

## **Review of the study by Tielidze et al.**

### **General comments**

The study by Tielidze et al. presents glacier inventories from three points in time (1947, 1988, 2019) for Heard Island along with an analysis of glacier changes, partly also for denser time series. The study is also investigating debris cover evolution, glacier length changes, climatic fluctuations, mass balance time series and a special calving event of one glacier. In my view this is an important and well-written study that closes major knowledge gaps in this remote part of the world. Apart from the wrong interpretation of the calving event, I have many small comments to the text and figures. I think quite a lot can be and partly should be improved to get things right. Still, these are all small points that the authors can hopefully consider.

My major objection is the interpretation of the ‘advance’ of Stephenson glacier in 2007/8 depicted in Figs. 7 and 11 and described in various parts of the text. I agree that it is looking like an advance of the tongue, but actually the retreat is continuous and what is advancing / moving forward / expanding is just floating ice bergs from the disintegration of the tongue. As it is a bit difficult to see in Fig. 7, I have downloaded the panchromatic (15 m) bands of the Landsat ETM+ scenes listed in Table 1 from 2001 to 2010 (plus two additional scenes from 2008) and then animated close-ups of the region at various speeds. I also flipped back and forth between two individual images to reveal the change.

By 2007 most of the SE branch of the tongue disintegrated, leaving an arc-shaped region at the glacier terminus. Between 2007 and 2008 there is very little change here but larger parts of eastern branch fell apart. The dense melange of icebergs is drifting to the sea, giving the impression that the glacier would advance. Flipping than back and forth between the 2008 images from 4.2. and 23.3. reveals that the upper part of the glacier tongue is static and does not show any movement, whereas the floating ice bergs continue their way outward. There is a little bit of tongue retreat from 2008 to 2009, but the major change is that all the floating icebergs melted away. This would not have been possible in just a year with a compact glacier tongue that had just advanced to this position. Please note that there is also no advance from 2001 to 2003. What looks like an advance is also the movement of the floating icebergs from the disintegrating and further retreating tongue.

I suggest measuring the changes again and revising the text accordingly. One might add the full (annotated) 2001 to 2010 time series of Landsat pan images in the supplement and/or provide screenshots in a zip file so that interested readers can also follow the development.

### **Specific comments**

L40: There are further (less negative) values from some other, more recent studies. Maybe cite these as well?

L42: I suggest writing here ‘glacier shrinkage’ to clearly include mass loss; the retreat of a tongue has usually only very limited impact on water supplies.

L44/45: I suggest adding some further studies related to applications of glacier inventories, for example [doi.org/10.1038/s41586-021-03436-z](https://doi.org/10.1038/s41586-021-03436-z), [doi.org/10.1038/s41558-017-0049-x](https://doi.org/10.1038/s41558-017-0049-x) or [doi.org/10.1126/science.abo1324](https://doi.org/10.1126/science.abo1324)

L47: I suggest writing ‘in combination with glacier outlines they provide crucial data ...’ The DEM alone does not proved any of these.

L65: I understand glacier retreat as a part of an ecosystem. An ecosystem should not be at risk from changing glacier extents. I suggest writing ‘at risk from the impact of human settlements’ as usually we are the problem.

- L66: I am a bit unsure how this could be important for a place like Heard Island? Do they have a problem with ‘overtourism’ or specifically protected areas? Please clarify. My understanding is that in this region nature (glaciers, volcanoes) pre-scribes the changes and human interference is - apart from some scientists - very limited.
- L74: I would suggest removing the ‘why’ question. Just from some sparse remote sensing data and some coarse resolution reanalysis data (but without any field measurements), I think our understanding of how the glaciers work in this region and why they are changing in the way they do is very limited. Adding geothermal heat flux, ash layers and ocean calving, I would rather say that we are quite far away from understanding anything here.
- L97: of Heart Island (no ‘the’)
- L136: What do other studies say about glacier flow velocities or ice thickness (e.g. doi.org/10.1038/s41561-021-00885-z)? Do they roughly agree?
- L145: What do today’s global scale studies say about the glaciers of Heard Island, e.g. regarding geodetic mass balance and derived gradients or future evolution?
- L163: Compared to glacier flow fields, the ice divides in RGI 6.0 do not look too bad in Fig. 1 of Millan et al. (2022). Please describe in the discussion section (or supplemental material) what the problems are.
- L188 (Fig. 2): I think panel d with the DEM is not required, at least not in this form. If at all, please show a hillshade version with elevation contours and glacier outline overlay. Apart from this, I have the impression that the images are a bit too small to see anything. If not in the main text, please show each image at full page width in the supplemental material.
- L194: Apart from cloud cover, I think also the commercial phase of Landsat was an issue. Images have just not been acquired in the 1990s.
- L223: Aren’t we at GDEM v3 in the meantime? And has the AW3D30 DEM also been checked? At times it has a better quality than the GDEM. Please shortly comment on it.
- L239: I would not say that manual mapping is more suitable in general, but already add here that for a small study region with only a few glaciers that are often debris-covered, complete manual delineation is a similar fast approach.
- L245: When there is (optically thick) debris cover on the glacier surface it does not only create uncertainty, but this part is then simply not mapped.
- L251: from days? This might be of interest for surging glaciers, but I think for all others annual resolution should be sufficient.
- L257: Please repeat this exercise for Stephenson Glacier after the terminus region has been digitized correctly.
- L269: When using the buffer method, please also mention that it only buffers the extents that are not ice-ice divides (where the method makes no sense). As many glaciers are debris covered and manual delineation has been used in this study, please also apply the multiple independent digitizing method for uncertainty assessment, at least for the terminus section of about five glaciers. The results obtained for the uncertainty will be more reliable. And please apply the method to both, the Landsat and the Pleiades images.
- L302 (Figs. 3b and c): I suggest removing these two plots as they only show what is already stated in the text and the trend is not too difficult to follow. Moreover, I dislike the fact that the ‘Year’ axis is not drawn to scale. The distances of the bars to the one from 1988 should be different at a 4:3 rate. Instead of these two panels, please show in a new Figure 4 a scatter plot with the area change rate per year (or decade) vs. size for each individual glacier, using different colours/symbols for the two periods and maybe also for the two islands. Is there a reason why the glacier south of Nr. 16 does not have a number?

- L305 (Fig. 4): Please remove the grey bars in the background, draw the years to scale and show boxplots representing the values for the individual glaciers in the background, maybe also colour coded (but please do not use red and green in the same plot red, blue and black might work instead).
- L313: Please explain why there is a downward shift of maximum elevation. This is not obvious from Fig. 3a where maximum elevation looks unchanged.
- L323: I think for such a small number of glaciers the statistical distributions are more governed by chance than by climate (in particular the count). If the information should be kept, I suggest writing explicitly 'By number, most glaciers on Heard Island are oriented towards ..., whereas most of the area is facing southwest' (or something similar).
- L337 (Fig. 5): Please indicate the zero point in the center with a small cross. If the graphs should be kept, please show them side-by-side. There is not too much info included so they can be shown smaller. Instead of showing absolute values in Figs. 5a and b, it would also be possible to present relative numbers, allowing a display of the two curves in the same plot.
- L349 (Fig. 6): I think there is no need to show length changes here and in Fig. 11 and suggest removing them here. Please also consider that 'Terminus change' on the right y-axis should read 'Cumulative length change' and that the years on the x-axis should be drawn to scale with the 1947 value being far away from 1988 and 1988 being 13 years away from 2001. The current display could be seen as a suggestive data manipulation and is also inappropriate to reveal that the recent retreat rate of Brown Glacier is much higher than in the decades before. Finally, given that the changes of Stephenson Glacier will be much less exciting and because annually resolved area changes have limited glaciological meaning, I suggest skipping Fig. 6 altogether and show the length changes in Fig. 11 only.
- L354-361: Please replace this section with what has really happened as described in the general comments (e.g. continuous disintegration of the tongue since 2001, movement of the dense pack of ice bergs to the sea, seemingly indicating an advance, the rapid meltdown of all ice bergs in just one year).
- L364 (Fig. 7): Please replace with correct and thicker outlines, instead of the dark red use a brighter orange. Please add the full time series as supplemental material (maybe annotated images in a PDF and the images itself).
- L367: I speculate here a bit, but as the source of the debris cover is likely by ash falls rather than by rock fall from ice-free headwalls, maybe this can be added in a short introduction to this section? Moreover, when trends are derived from just two images, the differences might only be related to different snow conditions rather than a real increase (e.g. when the snow line in 1988 was lower). Please mention this as well and consider it for the discussion.
- L382 (Fig. 8): Please show panels a and b side by side.
- L393: with a previous record
- L395: Why is the trend consistent and why 'glacier melting'? Are there any records of melting for the past 72 years? As far as I can see, only area and length changes are derived over this period and I would name this glacier retreat rather than melting, the latter being related to mass balance. As the relation between length and area changes is rather complex (e.g. depending on response times and ice thickness distribution), both length and area changes are difficult to link to climate. Although the values in Fig. 10 back to 1976 might be wrong, the low temperatures visible in Fig. 9 might indeed have caused positive mass balances until 1997 (except in a few years around 1981). Hence, I would expect stable or advancing rather than retreating glaciers from 1947 to 1988.

- L402: I will not go into too much detail here, but I find this interpretation a bit rough. For example, albedo changes would only occur if the rainfall removes snow cover and exposes bare ice. However, with nearly permanent cloud cover there is little incoming shortwave radiation so that albedo changes should have a rather limited impact.
- L403: Higher temperatures
- L406: I can see the increase, but think it is more over the past 30 rather than 70 years. Excluding the years around the 1980s, temperatures seem to be constantly low from 1947 to 1995 (or at least until 1980) and really rise only afterwards. As mentioned above, I would thus not expect much or constant retreat from 1947 to 1988.
- L414: Is this speculation about mass balance required? Given that the climate-glacier relation is not well known for this region and several glaciers terminate in lakes (one revealing a calving instability) or the ocean, I would not derive from just two observations of glacier extent what the governing mass balance might have been, in particular not for the same period, as response times have to be considered.
- L416: How do the corresponding elevation change maps look like? Are there any data gaps? I would also not plot linearized annual values when only 5-year means make sense. This could also be seen as a data manipulation (also because it is not described how the original data have been converted). Please show 5-year mean values (maybe with an uncertainty range) as a straight line covering the respective periods instead.
- L418/419: This might be correct, but as mentioned above, I would not directly link observed area trends to the governing mass balance forcing.
- L426: Why should the shift be human-induced? Do oceanic oscillations care for human activities?
- L429: increasing air temperatures
- L429: I am unsure if this conclusion can be made here. The glaciers investigated by Bakke et al. on South Georgia are rather different (flat cirques, calving instability) than those on Heard Island (mostly originating at a high volcano). I am also unsure what the issue should be with the impact of retreating glaciers on the landscape etc. The glaciers do also impact the landscape when they are present. Also the irreversibility is unclear to me. Why should glaciers not come back when it is getting colder again?
- L434 & 442: Again, I think you mean here glacier mass loss rather than retreat.
- L442: Due to the insulating effect, the deposition of tephra might decrease glacier mass loss.
- L446 (Fig. 9): Please remove panel a and add the scale with the real values to the right of the plot in panel b. There is no need to show the same curve twice. I would also repeat major tick marks on the lower x-axis. Currently the values are quite far away from the marks. One might also add major grid lines for the x-axis and minor tick marks for each year.
- L449: I think there should be a space between the 0.7 and °C as well as between 2 and m.
- L454 (Fig. 10): As mentioned above, I would replace the linear mass balance trend from Hugonnet et al. with the real 5-year averages for the region.
- L460: sparse
- L462: Isn't the volcano cone a bit too narrow (in its higher reaches) to create foehn winds, i.e. force the air to rise, or reduce precipitation? On the satellite images the air seems quite often to flow around the cone rather than over it. For the Cook Ice Cap on Kerguelen Island (which is much wider) the situation is rather different. And as described in L471ff the real driver for rapid retreat of glaciers 1, 14, 15 and 16 seems to be lake formation and calving.
- L476: Apart from the fact that a linear retreat rate cannot be shown in Fig. 11 as it has a highly non-linear scale, where is the linear retreat rate of Chamonix Glacier? From 2008 to 2019 it is a more or less straight line.

- L477: I think one should not directly compare retreat rates of Fox and Franz-Josef Glaciers at the selective temporal and extended length change scale presented here. Both had strong advances after 1980, which are suppressed here as values from 1988 to 2001 are not shown. Please use a linear scale for the years.
- L489 (Fig. 11): As mentioned above, please use a linear scale for the year (or only show a subset, e.g. start in 1988). Please also place the x-axis at the bottom (as in all other plots).
- L498: I think Stephenson is in its accumulation region very steep and thus not a low angle glacier. A small change of the ELA would only cause a small change in the size of the accumulation region, i.e. result in rather insensitive glaciers. What matters here is that the accumulation region is narrowing towards the top which is basically the opposite for usual valley glaciers such as Fox or Franz-Josef. A flat lower part can be sustained for quite some time as long as it is land terminating. The important point for the rapid retreat of Stephenson Glacier should thus be the lake formation and calving instability.
- L501: For glaciers 4, 5, and 6 'wave action' is obviously not a problem.
- L503/4: In effect, it is a calving instability caused by a likely overdeepened glacier bed filled with (relatively warm) water.
- L509: There was actually neither a small nor a large re-advance, this impression just resulted from flowing ice bergs (see general comments).
- L513 (Fig. 12): I am a bit unsure if this figure is adding anything to the science. I suggest removing it here and moving it to the supplemental material.
- L517: This section 6.3 is not really about the impact of debris cover on glacier retreat, but presents two contrasting trends of decrease/increase in debris cover. I think assessing the impact is not really possible from the data shown. Please rename.
- L518-527: I think this is a bit trivial. Indeed, when a glacier is losing its debris-covered tongue into a lake, the amount of debris cover will decrease. As indicated in L527, I would avoid speculating about debris-cover properties (it could also be a thin insulating ash layer) and please stick to the data derived in this study.
- L519: e.g. a substantial
- L531: The long bare ice cliff in Fig. 13 is in contrast to what is written here. Please check if the increase in debris cover is a result of a higher snowline in 2019 compared to 1988. It is difficult to see from Figs. 2b/c, but it looks like this.
- L537 (Fig. 13): I wonder why a Google Earth perspective view is shown (from which date is the image?) when a DEM and very high-resolution image from Pléiades is available to the authors? Maybe show perspective view images from 1988 and 2019 side-by-side, annotated with the outline of debris cover and the position of the snow line? This would also bring the observations closer to the text. Currently Fig. 14b is only showing the 1988 status, where is the change to 2019?
- L547: I think Scherler et al. have not mapped debris cover but clean ice (which is straight forward). They then subtracted the clean ice map from the RGI extents which include manually mapped debris-cover. Their larger debris extent might be due to cloud cover, maybe shadows and old extents (with a much larger Stephenson glacier) used in RGI 6.0.
- L556: I would call the sensor used high and very high resolution, medium is MODIS.
- L564-569: Please check if these statements are still valid and revise them accordingly
- L 571: What is meant here with dynamics that is not 'changes in extent'?

## References

Please apply a consistent style to the references, e.g. for citing doi's. Now it is a wild mix.