number and area, which has been specified in the revised manuscript.

**Comment #16:** l106: why is the reproducibility not assured? Not clear.

**Response:** Since different inventories use different approaches, datasets and at times the definition of the glacier itself varies among the inventories, therefore reproducibility is a

challenge. Furthermore, in case of the manually or at times the semi-automatically delineated glacier boundaries, glacier area estimate will depend on the perception of the analyst as such the results are often not reproducible.

**Comment #17:** L109: what about Brun et al 2017, Shean et al. 2020?...

**Response:** We agree that the mentioned studies have reported elevation/mass changes over the Himalayan region and have therefore been cited at appropriate places in the revised manuscript. However, here we have specifically mentioned the studies where the dataset is publicly available.

**Comment #18:** L110 and following: please move the comparison to the discussion section.

**Response:** As suggested, the section has been moved to the Discussion section in the revised manuscript.

**Comment #19:** L118: which basins and where? Not introduced

**Response:** The basin names (i.e., Jhelum, Suru and Chenab) has been specified in the revised manuscript.

**Comment #20:** L123: there exist already elevation change data sets for the same period (Brun et al.2017, Shean et al. 2020). So there exists already information on the glacier behavior.

**Response:** Agreed that the elevation change studies already exist over the region, however, it is pertinent to mention that these studies are carried over a larger spatial domain. In the present study, we carried out the elevation changes at local scale, furthermore, we also tried to assess the impact of topographic and morphological parameters including glacier size, DC, elevation, slope and aspect on the elevation changes which is included in the database.

**Comment #21:** L125: please rephrase this sentence. A quite weak motivation for this study.

**Response:** Thanks for the comment. As suggested, we have modified the motivation for the research work in the revised manuscript keeping in view the following argument.

Primarily, the motivation for the KUGI is to develop a high-resolution glacier inventory with improved accuracy with visual interpretation and manual delineation of glaciers from Landsat satellite data supported by the limited ground truth and supplementing the glacier outlines with additional data like debris-cover, thickness changes and other glaciological parameters, that are either missing or incorrect in the existing databases so that the database is made available to the large research community for various applications.

Purportedly the global and regional glacier databases that were chosen for comparison in this study have been generated using a semi-automated method allowing less human error, quick delivery, and high accuracy. However, it was found in this study that there are significant errors in the evaluated databases due to the misinterpretation of seasonal snow cover particularly on the glacier headwalls at high altitudes, shadow-covered glaciers and debris-cover.

Keeping in view the worldwide use and applications of global and regional databases, it is important that a rigorous evaluation of these global and regional inventories is undertaken for the continued refinement of the methodology which is a fundamental requirement for any meaningful application of the global or regional database. It is hoped that the future releases of the databases will improve these and other shortcomings identified in this manuscript.

**Comment #22:** L130: UIB not introduced

**Response:** UIB stands for Upper Indus Basin and the full form of the UIB has been incorporated upfront in the revised manuscript.

**Comment #23:** L132: "and" 73....

**Response:** The word "and" has been inserted between the latitude and longitude values in the revised manuscript.

**Comment #24:** L136: when is this area covered? All year long?

**Response:** Most parts of the study area above 3600 m asl remain snow-covered for the entire or most of the year. The sentence has been modified accordingly in the revised manuscript for more clarity and instead of 3600 m, we have mentioned ~4000 m asl to include that all the areas covered with snow.

**Comment #25:** Fig1: Please provide country borders and names in the overview map (upper right corner) for a better orientation. Please indicate the glacier coverage also outside the 3 basins. What are the sources of glacier outlines, debris cover and glacier volume?

**Response:** Thanks for the suggestion. The figure has been modified accordingly in the revised manuscript. The glacier outlines and the debris cover information is based on the KUGI. Further, the glacier volume has been derived using the slope-dependent scaling approach with the glacier area and slope information derived from KUGI.

**Comment #26:** \*L154: are you talking about mean or median altitudes? Not clear, the same for the other basins in the following.

**Response:** These are the mean elevations as mentioned earlier and this has been specified in the revised manuscript.

**Comment #27:** L163: ... in the northeast of the study area..

**Response:** As suggested "east" has been replaced by "northeast" in the revised manuscript.

**Comment #28:** L192: ...use of...

**Response:** Sorry for the typo, the word "use" this has been corrected in the revised manuscript.

**Comment #29:** \*Table1: could you please add the Path and Row numbers of the Landsat data. ASTER GDEM not listed. URL for ICIMOD inventory is missing., please provide also the date ranges of the inventories for your study area

**Response:** The suggested missing information pertaining to the data sets used in developing the glacier database has been incorporated in the revised manuscript. The images with path/rows 149/36, 148/36, 148/37, 147/37 dating between 2000 and 2002 have been used for the inventory development.

**Comment #30:** I208: add "C-band"

**Response:** As suggested the band information has been incorporated in the revised manuscript.

**Comment #31:** I211: please introduce the abbreviation "DEM" at the place, where it is used the first time.

**Response:** The full form of the DEM (Digital elevation Model) has been mentioned at the first occurrence (in abstract section) in the revised manuscript.

**Comment #32:** \*I209: please rephrase. TanDEM-X is still acquiring data. You are talking about the worldDEM phase

**Response:** Agreed, TanDEM-X mission is still acquiring the data, the information provided in the manuscript is relevant for the product version of the DEM (used in the present study) released in 2018 only. The text has been therefore modified accordingly in the revised manuscript.

**Comment #33:** I234: between or only in 1999 and 2003

**Response:** It is between as the authors have used data sets dated 1999, 2000, 2001 and 2002 for the generating the glacier inventory.

**Comment #34:** I298: no capital letters for Base and Target

**Response:** As suggested, the words "Base" and "Target" have been uncapitalized in the revised manuscript.

**Comment #35:** Section 4.3: This section is a bit unprecise and many details are missing. e.g. which DEMs did you use? How did you estimate the penetration bias

**Response:** The missing details and further description pertaining to the methodology has been provided in the revised manuscript. The penetration bias was computed as a function of altitude after Vijay and Braun, (2016).

**Comment #36:** I350: cite here Rolstad et al. 2009

**Response:** The reference has been incorporated in the revised manuscript.

**Comment #37:** \*I352: Seehaus et al. 2020, did not use the total glacier area for A. They used the area of each glacier complex.

**Response:** Agreed that Seehaus et al. (2020) used the area of each glacier complex. We also used the term to represent the analyzed area.

**Comment #38:** Section 4.4. b) This section is quite confusing and the equation to compute the uncertainty of the mass balance is missing. Please revise the whole section and use clear and individual variables!

**Response:** The uncertainty of glacier-wide specific elevation change ( $\Delta_h$ ) is computed as:

The , , and are uncertainty of DEM differencing, uncertainty due to void filling (since the DEMs especially SRTM has voids over the study area as such the DEMs coverage for each having voids >30% were excluded from the analysis whereas, the glaciers with <30% voids were filled with nature neighbor interpolation algorithm), temporal uncertainty of TanDEM-X and uncertainty of radar signal penetration respectively. The uncertainty of each of the individual parameter is described in detail in the revised manuscript.

**Comment #39:** \*I365: How did you compute the glacier volume ? Not mentioned in the Methods Section

**Response:** The glacier volume was estimated using the slope-dependent volume estimation approach (Haerberli and Hoelzle, 1995), the methodology to estimate the glacier volume has been incorporated in the revised manuscript.

**Comment #40:** Table 2: How did you compute the glacier volume? Why does it differ so strongly e.g. between KUGI and RGI at Jhelum? How did you assume the uncertainty in glacier area for the different inventories? Not explained!

**Response:** As mentioned, we used the slope dependent approach for volume estimation. The difference in volume estimates between KUGI and RGI is most probably due to the difference in the number of glaciers in the inventories.

**Comment #41:** 380 and following: are you talking about mean or media elevations? Or the total elevation span of the whole glacier?

**Response:** These are the mean elevation values.

**Comment #42:** Table 3,4,5,6,7: Units are missing. What means "A" and "N" and "DC"? not clear

**Response:** The "A" represents glacier area in km<sup>2</sup>, "DC" is glacier debris cover again in km<sup>2</sup>, whereas, "N" indicates the glacier number (count). The units as well as the description of each letter(s) has been specified in the revised manuscript in all the tables.

**Comment #43:** I396. delete sentence. Already mentioned in the methods

**Response:** The sentence has been removed from the revised manuscript as suggested.

**Comment #44:** \*Section 5.1: The whole Section can be strongly condensed. All information can be found in the tables and does not need to be repeated in the text.

**Response:** Thanks for the suggestion. Accordingly, we have trimmed this section in the revised manuscript.

**Comment #45:** \*Table 6: how did you compute the average glacier aspects? Please provide the formula somewhere.

**Response:** As mentioned above, the aspect has been now recalculated in the revised manuscript. Kindly see the response to **Comment #3**. The aspect sines and cosines of each of the glacier's DEM grid cells were summed and the mean aspect was calculated as the arctangent of the quotient of the two sums.

**Comment #46:** l483: how did you estimate the variations? Not explained!!!

**Response:** By the variation, we mean the difference not the statistical variance. The sentence has been rephrased accordingly for clarity in the revised manuscript.

**Comment #47:** \*Section 5.2: Same as for Section 5.1.! It can be strongly condensed and most of the information can be summarized in nice tables and/or graphs. The text is very long and the information is hard to find. Tables and graphs would be beneficial for the reader

**Response:** Thanks, as suggested the information has been already put in the form of tables and were referred at appropriate places in the revised manuscript. Further, the section has been modified/condensed in the revised manuscript as suggested.

**Comment #48:** \*Table 10: How did you define the elevation category? All pixels with in the interval? Or all glaciers with mean/median elevation within this interval? Unclear! How did you compute the uncertainties?

**Response:** In each elevation category, glaciers are grouped together in the elevation bins based on the mean elevation of individual glaciers. This has been specified in table caption in the revised manuscript. Furthermore, to assign the uncertainties for a sample average (for example glaciers in the elevation range between 5000-5500), we calculated the uncertainty of the sample-wide elevation change ( ) using the following (Huber et al.) , where  $\sigma_{\Delta h}$  is the uncertainty of each item  $i$  (glacier in our case) and  $n$  is the number of item in the sample.

**Comment #49:** Fig. 2,3,4: Please add a background. The glacier outlines would be also nice. The bar plot is too small an impossible to read. Does it show the mean elevation changes per glacier? Explain!

**Response:** Thanks for the suggestion. The figures have been modified accordingly. Yes, you are right, the bar graph is based on the mean elevation change per glacier.

**Comment #50:** l629: Are you talking about average elevation changes per glacier? Please clarify.

**Response:** Yes, we are talking about average elevation changes per glacier. This has been specified in the figure captions in the revised manuscript.

**Comment #51:** Table 11: is the slope take pixel by pixel or is it base on the mean slope per glacier?

**Response:** The slope is based on the mean slope per glacier. Specified in the table caption in the revised manuscript.

**Comment #52:** Table 12: same as for Table 11. is the aspect take from each pixel or the mean of each glaciers

**Response:** The aspect is based on the mean aspect of each glacier. Specified in the table caption in the revised manuscript.

**Comment #53:** l659: Maybe the bigger glaciers are located at lower altitudes? Please check

**Response:** Yes, the glaciers tend to be smaller at higher altitudes in the study area. For example, glaciers in the Suru and Chenab basins situated above 5500 m asl are generally



smaller compared to the glaciers situated between 5000-5500 m asl (Table 4 in the revised manuscript).

**Comment #54:** Table 13: Units are missing for area

**Response:** Units (km<sup>2</sup>) of area have been provided in the revised manuscript.

**Comment #55:** I685: By inspecting Fig. 2-4, it looks like most glaciers are not south facing. Please check your aspect computation! Do not use a simple mean of all pixel wise aspect values of a glacier. See RGI6.0 technical report.#

**Response:** As suggested, the aspect was recalculated in the revised manuscript as specified in the RGI technical document and accordingly, the correct aspect is depicted in the revised manuscript.

**Comment #56:** Fig.5: Date and source of background image?

**Response:** The background image is FCC (7,4,2) of Landsat ETM+ dated 04-09-2000. The information has been added to the figure caption.

**Comment #57:** Fig.6: Date and source of background image? There are at least 2 glacier tongues. Most likely they were connected in the past, but the mapped state shows 2 individual major glacier tongues. Therefore, it is not wrong to split the glacier are in 2 polygons. Please rephrase accordingly, also in the main text.

**Response:** The date and source of the image has been provided in the revised manuscript. We, agree that there are two tongues, however, when we drape the 2000 satellite images over DEM, the ridge-topography is not prominent enough to manifest the flow direction/ridge divide on the satellite images especially in the accumulation zone, as such we did not divide the glacier in multiple polygons.

**Comment #58:** Fig. 7: the outlines are hard to see. Use different colors or wider lines. Date and source of background image?

**Response:** Thanks for the suggestion. Accordingly, the figure has been modified as suggested for better presentation of the outlines in the revised manuscript.

**Comment #59:** Table 16: Can be merged with Table 2 to avoid doubling of data.

**Response:** We have merged **Table 16** with **Table 8** to represent the difference in glacier number and area in the revised manuscript. The information in the **Table 16** seems more relevant to **Table 8**, therefore the repeating information (area) has been removed from the merged tables in the revised manuscript.

**Comment #60:** I794: Unclear sentence

**Response:** The sentence attributes the higher thinning of south oriented glacier to the higher solar insolation received by southerly slopes. The sentence has been rephrased in the revised manuscript for clarity.