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Natural Hazards and Earth System Sciences
Discussions

Interactive comment on "Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and conditions of glacier hazards" *by* Davide Fugazza et al.

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We have prepared a point by point response to the reviewer's comments. In the following text, reviewer's comments are reported as RC, our answers as AC.

RC: Interactive comment on "Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and conditions of glacier hazards" by Davide Fugazza et al. S. Gindraux (Referee) saskia.gindraux@wsl.ch Received and published: 18 July 2017 Summary: In this manuscript, the authors describe and analyse geomorphological features on the tongue of a hazard-prone glacier in the Italian alps with the help of different (closerange) remote sensing methods. They found that the merging of point

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clouds generated from two methods (UAV- and terrestrial photogrammetry) present the best product in order to map glacier hazards. The idea for this “data fusion” is new and potentially interesting, however it is not sufficiently described. The manuscript has nice Figures, well-displayed tables and is written in an easy-to-follow language style, that I appreci-ated to read. However, sections are missing and there is a need for a re-shuffling work (i.e. put the information in the right sections). The authors also invested a lot of effort in the text by inserting a great deal of information but the manuscript is overall too long and needs shortening. This work on analysing glacier hazards for the population is surely valid but a stronger emphasis on its scientific relevance is needed. Due to these issues, I think this manuscript needs major revision.

AC: Dear Reviewer, thank you for your detailed comments. We have greatly shortened the manuscript, by selecting only the most important information for the reader. We have rewritten the introduction section to focus on glacier hazards and reorganized the results and discussion section. The data section has been shortened and a new methods section is now provided which explains the criteria used in the analysis of point clouds and the methodological basis for glacier hazard mapping. Finally, we have rewritten the conclusion section by summarizing the main findings of our work. The glacier hazards analyzed in this study are caused by the glacier collapse which is linked to climate change. Thus, they provide a dramatic evidence of this phenomenon in high mountain regions and we have highlighted this information in the manuscript..

RC: General comments:

The next paragraphs of this review contain the general issues in each manuscript sections. Introduction (Sec. 1): - Better define the aim and workflow of your work: The introduction section is constituted of three parts that are not well linked together. One of the main issue is that there is no clear “story” . I understand what the authorsdid in term of analysis but how they linked their results to the “evolution and conditions of glacier hazard” question mentioned in the title) was unclear to me. In order to better understand how the authors plan to use the remote sensing products in order to map

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(or analyse? This is also not clear) the differeùnt glacier hazards, including a dedicated method section would be very valuable.

- Link the paragraphs to prepare the reader and move information to other sections: o In the first part, the two first paragraphs (Lines 27 to 63) explains changes of glacier and permafrost environment to climate change and gives examples of changes and hazards. The GLOFs are also mentioned and not mentioned again until the conclusion, which is unsettling for the reader. Maybe listing the glacier natural hazards that will be analysed in this study would be useful for the reader. o In the section 1.1, the first paragraph (Lines 65 to 85) is on remote sensing and natural hazards monitoring (what the title promises), while the second (Lines 86 to113) is on the general use of UAV on glaciers. These two subjects do not link together and the reader is not prepared to read the second paragraph. Maybe it would be good to include it in a new method section? This depends on the "story" you want to tell. o The third paragraph of subsection 1.1 (Lines 114 to 126) does not include what the title suggests. Instead of a detailed text about remote sensing and glacier hazards, it identifies the research gap and the aim of the study. I suggest to merge everything (all introduction subsections) in one longer introduction and write a text that prepares the reader for the coming section (e.g. data,results,: : :), as well as states a clear research question and description of the methods used to answer it.

AC: We have rewritten and shortened the introduction which now focuses more on glacier hazards, especially those exacerbated by climate change as suggested by Reviewer 1. We have kept a description of hazards that we did not study in this article to widen its scope, as we believe that our approach could be useful to study all types of glacier hazards. We have deleted subsections and added links between paragraphs. Now, the first paragraph deals with glacier hazards and the second with remote sensing of glacier hazards, especially proximal remote sensing, i.e. terrestrial photogrammetry, UAVs and TLS. In the third paragraph, we state the research gap and our aims, and we specifically describe here the hazards we investigated in this study. We then

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briefly describe the data and methods we used to address our research question to prepare the reader for the data and methods section, which has also been widened by moving content from the former results section and adding information on mapping of glacier hazards and point cloud merging. The introduction section now reads: “Glacier and permafrost-related hazards can be a serious threat to humans and infrastructure in high mountain regions (Carey et al., 2014). The most catastrophic cryospheric hazards are generally related to the outburst of water, either through breaching of moraine- or ice-dammed lakes or from the englacial or subglacial system, causing floods and debris flows. Ice avalanches from hanging glaciers can also have serious consequences for downstream populations (Vincent et al., 2015), as well as debris flows caused by the mobilization of accumulated loose sediment on steep slopes (Kaab et al., 2005a). Less severe hazards, but still particularly threatening for mountaineers are the detachment of seracs (Riccardi et al., 2010) or the collapse of ice cavities (Gagliardini et al., 2011; Azzoni et al., submitted). While these processes are in part typical of glacial and periglacial environments, there is evidence that climate change is increasing the likelihood of specific hazards (Kaab et al., 2005a). In the European Alps, accelerated formation and growth of proglacial moraine-dammed lakes has been reported in Switzerland, amongst concern of possible overtopping of moraine dams provoked by ice avalanches (Gobiet et al., 2014). Ice avalanches themselves can be more frequent as basal sliding is enhanced by the abundance of meltwater in warmer summers (Clague, 2013). Glacier and permafrost retreat, which have been reported in all sectors of the Alps (Smiraglia et al., 2015; Fischer et al., 2014; Gardent et al, 2014; Harris et al., 2009), are a major cause of slope instabilities which can result in debris flows, by debuttressing rock and debris flanks and promoting the exposure of unconsolidated and ice-cored sediments (Keiler et al., 2010; Chiarle et al., 2007). Glacier downwasting is also increasing the occurrence of structural collapses and while not directly threatening human lives, sustained negative glacier mass balance can also cause shortages of water for industrial, agricultural and domestic use and energy production, negatively affecting even populations living away from glaciers. Finally, glacier retreat and the increase in

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glacier hazards negatively impacts on the tourism sector and the economic prosperity of high mountain regions (Palomo, 2017). The increasing threat from cryospheric hazards under climate change calls for the adoption of mitigation strategies. Remote Sensing has long been recognized as an important tool to produce supporting data to this purpose, owing to the ability to generate digital elevation models (DEMs) and multispectral images. DEMs are particularly useful to detect glacier thickness and volume variations (Fischer et al., 2015; Berthier et al., 2016) and to identify steep areas that are most prone to geomorphodynamic changes such as mass movements (Blasone et al., 2014). Multispectral images at a sufficient spatial resolution enable the recognition of most cryospheric hazards (Quincey et al, 2005; Kaab et al., 2005b). While satellite images from Landsat and ASTER sensors (15-30 m ground sample distance - GSD) are practical for regional-scale mapping (Rounce et al, 2017), the assessment of hazards at the scale of individual glaciers or basins requires higher spatial resolution, which in the past could only be achieved via dedicated field campaigns with terrestrial laser scanners (TLS) (Bodin et al., 2008; Riccardi et al., 2010). Recent years have seen a resurgence of terrestrial photogrammetric surveys for the generation of DEMs (Piermattei et al., 2015; Kaufmann and Seier, 2016) due to important technological advancements including the development of Structure-from-Motion (SfM) Photogrammetry and its implementation in fully automatic processing software, as well as the improvements in the quality of camera sensors (Westoby et al., 2012). In parallel, unmanned aerial vehicles (UAVs – Colomina & Molina, 2014, O'Connor et al., 2017) have started to emerge as a viable alternative to TLS for multi-temporal monitoring of small areas. UAVs promise to bridge the gap between field observations, notoriously difficult on glaciers, and coarser resolution satellite data (Bhardwaj et al., 2016a). Although the number of studies employing them in high mountain environments is slowly increasing (see e.g. Fugazza et al., 2015; Gindraux et al., 2016; Seier et al, 2017), their full potential for monitoring of glaciers and particularly glacier hazards has still to be explored. In particular, the advantages of UAV and terrestrial SfM-Photogrammetry, and the possibility of data fusion to support hazard management strategies in glacial

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environments needs to be investigated and assessed. In this study, we investigated a rapidly downwasting glacier in a protected area and highly touristic sector of the Italian Alps, Stelvio National Park. We focused on the glacier terminus and the hazards identified there, i.e., the formation of normal faults and ring faults. The former occur mainly on the medial moraines and glacier terminus and are due to gravitational collapse of debris-laden slopes. The latter develop as a series of circular or semicircular fractures with stepwise subsidence, caused by englacial or subglacial meltwater creating voids at the ice-bedrock interface and eventually the collapse of cavity roofs. While often overlooked, these collapse structures are particularly hazardous for mountaineers and likely to increase under a climate change scenario (Azzoni et al., submitted). They are more dangerous than crevasses because of the larger size and because they could be filled with snow and rendered entirely or partly invisible to mountaineers. We conducted our first UAV survey of the glacier in 2014; then, through a dedicated field campaign carried out in summer 2016, we compared different platforms and techniques for point cloud, DEM and orthomosaic generation to assess their ability to monitor glacier hazards: UAV photogrammetry, terrestrial photogrammetry and TLS. The aims were: (1) comparing UAV- and terrestrial photogrammetric products acquired in 2016 against the TLS point cloud; (2) identifying glacier-related hazards and their evolution between 2014-2016 using the merged point cloud from UAV and terrestrial photogrammetry and UAV orthophotos; and 3) investigating ice thickness changes between 2014-2016 and 2007-2016 by comparing the two UAV DEMs and a third DEM obtained from stereo-processing of aerial photos captured in 2007."

RC: o In my opinion, reading about the study area (Subsection 1.2; Lines 127 to 155), in the introduction is very uncommon. I would merge it in another section (e.g. in the data section or in the new? Method section). This section however is too long and it should be shortened, containing only the information the reader needs to understand your work.

AC: The study area has been moved to a dedicated section. Furthermore, we have

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shortened this section by deleting the sentences concerning recent glacier changes, the AWS and other research performed on the glacier as not strictly relevant to this study. We have deleted bullet points and rephrased the paragraph as follows: “The Forni Glacier (see Fig. 1) has an area of 11.34 km2 based on the 2007 data from the Italian Glacier Inventory (Smiraglia et al., 2015), an altitudinal range between 2501 and 3673 m a.s.l. and a North-North-Westerly aspect. The glacier retreated markedly since the little ice age (LIA), when its area was 17.80 km2 (Diolaiuti & Smiraglia, 2010), with an acceleration of the shrinking rate in the last three decades, typical of valley glaciers in the Alps (Diolaiuti et al, 2012, D’Agata et al; 2014). It has also undergone profound changes in dynamics in recent years, including the loss of ice flow from the eastern accumulation basin towards its tongue and the evidence of collapsing areas on the eastern tongue (Azzoni et al., submitted). One such area, hosting a large ring fault (see Fig. 2d) prompted an investigation carried out with Ground Penetrating Radar (GPR) in October 2015, but little evidence of a meltwater pocket was found under the ice surface (Fioletti et al., 2016). Since then, a new ring fault appeared on the central tongue, and the terminus underwent substantial collapse (see Fig. 2a,b,c,e). Continuous monitoring of these hazards is important as the site is highly touristic (Garavaglia et al., 2012), owing to its location in Stelvio Park, one of Italy’s major protected areas, and its inclusion in the list of geosites of Lombardy region (see Diolaiuti and Smiraglia, 2010). The glacier is in fact frequently visited during both summer and winter months. During the summer, hikers heading to Mount San Matteo take the trail along the central tongue, accessing the glacier through the left flank of the collapsing glacier terminus. During wintertime, ski-mountaineers instead access the glacier from the eastern side, crossing the medial moraine and potentially collapsed areas there (see Fig. 1).”

RC: Data Sources: acquisition and processing (Sec. 2): - Shorten the whole section: A lot of information in this section is not crucial for the reader that gets lost. I suggest rewriting it in a more succinct way and remove text. See more details in the short comments. - Re-order the subsections: It is hard to follow this Sec. 2 because, the reader is starting to read a section about a new UAV survey, then terrestrial survey,

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TLS, control points (that belong to UAV and TLS), and finally a UAV survey again. I suggest that the different subsections should be divided per surveying method rather than the different datasets. For instance: 2.1 UAV photogrammetry 2.1.1 Dataset 2014 Content example: Type of UAV, flights, GCP network, software to generate products (and eventually workflow), resolution of end product. 2.1.2 Dataset 2016 2.2 Terrestrial photogrammetry 2.3 TLS 2.4 Aerial photogrammetric survey

AC: We have reordered the data section according to your suggestion and shortened it following your minor comments.

RC:

Results (Sec. 3): - Shorten and merge sections: o The first part of the result section (subsection 3.1 and 3.11) is about statistics describing the point clouds, and is too long. The subsections could be merged and shortened, the number of tables and figures reduced. A large part of the text in these two sections also belong to the discussion section (see short comments).

AC: This subsection has been shortened. Part of it was moved to the methods section and part to the Discussion Section following your short comments. The results sections concerning point clouds comparison was merged into one section and tables and figures reduced according to your short comments. Now results section 5.1 reads: “The analysis of point density shows significant differences between the three techniques for point cloud generation (see Table 2). Values range from 103 to 2297 points/m2 depending on the surveying method, but the density was generally sufficient for the reconstruction of the different surfaces shown in Fig. 5, except for location 5. Terrestrial photogrammetry featured the highest point density, while UAV photogrammetry had the lowest. In relation to UAV photogrammetry, similar point densities were found in all sample locations, especially for the standard deviations that were always in the range 22-29 points/m2. Mean values were between 103-109 points/m2 in locations 2-4, while they were higher in location 5 (141 points/m2). Due to the nadir acquisition points, the

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3D modelling of vertical/sub-vertical cliffs in location 1 was not possible. In relation to TLS, a mean value of point density ranging from 141-391 points/m2 was found, with the only exception of location 5, where no sufficient data were recorded due to the position of this region with respect to the instrumental standpoint. Standard deviations ranged between 69-217 points/m2, moderately correlated with respective mean values. The analysis of the completeness of surface reconstruction also revealed some issues related to the adopted techniques (see Fig. 6). Specifically, TLS suffered from severe occlusions which prevented acquisition of data in the central part of the sample area, while UAV photogrammetry was able to reconstruct the upper portion of the sample area but not the vertical cliff. Only terrestrial photogrammetry acquired a large number of points in all areas. In terms of point cloud distance (see Table 3), the comparison between TLS and terrestrial photogrammetry resulted in a high similarity between point clouds, with no large differences between different sample areas. Conversely, the comparison between TLS and UAV photogrammetry and terrestrial and UAV photogrammetry provided significantly worse results, which may be summarized by the RMSEs in the range 21.1-37.7 cm and 20.7-30.4 cm, respectively. The worse values were both obtained in the analysis of location 2, which mostly represents a vertical surface, while the best agreement was found within location 3 which is less inclined. As the UAV flight was geo-referenced on a set of GCPs with an RMSE of 40.5 cm, the ICP co-registration may have not totally compensated the existing bias. ”

RC: o Some methodological description seems to be “hidden” in the result section. I suggest that the text is re-shuffled and shortened. More details can be found in the short comments.

AC: We have moved relevant parts of the result section to the methods section following your short comments. Methods section 4.1 now is dedicated to the comparison of point clouds and reads: “The comparison between point clouds generated during the 2016 campaign had the aim of assessing their geometric quality before their application for the analysis of hazards. These evaluations were also expected to provide

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some guidelines for the organization of future investigations in the field at the Forni Glacier and in other Alpine sites. Specifically, we analysed point density (points/m2) and completeness, i.e. % of area in the ray view angle. Point density partly depends upon the adopted surveying technique, since it is controlled by the distance between sensor and surface and the obtainable spatial resolution. In SfM-Photogrammetry, the latter property is affected by dense matching, while in TLS it can be set up as data acquisition input parameter. In this study, the number of neighbours N (inside a sphere of radius R=1 meter) divided by the neighbourhood surface was used to evaluate the local point density D in CloudCompare (www.cloudcompare.org). To understand the effect of point density dispersion (Teunissen, 2009), the inferior 12.5 percentile of the standard deviation ðİIJŐ of point density was also calculated. The use of these local metrics allowed to distinguish between point density in different areas, since this may largely change from one portion of surface to another. A further metric in this sense was point cloud completeness, referring to the presence of enough points to completely describe a portion of surface. In this study, the visual inspection of selected sample locations was used to identify occlusions and areas with lower point density. To analyse these properties, five regions were selected (see Fig. 5), located on the glacier topographic surface and characterized by different glacier features and the presence of hazards: 1) Glacial cavity composed by subvertical and fractured surfaces over 20 m high, and forming a typical semicircular shape; 2) glacial cavity over 10 m high with the same typical semi-circular shape as location 1, covered by fine- and medium-size rock debris; 3) normal fault over 10 m high; 4) highly-collapsed area covered by fine- and medium-size rock debris and rock boulders; and 5) planar surface with a normal fault covered by fine- and medium-size rock debris and rock boulders. The analysis of local regions was preferred to the analysis of the entire point clouds for the following reasons: 1) the incomplete overlap between point clouds obtained from different methods; 2) the opportunity to investigate the performances of the techniques in diverse geomorphological situations. Finally, we compared the point clouds in a pairwise manner within the same sample locations. Since no available benchmarking data set (e.g. accurate static

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GNSS data) was concurrently collected during the 2016 campaign, the TLS point cloud was used as a reference, as it less influenced by controlling factors (network geometry, object texture, lighting conditions). When comparing both photogrammetric data sets, the one obtained from UAV was used as reference because of the even distribution of point density within the sample locations. The presence of residual, non-homogenous geo-referencing errors in the data sets required a specific fine registration of each individual sample location, which was conducted in CloudCompare using the ICP algorithm (Pomerleau et al., 2016). Then, point clouds in corresponding sample areas were compared using the M3C2 algorithm implemented in CloudCompare (Lague et al., 2013). This solution allowed us to get rid of registration errors from the analysis, which could then be focused on the capability of the adopted techniques to reconstruct the local geometric surface of the glacier in an accurate way."

RC: o Part of the text in subsubsection 3.1.2 (Lines 517 to 570) belongs to the discussion section (see short comments for more details).

AC: We have moved relevant considerations in subsect. 3.1.2 to the discussion section and methodological descriptions to the methods section. More information is provided in the answer to your major comments about the discussion section and short comments.

RC: - Clarify "accuracy" and "comparison": Subsubsection 3.1.2 (Lines 517 to 570), concerns the assessment of the point clouds' accuracy. In principle, the absolute accuracy of such point clouds can only be assessed with perfect validation data (e.g. long-term precise GPS data). Each method has its advantages and drawback and thus, generates products with different kind of errors (i.e. they are all differently imperfect/inexact). Therefore, the accuracy of a point cloud cannot be calculated using a point cloud generated from another method; but a comparison can be made. The analysis performed with the help of cloud compare, looks at the differences between the 3D geometry of point cloud pairs only. I would make a clear distinction and use of these terms in the text.

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AC: We now avoid using the word “accuracy” during the analysis of point clouds and clarify that no available accurate reference data set was available. We chose TLS as the reference point cloud because it is less influenced by controlling factors (network geometry, object texture, lighting conditions). According to the International vocabulary of metrology JCGM 200:2012, accuracy is a qualitative term that indicates whether the uncertainty is lower than a threshold value identified as suitable for the purposes of a study. We therefore state that “The final accuracy of our UAV photogrammetric products was nevertheless adequate to investigate ice thickness changes over 2 years” in the discussion section following this definition. JCGM 200:2012, see http://www.bipm.org/utils/common/documents/jcgm/JCGM_200_2012.pdf

RC: - Add information: o It is not clear how the glacier thickness information (Section 3.2 and in general) isused in the assessment of glacier hazards. Could you please provide more information in the text?

AC: The information on glacier thickness change provides evidence concerning the processes of glacier downwasting that are linked to glacier hazards. It shows the extent and volume of collapsed areas and the acceleration of thinning rates that is linked to the increase in collapsed areas via higher availability of englacial and subglacial meltwater, which create voids at the ice-bedrock interface and eventually the collapse of cavity roofs. Glacier thinning is also a major cause of slope instabilities which can result in debris flows, by debuttressing rock and debris flanks and promoting the exposure of unconsolidated and ice-cored sediments (see e.g. Keiler et al., 2010; Chiarle et al., 2007). Thus, the information on glacier thinning is useful to provide evidence of increased susceptibility of high mountain areas to hazards related to climate change. Finally, glacier thinning can be considered a hazard by itself as it affects the availability of water resources for industrial and domestic use and the prosperity of high mountain regions, in view of the touristic value of glaciers. We now specify the reasons why we conducted the analysis in the introduction section, as: “Glacier and permafrost retreat, which have been reported in all sectors of the Alps (Smiraglia et al., 2015; Fischer et al.,

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2014; Gardent et al, 2014; Harris et al., 2009), are a major cause of slope instabilities which can result in debris flows, by debuttressing rock and debris flanks and promoting the exposure of unconsolidated and ice-cored sediments (Keiler et al., 2010; Chiarle et al., 2007). Glacier downwasting is also increasing the occurrence of structural collapses and while not directly threatening human lives, sustained negative glacier mass balance can also cause shortages of water for industrial, agricultural and domestic use and energy production, negatively affecting even populations living away from glaciers. Finally, glacier retreat and the increase in glacier hazards negatively impacts on the tourism sector and the economic prosperity of high mountain regions (Palomo, 2017)." and "in this study, we investigated a rapidly downwasting glacier in a protected area and highly touristic sector of the Italian Alps, Stelvio National Park. We focused on the glacier terminus and the hazards identified there, i.e., the formation of normal faults and ring faults. The former occur mainly on the medial moraines and glacier terminus and are due to gravitational collapse of debris-laden slopes. The latter develop as a series of circular or semicircular fractures with stepwise subsidence, caused by englacial or subglacial meltwater creating voids at the ice-bedrock interface and eventually the collapse of cavity roofs. While often overlooked, these collapse structures are particularly hazardous for mountaineers and likely to increase under a climate change scenario (Azzoni et al., submitted). They are more dangerous than crevasses because of the larger size and because they could be filled with snow and rendered entirely or partly invisible to mountaineers. ". In the conclusion, we have added: "The analysis of glacier thickness changes suggests a feedback mechanism which should be further analysed, with higher thinning rates leading to increased occurrence of collapses, with additional release of meltwater. Glacier downwasting is also of relevance for risk management in the protected area, providing valuable data to assess the increased chance of rockfalls following glacier retreat and to improve forecasts of glacier meltwater production."

RC: o Subsection 3.3 (Lines 571 to 602) also requires more information on how this dataset merging has been made. A method section would be useful, especially when you cite this merging be the best product to monitor glacier hazards in the conclusion.

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This could be a very interesting point! And maybe the main novelty of this study and should better be highlighted.

AC: We have added information on the dataset merging and moved Subsection 3.3. to the methods section. The section now reads: “To improve coverage of different glacier surfaces, including planar areas and normal faults, photogrammetric point clouds from the 2016 campaign were merged. Prior to point cloud merging, a preliminary co-registration was performed on the basis of the ICP algorithm in CloudCompare. Regions common to both point clouds were used to minimize the distances between them and find the best co-registration. The point cloud from UAV photogrammetry, which featured the largest extension, was used as reference during co-registration, while the other was rigidly transformed to fit with it. After this task, both original point clouds resulted aligned into the same reference system. In order to get rid of redundant points and to obtain a homogenous point density, the merged point cloud (see Fig. 5) was subsampled keeping a minimum distance between adjacent points of 20 cm. The final size of this data set is approximately 4.4 million points, which represents a manageable data amount on up-to-date computers. The colour RGB information associated to each point in the final point cloud was derived by averaging the RGB information of original points in the subsampling volumes. While this operation resulted in losing part of the original RGB information, it helped provide a realistic visualization of the topographic model, which can aid the interpretation of glacier hazards.”

RC: o Subsection 3.3 (Lines 571 to 602) present the fusion of two point cloud datasets. It is very confusing for the reader to switch between point cloud (Section 3.1 and 3.3) and DEM sections (Section 3.2). Can you maybe change the section’s order?

AC: We have changed the section order in the methods and results sections.Subsection 3.3. was also moved to the methods section. In methods, section 4.1 now deals with point cloud analysis, 4.2. with glacier hazards and 4.3 DEM coregistration in the methods section. In results, section 5.1 deals with point cloud analysis, 5.2 with glacier hazards and 5.3 with glacier thickness change.

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RC: o It was very unclear to me after reading the results section, why the authors performed all these different analyses (i.e point cloud statistical analysis, point cloud accuracy, point cloud fusion and glacier thickness change), when at the end (Discussion section) you present a map of the glacier hazards (location of collapse, Fig.15) generated with the help of UAV orthophotos?. Could you please better explain their link in the introduction and method section?

AC: We have conducted the analysis again by using primarily the information from point clouds to map glacier hazards, while UAV orthophotos were used as a cross-check. On point clouds, normal faults and ring faults are visible due to the vertical displacement caused by faulting or subsidence. On orthophotos, they can instead be identified owing to the contrast with their surroundings. Glaciological information (orientation and location of features) is also necessary to distinguish these features from crevasses. The new procedure actually allowed us to recognize more features. We now describe in the methods section the procedures used in mapping glacier hazards, as: “The investigation of glacier hazards was conducted by considering datasets from 2014 and 2016. In 2014, only the point cloud and UAV orthophoto were available, while in 2016 the point cloud obtained by merging UAV and close-range photogrammetric data sets was used in combination with the UAV orthophoto. In this study, we focused on ring faults and normal faults, which were manually delineated by using geometric properties from the point clouds while color information from orthophotos was used as a cross-check. On point clouds, mapping is based on visual inspection of vertical displacements following faulting or subsidence. On orthophotos, both types of structures also generally appear as linear features in contrast with their surroundings. As these structures may look similar to crevasses, further information concerning their orientation and location needs to be assessed for discrimination. The orientation of fault structures is not compatible with glacier flow, with ring faults also appearing in circular patterns. Their location is limited to the glacier margins, medial moraines and terminus (Azzoni et al., submitted). After delineation, we also analysed the height of vertical facies using information from the point clouds. ”.

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RC: Discussion (Sec. 4): - Link the discussion to the result section: The discussion section (Lines 611 to 687) is divided into two parts: One on the geomorphological evolution of the glacier tongue and the second about glacier-related hazards and how to risk is reduced through hazard mapping. Although the information is interesting, almost none of the discussion is based on the result section, and this is what the reader expects. Can you please change the text accordingly?

AC: We have removed the section about the evolution of the glacier tongue as not relevant to this study. We have also moved the glacier hazards mapping section to the results section. The discussion section now reports the advantages of different techniques for hazard mapping and risk assessment as suggested by you and the other Reviewer.

RC: - Discuss your results by comparing them to results of other studies: Comparing the different point clouds with a) statistical numbers, b) point density and c) completeness, and judging the best mapping method based on them, follow a correct method workflow and give good results but the later are not new. There are many papers that state the drawbacks of the surveying methods in a mountain terrain e.g. that the TLS data have a lot of “holes“ and that the UAV data do not represent the vertical geometry well. I would consider making reference to them and compare your results.

AC: We have moved relevant considerations from the results to the discussion section and added references to other studies conducted in glacial environments, where available, to investigate the advantages of the different techniques. The discussion section now reads: “The choice of a technique to monitor glacier hazards and the glacier geodetic mass balance can depend on several factors, including the size of the area, the desired spatial resolution and accuracy, logistics and cost. In this study, we focused on spatial metrics, i.e. point density, completeness and distance between point clouds to evaluate the performance of UAV, close-range photogrammetry and TLS in a variety of conditions. Considering point density, terrestrial photogrammetry resulted in a denser data set than the other techniques. This is mostly motivated by the possibil-

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ity to acquire data from several stations with this methodology, only depending on the terrain accessibility, reducing the effect of occlusions with a consequently more complete 3D modelling. However, the mean point density achieved when using terrestrial photogrammetry has a large variability both between different sample locations, and inside each location as shown by the standard deviations of D. Point densities related to UAV photogrammetry and TLS are more regular and constant. In the case of UAV photogrammetry, the homogeneity of point density is due to the regular structure of the airborne photogrammetric block. In the case of TLS, the regularity is motivated by the constant angular resolution adopted during scanning. Since any techniques may perform better when the surface to survey is approximately orthogonal to the sensor looking direction, terrestrial photogrammetry is more efficient for reconstructing vertical and subvertical cliffs (Sample areas 1 and 2) and high-sloped surfaces (Sample areas 3 and 4). On the contrary, airborne UAV photogrammetry provided the best results in location 5 which is less inclined and consequently could be well depicted in vertical photos. In general, point clouds from terrestrial photogrammetry provide a better description of the vertical and subvertical parts (see e.g. Winkler et al., 2012), while point clouds obtained from UAV photogrammetry are more suitable to describe the horizontal or sub-horizontal surfaces on the glacier tongue and periglacial area (Seier et al., 2017), unless the camera is tilted to an off-nadir viewpoint (Dewez et al., 2016; Aicardi et al., 2016). Results obtained from photogrammetry based on terrestrial and UAV platforms can thus be retained quite complementary. In agreement with other studies of vertical rock slopes (e.g. Abellan et al., 2014), we found that the TLS point cloud was affected by occlusions (see e.g. location 2 in Fig. 6). Data acquisition with this platform is in general difficult in regions that are subparallel to the laser beams and in the presence of wet surfaces. Its main disadvantage compared to photogrammetry is however the complexity of instrument transport and setup. In terms of logistics, up to five people were involved in the transportation of the TLS instruments (laser scanner, theodolite, at least two topographic tripods and poles, electric generator and ancillary accessories) while 2 people were required for UAV and close-range photogrammetric

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surveys. Meteorological conditions and the limited access to unstable areas close to the glacier terminus also prevented the acquisition of TLS data from other viewpoints as done with photogrammetry. Finally, TLS instruments are much more expensive at 70000-100000€ compared to UAVs (3500€ for our platform) and DSLR (Digital Single-Lens Reflex) cameras used in photogrammetry, in the range 500-3500€In this study, the uncertainty of the 2016 UAV dataset (40.5 cm RMSE on GCPs and 21.1-37.7 cm RMSE when compared against TLS) was slightly higher than previously reported in high mountain glacial environments (Immerzeel et al., 2014; Gindraux et al, 2017; Seier et al., 2017). Contributing factors might include the sub-optimal distribution and density of GCPs (Gindraux et al., 2017), the delay between the UAV surveys as well as between UAV and other surveys and the lack of coincidence between GCP placement and the UAV flights. This means the UAV photogrammetric reconstruction was affected by ice ablation and glacier flow, which on Forni Glacier range between 3-5 cm day-1 (Senese et al., 2012) and 1-4 cm day-1, respectively (Urbini et al., 2017). We thus expect a combined 3-day uncertainty on the 2016 UAV dataset between 10 and 20 cm, and lower on GCPs considering reduced ablation owing to their placement on boulders. A further contribution to the error budget of GCPs might stem from the intrinsic precision of GNSS/theodolite measurements and image resolution. The comparison between close-range photogrammetry and TLS, was less affected by glacier change as data were collected one day apart and the RMSE of 6-10.6 cm is in line with previous findings by Kaufmann and Landstaedter (2008). To improve the accuracy of UAV photogrammetric blocks, a better distribution of GCPs or switching to an RTK system should be considered, while close-range photogrammetry could benefit from measuring a part of the photo-stations as proposed in Forlani et al. (2014), instead of placing GCPs on the glacier surface. The uncertainty in UAV photogrammetric reconstruction also factored in the relatively high standard deviation still present after the coregistration between DEMs in areas outside the glacier (2.22 m between 2014 and 2016). Another important factor here is the morphology of the coregistration area, i.e. the outwash plain, still subject to changes owing to the inflow of glacier meltwa-

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ter and sediment reworking. The final accuracy of our UAV photogrammetric products was nevertheless adequate to investigate ice thickness changes over 2 years, while the integration with close-range photogrammetry was required to investigate hazards related to the collapse of the glacier terminus. We conducted UAV surveys under different meteorological scenarios, and obtained adequate results with early-morning operations with 0/8 cloud cover and midday flights with 8/8 cloud cover. Both scenarios can provide diffuse light conditions allowing to collect pictures suitable for photogrammetric processing, but camera settings need to be carefully adjusted beforehand (O'Connor et al., 2017). If early morning flights are not feasible in the study area for logistical reasons or when surveying east-exposed glaciers, the latter scenario should be considered. In our pilot study, we covered part of the Forni glacier tongue, and only investigated hazards related to the glacier collapse. Our maps can help identify safer paths where mountaineers and skiers can visit the glacier and reach the most important summits. However, the increase in collapse structures owing to climate change requires multi-temporal monitoring. A comprehensive risk assessment should also cover the entire glacier, to investigate the probability of serac detachment and provide an estimate of the glacier mass balance with the geodetic method. While our integrated approach using a multicopter and terrestrial photogrammetry should be preferred to investigate small individual ice bodies, fixed-wing UAVs, ideally equipped with an RTK system and ability to tilt the camera off-nadir, might be the platform of choice to cover large distances (see e.g. Ryan et al., 2017), potentially reducing the number of flights and solving issues with GCP placement. Such platforms could help collect sufficient data for hazard management strategies up to the basin scale in Stelvio National Park and other sectors of the Italian Alps, eventually replacing aerial LiDAR surveys. Cost analyses (Matese et al., 2015) should also be performed to evaluate the benefits of improved spatial resolution and DEM accuracy of UAVs compared to aerial and satellite surveys and choose the best approach for individual cases."

RC: Conclusion (Sec. 5): - Shorten and clarify the main message: The conclusion (Lines 688 to 730) are a mix of different sections, that are, presently, not well linked

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together. In particular, a clear conclusive message is missing. My advice would be to revise this part and to include, amongst other, a short summary for how and why this study has been done, which would help to present a better “overall story”.

AC: We have rewritten this section by including a short introductory paragraph summarizing the reason of this study and methods. We have added a bullet point to highlight the main finding of our work and add a final conclusive message at the end, as: “In our study, we compared point clouds generated from UAV photogrammetry, close-range photogrammetry and TLS to assess their quality and evaluate the potential in mapping and describing glacier hazards such as ring faults and normal faults, by carrying out a specific campaign in summer 2016. In addition, we employed orthophotos and point clouds from a UAV survey conducted in 2014 to analyze the evolution of glacier hazards and a DEM from an aerial photogrammetric survey conducted in 2007 to investigate glacier thickness changes between 2014 and 2016. The main findings of our study include: UAVs and terrestrial photogrammetric surveys provide reliable performances in glacial environments, outperform TLS in terms of logistics and costs, and are more flexible in relation to meteorological conditions. UAV and terrestrial photogrammetric blocks can be easily integrated providing more information than individual techniques to help identify glacier hazards. UAV-based DEMs can be employed to estimate thickness changes but improvements are necessary in terms of area covered and accuracy to calculate the glacier geodetic mass balance of large glaciers. The Forni Glacier is rapidly collapsing with an increase in ring faults size, providing evidence of climate change in the region. The glacier thinning rate increased owing to collapses to 5.20 ma-1 between 2014 and 2016. The maps produced from the combined analysis of UAV and terrestrial photogrammetric point clouds can be made available through GIS web portals of Stelvio National Park or Lombardy region (http://www.geoportale.regione.lombardia.it/). A permanent monitoring programme should be setup to help manage risk in the area, issuing warnings and assisting mountain guides in changing hiking and ski routes as needed. The analysis of glacier thickness changes suggests a feedback mechanism which should be fur-

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ther analysed, with higher thinning rates leading to increased occurrence of collapses, with additional release of meltwater. Glacier downwasting is also of relevance for risk management in the protected area, providing valuable data to assess the increased chance of rockfalls and to improve forecasts of glacier meltwater production. While our test was conducted on one of the largest glaciers in the Italian Alps, the integrated photogrammetric approach is easily transferrable to similar sized and much smaller glaciers, where it would be able to provide a comprehensive assessment of hazards and mass balance and become useful in decision support systems for natural hazard management. In larger regions, UAVs hold the potential to become the platform of choice but their performances and cost-effectiveness compared to aerial and satellite surveys need to be further evaluated."

RC: Comments on Figures and Tables: I generally enjoyed looking at the figures and tables. The colors, the size and the contast of the Figures are well chosen and their appearance encouraged me to read the text. Hereafter are a few suggestions of changes.

RC Figure 1: I suggest to reduce the area of figure 1a and to merge it with Figure 1b (Only one figure for the glacier's location). Can you please specify what are the black outlines and from which year? The location of the TLS standpoint would also be valuable.

AC: We now show only one figure for the glacier map, with a small inset illustrating the glacier location within Italy. The figure includes the location of features reported in Fig.2, UAV take-off/landing sites, TLS standpoint, GCPs, hiking/ski trails which determine the vulnerability to glacier hazards. Finally, we show the reference area for volume change calculation

RC Figure 2: It would be helpful to see where these pictures are located on the glacier. Maybe enlarge the glacier on Figure 1 and set the letters (a-e) at the correct location? Or make a new overview map similar to Figure 7.

AC: We now show the location of these features in Figure 1.

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RC Figure 3: b) A more exhaustive caption (with UAV name) and presentation of the other objects would be useful. Other that, Figure 3 does not seems to add much information. Consider merging it with Table 1.

AC: We have merged Table 1 and Figure 3 accordingly. The UAV full names are now provided in the table within the Figure.

RC Figure 4: Many other figures in the manuscript display the glacier tongue. Would it be possible to put the GCP location on one of them instead of creating a new image just for this? Caption: Add UAV in the caption, such as: "of the 2016 UAV survey".

AC: The location of GCPs is now shown in Figure 1.

RC Figure 5: Please increase the resolution of the image so that the GCP numbers are readable. Consider specifying the year of this survey (2016). Moreover, it would be nice to twist the images so that they have the same view angle (e.g. that on both images the GCP12 is front and GCP10 right).

AC: We have replaced the figure by adopting the same view for the upper and lower panel and adding labels over GCPs to improve readability. The caption now reads: "3D reconstruction of the glacier terminus from the terrestrial photogrammetric survey of 2016 : (a) locations of camera stations in front of the glacier and 3D coordinates of tie points extracted during SfM for image orientation; (b) point cloud of the glacier terminus with positions of GCPs."

RC Figure 6: This is a nice but large image that does not give much information. If you want to show the GCP or measuring device, part of the image can be cropped and merged in Figure 3 or another one.

AC: We have removed Figure 6 accordingly.

RC Figure 7: Please start numbering with 1 on the upper left corner. The background image could be brighter. Caption: Please elaborate (e.g. Location of different glacier features or hazard-prone areas on the tongue of Forni glacier were the point cloud

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comparison has been performed. The background image is the dense point cloud generated from the 2014 UAV survey).

AC: We have modified the image by numbering sample windows as suggested. We have rephrased the caption and moved here the description of sample windows. The caption now reads: "Figure 5: Location of different glacier features or hazard-prone areas on the tongue of Forni glacier were the point cloud comparison was performed. The background image is the merged point cloud generated from the 2016 UAV and terrestrial photogrammetry survey."

RC Figure 8: Figure 8 display part of the information of Table 5. As it does not show new information, consider removing it.

AC: We have removed figure 8 accordingly.

RC Figure 9 & 10: I think both images show the same information, so maybe remove one of them? Please enlarge the numbers on the scale bars.

AC: we have removed Figure 10 accordingly.

RC Figure 12: This is the same image than the background image of Figure 7 right? Either remove it and refer the reader to Figure 7 instead of 12, or show an image where the reader can see the difference between the 2014, the 2016 and the merged point cloud.

AC: We have removed figure 12 accordingly.

RC Figure 15: Please explain the differences between the red and the blue lines on the glacier. Rewrite the caption so that not only a year is given. A "N" close to the arrow would give a meaning to the arrow itself! The year of the glacier outline should be mentioned.

AC: The difference between normal faults and ring faults is explained in the introduction section, and the methods used to map them are now described in section 4.3. The

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glacier outlines were those from 2014 in panel a and 2016 in panel b, respectively. We have split the legend to clarify the year of glacier outlines and added an "N" close to the north arrow. We have rewritten the caption as: "Figure 7: location of collapse structures, i.e. normal faults and ring faults and trails crossing the Forni Glacier (a) 2014, with 2014 UAV ortophoto as basemap. The red box marks the area surveyed in 2016. (b) 2016, with 2016 UAV orthophoto as basemap."

RC Table 1: This is a nice summary table but most of the useful information are already in the text. The added value to the paper is minor. Consider removing this table or merge it with Figure 3.

AC: We have merged this table with figure 3 accordingly.

RC Table 2: The # symbols should be removed or indicate that it means "numbers".

AC: We have replaced the # symbol with "number" accordingly.

RC Table 3: The last column should display the elevation differences "with" co-registration right?. How do you explain that the standard deviation values are still of several meters? This should be discussed in the discussion section.

AC: We have replaced "with" with "without". The coregistration method is not expected to cancel out the standard deviation completely (Berthier et al., 2007). We attribute high residual values to two factors: 1) the uncertainty in UAV photogrammetric reconstruction, i.e. lack of GCPs during the 2014 survey and issues related to GCP accuracy during the second. 2) The morphology of the coregistration area, i.e. the glacier outwash plain, which is still subject to significant changes owing to the inflow of glacier meltwater and sediment reworking. We have added a paragraph in the Discussion section that reads: "The uncertainty in UAV photogrammetric reconstruction also factored in the relatively high standard deviation still present after the coregistration between DEMs in areas outside the glacier (2.22 m between 2014 and 2016). Another important factor here is the morphology of the coregistration area, i.e. the outwash

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plain, still subject to changes owing to the inflow of glacier meltwater and sediment reworking. The final accuracy of our UAV photogrammetric products was nevertheless adequate to investigate ice thickness changes over 2 years, while the integration with close-range photogrammetry was required to investigate hazards related to the collapse of the glacier terminus. ”

RC Table 4: For the #, same comment as for Table 2. The i, ii, iii are not necessary here, or define them. Giving a volume as size is very uncommon and I suggest using area (m2). Consider merging this table with Table 5.

AC: We have replaced the # symbol with “number” and replaced i,ii and iii with the names of the techniques. We also indicate the area instead of the size. The table is now merged with table 5.

RC Table 5: Please specify that the mean and standard deviation is calculated with a function computing local point density. Same note for i, ii and iii as above. Merge with Table 4.

AC: We have replaced i,ii,iii with the names of the techniques and merged the table with table 4. The caption now reads: “Table 2: Area and number of points in each sample window on the Forni Glacier terminus, mean and standard deviation of local point density and number of points above the lower 12.5% percentile in each window..”

RC Table 6: Caption: As it is, the reader does not understand what the M3C2 is. Please define so that every image can be understood as stand-alone.

AC: We have modified the caption of this table as: “Statistics on distances between point clouds computed on the basis of M3C2 algorithm.”

RC Table 7: The information of Table 8 is more useful in the sense that we can compare the the mean thickness change etc. over the same area of interest (of 0.32 km2). I would not include Table 7 in the manuscript.

AC: We have removed table 7 accordingly.

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RC Table 8: Remove the last sentence. The reader will usually read the text if he/she wants more information ;-)

AC: We have removed the last sentence accordingly.

RC Short comments: The short comments are listed in a supplement .pdf file.

Please also note the supplement to this comment: https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-198/nhess-2017-198- RC2-supplement.pdf Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-198, 2017.

RC Short comments:

RC Line 27 Page 1: Replace “on” with “in”.

AC: We have replaced “on” with “in” accordingly while changing the sentence to focus on glacier hazards.

RC Line 33 Page 2: I would change this word or maybe say: "glacier and permafrost areas are shrinking". So something alike!

AC: The sentence was changed due to restructuring of the introduction section to: “Glacier and permafrost retreat, which have been reported in all sectors of the Alps (Smiraglia et al., 2015; Fischer et al., 2014; Gardent et al, 2014; Harris et al., 2009), are a major cause of slope instabilities which can result in debris flows, by debuttressing rock and debris flanks and promoting the exposure of unconsolidated and ice-cored sediments (Keiler et al., 2010; Chiarle et al., 2007). ”

RC Lines 39-42 Page 2: hazards evolving in a downstream direction sounds not right. what about rephrasing like: " Rising temperatures generate land-surface instabilities and therefore increase the occurrence of geomorphological hazards in glacier and permafrost environments."?

AC: The sentence has removed to shorten the introduction.

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RC Line 55 Page 2: Refer to Fig. 1 first.

AC: We have removed the reference to Fig.2.

RC Lines 91-99 Page 4: I think this does not need bullet points (as it is not information that you really want to highlight in your text) and can be listed in the text.

AC: We have removed this information to shorten the introduction section.

RC Line 104 Page 5: supraglacial lakes? if yes supraglacial is not needed.

AC: We have deleted this description to shorten the introduction section.

RC Line 114 Page 5: remove “and accuracy evaluation of point clouds”.

AC: We have removed these words due to restructuring of the introduction section.

RC Line 121 Page 5: the reader reads this information later ;-)

AC: We have deleted the words accordingly.

RC Line 122 Page 5: Why a reference (and why this one?) here and after TLS but not after the UAV method? I would not put any references here as you are listing methods.

AC: We have deleted references accordingly

RC Line 123 Page 5: “The aims are:”

AC: we have replaced “with the aim of” with “our aims were:”

RC Line 125 Page 5: “which can represent a risk”.

AC: we have removed the description here in view of your comment and the other reviewer’s one. The specific hazards investigated in this study are described at the start of the paragraph as “In this study, we investigated a rapidly downwasting glacier in a protected area and highly touristic sector of the Italian Alps, Stelvio National Park. We focused on the glacier terminus and the hazards identified there, i.e., the formation of normal faults and ring faults. The former occur mainly on the medial moraines and

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glacier terminus and are due to gravitational collapse of debris-laden slopes. The latter develop as a series of circular or semicircular fractures with stepwise subsidence, caused by englacial or subglacial meltwater creating voids at the ice-bedrock interface and eventually the collapse of cavity roofs. While often overlooked, these collapse structures are particularly hazardous for mountaineers and likely to increase under a climate change scenario (Azzoni et al., submitted). They are more dangerous than crevasses because of the larger size and because they could be filled with snow and rendered entirely or partly invisible to mountaineers. ".

RC Lines 128-131 Page 6: Here there is a lot of information that is not really necessary to know to understand the rest of the manuscript. Could you rephrase it? I suggest the following: ..."has an area of 11.34 km2 (based on the 2007 data of the Italian Glacier Inventory)",...

AC: We have modified the paragraph accordingly.

RC Lines 134 and 140-143 Page 6: "which is a typical evolution of valley glacier in the Alps". You can merge everything!

AC: We have merged this sentence with the previous one as suggested.

RC Lines 169-171 Page 7: delete this sentence

AC: we have deleted the sentence accordingly.

RC Line 172 Page 7: add "around midday".

AC: we have added "around midday" accordingly. We have also added "with 8/8 of the sky covered by stratocumulus clouds" as requested by reviewer 1.

RC Line 174 Page 7: Fig. 3a before 3b!

AC: The description of the 2014 survey has been placed before the 2016 survey, so the figure order is now correct.

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RC Lines 175-179 Page 7:Could be condensed in: "Two different take-off and landing places were chosen in order to..." for instance.

AC: We have shortened the sentence accordingly.

RC Lines 194-195 Page 8: Here why not citing the original work on these methods?

AC: We have replaced the first reference with “Spetsakis and Aloimonos (1991)” and the second with “Furukawa and Ponce (2009)“. The sentence was also moved to the description of the 2014 survey where the approach was first used in our study.

RC Lines 210-211 Page 9:Do you produce DEMs the same way than this study? If yes I would write: ... "to produce a DEM with the same method used in Immerzeel et al., 2014",... Otherwise the reader has to guess this, or misunderstand that this study is the first one to interpolate UAV point clouds to DEMs.

AC: We have modified the manuscript accordingly. This part has been moved to the description of the 2014 dataset, which is now at the top of the data section.

RC Line 224 Page 10: Is this relevant for later reading?

AC: we have deleted this part accordingly.

RC Line 252 Page 11: What does that mean? is it relevant for the reader?

AC: we have deleted this part accordingly.

RC Line 253 Page 11: Maybe put here a reference to a Fig. that show the location?

AC: we now show the location of the TLS standpoint in Figure 1 and added a reference in the text.

RC Lines 253-256 Page 11: I think this info might be better situated in the discussion, if you want to explain the advantages and drawbacks of this method!

AC: we have moved this part to the discussion section accordingly.

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RC Line 262-265 Page 11: Similar comment than for L253 to L256.

AC: we have moved this part to the discussion section accordingly.

RC Line 267 Page 12: Rephrase as: "Prior the 2016 UAV surveys..." ?

AC: We have rephrased as “prior to the 2016 surveys” according to your comment.

RC Line 276 Page 12: place between brackets

AC: We have modified the manuscript accordingly.

RC Line 288 Page 13: 3b

AC: The image refers to figure 3a correctly now since the section about the 2014 dataset was moved to the top of the data section.

RC Lines 294-296 Page 13: L294 to 296 and L297 to 299 give the same information. I would recommend to remove this sentence.

AC: we have merged the two sentences at lines 294-298 as: “Early morning operations were preferred to avoid saturating camera pictures, as during this time of day the glacier is not yet directly illuminated by the sun, and to minimize blurring effects due to the UAV motion, since wind speed is at its lowest on glaciers during morning hours (Fugazza et al., 2015). ”

RC Lines 298-299 Page 13: This breaks the link between the two other sentences. I suggest to remove it,

AC: we have removed this sentence accordingly.

RC Line 302-304 Page 13: I would remove this sentence as this is a well-known fact.

AC: we have removed the sentence accordingly.

RC Line 306-308 Page 13: I think it does not add value to the text to know the reason of a reduced surveyed area.

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AC: we have removed the sentence accordingly.

RC Lines 330-340 Page 1-15: All these information have already been written in the previous sections. I think there is no need to duplicate the text.

AC: We have removed this part accordingly.

RC Line 360 Page 16: Be more precise to prepare the reader of the topic to come.

AC: We have replaced “Comparison between observations” with “Analysis of point clouds”

RC Line 360 Page 16: The highlighted information in this section is the size and the number of points generated per location. The number of point is depending on the size of the areas so I would prefer reading the the number of points per square meters (only) to be able to compare the different methods. This section, that has in the title the word "comparison", contains few information and the average reader probably expect more results. You could consider merging the 3.1 and 3.1.1.

AC: We have replaced the size with the area in the table, now merged with the table showing point density. However, we specify the absolute number of points (not per m2) to show the differences between sample locations.

RC Line 361 Page 16: Replace “data sets collected” with “point clouds generated”

AC: We have replaced the words accordingly.

RC Lines 365-366 Page 16: I suggest rephrasing as: "In our study, we refer to the work of Eltner et al., 2016 which applied criteria and metrics for comparing point clouds for different techniques, namely,..."

AC: we have deleted this sentence. We have rephrased the paragraph as: “The comparison between point clouds generated during the 2016 campaign had the aim of assessing their geometric quality before their application for the analysis of hazards. These evaluations were also expected to provide some guidelines for the organization

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of future investigations in the field at the Forni Glacier and in other Alpine sites. Specifically, we analysed point density (points/m2) and completeness, i.e. % of area in the ray view angle. ”

RC Line 367 Page 16: What about rephrasing such as: "that applies different criteria and metrics for point clouds generated from (i) UAV photogrammetry, (ii),..."?

AC: We have rephrased the paragraph as described in the previous comment.

RC Line 368 Page 16: criteria and metrics are vague terms. Can you please develop?

AC: The criteria used are those cited in the manuscript. We have therefore deleted this sentence.

RC Lines 372-375 Page 16: I think most people in this field of research know this. I would consider removing this sentence and the previous one.

AC: We have deleted this paragraph accordingly.

RC Lines 378-390 Page 16-17: This paragraph shows that the authors put effort in trying to explain the reader what the different point-cloud properties are. However, I think this is known from many people in the field and too detailed. My suggestions how to give the definition (in brakets) are below.

AC: We have deleted the paragraph accordingly.

RC Lines 391-392 Page 17: insert short description of criteria between brackets.

AC: we have replaced the description of point density and completeness as suggested. We have replaced the description of accuracy with a description of point cloud comparison in view of your major comment concerning the difference between accuracy and comparison. The paragraph now reads: “Specifically, we analysed point density (points/m2) and completeness, i.e. % of area in the ray view angle. Point density partly depends upon the adopted surveying technique, since it is controlled by the distance between sensor and surface and the obtainable spatial resolution. In SfM-

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Photogrammetry, the latter property is affected by dense matching, while in TLS it can be set up as data acquisition input parameter. In this study, the number of neighbours N (inside a sphere of radius R=1 meter) divided by the neighbourhood surface was used to evaluate the local point density D in CloudCompare (www.cloudcompare.org). To understand the effect of point density dispersion (Teunissen, 2009), the inferior 12.5 percentile of the standard deviation of point density was also calculated. The use of these local metrics allowed to distinguish between point density in different areas, since this may largely change from one portion of surface to another. A further metric in this sense was point cloud completeness, referring to the presence of enough points to completely describe a portion of surface. In this study, the visual inspection of selected sample windows was used to identify occlusions and areas with lower point density. To analyse these properties, five regions were selected (see Fig. 5), located on the glacier topographic surface and characterized by different glacier features and the presence of hazards. The analysis of local regions was preferred to the analysis of the entire point clouds for the following reasons: 1) the incomplete overlap between point clouds obtained from different methods; 2) the opportunity to investigate the performances of the techniques in diverse geomorphological situations. Finally, we compared the point clouds in a pairwise manner within the same sample windows. Since no available benchmarking data set (e.g. accurate static GNSS data) was concurrently collected during the 2016 campaign, the TLS point cloud was used as a reference, as it less influenced by controlling factors (network geometry, object texture, lighting conditions). When comparing both photogrammetric data sets, the one obtained from UAV was used as reference because of the even distribution of point density within the sample windows. The presence of residual, non-homogenous geo-referencing errors in the data sets required a specific fine registration of each individual window, which was conducted in CloudCompare using the ICP algorithm (Pomerleau et al., 2016). Then, point clouds in corresponding sample windows were compared using the M3C2 algorithm implemented in CloudCompare (Lague et al., 2013). This solution allowed us to get rid of registration errors from the analysis, which could then be focused on the

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capability of the adopted techniques to reconstruct the local geometric surface of the glacier in an accurate way. ”

RC Line 393 Page 17: insert “are”. I am not sure we can talk about "geomorphological properties" for something that looks more like "glacier features". If you don’t like it, properties is the word to change ;-) And maybe hazard-prone areas? Remember that your paper is on hazards.

AC: we have removed both “are” to shorten the sentence. We have replaced “geomorphological properties” with “glacier features” and added “and the presence of hazards”. The sentence now reads: “To analyse these properties, five regions were selected (see Fig. 5), located on the glacier topographic surface and characterized by different glacier features and the presence of hazards.”

RC Lines 393-394 Page 17: This is a repetition of the first sentence.

AC: We have deleted this sentence accordingly.

RC Lines 394-397 Page 17: This is a repetition of the first two sentences.

AC: we have deleted the first sentence but kept the ones motivating the choice of analysing individual regions to answer the other Reviewer’s comment.

RC Line 398 Page 17: Maybe change these words with "location" or synonym? sample window is not very clear.

AC: We have replaced “window” with “location” or “sample area” throughout the manuscript.

RC Line 410 Page 18: I would more refer to an area (m2).

AC: We now specify the area in Table 2.

RC Lines 411-413 Page 18: Here I would specify that not all location were surveyed (or only partially surveyed), by writing for instance "when available" or something alike.

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Then the next two sentences are not needed anymore.

AC: We have deleted this sentence and added “where available” accordingly.

RC Lines 413-417 Page 18: This belongs to the discussion

AC: We have moved this part to the discussion section.

RC Lines 418-443 Pages 18-19: This would rather belong to a method section. It would be better for the reader to read a Method section first, were you detail all statistical calculation you will perform, and only display the results in the Results section.

AC: We have moved this part to the methods section and shortened it as suggested by reviewer and as described in the answer to your comment at line 391.

RC Line 444 Page 20: Here I would include what you actually see in this table (you wrote a full paragraph later in the text that can be summarized such as. "Although these values ranges from 103 to 2297 points/m2 depending on the surveying method, the density was sufficient for the reconstruction of the different surfaces (depicted on Fig. 7), except in the case of the location 5.") Figure 8 only displays few numbers of Table 5. So removing it would decrease your high number of Figures ;-)

AC: We have removed Figure 8 accordingly. We have rephrased the paragraph as: “The analysis of point density shows significant differences between the three techniques for point cloud generation (see Table 2). Values range from 103 to 2297 points/m2 depending on the surveying method, but the density was generally sufficient for the reconstruction of the different surfaces shown in Fig. 5, except for location 5. Terrestrial photogrammetry featured the highest point density, while UAV photogrammetry had the lowest. In relation to UAV photogrammetry, similar point densities were found in all sample locations, especially for the standard deviations that were always in the range 22-29 points/m2. Mean values were between 103-109 points/m2 in locations 2-4, while they were higher in location 5 (141 points/m2). Due to the nadir acquisition points, the 3D modelling of vertical/sub-vertical cliffs in location 1 was not possible. In

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relation to TLS, a mean value of point density ranging from 141-391 points/m2 was found, with the only exception of location 5, where no sufficient data were recorded due to the position of this region with respect to the instrumental standpoint. Standard deviations ranged between 69-217 points/m2, moderately correlated with respective mean values."

RC Line 445-458 Page 20: From line 445, this belongs to the discussion.

AC: We have moved this part to the discussion section and shortened it.

RC Line 451 Page 20: You defined them already one time and using (i) are for enumerating a list and not a word. I would consider creating an accronym.

AC: we have removed ordinals accordingly.

RC Line 458 Page 20: This section could be shortened (written in a denser manner).

AC: we have shortened this section accordingly.

RC Lines 459-468 Pages 20-21: This might also go in a method section?

AC: This part was shortened and moved to the methods section as described in the answer to your comment at line 391.

RC Lines 469-476 Page 21: This section could be shortened and set around line 444. You can either put the numbers in the text or in a table (better) but not both, because this makes a repetition.

AC: We have deleted this part as numbers are already shown in the table

RC Lines 477- 485 Page 21: This paragraph belongs to the discussion and I think could be more concise.

AC: Part of this paragraph was kept in the results section as it only shows a numeric comparison. Relevant considerations were made in the discussion section.

RC Lines 486-492 Pages 21-22: Same as above paragraph. It belongs to the discus-

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sion. It also should be more concise.

AC: Part of this paragraph was kept in the results section as it only shows a numeric comparison. Relevant considerations were made in the discussion section.

RC Line 493 Page 22: Are the two Figures showing similar results but for two different location? If yes, I think only having one of them is enough and I would remove Fig. 10.

AC: We have removed Figure 10 accordingly.

RC Line 497 Page 22: Fig.11 should come first. Refer to another figure to understand a figure is not great. It means that one would be enough. Is Figure 12 really needed?Refer to another figure to understand a figure is not great. It means that one would be enough. Is Figure 12 really needed? What results? What did you do in this figure? How did you merged two point clouds from different methods? where they corresponding? How is that better? The first question should go in the method section, the second in the results and the third in the discussion ;-)

AC: We have removed Figure 12. The sentence “Results are also satisfying in gently sloped areas, as it can be observed in windows 2 and 3” has been removed. We now specify how the merging was performed in the methods section, and discuss the improvements of merging in the discussion section.

RC Line 499 Page 22: what terrestrial sensor? Inserting a camera in cavities and take pictures in the cavity? why this has not been possible with terrestrial photogrammetry?

AC: The sentence lacked clarity and has been deleted.

RC Lines 500-503 Page 22: This paragraph could be merged with the previous one. The outcome of the last 2-3 paragraphs is on the advantages and drawbacks of each methods. This should be written clearly and in the discussion section.

AC: The paragraph was shortened and merged in the new discussion section.

RC Lines 504-514 Pages 22-23: Same comment as above. And please it would be

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nice if you select only the useful information for the reader.

AC: The paragraph has been shortened and merged in the new discussion section.

RC Line 516 Page 23: Here I understand that fractures and faults are not well reconstructed and therefore can be well detected. For what is this information? Can you specify? Otherwise I would think that where you have partial reconstruction is where you have fractures and faults and this is where the hazards are located.

AC: This sentence lacked clarity and has therefore been deleted.

RC Lines 518-522 Page 23: I think these two sentences are not necessary for the reader, which could get confused.

AC: We have removed this part accordingly.

RC Line 522 Page 23: Insert “such as”.

AC: We have rewritten this sentence as: “Since no available benchmarking data set (e.g. accurate static GNSS data) was concurrently collected during the 2016 campaign, the TLS point cloud was used as a reference, as it less influenced by controlling factors (network geometry, object texture, lighting conditions).” in view of your major comment on accuracy.

RC Line 524 Page 23: Replace “to compare” with “for comparison”

AC: We have removed this part to shorten the manuscript.

RC Line 526 Page 23: the point clouds in a pairwise manner. (or reformulate in a similar way)

AC: We have rephrased this sentence as “Finally, we compared the point clouds in a pairwise manner within the same sample areas.”.

RC Line 527 Page 23: selected location

AC: We have replaced “sample windows” with “selected locations” accordingly.

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RC Line 530 Page 23: Is that the ICP from cloud compare as well?

AC: We have added “in CloudCompare” at the end of the sentence.

RC Lines 532-539 Pages 23-34: This algorithm has already been used in the studies of x and x for instance and proved to be suitable for ... . This is enough for the reader to know why you used that one. There is no need to go in details and explaning what the advantage of this algorithm is.

AC: We have deleted this part to shorten the manuscript.

RC Line 534 Page 23: I do not understand the meaning of "positive direction of distances" can you please explain or reword?

AC: This part has been deleted as suggested in your previous comment.

RC Line 541 Page 24: The second part of the sentence make the reader think that your reference point cloud is actually bad.

AC: We have deleted the second part of the sentence as it lacked clarity.

RC Lines 518-543 Pages 23-24: From L518 to here is information that could go in the method section.

AC: We have moved this information in the methods section accordingly, see the answer to your comment at line 391.

RC Line 546 Page 24: We can see this in the table.

AC: We have rephrased this paragraph as: “In terms of point cloud distance (see Table 3), the comparison between TLS and terrestrial photogrammetry resulted in a high similarity between point clouds, with no large differences between different sample windows. Conversely, the comparison between TLS and UAV photogrammetry and terrestrial and UAV photogrammetry provided significantly worse results, which may be summarized by the RMSEs in the range 21.1-37.7 cm and 20.7-30.4 cm, respectively.

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The worse values were both obtained in the analysis of window 2, which mostly represents a vertical surface, while the best agreement was found within window 3 which is less inclined. As the UAV flight was geo-referenced on a set of GCPs with an RMSE of 40.5 cm, the ICP co-registration may have not totally compensated the existing bias."

RC Line 548 Page 24: departures? what does that mean in this context? or do you mean outliers?

AC: We have replaced the word "departures" with "differences".

RC Line 558 Page 24: This is italian-english ;-) Would "make use of" or "using" work in the sentence instead?

AC: We have replaced "recurring to" with "placing". The sentence has been also moved to the discussion section.

RC Line 561 Page 25: Not right word. see comment above.

AC: We have removed this sentence and moved considerations in the discussion section.

RC Line 571 Page 25: not only... there is also 2007 and 2014 as well as 2014 and 2016. Maybe change the title to fix this issue?

AC: we have changed the title to "glacier thickness change" accordingly.

RC Lines 574-576 Page 25: delete this part.

AC: We have deleted this part accordingly.

RC Line 576 Page 25: When different area of interest are used for computation, it is very hard to compare and make use of these results. Table 8 does it very well, so I would not include Table 7. AC: We have removed table 7 accordingly.

RC Lines 576-579 Page 25: No need to talk about maximum extension of DEMs. I think it is normal that authors display all data available

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AC: We have removed reference to the maximum extension of DEMs.

RC Lines 579-581 Page 25: I think the reader understood this already from the previous paragraphs

AC: We have removed this sentence accordingly.

RC Lines 581-583 Pages 25-26: Delete this sentence

AC: We have shortened the paragraph, which now reads: “After DEM co-registration, the resulting shifts reported in Table 1 were applied to each ‘slave’ DEM, including the entire glacier area. Then the elevations of the ‘slave’ DEM were subtracted from the corresponding elevations of the ‘master’ DEM to obtain the so called DEM of Differences (DoD). Over a reference area common to all three DEMs (Fig. 1), we estimated the volume change and its uncertainty following the method proposed in Howat et al. (2008), which expresses the uncertainty of volume change as the combination of the standard deviation computed from the residual elevation difference over stable areas, and the truncation error implicit when substituting the integral in volume calculation with a finite sum, according to Jokinen and Geist (2010).”, and moved it to the methods section.

RC Line 588 Page 26:So where are the results? Table 8?

AC: the results are provided in table 4 (former table 8) but since the part has been moved to the methods section the reference to the table is only provided in the results section.

RC Lines 589-591 Page 26:I would not include this. The reader does not get much information out of it. And "only lost 15m" is a point of view ;-)

AC: we have deleted this sentence accordingly.

RC Line 602 Page 26:This paragraph is unclear to me and the numbers are questionable. How can (L.595) an ice thickness change be of -40 to -50m over 2 years? And a

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few lines below (L.598) have a glacier thinning of 10m over the same amount of time?

AC: “2014” at line 595 should have read “2007”, while “10 m” at line 599 was lacking a minus sign. However, to improve clarity, we have rewritten the paragraph. We use minus signs when we employ the term “change” and no sign when we talk about thinning since the term already implies a loss. The paragraph now reads:“The Forni Glacier tongue was affected by substantial thinning throughout the observation period. Between 2007 and 2014, the largest thinning occurred in the eastern section of the glacier tongue, with changes persistently below –30 m, whereas the upper part of the central tongue only thinned by 10/18 m. The greatest ice loss occurred in correspondence with the normal faults localized in small areas at the eastern glacier margin (see Fig. 8a), with local changes generally below -50 m and a minimum of -66.80 m, owing to the formation of a lake. Conversely, between 2014 and 2016 the central and eastern parts of the tongue had similar thinning patterns, with average changes of -10 m. The greatest losses are mainly found in correspondence with normal faults, with a maximum change of -38.71 m at the terminus and local thinning above 25 m on the lower medial moraine. The ring fault at the left margin of the central section of the tongue also shows thinning of 20/26 m. In the absence of faults, little thinning occurred instead on the upper part of the medial moraine, where a thick debris cover shielded ice from ablation, with changes of -2/-5 m (see Fig. 8c). Considering a common reference area (see Fig. 1, table 4), an acceleration of glacier thinning seems to have occurred over recent years over the lower glacier tongue, from -4.55± 0.24 ma-1 in 2007-2014 to -5.20± 1.11 ma-1 in 2014-2016, also confirmed by the value of -4.76± 0.29 ma-1 obtained from the comparison between 2007 and 2016. Comparing the first two DoD, the trend seems to be caused by the increase in collapsing areas (Fig.8a,b). This equates to 13.46 ±0.14 million m3 of ice lost over the entire study period. ”

RC Line 606 Page 27: replace “fused together” with “merged” and “merged” with “resulting.

AC: We have replaced “fused together” with “merged” and “merged” with “final”. New

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information has been added as described in the answer to your major comment concerning Subsection 3.3 (Lines 571 to 602)

RC Line 609 Page 27: Is that Figure 12? If yes please precise.

AC: The RGB colored point cloud can now be seen in Fig. 5

RC Line 635 Page 28:Would be nice to start talking about the upper transect, then middle, and finally lower. This paragraph gives new information and does not discuss or directly links to the results found. Please make it more clear why you now describe the glacier tongue in detail.

AC: The entire section has been deleted as not strictly relevant to this study.

RC Line 645 Page 28: Same comment than above. This new information has nothing to do in the discussion section.

AC:The entire section has been deleted as not strictly relevant to this study.

RC Line 648 Page 28: geometry?

AC: we have deleted the second part of the sentence. The sentence has also been moved to the introduction section where we specify why we mapped these specific hazards.

RC Line 665 Page 29:what is a repeat pace?

AC: we have rephrased the sentence as: “It is likely that the terminus will recede along the fault system on the eastern medial moraine and following the ring faults at the eastern and western margins, increasing the occurrence of hazardous phenomena in these areas.”

RC Line 668 Page 29: two words

AC: we have deleted this part to shorten the manuscript.

RC Line 698 Page 30: roughness?

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AC: we have restructured the conclusion section and thus the word has been deleted.

RC Line 715 Page 31: There is not much luck in science ;-) ... " due to higher camera location/ image angles"...

AC: We have removed this sentence as the conclusion section has been restructured.

RC Line 742 Page 32: For all references: Please, - check the spelling of the journals (uppercase or not). - put doi or DOI but not a mix - put the doi at the end of the citation (after the year) and without the webpage - check that all articles have a volume a page and a doi. - check that your proceedings references all have the same information in the right order (in the journal guidelines).A For all references, we have checked the journal spelling replacing lowercase with uppercase letters and kept the full name for consistency. We have added the doi were it was missing (always lowercase) and placed it always at the end of the reference, after the year. Now every entry has volume, pages and doi, except: Fioletti et al., 2016; Mugnier, 2005; Riccardi et al. 2010; Teunissen, 2009 and conference proceedings except for the ones from 2016 - No doi available Berthier et al., 2016; Gagliardini et al., 2011; Howat et al. 2008; Ryan et al., 2017; Urbini et al., 2017 - in Geophysical Research Letters, Annals of Geophysics and Frontiers in Earth Science the page number is not indicated as each article is numbered separately starting from 1. Only the letter or article number is reported and we have added that in the manuscript.

Please also note the supplement to this comment:
https://www.nat-hazards-earth-syst-sci-discuss.net/nhess-2017-198/nhess-2017-198-AC2-supplement.pdf

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Interactive comment on Nat. Hazards Earth Syst. Sci. Discuss., https://doi.org/10.5194/nhess-2017-198, 2017.

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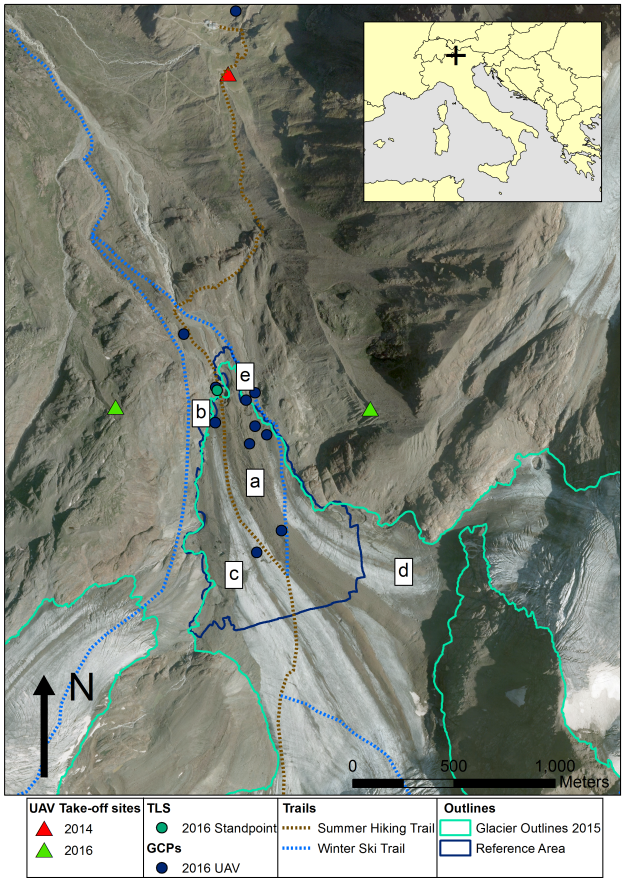

Fig. 1.

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Aircraft type	Swinglet CAM, Commercial platform
Digital Camera	Canon Ixus 127 HS
Camera technical features	16 Megapixel, focal length 4.3 mm
GNSS antenna	GPS only
Weight (incl. payload)	0.50 Kg
Battery time	30 minutes

Aircraft type	Customized, with Tarot frame 650 size, VR Brain 5.2 Autopilot & APM Arducopter 3.2.1 Firmware
Digital camera	Canon Powershot ELPH 320 HS
Camera technical features	16 Megapixel, focal length 4.3 mm
GNSS antenna	GPS+GLONASS (Galileo compatible)
Weight (incl. pay-load)	2.75 Kg
Battery time	20-25 minutes

Fig. 2.

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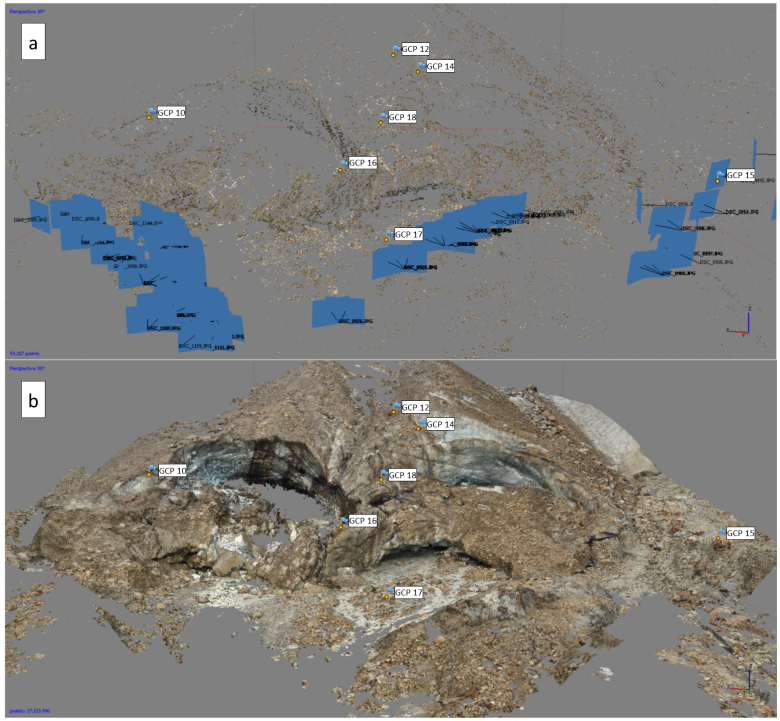

Fig. 3.

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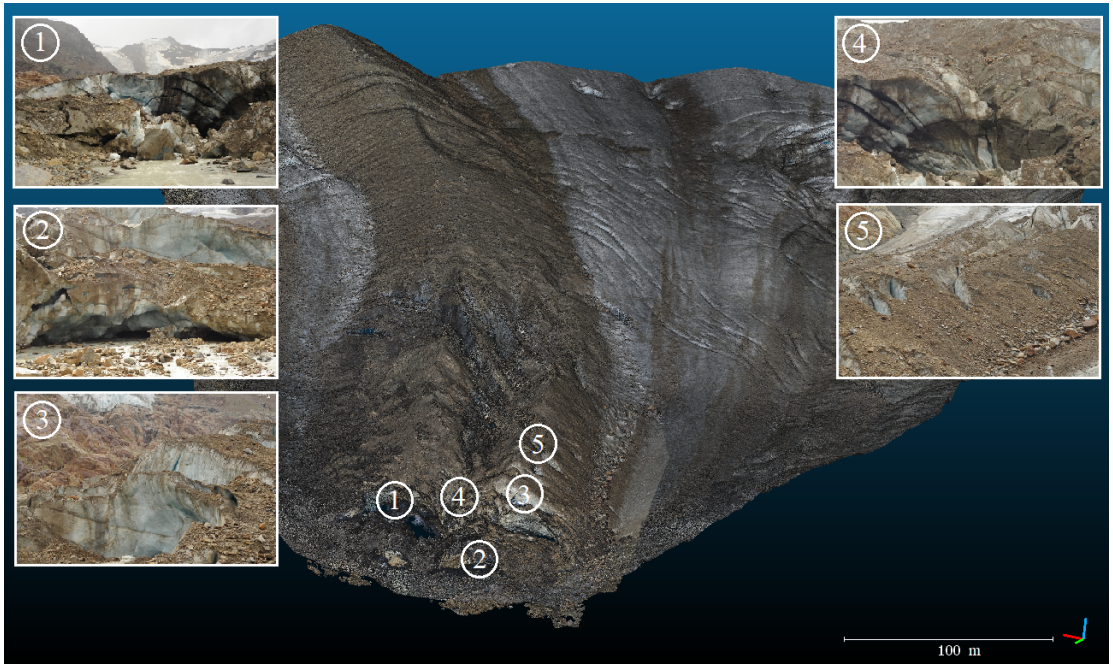

Fig. 4.

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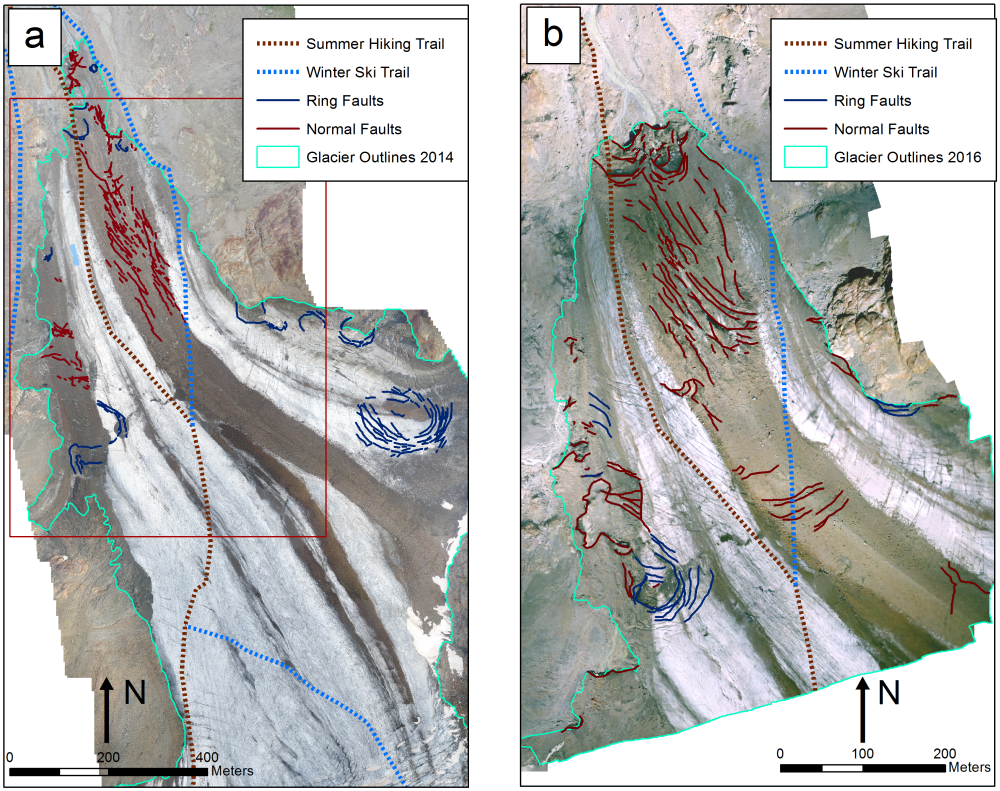

Fig. 5.

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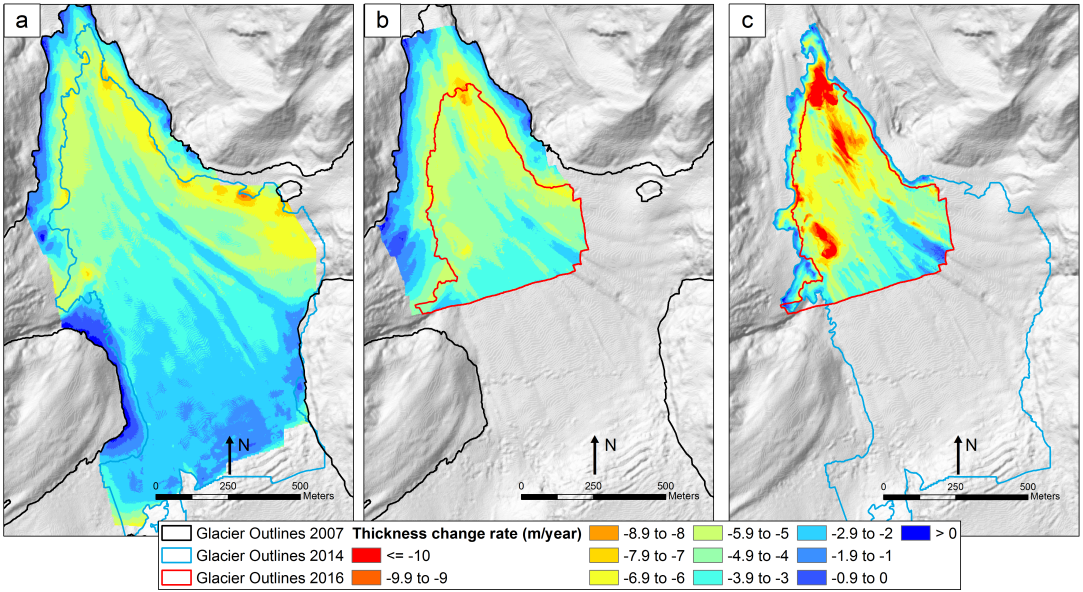

Fig. 6.

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