Dear Editor,

We have carefully revised the manuscript taking into account all suggestions by the reviewers.

Specifically, we the manuscript has been proofread by a professional mother tongue consultant to improve its readability. We have clarified the advantages of point cloud merging through a figure and a paragraph in the results section; we have also revised and numerically quantified the uncertainty of UAV volume calculations and revised the text with a consistent use of 'uncertainty' in place of 'accuracy' and 'thickness changes' in place of 'mass balance'; we have added explanations for the algorithms used in point cloud comparison. Finally, we have restructured the discussion section and added references to the articles suggested by one of the reviewers. In addition, we have improved the figures and tables thanks to the reviewers' suggestions.

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 italics, our answers as AC in plain text while our changes to the text are in bold black.

RC Review of the manuscript:

Combination of UAV and terrestrial photogrammetry to assess rapid glacier evolution and conditions of glacier hazards. Fugazza et al.

General comments:

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 three different (close-range) remote sensing methods. They found that UAV- and terrestrial photogrammetry are the best surveying techniques to assess ice thickness change and map glacier hazards. Compared to the first manuscript, the authors reduced significantly the length of the manuscript which was preconized by both reviewers, set the aims more clearly and reorganized the different sections in a much better way. However, there are still several points of the paper that require substantial improvements, such as:

RC 1) This version of the paper in my opinion, is poorly written. I had large difficulties understanding several sections of the manuscripts, due to the use of unconventional words and wrong sentence construction. As this is not my mother-tongue either, I could not give suggestions for every case and did not highlighted all of them. A English proof reading is surely needed before considering this paper for publication.

AC: The manuscript has been proofread by a professional mother tongue consultant. Since minor errors were found, we have not reported all changes to the manuscript here, but they can be seen in the tracked manuscript version.

RC 2) The individual methods and comparison of the methods used as suggested in this version of the manuscript are not new. The only aspect that could have been interesting and relatively new, is the merging of different datasets. However, the authors only merged the terrestrial and UAV photogrammetry point clouds, without giving a quantitative explanation of how this merged point cloud is much better than the terrestrial one alone. Looking at Figure 6, and the very sparse point cloud they obtained from UAV photogrammetry compared to terrestrial photogrammetry, I doubt that the merging of both point clouds did make a big difference. It would however be good if the authors could give more information on this point. Moreover in this study, this merged point cloud is only used to map the hazards (along with the orthophoto), which I guess, could have also been done with the point cloud from one method only (the terrestrial photogrammetry). So I am not sure if this merged point cloud was really necessary. I think the authors should emphasis more on the scientific value of this study.

AC: The reason why we chose to compare UAV and terrestrial SfM-photogrammetry was because they were the two lower cost techniques, and we have added this information in the text. While terrestrial photogrammetry has the highest point density, it only covers those portions of the glacier surfaces that could be depicted from ground-based photo-stations. The point cloud obtained from terrestrial photogrammetry covers the terminus and makes it possible to investigate vertical and sub-vertical areas. The point cloud derived from UAV-

photogrammetry covers a larger part of the glacier and allows to investigate sub-horizontal areas such as the ring faults on the central and eastern tongue. In general, the UAV and terrestrial photogrammetry point clouds only partially overlap. Therefore, merging these point clouds enables to cover a larger area than with individual point clouds and investigate different types of hazards. We have added a figure showing the glacier area covered with both techniques and discuss this aspect in the results section, where we have added a paragraph which reads: "In terms of spatial coverage, considering the entire surface examined using each technique outside the sample locations, the UAV survey extended over the widest area (0.59 km²), including part of the proglacial plain, the entire terminus and the glacier tongue up to the collapsed area on the central part, but with data gaps on the vertical and sub-vertical walls (see Fig. 6a). The point cloud obtained from terrestrial photogrammetry covered approximately a third of the area surveyed with the UAV (see fig. 6b), including the full glacier terminus at very high spatial resolution, with the exception of a few obstructed parts, while the TLS point cloud covered the terminus, although with some holes due to the obstructions.". In addition, we proposed here the use of such a methodology because we think it may have a larger applications in other case studies related to Alpine glaciers.

RC 3) I think that the authors wrote a lot about the differences between the methods they used, but very little refer to other literature. There are a lot of papers (below only a few for example) comparing point clouds and DEMs generated from different surveying methods.

a. Baltsavias, 1999: A comparison between photogrammetry and laser scanning
 b. Rayburg et al. 2009: A comparison of digital elevation models generated from different data sources

c. Naumann et al. 2013: Accuracy comparison of digital surface models created by unmanned aerial systems imagery and terrestrial laser scanner

In most sections of the results and discussion, the authors report results that have already been found in other studies. For instance in the discussion section, where the advantages and drawbacks from all methods are explained, the authors cite publications that found the same results (but several years ago). As several papers are already stating these, I think this information should not be discussed anymore, but taken as granted. I suggest the authors to integer older and newer publications related to the comparison of point clouds and DEM specifically.

AC: The publications we have cited in the discussion section related to the point density/completeness comparison of different techniques are from 2012, 2016 (2) and 2017, therefore on average rather recent, and mainly describe surveys of non-glacial environments. Thus, we have decided to keep the references to these publications, to provide confirmation for the findings and conclusions drawn there. We have now restructured the discussion section separating it into four sub-sections 1) point density and completeness; 2) point cloud uncertainty; 3) logistics and costs; 4) additional remarks. In the last section, we have added references to Rayburg et al. (2009) and Naumann et al. (2013) among others and also compare the techniques we used against ALS and aerial photogrammetry in terms of logistics, cost, accuracy and spatial resolution but have not cited Baltsavias (1999), as it is a much older publication.

RC 4) To my point of view, the authors are often making statements such as: "The UAVbased DEMs hold the potential to become a standard tool to investigate geodetic mass balance", but the authors did not try to do this and the publications that succeeded to do it are very rare. Another one: "The final accuracy of our UAV photogrammetric products was nevertheless adequate to investigate ice thickness change over two years,...". The reader don't know for what it is "adequate", as the authors found DEM errors over two meters (for these two years). They do not give any percentage error that would mean on the total melt. Moreover, the authors do not state why they need ice thickness data. We only know that ice thickness change is related to an increase of natural hazards.

I think in general, the manuscript needs to be more carefully written, with results presented in a more quantitative robust way.

AC: We have replaced 'mass balance' with 'ice thickness', which is what we investigated. As concerns the uncertainty in ice thickness change, in all three cases it is below 3% of the total ice volume change (see answer to your comment at line 325). As the accuracy depends on the application of the data, we have decided to avoid using this term and we have added percentage values of volume uncertainty in Table 4. We further comment them in section 5.3, where we have added: **"In all DoDs, the uncertainty in ice thickness change results in less than 3% of the respective volume change (see Table 4)**." at the end of the section. Finally, we have deleted the word 'adequate' and specified the percentage uncertainty. Thus, we have replaced 'The final accuracy of our UAV photogrammetric products was nevertheless adequate to investigate ice thickness changes over 2 years' with 'UAV photogrammetric products permitted us to investigate ice volume changes over 2 years with an uncertainty of 2.60%'.

The ice thickness data are useful for hazard management because glacier downwasting is a hazard per se, as noted by Kaab et al. (2005). In fact, changes in glacier length, area and volume cause variations in water resources and their availability for human consumption, hydropower generation and irrigation. We have better clarified why glacier downwasting contributes to natural hazards, by replacing: "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." with "Glacier downwasting causes changes in water resources, with an initial increase in discharge due to enhanced melt and a long-term reduction, affecting drinking water supply, irrigation and hydropower production (Kaab et al., 2005b) and is also increasing the occurrence of structural collapses (Azzoni et al., 2017).".

Besides, we have explained that ice thickness data are useful for hazard management in the introduction, where have replaced "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." with "In particular, the advantages of UAV and terrestrial SfM-photogrammetry and the possibility of data fusion and volume change estimation to support hazard management strategies in glacial environments needs to be investigated and assessed." With "In particular, the advantages of UAV and terrestrial SfM-photogrammetry and the possibility of data fusion and volume change estimation to support hazard management strategies in glacial environments needs to be investigated and assessed."

RC: I think the manuscript requires again major revision before being considered for publication in NHESS. More specific and short comments are reported in the supplementary material as .pdf.

Comments on Figures and Tables:

RC Figure 1:

- I would zoom in more as there is a lot of space under the reference area, and eventually show the positions of the terrestrial pictures.

- It's hard to make the difference between the green triangle and the green points. Can you change the colour? If you do this, I think you can also remove the " (in 2016 two different...)" in the caption, because we can see it on the map.

- Is the number after +/- based on 1 standard deviation? Or 2?

AC:

- We have zoomed in the figure but have chosen not to show the terrestrial pictures as there are too many of them and they would make the map too cluttered.
- We have changed the color of the green point which is now brown
- It is not clear what the last comment refers to, as there are no numbers with +/- in this or other figures.

RC Figure 2:

- It is very hard for the reader to have an idea about the size of the feature. Could you insert a scale?

- This Figure shows the hazardous features on the glacier but these are not the ones that you survey and studied. So I am wondering what kind of information the reader gets out of this Figure. I would maybe recommend to put them on the right side of Fig.1 where there is some space left before the caption's end, and delete the Figure 2.

AC: These photographs were taken in 2016 during the field campaign between 29th August and 1st September. They do represent features that we have surveyed and studied in our analysis of glacier hazards (section 5.2). Figure 1 already provides a lot of information and we believe that adding more makes it less clear. We have therefore decided to keep this Figure on its own. Unfortunately, these figures were taken without a scale (person and other object). While we could add a vertical scale from the analysis of point clouds, this information belongs to the results, thus we have decided not to introduce it here. The height of the features is reported in the results section 5.2. In the previous version of the manuscript, we referenced panels c and d. We have added references to the other three panels (a, b and e) in section 5.2 to help the reader understand the size of these features.

RC Figure3:

- Very clean Figure
- I would only centre the b in the white case

AC: We have centered the 'b' as suggested.

RC Figure 4:

- I think this figure does not give much information to the reader. My suggestion is that you either put the location of the images on Fig 1., or that you merge a and b.

- Caption: Small question in (a). In the text you say that you took 134 pictures. Are they all displayed here? I have the feeling that they don't, so did they all align in the software?

AC: All photos have been displayed here and all of them have been aligned. As explained in the answer to your previous comment to Figure 1, there are too many images to be shown on Figure 1. The reason why it seems that fewer photos are displayed is that some photos were captured from very close locations and they look as from a single camera station. Besides, some photos were collected from the same position but with the camera rolled 90 degrees to provide a more suitable configuration for camera self-calibration. This are standard rules in close-range photogrammetry (see Luhmann et al., 2014, Close-range Photogrammetry).

Following your comment at line 134, we have chosen to delete this figure and we now show the coverage of UAV, terrestrial photogrammetry and the merged point cloud in a new figure (fig.6)

RC Figure 5:

- The background image is very dark. It would be nice to see more lighter colours

- Also here on the image it is hard to see how big these features are. As you don't have much space, I suggest you make a similar scale everywhere and that you add it on top of the 100 scale bar and you show the number here.

AC: We have changed the background, showing lighter colors. We have further added a vertical approximate scale on each sample location panel representing a height of 10 m and have added this bar on top of the horizontal distance bar

RC Figure 6:

- Caption: Maybe you could mention that the scale bars don't have the same scale?

AC: We have followed the suggestion of reviewer 2 by producing a uniform scale for each panel, although this makes it impossible to understand how different features are represented by each technique. We kindly ask the editor to choose which version is best suited for point density analysis.

RC Figure 7:

- Caption: "L" in Location

- In the caption and in the main text you use orthomosaic and orthophotos. Please stick to one term.

- I would add after (a) and (b), situation in 2014 (situation in 2016) or something similar, so that you don't start with a year.

AC: - 'L' is now uppercase.

- We now use the term '**orthophoto'** throughout the manuscript.
- We have added 'Collapse structures in' after each letter and before the year.

RC Figure 8:

- Maybe consider to change the total ice thickness change! In the manuscript you are stating values to -30 and -50m that we don't see on the map! The reader needs to calculate if he/she has the yearly values.

AC: The purpose of Fig. 8 is to enable a comparison between different DEM pairs, which is only possible if the DoDs are normalized, using yearly rates instead of absolute values. To help the reader switch between absolute and yearly values, we have added the yearly rates between parentheses in the text (see answers to your comments at lines 375, 377, 382 and 384.

RC Table 1:

- In the caption, it would be nice if you could state something like:" DEM 2007 from aerial multispectral survey, DEM2014 and DEM 2016 from UAV photogrammetry." So that the reader do not need to go back to the text to remember which DEM is which.

AC: We have added this information in the caption as suggested.

RC Table 2:

- This table definitely need some adjustments, because it's not easy to read.

1. The "sample window" text could be rotated 90°, and use all space above the numbers (merge cells).

2. The meaning of k should be explained in the caption

3. You could choose 3 abbreviations (UAV, TP and TLS) in the table and explain them in the caption, so that the text is less squeezed.

4. Watch that you use capital letter at the beginning or you text everywhere.

5. The numbers with 1645+/- 54 need to be in one line! Otherwise the reader asks: what is the number below it? There seems to be a bit of space left on the right side of your table to enlarge it (till the level of your caption right).

AC:

- 1) We have rotated the text by 90° and merged cells to use all spaces above the numbers.
- 2) The meaning of k is now explained in the caption as "k stands for thousands of points".
- 3) We have used the suggested abbreviations and explained them in the caption.
- 4) The first letter of each column title is now uppercase
- 5) The numbers separated by +- signs are now on the same line.

We have rewritten the caption as: "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. k stands for thousands of points. UAV refers to UAV photogrammetry, TP to terrestrial photogrammetry and TLS to terrestrial laser scanning."

RC Table 3:

1. The "sample window" text could be rotated 90°, and use all space above the numbers.

- 2. Same comment as above with the abbreviations
- 3. Explain what is "-" and Ref. in the caption?
- 4. The caption could be a bit more elaborated!

AC: We have modified the table and caption as suggested. The caption now reads: "Table 3: Statistics on distances between point clouds computed on the basis of the M3C2 algorithm, showing mean, standard deviation and root mean square error (RMSE) of each point cloud pair. UAV refers to UAV photogrammetry, TP to terrestrial photogrammetry and TLS to terrestrial laser scanning. Ref. stands for reference and "-" means no comparison was performed."

RC Table 4:

- The text could be all set on left side of the cell
- Caption: Could you explain what is sigma?

AC: We have replaced sigma with '**standard deviation**' and moved text to the left as suggested.

Minor Comments

RC Line 1: are abbreviations authorized in the title?

AC: There are a number of manuscripts in the same special issue as this article with 'UAV' abbreviated in the title. <u>https://www.nat-hazards-earth-syst-sci.net/special_issue859.html</u> We therefore assumed this is acceptable. We kindly ask the editor to confirm this.

RC Line 14: What is a geo-site?

AC: We meant geosite without hyphen. According to the encyclopedia of geomorphology, geosites are "portions of the geosphere that present a particular importance for the comprehension of Earth history. They are spatially delimited and from a scientific point of view clearly distinguishable from their surroundings. More precisely, geosites are defined as geological or geomorphological objects that have acquired a scientific (e.g. sedimentological stratotype, relict moraine representative of a glacier extension), cultural/ historical (e.g. religious or mystical value), aesthetic (e.g. some mountainous or coastal landscapes) and/or social/economic (e.g. aesthetic landscapes as tourist destinations) value due to human perception or exploitation." (Reynard, 2004, p.440).

Reynard, E., Geosite, in Goudie, A.S. (ed), Encyclopedia of geomorphology, volume 1, 2004, Routledge, London, UK.

RC Line 16: Explain the abbreviation.

AC: We have added 'unmanned aerial vehicle' as suggested.

RC Line 18: Explain the abbreviation

AC: We have added 'digital elevation model' as suggested.

RC Line 22: Did you investigate glacier geodetic mass balance? If not, I think this is a very strong (and not founded) assumption. And it would keep it on the natural hazard topic.

AC: we have replaced 'mass balance' with 'thickness changes'.

RC Line 44: I would put here reference.

AC: We have added: 'Azzoni et al. (2017)' as suggested.

RC Lines 44-46: I would remove his sentence because you are talking about glaciers and natural hazards in this section, and that this sentence come a bit out of the blue and covers very general topics (that we generally find at the very beginning of the introduction).

AC: While these topics are general, they demonstrate why glacier volume change is important in connection to glacier hazards, i.e. because it is related to changes in water resources. We have replaced this sentence with "Glacier downwasting causes changes in water resources, with an initial increase in discharge due to enhanced melt followed by a long-term reduction, affecting drinking water supply, irrigation and hydropower production (Kaab et al., 2005b)" to better clarify this, as explained in the answer to your major comment.

RC Line 51: I find the english really heavy here. You could replace it by: such as

AC: We have replaced 'owing to the ability to generate' with 'such as' as suggested.

RC Lines 58-59: And what about aerial photogrammetric surveys? Aerial LIDAR surveys? I think your assumption is wrong.

AC: While the spatial resolution that can be obtained with conventional aerial surveys (higher flying altitude compared to UAVs) is generally lower, we now mention them as well. We have therefore added: "via aerial laser scanner/photogrammetric surveys (Vincent et al., 2010; Janke, 2013)" and the relative entries in the bibliography.

RC Line 70: for the monitoring of glacier or for monitoring glaciers

AC: We have replaced 'for monitoring of glaciers' with 'for monitoring glaciers'

RC Lines 81-83: Crevasses can also be filled with snow and be invisible... I would remove this sentence.

AC: We have removed the sentence as suggested.

RC Line 82: their

AC: we have replaced 'the' with 'their' as suggested.

RC Lines 84-85: I found this not very clear. What about: ...2014. In summer 2016 the glacier was survey with three different techniques allowing for the generation of pt-cloud, DEM and orthomosaic. The aims were: (1) compare the different methods and select the "better" one for monitoring glacier hazards (2)...

AC: We have rephrased the sentence from: "then, through a dedicated field campaign 85 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;" to "in summer 2016, the glacier was surveyed using three different techniques for the generation of point clouds, DEMs and orthophotos. The aims were: (1) to compare the different methods and select the most appropriate ones for monitoring glacier hazards"

RC Lines 89-90: The reader is not ready for this information. The merged pt cloud is only described later! I would remove.

AC: we have removed this part of the sentence as suggested.

RC Line 97: If you don't use little ice age later in the text, there is no need to add an abbreviation to it.

AC: we have removed the abbreviation as suggested.

RC Line 100: such as

AC: we have replaced 'including' with 'such as' as suggested.

RC Lines 102-105: I think the first sentence is grammatically wrong and to my point of view, this information is not needed, as you are not discussing the processes triggering ice collapses later. I would remove.

AC: we have removed the sentence as suggested.

RC Lines 107-108: To my point of view this information is not relevant. I think it's enough to say it's touristic!

AC: we have removed this part of the sentence as suggested.

RC Line 121: ...70%. In our study, sidelap,...

AC: we have modified the text as suggested.

RC Line 122: I would say between 7 and 9am. Knowing the precise time is not relevant.

AC: the sentence now reads: "Flight operations started around 07:30 and ended around 08:30."

RC Line 128: just? what does this word bring? I would remove it, as it almost sounds negative.

AC: we have removed this word as suggested.

RC Line 129: not needed, we are redirected on the map.

AC: we have removed 'lake Rosole, close to Branca Hut' as suggested

RC Lines 132-133: These guys are not the ones that created the SfM algorithm of Agisoft Photoscan. They didn't even wrote the first SfM algorithm. Can you please explain why you cited this paper? Same comment as before. Why this one?

AC: Agisoft Photoscan is closed source, therefore the exact algorithm that is used is unknown. Both articles are cited by Westoby et al. (2012) in their description of the SfM-workflow. We have replaced the references with Westoby et al. (2012), which is more recent.

RC Line 134: The reader do not know what it is and what it is for at that point... I suggest you move the part on the GNSS survey as section 3.1.1 and state what is a GCP there (Ground Control Point).

AC: We have considered this suggestion. However, placing the GNSS subsection at the start would disrupt the chronological flow previously recommended by you and the other reviewer. We have therefore added a paragraph at the start of section 3, including information about GCPs and the workflow used for photogrammetric processing (see e.g. comment at line 158). The paragraph reads:"In this study, we took advantage of a UAV survey performed in 2014 (Fugazza et al., 2015). Then, through a field campaign in 2016, we conducted different surveys using a UAV, terrestrial photogrammetry and TLS. In the 2014 UAV survey, no ground control points (GCPs) were collected, while in 2016 we specifically set up a control network for geo-referencing purposes. Processing of the UAV and terrestrial images was carried out using Agisoft Photoscan version 1.2.4 (www.agisoft.com), implementing a SfM algorithm for image orientation followed by a multi-view dense-matching approach for surface 3D reconstruction (Westoby et al., 2012). In addition, we employed a DEM from an aerial survey of 2007 to calculate glacier thickness changes over a period of 7 to 9 years."

RC Line 138: You used the SfM method. Is Immerzeel using a different one? Or did you followed his workflow in Agisoft Photoscan. If yes, please specify.

AC: we have deleted this sentence as we now explain that Photoscan was used at the start of section 3, as suggested by you, e.g. in your comment at line 158.

RC Line 142: Two UAV surveys...The reader do not know or do not remember that you already talked about them.

AC: we have modified the text as suggested.

RC Lines 147-149: I think this sentence do not give more information than the map. I suggest to remove

AC: we have removed the sentence as suggested.

RC Line 151: To have parallel flights you need two of them no? So why individual? And how can you do parallel flights in zig zag? I suggest rephrasing.

AC: we have replaced 'several individual parallel flights' with 'several flights'.

RC Line 158: 2014 as well... so maybe you can say somewhere that all UAV data were processed with the same software and version?

AC: We have added a paragraph at the start of section 3.1 including this information, see comment at line 134, and removed it from this sentence.

RC Line 160: the GCP cannot have a rmse. The error of their positioning maybe. Please correct

AC: we have modified the text as suggested.

RC Line 167: I would put the reference after "subvertical surfaces" because otherwise the reader expects to see a UAV and a camera looking downwards

AC: we have moved the figure reference as suggested.

RC Line 170: Can you put the location of the pictures on the map maybe?

AC: As there are 134 pictures, placing them on the map would make it less clear. We therefore preferred to keep a separate figure showing the picture location.

RC Line 174: that's the third time you mention this software. See above comment, I would mention it only once.

AC: We have added a paragraph at the start of section 3.1 including this information, see comment at line 134, and removed it from this sentence.

RC Line 183: For me these are results already. You show only the reconstruction of the terrestrial survey because it's the best I guess. However, Figure 6 already shows the comparison. So I do not understand what this Figure brings to the reader. Consider removing.

AC: We have moved this paragraph to the results section where we now also show the full spatial coverage of UAV and terrestrial photogrammetry and have removed this figure accordingly.

RC Line 186: I think the location alreadygives an idea of the angle of measurement. I would remove also because it does not sound right as the adverb is at the wrong place.

AC: we have removed the word 'frontally' as suggested.

RC Line 195: The glacier is not a room ;-) "at the glacier vicinity" or "outside the glacier extent" or "on the periglacial area"

AC: we have replaced 'outside the glacier' with 'on the periglacial area'.

RC Line 196: Define GNSS

AC: we have added global navigation satellite system between parentheses.

RC Line 196: The location of the data? what is this? Can you rephrase?

AC: we have replaced 'at their location' with 'at the target location'.

RC Lines 197-199: I don't understand your sentence. Please rephrase.

AC: we have rephrased this sentence as: "GCPs were used 1) to geo-reference UAV data directly, by identifying the targets on the images in Photoscan; 2) to register theodolite measurements for georeferencing terrestrial photogrammetry and TLS."

RC Line 199: ... consisted of a square white fabric (80x80cm),... ?

AC: We have replaced 'consisted in a piece of white fabric 80x80 cm wide' with 'consisted in a square piece of white fabric (80 x 80 cm)'

RC Line 205: precise point beside the Branca Hut, with coordinates...

AC: we have modified the text as suggested.

RC Lines 208-2012: I would shorten such as: "but due to the local topography preventing the radio link and mobile phone services (for RTK), fixed points with measurement time of approx. 12 min were surveyed."

AC: only a few points were measured in static mode. We have rephrased the sentence as: "but due to the local topography preventing the radio link and the lack of mobile phone services (for RTK), some points were measured in static mode with measurement time of approximately 12 minutes"

RC Lines 212-213: I think there should not be theories on accuracy here ;-) The device or the post-processing software should give you a pretty good approximation of your points error. Can you find them? AC: sometimes terms related to accuracy are not used in a common way by scientists coming from different fields. In Geodesy, the term "theoretical accuracy" refers to the estimated accuracy of estimated values obtained on the basis of observed data processing. Typically, it is the case of estimated accuracy contained in a covariance matrix output after least squares adjustment. This value is obtained from variance-covariance propagation, but also it takes into considerations the quality of adopted observations, as can be found in books about Least Squares. In such a case, what we termed as "theoretical accuracy" does not come from theory, but it is just the estimated value output by the RTK-GNSS processing software.

Thus this is exactly what the Reviewer would like to see. We slightly modified this sentence to make this point clearer and have replace the word 'accuracy' with 'uncertainty' as we preferred to avoid using the term 'accuracy' as indicated in the previous author's response:

"The theoretical uncertainty of GCPs provided by the processing code was in the order of 2-3 cm."

RC Line 215: by the

AC: we have added 'the' as suggested.

RC Line 2016: space

AC: we have added a space as suggested

RC Lines 218-224: I would shorten the whole as: for instance: "...2x2 m, with a +/-3m accuracy. We converted the DEM from the "Gause Boaga" to the "ITRS2000" datum and the heigth from ellipsoidal to geodetic using the official software for datum transformation in Italy (Verto ver.3)

AC: we have rephrased the sentence as suggested.

RC Lines 224-225: The 7 parameter transformation is done in the software is it? If yes this information is a bit too detailed I think.

AC: we have deleted this sentence as suggested.

RC Line 226: In the introduction you state that "possibility of data fusion needs to be investigated", then there is a methodology section which is called "Merging UAV and close-range photogrammetric point clouds" that comes a bit out of the blue (why not a combination of other methods and only these two?)

AC: The reason why we chose to compare the two photogrammetric techniques is because they are less costly than TLS. We have added this explanation at the start of the paragraph, in a sentence that reads: "We chose to avoid TLS and employed the two lower cost techniques (Chandler and Buckley, 2016) to assess their potential for combined future use."

RC Line 232: as well as

AC: we have replaced 'and' with 'as well as' as suggested.

RC Line 233: The point density is controlled by the obtainable spatial resolution? What does it mean? Please rephrase.

AC: We have replaced "and the obtainable spatial resolution" with "and determines spatial resolution"

RC Line 233: I think you can use "the former, the later" only when you listed sth before. You only talked about point density, so I would use "it" or re-write "point density" instead of "the latter property".

AC: we have replaced 'the latter property' with 'point density' as suggested.

RC Lines 233-234: I think not only. If your images are taken on a surface with little contrast, the dense matching tool will not be able to do anything. Please rephrase the whole sentence.

AC: We have rephrased this sentence as: "point density is affected by image texture, sharpness and resolution, which affect the performance of dense matching algorithms (Dall'Asta et al., 2015)"

RC Line 253: Finally can be used if you use firstly, secondly, ... it's not the case and surprises the reader that ask himself if he has not missed sth. Please change.

AC: We have rephrased the sentence as: "Within the same sample locations, we compared the point clouds in a pairwise manner."

RC Lines 255-256: But TLS is influences by atmospheric condition and angle of survey. So it also has errors. If there is no other criteria of why you chose TLS I would not say anything else. Just say "TLS point cloud was used as reference". You say in the abstract that UAV outperforms TLS, so why not using UAV as reference then? To me it is contradictory

AC: We have modified the manuscript as suggested. TLS is generally regarded as more accurate compared to UAV photogrammetry (see also your suggested reference Naumann et al., 2013), while the main findings of our work are that UAV is superior to it in terms of coverage, logistics and cost and thus should be preferred in glacial environments unless obtaining absolute accuracy is paramount.

RC Line 261: Which does what?

AC: we have extended and better explained this part since Reviewer 2 asked to provide more details. We have therefore added the following text: **"As discussed in Fey and Wichmann (2016), the distance between a pair of point clouds is often evaluated by comparing elevations at corresponding nodes of DEMs, after resampling of the original data. This approach works properly when both point clouds are** approximately aligned along the same planar direction, but not when there are structures with different alignments as in the case of the glacier surfaces under investigation. In fact, the M3C2 algorithm does not always evaluate the distance between two point clouds along the same directional axis, but computes a set of local normals using points within a radius *D* depending on the local roughness, which is directly estimated from the point cloud data, and also considering the uncertainty of preliminary local registration refinement using ICP. In this case, a radius *D*=20 cm and a pre-registration uncertainty of 5 cm were considered, the latter obtained from ICP residuals"

RC Line 262: this is English slang :-) A synonym would be better

AC: We have replaced 'get rid of' with 'remove' as suggested.

RC Lines 262-263: what could then be focused? This solution? the registration errors from the analysis? I do not understand the sentence. Please rewrite.

AC: we have replaced 'which could then be focused' with 'and focus'.

RC Line 265: UAV is also a close-range remote sensing technique. Maybe change to UAV and terrestrial?

AC: we have replaced 'close-range' with 'terrestrial' as suggested.

RC Line 267: please define (UAV and terrestrial) for the reader (that probably do not remember what you used in 2016).

AC: We have added '(UAV and terrestrial)'.

RC Line 268: You use ICP a lot in your text afterward and use it for registration. So maybe it would be useful at a point that you explain what ICP means and what it does?

AC: We have spelled out the ICP acronym by adding '(iterative closest point)' between parentheses and added a description of the algorithm, which reads: "ICP iteratively matches a source point cloud to a reference point cloud in Euclidean space and calculates the necessary rotation and translation to align the source point cloud to the reference based on minimization of a distance metric (usually point-to-point)."

RC Line 272: They were not in the same reference system before? I think what you want to say is: "After many iterations, both point clouds were aligned based on the best solution found by the ICP". Solution is not the right word but something alike.

AC: Thanks for the suggestion. It appears that 'solution' is a widely used term to describe the optimal alignment (e.g. Low, 2004), and thus we have rephrased this sentence from: "After this task, both original point clouds resulted aligned into the same reference system." to "After many iterations, both point clouds were aligned based on the best solution found by the ICP" as suggested.

Low, K-L: Linear Least-Squares Optimization for Point-to-Plane ICP Surface Registration, Technical Report TR04-004, Department of Computer Science, University of North Carolina at Chapel Hill, February 2004, available from:

http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.298.4533&rep=rep1&type=pdf

RC Line 273: Same comment as before: Better find a synonym like "remove" or "delete"

AC: we have replaced 'get rid of' with 'remove' as suggested.

RC Line 275: this merged data set?

AC: we have added 'merged' as suggested.

RC Lines 275-276: I think the concept of up-to-date changes every day. What does it mean? I suggest either remove the sentence or put the model of your computer there.

AC: we have removed this part of the sentence.

RC Line 279: I suggest to replace: and therefore

AC: we have replaced 'and aid in the interpretation of glacier hazards' with 'and therefore interpret glacier hazards'.

RC Line 282: only sounds negativ

AC: we have deleted 'only' as suggested.

RC Line 283: See my comment above: change with "terrestrial"

AC: we have replaced 'close-range' with 'terrestrial' as suggested.

RC Line 284: You could shorten the section here as: " The investigation of glacier hazards was conducted using the point cloud and orthophoto from the 2014 UAV dataset as well as the merged (UAV and terrestrial) point cloud and orthophoto from 2016).

AC: We have rephrased the sentence as suggested.

RC Line 284: I would insert here "using visual inspection", so that you don't need the next sentence

AC: We have rephrased the sentence from: 'In this study, we focused on ring faults and normal faults, which were manually delineated by using geometric properties from the point clouds' to 'In this study, we focused on ring faults and normal faults, which were identified by visually inspecting their geometric properties in the point clouds and manually delineated'.

RC Lines 286-287: delete the sentence

AC: we have deleted this sentence as suggested.

RC Lines 287-288: I don't understand. Please check if this is relevant and if yes rephrase.

AC: We have rephrased from: "On orthophotos, both types of structures also generally appear as linear features in contrast with their surroundings" to: "On orthophotos, both types of structures generally appear as dark linear features owing to shadows projected by fault scarps"

RC Lines 288-292: This second part of the paragraph has more its place in the results section for me, because you already describe the form and the location of the structures. I would move it.

AC: We have considered this suggestion. However, location and orientation are criteria used to discriminate normal faults and ring faults from crevasses, which were not included in this study, therefore we have decided to keep the sentence in the method section.

RC Line 321: over a common glacier area

AC: we have replaced 'over a reference area common to all three DEMs' with 'over a common glacier area' as suggested.

RC Line 324: I don't understand. Can you please rewrite?

AC: we have rephrased as: "the truncation error caused by the use of a discrete sum (sum of DEM difference at each pixel multiplied by pixel area) in place of the integral in volume calculation (Jokinen and Geist, 2010)."

RC Line 325: It is not clear what kind of other information than the standard deviation can this

AC: according to Jokinen and Geist (2010), the volume between two surfaces at times t_1 and t_2 can be expressed as:

$$\Delta V = \int_{\Omega} \int (z(x, y, t_2) - z(x, y, t_1)) \, dx \, dy$$

Where $(x, y) \in \Omega \subset R^2$

while in the case of DEMs, this formula is approximated as:

$$\Delta V = \sum_{k=1}^{K} \bar{d}_k A_k$$

Where \bar{d}_k is the average of differences $\bar{d}(x_i, y_i) = z(x_i, y_i, t_2) - z(x_i, y_i, t_1)$ at the vertices of Ω_k and A_k is the area of Ω_k

The uncertainty in volume change calculated from DEM differencing can then be expressed as a combination of two factors: 1) errors in elevation propagating to the elevation difference

and volume calculation and 2) truncation error, as the integral in the first equation is replaced by a finite sum in the second equation.

We have revised our calculations, using the approach by Rolstad et al. (2009) to calculate factor 1).

This approach takes into account spatial autocorrelation of elevation differences over bedrock. Thus, the standard deviation of DoD over bedrock $\sigma_{\Delta h}$ is scaled to account for the effective correlated area, A_{cor} .

 A_{cor} is calculated as $A_{cor} = \pi \times L^2$, where *L* is the radius of a circular area, and is equal to the correlation length.

We identified this correlation length by looking at the semivariograms of the DoDs in R software and found a mean value of 50 m for the three DoDs.

The standard deviation σ_{cor} is then calculated as $\sigma_{cor} = \sqrt{\sigma_{\Delta h}^2 \frac{A_{cor}}{5 \cdot A}}$, where *A* is the glacier

area.

Finally, the uncertainty on volume change is expressed as $\sigma_{\Delta V} = \sigma_{cor} \times A$, considering the error as entirely correlated.

As regards the truncation error $E_T(\Delta V)$, we calculated it following the approach by Jokinen and Geist (2010), i.e. using the formula

$$|E_T(\Delta V)| \leq \frac{h^4}{12} \sum_{k=1}^K \max(x, y) \in \Omega_k \left| \frac{\partial^2}{\partial x^2} d(x, y) + \frac{\partial^2}{\partial y^2} d(x, y) \right|$$

Where *h* is grid spacing and $\frac{\partial^2}{\partial x^2} d(x, y) + \frac{\partial^2}{\partial y^2} d(x, y)$ is the Laplacian operator of d(x, y)

RC Line 330: who says that this is enough? You or did you find a publication that found out the minimum points needed to get a certain accuracy? Can you please specify?

AC: from a rigorous point of view, this is simply an application of the "sampling theory." If you have a planar surface, three points would be enough to estimate the fitting plane. If you have a surface with a more complex shape, you need more points. An exact correlation between point sampling and surface approximation accuracy can be obtained by applying a Fourier analysis. Here we followed a simplified approach: considering that a minimum point density of approximately 100 points/m² was found (i.e., one point every one square decimeter on the glacier surface), we retained that the errors in the reconstructed surface were lower than the local surface roughness and noise.

RC Line 332: It it clear from Fig. 6 that the terrestrial photogrammetry is the method that produces the best results in term of point density and UAV the "worse". I did not understand how much in brings you to merge the point clouds from both techniques if the UAV point cloud is so sparse! What difference did it make?

AC: as explained in the answer to your major comment, and now reported in the results section, the two point clouds cover different areas. We have added a figure in the results section showing this and added a paragraph explaining the different coverage of the techniques.

RC Line 349: larger deviations

AC: We have replaced 'worse values' with 'greater deviations'.

RC Line 357 and Line 361: Fig.7

AC: we have written 'Fig.7' as suggested

RC Line 375: On Fig.8a, we can see loss between 0 to -9m. Where are these -30 meters taking place?

AC: Fig. 8a reports thickness change rates instead of thickness changes to allow a comparison between the three DEM pairs. We have added the change rate between parentheses here and throughout the paragraph.

RC Line 377: Same as before, I don't see these numbers on the map in Fig.1

AC: see the answer to your comment above.

RC Line 382: 20 to 26m?

AC: we have replaced '20/26 m' with '20 to 26 m' as suggested.

RC Line 384: -2 to -5m

AC: we have replaced '-2/-5 m' with '-2 to -5 m' as suggested.

RC Line 392: You write about geodetic mass balance in the abstract and in the discussion part, but none of your results deals with glacier mass balance. This is very surprising for the reader that is wondering what's going on. Maybe consider removing it.

AC: we have replaced 'geodetic mass balance' with 'thickness changes'.

RC Line 404: I think you should write this as suggestion, as you did not tested it.

AC: we have replaced 'is due' with 'might be due'.

RC Line 416: That's right. The literature has already shown that UAV are better on flat surfaces and terrestrial photogrammetry and TLS on steeper topography. So what do your results bring more to this knowledge?

AC: as discussed in the answer to your major comment, these publications are rather recent and mainly describe surveys of non-glacial environments. We have kept the references to these publications to provide a review of their conclusions in a different environment, and restructured the discussion section adding a further paragraph discussing why our approach should be preferred to TLS and a comparison between our techniques, ALS and aerial photogrammetry. RC Lines 450-451: You say it's adequate. What does it mean? When looking at Table 1, at the elevation differences between the DSMs after co-registration, I see that the standard deviation of the elevation differences between both UAV DSMs is of 2.2 m. Considering that you have a melt of several meters (I'm guessing 6m per year, so 12 in two years), I'm not sure you can say that this technique is adequate. Can you please explain in a more quantitative way what "adequate" means to you?

AC: As explained in the answer to your major comment, the ice thickness change uncertainty results in 2.60% of the volume change uncertainty for the 2014-2016 comparison. We have replaced this sentence with: **"UAV photogrammetric products permitted to investigate ice volume changes over 2 years with an uncertainty of 2.60%**"

RC Line 459: this sounds negative. I would remove

AC: we have removed 'only' as suggested.

RC Line 459: You investigated different techniques to map/monitor glacier hazards.

AC: we have rephrased as: "different techniques to map/monitor hazards related to the glacier collapse"

RC Line 465: what about TLS?

AC: We integrated terrestrial and UAV photogrammetry, while TLS was used for comparison only. We now clarify that UAV and close-range photogrammetry should be preferred to TLS, and have rephrased the sentence as: "While our integrated approach using a multicopter and terrestrial photogrammetry should be preferred to TLS for the investigation of small individual ice bodies"

RC Line 470: Aerial LiDAR surveys? Did you have some for the Stelvio National Park? Why is this technique suddenly comming up here?

AC: We now mention ALS and aerial photogrammetry in the introduction and discussion to provide a more comprehensive comparison of different techniques and their advantages/drawbacks. We have replaced 'aerial LiDAR surveys' with 'higher altitude aerial surveys' to include both ALS and aerial photogrammetry and clarify we are not referring to UAVs.

RC Lines 482-483: I don't think the UAVs in the mountains are more flexible in terms of meteorological conditions...

AC: we have removed this part of the sentence

RC Line 487: You did not try to measure mass balance, so please remove.

AC: we have removed this part of the sentence.

RC Line 493: Your maps were produced with ortophotos right?

AC: The base layers of the maps in Figure 7 are indeed orthophotos but the analysis was mainly conducted based on the point clouds. We have added '**and orthophotos**' after 'point clouds'.

RC Line 499: This is also new... You never talked about this before. Why in the conclusion?

AC: we have deleted this part of the sentence.

RC Line 504: delete 'mass balance'.

AC: we have replaced 'mass balance' with 'thickness changes'.

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.

Review

The authors have benefited from two sets of very thorough reviews on their original manuscript. I have read these reviews and the authors' responses, which are mostly appropriate and well-justified. Importantly, the authors have shortened many sections and undertaken some restructuring which has improved the flow and clarity of the manuscript.

I have provided a few additional points for consideration prior to publication. These are minor and should not take the authors very long to address.

Dear Reviewer,

Thank you for your comments. We have provided our answers to your points below.

RC Line 50 – 'sensing', not 'Sensing'

AC: the word is now in lower case as suggested.

RC Line 63 and throughout – 'photogrammetry', not 'Photogrammetry'

AC: 'photogrammetry' is now lower case throughout the manuscript.

RC Line 69 – remove 'slowly'

AC: We have removed this word as suggested. This part of the sentence has now been changed as: "**is on the rise**"

RC Line 74 – would be useful to quantify 'rapidly downwasting' here – approximately how much surface lowering/terminus retreat is there per year?

AC: We have added "(almost 5 ma⁻¹ water equivalent, Senese et al., 2012)" to clarify the amount of surface lowering per year.

RC Line 102 – is it appropriate in NHESS for authors to list articles that have been 'submitted'? 'In press' or 'Accepted' – yes; 'submitted' – I'd perhaps not be comfortable with including this. This requires an Editorial decision.

AC: The article that was listed as 'submitted' has now been published on the Journal of Maps.

We have replaced '**submitted**' with '**2017**' and changed the entry in the reference list accordingly.

RC Line 160 – I assume that no independent check data were acquired to truly test the 'accuracy' of the UAV-SfM data during the model generation stage? If so, the wording needs changing here – the RMSE for the PhotoScan 'markers' in this situation is simply a reflection

of the internal project consistency (i.e. how well the software can shift/rotate/transform the data to fit the user-placed markers). It provides no true measure of accuracy, for which an independent set of check points is required. I would strongly suggest authors clarify this briefly, or change their terminology. I note that there has already been some discussion about the appropriateness of the term 'accuracy' elsewhere in the manuscript (see p24 of the author response), and request that the authors consider this a little further in this paragraph.

AC: Thanks for your comment. We have changed the terminology here, replacing "which can be used as an indicator of accuracy for the geo-referencing of the photogrammetric block." with "which can be used as an indicator of the internal consistency of the photogrammetric block", and deleted a similar comment in section 3.2 Terrestrial Photogrammetry, i.e. "which can be considered as the accuracy of absolute geo-referencing". We have further decided to avoid using the term accuracy in the manuscript, as the accuracy depends on the use of the data, as explained in the previous author response. Thus, we have replaced "The final accuracy of our UAV photogrammetric products was nevertheless adequate to investigate ice thickness changes over 2 years" with "UAV photogrammetric products permitted to investigate ice volume changes over 2 years with an uncertainty of 2.60%" in the discussion section and replaced the term accuracy with uncertainty throughout the manuscript, providing uncertainty values where available.

RC Line 261 – these sentences are a vast oversimplification of the M3C2 algorithm, which is complex and requires some more explanation – i.e. what was the radius for surface normal estimation, what was the value of the registration that was specified prior to analysis? A sentence explaining why you chose this method over others (e.g. 2.5D raster subtraction) would be useful – e.g. was the topography complex enough to require its use?

AC: Although keeping the discussion short, we have better explained the motivations for using M3C2 algorithm. Also we briefly reviewed the main features of this algorithm, and reported the values of the adopted parameters. The new text is reported below:

"As discussed in Fey and Wichmann (2016), the distance between a pair of point clouds is often evaluated by comparing elevations at corresponding nodes of DEMs, after resampling of the original data. This approach works properly when both point clouds are approximately aligned along the same planar direction, but not when there are structures with different alignments as in the case of the glacier surfaces under investigation. In fact, the M3C2 algorithm does not always evaluate the distance between two point clouds along the same directional axis, but computes a set of local normals using points within a radius *D* depending on the local roughness, which is directly estimated from the point cloud data, and also considering the uncertainty of preliminary local registration refinement using ICP. In this case, a radius *D*=20 cm and a pre-registration uncertainty of 5 cm were considered, the latter obtained from ICP residuals."

RC Line 371: 'thickness', not 'Thickness'

AC: the word is now lower case as suggested.

RC Table 1 – column 1 - please add some annotation to help the reader understand the source of each DEM – e.g. (TLS) / (UAV-SfM) etc

AC: Thanks for the suggestion. The information about the source of each DEM is now written in the caption, as suggested by the other reviewer.

RC Figure 4 – requires a distance scale on both or either of the panels

AC: We have deleted this figure as suggested by reviewer 1, and replaced it with a figure showing the full spatial coverage of UAV and terrestrial photogrammetric point clouds to better clarify the differences between the two and the advantages of merging the point clouds.

RC Figure 6 – I take issue with the different scales on each of these panels – it is impossible to compare like-for-like. Strongly suggest authors modify this so that the point densities between panels are directly comparable.

AC: We have produced a new figure with uniform color scales so point densities between panels are directly comparable. However, terrestrial photogrammetry has a much higher point density than the other techniques, whose panels now mostly show one single colour. This makes it impossible to understand how different features are represented by individual techniques (e.g. vertical cliffs vs horizontal features in UAV photogrammetry). We have provided the new figure but kindly ask you and the editor to choose which version is best suited for point density analysis.

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

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Abstract

13 Tourists and hikers visiting glaciers all year round face hazards such as the rapid formation ofsudden terminus collapses at the terminus, typical of such a dynamically evolving environment. 14 In this study, we analysed the potential of different survey techniques to analyze analyze hazards of 15 the Forni glacier, an important geo-sitegeosite located in Stelvio Park (Italian Alps). We carried out 16 surveys in the 2016 ablation season 2016 and compared point clouds generated from an unmanned 17 aerial vehicle (UAV) survey, close range photogrammetry and terrestrial laser scanning (TLS). To 18 19 investigate the evolution of glacier hazards and evaluate the glacier thinning rate, we also used UAV 20 data collected in 2014 and a **DEM**digital elevation model (DEM) created from an aerial photogrammetric survey of 2007. We found that the integration between terrestrial and UAV 21 22 photogrammetry is ideal to mapfor mapping hazards related to the glacier collapse, while TLS is affected by occlusions and is logistically complex in glacial terrain. Photogrammetric techniques 23 can therefore replace TLS for glacier studies and UAV-based DEMs hold potential to become for 24 25 becoming a standard tool to investigatein the investigation of glacier geodetic mass balancethickness changes. Based on our datasets, an increase in the size of collapses was found over 26 the study period, and the glacier thinning rates went from 4.55 ± 0.24 ma⁻¹ between 2007 and 2014 27 to 5.20 ± 1.11 ma⁻¹ between 2014 and 2016.-28

29 1 Introduction

- 30 Glacier and permafrost-related hazards can be a serious threat to humans and infrastructure in high
- 31 mountain regions (Carey et al., 2014). The most catastrophic cryospheric hazards are generally
- 32 related to the outburst of water outbursts, either through breaching of moraine- or ice-dammed
- 33 lakes or from the englacial or subglacial system, causing floods and debris flows. Ice avalanches
- 34 from hanging glaciers can also have serious consequences for downstream populations (Vincent et

35 al., 2015), as well as debris flows caused by the mobilization of accumulated loose sediment on 36 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 37 38 (Gagliardini et al., 2011; Azzoni et al., submitted 2017). While these processes are in part typical of 39 glacial and periglacial environments, there is evidence that climate change is increasing the 40 likelihood of specific hazards (Kaab et al., 2005a). In the European Alps, accelerated formation and 41 growth of proglacial moraine-dammed lakes has been reported in Switzerland, amongst concern of 42 possible overtopping of moraine dams provoked by ice avalanches (Gobiet et al., 2014). Ice 43 avalanches themselves can be more frequent as basal sliding is enhanced by the abundance of 44 meltwater in warmer summers (Clague, 2013). Glacier and permafrost retreat, which have been 45 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 46 47 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 48 49 thecauses changes in water resources, with an initial increase in discharge due to enhanced melt followed by a long-term reduction, affecting drinking water supply, irrigation and hydropower 50 51 production (Kaab et al., 2005b), along with a rising occurrence of structural collapses and while not 52 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 53 populations living away from glaciers. (Azzoni et al., 2017). Finally, glacier retreat and the increase 54 in glacier hazards both negatively influence the tourism sector and the economic prosperity of high 55 56 mountain regions (Palomo, 2017).

57 The <u>increasinggrowing</u> threat from cryospheric hazards under climate change calls for the adoption 58 of mitigation strategies. Remote <u>Sensingsensing</u> has long been recognized as an important tool to

59 produce for producing supporting data to for this purpose, owing to the ability to generate such as 60 digital elevation models (DEMs) and multispectral images. DEMs are particularly useful to detectfor detecting glacier thickness and volume variations (Fischer et al., 2015; Berthier et al., 61 62 2016) and to identify for identifying steep areas that are most prone to geomorphodynamic changes, such as mass movements (Blasone et al., 2014). Multispectral images at a sufficient spatial 63 resolution enable the recognition of make it possible to recognize most cryospheric hazards 64 65 (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, 66 2017), the assessment of hazards at the scale of individual glaciers or basins requires a higher 67 resolution, 68 spatial which in the past could only be achieved via aerial laser scanner/photogrammetric surveys (Vincent et al., 2010; Janke, 2013) or dedicated field campaigns 69 70 with terrestrial laser scanners (TLS) (Kellerer-Pirklbauer et al., 2005; Riccardi et al., 2010). Recent 71 years have seen a resurgence of terrestrial photogrammetric surveys for the generation of DEMs 72 (Piermattei et al., 2015, 2016; Kaufmann and Seier, 2016) due to important technological 73 advancements advances, including the development of Structure-from-Motion (SfM) 74 Photogrammetryphotogrammetry 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., 75 76 2012). In parallel, unmanned aerial vehicles (UAVs - Colomina & Molina, 2014, O'Connor et al., 77 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, 78 79 and coarser resolution satellite data (Bhardwaj et al., 2016). Although the number of studies 80 employing themthese platforms in high mountain environments is slowly increasing on the rise (see e.g. Fugazza et al., 2015; Gindraux et al., 2017; Seier et al., 2017), their full potential for 81 82 monitoring of glaciers and particularly glacier hazards has stillyet to be explored. In particular, the 83 advantages of UAV and terrestrial SfM-Photogrammetry, photogrammetry and the possibility of data

84 fusion and volume change estimation to support hazard management strategies in glacial
85 environments needs to be investigated and assessed.

86 In this study, we investigated a rapidly downwasting glacier (almost 5 ma⁻¹ water equivalent, Senese 87 et al., 2012) in a protected area and highly touristic sector of the Italian Alps, Stelvio National Park. 88 We focused on the glacier terminus and the hazards identified there, i.e., the formation of normal 89 faults and ring faults. The former occur mainly on the medial moraines and glacier terminus and are 90 due to gravitational collapse of debris-laden slopes. The latter develop as a series of circular or 91 semicircular fractures with stepwise subsidence, caused by englacial or subglacial meltwater creating 92 voids at the ice-bedrock interface-and, eventually leading to the collapse of the cavity roofs. While often 93 overlooked, these collapse structures are particularly hazardous for mountaineers and they are likely to 94 increase under a climate change scenario (Azzoni et al., submitted2017). They are more dangerous 95 than crevasses because of thetheir larger size and because they could be filled with snow and 96 rendered entirely or partly invisible to mountaineers...

We conducted our first UAV survey of the glacier in 2014; then, through a dedicated field campaign 97 98 earried out in summer 2016, we compared the glacier was surveyed using three different platforms 99 and techniques for point eloud, DEM and orthomosaie the generation to assess their ability to 100 monitor glacier hazards: UAV photogrammetry, terrestrial photogrammetry and TLS.of point 101 clouds, DEMs and orthophotos. The aims were: (1) comparing UAV- and terrestrial 102 photogrammetric products acquired in 2016 against the TLS point cloud; to compare the different 103 methods and select the most appropriate ones for monitoring glacier hazards (2) identifyingto 104 identify glacier-related hazards and their evolution between 2014-2016 using the merged point eloud from UAV and terrestrial photogrammetry and UAV orthophotos; and 3) investigating to 105 106 investigate changes in ice thickness changes between 2014-2016 and 2007-2016 by comparing the 107 two UAV DEMs and a third DEM obtained from stereo-processing of aerial photos captured in 108 2007.

109

110 2 Study Areaarea

The Forni Glacier (see Fig. 1) has an area of 11.34 km² based on the 2007 data from the Italian 111 112 Glacier Inventory (Smiraglia et al., 2015;); an altitudinal range between 2501 and 3673 m a.s.l. 113 and a North-North-Westerly aspect. The glacier has retreated markedly since the little ice age (LIA), when its area was 17.80 km² (Diolaiuti & Smiraglia, 2010), with an acceleration of the 114 115 shrinkingshrinkage rate inover the lastpast three decades, typical of valley glaciers in the Alps 116 (Diolaiuti et al., 2012, D'Agata et al.; 2014). It has also undergone profound changes in dynamics in 117 recent years, includingsuch as the loss of ice flow from the eastern accumulation basin towards its 118 tongue and the evidence of collapsing areas on the eastern tongue (see Fig. 2d; Azzoni et al., submitted). One such area, hosting a large ring fault (see Fig. 2d) prompted an investigation carried 119 120 out with Ground Penetrating Radar (GPR) in October 2015, but little evidence of a meltwater 121 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,e,e). 2017). 122 123 Continuous monitoring of these hazards is important, as the site is highly touristic (Garavaglia et al., 124 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 125 126 frequently visited during both summer and winter months. During the summer, hikers heading to 127 Mount San Matteo take the trail along the central tongue, accessing the glacier through the left flank of the collapsing glacier terminus- (see Fig. 2b, c). During wintertime, ski-mountaineers instead 128 129 access the glacier from the eastern side, crossing the medial moraine and potentially collapsed areas there (see Fig. 1)-, 2a). 130

131 **3 Data** Sourcessing: acquisition and processing

- 132 In this study, we took advantage of a UAV survey performed in 2014 (Fugazza et al., 2015). Then,
- 133 through a field campaign in 2016, we conducted different surveys using a UAV, terrestrial
- 134 photogrammetry and TLS. In the 2014 UAV survey, no ground control points (GCPs) were
- 135 <u>collected</u>, while in 2016 we specifically set up a control network for geo-referencing purposes.
- 136 Processing of the UAV and terrestrial images was carried out using Agisoft Photoscan version 1.2.4
- 137 (www.agisoft.com), implementing a SfM algorithm for image orientation followed by a multi-view
- 138 dense-matching approach for surface 3D reconstruction (Westoby et al., 2012). In addition, we
- 139 employed a DEM from an aerial survey of 2007 to calculate glacier thickness changes over a period
- 140 of 7 to 9 years.

141 **3.1 UAV Photogrammetry**photogrammetry

142 3.1.1 2014 Dataset

The first UAV survey took place on 28th August 2014, using a SwingletCam fixed wing aircraft (see 143 Fig. 3a). This commercial platform developed by SenseFly carries a Canon Ixus 127 HS compact 144 145 digital camera. The UAV was flown in autopilot mode with a relative flying height of approximately 146 380 m above the glacier surface, which resulted in an average GSD of 12 cm. The flight plan was 147 organized by using the proprietary software eMotion, by which the aircraft follows predefined 148 waypoints with a nominal along-strip overlap of 70%;%. In our study, sidelap was not regular because of the varying surface topography, but wasit averaged approximately 60%. Flight 149 150 operations started ataround 07:4430 AM and ended ataround 08:2230 AM. Early morning 151 operations were preferred to avoid saturating camera pictures, as during this time of day the glacier 152 is not yet directly illuminated by the sun, and to minimize blurring effects due to the UAV motion, 153 since wind speed is at its lowest on glaciers during morning hours (Fugazza et al., 2015). Pictures 154 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 155

156 survey covered an area of 2.21 km² in just-two flight campaigns, with a low altitude take-off (lake
157 Rosole, close to Branea Hut, see Fig. 1). Both the terminal parts of the central and eastern ablation
158 tongue were surveyed.-

Processing of data from the 2014 UAV flight was carried out using Agisoft Photoscan version 1.2.4 159 (www.agistoft.com), implementing a SfM algorithm for image orientation (Spetsakis and 160 161 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 162 163 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 1.5-2 164 m resulted after geo-referencing, and no control on the intrinsic geometric block stability eould 165 166 bewas possible. After the generation of the point cloud, a DEM and orthoimageorthophoto were produced using the method described by Immerzeel et al. (2014), with spatial resolutions of 60 cm 167 168 and 15 cm, respectively.

169

170 **3.1.2 2016 Dataset**

The two Two UAV surveys were carried out on 30th August and 1st September 2016, both around 171 172 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 173 174 camera. Two different take-off and landing sites were chosen to gain altitude before take-off and 175 maintain line-of-sight operation with a flying altitude of 50 m above ground, which ensured an 176 average ground sample distance (GSD) of 6 cm. The first take-off site was on the eastern lateral moraine (elevation approx. 2700 m a.s.l.), while the second site was a rock outcrop on the 177 178 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 km².

Processing of data from the 2016 UAV flight was carried out using Agisoft Photoscan version 1.2.4. 188 189 Eight GCPs (see Fig. 1) were measured for the registration of the photogrammetric blocks and its 190 by-products into the mapping system. The root mean square error (RMSE) of the GCPsGCP 191 location was 40 cm, which can be used as an indicator of accuracy for the geo-referencinginternal 192 consistency of the photogrammetric block. The point cloud obtained from the 2016 UAV flight was 193 interpolated to produce a DEM and orthoimageorthophoto with the same cell resolution as the 2014 194 dataset, i.e., 60 and 15 cm, respectively. Both products were exported in the ITRS2000 / UTM 32N 195 mapping reference system.

196 **3.2 Terrestrial photogrammetry**

197 The terrestrial photogrammetric survey was carried out during on 29th August 2016 to reconstruct 198 the topographic surface of the glacier terminus, which presented several vertical and subvertical 199 surfaces (see Fig. 2e) whose measurement was not possible from the UAV platform carrying a 200 camera in nadir configuration (see Fig. 2e). 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-lensreflex 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 Photosean 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 207 208 adjustment computation in Agisoft Photoscan. Measurement of GCPs in the field was carried out 209 by means of a high-precision theodolite. The measurement of points previously recorded with a 210 GNSS geodetic receiver allowed made it possible to register the coordinates of GCPs in the mapping 211 reference system. The RMSE of 3D residual vectors on GCPs was 34 cm, which can be considered 212 as the accuracy of absolute geo-referencing. The final point cloud obtained from the dense matching tool implemented in Agisoft Photosean covers at a very high spatial resolution the full glacier 213 terminus, with the exception of a few obstructed parts (see Fig. 4b)... 214

215 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. 223 Considering the accuracy of registration and the expected precision of laser point measurement, the 224 global accuracy uncertainty of 3D points was estimated inon the order of ± 7.5 cm.-

225 3.4 GNSS ground control points

Prior to the 2016 surveys, eight control targets were placed both outsideon the glacierperiglacial 226 227 area and on the glacier tongue (see Fig. 1). Differential GNSS (global navigation satellite system) 228 data were acquired at their the target location for accurate the geo-referencing of UAV, terrestrial photogrammetry and TLS data. While for GCPs were used 1) to geo-referencing of reference UAV 229 230 data the GCPs were directly visible, by identifying the targets on the quadcopter images, for in 231 Photoscan; 2) to register theodolite measurements for geo-referencing terrestrial photogrammetry 232 and TLS-they were adopted for the registration of theodolite measurements... The targets consisted 233 in a square 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 234 GCPs were positioned on large, flat boulders to provide a stable support and reduce the impact of 235 236 ice ablation between flights.-

237 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 238 239 master on a boulderprecise point beside Branca Hut, where a monument had been establishedhut, 240 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 241 242 distance between master and rover was less than 1.5 km, but <u>due to</u> the local topography prevented 243 broadcastingpreventing the differential corrections in a few zones of radio link and the glacier. 244 Unfortunately, no lack of mobile phone services were available and consequently the internet 245 network could not be accessed, precluding the use of the regional GNSS real-time positioning service. Non-(for RTK), some points were processed measured in fast-static mode, requiring a 246

247 longer_with measurement time of approx.approximately 12 minutes. The theoretical
248 accuracyuncertainty of GCPs provided by the processing code was estimated inon the order of 2-3
249 cm.

250 **3.5 2007 DEM**

The 2007 TerraItaly DEM was produced by the BLOM C.G.R. company for the Lombardy region. 251 252 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 253 254 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 ± 3 m uncertainty. We converted the former national 255 256 'Gauss Boaga - Fuso I' mapping reference system based on DEM from the "Monte Mario" to the 257 "ITRS2000" datum (Mugnier, 2005). Heights were converted and the height from ellipsoidal to geodetic using the official software for datum transformation in Italy (Verto ver. 3), which is 258 259 distributed by the Italian Geographic Military Institute (IGMI). The final vertical accuracy reported by BLOM C.G.R. is \pm 3 m. The only processing step performed within this study was the datum 260 261 conversion to ITRS2000, using a seven-parameter similarity transformation based on a local 262 parameter set provided by IGMI.3).

263 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/m²) and completeness, i.e. % of area in the ray view angle. Point density partly depends upon the adopted
271 surveying technique used, since it is controlled by the distance between sensor and surface, and the 272 obtainable determines spatial resolution. SfM-Photogrammetry, the latter In propertyphotogrammetry, point density is affected by image texture, sharpness and resolution, 273 274 which influence the performance of dense matching, algorithms (Dall'Asta et al., 2015), while in 275 TLS it can be set up as a data acquisition input parameter. In this study, the number of neighbours N276 (inside a sphere of radius R=1 meter) divided by the neighbourhood surface was used to evaluate 277 the local point density D in CloudCompare (<u>www.eloudcompare.org</u>). www.eloudcompare.org). To understand the effect of point density dispersion (Teunissen, 2009), the inferior 12.5 percentile of 278 the standard deviation σ of point density was also calculated. The use of these local metrics allowed 279 280 us to distinguish between point densitydensities in different areas, since this may largely change 281 from one portion of surface to another. A further metric in this sense was point cloud completeness, 282 referring to the presence of enough points to completely describe a portion of surface. In this study, 283 the visual inspection of selected sample locations was used to identify occlusions and areas with 284 lower point density.

To analyse these properties, five regions were selected (see Fig. 54), located on the glacier 285 286 topographic surface and characterized by different glacier features and the presence of hazards: 1) 287 Glaciala glacial cavity composed by of subvertical and fractured surfaces over 20 m high, and forming a typical semicircular shape; 2) a glacial cavity over 10 m high with the same typical semi-288 289 circular shape as location 1, covered by fine- and medium-sizesized rock debris; 3) a normal fault 290 over 10 m high; 4) a highly-collapsed area covered by fine- and medium-sizesized rock debris and 291 rock boulders; and 5) a planar surface with a normal fault covered by fine- and medium-sizesized 292 rock debris and rock boulders. The analysis of local regions was preferred to the overall analysis of 293 all the entire point clouds for the following reasons: 1) the incomplete overlap between point clouds

294 obtained from different methods; 2) the opportunity to investigate the performances of the
295 techniques in diverse geomorphological situations.-

296 FinallyWithin the same sample locations, we compared the point clouds in a pairwise manner 297 within the same sample locations. Since no available benchmarking data set (e.g. accurate static 298 GNSS data) was concurrently collected during the 2016 campaign, -the TLS point cloud was used 299 as a reference, as it less influenced by controlling factors (network geometry, object texture, lighting 300 conditions). When comparing both photogrammetric data sets, the one obtained from the UAV was 301 used as reference because of the even distribution of point density within the sample locations. The 302 presence of residual, non-homogenous geo-referencing errors in the data sets required a specific 303 fine registration of each individual sample location, which was conducted in CloudCompare using 304 the ICP algorithm (Pomerleau et al., 2016). Then(iterative closest point) algorithm (Pomerleau et 305 al., 2013). ICP iteratively matches a source point cloud to a reference point cloud in Euclidean space and calculates the necessary rotation and translation to align the source point cloud with the 306 307 reference based on minimization of a distance metric in a point-to-point fashion. After fine 308 registration, point clouds in corresponding sample areas were compared using the M3C2 algorithm 309 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 2013). As discussed in Fey and 310 311 Wichmann (2016), the distance between a pair of point clouds is often evaluated by comparing 312 elevations at corresponding nodes of DEMs, after resampling of the original data. This approach works properly when both point clouds are approximately aligned along the same planar direction, 313 314 but not when there are structures with different alignments as in the case of the glacier surfaces 315 under investigation. In fact, the M3C2 algorithm does not always evaluate the distance between two point clouds along the same directional axis, but computes a set of local normals using points within 316 317 a radius D depending on the local roughness, which is directly estimated from the point cloud data,

318 and also considering the uncertainty of preliminary local registration refinement using ICP. In this
319 case, a radius *D*=20 cm and a pre-registration uncertainty of 5 cm were considered, the latter
320 obtained from ICP residuals. This solution allowed us to remove registration errors from the
321 analysis, and focus on the capability of the adopted techniques to reconstruct the local geometric
322 surface of the glacier in an accurate way.—

323 **4.2 Merging of UAV and close-range photogrammetric point clouds**

324 4.2 Point cloud merging

325 To improve coverage of different glacier surfaces, including planar areas and normal faults, photogrammetric point clouds from the 2016 campaign were merged.(UAV and terrestrial surveys) 326 327 were merged. We chose to avoid TLS and employed the two lower cost techniques (Chandler and Buckley, 2016) to assess their potential for combined future use. Prior to point cloud merging, a 328 329 preliminary co-registration was performed on the basis of the ICP algorithm in CloudCompare. 330 Regions common to both point clouds were used to minimize the distances between them and find 331 the best co-registration. The point cloud from UAV photogrammetry, which featured the largest 332 extension, was used as reference during co-registration, while the other was rigidly transformed to 333 fit with it. After this taskmany iterations, both original point clouds resultedwere aligned intoaccording to the same reference system. best solution found by the ICP. In order to get rid 334 335 ofremove redundant points and to obtain a homogenous point density, the merged point cloud (see 336 Fig. 5) was subsampled keeping a minimum distance between adjacent points of 20 cm. The final 337 size of this merged data set is approximately 4.4 million points, which represents a manageable data 338 amount on up-to-date computers. The RGB colour RGB information associated towith each point 339 in the final point cloud was derived by averaging the RGB information of original points in the 340 subsampling volumes. While this operation resulted in losing part of the original RGB information,

341 it helped to provide a realistic visualization of the topographic model, which can aid the
 342 interpretation of and therefore to interpret glacier hazards.

343 4.2 Glacier hazard mapping

344 The investigation of glacier hazards was conducted by considering datasets from 2014 and 2016. In 2014, only using the point cloud and UAV orthophoto were available, while in 2016 from the 2014 345 346 UAV dataset as well as the merged (UAV and terrestrial) point cloud obtained by merging UAV and elose-range photogrammetric data sets was used in combination with the UAV and orthophoto from 347 2016. In this study, we focused on ring faults and normal faults, which were manually delineated by 348 349 using identified by visually inspecting their geometric properties from in the point clouds and 350 manually delineated, while colorcolour information from orthophotos was used as a cross-check. 351 On point clouds, mapping is based on visual inspection of vertical displacements following faulting 352 or subsidence. On orthophotos, both types of structures also generally appear as <u>dark</u> linear features in contrast with their surroundingsowing to shadows projected by fault scarps. As these structures 353 354 may look similar to crevasses, further information concerning their orientation and location needs to 355 be assessed for discrimination. The orientation of fault structures is not coherent with glacier flow, 356 with ring faults also appearing in circular patterns. Their location is limited to the glacier margins, 357 medial moraines and terminus, whereas crevasses can appear anywhere on the glacier surface 358 (Azzoni et al., submitted2017). After delineation, we also analysed the height of vertical facies 359 using information from the point clouds.-

360 **4.3 DEM <u>eoCo</u>**-registration for glacier thickness change estimation

361 Several studies have found that errors in individual DEMs, both in the horizontal and vertical 362 domain, propagate when calculating their difference_a leading to inaccurate estimations of thickness 363 and volume change (Berthier et al., 2007; Nuth & Kaab, 2011). In the present study, different 364 approaches were adopted for geo-referencing all the DEMs (2007, 2014, 2016) used in the analysis 365 of the volume change of the Forni Glacier tongue. (2007, 2014, 2016). To compute the relative differences between the DEMs, a preliminary co-registration was therefore required. The method 366 367 proposed by Berthier et al. (2007) for the co-registration of two DEMS was separately applied to 368 each DEM pair (2007-2014; 2007-2016; 2014-2016). Following this method, in each pair one DEM 369 plays as reference ('master'), while the other is used as 'slave' DEM to be iteratively shifted along x 370 and y directionsaxes by fractions of a pixel to minimize the standard deviation of elevation 371 differences with respect to the 'master' DEM. Only areas assumed to be stable are considered in the 372 calculation of the co-registration shift. The ice-covered areas were excluded by overlaying the 373 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 374 2014 and 2016 DEMs with the 2007 DEM, both were resampled to 2 m spatial resolution, whereas 375 376 the comparison between 2014 and 2016 was carried out at the original resolution of these data sets 377 (60 cm).-

378 All points resulting in elevation differences largergreater than 15 m were labelled as unreliable, and 379 consequently discarded from the subsequent analysis. Such largergreater discrepancies may denote 380 errors in one of the DEMs or unstable areas outside the glacier. Values exceeding this threshold, 381 however, were only found in a marginal area with low image overlap in the comparison between the 382 2014 and 2016 DEMs, with a maximum elevation difference of 36 m. Once the final co-registration 383 shifts were computed (see Table 1), the coefficients were subtracted from the top left coordinates of 384 the 'slave' DEM; the residual mean elevation difference was also subtracted from the 'slave' DEM 385 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' 386 387 DEM were subtracted from the corresponding elevations of the 'master' DEM to obtain the so388 called DEM of Differences (DoD). Over a reference area common to all three DEMs glacier area 389 (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 can be expressed as the 390 391 combination of the standard deviation computed from the residual 1) uncertainty due to errors in 392 elevation difference over stable areas, and 2) the truncation error implicit when substituting the 393 caused by the use of a discrete sum (sum of DoD at each pixel multiplied by pixel area) in place of 394 the integral in volume calculation with a finite sum, according to (Jokinen and Geist, 2010). We 395 calculated the former following the approach of Rolstad et al. (2009), taking into account spatial autocorrelation of elevation change over stable areas, considering a correlation length of 50 m; for 396 397 the latter, we used the method described by Jokinen and Geist (2010).

398 5 Results

399 5.1 Point cloud Analysis

The analysis of point density shows significant differences between the three techniques for point 400 cloud generation (see Table 2). Values range from 103 to 2297 points/m² depending on the 401 402 surveying method, but the density was generally sufficient for the reconstruction of the different 403 surfaces shown in Fig. 54, except for location 5. Terrestrial photogrammetry featured the highest 404 point density, while UAV photogrammetry had the lowest. In relation to UAV photogrammetry, 405 similar point densities were found in all sample locations, especially for the standard deviations that 406 were always in the range-22-29 pointspoint/m² range. Mean values were between 103-109 points/m² 407 in locations 2-4, while they were higher in location 5 (141 points/m²). Due to the nadir acquisition 408 points, the 3D modelling of vertical/sub-vertical cliffs in location 1 was not possible. In relation to 409 TLS, a mean value of point density ranging from 141-391 points/m² was found, with the only 410 exception of location 5, where no sufficient data were recorded due to the position of this region with respect to the instrumental standpoint. Standard deviations ranged between 69-217 points/m², 411

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. 65). 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.

418 In terms of point cloud distance (see Table 3), the comparison between TLS and terrestrial 419 photogrammetry resulted in a high similarity between point clouds, with no largegreat differences 420 between different sample areas. Conversely, the comparison between TLS and UAV 421 photogrammetry and terrestrial and UAV photogrammetry provided significantly worse results, 422 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 greater deviations were in both cases obtained in the analysis of location 2, which 423 424 mostly represents a vertical surface, while the best agreement was found within location 3 which is 425 less inclined. As the UAV flight was geo-referenced on a set of GCPs with an RMSE of 40.5 cm, 426 the ICP co-registration may have not totally compensated the existing bias.-

- 427 In terms of spatial coverage, considering the entire surface examined using each technique outside 428 the sample locations, the UAV survey extended over the widest area (0.59 km²), including part of the proglacial plain, the entire terminus and the glacier tongue up to the collapsed area on the 429 430 central part, but with data gaps on the vertical and sub-vertical walls (see Fig. 6a). The point cloud 431 obtained from terrestrial photogrammetry covered approximately a third of the area surveyed with 432 the UAV (see fig. 6b), including the full glacier terminus at very high spatial resolution, with the 433 exception of a few obstructed parts, while the TLS point cloud covered the terminus, although with 434 some holes due to the obstructions.
- 435 **5.2 Glacier-related hazards and risks** 18

436 The tongue of Forni glacier hosts a variety of hazardous structures. While most collapsed areas are 437 normal faults, two large ring fault systems can be identified: the first, located in the eastern section 438 (see Fig. 2d and Fig. 7), covered an area of 25.6×10^3 m² and showed surface loweringdips of up to 5 439 m in 2014. This area was not surveyed in 2016, since field observation did not show evidence of 440 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 441 442 extending south-eastward (see Fig. 2c and Fig. 7), thus potentially widening the extent of collapse 443 in the future. Further smaller ring faults were identified in 2014 at the eastern glacier margin. Only 444 one of them was included in the area surveyed in 2016, with further 2 m subsidence and an increase 445 in subparallel fractures.

446 Normal faults are mostly found on the eastern medial moraine and at the terminus. Between 2014 447 and 2016, the first (see Fig. 2a) developed rapidly in the vertical domain reaching a height of 12 m 448 in 2016. The collapse was even more rapid at the terminus, leading to the formation of three sub-449 vertical facies, up to 24 m high; (see Fig. 2b and 2e), while the height of the vault is as low as 10 m. 450 Several fractures also appear in conjunction with the large ring fault located in the central section of 451 the glacier, extending the fracture system to the western glacier margin. It is likely that the terminus 452 will recede along the fault system on the eastern medial moraine and following the ring faults at the 453 eastern and western margins, increasing the occurrence of hazardous phenomena in these areas.-

454 **5.3 Glacier Thicknessthickness change**

The Forni Glacier tongue was affected by substantial thinning throughout the observation period. Between 2007 and 2014, the largestgreatest thinning occurred in the eastern section of the glacier tongue, with changes persistently belowlower than -30 m_{7} (more than 4 ma⁻¹ thinning), whereas the upper part of the central tongue only thinned by 10/18 m₇ (between approximately 1 and 2.5 ma⁻¹). 459 The greatest ice loss occurred in correspondence with the normal faults localized in small areas at 460 the eastern glacier margin (see Fig. 8a), with local changes generally belowlower than -50 m (more 461 than 7 ma⁻¹ thinning) and a minimum of -66.80 m, owing to the formation of a lake. Conversely, 462 between 2014 and 2016 the central and eastern parts of the tongue had similar thinning patterns, 463 with average changes of -10 m⁻ (5 ma⁻¹). 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 464 465 abovegreater than 25 m on the lower medial moraine. The ring fault at the left margin of the central 466 section of the tongue also shows thinning of $20 \neq to 26$ m- $(10-13 \text{ ma}^{-1})$. In the absence of faults, little 467 thinning occurred instead on the upper part of the medial moraine, where a thick debris cover 468 shielded ice from ablation, with changes of $-2-to -5 \text{ m} (1 \text{ to } 2.5 \text{ ma}^{-1} \text{, see Fig. 8c})$. Considering a 469 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 \pm 0.24 ma⁻¹ in 2007-2014 to 470 -5.20 ± 1.11 ma⁻¹ in 2014-2016, also confirmed by the value of -4.76 ± 0.29 ma⁻¹ obtained from the 471 472 comparison between 2007 and 2016. Looking at the first two DoD, the trend seems to be caused by 473 the increase in collapsing areas (Fig.8a,b). In all DoDs, the uncertainty in ice thickness change 474 affects less than 3% of the respective volume change (see Table 4).

475

476 **6** Discussion: comparison of techniques for point cloud generation

The choice of a technique to monitor glacier hazards and the glacier geodetic mass balance can depend<u>thickness changes depends</u> 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.

482 6.1 Point density and completeness

483 Considering point density, terrestrial photogrammetry resulted in a denser data set than the other 484 techniques. This is mostly motivated by the possibility to acquire of acquiring data from several 485 stations withusing this methodology, only depending only on the terrain accessibility, reducing the 486 effect of occlusions with a consequently more complete 3D modelling. However, the mean point 487 density achieved when using terrestrial photogrammetry has a large variability is highly variable, 488 both between different sample locations, and inside within each location as shown by the standard 489 deviations of D. Point densities related to UAV photogrammetry and TLS are more regular and 490 constant. In the case of UAV photogrammetry, the homogeneity of point density is might be due to 491 the regular structure of the airborne photogrammetric block. In the case of TLS, the regularity is 492 motivated by the constant angular resolution adopted during scanning. Since any 493 techniquestechnique may perform better when the surface to survey is approximately orthogonal to the sensor looking direction, sensor's point of view, terrestrial photogrammetry is more efficient for 494 495 reconstructing vertical and subvertical cliffs (Sample areas 1 and 2) and high-sloped surfaces 496 (Sample areas 3 and 4). On the contrary, airborne UAV photogrammetry provided the best results in 497 location 5 which is less inclined and consequently could be well depicted in vertical photos. In 498 general, point clouds from terrestrial photogrammetry provide a better description of the vertical 499 and subvertical parts (see e.g. Winkler et al., 2012), while point clouds obtained from UAV 500 photogrammetry are more suitable to describe the horizontal or sub-horizontal surfaces on the 501 glacier tongue and periglacial area (Seier et al., 2017), unless the camera is tilted to an off-nadir 502 viewpoint (Dewez et al., 2016; Aicardi et al., 2016). Results obtained from photogrammetry based 503 on terrestrial and UAV platforms can thus be retained considered quite complementary.

and they support the concept of merging the point clouds from these two techniques, as seen in Fig.
<u>6c.</u> 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)., <u>4</u>, <u>5</u>), which can only

507 <u>be compensated by increasing the number of stations.</u> Data acquisition with this platform iswas in 508 general difficult in regions that are subparallel to the laser beams and in the presence of wet 509 surfaces. Its main disadvantage compared to photogrammetry is however the complexity of 510 instrument transport

6.2 Point cloud and setup. In terms of logistics, up to five people were involved in the 511 512 transportation of the TLS instruments (laser scanner, theodolite, at least two topographic tripods and 513 poles, electric generator and ancillary accessories) while 2 people were required for UAV and elose-514 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 515 516 done with photogrammetry. Finally, TLS instruments are much more expensive at 70000-100000€ 517 compared to UAVs (3500€ for our platform) and DSLR (Digital Single-Lens Reflex) cameras used 518 in photogrammetry, in the range 500-3500€. DEM uncertainty

519 In this study, the distance between the UAV and TLS point clouds (21.1-37.7 cm RMSE), assumed 520 as a measure of the uncertainty of the 2016 UAV dataset (40.5 cm RMSE on GCPs and 21.1-37.7 521 em RMSE when compared against TLS), was slightly higher than previously reported in high 522 mountain glacial environments (e.g. Immerzeel et al., 2014; Gindraux et al., 2017; and Seier et 523 al., 2017)., although in these studies the comparison was between DEMs and GNSS control points. 524 Contributing factors might include the sub-optimal distribution and density of GCPs (Gindraux et 525 al., 2017), the delay between the UAV surveys as well as between the UAV and other surveys TLS, 526 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 527 Glacier range between 3- and 5 cm day⁻¹ (Senese et al., 2012) and 1-4 cm day⁻¹, respectively (Urbini 528 529 et al., 2017). We thus expect a combined 3-day uncertainty on the 2016 UAV dataset between 10 530 and 20 cm, and lower on GCPs considering reduced ablation owing to their placement on boulders.

531 A further contribution to the GCP error budget of GCPs might stem from the intrinsic precision of 532 GNSS/theodolite measurements and image resolution. The comparison between close-range 533 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 534 (2008). To improvereduce the accuracyuncertainty of UAV photogrammetric blocks, a better 535 536 distribution of GCPs or switching to an RTK system should be considered, while close-range 537 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. 538

539 The uncertainty in UAV photogrammetric reconstruction also factored in the relatively high 540 standard deviation still present after the coregistration co-registration between DEMs in areas 541 outside the glacier (2.22 m between 2014 and 2016). Another important factor here is the morphology of the coregistration co-registration area, i.e. the outwash plain, still subject to changes 542 543 owing to the inflow of glacier meltwater and sediment reworking. The final accuracy of our UAV photogrammetric products was nevertheless adequatepermitted us to 544 investigate ice 545 thickness volume changes over 2 years, with an uncertainty of 2.60%, while the integration with 546 close-range photogrammetry was required to investigate hazards related to the collapse of the 547 glacier terminus.-

548 We conducted UAV surveys under different meteorological scenarios, and obtained adequate results 549 with 6.3 Logistics and costs

In our surveys, it became evident that the main disadvantage of TLS compared to photogrammetry
is the complexity of instrument transport and setup. In terms of logistics and workload, 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 two people

554 were required for UAV and close-range photogrammetric surveys, which were also considerably 555 faster. 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 556 557 photogrammetry. Concerning UAV surveys, we conducted them under different meteorological scenarios, and obtained adequate results in early-morning operations with 0/8 cloud cover and 558 559 midday flights with 8/8 cloud cover. Both scenarios can provide diffuse light conditions allowing to 560 collect<u>collection of</u> pictures suitable for photogrammetric processing, but camera settings need to be 561 carefully adjusted beforehand (O'Connor et al., 2017). If early morning flights are not feasible in 562 the study area for logistical reasons or when surveying east-exposed glaciers with eastern 563 exposures, the latter scenario should be considered.-

In terms of costs, UAV and terrestrial photogrammetric surveys are also advantageous, since TLS
instruments are much more expensive at €70,000-100,000 compared to UAVs (€3500 for our
platform) and DSLR (Digital Single-Lens Reflex) cameras used in photogrammetry, in the €5003500 range.

568 6.4 Additional remarks

569	In summary, although TLS point clouds are regarded as the most accurate (Naumann et al., 2013),
570	they suffer from inhomogeneous point density and cumbersome logistics, and their potential in
571	glacial environments is limited, unless a maximum uncertainty of 5-10 cm can be tolerated. Laser
572	scanners are also employed on aerial platforms, including UAVs, where they can reconstruct terrain
573	morphology with only slightly higher uncertainty than the terrestrial counterparts with a much
574	greater coverage (Raymond et al., 2009), but the high operational cost has limited the diffusion of
575	this technique. Lastly, photogrammetry from higher altitude aerial platforms (mostly planes, but
576	also helicopters and satellites) can similarly achieve low uncertainty (3 m, Andreassen et al., 2002)

and extensive coverage at the price of a lower spatial resolution compared to UAVs (e.g. 2 m in our
case), and due to its popularity in the past it is often the only means to acquire good quality archive
data to investigate glacier changes over broad time scales (Andreassen et al., 2002; Molg et al.,
2017).

581 In our pilot study, we covered part of the Forni glacier tongue, and only-investigated different 582 techniques to map/monitor hazards related to the glacier collapse. Our maps can help identify safer 583 paths where mountaineers and skiers can visit the glacier and reach the most important summits. 584 However, the increase in collapse structures owing to climate change requires multi-temporal 585 monitoring. A comprehensive risk assessment should also cover the entire glacier, to investigate the 586 probability of serac detachment and provide an estimate of the glacier mass balance with the 587 geodetic method. While our integrated approach using a multicopter and terrestrial photogrammetry 588 should be preferred to investigate TLS for the investigation of small individual ice bodies, fixed-589 wing UAVs, ideally equipped with an RTK system and the ability to tilt the camera off-nadir, might 590 be the platform of choice to cover large distances (see e.g. Ryan et al., 2017), potentially reducing 591 the number of flights and solving issues with GCP placement. Such platforms could help collect 592 sufficient data for hazard management strategies up to the basin scale in Stelvio National Park and 593 other sectors of the Italian Alps, eventually replacing higher altitude aerial LiDAR surveys. Cost 594 analyses (Matese et al., 2015) should also be performed to evaluate the benefits of improved spatial 595 resolution and lower DEM accuracy uncertainty of UAVs compared to aerial and satellite surveys 596 and choose the best approach for individual cases.

597 7 Conclusions

598 In our study, we compared point clouds generated from UAV photogrammetry, close-range 599 photogrammetry_a and TLS to assess their quality and evaluate thetheir potential in mapping and

describing glacier hazards such as ring faults and normal faults, by carrying outin a specific
campaign carried out in summer 2016. In addition, we employed orthophotos and point clouds from
a UAV survey conducted in 2014 to analyzeanalyse the evolution of glacier hazards-and, as well as
a DEM from an aerial photogrammetric survey conducted in 2007, to investigate glacier thickness
changes between 20142007 and 2016. The main findings of our study include:____

- UAVs and terrestrial photogrammetric surveys provide reliable performances in glacial
 environments, and 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 <u>and volume</u> changes but
 improvements are necessary in terms of area covered and accuracy to calculate the geodetic
 mass balance of large glaciersto reduce uncertainty.
- The Forni Glacier is rapidly collapsing with an increase in ring <u>faults sizefault sizes</u>,
 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.

617 The maps produced from the combined analysis of UAV and terrestrial photogrammetric point clouds and orthophotos can be made available through GIS web portals of the Stelvio National Park 618 619 or the Lombardy region 620 (http://www.geoportale.regione.lombardia.it/).http://www.geoportale.regione.lombardia.it/). А 621 permanent monitoring programme should be setupset up to help manage risk in the area, issuing warnings and assisting mountain guides in changing hiking and ski routes as needed. The analysis 622 623 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<u>transferable</u> to similar sized and much smaller glaciers, where it would be able to provide a comprehensive assessment of hazards and mass balance<u>thickness changes</u> and become useful in decision support systems for natural hazard management. In larger regions, UAVs hold the potential to become the platform of choice<u>_</u> but their performances and cost-effectiveness compared to aerial and satellite surveys need to be further evaluated.

635 Competing interests

636 The authors declare that they have no conflict of interest.

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648 References

- 649 Abellán, A., Oppikofer, T., Jaboyedoff, M., Rosser, N. J., Lim, M. and Lato, M. J.: Terrestrial laser
- scanning of rock slope instabilities. Earth Surface Processes and Landforms, 39, 80–97, 2014,
 doi:10.1002/esp.3493.
- 652 Aicardi, I., Chiabrando, F., Grasso, N., Lingua, A.M., Noardo, F. and Spanò, A.: UAV
- 653 photogrammetry with oblique images: first analysis on data acquisition and processing,
- 654 International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences,
- 655 XXIII ISPRS Congress, Prague, Czech Republic, 12–19 July 2016, 41-B1, 835-842, 2016, doi:
- 656 10.5194/isprs-archives-XLI-B1-835-2016.
- Andreassen, L.M., Hallgeir, E. and Kjollmoen, B.: Using aerial photography to study glacier
 changes in Norway, Annals of Glaciology, 34, 343-348, 2010, doi: 10.3189/172756402781817626
- 659 | Azzoni, R.S., Fugazza, D., Zennaro, M., Zucali, M., D'Agata, C., Maragno, D., Cernuschi, M.,
- 660 Smiraglia, C. and Diolaiuti, G.A.: Recent structural evolution of Forni Glacier tongue (Ortles-
- 661 Cevedale Group, Central Italian Alps), submitted to). Journal of Maps., 13, 870-878, 2017, doi:
- 662
 10.1080/17445647.2017.1394227
- 663 Berthier, E., Arnaud, Y., Kumar, R., Ahmad, S., Wagnon, P. and Chevallier, P.: Remote sensing
- 664 estimates of glacier mass balances in the Himachal Pradesh (Western Himalaya, India), Remote
- 665 Sensing of Environment, 108, 327-338, 2007, doi: 10.1016/j.rse.2006.11.017.
- 666 Berthier, E., Cabot, V., Vincent, C. and Six, D.: Decadal Region-Wide and Glacier-Wide Mass
- 667 Balances Derived from Multi-Temporal ASTER Satellite Digital Elevation Models. Validation over 668 the Mont Blanc Area Erentians in Earth Science 4, 63, 2016, doi: 10.2280/facrt 2016.00062
- the Mont-Blanc Area, Frontiers in Earth Science, 4, 63, 2016, doi: 10.3389/feart.2016.00063.
- Bhardwaj, A., Sam, L., Akanksha, Martin-Torres, F.J. and Kumar, R.: UAVs as remote sensing
 platform in glaciology: Present applications and future prospects, Remote Sensing of Environment,
 175, 196-204, 2016, doi: 10.1016/j.rse.2015.12.029.
- Blasone, G., Cavalli, M. and Cazorzi, F.: Debris-Flow Monitoring and Geomorphic Change
- 673 Detection Combining Laser Scanning and Fast Photogrammetric Surveys in the Moscardo
- 674 Catchment (Eastern Italian Alps), in: Lollino, G., Arattano, M., Rinaldi, M., Giustolisi, O.,
- 675 Marechal, J.C. and Grant, G. (eds) Engineering Geology for Society and Territory, 3, Springer,
- 676 Cham, 51-54, 2015, doi: 10.1007/978-3-319-09054-2_10.
- 677 Carey, M., McDowell, G., Huggel, C., Jackson, M., Portocarrero, C., Reynolds, J.M. and Vicuña,
- 678 L.: Integrated approaches to adaptation and disaster risk reduction in dynamic sociocryospheric
- 679 systems, in: Haeberli, W. and Whiteman, C. (Eds.), Snow and Ice-related Hazards, Risks and
- 680 Disasters, Elsevier, 219-261, 2014, doi: 10.1016/B978-0-12-394849-6.00008-1.-
- 681 Chandler, J.H. and Buckley, S.: Structure from motion (SFM) photogrammetry vs terrestrial laser
 682 scanning. In: Carpenter, M.B. and Keane, C.M. (eds.) Geoscience Handbook 2016, AGI Data
- 683 Sheets, 5th ed. Alexandria, US, American Geosciences Institute, Section 20.1, 2016.
- 684 Clague, J.: Glacier Hazards, in: Bobrowski, P. (Ed.), Encyclopedia of Natural Hazards, Springer,
 685 400-405, 2013, doi: 10.1007/978-1-4020-4399-4_156.

- 686 Chiarle, M., Iannotti, S., Mortara, G. and Deline, P.: Recent debris flow occurrences associated with
- 687 glaciers in the Alps, Global and Planetary Change, 56, 123-136, 2007, doi:
- 688 | 10.1016/j.gloplacha.2006.07.003.-
- Clague, J.: Glacier Hazards, in: Bobrowski, P. (Ed.), Encyclopedia of Natural Hazards, Springer,
 400-405, 2013, doi: 10.1007/978-1-4020-4399-4 156.
- 691 Colomina, I. and Molina, P.: Unmanned aerial systems for photogrammetry and remote sensing: A
- review, ISPRS Journal of Photogrammetry and Remote Sensing, 92, 79-97, 2014, doi:
- 693 10.1016/j.isprsjprs.2014.02.013.
- 694 D'Agata, C., Bocchiola, D., Maragno, D., Smiraglia, C. and Diolaiuti, G.A.: Glacier shrinkage
- 695 driven by climate change during half a century (1954–2007) in the Ortles-Cevedale group (Stelvio 696 National Park, Lombardy, Italian Alps), Theoretical and Applied Cimatology, 116, 169-190, 2014,
- 697 doi: 10.1007/s00704-013-0938-5.
- 698 Dall'Asta, E., Thoeni, K., Santise, M., Forlani, G., Giacomini, A., Roncella, R.: Network design and
 699 quality checks in automatic orientation of close-range photogrammetric blocks, Sensors, 15, 7985 700 8008, 2015, doi: 10.3390/s150407985
- 701 Dewez, T.J.B., Leroux, J. and Morelli, S.: Cliff collapse hazard from repeated multicopter UAV
- 702 acquisitions: return on experience, The International Archives of the Photogrammetry, Remote
- 703 Sensing and Spatial Information Sciences, XXIII ISPRS Congress, Prague, Czech Republic, 12–19
- 704 July 2016, 41-B5, 805-811, 2016, doi: 10.5194/isprs-archives-XLI-B5-805-2016
- 705 Diolaiuti, G.A. and Smiraglia, C.: Changing glaciers in a changing climate: how vanishing
- 706 geomorphosites have been driving deep changes in mountain landscapes and environments,
- 707 Géomorphologie : Relief, Processus, Environnement, 2, 131-152, 2010, doi:
- 708 10.4000/geomorphologie.7882.
- 709 Diolaiuti, G.A., Bocchiola, D., D'Agata, C. and Smiraglia, C.: Evidence of climate change impact
- upon glaciers' recession within the Italian Alps, Theoretical and Applied Climatology, 109,429-445,
 2012 doi: 10.1007/s00704-012-0589-y
- 711 2012, doi: 10.1007/s00704-012-0589-y
- Fltner, A., Kaiser, A., Castillo, C., Rock, G., Neugirg, F. and Abellán, A.: Image-based surface
 reconstruction in geomorphometry merits, limits and developments. Earth Surface Dynamics, 4,
- 714 | 359-389, 2016, doi: 10.5194/esurf-4-359-2016.
- 715 Fioletti, M., Bonetti, M., Smiraglia, C., Diolaiuti, G.A., Breganze, C., dal Toso, M. and Facco, L.:
- 716 Indagini radar per lo studio delle caratteristiche endoglaciali del ghiacciaio dei Forni in alta Valtellina, 717 Nava a Valenche 87, 40, 45, 2016
- 717 Neve e Valanghe, 87, 40-45, 2016
- Fey, C. and Wichmann, V.: Long-range Terrestrial laser scanning for geomorphological change
 detection in alpine terrain handling uncertainties. Earth Surface Processes and Landforms, 42,
 789-802, 2016, doi: 10.1002/esp.4022.
- 721 | Fischer, M., Huss, M., Barboux, C. and Hoelzle, M.: The new Swiss Glacier Inventory SGI2010:
- relevance of using high-resolution source data in areas dominated by very small glaciers, Arctic,
- 723 Antarctic and Alpine Research, 46,933-945, 2014, doi: 10.1657/1938-4246-46.4.933.

- Fischer, M., Huss, M. and Hoelzle, M.: Surface elevation and mass changes of all Swiss glaciers 1980–
 2010, The Cryosphere, 9, 525-540, 2015, doi: 10.5194/tc-9-525-2015
- Forlani, G., Pinto, L., Roncella, R. and Pagliari, D.: Terrestrial photogrammetry without ground control points, Earth Science Informatics, 7, 71-81, 2014, doi: 10.1007/s12145-013-0127-1.
- Fugazza, D., Senese, A., Azzoni, R.S., Smiraglia, C., Cernuschi, M., Severi, D. and Diolaiuti, G.A.:
 High-resolution mapping of glacier surface features. The UAV survey of the Forni glacier (Stelvio
 national park, Italy), Geografia Fisica e Dinamica Quaternaria, 38, 25-33, 2015, doi:
 10.4461/GFDQ.2015.38.03.
- Furukawa, Y. and Ponce, J.: Accurate Camera Calibration from Multi-View Stereo and Bundle
 Adjustment, International Journal of Computer Vision, 84, 257–268, 2009, doi: 10.1007/s11263009-0232-2.
- Garavaglia, V., Diolaiuti, G.A., Smiraglia, C., Pasquale, V. and Pelfini, M.: Evaluating Tourist
 Perception of Environmental Changes as a Contribution to Managing Natural Resources in
 Glacierized areas: A Case Study of the Forni Glacier (Stelvio National Park, Italian Alps),
 Environmental Management, 50, 1125-1138, 2012, doi: 10.1007/s00267-012-9948-9.
- Gagliardini, O., Gillet-Chaulet, F., Durand, G., Vincent, C. and Duval, P.: Estimating the risk of
 glacier cavity collapse during artificial drainage: The case of Tête Rousse Glacier, Geophysical
 Research Letters, 38, L10505, 2011, doi:10.1029/2011GL047536.
- Gardent, M., Rabatel, A., Dedieu, J.-P., Deline, P.: Multitemporal glacier inventory of the French
 Alps from the late 1960s to the late 2000s, Global and Planetary Change, 120, 24-37, 2014. doi:
 10.1016/j.gloplacha.2014.05.004.
- Gindraux, S., Boesch, R. and Farinotti, D.: Accuracy Assessment of Digital Surface Models from
 Unmanned Aerial Vehicles' Imagery on Glaciers, Remote sensing, 9, 186, 2-15, 2017,
 doi:10.3390/rs9020186.
- Gobiet, A., Kotlarski, S., Beniston, M., Heinrich, G., Rajczak, J., Stoffel, M.: 21st century climate
 change in the European Alps—A review, Science of The Total Environment, 493, 1138-1151, 2014,
 doi: 10.1016/j.scitotenv.2013.07.050.
- Harris, C., Arenson, L.U., Christiansen, H.H., Etzelmueller, B., Frauenfelder, R., Gruber, S.,
 Haeberli, W., Hauck, C., Hoelzle, M., Humlum, O., Isaksen, K., Kaab, A., Kern-Luetschg, M.,
 Lehning, M., Matsuoka, N., Murton, J.B., Noetzli, J., Phillips, M., Ross, N., Seppaelae, M.,
 Springman, S.M. and Vonder Muehll, D.: Permafrost and climate in Europe: Monitoring and
 modelling thermal, geomorphological and geotechnical responses, Earth-Science Reviews, 92, 117171, 2009, doi: 10.1016/j.earscirev.2008.12.002.
- Total Anti-Total Ant
- 759 Howat, I.M., Smith, B.E., Joughin, I. and Scambos, T.A.: Rates of southeast Greenland ice volume
- 760 loss from combined ICESat and ASTER observations, Geophysical Research Letters, 35, L17505,
 761 2008, doi:10.1029/2008GL034496.

762 Immerzeel, W.W., Kraaijenbrink, P.D.A., Shea, J.M., Shrestha, A.B., Pellicciotti, F., Bierkens,
763 M.F.P. and de Jong, S.M.: High-resolution monitoring of Himalayan glacier dynamics using
764 unmanned aerial vehicles, Remote Sensing of Environment, 150,93-103, 2014, doi:
765 10.1016/j.rse.2014.04.025.

Janke, J.R.: Using airborne LiDAR and USGS DEM data for assessing rock glaciers and glaciers,
 Geomorphology, 195, 118-130, doi: 10.1016/j.geomorph.2013.04.036

Jokinen, O. and Geist T.: Accuracy aspects in topographical change detection of glacier surface, in:
Remote sensing of glaciers, CRC Press/Balkema, Leiden, the Netherlands, 269-283, 2010, doi:
10.1201/b10155-15.

Kaab, A., Huggel., C., Fischer, L., Guex, S. Paul, F., Roer., I., Salzmann, N., Schlaefli, S., Schmutz,
K., Schneider, D., Strozzi, T. and Weidmann, Y.: Remote sensing of glacier- and permafrost-related
hazards in high mountains: an overview, Natural Hazards and Earth System Sciences, 5, 527–554,
2005a, doi: 10.5194/nhess-5-527-2005.

Kaab, A., Reynolds, J.M. and Haeberli, W.: Glacier and Permafrost hazards in high mountains, in:
Huber U.M., Bugmann H.K.M., Reasoner M.A. (eds) Global Change and Mountain Regions.
Advances in Global Change Research, Springer, Dordrecht, 225-234, 2005b, doi: 10.1007/1-40203508-X 23.

Kaufmann, V. and Ladstädter, R.: Application of terrestrial photogrammetry for glacier monitoring
in Alpine environments, International Archives of the Photogrammetry, Remote Sensing and Spatial
Information Sciences, Beijing, China, 37-B8, 813-818, 2008.-

Kaufmann, V. and Seier, G.: Long-term monitoring of glacier change at Gössnitzkees (Austria)
using terrestrial photogrammetry, The International Archives of the Photogrammetry, Remote
Sensing and Spatial Information Sciences, XXIII ISPRS Congress, Prague, Czech Republic, 12-19
July 2016, 41-B8, 495-502, 2016, doi: 10.5194/isprs-archives-XLI-B8-495-2016

Keiler, M., Knight, J. and Harrison, S.: Climate change and geomorphological hazards in the eastern
European Alps, Philosophical Transactions of The Royal Society A, 368, 2461–2479, 2010, doi:
10.1098/rsta.2010.0047.

Kellerer-Pirklbauer, A., Bauer, A. and Proske, H.: Terrestrial laser scanning for glacier monitoring:
 Glaciation changes of the Gößnitzkees glacier (Schober group, Austria) between 2000 and 2004,

790 Glaciation changes of the Gobintzkees glacter (Schober group, Austral) between 2000 and 2004, 791 3rd Symposion of the Hohe Tauern National Park for research in protected areas, castle of Kaprun,

792 Austria, 15-17 September 2005, 97-106, 2005.

Lague, D., Brodu, N., Leroux, J.: Accurate 3D comparison of complex topography with terrestrial
laser scanner: application to the Rangitikei canyon (N-Z). Journal of Photogrammetry and Remote
Sensing, 82, 10–26, 2013, doi:10.1016/j.isprsjprs.2013.04.009.

793 Sensing, 82, 10–20, 2013, doi:10.1010/j.isprsjprs.2013.04.009.

Matese, A., Toscano, P., Di Gennaro, S.F., Genesio, L., Vaccari, F.P., Primicerio, J., Belli, C.,
Zaldei, A., Bianconi, R., Gioli, B.: Intercomparison of UAV, Aircraft and Satellite Remote
Sensing Platforms for Precision Viticulture, Remote Sensing, 7, 2971-2990, 2015,
doi:10.3390/rs70302971.

 ⁸⁰⁰ Mugnier, C.J.: Grids & Datum. Italian Republic. Photogrammetric Engineering and Remote 801 Sensing, 71, 889-890, 2005.

- Moelg, N. and Bolch, T.: Structure-from-Motion Using Historical Aerial Images to Analyse
 Changes in Glacier Surface Elevation, Remote Sensing, 9, 1021, 2017, doi:10.3390/rs9101021
- Naumann, M., Geist, M., Bill, R., Niemeyer, F. and Grenzdoerffer, G.: Accuracy comparison of digital surface models created by Unmanned Aerial Systems imagery and Terrestrial Laser Scanner, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, UAV-g2013, 4-6 September 2013, Rostock, Germany, 61-W2, 281-286, 2013, doi: 10.5194/isprsarchives-XL-1-W2-281-2013
- Nuth, C. and Kaab, A.: Co-registration and bias corrections of satellite elevation data sets for
 quantifying glacier thickness change, The Cryosphere, 5, 271-290, 2011, doi: 10.5194/tc-5-2712011.
- 812 Oborne, M.: Mission planner software. Available at: http://ardupilot.org/planner/, last access:
 813 18/05/2017, 2013.
- 814 O'Connor, J., Smith, M.J. and James, M.R.: Cameras and settings for aerial surveys in the
- 815 geosciences: optimising image data, Progress in Physical Geography, 41, 1-20, 2017, doi:
 816 10.1177/0309133317703092.
- 817 Palomo, I.: Climate Change Impacts on Ecosystem Services in High Mountain Areas: A
- 818 Literature Review, Mountain Research and Development, 37,179-187, 2017, doi:
- 819 **10.1659/MRD-JOURNAL-D-16-00110.1**.
- 820 Piermattei, L., Carturan, L. and Guarnieri, A.: Use of terrestrial photogrammetry based on structure
- from motion for mass balance estimation of a small glacier in the Italian Alps. Earth Surface
 Processes and Landforms, 40, 1791-1802, 2015, doi: 10.1002/esp.3756.
- 823 Piermattei, L., Carturan, L., de Blasi, F., Tarolli, P., Dalla Fontana, G., Vettore, A. and Pfeifer, N.:
- 824 Suitability of ground-based SfM–MVS for monitoring glacial and periglacial processes, Earth
- 825 Surface Dynamics, 4, 325-443, 2016, doi: 10.5194/esurf-4-425-2016.
- Pomerleau, F., Colas, F., Siegwart, R. and Magnenat, S.: Comparing ICP variants on real world data
 sets. Autonomous Robots, 34, 133–148, 2013, doi: 10.1007/s10514-013-9327-2.
- 828 Quincey, D.J., Lucas, R.M., Richardson. S.D., Glasser, N.F., Hambrey, N.J. and Reynolds, J.M.:
- 829 Optical remote sensing techniques in high-mountain environments: application to glacial hazards,
- 830 Progress in Physical Geography, 29, 475-505, 2005, doi: 10.1191/0309133305pp456ra.
- 831 Rayburg, S., Thoms, M. and Neave, M.: A comparison of digital elevation models generated from
 832 different data sources, Geomorphology, 106, 261-270, 2009, doi: 10.1016/j.geomorph.2008.11.007
- Riccardi, A_{7.2} Vassena, G., Scotti, R., Sgrenzaroli, M.: Recent evolution of the punta S.Matteo serac
 (Ortles-Cevedale Group, Italian Alps), Geografia Fisica e Dinamica Quaternaria, 33, 215-219, 2010.
- Rolstad, C., Haug, T. and Denby, B.: Spatially integrated geodetic glacier mass balance and its
 uncertainty based on geostatistical analysis: application to the western Svartisen ice cap, Norway,
- 837 Journal of Glaciology, 55, 666-680, 2009, doi: 10.3189/172756409787769528

Rounce, D.R., Watson, C.S. and McKinney, D.C.: Identification of Hazard and Risk for Glacial
Lakes in the Nepal Himalaya Using Satellite Imagery from 2000–2015, Remote Sensing, 9, 654,
2017, doi:10.3390/rs9070654.

Ryan, J.C., Hubbard, A., Box, J.E., Brough, S., Cameron, K., Cook, J.M., Cooper, M., Doyle, S.H.,
Edwards, A., Holt, T., Irvine-Fynn, T., Jones, C., Pitcher, L.H., Rennermalm, A.K., Smith, L.C,
Stibal, M. and Snooke, N.: Derivation of High Spatial Resolution Albedo from UAV Digital
Imagery: Application over the Greenland Ice Sheet, Frontiers in Earth Science, 5, 40, 2017, doi:
10.3389/feart.2017.00040.

- 846 Seier, G., Kellerer-Pirklbauer, A., Wecht, M., Hirschmann, S., Kaufmann, V., Lieb, G.K. and Sulzer,
- 847 W.: UAS-Based Change Detection of the Glacial and Proglacial Transition Zone at Pasterze Glacier,
- 848 Austria. Remote Sensing, 9, 549, 2017, doi:10.3390/rs9060549.-

Senese, A., Diolaiuti, G.A., Mihalcea, C. and Smiraglia, C.: Energy and Mass Balance of Forni
Glacier (Stelvio National Park, Italian Alps) from a Four-Year Meteorological Data Record, Arctic,
Antarctic and Alpine Research, 44, 122-134, 2012, doi: 10.1657/1938-4246-44.1.122.

Smiraglia, C., Azzoni, R.S., D'Agata, C., Maragno, D., Fugazza, D. and Diolaiuti, G.A.: The
evolution of the Italian glaciers from the previous data base to the new Italian inventory.
Preliminary considerations and results, Geogr. Fis. Dinam. Quat., 38, 79-87, 2015, doi:
10.4461/GFDQ.2015.38.08.

- 856 Spetsakis, M. and Aloimonos, J.Y.: A multi-frame approach to visual motion perception,
 857 International Journal of Computer Vision, 6, 245-255, 1991, doi: 10.1007/BF00115698.
- 858 | Teunissen, P.J.G.: Testing theory. An introduction. Series on Mathematical Geodesy and859 Positioning, VSSD Delft, The Netherlands, 2009.

Urbini, S., Zirizzotti, A., Baskaradas, J.A., Tabacco, I.E., Cafarella, L., Senese, A., Smiraglia, C.,
Diolaiuti, G.: Airborne radio echo sounding (RES) measures on alpine glaciers to evaluate ice
thickness and bedrock geometry: Preliminary results from pilot tests performed in the ortlescevedale group (Italian alps), Annals of Geophysics, 60, G0226, doi: 10.4401/ag-7122, 2017.

- 864 Vincent, C., Auclair, S. and Le Meur, E.: Outburst flood hazard for glacier-dammed Lac de
 865 Rochemelon, France, Journal of Glaciology, 56, 91-100, 2010, doi: 10.3189/002214310791190857
- 866 Vincent, C., Thibert, E., Harter, M., Soruco, A. and Gilbert, A.: Volume and frequency of ice
 avalanches from Taconnaz hanging glacier, French Alps, Annals of Glaciology, 56, 17-25, 2015,
 doi: 10.3189/2015AoG70A017.
- Westoby, M.J., Brasington, J., Glasser, N.F., Hambrey, M.J. and Reynolds, J.M.: Structure-fromMotion' photogrammetry: A low-cost, effective tool for geoscience applications, Geomorphology,
 179, 300-314, 2012, doi: 10.1016/j.geomorph.2012.08.021.
- Winkler, M., Pfeffer, W.T. and Hanke, K.: Kilimanjaro ice cliff monitoring with close range
 photogrammetry, International Archives of the Photogrammetry, Remote Sensing and Spatial
 Information Sciences, XXII ISPRS Congress, Melbourne, Australia, 25 August-1 September 2012,
 39-B5, 441-446, 2012.
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Tables

DEM pair	Elevation differences without	Co-regist	ration shifts	Elevation differences with co-	
	co-registration shifts $(\mu_{\Delta H} \pm \sigma_{\Delta H})$ [m]	X [m]	Y [m]	registration shifts $(\mu_{\Delta H} \pm \sigma_{\Delta H})$ [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	$0.00{\pm}2.60$	
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. DEM 2007 from aerial multispectral survey, DEM 2014 and

DEM 2016 from UAV photogrammetry.

S a m p l e W i n d o w	Area (m ²)	number <u>Number</u> of points in sample windows		Mean and standard deviation of point density [points/m ²]			Number of point <u>points</u> above the lower 12.5% percentile			
-		UAV photogra mm.	Terrestri al Photogra mm.<u>TP</u>	TLS	UAV Photogra mm.	Terrestrial Photogram m.<u>TP.</u>	TLS	UAV Phot ogra mm.	Terr estri al Pho togr am m.T P	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*886 *and standard deviation of local point density and number of points above the lower 12.5%*887 *percentile in each window. k stands for thousands of points.* UAV refers to UAV photogrammetry.
888 *TP to terrestrial photogrammetry and TLS to terrestrial laser scanning.*

S am		Means and Std. Dev.s of M3C2 distances [cm]			RMSE of M3C2 distances [cm]		
sam ple Win	Ref.	TLS	TLS	UAV Photogramm .	TLS	TLS	UAV Photogram m.
-	Slav e	Terrestrial Photogramm - <u>TP</u>	UAV Photogramm .	Terrestrial Photogramm - <u>TP</u>	Terrestrial Photogram m.<u>TP</u>	UAV Photogramm .	Terrestrial Photogram m.<u>TP</u>
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

- *clouds computed on the basis of the M3C2 algorithm, showing mean, standard deviation and root*
- *mean square error (RMSE) of each point cloud pair. UAV refers to UAV photogrammetry, TP to*
- *terrestrial photogrammetry and TLS to terrestrial laser scanning. Ref. stands for reference and "-"*
- *means no comparison was performed.*

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 ± 0.1217 (1.74%)
2007-2016	-42.86 ± 2.60	-4.76 ± 0.29	-13.46 ± 0.1420 (1.47%)
2014-2016	-10.41 ± 2.22	-5.20 ± 1.11	-3.29 ± 0.0508 (2.60%)

899 Table 4: Average ice thickness change, thinning rates and volume loss from DEM differencing
900 over a common reference area of 0.32 km² for all DEM pairs. Uncertainty of thickness change
901 expressed as +one standard deviation of residual elevation differences over stable areas after
902 DEM co-registration.











915916Figure 2: Collapsing areas on the tongue of Forni Glacier. (a) Faults cutting across the917eastern medial moraine; (b) glacier terminus; (c) Near-circular collapsed area on the cent-918ral tongue; (d) Large ring fault on the eastern tongue at the base of the icefall. Photo cour-919tesy of G.Cola; (e) Close-up of a vertical ice cliff at the glacier terminus. The location of920features is reported in Fig.1



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



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





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. 932







Figure 5

Figure 4: Location of different glacier features or hazard-prone areas on the tongue of Forni
938 glacier were the point cloud comparison was performed. The background image is the merged
939 point cloud generated from the 2016 UAV and terrestrial photogrammetry survey.






Figure 6<u>5</u>*: Maps of point density in sample location 2.*



Figure 5 (alternative): Maps of point density in sample location 2.



- *Figure 6: Spatial coverage of UAV- and terrestrial photogrammetry point clouds and merged point*
- *cloud from the two techniques. a) UAV photogrammetry point cloud; b) terrestrial photogrammetry*
- *point cloud; c) merged point cloud.*





- *Figure 7: locationLocation of collapse structures, i.e. normal faults and ring faults and trails cross-*
- *ing the Forni Glacier.* (a) <u>Collapse structures in</u> 2014, with 2014 UAV ortophoto as basemap. The
- *red box marks the area surveyed in 2016. (b) <u>Collapse structures in</u> 2016, with 2016 UAV or-*
- *thophoto as basemap._Trails from Kompass online cartography at https://www.kompass-1039_itali-*
- *a.it/info/mappa-online/.*





959 Figure 8: Ice thickness change rates from DEM differencing over (a) 2007-2014; (b) 2007-2016;

- 960 (c) 2014-2016. Glacier outlines from 2014 and 2016 are limited to the area surveyed during the
- 961 UAV campaigns. Base map from hillshading of 2007 DEM.
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