Dear Editor,
We have carefully revised the manuscript taking into account all comments suggested by the reviewers.
We have specifically rewritten the introduction and conclusion section to clarify the reasons and the aims of our study and summarize the main findings. We have also restructured the methods and results section to clearly separate them and written a new discussion section to comment on the differences between the techniques used in this study, the individual advantages and possible future improvements.
We think that the manuscript has improved and that the final result is clearer and more readable. We are grateful to the reviewers for their detailed and helpful comments.

You will find in the following text the detailed responses to the reviewers' suggestions and comments with relevant changes made to the manuscript directly reported in our answers. Finally, a marked up version of the manuscript with all changes is provided.

We hope that the revised version of the manuscript can now meet the reviewers' expectations and can be accepted for publication; otherwise, we are open to new improvements.

Best regards,
Davide Fugazza & coauthors.

We have prepared a point by point response to the reviewer's comments. In the following text, reviewer's comments are reported as RC and highlighted in italic, our answers as AC in plain text, while our changes to the text are in bold black.

RC

REVIEW OF THE MANUSCRIPT ENTITLED:

Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and conditions of glacier hazards

By D. Fugazza et al.

General comments

In this paper, Fugazza et al. present the results of photogrammetric surveys carried out on the lower ablation area of the Forni Glacier in 2014 and 2016. The surveys were performed using photographs taken from the ground and from unmanned aerial vehicles, and their results have been used for intercomparisons aimed at evaluating the accuracy of used techniques, for quantification of glacier changes across 9 years, and for the identification of hazards deriving from the current rapid shrinking of the glacier.

The work is interesting and potentially useful as a baseline for future developments of these remote sensing techniques. However, there are several points of the paper that require formal and substantial improvements. In particular:

i) there are several claims of uniqueness, originality, lack of previous work and of scientific knowledge, which are untrue and deserve a careful literature review by the authors. Consequently, the results are not unique, and have to be critically assessed in light of previous findings by other authors

ii) pros and cons of the tested methods require a thorough discussion, as well as their repeatability (e.g. the peculiar cloud cover conditions) and generalizability, costs, logistics and alternative solutions. A very weak point that requires discussion, in my opinion, is the limited areal extent of the surveyed zone, preventing possible applications aimed, for example, at the estimation of the glacier-wide geodetic mass balance. In addition, such a large glacier normally has several other hazardous areas along mountaineers' tracks, which cannot be comprehensively surveyed using the proposed approach. Which improvements (or alternative methods) would be required?

The paper is rather long and contains many descriptive sentences, too generic periods, scholastic explanations. In particular the Results section is difficult to read and wordy. My suggestion is to really focus on the results of the investigations, strongly shortening this part, and moving any (relevant) consideration in the Discussion section.

A careful English proof reading is also required to improve the readability and to make the manuscript appealing. The authors should also consider reducing the self-citations, which currently contribute to one third of the reference list.

In my opinion, the manuscript requires a major revision before being considered for publication in NHESS. A more complete description of the required formal and substantial improvements is reported in the following section.

AC

Dear Reviewer,

thank you for your comments. We have rewritten the introduction section reconsidering research gaps and aims of our work in view of the wider literature. We have also rewritten the discussion section entirely, comparing our results with findings from previous studies and discussing advantages and disadvantages of the techniques used in this study, including the small size of the area investigated. We have greatly shortened the manuscript, with particular attention to the results section, by summarizing key points, and moving considerations to the discussion section. We have carefully proofread the manuscript to improve its clarity and appeal and reduced self-citations and the number of citations in general. The answers to your major and minor comments are provided below.

RC Detailed comments

RC Line 30 Page 1: snow cover thickness and/or duration?

AC We have deleted this sentence to shorten the introduction section.

RC Line 39 Page 2: changes of glacier and…

AC We have deleted this sentence to shorten the introduction section.

RC Line 40 Page 2: anthropic activities

AC We have deleted this sentence to shorten the introduction section.

RC Lines 39-63 Pages 2-3: some of the mentioned processes are not strictly depending or worsened by climate variations. They are instead typical of the glacial, periglacial and paraglacial environments. I suggest rewriting this part to clarify which processes are typical and which ones are worsened by the current climatic phase. I also suggest mentioning debris flows

AC: We have rewritten the introduction section which now has a sharper focus on glacier hazards, distinguishing between those typical of glacial environments and those that are worsened by climate variations. We also mentioned debris flows following your suggestion. The paragraph 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, affecting even populations living away from glaciers. Finally, glacier retreat and the increase in glacier hazards negatively influence the tourism sector and the economic prosperity of high mountain regions (Palomo, 2017).**"

RC Line 68 Page 3: please add some references concerning glacier change detection using DEMs

AC: We have added “**Fischer et al. (2015); Berthier et al. (2016)**” accordingly.

RC Line 72 Page 3: remove indeed

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

RC Line 92 Page 4: please replace battery support with e.g. battery life or charge duration

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

RC: Line 110 Page 5: must be completely observable from….

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

RC: Lines 114-118 Page 5: previous work reporting comparison between photogrammetry and LiDAR or more traditional survey techniques on glaciers actually exists. Please, see for example Kaufmann and Ladstädter (2008), Piermattei et al., (2015 and 2016), Kaufmann and Seier (2016), Westoby et al., (2016), Seier et al., (2017), and contributions in the book from Pellikka and Gareth Rees (2010).
Kaufmann, V. and Seier, G., 2016. LONG-TERM MONITORING OF GLACIER CHANGE AT GÖSSNITZKEES (AUSTRIA) USING TERRESTRIAL PHOTOGRAMMETRY. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 41.
Kaufmann, V. and Ladstädter, R., 2008. Application of terrestrial photogrammetry for glacier monitoring in Alpine environments. Ele, 2700(2800), p.2900.
Petri Pellikka, W. Gareth Rees. Remote Sensing of Glaciers, Taylor & Francis Group, London, UK (2010)
Seier, G., Kellerer-Pirklbauer, A., Wecht, M., Hirschmann, S., Kaufmann, V., Lieb, G.K. and Sulzer, W., 2017. UAS-Based Change Detection of the Glacial and Proglacial Transition Zone at Pasterze Glacier, Austria. Remote Sensing, 9(6), p.549.
Westoby, M.J., Dunning, S.A., Hein, A.S., Marrero, S.M. and Sugden, D.E., 2016. Interannual surface evolution of an Antarctic blue-ice moraine using multi-temporal DEMs. Earth Surface Dynamics, 4(2), p.515.

AC: Thank you for the interesting list of articles which we had overlooked. We have rewritten this paragraph, mentioning studies conducted with terrestrial and UAV photogrammetry in high mountain glacial environments. The paragraph now reads: “**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 environments needs to be investigated and assessed**.”.

RC Line 119 Page 5: protected in which sense?

AC: Forni Glacier lies in Stelvio National Park, which is a protected area under the Italian law. We have added “**(Stelvio National Park)**” to clarify this point.

RC Line 121 Page 5: two distinct aircrafts

AC: The words within parentheses have been deleted as suggested by the other reviewer.

RC: Line 124 Page 5: please provide a length for short and long time scales

AC: We have rewritten this sentence as "**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.**" to clarify the length of scales involved.

RC: Lines 125-126 Page 5: please try to improve this sentence, which is too long

AC: We have rewritten this sentence as: "**identifying glacier-related hazards and their evolution between 2014-2016 using the merged point cloud from UAV and terrestrial photogrammetry and UAV orthophotos**". The description of glacier hazards mapped in this study was moved at the start of the paragraph.

RC Line 129 Page 6: confluencing ice tongues?

AC: This part has been deleted as suggested by reviewer 2.

RC Line 134 Page 6: retreating rate? Shrinking rate?

AC: The papers describe an acceleration in the shrinking rate. We have changed the sentence accordingly.

RC Lines 135-136 Page 6: AWS1 Forni was not the first. There is at least one precedent, i.e. the AWS that has been operated on the Careser Glacier (10 km from Forni) from 1989 to 1998 (Rossi and Stojkovich, 1992; Novo and Rossi, 1998).
Rossi G. C. and Stojkovic, P. (1992) Scientific programmes for meteo-climatic and environmental observations in Alpine glacial areas. Presented at First Ev-K2-CNR Scientific Conf. on Scientific and Technological Research at High Altitude and Cold Regions. Milano, 10–11 April 1992.
Novo, A. and Rossi, G.C., 1998. A four-year record (1990–94) of snow chemistry at two glacier fields in the Italian Alps (Careser, 3090m; Colle Vincent, 4086m). Atmospheric Environment, 32(23), pp.4061-4073.

AC: The sentences concerning the AWS have been deleted as not strictly relevant to this study.

RC: Lines 142-155 Page 6: I suggest shortening these points and possibly moving some of the concepts and references in the discussion section (if relevant). In section 1.2 all references are self-references. I wonder how much they are functional to this work.

AC: We have deleted the sentences about recent glacier changes, the AWS (see previous comment) and previous research on the site (and related references), deleted bullet points and merged their content with the previous sentence, as suggested by reviewer 2. The paragraph now reads: "**The Forni Glacier (see Fig. 1) has an area of 11.34 km^2 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 km^2 (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 Line 159 Page 7: the meaning of reconstructing is not fully clear, I suggest writing explicitly that it is a topographic survey (also in the following)

AC: We have revised in the paper the use of the term "reconstruction," changing or integrating this word to make it clear we mean the generation of a faithful digital 3D model of the object. The term "topographic survey" is generally used when geodetic methods are applied, so we preferred to use of "3D surface reconstruction", "3D modelling" or "point cloud acquisition."

RC Lines 169-171 Page 7: it is not clear why morning hours should be preferable to the central hours of the day. Please state it clearly.

AC: The explanation is provided in the description of the 2014 survey, which has now been moved to the top of the data section as suggested by you and the other reviewer.

RC Lines 171-173 Page 7: it is not clear how low cloud cover inhibits direct solar radiation, it should be the contrary. Moreover, what to the authors mean with low cloud cover? Which fraction of the sky covered? By which type of clouds? And why should the direct solar radiation be avoided? How often can these ideal meteorological conditions be met in the alpine environment during summer? Which is the impact of ice ablation during the three-day survey period? Is there any measurement? In my opinion this information is of relevance for future applications and repeatability of the proposed survey techniques.

AC: The reason why direct solar radiation should be avoided is that it can lead to image saturation on highly reflective surfaces such as ice or snow, as explained in the paragraph describing the 2014 survey. On both surveys in 2016, the weather was too unstable in the morning (i.e. chance of rain). When we actually undertook the surveys, the sky was overcast, i.e. 8/8 of the sky were covered by stratocumulus clouds. We thus found that these peculiar cloud cover conditions are suitable for UAV flights, while also common in Alpine environments during the summer.
We have rephrased this sentence as "**both around midday with 8/8 of the sky covered by stratocumulus clouds**" and further discuss meteorological conditions in the discussion section where we have added a paragraph that reads: "**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.**".
As concerns the impact of ice ablation, measurements from ablation stakes collected in summers 2009-2010 (Senese et al., 2012) and 2015 (unpublished data) indicate values of 3-5 cm day^{-1}. Additionally, Ice flow ranges between 1 and 4 cm day^{-1} (Urbini et al., 2017). This mostly affected the photogrammetric reconstruction of the UAV dataset from 2016 as surveys were performed two days apart and the last one 3 days since GCP

placement, and the comparison between the UAV point cloud and other techniques. Measurements of the vertical displacement of stakes taken with GNSS in 2006 also show similar values ranging between 2.8 and 4.6 cm day^{-1} (unpublished data). We can thus hypothesize a combined effect on the uncertainty of UAV photogrammetric reconstruction between 10 and 20 cm, and lower on GCPs as they were placed on boulders where ablation is reduced.
have added a paragraph in the discussion section that reads: "**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, being only one day apart, was less affected by glacier change 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.**".

RC Line 177 Page 8: potentially causing motion blur to the acquired imagery

AC: This sentence was shortened as suggested by Reviewer 2.

RC Line 179 Page 8: at a relatively low altitude of 50 m

AC: By "Relative" in this sentence we meant "relative to ground". We have rephrased the sentence to clarify this point, from "**with flights at low relative altitude of 50 m**" to "**with a flying altitude of 50 m above ground**"

RC Line 216 Page 9: please consider replacing coordinate frame with coordinate system (also in the following)

AC: We have replaced the word frame with system accordingly throughout the manuscript.

RC: Line 218 Page 10: same days of the UAV survey?

AC: We have specified the exact dates when the surveys took place. We discuss potential issues due to ice ablation between surveys in the discussion section, as described in the answer to your comment at lines 171-173.

RC Line 225 Page 10: consider replacing pipeline with workflow

AC: We have replaced this word accordingly.

RC Line 245 Page 11: evolves rapidly, or is rapidly evolving

AC: This sentence was deleted as it was connected to the following one, see next comment.

RC Line 246 Page 11: it is unclear why a complex shape and a rapid evolution make the glacier terminus not suitable for quantitative evaluation of the ice bulk? What do the authors mean with this sentence?

AC: We have removed this sentence as it lacked clarity and was unnecessary for the reader.

RC Line 249 Page 11: including GCP surveying

AC: We have modified the manuscript accordingly. The sentence was moved to the Discussion section as suggested by Reviewer 2.

RC: Line 251 Page 11: same days of the UAV survey?

AC: The TLS survey was conducted on the same day as the first UAV survey. We have added "**On the same days as the first UAV survey of 2016,**" at the start of the paragraph to clarify this point.

RC Line 268 Page 11: remove the purpose of

AC: We have modified the manuscript accordingly

RC Line 274 Page 12: how much stable has to be considered a GCP placed at the glacier surface, close to the terminus and for more than one day during the ablation season? Please discuss this issue

AC: All GCPs at the terminus were actually located on large boulders, whereas only one GCP at the highest site on the central part of the tongue was placed directly on the glacier surface. Large boulders are known to shield the underlying ice from ablation, often leading to the formation of glacier tables. Thus, the effect of ice ablation on GCPs is reduced. We have added a paragraph concerning this issue in the discussion section, see the answer to your comment at lines 171-173.

RC: Lines 284-285 Page 12: with which consequences? Fewer than planned surveyed GCPs? Why not using post-processing correction?

AC: Two of the points had to be collected and post-processed in fast-static mode due to the loss of radio connection. This effect could have not been planned in advance. We have added: "**Non-RTK points were processed in fast-static mode, requiring a longer measurement time of approx. 12 minutes.**"

RC Line 287 Page 13: in my opinion it should be better arranging the methods in chronological order

AC: The paragraph about the 2014 survey was moved to the top of the data section, in accordance with your comment and the other reviewer's. We have followed the other reviewer's suggestion as to the order of the data section, leaving the 2007 aerial photogrammetric data at the bottom as it is the only dataset we did not collect ourselves and we believe it should be separated from the others.

RC Lines 294-301 Page 13: here is the explanation why early morning is preferable. Another reason for moving this part above the 2016 survey, according to me. What about cast shadows? Are they a further reason to avoid direct solar radiation and/or surveys carried out later in the day, with the possible occurrence of shadows from scattered cumulus clouds? What is the repeatability of this method if applied to east-exposed glaciers?

AC: We did not experience cast shadows from cumulus clouds during the 2016 survey. Based on our experience with UAVs, it is generally possible to adjust camera settings (ISO, aperture and shutter speed) before each flight to account for different light conditions, and produce pictures that are suitable for photogrammetric processing (see also O'Connor et al., 2017), although cast shadows will decrease the image dynamic range and might complicate the matching process owing to the lack of contrast. As a rule of thumb, early morning flights with 0/8 cloud cover might generate the best images for photogrammetric processing, but are not always possible due to logistical constraints and meteorological conditions. As you also mention, it might not be possible to obtain these conditions when monitoring east-exposed glaciers. However, we also demonstrate how UAV flights with overcast conditions under stratocumulus clouds produce suitable images. We have added a paragraph where we discuss issues related to meteorological conditions in the discussion section, as described in the answer to your comment at lines 171-173.

RC Lines 332-340 Page 15: this part has some repetitions from previous paragraphs. Please rephrase

AC: This part was deleted to avoid repetitions.

RC Line 358 Page 16: what about spatial trends in elevation differences? Are they inexistent, negligible or not taken into account?

AC: We did not take into account spatial trends in elevation differences but when calculating the uncertainty of volume changes, we assumed the uncertainty of elevation differences as totally correlated in space. This is unlike other approaches where errors in elevation differences are assumed as random and the final uncertainty of volume change is smaller (Fischer et al., 2015). Thus, our estimates of volume change uncertainty represent a worst-case scenario.

Fischer, M.; Huss, M. and Hoelzle, M (2015). Surface elevation and mass changes of all Swiss glaciers 1980–2010, The Cryosphere, 9, 525-540

RC Lines 361-390 Page 16: this part is too long and does not present results

AC: This part has been condensed as follows: "**The analysis of 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 of future investigations in the field at the Forni Glacier and in other Alpine sites.** " and moved to subsection 4.1 in the methods section.

RC Lines 391-409 Page 17: why not using the entire overlapping area? The area surveyed by terrestrial photogrammetry is already small, therefore I do not understand why the authors decided to perform a (subjective) sub-sampling taking very small areas, which on the other hand are very similar to each other. I suggest comparing the entire area in common among the different surveys, and then analyse separately glacier areas with peculiar characteristics

AC: We have considered this suggestion. However, there are some independent registration errors in the data sets from UAV photogr., terrestrial photogr. and TLS. While these errors do not have any influence when analysing the point density and completeness, they do when computing the distances between point clouds. Therefore, we preferred to perform this analysis in individual sample locations, so that the errors due to registration could be compensated by a local refinement of the co-registration between point clouds.
We have therefore rewritten the paragraph about the comparison between point clouds as: "**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 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." and moved it to the methods section.

RC Lines 410-411 Page 18: please avoid describing in the text what figures and table present (their caption already does it)

AC: This sentence has been removed accordingly.

RC Lines 414-415 Page 18: a more dense point cloud? The term consistent has a too general meaning (and here is misleading)

AC: We have modified the manuscript accordingly.

RC Lines 415-417 Page 18: the flexibility of terrestrial photogrammetry, compared to UAV photogrammetry, is questionable

AC: We have modified the sentence as follows: "**Considering point density, terrestrial photogrammetry resulted in a denser data set than the other techniques. This is mostly motivated by the possibility 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.** ". The sentence was also moved to the discussion section.

RC Lines 419-432 Pages 18-19: please summarize this part and avoid too scholastic sentence such as the first. I suggest simply stating which metrics are used and which results they provided.

AC: This part has been shortened as follows: "**Specifically, we analysed point density (points/m^2) 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 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.**"

RC Lines 437-443 Page 19: here the authors skip to the concept of point cloud completeness, introducing a heuristic evaluation method that is not fully described. Afterwards, they resume with point density. My suggestion is to rearrange paragraphs in a more logical order

AC: This paragraph has been reorganized by introducing first point density and then point completeness. Visual inspection of the sample locations was used to identify areas of occlusions or with lower point density. We now specify this in the text as: “**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.**”

RC Line 445 Page 20: please remove the sentence: The following general considerations can be made (and other analogous sentences in the manuscript).

AC: We have removed this and similar sentences throughout the manuscript.

RC Line 448 Page 20: comparable or three times smaller?

AC: We have modified these sentence as follows since Table 5 already displays the results: “**Terrestrial photogrammetry featured the highest point density, while UAV photogrammetry had the lowest.**”.

RC Lines 454-455 Page 20: this is expected and confirmation of findings from previous works. Please add references

AC: We have reorganized this part of the text, which has been moved in the Discussion Section. This sentence has been modified as follows: “**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).** ”

RC Lines 455-458 Page 20: which are the practical consequences? Which method for which application? Please discuss in the appropriate section

AC: These sentences have been moved in the Discussion Section, where the optimal type of terrain per each method is described. The main practical consequence is that to have an exhaustive 3D model of the whole surface topography, both point clouds from terrestrial and UAV photogrammetry should to be merged. We have thus added a sentence in the Discussion section, which describes our practical suggestions and reads: “**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.** ”

RC Line 469 Page 21: this is another highly-expected result. However this is a very small area, compared to the entire tongue (or the entire glacier). Further considerations are required, e.g. in the discussion.

AC: This part was condensed as suggested by Reviewer 2, 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/m^2 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 high point density, while UAV photogrammetry had the lowest. ". We have added further considerations in the Discussion section as follows: "**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.** "

RC Line 477 Page 21: similar point densities were found

AC: We have modified the manuscript accordingly.

RC Line 484 Page 21: the former are more suitable….

AC: We have rephrased this sentence as described in the answer to your comment at lines 454-455

RC Line 486 Page 21: please see comment L445. These sentences make the paper boring and difficult to read

AC: We have modified the manuscript as follows: "**In relation to TLS, a mean value of point density ranging from 141-391 points/m^2 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.**"

RC Lines 491-492 Page 22: the suitability of a survey technique depends largely on the final aims of the survey. LiDAR DEMs obtained with point densities as low as 2 pt/m2 are enough for glacier-wide and/or regional scale glacier change assessments, for example. Please comment on that in the discussion

AC: These lines belong to a part that has been cancelled to shorten the manuscript. We discuss the suitability of the techniques employed in our study in the discussion section. While it is outside the scope of this manuscript to present a comprehensive comparison of aerial LiDAR vs UAV for natural hazard management and glaciological purposes, UAVs have already been used to cover distances up to 280 km^2, e.g. by Ryan et al. (2017). We thus believe they could eventually replace this technique for the purposes mentioned in the study. We have added a paragraph in the Discussion section that reads: "**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 Line 493 Page 22: please see comment L410

AC: We have modified the manuscript as follows: "**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.**"

RC Line 496 Page 22: please replace here and elsewhere "exposed upward" with horizontal, or sub-horizontal, or moderately sloping (maybe adding slope thresholds for improved understanding).

AC: The term has been modified accordingly throughout the manuscript.

RC Line 516 Page 23: the sections 3.1 and 3.1.1 are very long and can be highly summarized, presenting just the results and moving further considerations in the discussion section.

AC: We have shortened these sections. Relevant considerations have been moved to the Discussion Section following your comments.

RC Lines 518-523 Page 23: I suggest removing or strongly summarizing this part

AC: These lines were deleted to shorten the manuscript.

RC Line 523 Page 23: do the authors have ablation measurements (or estimates) during the survey period? What is the impact of glacier ablation in calculations?

AC: We have added a paragraph concerning this issue in the Discussion section, as described in your comment to lines 171-173.

RC Line 540 Page 24: retained or based on some metrics/methodological constraints?

AC: The accuracy of TLS is less influenced by controlling factors (network geometry, object texture, lighting conditions) than the accuracy of photogrammetry. For this reason we have decided to adopt TLS point clouds as benchmarks. We have thus added:"**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).** "

RC Line 576 Page 25: ΔDEM could be replaced by the more commonly-used dem of difference (DOD)

AC: We have replaced the term accordingly throughout the manuscript

RC Lines 575-579 Page 25: this part is poorly written and hardly readable/understandable. Please reformulate

AC: We have deleted this part as suggested by Reviewer 2.

RC Lines 579-581 Page 25: this part is obvious and redundant

AC: We have removed this sentence accordingly.

RC Line 593 Page 26: please complete numbers with minus sign and measurement units

AC: We have modified the manuscript accordingly. We use minus signs when we use the term “changes” but no sign when we use the term “thinning” and related since thinning already implies a loss. We have added measurement units wherever needed.

RC Line 594 Page 26: the eastern part of the ablation tongue

AC: We have rephrased as “**the eastern section of the glacier tongue**”

RC Lines 603-610 Pages 26-27: I am not fully convinced that the paper deserves section 3.3. My suggestion is to remove it and move concepts above, when the authors write about the complementarity of the two survey techniques.

AC: Merging of the two datasets required a fine coregistration which was important to mention. We have therefore moved Subsection 3.3 to the methods section and provided more information on the merging procedure, as suggested by Reviewer 2.

RC Lines 613-622 Page 27: the authors try to validate their geodetic mass balance estimates in the lower glacier tongue, using specific mass balance estimations at the surface, for one point (whose location is not reported). Their approach is not correct, because they are comparing single-point vs. mean areal estimates, which can be highly different in the study area given the high lateral gradients in mass balance and elevation changes (Fig. 11), likely attributable to debris cover and differential ablation. Moreover, local geodetic and glaciological mass balance estimates seldom match on glaciers, because the surface elevation change is the result of a complex combination of surface, internal and basal mass exchanges, and of ice dynamics. In particular, vertical displacements (emergence velocity) have to be quantified for local comparisons of the two methods (see for example Fischer, 2011; Sold et al., 2013).

Fischer, A., 2011. Comparison of direct and geodetic mass balances on a multi-annual time scale. The Cryosphere, 5(1), p.107.
Sold, L., Huss, M., Hoelzle, M., Andereggen, H., Joerg, P.C. and Zemp, M., 2013. Methodological approaches to infer end-of-winter snow distribution on alpine glaciers. Journal of Glaciology, 59(218), pp.1047-1059.

AC: We have deleted this paragraph accordingly.

RC Lines 612-645 Pages 27-28: in my opinion this is not discussion, but mostly a presentation of results. Here the authors should discuss the accuracy of their results, the problematics in data collection and processing, the generalizability and the added values of the employed techniques. In particular, they should provide a discussion of the pros and cons of the proposed approaches, a comparison of their results with the existing literature, and critical evaluation of local-scale high-resolution surveys vs. glacier-wide surveys, which are required for geodetic mass balance estimates and comprehensive glacier hazard mapping. Which of the used methods has the highest potential for monitoring rapid glacier evolution and deriving hazards? Is there a method that has the potential to become a standard in glacier monitoring strategies, according to the authors? With which improvements/adjustments?

AC: We have moved the description of glacier hazards to the results section and deleted the paragraph on geomorphological evolution of the glacier tongue as not relevant to this study. In addition, the new Discussion section has been rewritten by rearranging content from the results section and providing more information to discuss the issues mentioned in your comment.

RC Line 687 Page 30: I wonder if there is a more quantitative approach to be used here (such as DOD) to better exploit the new technologies. All the surface features described in this section are so large to be clearly visible by quick field observations and the tourist path can be easily changed accordingly. In my opinion the advantage of AUV and/or terrestrial photogrammetry lies in the possibility of automatically mapping and measuring these features from the DOD. Therefore, I suggest to add this quantitative assessments, starting from elevation changes as displayed in Fig. 11, where the collapse structures are evident.

AC: We agree that tourist paths can be changed but to do so, one requires a comprehensive mapping of hazard features and an insight into their evolution which can not be obtained by simple field observation.
While the areas that underwent substantial collapse can be easily mapped with an automatic approach from the DoD, in other areas manual interpretation is required to map newly opened fractures whose vertical displacement is too low to be effectively recognized and to distinguish them from crevasses. Recent fractures are particularly important to map to predict the future evolution of the glacier. Therefore, we preferred manually mapping the hazard features. We now clarify the methodological basis for this mapping in the methods, section 4.2 and added further information concerning the vertical displacement of features in the results section. Section 4.2 now reads: "**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 coherent 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.** "

RC Line 695 Page 30: increased rate of surface lowering (not necessarily equal to surface ablation).

AC: We now use the term "thinning" or "thinning rate" throughout the manuscript.

RC References Page 32: the reference list is rather long and, notably, one third of the references are self-citations. Please check if all these references are pertinent and functional to the paper

AC: The list of references has been shortened from 72 to 61 references, of which 10 are self-citations.

RC Table 2 Page 40: please provide explanation for GSD

AC: The table was removed to shorten the manuscript.

RC Table 3 Page 41: I guess that the last column shows elevation differences "with" co-registration shifts

AC: We have modified the column header accordingly.

RC Table 8 Page 46: I suggest showing in a figure the extent and location of the common reference area

AC: The extent and location of the reference area is now provided in Figure 1

RC Figure 5 Page 51: I think that a) and b) are inverted

AC: We have modified the panel order accordingly.

RC Figure 7, 12 and 14 Page 53: these figures can be merged in a single image

AC: We have deleted Figure 12 and Figure 14. The location of trails is now shown in Fig. 1 and Fig. 7 where the hazards are shown as well.

We have prepared a point by point response to the reviewer's comments. In the following text, reviewer's comments are reported as RC and highlighted in italics, our answers as AC in plain text while our changes to the text are in bold black.

RC:

I*nteractive 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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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 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 (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 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, affecting even populations living away from glaciers. Finally, glacier retreat and the increase in glacier hazards negatively influence 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 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 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 km^2 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 km^2 (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, 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/m^2 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/m^2. Mean values were between 103-109 points/m^2 in locations 2-4, while they were higher in location 5 (141 points/m^2). Due to the nadir acquisition points, the 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/m^2 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/m^2, 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 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/m^2) 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 σ 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 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.*

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., 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. 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.

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 coherent 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.** ”.

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 possibility 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 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 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.

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 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 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±1.11 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 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 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.

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 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 and enlarged numbers on the scale bar in Figure 9 (now Figure 6).

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 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 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.

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 been removed to shorten the introduction.

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 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.

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.

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.

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 m^2) 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 of future investigations in the field at the Forni Glacier and in other Alpine sites. Specifically, we analysed point density (points/m^2) 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/m^2) 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 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 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. 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/m^2 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/m^2. Mean values were between 103-109 points/m^2 in locations 2-4, while they were higher in location 5 (141 points/m^2). Due to the nadir acquisition points, the 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/m^2 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/m^2, 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 discussion. 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 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.

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. 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

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 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. Looking at the first two DoD, the trend seems to be caused by the increase in collapsing areas (Fig.8a,b).**"

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 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?

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).

AC: 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.

Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and map glacier hazards

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Abstract

Tourists and hikers visiting glaciers all year round face hazards such as the rapid formation of collapses at the terminus, typical of such a dynamically evolving environment. In this study, we analysed the potential of different survey techniques to analyze hazards of the Forni glacier, an important geo-site located in Stelvio Park (Italian Alps). We carried out surveys in the ablation season 2016 and compared point clouds generated from UAV, close range photogrammetry and terrestrial laser scanning (TLS). To investigate the evolution of glacier hazards and evaluate the glacier thinning rate, we also used UAV data collected in 2014 and a DEM from an aerial photogrammetric survey of 2007. We found that the integration between terrestrial and UAV photogrammetry is ideal to map hazards related to the glacier collapse, while TLS is affected by occlusions and logistically complex in glacial terrain. Photogrammetric techniques can therefore replace TLS for glacier studies and UAV-based DEMs hold potential to become a standard tool to investigate the glacier geodetic mass balance. Based on our datasets, an increase in the size of collapses was found over the study period, and the glacier thinning rates went from 4.55 ± 0.24 ma^{-1} between 2007 and 2014 to 5.20 ± 1.11 ma^{-1} between 2014 and 2016.

1 Introduction

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.,

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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, affecting even populations living away from glaciers. Finally, glacier retreat and the increase in glacier hazards negatively influence 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

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Deleted: The effects of climate change due to global warming are increasingly seen on high mountain regions. In the European Alps, temperatures have increased twice the global average over the last century (Auer et al., 2007; Brunetti et al., 2009). Precipitation patterns show contrasting local trends, with an increase in the northern Alps and a decrease on the southern side (Brunetti et al., 2009), while snow cover has reportedly decreased in the last three decades (Bocchiola and Diolaiuti, 2010; Diolaiuti et al

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Deleted: The most sensitive indicators of climate change in mountain regions are glaciers and permafrost, both showing unequivocal signs of involution. In the Italian Alps, glaciers have lost at least about a third of their area since the 1950s (Smiraglia et al., 2015). A similar retreat has occurred in the Swiss Alps, where Fischer et al. (2014) report a loss of 28% since 1973, and in the French Alps, with a decrease in glacier area of 25% since the early 1970s (Gardent et al

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Deleted: Warming trends have also been reported at permafrost monitoring sites throughout Europe, with consequent thickening of the active layer (Harris et al., 2009).¶ Changes to glacier and permafrost environments, either by climate variations alone or in combination with anthropogenic activities, have been recognized to promote land-surface instabilities, playing a significant role in the generation of geomorphological hazards evolving in a downstream direction (Keiler et al., 2010). In glacial and periglacial regions, the most severe hazards are generally related to flooding, through the outburst of moraine- or ice-dammed lakes. Climate change has accelerated the formation of glacial lakes and the expansion of new ones, increasing the risk of devastating glacial lake outburst floods (GLOFs), which frequently occur in the Himalayas, Karakorum, Chilean Patagonia and Peruvian Andes (Wang et al., 2015). In recent years, the formation of moraine-dammed lakes has also been reported in the Swiss Alps, with growing

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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) (Kellerer-Pirklbauer et al., 2005; Riccardi et al., 2010). Recent years have seen a resurgence of terrestrial photogrammetric surveys for the generation of DEMs (Piermattei et al., 2015, 2016; 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 (Eltner et al., 2016; 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., 2016). Although the number of studies employing them in high mountain environments is slowly increasing (see e.g. Fugazza et al., 2015; Gindraux et al., 2017; 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 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

Deleted: glacial- and permafrost-related hazards, including glacier lakes and landslides, their geometric properties and kinematics (Kaab et al., 2005). Indeed, the crucial factors for monitoring of hazard events, which might be localized in small glacial and periglacial areas and evolve over short-time scales, are the revisit time of the sensor and its spatial resolution. In practice, sensors with a high-frequency revisit time often have a coarse spatial resolution (e.g., MODIS), while

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The use of UAV-based remote sensing for glacier research started in polar environments, in small-scale

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Deleted: gaining pace as a tool for the generation of high-resolution DEMs (see, e.g., Rippin et al., 2015). Few studies however have explored the potential of UAVs in high mountain environments, likely due to the following issues:¶
¶
<#>The reduced operating autonomy due to the limited battery support combined with the effects of lower air pressure and temperature; ¶ ...

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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.

2 Study Area

The Forni Glacier (see Fig. 1) has an area of 11.34 km^2 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 km^2 (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

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Deleted: on both long and short-time scales; (3) identifying glacier-related hazards, particularly the ones representing acute hazardous phenomena posing risk for mountaineers visiting the glacier during summer.

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Deleted: 1a, b), in the Ortles-Cevedale group, was the largest Italian valley glacier (Smiraglia et al., 2015) until 2015, when the easternmost part of its three ice tongues separated from its accumulation basin. The latest

Deleted: (based on 2007 data, i.e., before the separation), reported the total glacier area as 11.34 km^2

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Deleted: retreating trend in the last three decades (Diolaiuti et al, 2012, D'Agata et al; 2014). It gained scientific importance in 2005, when it was chosen as the site of the first Italian supraglacial automatic weather station (AWS1 Forni, see Citterio et al; 2007), included in the SPICE (Solid Precipitation Inter Comparison Experiment) and CryoNet networks of the WMO (World Meteorological Organization). Recent research on this glacier mainly focused on the modeling of the albedo and debris cover via terrestrial photography (Azzoni et al., 2016), satellite remote sensing (Fugazza et al., 2016), and a UAV survey (Fugazza et al., 2015). Beside its scientific relevance, the main reasons behind the choice of this glacier as a study area are:¶
<#>The significant retreat of the glacier since the LIA, which sets it as an example of the evolution of valley glaciers in the Alps;¶
The profound changes in glacier dynamics that have taken place

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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).

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3 Data Sources: acquisition and processing

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3.1 UAV Photogrammetry

3.1.1 2014 Dataset

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The first UAV survey took place on 28th August 2014, using a SwingletCam fixed wing aircraft (see Fig. 3a). This commercial platform developed by SenseFly carries a Canon Ixus 127 HS compact digital camera. The UAV was flown in autopilot mode with a relative flying height of approximately 380 m above the glacier surface, which resulted in an average GSD of 12 cm. The flight plan was organized by using the proprietary software eMotion, by which the aircraft follows predefined waypoints with a nominal along-strip overlap of 70%; sidelap was not regular because of the varying surface topography, but was approximately 60%. Flight operations started at 07:44 AM and ended at 08:22 AM. 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

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the UAV motion, since wind speed is at its lowest on glaciers during morning hours (Fugazza et al., 2015). Pictures were automatically captured by the UAV platform, selecting the best combination of sensor aperture (F=2.7), sensitivity (between 100-400 ISO) and shutter speed (between 1/125 s - 1/640 s). The survey covered an area of 2.21 km^2 in just two flight campaigns, with a low altitude take-off (lake Rosole, close to Branca Hut, see Fig. 1). Both the terminal parts of the central and eastern ablation tongue were surveyed.

Processing of data from the 2014 UAV flight was carried out using Agisoft Photoscan version 1.2.4 (www.agistoft.com), implementing a SfM algorithm for image orientation (Spetsakis and Aloimonos, 1991) followed by a multi-view dense-matching approach for surface 3D reconstruction (Furukawa and Ponce, 2009). Since no GCPs were measured during the 2014 campaign, the registration of this data set into the mapping reference system was based on GNSS (Global Navigation Satellite System) navigation data only. Consequently, a global bias in the order of 1.5-2 m resulted after geo-referencing, and no control on the intrinsic geometric block stability could be possible. After the generation of the point cloud, a DEM and orthoimage were produced using the method described by Immerzeel et al. (2014), with spatial resolutions of 60 cm and 15 cm, respectively.

3.1.2 2016 Dataset

The two UAV surveys were carried out on 30th August and 1st September 2016, both around midday with 8/8 of the sky covered by stratocumulus clouds. The UAV employed in these surveys was a customized quadcopter (see Fig. 3b) carrying a Canon Powershot 16 Megapixel digital camera. Two different take-off and landing sites were chosen to gain altitude before take-off and maintain line-of-sight operation with a flying altitude of 50 m above ground, which ensured an average ground sample distance (GSD) of 6 cm. The first take-off site was on the eastern lateral moraine (elevation approx.

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Deleted: 2.1 2016 surveys¶
At the end of August 2016, a data acquisition campaign was carried out with the specific aim of reconstructing the glacier tongue of the Forni Glacier. Multiple techniques were adopted and integrated, to evaluate the performances of different approaches and establish a methodology for future repeat surveys. A UAV-photogrammetric survey with a quadcopter (see Sec. 2.1.1) was conducted to provide a DEM of the glacier surface, to be compared with other DEMs dating back to 2007 and 2014. A photogrammetric survey carried out from ground stations (Sec. 2.1.2) was specifically aimed at reconstructing the glacier terminus. In order to assess the quality of the photogrammetric point clouds, a terrestrial laser scanning (TLS) survey of the same area was concurrently conducted (Sec. 2.1.3). In addition, a set of ground control points (GCPs) was measured with GNSS equipment in order to register all the previous point clouds into the mapping frame (Sec. 2.1.4). ¶
2.1.1 UAV Photogrammetry¶
The UAV survey took place on two separate days, on

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2700 m a.s.l.), while the second site was a rock outcrop on the hydrographic left flank of the glacier (see Fig. 1) at an elevation of approx. 2750 m a.s.l. To reduce motion blur, camera shutter speed was set to the lowest possible setting, 1/2000 s, with aperture at F/2.7 and sensitivity at 200 ISO.

Several individual parallel flights were conducted to cover a small section of the proglacial plain and different surface types on the glacier surface, including the terminus, a collapsed area on the central tongue, the eastern medial moraine and some debris-covered parts of the eastern tongue. A 'zig-zag' flying scheme was followed to reduce the flight time. The UAV was flown in autopilot mode using the open-source software Mission Planner (Oborne, 2013) to ensure 70% along-strip overlap and sidelap. In total, two flights were performed during the first survey and three during the second, lasting about 20 minutes each. The surveyed area spanned over 0.59 km^2.

Processing of data from the 2016 UAV flight was carried out using Agisoft Photoscan version 1.2.4. Eight GCPs (see Fig. 1) were measured for the registration of the photogrammetric blocks and its by-products into the mapping system. The root mean square error (RMSE) of the GCPs was 40 cm, which can be used as an indicator of accuracy for the geo-referencing of the photogrammetric block. The point cloud obtained from the 2016 UAV flight was interpolated to produce a DEM and orthoimage with the same cell resolution as the 2014 dataset, i.e., 60 and 15 cm, respectively. Both products were exported in the ITRS2000 / UTM 32N mapping reference system.

3.2 Terrestrial photogrammetry

The terrestrial photogrammetric survey was carried out during on 29th August 2016 to reconstruct the topographic surface of the glacier terminus, which presented several vertical and subvertical surfaces whose measurement was not possible from the UAV platform carrying a camera in nadir configuration (see Fig. 2e).

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Deleted: (www.agisoft.com), implementing a Structure-from-Motion (SfM) algorithm for image orientation (see Barazzetti et al., 2011) followed by a multi-view dense-matching approach for surface reconstruction (Remondino et al., 2014). The availability of GNSS navigation data was exploited to start the SfM procedure, shortening the time necessary to register the 288 images acquired by the quadcopter. No pre-calibration was applied, since the block configuration including strips flown along different directions was optimal for the estimation of camera calibration parameters (Zhang et al., 2017). A total number of 38,506 tie points (TPs) were extracted for image orientation, corresponding to an average number of 892 TPs per image (see Table 2). The large average number of rays per each TP (6.7) combined with the huge number of TPs offered a sufficient inner reliability for an effective outlier rejection procedure, which is applied during bundle adjustment (Kraus, 1997; Luhmann et al., 2014) in Agisoft Photoscan. This package implements a standard photogrammetric bundle adjustment where GCPs are used as regular weighted observations, unlike most software packages including SfM algorithms where GCPs are only used for estimating a 3D rigid-body transformation for geo-referencing the final point cloud. Eight GCPs (see Fig. 4 and Sec. 2.1.4

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Images were captured from 134 ground-based stations, most of them located in front of the glacier, and some on both flanks of the valley in the downstream area, as shown in Fig. 4a. A single-lens-reflex Nikon D700 camera was used, equipped with a 50 mm lens, and a full-frame CMOS sensor (36x24 mm) with 4256x2823 pixels. This photogrammetric block was processed using Agisoft Photoscan version 1.2.4. In this case, since no preliminary information about approximate camera position was collected, the SfM procedure was run without any initial information.

Seven natural features visible on the glacier front were used as GCPs to be included in the bundle adjustment computation in Agisoft Photoscan. Measurement of GCPs in the field was carried out by means of a high-precision theodolite. The measurement of points previously recorded with a GNSS geodetic receiver allowed to register the coordinates of GCPs in the mapping reference system. The RMSE of 3D residual vectors on GCPs was 34 cm, which can be considered as the accuracy of absolute geo-referencing. The final point cloud obtained from the dense matching tool implemented in Agisoft Photoscan covers at a very high spatial resolution the full glacier terminus, with the exception of a few obstructed parts (see Fig. 4b).

3.3 Terrestrial Laser Scanning

On the same days as the first UAV survey of 2016, a long-range terrestrial laser scanner Riegl LMS-Z420i was used to scan the glacier terminus frontally. One instrumental standpoint located on the hydrographic left flank of the glacier terminus (see Fig. 1) was established. The horizontal and vertical scanning resolution were set up to provide a spatial point density of approx. 5 cm on the ice surface at the terminus. Geo-referencing was accomplished by placing five GCPs consisting in cylinders covered by retroreflective paper. The coordinates of GCPs were measured by using a precision theodolite following the same procedure adopted for terrestrial photogrammetry. Considering the accuracy of

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Deleted: is applied first on a block of images at down-sampled resolution. This process may provide approximate orientation, limiting the search space for corresponding points in the final SfM, which is applied to full resolution images (Barazzetti et al., 2010).¶
The geometric configuration of the photogrammetric block of the glacier terminus, including hyper-redundant convergent images as well as 90° rolled images,

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Deleted: A very high number (59,157) of tie points (TPs) was found on the images after SfM (see Table 2). In addition, the large mean number of rays per each TP (5.6) resulted in a high reliability of the observations, which mitigates the risk of undetected errors.

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registration and the expected precision of laser point measurement, the global accuracy of 3D points was estimated in the order of ±7.5 cm.

3.4 GNSS ground control points

Prior to the 2016 surveys, eight control targets were placed both outside the glacier and on the glacier tongue (see Fig. 1). Differential GNSS data were acquired at their location for accurate geo-referencing of UAV, terrestrial photogrammetry and TLS data. While for geo-referencing of UAV data the GCPs were directly visible on the quadcopter images, for terrestrial photogrammetry and TLS they were adopted for the registration of theodolite measurements. The targets consisted in a piece of white fabric 80 x 80 cm wide, with a circular marker in red paint chosen to provide contrast against the background. Except for the one GCP located at the highest site, such GCPs were positioned on large, flat boulders to provide a stable support and reduce the impact of ice ablation between flights.

GNSS data were acquired by means of a pair of Leica Geosystems 1200 geodetic receivers working in RTK (Real-Time Kinematics) mode (see Hoffman-Wellenhof, 2008). One of them was set up as master on a boulder beside Branca Hut, where a monument had been established with known coordinates in the mapping reference system ITRS2000 / UTM 32N. The second receiver was used as a rover, communicating via radio link with the master station. The maximum distance between master and rover was less than 1.5 km, but the local topography prevented broadcasting the differential corrections in a few zones of the glacier. Unfortunately, no mobile phone services were available and consequently the internet network could not be accessed, precluding the use of the regional GNSS real-time positioning service. Non-RTK points were processed in fast-static mode, requiring a longer measurement time of approx. 12 minutes. The theoretical accuracy of GCPs was estimated in the order of 2-3 cm.

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3.5 2007 DEM

The 2007 TerraItaly DEM was produced by BLOM C.G.R. company for Lombardy region. It is the final product of an aerial survey over the entire region that was conducted with a multispectral pushbroom Leica ADS40 sensor acquiring images from a flying height of 6,300 m with an average GSD of 65 cm. The images were processed to generate a DEM with a cell resolution of 2 m x 2 m, and projected in the former national 'Gauss Boaga - Fuso I' mapping reference system based on Monte Mario datum (Mugnier, 2005). Heights were converted from ellipsoidal to geodetic using the official software for datum transformation in Italy (Verto ver. 3), which is distributed by the Italian Geographic Military Institute (IGMI). The final vertical accuracy reported by BLOM C.G.R. is ± 3 m. The only processing step performed within this study was the datum conversion to ITRS2000, using a seven-parameter similarity transformation based on a local parameter set provided by IGMI.

4 Methods

4.1 Analysis of point clouds from the 2016 campaign: UAV/terrestrial photogrammetry and TLS

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 of future investigations in the field at the Forni Glacier and in other Alpine sites. Specifically, we analysed point density (points/m^2) 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

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Moved up [8]: Consequently, a global bias in the order of 1.5-2 m resulted after geo-referencing, and no control on the intrinsic geometric block stability could be possible. After the generation of the point cloud, a DEM and orthoimage were produced

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effect of point density dispersion (Teunissen, 2009), the inferior 12.5 percentile of the standard deviation σ 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 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

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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.

4.2 Merging of UAV and close-range photogrammetric point clouds

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.

4.2 Glacier hazard mapping

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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 coherent 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.

4.3 DEM co-registration for glacier thickness change estimation

Several studies have found that errors in individual DEMs, both in the horizontal and vertical domain, propagate when calculating their difference leading to inaccurate estimations of thickness and volume change (Berthier et al., 2007; Nuth & Kaab, 2011). In the present study, different approaches were adopted for geo-referencing all the DEMs (2007, 2014, 2016) used in the analysis of the volume change of the Forni Glacier tongue. To compute the relative differences between the DEMs, a preliminary co-registration was therefore required. The method proposed by Berthier et al. (2007) for the co-registration of two DEMS was separately applied to each DEM pair (2007-2014; 2007-2016; 2014-2016). Following this method, in each pair one DEM plays as reference ('master'), while the other is used as 'slave' DEM to be iteratively shifted along x and y directions by fractions of pixel to

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minimize the standard deviation of elevation differences with respect to the 'master' DEM. Only areas assumed to be stable are considered in the calculation of the co-registration shift. The ice-covered areas were excluded by overlaying the glacier outlines from D'Agata et al. (2014) for 2007 and Fugazza et al. (2015) for 2014. The oldest DEM, which is also the widest in each comparison, was always set as the master. To co-register the 2014 and 2016 DEMs with the 2007 DEM, both were resampled to 2 m spatial resolution, whereas the comparison between 2014 and 2016 was carried out at the original resolution of these data sets (60 cm).

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All points resulting in elevation differences larger than 15 m were labelled as unreliable, and consequently discarded from the subsequent analysis. Such larger discrepancies may denote errors in one of the DEMs or unstable areas outside the glacier. Values exceeding this threshold, however, were only found in a marginal area with low image overlap in the comparison between the 2014 and 2016 DEMs, with a maximum elevation difference of 36 m. Once the final co-registration shifts were computed (see Table 1), the coefficients were subtracted from the top left coordinates of the 'slave' DEM; the residual mean elevation difference was also subtracted from the 'slave' DEM to bring the mean to zero. 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).

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5 Results

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5.1 Point cloud Analysis

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/m^2 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/m^2. Mean values were between 103-109 points/m^2 in locations 2-4, while they were higher in location 5 (141 points/m^2). Due to the nadir acquisition points, the 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/m^2 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/m^2, 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

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The comparison between data sets collected during the 2016 campaign had the aim of assessing the quality of different data sources to be used for subsequent physical analyses. In addition, these evaluations were expected to provide some guidelines for the organization of future investigations in the field at the Forni Glacier and in other Alpine sites. ¶
Specifically, in this case the analysis consists in comparing point clouds. It is out of the scope of this article to address this topic in an exhaustive manner. While the reader may refer to other pieces of literature to have a broader view about it (e.g., Eltner et al., 2016), here the aim is to apply some existing criteria and metrics to find out which techniques among UAV photogrammetry (i), terrestrial photogrammetry (ii), and TLS (iii) should be privileged for glaciological studies under certain conditions. Of course, comparing two point clouds, which is the simplest case that may be considered, is more complex than comparing coordinates of specific points that have been measured, e.g., with theodolites, GNSS sensors or target-based photogrammetry ...

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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.

5.2 Glacier-related hazards and risks

The tongue of Forni glacier hosts a variety of hazardous structures. While most collapsed areas are normal faults, two large ring fault systems can be identified: the first, located in the eastern section (see Fig. 2d and 7), covered an area of 25.6x10^3 m^2 and showed surface lowering up to 5 m in 2014. This area was not surveyed in 2016, since field observation did not show evidence of further subsidence. Conversely, the ring fault that only emerged as a few semi-circular fractures in 2014 grew until cavity collapse, with a vertical displacement up to 20 m and further fractures extending south-eastward (see Fig. 2c and 7), thus potentially widening the extent of collapse in the future. Further smaller ring faults were identified in 2014 at the eastern glacier margin. Only one of them was included in the area surveyed in 2016, with further 2 m subsidence and an increase in subparallel fractures.

Normal faults are mostly found on the eastern medial moraine and at the terminus. Between 2014 and 2016, the first developed rapidly in the vertical domain reaching a height of 12 m in 2016. The collapse was even more rapid at the terminus, leading to the formation of three sub-vertical facies, up to 24 m high, while the height of the vault is as low as 10 m. Several fractures also appear in conjunction with the large ring fault located in the central section of the glacier, extending the fracture system to the western glacier margin. 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.

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5.3 Glacier Thickness change

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. Looking at the first two DoD, the trend seems to be caused by the increase in collapsing areas (Fig.8a,b).

6 Discussion

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

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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 possibility 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.

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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 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

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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 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.

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

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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.

7 Conclusions

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.

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- 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 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 ± 1.11 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 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 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

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to become the platform of choice but their performances and cost-effectiveness compared to aerial and satellite surveys need to be further evaluated.

Competing interests

The authors declare that they have no conflict of interest.

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Tables

DEM pair	Elevation differences without co-registration shifts ($\mu_{\Delta H} \pm \sigma_{\Delta H}$) [m]	Co-registration shifts		Elevation differences with co-registration shifts ($\mu_{\Delta H} \pm \sigma_{\Delta H}$) [m]
		X [m]	Y [m]	
2007-2014	1.96±2.60	1.11	-1.11	0.00±1.70
2007-2016	-0.43±3.48	2.44	-1.11	0.00±2.60
2014-2016	-2.92±3.21	-0.20	-1.30	0.00±2.22

Table 1: Statistics of the elevation differences between DEM pairs before and after the application of co-registration shifts.

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Sample Window	Area (m^2)	number of points in sample windows			Mean and standard deviation of point density [points/m^2]			Number of point above the lower 12.5% percentile		
		UAV photogramm.	Terrestrial Photogramm.	TLS	UAV Photogramm.	Terrestrial Photogramm.	TLS	UAV Photogramm.	Terrestrial Photogramm.	TLS
1	2793	-	1984k	141k	-	1654±637	226±100	-	880	26
2	1806	76k	2175k	130k	109±29	2297±708	391±217	61	881	0
3	495	43k	712k	25k	103±27	1978±606	151±60	49	766	31
4	672	62k	557k	33k	108±22	1384±530	141±69	62	324	2
5	3960	406k	810k	-	141±22	485±227	-	97	31	-

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.

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Sample Window		Means and Std. Dev.s of M3C2 distances [cm]			RMSE of M3C2 distances [cm]		
	Ref.	TLS	TLS	UAV Photogramm.	TLS	TLS	UAV Photogramm.
	Slave	Terrestrial Photogramm.	UAV Photogramm.	Terrestrial Photogramm.	Terrestrial Photogramm.	UAV Photogramm.	Terrestrial Photogramm.
1		4.5±7.4	-	-	8.7	-	-
2		-1.1±10.5	14.8±34.7	-14.5±26.7	10.6	37.7	30.4
3		8.4±4.1	14.7±15.1	-8.5±18.9	9.4	21.1	20.7
4		2.8±5.3	9.4±22.2	-2.3±24.9	6.0	24.0	25.0
5		-	-	-8.5±25.3	-	-	26.7

Table 3: Statistics on distances between point

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clouds computed on the basis of M3C2 algorithm.

DEM pair	Mean thickness change [m]	Mean thinning rates [ma^{-1}]	Volume Change [10^6 m^3]
2007-2014	-31.91 ± 1.70	-4.55 ± 0.24	-10.00 ± 0.12
2007-2016	-42.86 ± 2.60	-4.76 ± 0.29	-13.46 ± 0.14
2014-2016	-10.41 ± 2.22	-5.20 ± 1.11	-3.29 ± 0.05

Table 4: Average ice thickness change, thinning rates and volume loss from DEM differencing over a common reference area of 0.32 km^2 for all DEM pairs. Uncertainty of thickness change expressed as 1σ of residual elevation differences over stable areas after DEM co-registration.

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DEM pair

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Figures

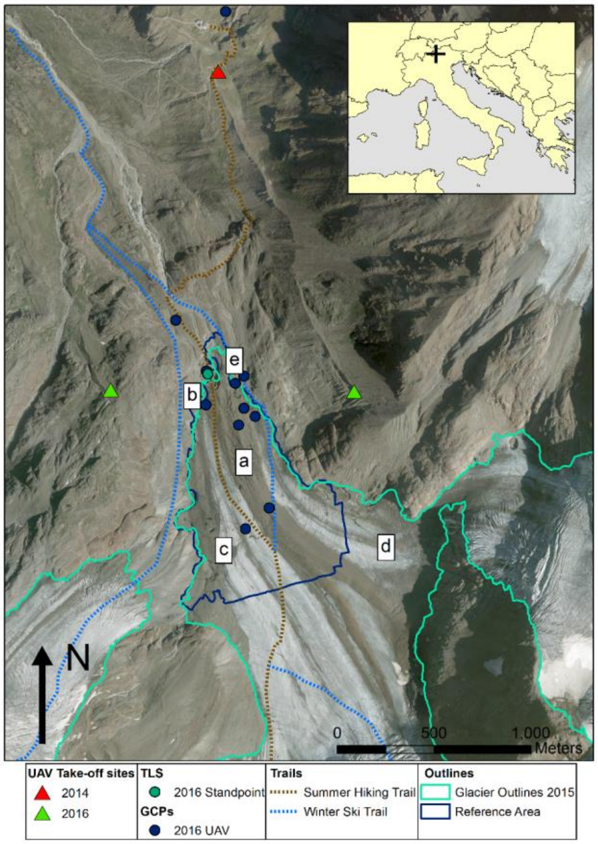
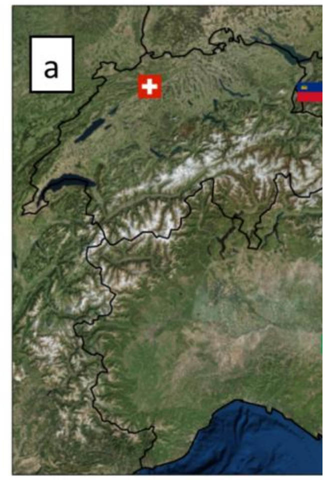
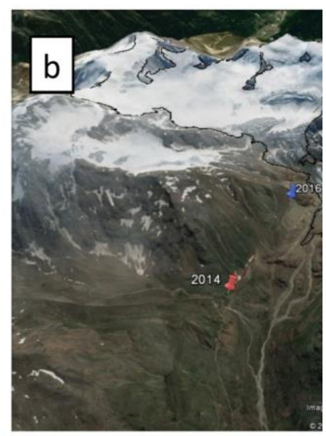


Figure 1: the tongue of Forni Glacier. The map shows the location of take-off/landing sites for the 2014 and 2016 UAV surveys (in 2016 two different landing sites were used), standpoint of TLS survey, GCPs used in the UAV photogrammetry surveys and trails crossing the glaciers. Letters a-e identify the location of features described in Fig.2. Base map from 2015 courtesy of IIT Regione Lombardia WMS Service. Trails from Kompass online cartography at https://www.kompass-italia.it/info/mappa-online/.





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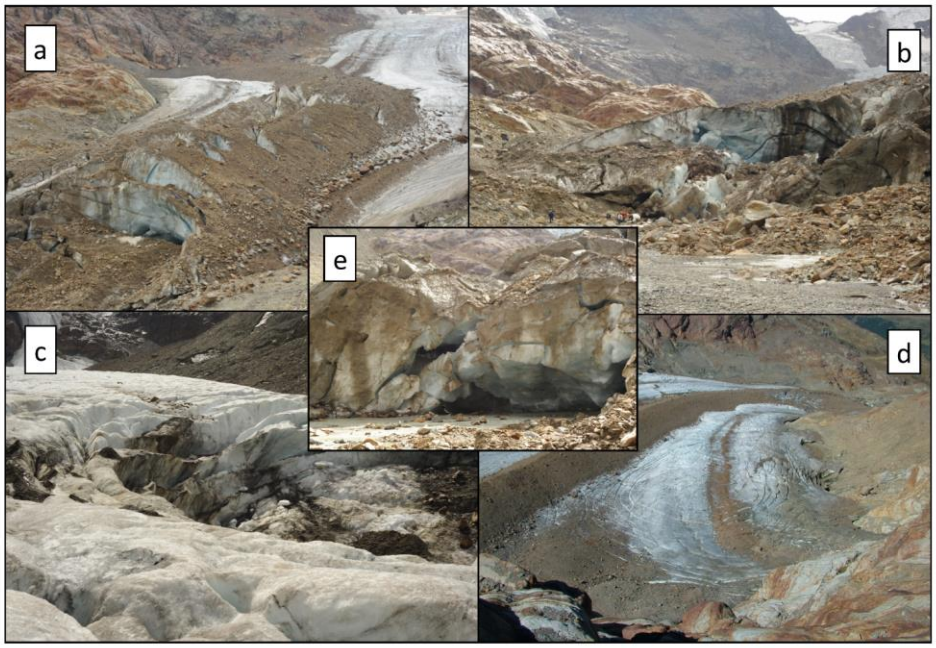

Figure 2: Collapsing areas on the tongue of Forni Glacier. (a) Faults cutting across the eastern medial moraine; (b) glacier terminus; (c) Near-circular collapsed area on the central tongue; (d) Large ring fault on the eastern tongue at the base of the icefall. Photo courtesy of G.Cola; (e) Close-up of a vertical ice cliff at the glacier terminus. *The location of features is reported in Fig.1*

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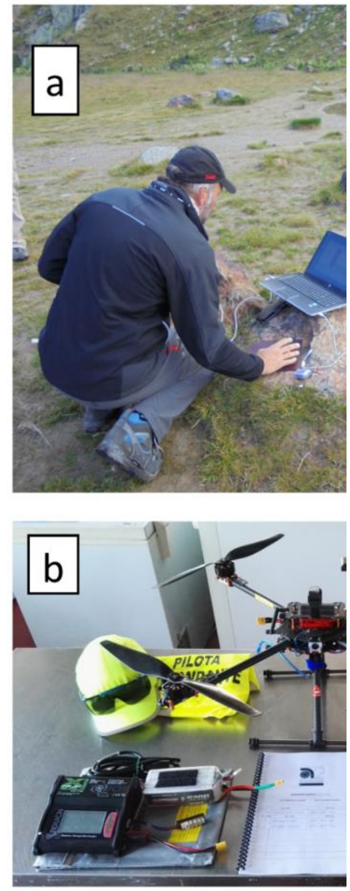
Aircraft type	Swinglet CAM, Commercial platform
Digital Camera	Canon Ixus 127 HS
Camera technical features	16 Megapixel, focal length 4.3 mm
GNSS antenna	GPS only
Weight (incl. payload)	0.50 Kg
Battery time	30 minutes

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

Figure 3: The UAVs used in surveys of the Forni Glacier and their characteristics. (a) The SwingletCam fixed-wing aircraft employed in 2014, at its take off site by Lake Rosole; (b) The customized quadcopter used in 2016 in the lab.



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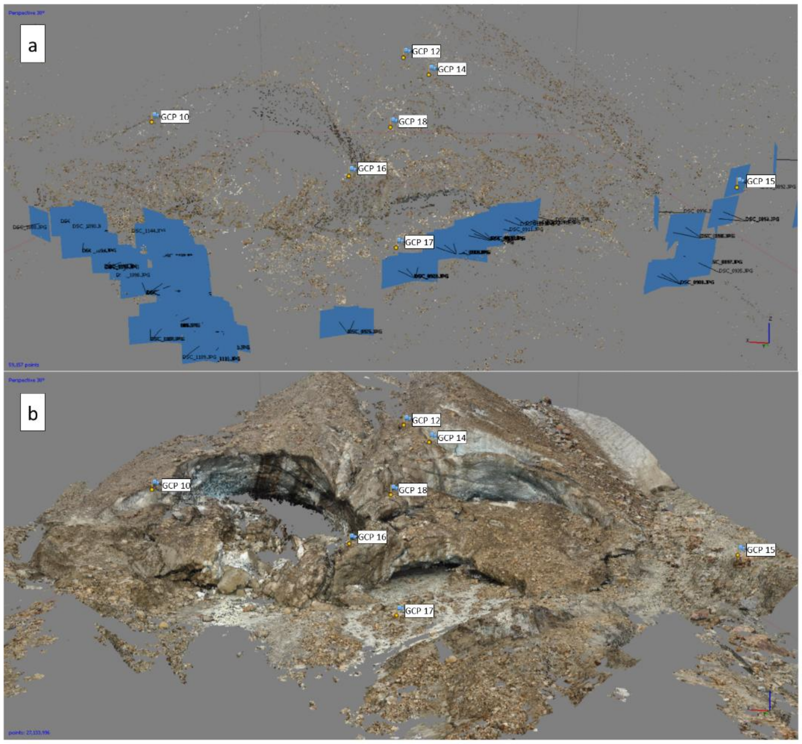
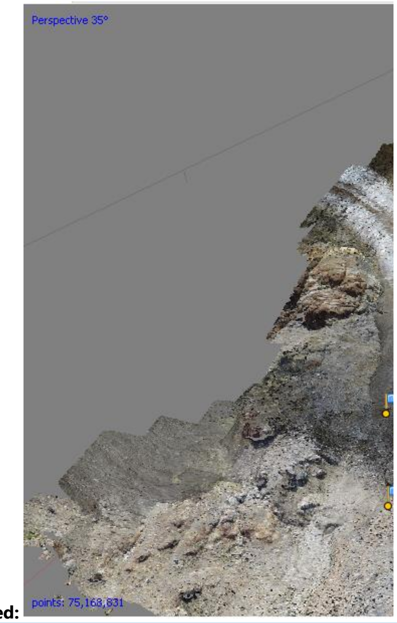


Figure 4: 3D reconstruction of the glacier terminus from the terrestrial photogrammetric survey of 2016 : (a) locations of camera stations in front of the glacier and 3D coordinates of tie points extracted during SfM for image orientation; (b) point cloud of the glacier terminus with positions of GCPs.

Deleted: 

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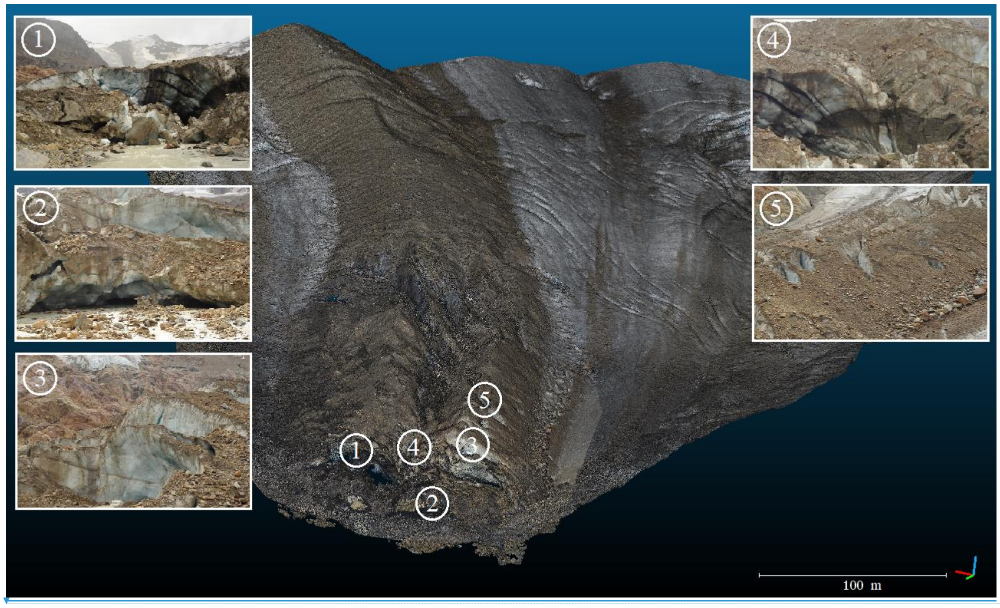

Figure 5: Location of different glacier features or hazard-prone areas on the tongue of Forni glacier were the point cloud comparison was performed. The background image is the merged point cloud generated from the 2016 UAV and terrestrial photogrammetry survey.

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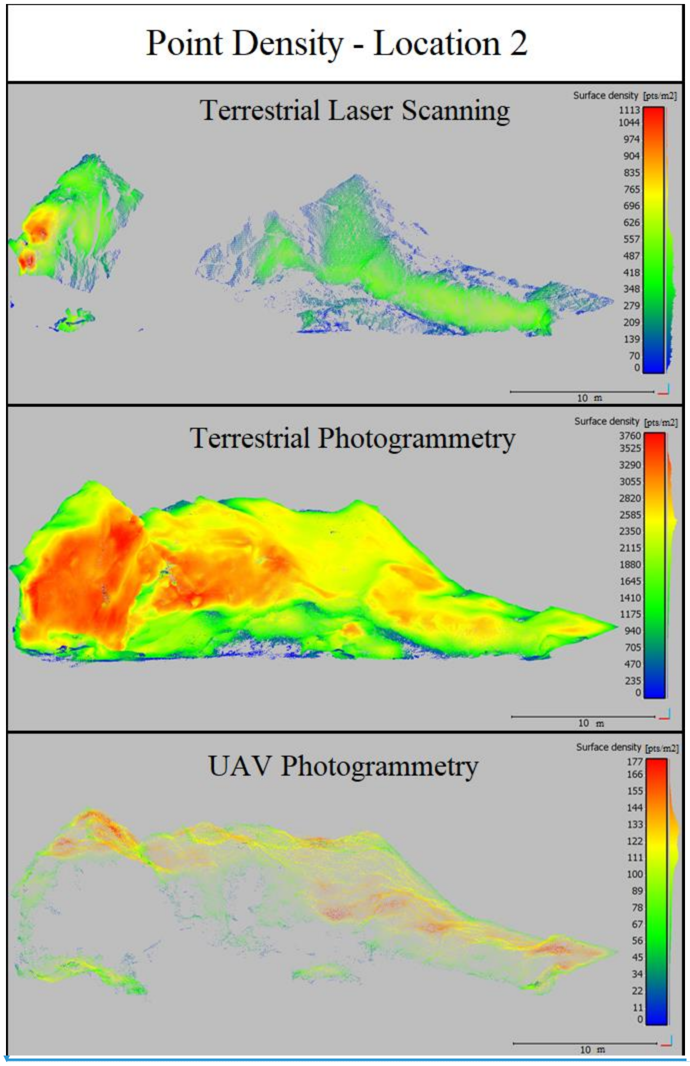
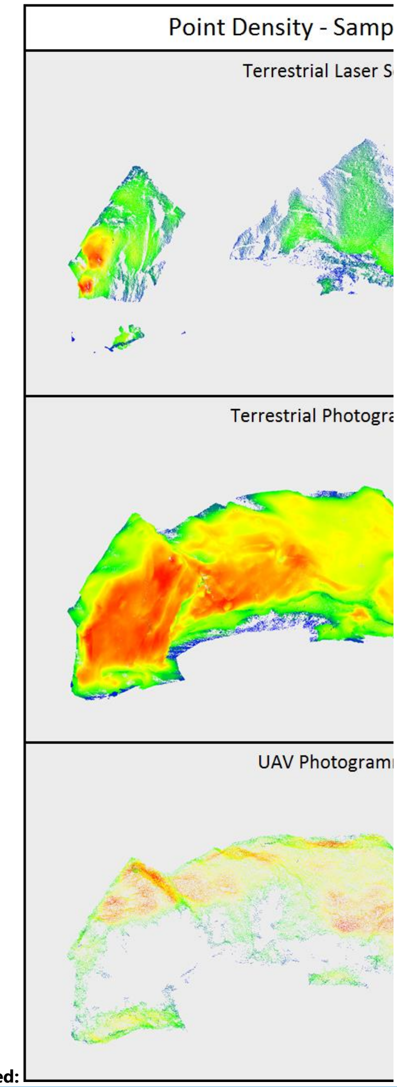


Figure 6: Maps of point density in sample location 2.

Deleted: 

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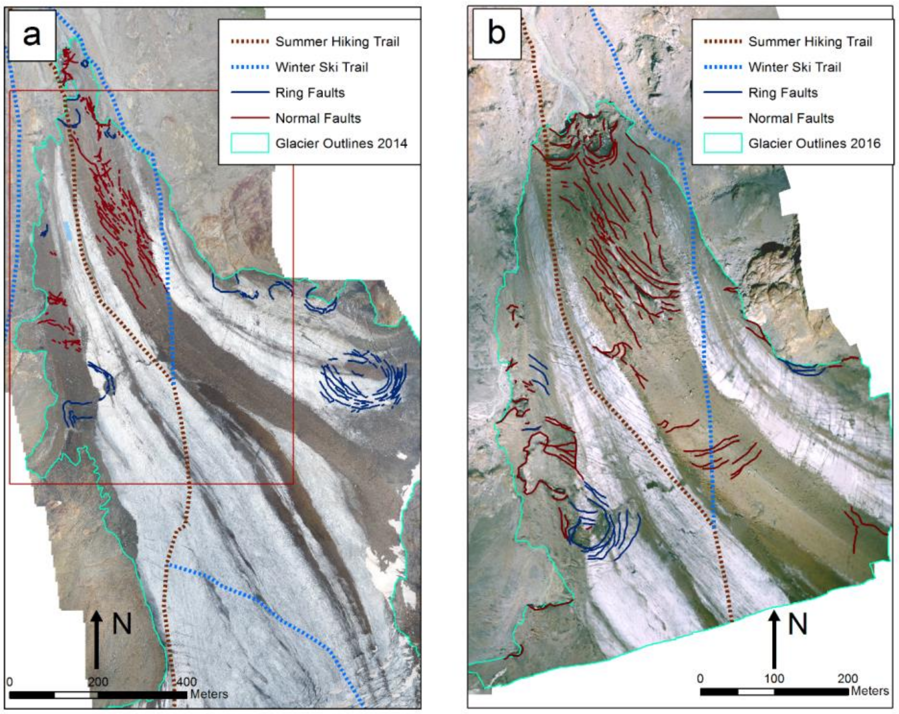

Figure 7: location of collapse structures, i.e. normal faults and ring faults and trails crossing the Forni Glacier (a) 2014, with 2014 UAV ortophoto as basemap, The red box marks the area surveyed in 2016. (b) 2016, with 2016 UAV orthophoto as basemap.Trails from Kompass online cartography at https://www.kompass-italia.it/info/mappa-online/.

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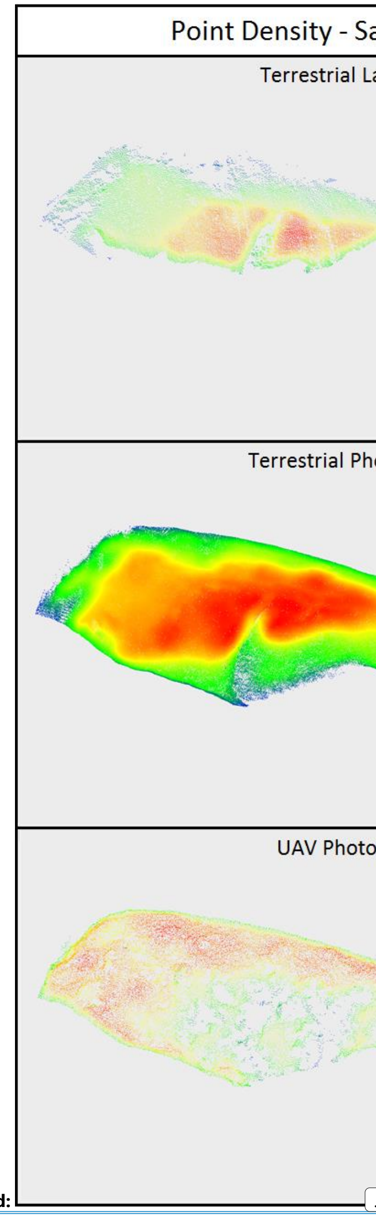

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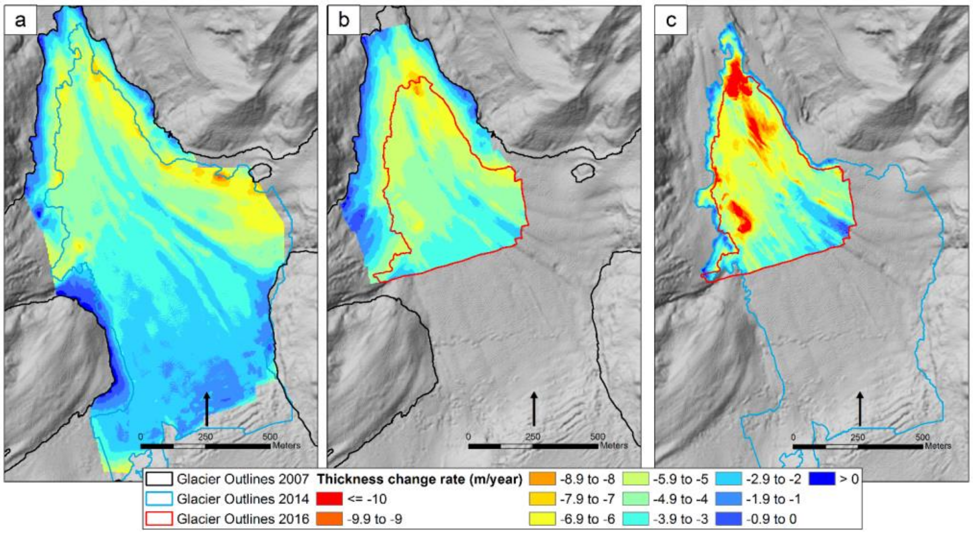

Figure 8: Ice thickness change rates from DEM differencing over (a) 2007-2014; (b) 2007-2016; (c) 2014-2016. Glacier outlines from 2014 and 2016 are limited to the area surveyed during the UAV campaigns. Base map from hillshading of 2007 DEM.

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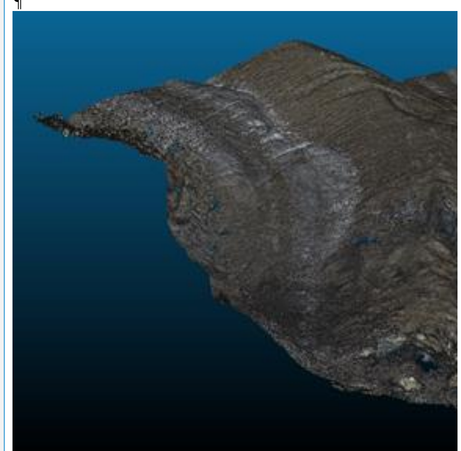

Figure 12: Merged 3D model of the Forni Glacier tongue, integrating points clouds derived from UAV and terrestrial photogrammetry, subsampled to keep a minimum distance between adjacent points of 20 cm, and coloured with RGB information from images.

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