Dear Editor and Reviewers,

Thank you for your detailed comments and suggestions about our manuscript entitled "A high frequency and high resolution image time series of the Gornergletscher – Swiss Alps – derived from repeated UAV surveys".

We identified two main caveats noted by both reviewers. We answer hereafter to these concerns in a general manner with propositions of improvement, and then give detailed responses (with additional tests and quality checks when needed) to all comments in an itemized manner.

Response to the main concerns:

Absence of actual GCPs.

The first concern is related to the absence of actual GCPs to geo-reference our dataset, and to avoid internal deformations within the dataset.

We agree that the absence of GCPs can lead to some deformations in the master bundle adjustment (9^{th} June), in particular a doming effect due to an imperfect lens calibration. However, while these deformations can lead to significant absolute positioning errors, we do not think that they translate in large errors for relative measurements, and in particular for the computed ice velocities. Indeed, velocities depend on the relative positioning errors, which we argue are small here (see response to reviewer#2 for details). This is because: (1) the internal deformations are relatively small (max. few meters) thanks to a careful photogrammetric processing, (2) these deformations are smoothly distributed in space thanks to the bundle adjustment of each campaign, and (3) the deformations are almost constant in time thanks to the co-registration procedure. It follows that for most of the expected uses of the present dataset, which focus on change detection, the errors imputable to the internal deformations of the master bundle adjustment can be regarded as negligible compared to other sources of uncertainty. As an illustration, the error in horizontal velocities over a two-weeks period that can be imputable to the internal deformations is less than 1mm/day (see response to reviewer#2 for details), which we believe is acceptable.

Having said this, we acknowledge that these points were not discussed enough in the manuscript. Furthermore, internal deformations must be carefully described, assessed and documented in the description of the dataset. We therefore propose the following modifications of our manuscript to address the reviewers' comments:

- Deformation errors will be described in detail in a new paragraph at the end of section 3.1: generation of co-registered orthomosaics and DEMs. We will include the references suggested by the reviewers, and inform the reader about the impact of internal deformations on our dataset.

- In addition, we adopted solution 3 proposed by Reviewer#2 to assess the internal deformations that may exist in the master bundle adjustment (June 9th). We therefore co-registered our master bundle adjustment on an orthomosaic provided by the Swiss mapping agency, SwissTopo. This orthomosaic has a 50 cm resolution and has been acquired in 2009. This led to two interesting products, which will be added to the dataset and discussed in the revised manuscript: (1) a transform function allowing to geo-reference our dataset in the Swiss national reference frame (CH1903-LV03), and (2) a map of residuals between adjusted and observed tie-point coordinates allowing to assess and visualize the internal deformations of the master bundle adjustment.

Non-standard procedure to compute the Matching Maps.

The second concern addressed by both reviewers is the application of a non-standard procedure to compute the matching maps.

We argue that we did follow a best-practice procedure but adapted it to match the requirements of the present application (see response to reviewer#1 for details). We tracked within-scene motions by block matching, which is the basis of the vast majority of change detection software used for ice velocity tracking (e.g. CIAS, ImCorr, COSI-Corr, GoLive). Compared to these tools, our feature tracking strategy only differs by some technical details, mostly driven by: (1) the need to handle high resolution data acquired by UAV (10 cm resolution) in contrast to the relatively coarse satellite images (few meters resolution) for which the aforementioned software have been designed; and (2) the wish to match every pixel of the input ortho-mosaics in order to generate dense matching maps and not sparse velocity fields. To ensure that the outputs of our Matching Map Maker utility are robust, we carried out some additional tests, which show that the velocities computed by our utility are in line with the ones obtained by two well-established glacier surface tracking algorithms (see response to revewer#1 for the detailed results).

This said, we fully understand the reviewers when they ask for better assessment and description of our feature tracking approach. We therefore propose the following modifications of our manuscript to answer these requests:

- We will describe in more detail the procedure we used to compute the matching maps, with particular attention paid to put our approach in context with existing methods (using the references suggested by both reviewers). To motivate these choices, we will add a paragraph focusing on the specific requirements of UAV acquisitions, the differences compared to satellite applications, and their implications for feature tracking.
- Building on a comment of Reviewer#1, we will discuss the sensitivity of the estimated velocity fields in relation to the similarity score used in the matching procedure.
- We will add the results of the benchmarking tests mentioned above to a sub-repository of the Matching Map Maker utility, and mention the results of these tests in the revised version of the manuscript. We hope this will help the users to evaluate the performance of our utility with respect to other tools.

<u>Responses to the comments of Reviewer #2:</u>

In the following point-by-point reply, RC denotes a reviewer comment and AR denotes our response to the comment.

RC: In this case it appears the authors used the later method relying on consumer grade GPS positions of the UAV to generate the 9 June orthomosaic and DEM, all other datasets are then coregistered to this 'master' dataset using stable bedrock features. What this means is that the stacks themselves are co-registered accurately and we can therefore observe changes between images pairs fairly precisely. However, the master 9 June dataset is likely to be so inaccurate positionally that any measurements made from these data are likely to be highly inaccurate.

AR: We agree with the fact that our dataset is not accurately geo-referenced, and we will remediate to this problem by applying the solution (3) proposed by Reviewer#2, and update our manuscript accordingly. We also agree that some internal deformations are possible in the master bundle adjustment (June 9th), in particular due to uncertainties in lens calibration. However, we rather disagree with the statement 'any measurements made from these data are likely to be highly inaccurate'. Indeed, since our dataset is self-consistent thanks to a careful co-registration, we think

that most of relative measurements (and in particular change measurements) are precise, despite the absence of absolute geo-referencing. To better explain this point, we discuss hereafter the impact of possible internal deformations on our dataset, and illustrate it in the case of computing velocity maps from the dataset (i.e. we discuss the fraction of the error in the Matching Maps that can be imputed to the internal deformations, and show that it is small).
As expected by both reviewers from a theoretical error analysis, and verified in practice by our additional tests (see figure R2.1 below), internal deformations are limited to a metric amplitude and are smooth in space (i.e. spread across the whole area, and not concentrated at a single location). Therefore, balanced by the size of the study area (few kilometers), the relative error induced by the deformations is on the order of 1/1000. Roughly speaking, one can expect a 1m error when measuring 1km wide objects, or a 10 cm error (i.e. close to the resolution of the final products) when measuring 100m wide features. But one should keep in mind that thanks to the co-registration procedure, the same deformations apply to the whole dataset (i.e. to each acquisition date), which mitigates dramatically their impact in all change detection applications. For instance, in case of horizontal velocity measurements (i.e. what is reported in our matching maps), the order of magnitude of glacier displacement in two weeks is 30 cm/day x 14 days = 4.2 m. Since deformations are similar for both dates (due to the co-registration procedure), the error related to internal deformations is a scaling factor of 1/1000 on distance measurement, i.e. in this particular case: 4.2m x 1/1000=4.2 mm. It follows that the error in velocity due to internal deformations is 4.2mm/14days=0.3 mm/day, which is in our opinion negligible compared to other error sources.
All in all, we believe that because changes are of limited amplitude (e.g. ice ablation reaches few cm/day, and ice flow <1m/day in the Gornergletscher ablation zone), the errors generated by internal deformations are small compared to other sources of uncertainty for most of change detection applications. In consequence, we believe that our dataset can be safely used to measure relative changes over time, with a decent accuracy (although this is not the case for absolute positions).

RC: Below I have outlined a few potential methods for remedying this issue. 1) Install ground control targets in the survey area and conduct another survey of the glacier, then use this as the master dataset to co-register the other datasets to, using stable/no change locations. This is that was done in the (Immerzeel et al., 2014; Kraaijenbrink et al., 2016) articles that the authors use as justification for the co-registration method they employed. Obviously installing ground control targets on glaciers and over a large area is extremely difficult and often not possible given access, safety and logisitical challenges. This is one of the major limitations of collecting research grade UAV datasets over challenging environments. Because of these limitations we are often forced to live with poorly distributed or inadequate numbers of ground targets. In the glacier context this means ground control is often restricted to installations along the moraine edges, but even this is much better than none. And, would in my opinion provide an acceptable product in line with other UAV/glacier publications. Furthermore, the authors did use some ’on-ice’ GNSS data to assess the accuracy of the velocity measurements - these stations could be used in conjunction with moraine ground control targets alongside perhaps two more on ice targets - e.g. one near terminus, one near middle, limiting labour/time investment. 2) Fly a UAV equipped with L1 or L1/L2 differential GNSS and use an RTK or PPK positional solution to derive a more accurate master data set. Then use this dataset to co-register the other dates. An example of this method as applied to glaciers is currently under review in the cryosphere discussions: Chudley et al., 2018. 3) If there is a high quality DEM and imagery data from other sources e.g. LiDAR/airborne imagery/high resolution satellite data, then authors could extract ground control positions from these data and co-register the UAV datasets to this.

AR: We agree with the need of (1) assessing the internal deformations in the master bundle adjustment, and (2) better geo-referencing our dataset in the legal reference system of Switzerland

(CH1903 – LV03), especially for potential users that may require absolute positioning. To this end, we implemented the proposition 3) of Reviewer#2, and co-registered our master bundle adjustment on a 50 cm-resolution orthomosaic provided by the Swiss national mapping agency (SwissTopo). In the revised version of the manuscript, the results (Fig. R2.1) will be used to improve the section '4.1 Bundle adjustment and co-registration' following two guidelines:

- Provide to the user the transformation parameters allowing to reference our dataset (currently in imprecise WGS84 – UTM32) in the Swiss national reference frame (CH1903 – LV03).

- Assess the magnitude of the internal deformations of the master bundle adjustment by analyzing the residuals on the tie points used for the co-registration. Figure R2.1 shows that the internal deformations are mild (max few meters in the horizontal component) and spread over the whole area of interest. We are aware that this procedure only assesses the horizontal deformations and that the vertical component can be more affected by the doming effects than the horizontal one, but for now we do not have access to a precise enough DEM to carry out a similar assessment on the vertical component. This will also be discussed in the revised version of the manuscript.

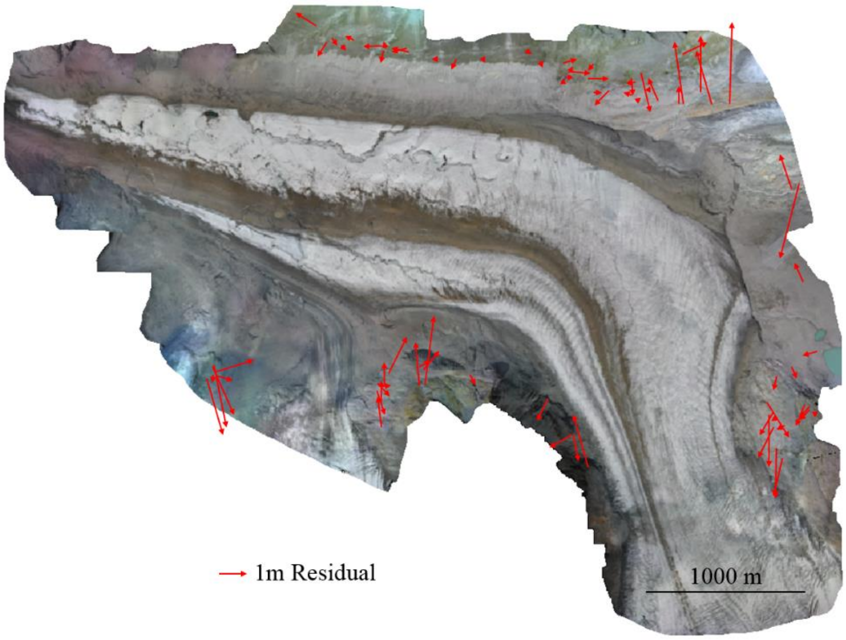

Figure R2.1: Residuals after co-registration of the master bundle adjustment on a 50 cm-resolution and accurately referenced orthoimage acquired in 2009 and provided by the Swiss national mapping agency. The transformation used for co-registration is a 2D-similarity. The resulting residuals can be interpreted as a proxy of the internal deformations of the master bundle adjustment (June 9th 2017).

RC: Finally, I have read the other posted review for this paper and agree with their suggestions regarding the matching maps. Further description of how these were derived is needed as they are non-standard, and ideally more widely used methods for velocity field derivation should be applied – e.g. COSI-CORR as this would be 1) easier to follow, 2) likely to be more useful to other researchers.

AR: We agree that matching maps require more explanations, and that a thoughtful comparison with more widely used methods is needed. We therefore compared our Matching Maps with velocity maps computed with two well-established correlation algorithms (CIAS and ImCorr), as well as with velocity fields computed with our utility but with different similarity scores (e.g. normalized cross correlation). The results of these tests show that our procedure is robust and produces reliable Matching Maps (see response to Reviwer#1 for details).

To capitalize on these positive results, we will improve the section ‘3.2 Surface displacement tracking: generation of Matching Maps’ of our manuscript following three guidelines (as proposed in the response to Reviewer#1 comments):
- Clearly state that Matching Maps are nothing but displacement maps.
- Contextualize our procedure with respect to well established software, with a clear explanation of which aspects are similar and which are different.
- Add the results of the benchmark of our Matching Map Maker utility with respect to CIAS and ImCorr to the repository of the MMM source code, and mention these results in the main manuscript.

RC: Additional points: To prevent the use of incorrect data by others the authors should clip out obviously erroneous regions in the DEM and orthomosaic, i.e. along the edges of the survey area. Ideally all datasets could be clipped to a common extent boundary and raster grid for ease of use, though this is less important.

AR: We agree with these points, and we will therefore add quality masks for the orthomosaics to our dataset (as was already done for the Matching Maps).

<u>Responses to the comments of the Editor:</u>

In the following point-by-point reply, EC denotes an editor comment and AR denotes our response to the comment.

EC: I understand that you have used a commercial software package for the bulk part of the processing. This is ok, however, I believe the underlying algorithms should be explained/mentioned explicitly so that your study remains reproducible. For example, for people without access to pix4D Mapper, it is not helpful to state that the "default values" (p5/l5) were chosen.

AR: We agree with this comment, and we will therefore better explain the structure from motion (SfM) algorithms implemented in Pix4D, with references not only to the use of this software but also more general references explaining the use of SfM for glacier mapping.

EC: Fig. 5 has peculiar gray box behind that image which should be removed (maybed this is PDF viewer dependent? I have used Preview on MacOS.

AR : We will improve this figure.

EC: Consider changing the chosen colormaps to a sequential colormap. The rainbow colormaps (and their relatives) are prone to introduce false boundaries (e.g. https://www.climate-lab-book.ac.uk/2016/why-rainbow-colour-scales-can-be-misleading/ by Ed Hawkins).

AR: We will use a sequential colormap in our figures.

EC: Fig. 1c: Label Zwilings-GL is hard to read. Maybe move it to the heaven-part of the picture and use arrows? Not sure.

AR: We will improve this figure.