Initial paragraph or section evaluating the overall quality of the discussion paper ("general comments")

This manuscript aims to present a methodology combining RPAS and photogrammetry to capture high-resolution snow depth estimates, to provide its accuracy and associated statistics. I believe the study itself has some strengths and interesting aspects; they cover a relatively large area catchment area using a fixed-wing UAS (compared to most studies using rotor based UAS), there is a considerable elevation change, it provides some distinct statistical investigations, and is done for 2 epochs.

However, in my opinion the authors have overlooked recent literature treating the same subject, and therefore have framed the study on a too general context, lacking some novelty and specific aims within the research of this methodology. Furthermore, there are also some other scientific comments, which I will try to inquire further.

Therefore, I recommend major revisions to provide the opportunity to re-orient the focus and frame of their study, highlighting the strengths and further clarify on some more specific aspects of the method noted in literature.

Technically, I think the manuscript embodies a well-presented and carried-on study. Some structural changes and clarifications are recommended.

Section addressing individual scientific questions/issues ("specific comments")

<u>TITLE AND OVERALL AIMS OF THE STUDY:</u>

I think the title and aim are too general considering that there are already several studies investigating the same snow depth mapping method, looking at similar datasets (multiple DEMs + GCPs + snow probing validation). Furthermore, very similar validation methods have already been applied in other studies for multiple types of terrain/snow and providing almost the same results in terms of accuracy and resolution (although some for smaller areas). The manuscript here presented has referenced and discussed only four of them, but some additional studies on the method are missing:

Avanzi, F.; Bianchi, A.; Cina, A.; De Michele, C.; Maschio, P.; Pagliari, D.; Passoni, D.; Pinto, L.; Piras, M.; Rossi, L. Centimetric Accuracy in Snow Depth Using Unmanned Aerial System Photogrammetry and a MultiStation. Remote Sens. ***2018***, 10, *765.*

Yves Bühler, Marc S. Adams, Andreas Stoffel & Ruedi Boesch (2017) Photogrammetric reconstruction of homogenous snow surfaces in alpine terrain applying near-infrared UAS imagery, International Journal of Remote Sensing, 38:8-10, 3135-3158, DOI: 10.1080/01431161.2016.1275060

Cimoli, E.; Marcer, M.; Vandecrux, B.; Bøggild, C.E.; Williams, G.; Simonsen, S.B. Application of Low-Cost UASs and Digital Photogrammetry for High-Resolution Snow Depth Mapping in the Arctic. Remote Sens. ***2017***, 9, *1144.*

Avanzi, F., Bianchi, A., Cina, A., De Michele, C., Maschio, P., Pagliari, D., Passoni, D., Pinto, L., Piras, M., and Rossi, L.: Measuring the snowpack depth with Unmanned Aerial System photogrammetry: comparison with manual probing and a 3D laser scanning over a sample plot, The Cryosphere Discuss., https://doi.org/10.5194/tc-2017-57, 2017.

Fernandes, R., Prevost, C., Canisius, F., Leblanc, S. G., Maloley, M., Oakes, S., Holman, K., and Knudby, A.: Monitoring snow depth change across a range of landscapes with ephemeral snow packs using Structure from Motion applied to lightweight unmanned aerial vehicle videos, The Cryosphere Discuss., https://doi.org/10.5194/tc-2018-82, in review, 2018.

I believe it would be good to have a look at these, and better frame the motivation and title of the study to the suggested gaps in the research stated in literature. Snow depth mapping with RPAS as you present it is not so novel, and accuracy has already been assessed in multiple ways with similar (or higher) sample sizes. Nevertheless, this study can emphasize other really interesting aspects (e.g. larger area, fixed wing and focus on discussing other statistics as already partially done) but limitations needs to be discussed and literature accounted.

An example of a more specific title suggestion could be:

"Investigating snow depth retrieval of an alpine catchment area using photogrammetry and fixed-wing RPAS"

<u>1. INTRODUCTION:</u>

Paragraph starting at line 23: there might be too much information on satellites and SCA. I think snow depth mapping with RPAS is not directly comparable with satellite in terms of applications and uses, therefore I would personally not give too much weight on comparing both. In addition, I think you speak a lot about SCA in the introduction, but you do not mention its retrieval as part of your objectives and rarely speak about it again during your methods, results and so on. So maybe part of it is avoidable, I guess your focus is snow depth here and SCA is just intrinsically bounded to it.

<u>2. STUDY SITE:</u>

Here a lot has been said about the topography, but what about the snow?

It is important to add information about the daylight conditions of the surveys, and the snow textures/types encountered. It is recognized that these can affect SfM reconstructions on snow, and potentially the final DEM product. Maybe add to Table 1 and describe change in snow conditions over time.

In my opinion, an interesting aspect of your study area is the variable slope, and the different types of snow encountered over the epochs (if different), so highlighting these over time and space would be good (as you have already partially done).

Finally, It would be great to add to Figure 1 (or as you see fit) the orthophoto of the Autumn DEM, this is not present in the manuscript and its very important to better showcase your terrain DEM, vegetation areas and so on.

<u>3. DATA AND METHODS:</u>

<u>3.1.1 RPAS platform and payload</u>

What is the cost of the unit? You mention is low-cost, but compared to what? It does not sound like a very low cost system within the realm of drones (particularly if you consider DIY solutions), but it is low-cost compared to manned aerial systems. Please specify. Please use SI units, e.g. meters and not feet. Also, I does not seem you have specified what was your average flying altitude for each flight.

<u>3.1.2 RPAS flights</u>

Maybe more information like frame rate, software used for mission planning, how the missing was planned in such scenario etc. would be good.

<u>3.1.3 Ground control survey</u>

Same here, some information on the software used for processing GNSS data, and a reference (if available) would be good (e.g. the manual).

In addition, it is not clear from the text if you used some of the points for co-registration of the multiple DSMs (I understand you did not, why?). Particularly since you speak about co-registration later, in chapter 5.2.2. Please make this clear in the text and if yes, display these points on one of the figures.

3.1.4 In situ snow depth measurements

I would call this chapter "snow probing validation" or something else similar.

Also, please specify the GNSS accuracy of your RTK snow depth samples, and how are they representative of your claimed spatial resolution (0.15 m) if they are averaged over and arm distance of a meter or so.

3. DATA PROCESSING

3.2.1 Photogrammetric processing

Is all the formulation needed? Since all the calculations are carried on by a black-box software, maybe only a couple of references on the general photogrammetric principle should suffice.

In addition, many of the variables/parameters in the equations are not defined and need to be specifically declared in the text.

This section could also be coupled and properly merged with the following one, "software". (I assume they are black-box/off the shelf software, but little to none information is provided in this manuscript, particularly as you heavily discuss it in the discussion section).

3.2.2 Software

Since the software's employed are out of the commonly used by the UAS snow depth mapping community, maybe a small introduction on how they compare to Photoscan (or others) and some references on them would be beneficial. Particularly as they are heavily discussed further on.

An example: how do you locate GCPs in the DEM for this software, manually or automatically? From personal experience, this can be a considerable source of error and is worth mentioning.

The paragraphs following line 29, are somewhat confusing. Does the process of removing GCPs you mention refers only to the autumn mapping? Is it an analysis that was performed before you place the GCPs on the other epochs? I think I understood, but please clarify this on the text.

In addition, you do not mention which specific GCPs you removed. CPs RMSE values would probably change if you select a different combination of points, of the same sample size (e.g. 14), among your set. This is because overall total CP RMSE will be dependent not only on the number of GCPs you have used in your model, but also on their location, their accuracy in image identification and GPS precision. Is not clear if you tested this or not.

An interesting statistical approach would be to do a CPs validation using a bootstrap or similar method. By this I mean selecting random samples out of your GCPs and using them as CPs, multiple times. This would actually be an interesting approach to take that no study snow mapping study with RPAS has undertaken before. This for example be an interesting addition to your statistical investigation that has not been undertaken by previous studies.

3.2.3 Deliverables

I think this section would be better moved to the beginning of results, to outline all the final output retrieved.

3.3 Quality and accuracy assessment

Three methods for assessing the accuracy of the method are here employed; calculated error propagation, manual snow probing and snow free validation. I agree that combination of all of them helps assessing the overall accuracy of your results. However, each of them carry some limitations in this case, which require to be mentioned.

First, as RPAS photogrammetry provides very high spatial resolution measurements, I think the best way to obtain a strong accuracy estimate would be to compare it with other high spatial resolution estimates such as Lidar. Therefore, it is important to note that the validation applied in this study still lacks such estimate comparison.

Regarding validation tests for snow free areas, you need to mention that this validation is mostly representative of snow free areas, and not much of the snow-covered areas. Particularly since you have not mentioned anything about the snow type and about the photogrammetric reconstruction performance. Snow free areas can help assessing if the DSMs used for subtraction are shifted horizontally, and partially support you DSM reconstruction, but they cannot be used as a rigorous estimate of accuracy of snow depth mapping. I think is just important to mention this caveat.

Finally, in line 3 of page 9, you highlight the calculation of error propagation as the most rigorous validation among them and a bonus of this study. In my opinion, is the actual snow probing that validates better and independently your dDSM, particularly because for your calculation you have only a sample of 6 CPs each as I understand, whereas you have 86 snow depth probing samples.

3.3.1 Uncertainty associated with RPAS-derived snow depth

Please mention why did you assume that planimetric precision of each constituent DSM is negligible. In my experience, if you subtract two DSMs and there is just a slight misalignment, errors in the final dDSM (and bulk snow pack volume) can be considerable. That is why other studies have shown that co-georeferencing the DSMs using common GCPs can improve accuracy of the method.

3.3.3 Repeatability of photogrammetric modelling

Please describe a little bit more what you have done in your classification algorithm.

What do you mean by $dDSM_3$? I can't find this DSM identifier anywhere else in the text/tables.

4. RESULTS

4.2.2 Assessment against reference probe data

It would be great if you can also display on map the difference between snow probed and RPAS estimated snow depth for each of the 86 sample points. That would give a spatial overview of the error, or across the slope for example. It could also open up for discussion of accuracy across slope and epochs or snow types.

4.2.3 Comparison of DSMs from independent RPAS flights

I would suggest merging Figure 6 and Figure 5 somehow. I think the manuscript has already too many Figures that can be reduced.

5. DISCUSSION

5.1 Performance of RPAS photogrammetry for resolving snow depth

I believe here you highlight well the main strength of your study; that is a relatively larger area and mapped at high resolution. This is interesting and perhaps your study should be more centered on this. However, you should highlight what are some of the limitations in your validations here.

Line 3, page 14: "Achievement of uncertainties <0.13 m": Please mention to which statistics you refer. I guess the propagation of error?.

5.2.1 Vegetation

This has been highlighted by every study on snow depth mapping from RPAS, so should not be much of a novel finding discussion topic. I would however mention how it affected your dataset (as you already do), how it affected other studies and stress that solutions are really needed to solve this important caveat of the methodology.

It would be interesting to know instead how did error varies with slope or with snow type spatially across your catchment area and across epochs (if any difference is noticeable).

5.2.2 Geo-location and co-registration

It would be good if the authors stress more clearly/directly/shortly what is the importance of all this and its relevance in a RPAS snow-mapping context. What I understand here is that the authors first want to point out that vertical dDSM uncertainties and errors increase when planimetric and horizontal geo-location errors are present, and particularly on steep slopes or presence of rock outcrops (not surprisingly). Then the aim to is to justify the found statistics in this study, particularly for the slope and this is interesting, but requires a more clearer explanation of the benefits and consequences.

The main issue here is that is claimed that utilizing independent aero triangulation is better that co-georeferencing the DSMs. I personally disagree with this statemet, co –georeferencing saves considerable time when snow free areas are available. And if not available, it's always easier to leave artificial features like high poles (seen all over the year), which require only 1 measurement for the entire seasonal snow cycle over multiple years. Many studies have reported that co-georeferencing their terrain and snow DSMs using common GCPs considerably improved the snow depth maps accuracy performance (because of all the problems you mentioned). They mitigate considerably all the issues of planimetric misalignment.

In addition, I would see this discussion to be more focused on snow itself, and its changes in aspect, and elevation in accordance with underlying terrain and how this will affect statistics of other people employing the method, under different snow landscapes. This rather than focusing on a general DSM context.

Finally, you mention that high quality GCPs are important, but you don't discuss the future of systems with on-board RTK which will probably substitute GCPs in the near future and can account more directly and precisely the errors you mention in roll, pitch and yaw by integrating IMU components.

5.3 Pitfalls and limitation of RPAS photogrammetry

This large sub-chapter and more than three figures are dedicated to comparing the performance of two different black-box photogrammetric software's. I guess this is not part of your initial aims, and while is partially interesting for some communities, I think your goal is to outline a snow depth mapping method and not the performance of the particular software's. Therefore, I would personally reduce considerably this section. Particularly since inferences are made based on two different black-box software's and you don't really comment/outline/reference on the particular workflow of these products.

Another issue is that here you generalize as "limitations and pitfalls of RPAS photogrammetry" problems that were encountered within the particular software employed. Other studies have not reported these discussed issues with other software that I am aware (or they could not be verified?). Therefore, is difficult generalize such a discussion for snow depth mapping with RPAS.

5.4 Spatial and temporal trends in snow cover

This section much better highlights the strengths of your study and more should be reflected in the introduction and aims. The same can be said about your conclusion. Nevertheless, more could be said about the high repeatability/change detection potential of your methodology, since your covered 2 distinct epochs.

Purely technical corrections at the very end ("technical corrections": typing errors, etc.).

Please make units consistent thorough the manuscript. Either cm or m (e.g. line 4 of page 6).

In all tables and figures, please include full names and abbreviations. Often, only abbreviations are shown and the reader is forced to look for them in the text.

Line 4 page 11: There is clearly a typographical error.

In figure 2 please add "points" to Ground Control…