Review of Hynek et al.: "Accumulation by avalanches as significant contributor to the mass balance of a High Arctic mountain Glacier"

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.

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:

$$\frac{\partial h}{\partial t} = \frac{\dot{b_S}}{\rho} + w_S - u_S\frac{\partial h}{\partial x} - v_S\frac{\partial h}{\partial y}$$

With h being the glacier surface, $\frac{\dot{b_S}}{\rho}$ the surface mass balance normalized by density, w_S the vertical velocity, u_S and v_S the components of the horizontal velocity and $\frac{\partial h}{\partial x}$ and $\frac{\partial h}{\partial x}$ the components of the local slope. $w_S - u_S\frac{\partial h}{\partial x} - v_S\frac{\partial h}{\partial y}$ is named the emergence velocity and $-u_S\frac{\partial h}{\partial x} - v_S\frac{\partial h}{\partial y}$ 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.

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.

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?

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

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

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

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).

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

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.

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.

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.

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

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.

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?

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.

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.

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

L243-244: repetition of L230

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.

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?

L257: issues with the citation formatting

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.

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.

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.

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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