Response to Review 1 of "Accumulation by avalanches as significant contributor to the mass balance of a High Arctic mountain Glacier"

Bernhard Hynek, Daniel Binder, Michele Citterio, Signe Hillerup Larsen, Jakob Abermann, Geert Verhoeven, Elke Ludewig, Wolfgang Schöner. January 2024

RC: Reviewer Comment AR: Author Response

This is an interesting paper reporting the effect of an exceptional avalanche cycle in 2018 on the mass balance of a small polythermal glaciers in NE Greenland. The analysis is based on an extensive data set of glaciological mass-balance measurements and two DEMs of the glacier. The underlying assumptions for volume-to-mass conversion that are used in the paper to compute geodetic mass balance need to be improved.

We appreciate the reviewer's thorough and insightful review of our manuscript! In the following, we respond to the individual comments and describe how we would like to address them in a revised version of the manuscript.

Comments:

The introduction states that mountain glaciers and ice caps are responsible for ~8% of the world's land ice contribution to sea-level rise during the last 60 years. This seems implausibly low. Please check the papers quoted in line 46 and IPCC reports to verify this.

This number refers to the glaciers and ice caps in Greenland, not to glaciers and ice caps globally. As that was obviously unclear, we will clarify that in the text.

My most important comment concerns the methodology to convert elevation change to geodetic mass balance, which contains a possible error that has to do with the effect of ice flow and densification. The use of surface densities for the volume-to-mass conversion (described in the paragraph in lines 146 to 152), neglects the effect of the conversion of firn to ice at depth and the related effect of submergence/emergence velocity in the accumulation and ablation areas, see Huss (2013). The analysis of this problem by Huss (2013) is referenced on page 9 in the paper and in the discussion section but Huss' conclusion that an average conversion factor close to ice-density (850±60 kg/m³) is often appropriate for several-years-long periods or longer is not properly used in my opinion. The snow avalanches that the paper concludes led to (part of) the elevation increase in the accumulation area fell in the spring of 2018 and their deposits are, therefore, four years old in late summer/fall 2021 (in terms of the number of summers they have "experienced"), when the second DEM was measured. Densification due to continued snow/firn metamorphosis in the second to fourth year after deposition may be expected to have taken place and increased the density of the buried avalanche deposits. The density of the buried snow avalanche deposits in 2021 must, therefore, be substantially larger than typical surface density in the fall (600 kg/m³). In addition, part of the thickening in the accumulation area of Freya Glacier in 2013–2021 may have been do to "... continued thinning in lower elevations and thickening in higher elevations", which has been observed at many glaciers in Northeast Greenland (and elsewhere such as in Iceland) in recent years as mentioned in lines 50–54 of the paper. Geometry and volume changes due to such prolonged adjustment of glaciers to changes in mass balance must be expected to be captured with a volume-to-mass conversion factor close to the value recommended by Huss (2013). The authors should discuss this problem with reference to Huss (2013) and perhaps adopt some appropriate value, higher than 600 kg/m³, for an estimate of the density of the remaining avalanche deposits in the accumulation area but adopt a conversion factor close to Huss' recommendation for other volume changes during the period 2013–2021 that may have taken place). This may be difficult to differentiate but should at least be discussed. If there is some knowledge of density profiles at depth for Freya Glacier, or if observations at other polythermal glaciers under similar conditions are available, density values for four-years-old firn might be appropriate for the buried avalanche deposits. If such observations indicate density > ~(750–800) kg/m³ for several-years-old firn at the expected depth of the buried avalanche deposits on Freya Glacier in 2021, using Huss' recommended value for the entire volume change integrated over the entire glacier may perhaps be the simplest and best choice (?).

We are grateful for this important comment! The reviewer calls our attention to a methodological error that we have committed in the volume to mass conversion by assigning surface densities to elevation changes on different areas of the glacier. We will build on this, discuss the subject in more detail and integrate the density estimation over the entire surface and use the scalar result to convert volume to mass. As there are only a few observations on snow and firn density available for Freya Glacier, we will use density profiles from the literature, as the reviewer suggested.

The easiest way to see the problem with using local surface densities to convert elevation changes to geodetic mass balance is to imagine a surface lowering in the accumulation area due to an ice-flow perturbation that is exactly compensated with an equal surface height increase in the ablation area. The use of surface densities leads to a prediction of a considerable mass increase in this case but it is obvious that the mass change is in fact zero.

Thanks for clarifying this; we agree!

The arguments of the authors for using firn density of 600 kg/m³ for the avalanche deposits (and other volume changes due to an elevation increase) comes first in the discussion section. Part of this discussion should be presented already in the methods section as this is the basis for the rest of the paper. Then the discussion might include further elaboration about this question. From the discussion section, it appears that the entire (positive) elevation change in the accumulation area is assumed to have the density (or volume-to-mass conversion factor) of 600 kg/m³ which seems low for other possible contributions of to an elevation increase in the accumulation area, as mentioned above.

Thank you again, we will move the main part of the density assumptions to the methods section.

I find it hard to understand the discussion in the paragraph in lines 274–278 on page 9. It is not clear how the contribution of the avalanches to the winter balance of 2018 is different from the contribution of the avalanches to the mass balance of the period 2013–2021. Of course such a difference can be due to an error, but physically it does not make sense to discuss this as a real quantitative difference. The avalanches are a definite event that deposited a certain amount of snow on the surface of the glacier. It sounds confusing to discuss this contribution to vary with time due to later melting that must be hard to differentiate from melting of other positive contributions to the mass balance of the glacier from 2018 to 2021.

Thank you very much, we agree. This part has been hard to understand and needs rewording, considering your comments. We will change that.

Minor and editorial comments:

In figure 5b (and the same figure in the graphical abstract), the legend shows a special pattern to denote avalanche deposits but the map does not seem to show these deposits (the avalanche deposits are shown in figure 5a but not 5b).

line 21: add "°" in "20.82°W"

line 45: perhaps say "their recent contribution to mass loss from Greenland and global sea-level rise is disproportionately"

line 50: perhaps say "has accelerated globally during"

line 59: perhaps say "in Greenland are monitored"

line 62: perhaps say "both at 74°N"

line 113: period missing at end of sentence

line 125: perhaps say "Snowfall on 14th August"

line 144: perhaps say "These parts of the glacier"

line 144: perhaps say "April 2018" to be consistent with line 169?

line 144: perhaps say "total length of"

line 158: perhaps say "onto a grid of"

line 185: perhaps say "poorly covered"

line 189: perhaps say "on the adjacent ridges"

line 191: perhaps say "worse than"

line 201: drop "of the glacier"

line 203: perhaps say "mainly at elevations"

line 207: perhaps say "large side valleys"

line 207: perhaps say "for the entire glacier" rather than "for the total glacier area"

line 236: perhaps say "larger than the lower bound"

line 245: perhaps say "The bias with respect to"

Thanks for your editorial suggestions. We will include those in the revised submission!

Excessive use of acronyms make the text awkward to read in places, especially because the paper is otherwise generally well written. It sounds awkward to use the acronym "FG" about the Freya Glacier, which is the main subject of the paper with a relatively short name that deserves to be written out in full when this glacier is mentioned. In some places, the full name can be written as just "glacier" or "the glacier", when the context is clear, so the use of the full name will not make the text much longer. "FG" is used 12 times in the manuscript, sometimes up to three times in the same paragraph. The acronym "MGIC" for "mountain glaciers and ice caps" is also awkward and used much too often. The paragraph in lines 56 to 60 would, for example, be much easier to read without this uncommon acronym. Try to use as few acronyms as possible. In many cases, a minor rewording will eliminate the acronym and make the text flow better.

Thank you for this comment. We will minimize acronyms in the text. We used the acronym MGIC for mountain glaciers and ice caps of Greenland, to distinguish them from the Greenland ice sheet. We will use peripheral glaciers (of Greenland) instead, where we think it is necessary.

The use of hyphens ("-"), en-dashes ("–") and minus signs ("−") in composite words, negative numbers, number ranges and date ranges is inconsistent in many places. Use an en-dash or a proper minus sign for all negative numbers, also in superscripts such as "a^{-1}", and for all number and date ranges. Since you write "high-resolution DEM", you should probably also write "sea-level rise", and similarly for other compound adjectives (very many instances). The unit "meters water equivalent per year" should be written "m w.e. a^{-1}", not "m a^{-1} w.e. "

Thank you for the useful remark, we will change that accordingly.