Response to Review 2 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

In this paper, Hynek and colleagues present and analysis of very interesting data collected on Freya Glacier, one of Greenland's peripheral glaciers. They report annual glacier-wide mass balance observations from the glaciological method (2007 to 2022), as well as a geodetic survey between summer 2013 and summer 2021. They find close to equilibrium mass balance conditions, with a geodetic mass balance of 0.25 +/- 0.21 m w.e. over the eight years of survey. They link the observed pattern of elevation changes with the imprints of large avalanches that affected Freya Glacier in winter 2017/18, and that were investigated with an extensive ground penetrating radar survey.

The study is very interesting, and the data collected are of remarkable quality. This contribution is a long awaited one, as the topic of avalanche contribution to glacier mass balance remains poorly explored. Still I recommend major revisions, because there are two main points that would require some attention.

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

Major comments:

1- Quantification of the avalanche contribution in the geodetic mass balance

Here I am sorry to be direct, and I might be wrong, but I am not sure that the method presented by the authors to separate the geodetic mass balance into areas that are affected by avalanches and areas not affected by avalanches is actually valid (L161-164). I do not understand why the mean elevation change of an areas that were not mapped as avalanche deposits in winter 2017/18 should not be affected by avalanches as well. If we write the kinematic relation for surface elevation changes, we get:

$\partial h \partial t = bS\rho + wS - uS\partial h\partial x - vS\partial h\partial y$

With h being the glacier surface, $bS\rho$ the surface mass balance normalized by density, wS the vertical velocity, uS and vS the components of the horizontal velocity and $\partial h\partial x$ and $\partial h\partial x$ the components of the local slope. $wS - uS\partial h\partial x - vS\partial h\partial y$ is named the emergence velocity and $-uS\partial h\partial x - vS\partial h\partial y$ is named the advection of topography. This equation tells that the elevation change is the sum of surface mass balance and emergence velocity (or divergence of ice flux). The integral of the elevation change is equal to the integral of the mass balance only if done on a closed surface, which is not the case here, as there is a spatial continuity between the areas affected by avalanches and the areas not affected. As a simple example, one can imagine the deposit from an avalanche that would be advected by the

flow and could change location within an elevation band, or change elevation band. Avalanches have also likely a non-local influence on the emergence velocity, simply because they lead to larger mass inputs, and thus larger ice flow. One solution to circumvent this difficulty is to calculate the distributed surface mass balance of the glacier from the elevation change map (e.g., Van Tricht et al., 2021; Vincent et al., 2021), but this required accurate knowledge of the glacier surface velocity, thickness, and to a lesser extent thermal regime.
I might also be wrong in my reasoning, and I think that the authors are absolutely right in their interpretation of the large impact of the winter 2017/18 avalanches, I would just be more careful on the quantitative side. Qualitative arguments are already quite strong regarding the persistence of snow three years after the event, and the good match between positive elevation changes and location of the deposits.

Thank you for this very relevant comment on the influence of glacier dynamics, namely the emergence velocity, which has the potential to alter the results of our quantitative assessment. We missed to tackle this question in depth in our initial submission. We also appreciate your suggestions for solving this problem based on the recent work on the subject.

Freya Glacier is a polythermal glacier with temperate ice only in a limited area near to the bottom of the glacier. Surface slope is generally rather small (0-20°) over large areas of the glacier. Observed horizontal surface velocities at the stakes are on average 6 m a^{-1} and computed vertical velocities (derived from measurements of ablation and surface elevation) are between -0.6 and 0.6 m a^{-1}. For the 8 year period 2013 - 2021, for which the elevation change was measured, glacier motion roughly adds a mean horizontal displacement of ~ 50 m and emergence/submergence between about -5 m and +5 m.

The slow glacier dynamics tempted us to neglect the influence of emergence velocity in our quantitative assessment without discussing it in the manuscript. In other words, we based our analysis on the following assumptions:

1. Although the surfaces over which we integrate the elevation changes are not closed, as the reviewer correctly notes, we assume that the emergency velocity over these areas is negligible compared to the mean elevation changes.
2. The distribution of emergence velocity on the glacier is not significantly changed by the avalanche deposits (and/or this effect would be hard or impossible to quantify) or the related change in emergence velocity is significantly smaller than the elevation change by the avalanche deposits.

We plan to address this question by clearly describing and discussing the assumptions on which our assessment is based and discuss the introduced uncertainty of these assumptions. We note, that other uncertainties or errors also exist, mainly the unknown density of the avalanche deposits or the uncertainty of the delineation of avalanche deposits, so the quantification of the mass contribution by avalanches should be seen as a rough estimate.

2- How frequent are the avalanches/how exceptional is winter 2017/18?

While the authors demonstrate clearly that the winter 2017/18 corresponds to a mass balance that is two sigma above the average and report that they are not aware of other large avalanches that affected Freya Glacier, I am not convinced that the glacier is not avalanche prone on “normal” years for some of its areas. In the hillshade from August 2013, there are signs of avalanche deposits or cones on the glacier surface, especially at the foot of the north east face, but also on the topographic right, around 600 m a.s.l. The authors could discuss whether the winter 2017/18 was exceptional compared with “normal” winters. One option would be to show other snow height maps to highlight the abnormal avalanche deposits. You could also investigate the climate records/reanalysis to assess the causes of this exceptional avalanche activity.

Thank you for this comment, we will add more information/observations on this interesting question. As we wrote in the original submission (L 216), remnants of avalanches have been observed also in other years, but the coverage of the avalanche deposits (and most likely also the mass input) was much smaller than in 2018. To provide more information on this, we will compile all available observations of avalanches from previous years. This includes: Reduced melt rates at stake 1 by avalanches and orthophotos and satellite imagery that show imprints of avalanches in “normal years”.

To demonstrate the climatologically exceptional winter of 2018 compared to other winters in the region, we will add winter precipitation data from the station Zackenberg and from reanalysis and contextualize it with the snow depth time series at Freya Glacier since the beginning of the measurements.

Specific comments:

L30-31: this sentence is not really clear to me. Do you suspect a bias in the data? Or do you observe a shift in the mass balance?

We observe a bias in the direct mass balance data (see Fig.8), which appears too negative in comparison with the geodetic mass balance 2013-2021. As for now, we do not know the reason for this bias, therefore we recommend a reanalysis of the annual direct mass balances following the procedure of Zemp et al (2013). While in mass balance years before 2016/17 the annual mass balance is based on more than 10 point observations, in the following years the annual mass balance is only based on one point observation (at the AWS) which introduces a much higher uncertainty. Apparently, this phrase causes confusion, so we will describe this more clearly in the revised version of the paper.

Since 2016, mass balance fieldwork usually takes place in spring. During the fieldwork we measure the ablation of the previous year at the stakes. If the snow cover in winter is too thick, the stakes do not stick out of the snow and are hard to find. This is the reason why high accumulation rates led to fewer mass balance point observations in the past.

There are limited links between the different paragraphs of the introduction. I think it should be possible to improve it a bit.

Thanks for this comment. We will insert a few more sentences to make the transitions smoother.

L72-73: the reference is an abstract from EGU. Consider removing it?

Yes, we will remove it.

There are many acronyms in the text. Consider spelling out Freya Glacier instead of its acronym. Same for the MGIC.

Thank you for this comment, this was also mentioned by reviewer 1. We will change this accordingly. Instead of MGIC we will use the term peripheral glaciers (of Greenland).

Supplement: I found the supplementary material by accident because it is not referred to in the text. I think it is important material, that demonstrates the very high quality of the two photogrammetric surveys, and it should be better emphasized (in L148 for example).

Thank you for this comment and the positive words about our data. We will describe the error statistics on stable terrain more prominently in the text and refer to the supplementary material more clearly in the text.

L112: I enjoyed very much looking at the automatic camera photographs! Thanks!

We are pleased to hear that you enjoyed it!

L134, 151-152 and 210-213: the correction applied to the geodetic survey is confusing because it is mentioned are three distinct locations, and inconsistent in some places (typo on the units on L212). I suggest to write from the beginning state that you apply a -0.60 m w.e. correction to the glacier wide mass balance, and potentially introduce the notations you use later on.

Thank you for this comment. We will bring that in line.

L143-144: how are the two DEMs/orthos merged? Consider providing more details about the elevation different on areas that are covered by both surveys.

Thank you for this advice. Yes, there is an area in the middle of the glacier, which is covered by both surveys in 2013. Due to the poor coverage of that area (no near photo points and snow cover in diffuse illumination), surface reconstruction uncertainty in that area is higher than in other parts. We will describe the methodology how we merged the DEMs and we provide a figure of these vertical differences in the supplementary material.

L154: “If feasible” suggests that you collected other GPR surveys of the snow thickness. It might be interesting to show some results from these surveys to highlight how winter 2017/18 is different from “average” winters.

We performed GPR surveys with a similar point observation density in spring of 2008 and 2017, in other years we have fewer snow depth point observations (see point observation number in Figure 8 (top panel). In 2008 and 2017 the mean snow depth was close to average, so that we can calculate an average snow distribution from the two surveys and use this as a basis for determining 2018 anomalies.

L156-158: more details are needed about the avalanche deposit delineation. Which criteria do you use?

The delineation of avalanche deposits is a crucial step in the quantification and we will add more information about it in the revised version of the paper. The delineation of the avalanche affected areas did not follow strict criteria, as this seemed hardly feasible and not beneficial based on the available information. Along the GPR tracks we used a strong increase in GPR snow depth as an indication for deposits. To complete the delineation in areas without GPR tracks we used a best estimate based on photos of avalanche fracture lines, remnants of avalanches in the orthophoto of 2021 and above average local elevation changes together with likely avalanche flow paths based on topography. Besides better description we will evaluate the impact of delineation uncertainty on the derived contribution of avalanches to the mass balance.

L158 [IMPORTANT]: what is the impact of this spline interpolation on the average snow thickness? On figure 8, it seems that the maximum snow thickness is not directly observed but extrapolated from the spline function. The pattern looks reasonable to me, as we expect maximum snow thickness close to the edges, but I think some lines about the uncertainty of this interpolation are needed.

Thank you for this important comment. We will evaluate and shortly describe the effect of the uncertainty introduced by the snow height interpolation method although we deem this small compared to other error sources.

L161: what is the value of the "bulk snow density"? Do you have multiple snow density estimates? Do you have density estimates of the avalanche deposits?

In spring 2018 we could carry out one snow density measurement within a snow pit next to the AWS (see line 223). We will remove the word "bulk", as it is misleading. Snow density at the snow pit next to the AWS at stake 6 was 385 kg/m³. There were no further snow density measurements possible in 2018. Particularly, there are no observations of the snow density of the avalanche deposits. As the density of snow and firn plays an important role in the calculation of the mass balance and the quantification of the contribution by avalanches, we will add the data of the snow pit to the supplementary material and describe our assumptions on extrapolating the local snow density in more detail.

L174-179: much more details are needed. First of all, it is not that usual to do fieldwork in spring to calculate annual mass balance. I imagine that there are some logistical constraints that explain this. You need to better explain how you find the ice surface and/or the horizon of the previous year. You also need to provide more details about the calculation of glacier-wide mass balance when only one or two stakes are found. The "statistical relationship" needs to be described, as well as the associate uncertainties.

In 2016 the monitoring strategy at Freya Glacier was changed from summer visits to spring visits due to logistical reasons. In summer, Freya Glacier can only be reached by boat and a long walk, while in winter, it is easier and faster accessible on snow scooters, which also allows the transportation of heavier equipment like weather stations or a snow radar. Moreover, one single visit to the glacier per year allows us to determine both the winter and annual balance of the glacier (not in all years). While the ablation stakes can be measured easily, as long as they stick out of the winter snow, it is more difficult to measure accumulation. To get accurate information on the extent of the annual accumulation area, we installed the automatic cameras. We will describe the method of mass balance evaluation and related uncertainties more precisely in the revised version of the paper.

L230: the current units for the stake measurements are m. This is a bit confusing and it would be better to use m w.e., as we are talking about surface mass balance here. The period is needed as well. On figure 5, the same comment applies: at stake location, the numbers correspond to elevation change (as suggested by the legend), or do they correspond to surface mass balance (as suggested by the text)? You could consider comparing the surface mass balance and elevation change at the stake location, this would give and idea of the impact of the dynamic.

Thank you for this comment. We will clarify this and use only the units m w.e.. In figure 5 we will change the units and clarify that the given value is the local mass balance. In addition we will add a table, where we compare ablation and elevation change at the stakes to show the dynamic component.

L234: see my major comment 1, I doubt that the method can “predict” the glacier-wide mass balance without avalanches

To answer this, please see our answer to your comment 1.

L243-244: repetition of L230

Thank you. We will bring that in line.

L245: I find the unit m w.e. a-1 clearer that the unit ma-1 w.e. that is used here. Consider changing. Discussion: the transition from the result section to the discussion is rather abrupt. Consider adding a few sentences to make a more seamless transition.

Thank you. We will change this accordingly.

L249-262: this discussion is very interesting, but it could be expanded a bit by testing the impact of the different choices of density on the results?

Yes, we will expand the discussion.

L257: issues with the citation formatting

Thanks, we correct that.

In general, the discussion could be sharpened and expended a bit. One aspect could be the climate context of Freya Glacier. I assume that there are very few climate record in the area, but it would be interesting to see whether the winter 2017/18 stands out in the climate record as particularly wet, and then cold or warm.

Thank you for that suggestion. We are happy to add more about the climate context of Freya Glacier and the year of 2018.

L297-299: I agree with this statement, but it is never mentioned in the text before so it is a bit surprising to find it in the conclusion.

Thank you for that comment. We suggest expanding on that question a little more within a new climate context section.

The data availability statement could be more precise. The mass balance data are available through WGMS I assume? The DEMs or dh maps and snow depth maps could potentially be deposited on a repository.

Thank you for that comment. We will add more data and information on data availability here.

References

Van Tricht, L., Huybrechts, P., Van Breedam, J., Vanhulle, A., Van Oost, K., and Zekollari, H.: Estimating surface mass balance patterns from unoccupied aerial vehicle measurements in the ablation area of the Morteratsch–Pers glacier complex (Switzerland), The Cryosphere, 15, 4445–4464, https://doi.org/10.5194/tc-15-4445-2021, 2021.

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