Milano, January 2016

Dear Prof. Philip Marsh, Editor,

We thank you for your reconsideration about this manuscript. We have revised it as kindly suggested by you and the three Referees. You will find attached to this letter a version of the revised manuscript with major changes highlighted (yellow). In the next pages, you will find our point-by-point reply to the insightful comments by the three reviewers.

We agree with all of you that our strategy about point data collection can be improved by performing additional measurements. This is in fact the main suggestion by all the three Referees, and our main task for future investigations. We are currently planning to perform similar analyses in the future at different sites with different vegetation and/or topographic coverage. Moreover, we will consider a multi-temporal framework to enable the assessment of U.A.S. performance during the season, as you kindly suggested to us by mentioning the interesting work by Nolan et al. (2015). This is the main target of future research, and we are now very explicit in our manuscript about the urgency of this development (see e.g. lines 402-407) and the limitations of this analysis (see lines 272-280). On the other hand, we have also clarified why we collected such a restricted amount of points (see lines 177-190): this should improve the overall clarity of the manuscript. In addition, we now introduce digital photogrammetry and U.A.S.s separately and this should clarify that photogrammetry, *as a survey technique*, has been already tested extensively on snow, whereas the main point here is doing photogrammetry using U.A.S. (see lines 75-82). Moreover, we welcomed the substantial suggestion by Dr. Fassnacht and we have avoided an extensive and in-depth analysis of point data retrieval or interpolation performance.

Apart from this major point, we tried to address referees' suggestions at our best. Please find additional details in the next pages. Here we provide a general inventory about our changes to the manuscript. We apologize with Dr. Fassnacht, who has asked us to be more specific in our responses to referees. Clearly, this was not intentional and may be due to the timing of our public comments during the review process: when we replied to Referee #1 stating "We will try to include a wider context about survey uncertainty with respect to the existing literature", we had not started our revision of the manuscript yet (May 2015). This is because that sentence (or similar statements) was a reply in a preliminary public discussion, and we could not be more specific about the changes we would have operated in the future. However, we recognize that more specificity could have been helpful to the referees. We have tried to improve this here.

Title and Abstract	We have slightly modified the title to specify our novelty in a better way. By revising existing literature on this topic, our idea is that most of the existing literature has used multi-rotor devices to map snow depth (see lines 75-82 for details), whereas here we document the use of a fixed wing device. The difference is not just technological, because fixed wing devices enable larger surveys (which is clearly interesting from a hydrologic point of view), but are sometimes problematic in alpine areas due to their lower resistance to strong winds. We revised the text (abstract included, see lines 3-7) to specify our contribution. In the Abstract, we now include an indication of the RMSE of the comparison between manual snow depth data and U.A.S. measurements (as widely done by existing literature). We removed the sentence about the comparison between interpolation techniques and the U.A.S.-based volume of snow: following suggestions by Referees about our strategy used to collect point data, the relevance of this comparison has been reduced.

Introduction	This Section has been shortened (we have removed the first two paragraphs) in order to reduce the length of the paper, as kindly suggested by you. These two paragraphs were based on the literature and were very generic. Moreover, we have also modified the paragraphs dealing with U.A.S.s (see lines 51-82) to introduce digital photogrammetry and its performance separately, as kindly suggested (specifically, the papers by Nolan et al. 2015 or Bühler et al. 2015, see text for references). We also updated this paragraph with existing literature on using U.A.S. to map snow depth. While performing a literature review on this topic, we observed a general scarcity of contributions, as widely expected, and, in general, a systematic overlap between papers and grey literature (e.g. conference proceedings or dissertations). This is typical of an emerging field of research. However, TC guidelines state "Informal or so-called "grey" literature may only be referred to if there is no alternative from the formal literature". Accordingly, we have resolved to cite only formal papers that are clearly focused on measuring snow depth quantitatively and may provide e.g., maps and tables to prove this (thus excluding e.g. conference abstracts or dissertations). We added some additional references on using U.A.S. in cryospheric science in general in Section 4.4 (Outlook).
The study area	Here, we included additional details as requested by referees. In particular, we have specified site aspect, slope, vegetation, and topography - snow/ice coverage during the season (see lines 96-101). We have also considered including a picture of this area, but we have found no decent solution on this point.
Methods	In this Section, we have elaborated on 1) the choice of the original resolution of our maps (see lines 162-168); 2) point data collection (see lines 177-190) and 3) interpolation methodologies (see lines 211-218). As for point (2), we have shortened the general description. We have provided clear reasons why we were not able to collect a massive data set (see lines 177-190). Moreover, we have eliminated all references to previous strategies in evaluating remote sensed techniques, in order to address referees' concerns and present our point data collection as a mere comparison rather than an evaluation / validation. As for point (3), Section 3.4 has been shortened by 1) eliminating the extensive review of interpolation techniques (as suggested by e.g. Dr. Fassnacht), 2) including some new references on the degradation of DSM quality (see line 203) and 3) clarifying the rationale behind the comparison between DSMs at 5, 10 and 20 cm (see lines 162-168).
Results and Discussion, Section 4.1	Here, we have included some additional statistics about the validation of the bare soil DSM (see lines 225-236). Moreover, we have also added some discussion about the benefit of dust on snow for photogrammetric purposes, as asked by the anonymous referee (see lines 241-247).
Results and Discussion, Section 4.2	This Section has been revised in order to clarify that snow probes data are used as a mere comparison and cannot provide a sufficient validation of the technique. We removed "point evaluation" from the title and we shortened the paragraph dealing with this specific topic (see lines 259-271). Accordingly, we have removed the comparison with other techniques. This comparison was originally suggested during the first round of revision, but this is still a preliminary contribution and it may be inappropriate to focus on this topic here. On the contrary, we have included a more specific comparison between our performance and the

	performance obtained by other contributions on this topic (see again lines 259-271). This is probably more appropriate and useful in this Section.
Results and Discussion, Section 4.3	In this Section, we have operated some important changes. In Section 4.3.1, we clarified the implications of our analysis. We have removed any reference to a possible "trade-off", as we agree with referees that additional resolutions should have been considered for this purpose. On the contrary, we now specify that this comparison reveals that no benefit is evident when passing from a decimeter to a centimeter resolution (i.e., from 20/10 cm to 5 cm). This is clearly more appropriate here (see lines 287-291). We have also included a specific focus on possible vegetation effects on this analysis (see lines 292-302). In Section 4.3.2, we have clarified the implications of our analysis about degrading DSM resolution (see lines 310-318). Moreover, we have eliminated former Figure 9 (difference between the original DSM and a degraded one): we agree that its role in the manuscript was marginal. As suggested, we have enlarged and clarified our analysis on current Figure 9 (see lines 324-340) and fixed some technical comments as suggested.
Results and Discussion, Section 4.4	At the end of Section 4, we have added a new Subsection (4.4): here, we have included some considerations about the use of fixed wing U.A.S. in Alpine areas and a comparison with pros and cons of multi-rotor devices (see lines 373-385). Moreover, we have moved here the Outlook (see lines 386-407) in order to include it directly in the Discussion Section of our manuscript. This is because an Outlook Section is essential for this manuscript, and we feel this position is more central than the end of the manuscript, where it was positioned in the previous version.
Conclusions	This Section underwent minor modifications.
Tables	In Table 1, we added RMSE and percentage ratios between U.A.S. and manual snow depth measurements, as requested. Table 2 was not changed. We have resolved to keep Table 3 in the text. We agree with the main argument of Dr. Fassnacht about limiting a vast analysis about point measurements. In this perspective, we have removed the literature review about interpolation techniques for snow. However, we think that showing interpolation results for different (simple) techniques may help reducing the subjectivity in our results that may arise from choosing a specific interpolation methodology (e,g, Kriging). This is the reason why we chose to keep Table 3. However, we are clearly open to eliminate this Table.
Figures	Figure 9 was modified as requested. We did not modify Figures 3, 4, 5 and 7 to increase transparency: in our opinion, this solution is problematic because it reduces the contrast of the significant information (that is the orthophotos or DSMs).

We would like to thank you and the referees for providing important suggestions to improve this manuscript. We think that the overall quality of our analysis has now increased.

Dear Prof. Steven R. Fassnacht,
We thank you for your additional comments on this manuscript. We have incorporated these suggestions in the revised version of the manuscript. Please find here additional comments on your revision.

The authors of the revised version of "tc-2015-16" have done good job addressing both of the reviewers comments. Overall the text reads much better and the Methods are presented much clearer.

The two remaining problems are: 1) the addressing of the reviewer comments and 2) the use of 12 points to evaluate the dataset. With the first point, the authors make statements such as "We agree with your point of view. We will try to include a wider context about survey uncertainty with respect to the existing literature." Be specific. What did you do. Tell us explicitly what the changes are. In reading the revised version, I can pick up some of these. Did you just consider what we asked or did you actually address the comment.

> We are sorry about this lack of specificity. This was clearly not intentional and probably partially caused by the timing of our responses to referees during the open discussion and the following re-submission. When we wrote our answer to Referee #1, we had not started to change our manuscript yet (May 2015). As a result, we could not be very specific about the exact changes in the manuscript and our sentences referred to intentions. When we uploaded our answer to you (June 2015), we also uploaded our revised manuscript, including a list of major changes to the manuscript, addressed to the Editor. In our intentions, this was our point-by-point list of modifications. This submission included a version of the manuscript with major changes highlighted. This process is different from a traditional review process in which responses to referees are written after preparing the revised manuscript and this could have caused some misunderstanding. Here, we will be more specific on our changes. We start from the current revision, but we are open to provide additional details about the previous round if needed.

For the second point, the authors state in the revised paper: "In the literature, it is known how to determine the number of points that would theoretically be needed to get an estimation of mean snow depth within a certain error range ... On the contrary, no specific rule or common practice exists to determine the minimum number of manual snow depth measurements, over a given area, needed to evaluate whether a given remote sensed technique returns satisfactory performances or not. Although this amount of points allows for a preliminary evaluation of the performances, more data could help to assess the performances of this technique in a more extensive way." While there is some truth to this statement, they only measured 12 points. This is by no means enough. The paper is interesting enough that it would not be prudent to ask the authors to repeat this effort and "get more points." So, they should acknowledge that this is too few but that's what they measured at the time. The should "own it" and move on without vast analysis based on 12 points. Such analysis should be removed. For example, in lines 241-265 they discuss the various interpolation methods for the manual data. This is not necessary. There is enough literature related to interpolation of snow data, so they should state that various methods exist (give a few references), pick one method (kriging) and move forward with that. In section 4.2, the "point evaluation" section could be removed.

> We agree with you on this point. Our strategy about point measurements of snow depth has been at the center of this revision since our first submission and we recognize that additional efforts are mandatory to improve our assessment on this point in the future. As a result, we now stress that our manuscript provides just a preliminary comparison with point measurements of snow depth (see lines 272-280 or lines 185-190). We have also shortened the Section reviewing existing interpolation methodologies for snow depth (see lines 211-218) and the Discussion of these results (see lines 347-362). In Section 4.2, "point evaluation" has been removed; the discussion in this Section has been modified to avoid extensive

discussions on this comparison, as you have suggested. Moreover, we have also included a comparison between our performance and those by other authors (see lines 262-271). This discussion replaces the previous comparison between our performance and those by other techniques: this solution is probably more appropriate since this is still a preliminary contribution on this topic.

In lines 232-240, they degrade the quality of the interpolated UAS-based dataset. There could be references to existing literature (Cline et al., 1998 Hydrol. Proc.; Molotch et al., 2005 Hydrol. Proc.). The component examining the impacts of degradation is reasonable.

We have added references on this point (see line 203).

The authors have taken the review comments to heart, especially for improving the figures. Figure 6 is an interesting and relevant addition to the paper. I don't know what Figure 9 adds, and Figures 10 and 11 should be stacked and clarified. The y-axes are not clear and when these go to print the lines will be hard to see.

Thank you. We have removed Figure 9 as we agree with you that its role in the manuscript was marginal. Former Figures 10 and 11 were stacked. We also clarified their content and increased lines thickness.

The "Outlook" section at the end is a good touch.

Thank you. This Section has been moved within the Results and Discussion Section (Section 4.4) in order to increase its relevance in the manuscript and to include a more general discussion about using fixed wing U.A.S.s for mapping snow depth distribution.

Dear Referee #3,

We thank you for your comments to the manuscript. Please find below a point-by-point reply to your comments.

The revised version of the paper "Using drones to map snow depth variability at cm resolution: an evaluation at peak accumulation" by De Michele and others introduces the application of UASs to map snow depth in alpine settings. The author present a qualitative accuracy analysis of the summer DEM based on a topographic map and an evaluation of the accuracy of snow depth by comparing to few probe measurements. And they compare snow volumes derived from different interpolation techniques to the volume measured by UAS. The topic is very relevant and the next years will probably see many applications of UAS for snow cover mapping.

Most of the comments of the two reviewers have been addressed in the new version. An analysis on the aggregation of the data sets from cm to 100m cell resolution has been included which clearly improves the content of the paper by providing indication on required sample resolutions. Still, the implications of these results should be discussed in more detail.

> We agree with you that the discussion of the implications of results reported in Section 4.3.2 could be improved. In the revised manuscript, we have elaborated on this point (see lines 310-318 and following lines).

However, the main shortcomings of the study which is the sparse data set used for the snow depth validation are still existing and cannot be solved in a simple review. A robust data set for validation would include many more points, more than a single winter survey and possibly even more study sites. In my opinion more of these surveys should have been performed before submission. This shortcoming reduces the impact of a very promising paper to a very preliminary piece of work (as the authors correctly state). I do not want to reject the paper as it is in principal very valuable. But I strongly suggest to perform more field campaigns in the coming winter and to resubmit an extended version of the paper in the next spring. In the meanwhile the "preliminary" results are still available to the public in the TCD manuscript. The design of additional field campaigns could benefit from the suggestions of the reviewers, it could even be considered to include state of the art areal snow depth measurements such as laser scanning for validation.

> We agree with you that additional investigations are needed on this point. While revising the manuscript, we stressed this point repeatedly (see lines 177-190 or lines 272-280). In particular, we now present this discussion as a mere comparison, whereas the need for a more extensive validation is clearly included in the Outlook section (see lines 403-407).

Specific comments:
P4 Study area: Please provide some more characteristics on the study site such as aspect, slope angles, vegetation cover and their variability

> We provided some additional information about site characteristics (aspect, slope, vegetation coverage, absence of firn or glacier ice etc., see lines 96-101).

L179 why were three different resolutions extracted? What are advantages/disadvantages of the different resolution (processing)

> We chose these resolutions since they are very fine with respect to existing data sets (see text for references on this point). On the other hand, 5 cm is probably a proper lower limit given the typical size of

snow grains. We have added some specifications about pros and cons of a higher resolution: computational/logistical costs are likely to increase, whereas a U.A.S. needs to fly at a lower elevation. See lines 162-168 on this point.

L186: If a total station was already at site I wonder why no additional measurements of the snow surface were performed for the validation of the UAS data set. A total station allows to collect very accurate surface data (much more accurate than snow depth measurements by probing) and would have been a good supplement to the probing (such measurements have been used for the validation of terrestrial laser scanners by Prokop et al. 2008 and Grünewald et al. 2010)

We agree with you that measuring additional points using the total station could have been useful. During our field survey, we focused on obtaining probe data of snow depth, thus using the theodolite only to retrieve point coordinates. On the other hand, using snow depth measurements from another instrument could add additional noise to the problem as snow depth data taken using a total station are not manual and may be affected by, e.g., obstructions. In the revised version of the manuscript, we are now explicit in stating that additional investigations may help improving our preliminary analysis (see lines 386-407).

L188 please add that the "horizontal" accuracy is meant

We added this specification.

L207-2010; The authors state that there are guidelines in literature to define the number of samples but they do not apply them (also suggested by Reviewer 1). I wonder why. Of course, it is too late now but it could at least be tested and commented if the 12 samples were reasonable number or not.

This paragraph has been removed in a general attempt to reduce the relevance of point measurements of snow depth in this manuscript (as suggested by e.g. Dr. Fassnacht). However, we specify here that the guidelines we found in the literature refer to proper methods to estimate a mean snow depth within a given area or study plot. On the contrary, we were not able to find any specific rule to calculate the amount of snow depth data that are needed to evaluate the performance of a given technique. Our *good* practice here was to prefer quality than quantity.

L2018 The formulation is unclear, what is meant by "worst case" and why was it chosen?

This sentence was also removed (see previous point on this). However, we specify that this sentence (that does not appear in the manuscript anymore) meant that we wanted our choice of points location to be independent of any external information (i.e., purely random).

L271ff the analysis of the contour lines just provide qualitative accuracy estimation. Only the comparison with the DEM gives some quantitative measure. This measure should be mentioned in the text and possibly a figure of the comparison could be added.

We thank you for this suggestion. In the revised manuscript, we have added a new Figure reporting a map of the differences between our DSM of bare soil and the one provided by the Lombardia Regional Authority (independent source). We have also added some additional specification on this topic in the text (see lines 224-234).

L284-286: what would be the consequence if no "brown" areas would be available. Would it reduce the accuracy? This is very important as one cannot assume to find such contrasts when mapping snow. It could be considered to calculate, show and discuss the differences between calculating the maps with "brown areas" and without such areas (only using the parts of the map which are white snow.

> We have appreciated this question. In the manuscript, we have added some additional discussions on this point (see lines 241-247). In particular, we have randomly selected a "brown" and a "white" area (i.e., areas with or without dust) and we have calculated the density of points in the cloud within each of these areas. The density of points obtained within the "brown" area is equal to 44.7 points/m^2, whereas the density of points in the "white" area is 35.9 points/m^2. Therefore, we see a – 20% of points in the white area if compared with a brown area. However, note that 35.9 points/m^2 is satisfactory considering e.g. the 20 cm spatial resolution. Moreover, we also note that, during a U.A.S. photogrammetric survey on snow, additional topographic features are captured (e.g., emerging rocks, depressions of snow near rivers, small buildings) that may provide common points.

Table 1: 1) Root mean squared error or the absolute mean difference should also be provided; 2) A scatter plot would be more illustrative than a table. 3) observations 3 to 6 seem to be outliers in comparison to the other values. This illustrates one of the problems with only 12 measurements: More points would enable to clearly detect outliers . Is there an explanation for these outliers? Where are they located?

> We added the calculated RMSE to Table 1. We have appreciated this suggestion since RMSE is probably the most popular indicator of U.A.S. performance in cryospheric literature (see lines 241-247): including this value enables a direct comparison with other papers on this topic. We would like not to include a scatter plot using data in Table 1. This is because the total amount of points is small and a scatter plot may have reduced significance. Observations from 3 to 6 are located within the northern area of the domain, where several rocks are present. These may have caused additional noise in the DSM (see lines 292ff).

L339-41: This statement cannot be reasoned from the analysis: It can be said that 20cm resolution is not much worse than 10 cm but one does not know if the "trade off" could be even higher (e.g. 25, 50 or 100cm). What is the consequence if 20cm can be used instead of 10? How far does this reduce processing? Or does it imply that a higher flying altitude would be adequate (which would be good because one could cover larger areas)?

> We recognize that the term "trade-off" may be misleading since we did not consider coarser resolutions. We modified the text to clarify our methodology (see lines 200-201). During the preparation of this manuscript, we found widespread availability of snow depth maps at meter scale in the literature (see references in the text) and few examples of surveys at decimeter scale (see again text). U.A.S. & digital photogrammetry enable to capture snow depth variability at centimeter scale with limited increased efforts with respect to decimeter scale. However, we observe that at peak accumulation statistics of snow depth over our study area are similar at decimeter or centimeter resolution, thus suggesting no specific benefit when forcing resolution at centimeter scale. Clearly, flying at higher elevations means that the DSM would be reconstructed with less precision. In this perspective, keeping a 20 cm resolution enables to reduces logistical costs, as you have correctly noted.

L361-62 I do not understand this sentence

This sentence has been removed. Its meaning was that statistics of each map have been calculated by using all the data in that map. We think that this is clear from the context and that no specification is needed on this point.

L366f: Please reason why minimum and maximum appear to be constant. One would expect that also at the smaller cell sizes some degree of smoothing should result from the aggregation.

We agree with you on this point. Actually, maximum and minimum values are not constant, but their variation as a function of raster cell size is very small below 1.6 m. In particular, maxima are between 4.38 m and 4.21 m. Minima are systematically negative at these cell sizes (reasons are discussed at lines 292ff). This is clearly spurious, and we prefer to set minima to 0 in this Figure for clarity (see lines 325ff). We have clarified this point in the text.

L370-371: this is a very interesting finding and it should be discussed in more detail what it means for future studies (e.g. that a sample resolution of 1m might be enough)

We thank you for this appreciation. We have enlarged our discussion on this point (see lines 329ff).

Technical comments:
L33 sun
L44 an
*L123 30*104 m2 poor diction write 30000 m2 or 0.3 km2 instead*
L284 I think "interested" is the wrong word
L297 thickness
L361 cell size instead of "maps resolution"

All technical comments have been included in the revised manuscript.

Dear Dr. Bavera,

We thank you for your comments on the manuscript. Please find below a point-by-point reply to your suggestions.

The paper presents a very promising application for snow measurement and SWE assessment in the near future that could be quite cheap and easy to retrieve. The topic is relevant for the journal and interesting for scientific and technological development, for hydrological aims, and for other applications (e.g. avalanche monitoring and safety). At the same time, anyway this contribution is week in terms of comparative analysis and validation of its results.
Some comparisons should have been made against one of the already tested distributed techniques (e.g. laser scanner) to be more effective and relevant. Or, at least, against a validated physical based model or even using a much more dense set of manual measurements. This at least to have evidence of the expected effect of local topography and provide a validation of the method a little bit more reliable and significant.
To improve reliability and relevance of the measures and methods it is advisable to define and put in place some snow poles, properly and precisely located with GPS. These can be also used referencing images afterwards providing common points, and could give more information than probes, for time depletion curves, accumulation and melting processes. Finally, in any case I would add a great number of measure with snow probes in the peak accumulation survey as already suggested by other reviewers.
As the authors suggest, a more detailed and exhaustive comparison with existing techniques is advisable, and a greater number of points for snow probe measurement is required.

> We thank you for these comments. As we have already mentioned in previous responses, we recognize that our strategy for collecting point measurements of snow depth could be improved in future investigations. In the revised version of the manuscript, we are now more specific on 1) reasons that led us to collect few points (see lines 177ff), 2) the significance of this comparison, that cannot represent a complete and exhaustive validation of this methodology (see lines 272-280), and 3) future developments and needs (see Section 4.4).
>
> While reviewing the existent literature on this topic (see our reply to the Editor) we noticed that attempts to measure snow depth using U.A.S. reported in the literature have used multi-rotor systems (to our knowledge). We therefore chose to re-focus our contribution on using a fixed wing system for this purpose (see lines 2-7). However, we are now very explicit in the Outlook section about needs for future investigations and developments to achieve a thorough evaluation of this methodology (see Section 4.4). This may include using alternative sensors.
>
> Evaluating U.A.S. performance using a model may be problematic since uncertainties in modeling would combine with uncertainties in measuring; as a result, this validation would be severely hampered. We appreciated your suggestion about poles; we will consider this in the future.

Deductions described in paragraph 4.3.2 appear not to be significantly innovative and quite week and not really straightforward. They sound to be not really convincing. Dataset is and remain quite poor and this statistics analysis is not giving a real plus, in my opinion.
The most informative analysis in this paragraph, in my opinion, is the part regarding standard deviation and CV (fig. 11). I would summarize or remove the other parts.

We have restructured this Section according to this suggestion. In particular, we have eliminated former Figure 9 given that its role in the manuscript was marginal; we enlarged our discussion about snow depth statistics at different cell sizes.

Paragraph 4.3.3 assumes without any validation that U.A.S. output for snow volume is the correct one. Even if the analysis then is correct and appropriate, a rigorous validation against a spatial already tested technique is missing and should be included to provide strengthens to the assertions.

We apologize if our previous formulation on this point could be misleading. Clearly, we do not have sufficient evidences at this stage to validate our snow depth distribution in a definitive way. In this perspective, that comparison was aimed at providing evidences about the large difference we found between a simple (and rather traditional) interpolation of snow depth data and U.A.S. snow depth values. This result has clear hydrologic implications; moreover, U.A.S. relies on photogrammetry, which is a traditional and already validated technique, and this increases our confidence towards its performance. On the other hand, no additional speculation is possible at this stage. We corrected the text on this point (see lines 354ff).

Outlook section is essential to define the awareness for limitation of this research. In any case I would recommend to strengthen the sample data and/or the comparison with other distributed (remote sensing data or physical model) dataset.

We agree on this point. In the revised version, the Outlook Section has been moved in the "Results and Discussion" Section in order to enhance its role in the manuscript. Moreover, we have also elaborated on possible future developments.

Specific Comments:

Title: I would remove resolution info in title

We have removed resolution from the title.

l. 10: manual measurements: how? Where? Provide more details. As already said you should have collected more than 12 points

We already provide details about manual data elsewhere in the text (Section 3.3) so we have preferred not to include additional details on this point in the Abstract in order to avoid repetitions and to keep the text as concise as possible.

l. 17: add results of point values also in percentage

We have added percentages in Table 1, whereas in the Abstract we have preferred to include RMSE as this is probably the most popular performance indicator in all the papers about measuring snow depth using U.A.S. (see lines 260ff) and this enables a direct comparison. However, we are open to include percentages if this is considered mandatory.

l. 21: include a short motivation about snow volume difference

In the revised Abstract, we have removed any specific indication about interpolation results in order to reduce the relevance of this topic in the manuscript. Again, we are open to include this if it is considered mandatory.

l. 104: in my opinion the survey should has been made for two or three years to have more information

Some considerations on this point are now incorporated in the Outlook Section.

l. 109: include more details about 12 points measurements

We already provide details about manual data elsewhere in the text (Section 3.3), so we have preferred not to include additional details on this point in the Introduction in order to avoid repetitions and to keep the text as concise as possible.

l. 121: change "since it is an elevation that guarantees" with "since the elevation guarantees". I would stress more clearly that it is important that the study area has NO permanent snow.

We have specified that no part of the study case presents firn of glacier ice, whereas a specification of challenges of moving glacier surfaces has been included in the Outlook (see lines 399-400). As for your first suggestion, that sentence was eliminated in the text since it added no significant information (it was merely logistical).

l. 275: in order to better verify the quality of the surveyed data it would be better to compare the U.A.S. DSM with an already validated one, computing some statistics of the differences between the two DSM: please show results of the comparison you made.

We thank you for this suggestion. In the revised manuscript, we have added a new Figure reporting a map of the differences between our DSM of bare soil and the one provided by the Lombardia Regional Authority (independent source). We have also added some additional specification on this topic in the text (see lines 225ff).

l. 315: snow probe measurements should be more numerous and possibly located in flat zone, local maxima and local minima of the topography, in order to get the greatest variability

Some considerations on this point are now incorporated in the Outlook Section.

l. 340: "Basing on these results, a spatial resolution of 20 cm seems to be the trade-off between the number of pixels considered (i.e., computational time) and the description of the snow micro-topography for the considered area": this deduction is not straightforward. How do you evaluated 20 cm as the bets compromise? Rougher resolutions have not been investigated and an evaluation index is missing.

We recognize that using "trade-off" was probably misleading. In the revised manuscript, we modified the text to clarify our methodology (see lines 200-201). During the preparation of this manuscript, we found widespread availability of snow depth maps at meter scale in the literature (see references in the text) and few examples of surveys at decimeter scale (see again text). U.A.S. & digital photogrammetry enable to capture snow depth variability at centimeter scale with limited increased efforts with respect to decimeter scale. However, we observe that at peak accumulation statistics of snow depth over our study area are similar at decimeter or centimeter resolution, thus suggesting no specific benefit when forcing resolution at centimeter scale. On the other hand, limiting the requested resolution to 20 cm needs less computational and logistical constraints (see lines 290ff).

l. 345: "While the three maps considered in the previous section...": if you talk about these maps you should show them in figures

We have removed this sentence. In the previous version of the manuscript, it was aimed at clarifying the main difference between degraded maps at increasing resolution and the three original maps at 5, 10 and 20 cm. Whereas the latter ones were directly obtained from the cloud of points, degraded maps were obtained by starting from the map at 5 cm. However, we believe that this is clear from the context and does not need additional specifications. This limits the number of Figures of this manuscript. However, we can include these maps if the Editor considers this mandatory.

l. 349: "...the larger cell size, the lower degree of detail..." this assertion is quite obvious, please rephrase the sentence

We have removed this sentence entirely; we agree with you that it was quite obvious.

l. 445: I would use "vehicle" or something similar instead of "support"

In the revised manuscript, we have introduced digital photogrammetry and U.A.S.s separately. As a result, the sentence including this word is not necessary anymore.

tab. 1: it seems that absolute and percentage (please add this information to the table) difference are greater for lower snow depth. This is reasonable but should be more in detail investigated and commented, and, also for this aim, much more measurements would be required.

We have added percentages to Table 1. In principle, we agree with you that measuring a lower snow depth is difficult: we mention this issue in the text (see lines 272FF). On the other hand, we do not detect a systematic error in lower snow depths when analyzing our 12 points. For instance, points 1 and 11 returned minimum snow depth (H_M), but differences with respect to U.A.S. are lower than (point 11), or similar to (point 1), point 8, which returned the maximum H_M. Points 11 and 8 returned similar percentages. Clearly, we see that 12 points is a limited set of points: we are now very explicit in the text on this point.

tab. 2: negative values in Hmin? Explain the meaning or remove.

We have added a specification in the text on this problem (see lines 292ff). A similar problem has been already noted during photogrammetric surveys by, e.g., Nolan et al. (2015, reference in the text) and can be attributed to the effect of compressible vegetation. As they note, this effect hampers the general assumption that snow depth distribution can be simply obtained by differentiating two DSMs. This highlights the need for future investigations to address the issue of varying U.A.S. precision with vegetation.

tab. 3: result clearly show that the snow probe sample size and location is not suitable to assess snow volume, assuming that U.A.S. value is reliable. Please consider to significantly improve the snow probe sample, and detail comment section about this.

As suggested by Dr. Fassnacht, the relevance of our analysis about interpolating probe data has been limited. However, we now specify limitations of this analysis and state explicitly that more analyses are needed (see lines 272ff).

fig. 3, 4, 5 and 7: make the upper layers a bit transparent in order to make visible the underlying map.

See our reply to the Editor on this point.

fig. 9: please consider to change the color map in order to better highlight where the difference is close to zero, where you have overestimation and where you have underestimation.

We have decided to remove Figure 9 as its role in the paper was marginal (see our response to Dr. Fassnacht).

fig. 10 and 11: please consider to use different symbols instead of colors to allow black and white print and add the legend in the plots.

All lines in Figure 10 are now black. Moreover, symbols have been changed in order to distinguish these lines in B&W mode.

Grammar, typing, etc.: please check time of the verbs (past and present are used not in coherence) and improve readability of numbers (thousands, etc.).

We have checked our use of English in the revised manuscript.

Manuscript prepared for The Cryosphere
with version 2014/09/16 7.15 Copernicus papers of the LaTeX class copernicus.cls.
Date: 2 February 2016

Using a fixed wing U.A.S. to map snow depth distribution: an evaluation at peak accumulation

C. De Michele[1], F. Avanzi[1], D. Passoni[1], R. Barzaghi[1], L. Pinto[1], P. Dosso[2], A. Ghezzi[1], R. Gianatti[3], and G. Della Vedova[3]

[1]Politecnico di Milano, Department of Civil and Environmental Engineering, Piazza Leonardo da Vinci 32, 20133 Milano
[2]Studio di Ingegneria Terradat, Paderno Dugnano, Italy
[3]a2a Group, Grosio, Italy

Correspondence to: C. De Michele (carlo.demichele@polimi.it)

Abstract.

We investigate snow depth distribution at peak accumulation over a small Alpine area (~ 0.3 km^2) using photogrammetry-based surveys with a fixed wing Unmanned Aerial System (U.A.S.). These devices are growing in popularity as inexpensive alternatives to existing techniques within the field of remote sensing, but the assessment of their performance in Alpine areas to map snow depth distribution is still an open issue. Moreover, several existing attempts to map snow depth using U.A.S. have used multi-rotor systems, since they guarantee higher stability than winged systems. We have designed two field campaigns: during the first survey, performed at the beginning of the accumulation season, the digital elevation model of the ground has been obtained. A second survey, at peak accumulation, enabled to estimate the snow depth distribution as difference with respect to the previous aerial survey. Moreover, the spatial integration of U.A.S. snow depth measurements enabled to estimate the snow volume accumulated over the area. On the same day, we collected 12 probe measurements of snow depth at random positions within the case study to perform a preliminary evaluation of U.A.S.-based snow depth. Results reveal that U.A.S. estimations of point snow depth present an average difference with reference to manual measurements equal to -0.073 m and a RMSE equal to 0.14 m. We have also explored how some basic snow depth statistics (e.g., mean, standard deviation, minima and maxima) change with sampling resolution (from 5 cm up to $\sim$100 m): for this case study, snow depth standard deviation (hence coefficient of variation) increases with decreasing cell size, but it stabilizes for resolutions smaller than 1 m. This provides a possible indication of sampling resolution in similar conditions.

1 Introduction

The spatial distribution of snow depth and Snow Water Equivalent, SWE, has been widely measured and modeled, both at the local, slope and catchment scale (Grünewald et al., 2010). Modeling techniques include statistical approaches, such as Carroll and Cressie (1996); Elder et al. (1998); Erxleben et al. (2002); Anderton et al. (2004); Molotch et al. (2004); Dressler et al. (2006); López Moreno and Nogués-Bravo (2006); Skaugen (2007); Bavera et al. (2014), and conceptual, or physically-based models, e.g. Lehning et al. (2006, 2008). These works have improved our knowledge about, e.g., the relevance of single forcings in determining the distribution of snow on complex terrains (Anderton et al., 2004). In addition, they provide an useful tool to estimate the impact of future modifications of climate on the Earth system (Bavay et al., 2009, 2013).

Running a model often needs input and evaluation data at fine temporal resolutions (e.g., daily or hourly). These can be obtained by means of automated devices, such as snow pillows (De Michele et al., 2013), cosmic ray counters (Morin et al., 2012) and ultrasonic depth sensors (Ryan et al., 2008). These devices are usually placed in areas that are believed to be suitable locations for representative measurements at wider scales (i.e., unaffected by local heterogeneity). Nonetheless, their spatial resolution is often sparse, while Grünewald and Lehning (2014) report that, usually, point stations on flat areas tend to overestimate catchment mean snow depth, and that representative cells are usually randomly located, i.e. impossible to be determined *a priori*. These represent important drawbacks of point weather stations in the study of snowpack dynamics (see Rice and Bales (2010); Meromy et al. (2013); Grünewald and Lehning (2014) and references therein). Moreover, such instruments are usually affected by systematic and random errors, that degrade the precision of measurements (Avanzi et al., 2014).

Consequently, increasing interest is nowadays growing around distributed measurements of snow extent, depth and SWE (Dietz et al., 2012), able to substitute, or integrate, point, and usually sparse, measurements. Existing techniques include terrestrial or airborne laser scanning (see e.g. Hopkinson et al. (2004); Deems et al. (2006); Prokop et al. (2008); Dadic et al. (2010); Grünewald et al. (2010); Lehning et al. (2011); Hopkinson et al. (2012); Deems et al. (2013); Grünewald et al. (2013); Grünewald and Lehning (2014); Hedrick et al. (2014)), SAR (Synthetic Aperture Radar, Luzi et al. (2009)), aerial photographies (Blöschl and Kirnbauer, 1992; König and Sturm, 1998; Worby et al., 2008), time-lapse photography (Farinotti et al., 2010), optical and micro-waves data from satellite platforms (Parajka and Blöschl, 2006; Dietz et al., 2012). The good performance of these methods has been widely discussed, but survey expenses are still a constraint (Hood and Hayashi, 2010). Recently, digital photogrammetry has emerged as a cheaper tool to perform these surveys: as an example, Nolan et al. (2015) have evaluated this methodology in three study cases in Alaska and have compared airborne measurements of snow depth with ~ 6000 manual measurements. They have found a standard deviation between these two datasets around ± 0.1 m. Bühler et al. (2015) have applied a similar method in Switzerland and have estimated snow depth distribution with a Root Mean

Square Error (RMSE) of 0.30 m. This technique is therefore an accurate solution that may be used to obtain distributed information about snow depth dynamics at meter (or centimeter) resolution.

Traditional airborne photogrammetry is usually performed by manned aircraft and this increases its costs and limits the temporal resolution of surveys. Unmanned Aerial Systems (U.A.S.s, also known as drones) could potentially overcome these limitations. These systems provide an inexpensive airborne support for sensors operating at different wavelengths. This can autonomously determine its own position in a 3D reference, reproduce a pre-arranged photogrammetric flight, and reconstruct a high-resolution Digital Surface Model (hereinafter, DSM) of a given area (Watts et al., 2012) by setting a suitable (low) flight height over the target (say, $\sim$100 m). All these features can potentially enable automated, repeteable, cheap (Colomina and Molina, 2014) and low-risk surveys to be performed. Their use is nowadays rapidly increasing (Eisenbeiss, 2009; Watts et al., 2012; Colomina and Molina, 2014). Some examples regard ecology (Dunford et al., 2009; Koh and Wich, 2012), coastal engineering (Delacourt et al., 2009), geomorphological mapping (Lejot et al., 2007; Hugenholtz et al., 2013) or dust detection on snow (Di Mauro et al., 2015), see Colomina and Molina (2014) for an exhaustive review. In optical surveys, they usually adopt compact digital cameras, due to the limited payload (say $\sim 10^2$ g). Nonetheless, these are affected by higher deformations as compared with those of photogrammetric calibrated cameras (Pollefeys et al., 1999; Remondino, 2006; Stretcha et al., 2010; Sona et al., 2014). Performing photogrammetric surveys using U.A.S. may therefore represent a definitive solution to the problem of mapping snow depth with fine spatial and temporal resolutions. In the last few months, some early attempts, mainly using multi-rotor devices, have been published (Vander Jagt et al., 2015; Bühler et al., 2016) and they show promising results. Using multi-rotor devices guarantees high safety conditions due to their stability and resistance to wind. Nonetheless, this limits the areal extension of U.A.S. surveys due to logistical constraints (battery duration). Fixed wing devices may on the contrary perform larger investigations, but they need stable wind conditions and regular topography for landing operations.

Here, we investigate the possibility of using fixed wing U.A.S. to measure snow depth patterns at peak accumulation within a small mountainous basin, using centimeter/decimeter resolution. We chose as a field test the bare plateau around the Malghera lake, within the western Val Grosina valley (around 2300 m a.s.l.), northern Italy. A double airborne survey of this area was designed. During the first one, the DSM of the ground has been mapped, while during the second one, at peak accumulation, the same area has been surveyed again to determine the DSM of the snow cover. A preliminary performance evaluation of this technique has been operated using manual probe measurements at 12 points within the study domain.

2 The study area

The case study is located in the western Val Grosina valley, Lombardia region, northern Italy. It is a small plateau located nearby the Malghera lake, $\sim 46°20'2''$ N, $\sim 10°7'14''$ E, 2320 m a.s.l. The approximate extent of the study area is 0.3 km^2, see Fig.1. This Figure includes also a topographic map of bare soil, produced by the local regional administration (Lombardia region).

This site is characterized by sparse grass coverage and rocks, with no tree, firn or glacier ice. As a result, ground surface is bare during summer and autumn. Topography is relatively homogeneous and marked by frequent gullies and crests. Site aspect is Northeast, whereas the average slope in the NE-SW direction is $\sim 14\%$. Snow conditions are generally undisturbed, given site elevation and inaccessibility during winter. During our surveys, the only (visible) perturbation of snow was represented by unsystematic ski traces.

3 Methods

3.1 Design of the surveys

We design our study test to map snow depth distribution at peak accumulation. For this purpose, two different surveys are needed, i.e. one before accumulation starts (snow is absent and the survey can therefore map bare soil) and another one at peak accumulation. The first survey of the study area was performed on 26^{th} September 2013, while the second survey was operated on 11^{th} April 2014.

We used a light-weight fixed wing SwingletCAM system (SenseFly®). This device is characterized by limited weight (∼500 g) and size (wingspan of 80 cm). These features make it suitable for performing photogrammetric flights over limited areas (about 1 km^2) at a very high spatial resolution (3-7 cm of Ground Sample Distance - GSD). The device is mainly made by an expanded polypropylene (EPP) foam, a carbon structure and composite parts. The propulsion is electric, with a maximum flight time around 30 minutes. The nominal cruise speed is ∼36 km/h, with a wind resistance up to 25 km/h and a radio link range up to 1 km from the master station on the ground. The SwingletCAM is able to perform pre-planned flights in a fully automated mode, since it continuously analyzes data from the onboard GPS/IMU system. However, the operator can always recover full control of the system. It incorporates a compact camera Canon Ixus 220HS (12 Mp and fixed focal length of 4.0 mm) which can acquire images at a GSD of some centimeters (depending on flight height). The camera uses a bandpass filter for the three colors RGB. These are placed ahead of the complementary metal–oxide–semiconductor (CMOS) according to a Bayer filter.

In these two field surveys, the GSD was set to 4.5 cm, since such a value enables to perform a survey at a flying elevation of around 130 m above ground surface (the complete range of the height values is between 130 m and 135 m). This is a good safety condition for this U.A.S. device in a mountain area that is potentially subjected to strong winds. To gain the maximum stereoscopy and to avoid uncovered areas, forward and side overlaps were set to 80%. Following this approach, from six to seven strips were necessary to cover the area of interest.

3.2 DSMs production

For both the surveys, the flight lasted around 15–20 minutes; Fig. 2 reports the location of camera photos and their overlap. The left panel regards the survey made during September 2013, while the right panel refers to the survey performed during April 2014. Colors indicate the number of images covering each area. It is well known that the precision in coordinates estimation increases with an increasing number of images in which a point is present (Remondino and El – Hakim, 2006). In this perspective, most of the study area has been imaged at least by 3 or 4 images. Clearly, the overlap increases at the center of the study area. In that area, points have been imaged by a number of images ≥ 9.

In the survey made on 26^{th} September 2013, the U.A.S. collected a block of 47 images divided in 6 strips. Due to the high image overlap, all the ground points are visible in many images (from 3 to 9). Thirteen pre-signalized Ground Control Points (henceforth, GCPs), measured through GPS rapid static survey, enabled the referencing of the block and the accuracy analyses. The standard deviation of the three coordinates of GCPs are around 3 cm in the horizontal components, and 5 cm in the vertical one.

In the survey performed on 11^{th} April 2014, the U.A.S. collected a block of 84 images divided in 12 strips (6 regular strips as in the autumn survey plus 6 cross strips). Fourteen pre-signalized GCPs, measured through a GPS static survey and theodolite, enabled the referencing of the block. This set of GCPs is different from the one used during the first survey. We chose points that were reasonably distributed over the area, and we referred them to the same reference frame. Based on this survey, GCPs coordinates have been estimated with a standard deviation of about 1 cm.

The blocks of images were processed using Agisoft Photoscan. This is a 3D modelling software that enables the exterior orientation of large datasets, by carrying out the image relative orientation, together with the self-calibration, in an arbitrary reference system, which is often obtained using a minimum constraint coming from the approximate orientation provided by telemetry. Details about the processing procedure can be found in the Photoscan user manual (Agisoft, 2014), as well as at the Agisoft website (http://www.agisoft.com/). Moreover, several papers are available that describe the use of Photoscan to generate 3D models of surfaces (Verhoeven, 2011; Koutsoudis et al., 2014). Firstly, for each block of images, the position of the camera for each image is determined searching common points on the images. Then the extraction of topographic points (which represent a cloud of points), and the rejection of outliers are made for each survey. The subsequent use of GCPs allows translating and rotating the photogrammetric blocks in a specific reference frame, i.e. ETRF2000. Then, starting from the cloud of points, DSMs at different spatial resolutions are extracted by generating a polygonal mesh model from the cloud data through interpolation. By making the differences of the two DSMs (at the same spatial resolution), maps of snow depth distribution can be obtained.

In this application, we considered spatial resolutions of 5, 10 and 20 cm. These are very fine with respect to other existing data-sets of snow depth (see López Moreno et al. (2015) as an example). However, U.A.S.s enable to collect high-resolution data with sensible lower effort than, e.g., manual probing; this can provide useful indications for future surveys using the same devices. Increasing spatial resolution means that computational/logistical costs are higher: for instance, flight elevation must be lower. Note that 5 cm is probably a proper lower limit given the typical size of snow grains/clusters (Fierz et al., 2009).

3.3 Point data collection

During the survey performed in April 2014, 12 point manual measurements of snow depth were operated using probes. Locations of these measurements have been randomly chosen, but they were distributed as much as possible over the study area. We have used these data to perform a preliminary evaluation of U.A.S. performance in retrieving point values of snow depth, as already done by, e.g. Bühler et al. (2016). In particular, we have calculated the mean and standard deviation of the differences between manual and U.A.S.-based estimations of snow depth, and RMSE. Note that point locations were chosen neglecting spatial correlation in snow depth.

Snow depth distribution is usually marked by strong spatial variability at small scales (Grünewald et al., 2010; López Moreno et al., 2013; Mott et al., 2014; López Moreno et al., 2015) and this hampers our evaluation since coordinates of probes data must be collected with a very high spatial precision due to the spatial resolution we have considered. For this purpose, coordinates were obtained by total station theodolite observations referred to GPS baselines that were surveyed by static approach (40 minutes sessions). The horizontal accuracy of the obtained coordinates is of the order of 2-3 cm (i.e., comparable with the spatial resolution of the DSM at the maximum resolution). This procedure makes difficult collecting a massive database of evaluation data, but guarantees a very high spatial precision in coordinates retrieval. On the other hand, this amount of data is clearly reduced in comparison with previous evaluations of remote sensing techniques by, e.g., Prokop et al. (2008); Nolan et al. (2015); Bühler et al. (2016). Photogrammetry is rather traditional, and this increases our confidence towards its performance. However, we stress that this amount of points allows only a preliminary evaluation, since the main focus here is on using a fixed wing U.A.S. in mountain areas to map snow depth, and that more data are needed to perform a definitive evaluation.

On the same day, a snow pit was excavated, and a snow density profile was measured through gravimetry (using a cylindrical sample holder, 15 cm long and with a 7.5 cm diameter). Measurements were taken at $\sim$ 20 cm intervals along 210 cm of snow depth at that point. Density values spanned between 330 $\mathrm{kg/m^3}$ and 570 $\mathrm{kg/m^3}$ (mean value $\sim$ 450 $\mathrm{kg/m^3}$).

3.4 Spatial sampling vs. snow depth statistics and volume

In the following, we will consider three different tests to assess how spatial sampling affects snow depth measurement at peak accumulation. As a first step, we have estimated some basic snow depth statistics, i.e. minimum, mean and maximum snow depth and total snow volume, using the three snow depth maps we obtained directly from the survey cloud of points (i.e., maps at 5, 10 and 20 cm resolution). This aims at clarifying any benefit to increasing spatial resolution from decimeter to centimeter scale.

As a second step, we have repeatedly resampled the snow depth map using an increasing cell size, starting from 5 cm resolution (see e.g. Cline et al. (1998) on this point). For this purpose, we have progressively aggregated cells by doubling cell size and estimating snow depth for each new cell using the mean of the snow depth of the aggregated cells. Consequently, we have produced estimated snow depth distributions using the following cell sizes: 5 cm (the original one), 10 cm, 20 cm, 40 cm, 80 cm, 160 cm, 320 cm, 640 cm, 1280 cm, 2560 cm, 5120 cm, 10240 cm. Missing values have been disregarded. We have then calculated mean snow depth (μ), standard deviation (σ), coefficient of variation (CV) and minimum(maximum) value within each of these maps. The main purpose of this calculation is assessing how snow depth variability evolves with increasing/decreasing cell size.

As a third step, we have compared the estimates of snow volume by simple spatial interpolations of snow probes data with the distributed estimation of snow volume obtained using U.A.S.. Different spatial interpolation methods have been considered for snow (Fassnacht et al., 2003; López Moreno and Nogués-Bravo, 2006; Marsh et al., 2012); we will consider here inverse distance weighting, Thiessen method, and ordinary Kriging. In addition, we will consider also the arithmetic mean of snow depth measured at probes. We have chosen these techniques since they are easy to be interpreted and represent among the most used techniques in interpolation problems. The application of more complex techniques (e.g., cokriging) is also hampered by the paucity of ground truth data collected.

4 Results and discussion

4.1 DSMs evaluation

Figures 3 and 4 report the two orthophotos of autumn and spring surveys. Figure 5 describes the related DSMs, both characterized by a pixel size of 5 cm. Red lines depict contour lines (10 m interval).

The autumn DSM (Fig. 5, panel (a)) shows good coherence with the topographic map reported as background. For example, rivers and Malghera Lake outlet are correctly located. We have carried out a quantitative evaluation of this DSM by using as an independent map of the area a 5×5m^2 DSM of the Lombardia Regional Authority, which is based on the digitalization of the 1:10000 map reported as background in all the Figures of this paper. In particular, Fig. 6, panel a, reports a map of the differences between the U.A.S.-based DSM and this DSM, used as reference. Maximum and minimum differences are 5.58 m and -6.61 m, whereas the mean difference and the standard deviation are -0.92 m and 1.63 m. The precision of original contours in the 1:10000 map by the regional administration is $\pm$2.5m: differences in the range $\pm$ 7.5 m between these two DSMs are therefore within the range ± 3 standard deviations, i.e. within tolerance. The statistics of the differences are therefore coherent with the accuracy of the DSM. In Figure 6, panel b, U.A.S.-based contours (in red) are directly superimposed to the contours of the topographic map. This comparison shows that the agreement increases with steeper terrains.

An evaluation of the spring survey (Fig. 4 and Fig. 5, panel b) is less straightforward due to lack of independent maps of snow surface at this site. The snow depth surface on this area is marked by patchy coverage of sand dust transported by wind storms. This is visible as brown areas in the orthophoto (Fig. 4), and has helped referencing the images of the spring survey since it provided common points on photographs. In fact, the density of points obtained within one of these brown areas (randomly chosen) is equal to 44.7 points/m^2, whereas the density of points in one white area (i.e., an area with no dust, again randomly chosen) is 35.9 points/m^2. However, we note that within our study case several additional topographic irregularities (e.g., snow depressions near rivers, emerging rocks or buildings) may help as well. The DSM shows contour lines which are different from those obtained during the September survey. This is an effect of snow depth presence on the ground; this causes a slight reduction in topography irregularities too.

4.2 Snow depth map

Figure 7 reports a map of snow depth distribution over the study area (at 5 cm resolution) and the location of the 12 manual measurements. Snow depth shows a remarkable micro-topographic variability (i.e., at distances comparable with map resolution), although this area is rather limited in extension and characterized by bare soil. Most of the central study area is characterized by an alternation of low and high snow depth values. Clusters of high values of snow depth correspond to rivers' location or depressions in micro-topography. On the contrary, low snow depths are observed on topographic local maxima, probably because of wind effects. Legend scale shows that micro-topographic differences can be equal to $\sim 2-3$ m. This illustrates the relevant variation of accumulation dynamics of snow depth (Nolan et al., 2015), and the scarce representativeness of point measurements (Grünewald and Lehning, 2014).

We report in Table 1 a comparison between manual (H_M) and U.A.S. based ($H_{U.A.S.}$) snow depth measurements. Manual measurements are associated with a standard resolution of $\pm$ 1 cm. Differences span -0.21 m and 0.08 m, whereas the average difference between measurements is equal to -0.073 m, with an associated standard deviation of 0.128 m. The RMSE is equal to 0.143 m. These statistics are coherent with previous attempts to using a combination between digital photogrammetry and U.A.S. to measure snow depth. As an example, Vander Jagt et al. (2015) found RMSEs equal to 0.096 m and 0.184 m while mapping snow depth distribution in Tasmania within an area of $\sim$ 0.007 km^2 (differences in performance depend on the methodology considered during bundle adjustment), whereas Bühler et al. (2016) has recently reported an RMSE around 0.07 - 0.30 m (depending on ground properties, e.g. the presence of vegetation underneath snow) when mapping snow depth in two study sites in Switzerland (areas spanning 0.363 km^2 and 0.057 km^2). A similar performance has been recently reported also for digital photogrammetry surveys of snow distribution using manned aircraft (Nolan et al., 2015; Bühler et al., 2015).

Thus, this survey provides evidences that U.A.S.s seem able to locally estimate the snow depth values with a precision of $\sim$ 10 cm. Errors could be explained by slight differences (at centimeter scale) in the position of manual measurements and U.A.S. estimates, instrumental resolution or vegetation effects, as already reported by Vander Jagt et al. (2015); Bühler et al. (2016). However, the amount of points data we have used is very small, and snow depth at probe positions varies between 1.48 and 2.11 m, which represents a reduced variability with respect to the complete range of variation of U.A.S. snow depth values. These represent important limitations of this study: additional investigations are necessary to extensively assess U.A.S. performance in case of, e.g., shallow or patchy snow cover conditions (see Section 4.4).

4.3 Snow depth statistics

4.3.1 Test 1: spatial resolution vs. snow depth distribution

Table 2 proposes a comparison in terms of number of pixels, average/maximum/minimum snow depth and snow volume estimated according to the DSMs at 5, 10 and 20 cm that have been directly obtained from the cloud of points of this survey. Clearly, increasing spatial resolution from decimeter to centimeter scale would increase the number of pixels. Nevertheless, this seems to marginally affect the estimations of average/maximum/minimum snow depth or total snow volume. Basing on these results, we do not see clear benefits in increasing cell size of snow depth maps from decimeter (10 cm or 20 cm) to centimeter (5 cm) scale at peak accumulation. Clearly, keeping resolution at 20 cm may help limiting logistical/operational costs, as flight height is related to precision. Additional investigations on this point are proposed in the next Section.

Note that minimum snow depth is systematically negative for all these three resolutions. These values were set to 0 in Figure 7 for readability. Spurious negative snow depths have been already noted during photogrammetric surveys by, e.g., Nolan et al. (2015) and can be attributed to the effect of compressible vegetation (and instrumental precision). As Nolan et al. (2015) note, this effect hampers the general assumption that snow depth distribution can be simply obtained by differentiating two DSMs. A similar effect may be also the cause of the large differences between H_M and $H_{U.A.S.}$ at points from 3 to 6 in Table 1, that nonetheless lie in areas with scattered rocks, which may have caused additional noise in the DSM. During the autumn survey, we did not notice systematic presence of shrubs, bushes or other vegetation types that might be compressed by snow in areas that were subsequently probed in April. This highlights the need for future investigations to address the issue of varying U.A.S. precision with vegetation.

4.3.2 Test 2: the effect of spatial sampling on snow depth statistics

We report in Figure 8 some examples of the snow depth maps we have obtained by progressively doubling the cell size of the original map at 5 cm. In particular, we report maps with cells size equal to 640 cm (panel a), 2560 cm (panel b) and 10240 cm (panel c). The coarsest map ($\sim$ 100 m resolution) retains only a small fraction of original spatial variability (i.e., a lower-than-average snow depth in the proximity of the Malghera Lake, and a greater-than-average snow depth on slopes), but most of the spatial patterns in snow depth are lost.

Notably, a spatial resolution of 10 m - 100 m is much higher than the typical spatial density of instrumental networks that are currently implemented worldwide to monitor snow dynamics (see e.g. Serreze et al. (1999)). Such a cell size is also smaller than the ordinary resolution of satellite products (see e.g. Dietz et al. (2012)). In this perspective, U.A.S. may be a valid intermediate step between point measurements of snow variables at high temporal resolutions (e.g., pillows or depth sensors) and satellites, which usually provide distributed information with low temporal and spatial resolution (see also Nolan et al. (2015) on this point). Our results show in fact that a metric (or lower) resolution provides relevant spatial patterns to describe the relation between topography and snow accumulation (Grünewald et al., 2010; Grünewald and Lehning, 2014).

Figures 9 reports statistics in terms of minimum, mean (μ) and maximum snow depth, its standard deviation σ and the corresponding CV of each map, as a function of cell size. This Figure reveals that μ is quite constant across all the resolutions (values range between 2.25 m and 2.33 m). This is probably due to the algorithm we used for this aggregation, that estimates the snow depth for an aggregated cell as the mean of the cells that are aggregated. Consequently, spatial differences are gradually homogenized when increasing the cell size. Minima and maxima are rather constant below $\sim$ 1.6 m. In this range of resolution, maximum snow depth spans 4.38 m and 4.21 m, whereas minima are spuriously lower than zero, probably due to vegetation effects or instrument resolution (negative values set to zero in Fig. 9 for clarity). For larger cell sizes, these quantities start to converge towards the mean due to progressive homogenization.

An interesting result of Figure 9 is that, within our case study, σ presents a well defined upper boundary (as well as CV). In particular, it is minimum for coarser resolutions ($\sigma = 0.28$ m for a cell size equal to 10240 cm), whereas it increases monotonously with smaller cell sizes ($\sigma = 0.39$ m for a cell size equal to 160 cm). This effect may be due again to the methodology used for the aggregation, but it shows that increasing the spatial resolution of the survey enables to add significant information, since this captures additional variability in snow depth. On the other hand, σ stabilizes when cell size is $\leq$1 m. The CV has similar dynamics. In the literature, it has been observed that snow depth variability increases with higher sampling resolutions (López Moreno et al., 2015), but, to our knowledge, few data-sets are available with a sub-meter horizontal sampling resolution (Nolan et al., 2015). Consequently, it is uneasy to compare this behavior with other analyses. These dynamics will be object of future investigations since, if confirmed, they may define a threshold for sampling resolution when measuring snow depth during the accumulation season (say, 1 m resolution).

The range of CV that we have found here is lower than those reported by, e.g., López Moreno et al. (2015), but seems in agreement with the results by López Moreno et al. (2011) for a survey performed during January. Snow depth spatial variability increases with time during the year (Ménard et al., 2014; López Moreno et al., 2015), due to local heterogeneity in ablation dynamics. It follows that a reduced CV at peak accumulation may be expected.

4.3.3 Test 3: U.A.S.-based volume of snow vs. spatial interpolation

Table 3 reports the comparison between the estimated snow volume using a set of simple interpolation techniques of the 12 snow depth probes and the estimation of snow volume operated by the U.A.S. system (5 cm resolution). Results show that the average difference between estimations by interpolation techniques and the snow volume estimated by the U.A.S. system is equal to $\sim 21\%$. In terms of absolute values, the average difference is $\sim$ 96350 m^3. Considering an average bulk snow density of 450 kg/m^3 (as measured in the snow pit), this would entail an absolute difference in SWE estimation of $\sim$ 43358 m^3.

A $\sim$ 21% difference provides interesting suggestions about the possible impact of U.A.S. for hydrologic applications, as interpolating points data has represented a widely used technique in snow hydrology for decades. In fact, such a high difference clarifies the benefits of using a distributed estimation of snow depth at high spatial resolution. However, the snow volume obtained by U.A.S. is affected by uncertainties and noise and must not be considered as the best estimate among those reported in Table 3. For example, all interpolation techniques return an underestimated volume of snow, but this is a case-specific result, that is due to the choice of probe positions. In fact, Figure 7 shows that manual measurements were accidentally taken in areas that were mainly characterized by shallow snow cover.

4.4 Using fixed wing U.A.S. for mapping snow depth: lessons learnt and outlook

U.A.S.s have interesting potentialities within the framework of available methods to reconstruct the spatial variability of snow surface. In fact, they enable to obtain semi-automated, quick and repeatable surveys of limited areas, with a quite high vertical precision. Although the device that we used here needs the operator to assist it during take-off operations, other devices (currently not available to the authors) can take off and land in a semi-automated way, and can cover much wider areas. This could let repeated (say, daily) surveys to be autonomously obtained, even without needing an operator to reach the target area. This, together with the possibility to substitute, or integrate, optical sensors with sensors at different wavelengths, could represent in the future an alternative to automated point stations to directly obtain distributed measurements of snow variables.

Results by Vander Jagt et al. (2015); Bühler et al. (2016) were obtained using multi-rotor systems. These devices have the clear advantage of a higher stability to strong winds. Moreover, they can take off and land along a vertical direction and this is advantageous in mountain areas. On the other hand, battery duration is restricted and this is a major drawback since maximizing areal extension is important when using U.A.S. in hydrologic applications given the extension (and spatial variability) of the processes investigated. This has been the main reason why we initially chose a fixed wing device. From an operational point of view, using fixed wing U.A.S. in Alpine areas means that the success of the survey is highly dependent on fair and stable weather conditions. This may cause frequent failures in surveys due to, e.g., unexpected changes in weather conditions. However, note that attempts have been already made to design supports that could be able to resist to harsh climatic conditions (Funaki et al., 2008), which would make unfeasible a survey using the same sensor used here. Other challenges include possible absence of satellites signal or reduced battery duration due to air temperature effects.

Future developments of this work should compare the performance of this technique during multi-year study cases in different snow conditions and using more extensive data sets of snow depth data for evaluation purposes. The main reason is that this test has been performed during just one day, and one location, in order to provide a preliminary assessment of the feasibility of using U.A.S.s to retrieve snow depth over a limited area. No evident limitation hampers the use of these devices over larger areas, apart from batteries duration, or within areas characterized by patchy snow cover conditions. On the other hand, different weather conditions (such as precipitation events, or scarce visibility), different snow cover conditions (such as shallow snow covers) and/or different topographic patterns could have an impact on the performance of these devices that must be still assessed. A shallow snow cover (say, snow depth lower than 20/30 cm) is likely to be difficult to be measured correctly given the standard deviation we found here (12.8 cm), whereas unexpected vegetation represents an important challenge and source of errors or ambiguity that must be carefully addressed in future investigations. This problem may be partially solved by using optical data to detect snow covered areas, only. An additional challenge is represented by moving glacier surfaces, that may hamper DSMs differentiation. Moreover, scarce visibility can potentially undermine a photogrammetry-based survey given the difficulties in detecting the ground (or snow) surface from an elevation of around 100 m during, e.g., fog events or intense rainfalls (or snowfalls). We suggest a multi-site multi-temporal framework like that performed by, e.g., Nolan et al. (2015) as a possible future development of this work. Similar analyses using U.A.S. are still lacking: an evidence is given by the sparse literature on this topic that is nowadays growing within cryospheric sciences (Lucieer et al., 2014; Vander Jagt et al., 2015; Bühler et al., 2016; Di Mauro et al., 2015; Fugazza et al., 2015; Ryan et al., 2015).

5 Conclusions

For the first time, we have here mapped snow depth variability at cm scale by means of a photogrammetry-based survey using fixed wing U.A.S. over a small Alpine area (~ 0.3 km^2). For this purpose, we performed two surveys. The first one, during September 2013, enabled to reconstruct ground topography. This survey will not be necessary for future assessments of snow distribution in the same area. Then, during April 2014, a second survey enabled to reconstruct the variability of snow depth, by vertical differentiation of the maps.

Results show that: 1) the orthophoto and DSM of autumn survey are in agreement with the topographic map available for the study area (standard deviation of the differences between these two DSMs is 1.63 m); 2) the average difference between manual and U.A.S. based measurements of snow depth (and the associated standard deviation) seems competitive with the typical precision of point measurements and other distributed techniques (the average difference obtained is equal to -7.3 cm, with an associated standard deviation of 12.8 cm). The overall RMSE is equal to 0.143 m; 3) the standard deviation (and CV) across the study area increases with decreasing spatial sampling distances, but stabilizes below 1 m resolution, thus suggesting the existence of a possible compromise between increasing spatial resolution of surveys and the amount of significant information obtained for hydrological applications.

Acknowledgements. The Authors want to thank A2A for the logistic support during the set up of the experiment. We would like to thank Mr. Riccardo Capetti and Mr. Amilcare Marchetti (A2A) for their assistance during field activities. We would like to thank the Editor, Prof. Philip Marsh, Prof. Steven R. Fassnacht, Dr. Davide Bavera and two anonymous referees for their feedbacks on the manuscript.

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Table 1: Comparison between manual (H_M) and U.A.S. ($H_{U.A.S.}$) snow depth measurements.

ID	H_M [m]	$H_{U.A.S.}$ [m]	$H_M - H_{U.A.S.}$ [m]	$H_{U.A.S.}/H_M$
1	1.48	1.40	0.08	94.6%
2	2.07	2.06	0.01	99.5%
3	1.75	1.96	-0.21	112%
4	1.88	2.05	-0.17	109%
5	1.68	1.93	-0.25	114%
6	1.85	2.13	-0.28	115%
7	1.96	2.03	-0.07	103%
8	2.11	2.17	-0.06	102%
9	1.91	1.96	-0.05	102%
10	1.89	1.81	0.08	95.7%
11	1.45	1.49	-0.04	102%
12	1.60	1.52	0.08	95.0%
Average difference [m]			-0.073	
St. dev. difference [m]			0.128	
RMSE [m]			0.143	

Table 2: Snow volume calculation using U.A.S. measurements and three different spatial resolutions: 5, 10, 20 cm.

Resolution [cm]	pixels [#]	$\bar{H}$ [m]	H_{max} [m]	H_{min} [m]	V [m^3]
5	81918743	2.26	4.21	-0.22	463652.3
10	20479686	2.26	4.35	-0.24	462957.8
20	5119921	2.27	4.15	-0.24	464093.0

Table 3: Comparison between the snow volume via U.A.S. $V_{U.A.S.} = 463652.3$ m^3 and the one obtained via spatialization techniques (V_T).

Technique	V_T [m^3]	$V_{U.A.S.} - V_T$ [m^3]
Arith.c mean	369146.3	94505.9
IDW	368216.9	95435.3
Thiessen	363400.5	100251.7
Kriging	368433.1	95219.2

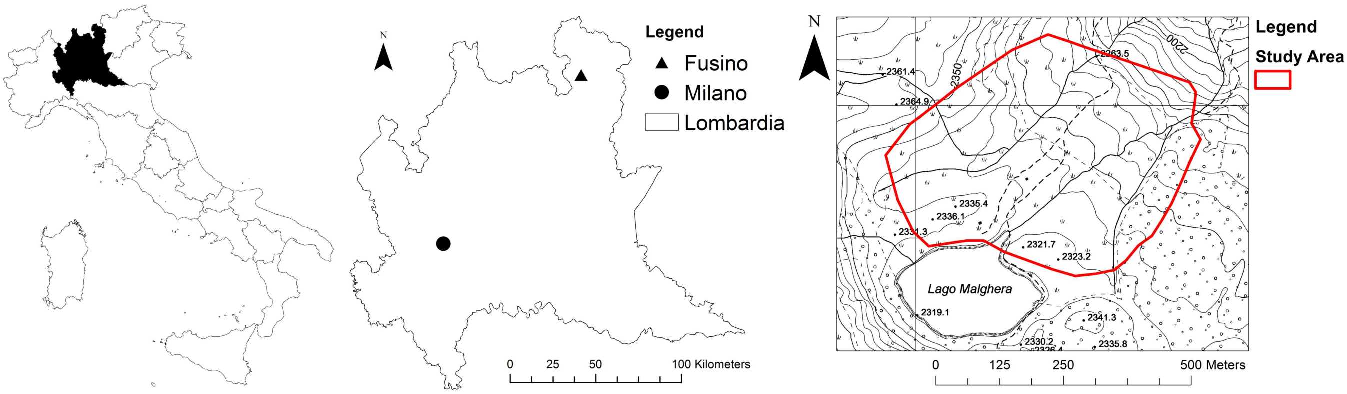

Figure 1: Location of the study area in western Val Grosina valley, Lombardia region, northern Italy. In the right panel, it is reported a topographic map of the area, with isolines every 10 m and the elevation (in m) of some points of interest. Topographic map from http://www.geoportale.regione.lombardia.it/

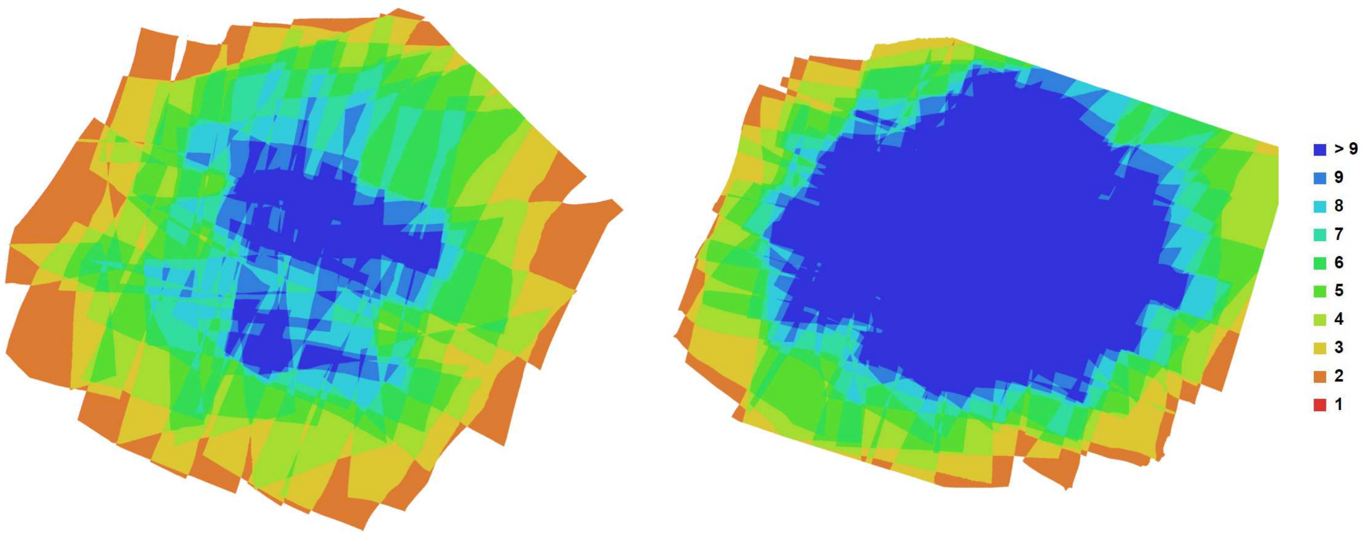

Figure 2: Camera images and their overlaps during each of the two surveys. The left panel refers to the survey made during September 2013, while the right panel regards the survey made in April 2014. The legend indicates the number of images covering each area.

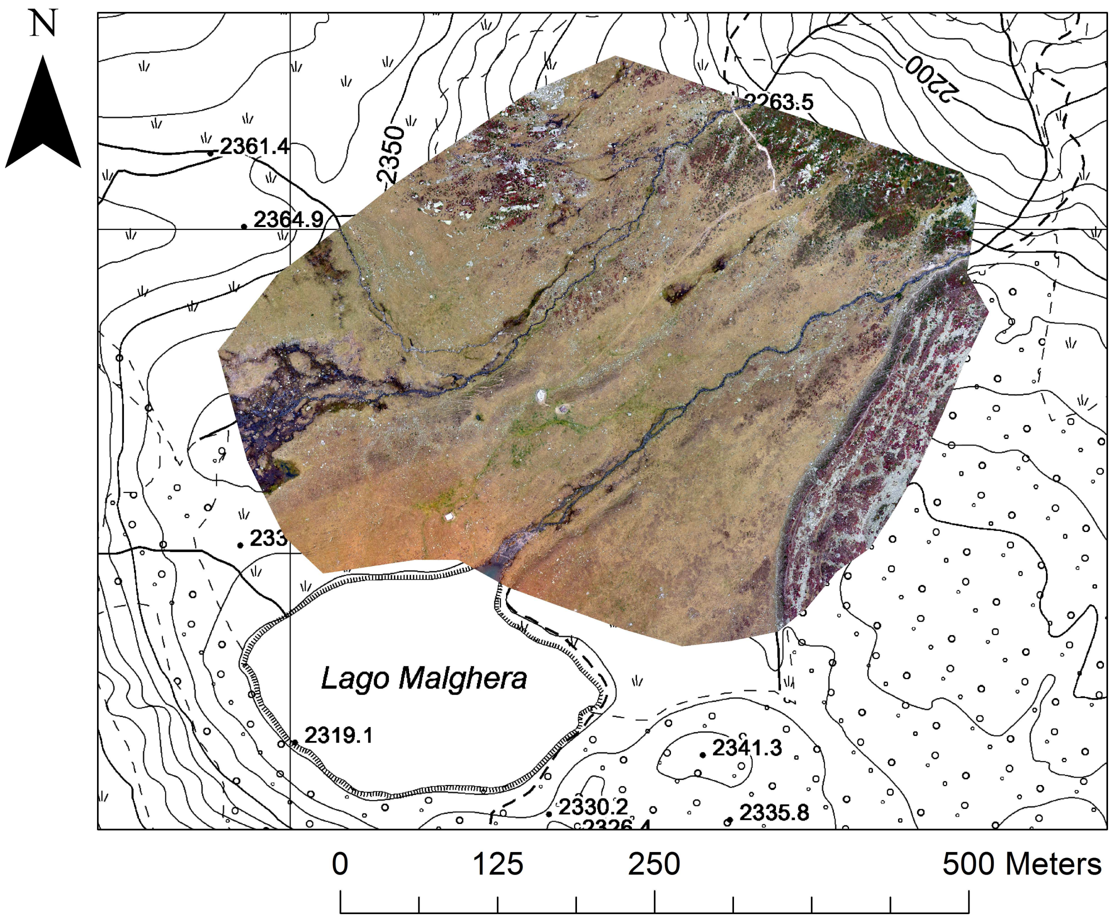

Figure 3: Orthophoto of the survey performed on 26th September 2013.

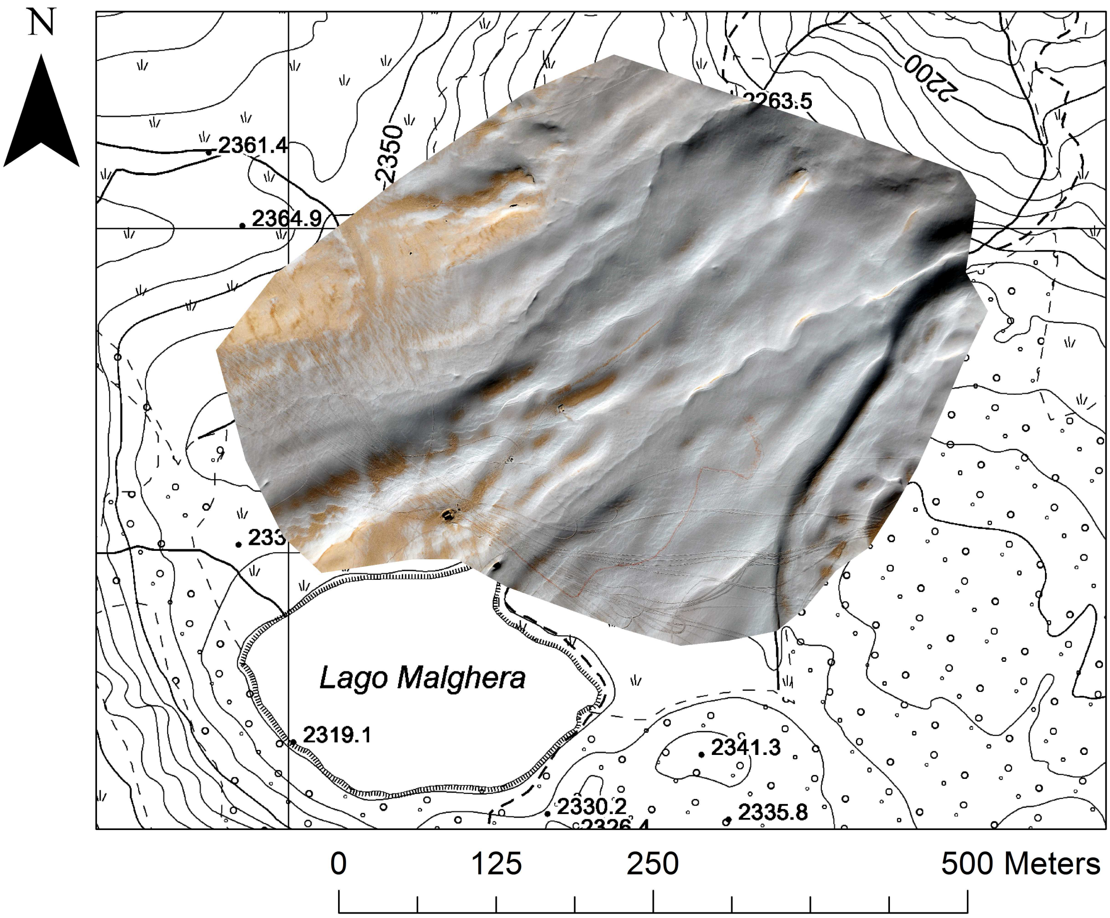

Figure 4: Orthophoto of the survey performed on 11th April 2014.

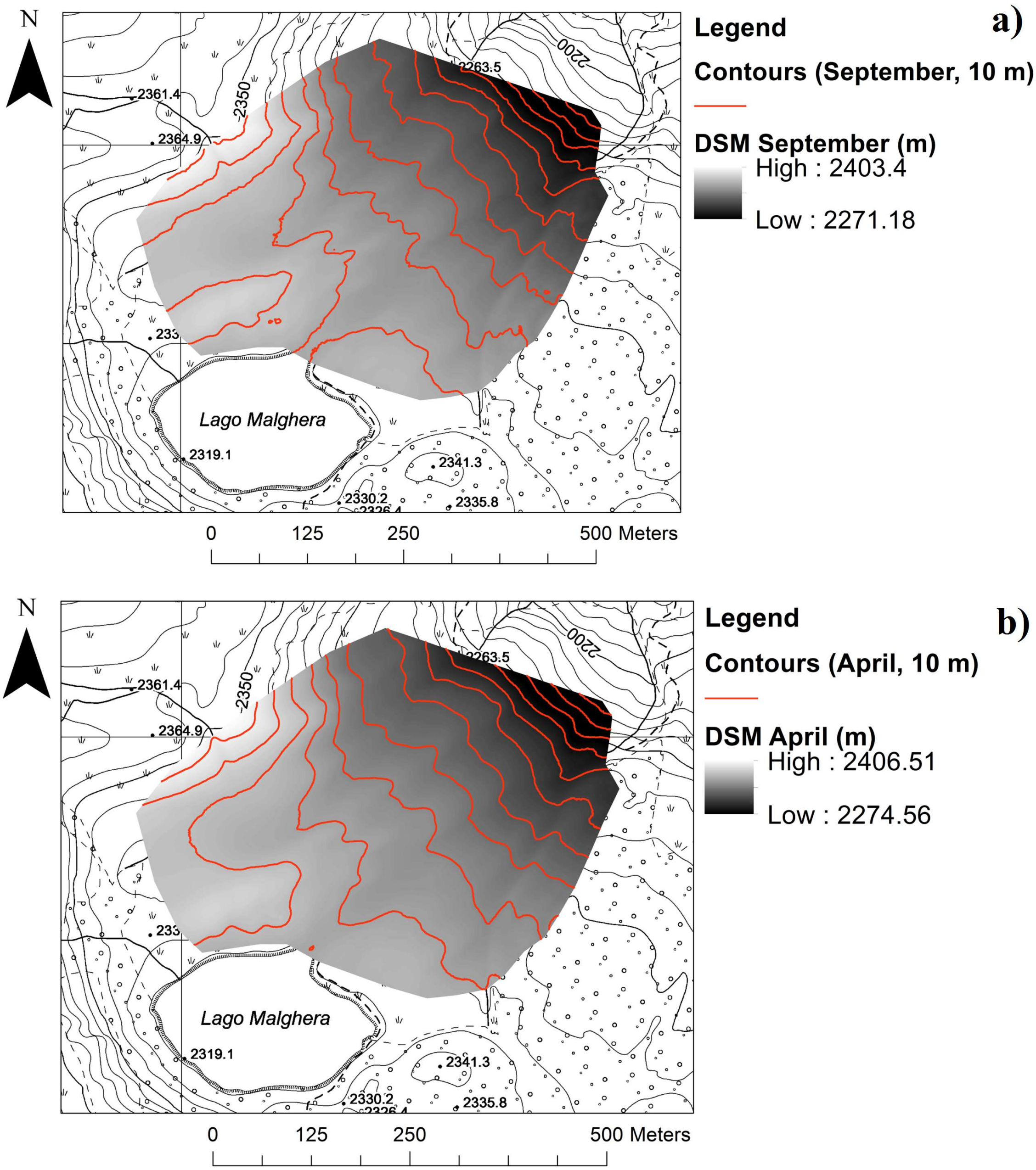

Figure 5: Digital surface model (DSM) of the two surveys. Panel a: DSM of the survey performed during September 2013. Panel b: DSM of the survey performed during April 2014. For both DSMs, a 5×5 cm^2 cell size has been used.

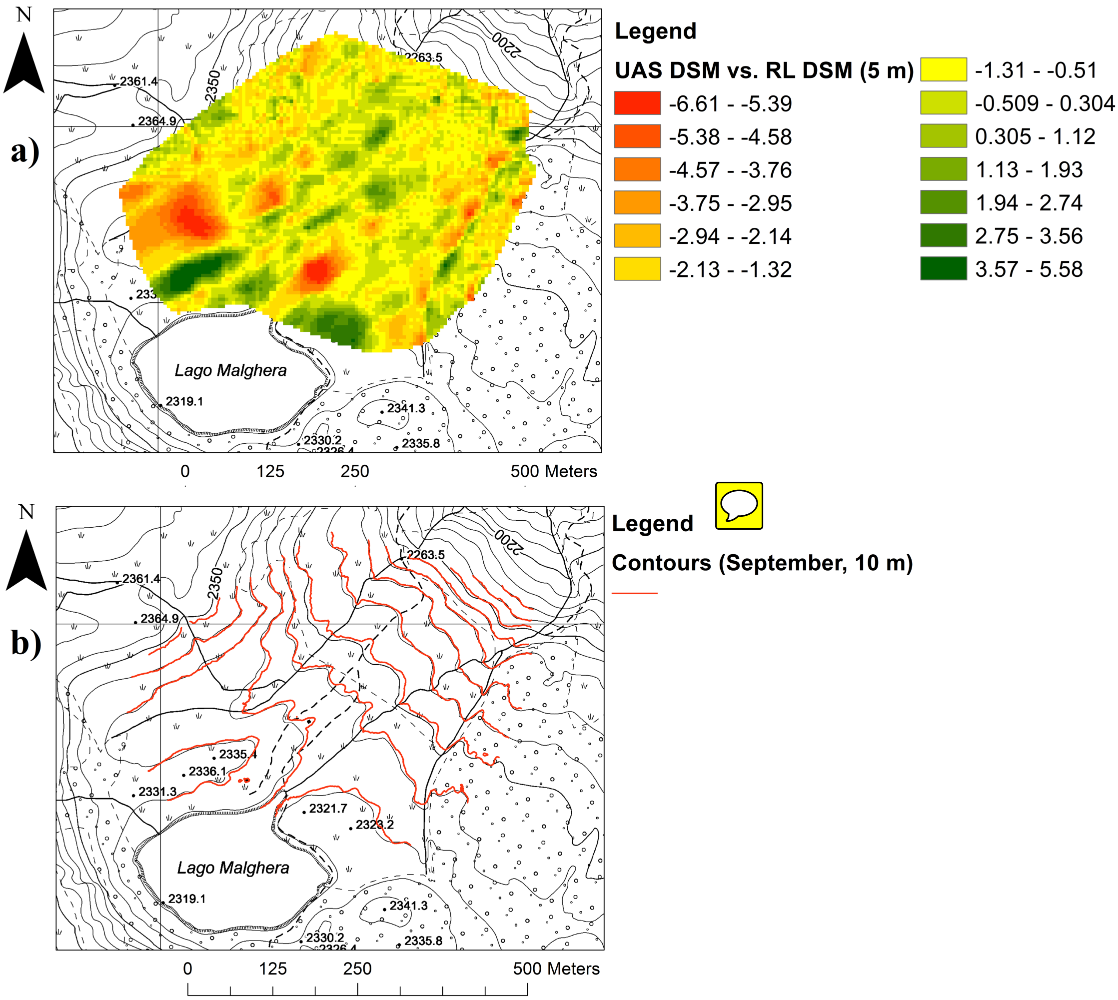

Figure 6: Validation of the DSM of bare soil (September 2013). Panel a: map of the differences between the U.A.S.-based DSM and an existing DSM provided by the Lombardia Regional Authority (5 m cell size). Panel b: comparison between U.A.S.-based contours (10 m, in red) and those reported in the topographic map of the area (in black).

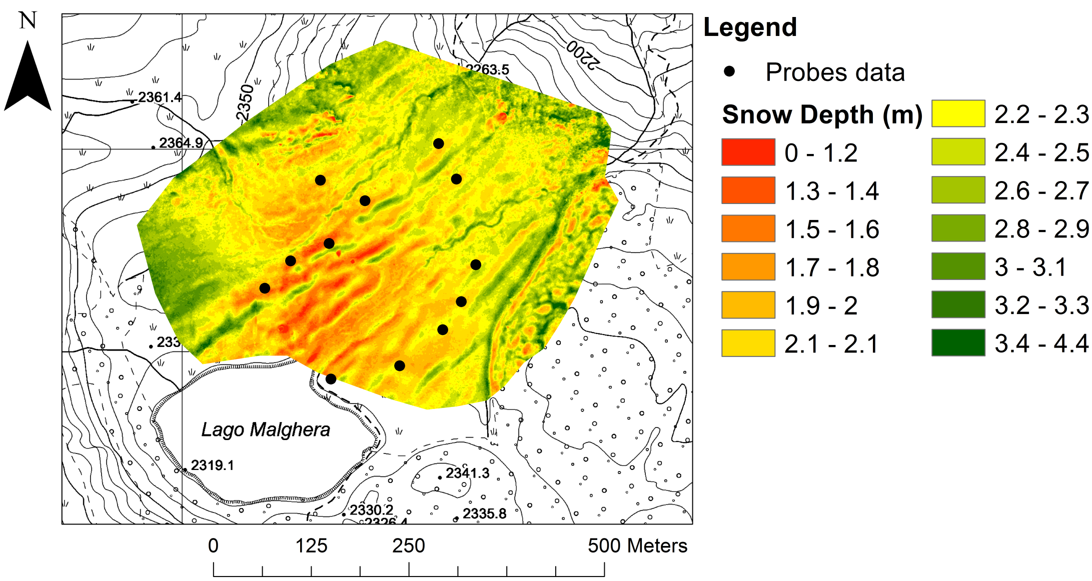

Figure 7: A map of snow depth distribution over the study area, obtained by means of difference of the elevations of the maps reported in Fig. 5 (5×5 cm^2 cell size). Different colors indicate different values of snow thickness (see the legend scale). Black dots indicate the location of the 12 manual measurements of snow depth.

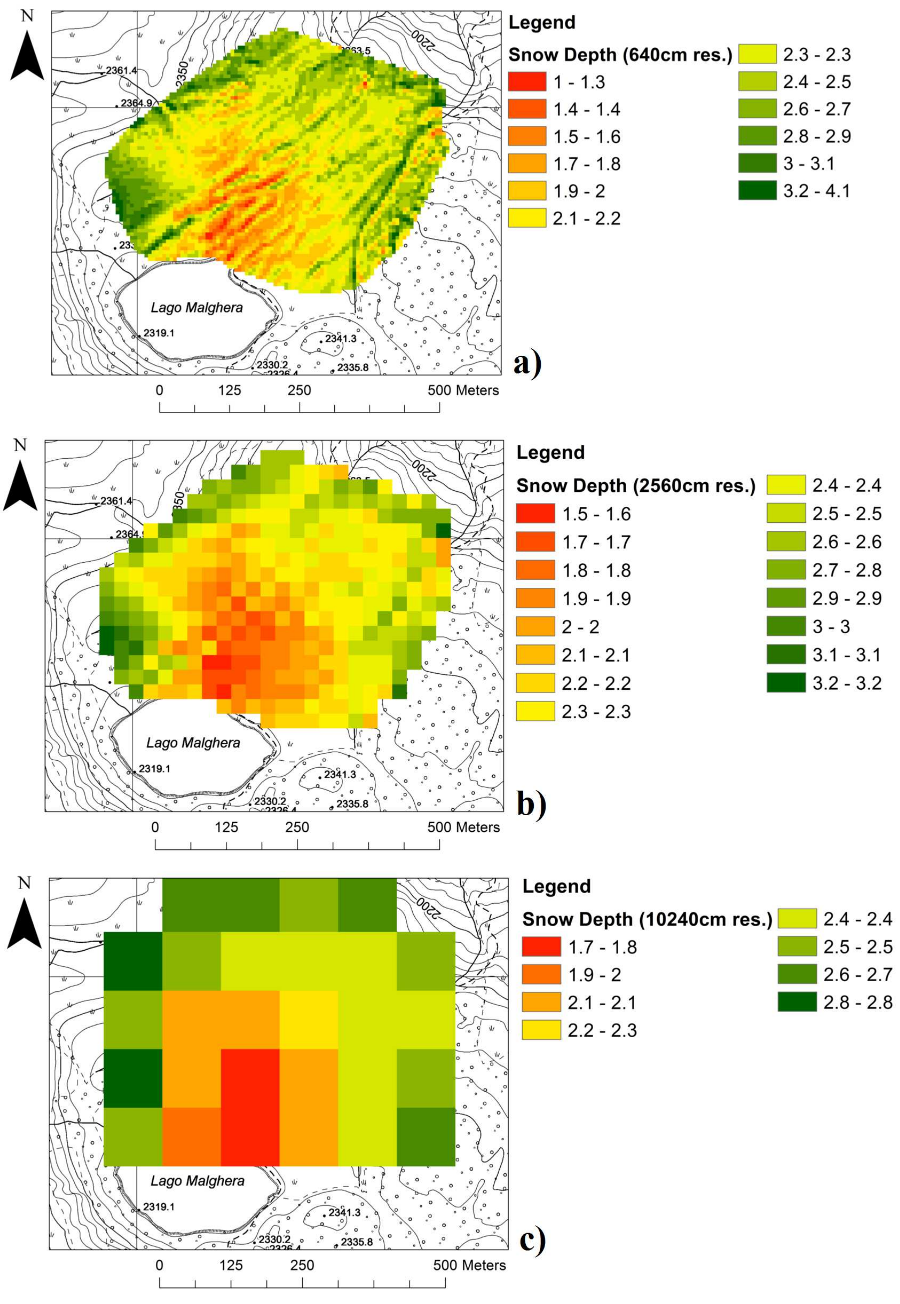

Figure 8: Rescaled maps of snow depth at different cell sizes. Panel a: 640 cm, panel b: 2560 cm, panel c: 10240 cm. See Section 4.3.2 for details.

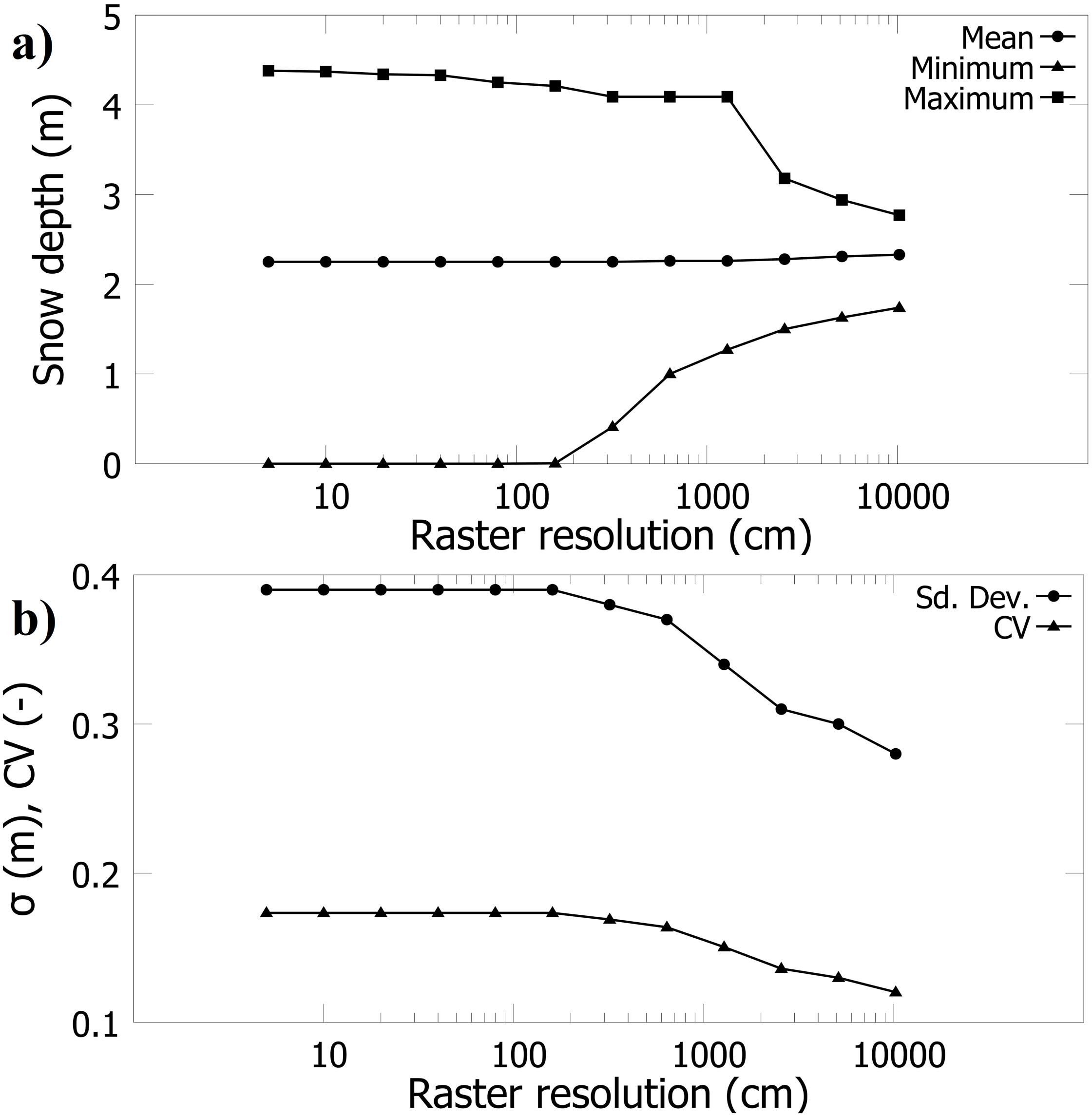

Figure 9: Snow depth statistics within the study domain as a function of map cell size. Panel (a) reports minimum, mean and maximum snow depth; panel (b) reports snow depth standard deviation (σ) and coefficient of variation (CV).