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Interactive comment on "Identification of blowing snow particles in images from a multi-angle snowflake camera" *by* Mathieu Schaer et al.

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Identification of blowing snow particles in images from a multi-angle snowflake camera

The Cryosphere #tc-2018-248

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Responses to reviewers

We would first like to apologize for the delay in preparing the revised version. We then thank the reviewers for their constructive comments which greatly helped improve the manuscript. In the present document, we provide our responses to the comments of the two reviewers. The comments of the reviewers are reported in *italic*, our responses in normal font and the corresponding modifications in the manuscript in blue. Page and line numbers referred to in our responses correspond to the version with changes highlighted.

Reviewer 1

General comments

1. *Section 4.1 describes the selection of features used in the classification. The au-thor use four categories of descriptors and mention in Sect. 4.1 which descriptor was finally kept within each category. However, the selection of the descriptors is only qualitatively described and only the final selection is given. The authors should better justify the choice of the descriptors based on quantitative results. Figures 5 and 6 could certainly help but they are never described in the text.*

   Section 4.1 describes how the features are selected using an objective quan-titative criterion, but we added text to better explain the approach and the information presented in Fig.5 (p.10, l.15-24):
   The marginal distributions of the selected descriptors for the training set are shown in Figure 6 to provide an idea of their respective magnitude and variability, as well as to illustrate their discrimination potential. As noted above, the image frequency is the most informative descriptor to distinguish blowing snow and precipitation.
   In summary, four descriptor categories (related to particle size, particle geometry and particle distribution within the image as well as image frequency) have been defined to distinguish images collected during blowing snow or snowfall, based on 20 the expected differences in particle size and concentration between the two. A number of descriptors were estimated from each image by computing various quantiles and moments of the distributions of geometric properties of the particles in the considered image. One descriptor from each of the four categories defined above (listed in Table 2) was then selected to be further used for classification as the one maximizing the "inter-clusters over intra-clusters"

distance defined in Eq. 1.

2. *It would be also interesting to associate the choice of the final descriptors with physical processes occurring during wind-driven snow transport. For example, the choice of the descriptors related to the size and shape of the particles can be associated with the fragmentation of particles (Comola et al. 2017). Comola, F., Kok, J. F., Gaume, J., Paterna, E., Lehning, M. (2017). Fragmentation of wind blown snow crystals. Geophysical Research Letters, 44(9), 4195-4203.*

We thanks the reviewer fro this suggestion, that we have added in the text in the beginning of Section 3.2 (p.7, l.27-29):
Because of the fragmentation of ice crystals when hitting the ground surface (e.g. Comola et al., 2017), blowing snow is expected to be characterized by much smaller particle size and much higher particle concentration than snowfall (e.g. Nishimura and Nemoto, 2005; Naaim-Bouvet et al., 2014).

3. *The authors are presenting the results of their method in Section 5. This section contains 1 table and 5 figures for a total of 9 lines of text. I understand that this paper is centered around the description and evaluation of the identification method but the authors should provide a more exhaustive description and discussion of the results that they decided to show to illustrate the use of their method. For example, Figure 11 is quite interesting and should be analyzed more in details by the authors. They could add on this figure the meteorological conditions (wind speed, precipitation) to better explain the transition from a precipitation event to a blowing event.*

We have revised and significantly extended Section 5 to provide more description

and analysis of the results presented in the various figures (see p.16-21).

4. *The same apply to Figure 12. Can the authors comment on the different particle size distribution? For blowing snow particles, how does it compare with particle size distribution measured with Snow Particle Counters (Sato et al., 1993)?*

   We have added a few paragraphs at the end of the new Section 5 to discuss the comparison between the size distribution obtained from MASC images and size distributions based on SPC reported in the literature (see p.20-21).

Specific comments

1. *P 2 L 9: present weather have also been used to monitor drifting and blowing snow near the surface (Bellot et al. , 2011).*
   Bellot, H., Trouvilliez, A., Naaim-Bouvet, F., Genthon, C., Gallée, H. (2011). Present weather-sensor tests for measuring drifting snow. Annals of Glaciology, 52(58), 176-184.

   We thank the reviewer for this relevant reference, that was added (p.2, l.10).

2. *P 2 L 18-20: Naaim Bouvet et al. (2014) developed a automatic method to estimate the occurrence of snowfall as well as snowfall amount during blowing snow events using measurements from photoelectric sensors. It could be interesting to mention this study in the introduction since it dealt with topics similar to the ones presented in this paper.*
   Naaim-Bouvet, F., Bellot, H., Nishimura, K., Genthon, C., Palerme, C., Guy-omarc'h,G., Vionnet, V. (2014). Detection of snowfall occurrence during blowing

snow events using photoelectric sensors. Cold Regions Science and Technology, 106, 11-21.

We thank the reviewer for this relevant reference, that was added (p.2, l.20 + p.7, l.29).

3. *P 4 L 4: the expression "exceptionally important" is rather unclear and the authors should provide typical values of the image frequency during blowing snow events.*

We modified the sentence to be more clear (p.5, l.5):
It was noticed that during strong blowing snow events, the number of images captured by the MASC was much larger than during precipitation events (more than 1 image per second, see Fig. 6).

4. *P 4 L 15-16: we can expect different properties (size, shape and complexity) for the fresh-wind blown snow particles coming from the edges of the DFIR compared to more classic blown snow particles that have been exposed to transport in saltation and turbulent suspension. Can the author comment about it?*

The new Figure 14 is similar to Figure 7 and presents the distributions of the four selected descriptors, for the entire Antarctic and Alpine data sets, distinguishing pure precipitation and pure blowing snow. These distributions illustrate the differences between blowing snow particles in the two data sets: they appear less fragmented (larger size and fractal index), less scattered within the images (larger distance transform) and with lower image frequencies in Davos than in Dumont d'Urville. This has been added in the text (p.18, l.13 - p.20, l.5):

C6

Considering the full Antarctic and Alpine data sets, it is interesting to analyze the potential differences in their characteristics. Figure 14 presents the distributions of the four descriptors as in Figure 6, but estimated from the entire data sets and not only the training sets. It can be seen that while the differences are limited for precipitation (slightly more frequent and larger in Davos than in Dumont d'Urville), they are significant for blowing snow: the blowing snow particles appear less fragmented (larger size and fractal index), less scattered within the images (larger distance transform) and with lower image frequencies in Davos. It should be recalled that the MASC was located in a wind-protecting fence in Davos, so first the occurrence of blowing snow is much smaller (0.6 vs 36.5%), and second it is likely related to fresh snow blown away from the top of the nearby fence.

5. *In addition, the authors should comment on the potential deposition of blowing snow particles from the surrounding crests. Is it something that can be observed at the experimental site above Davos?*

We discussed with colleagues involved in field measurements at the Davos location, and it is not clear if blowing snow particles from the surroundings could deposit or not into the MASC. So unfortunately, we cannot provide a reliable answer to this question.

6. *P 6 L3-7: The beginning of Section 3.1 contains a brief description of the MASC. Other technical details are provided at different places in Sections 1, 2 and 3. I recommend the author to create in Section 2 a sub-section dedicated to the presentation of the MASC and summarizing the main characteristics of the instrument. In this subsection, it would be interesting to add more details regarding the MASC image frequency since it is used by the authors in their*

image classification method. What is the maximal frequency of the instrument? How does in depend on the particle concentration? To my knowledge, it is the first time the MASC is used to characterize blowing snow particles.

A new sub-section (2.1) describing the MASC has been added (p.3-4).

7. *It would be interesting if the authors can briefly compare the characteristics of the MASC and the Japanese Snow Particle Counters (SPC) (Sato et al., 1993) in terms of particle characterizations. The SPC can be currently considered as the reference device for blowing snow measurements (fluxes and particle size distribution).*
Sato, T., Kimura, T., Ishimaru, T., Maruyama, T. (1993). Field test of a new snow-particle counter (SPC) system. Annals of Glaciology, 18, 149-154.

See response above.

8. *P 6 L 31-33: The authors computed quantiles and moments of the distribution of the considered feature. What are the typical numbers of particles on an image in the different situations: blowing snow, precipitation, and mixed situation?*

The number of particles on an image is not a descriptor that has been selected for the classification, so it was not analyzed. We can however mention that:

- For precipitation: from 1 particle (ideal case) to several (maybe 10) in case of high intensity snow.
- For blowing snow: from several to one hundred.
- For mixed case: no typical values.

C8

9. *P 9 L 11: the authors use the term "soft clustering" and the term "hard clustering" at P 10 L 24. These 2 terms can be indirectly understood when reading the text but I recommend the other to include in the text one or two sentences that clearly define these 2 terms.*

We have specified the meaning of these two terms (p.11, l.14 and p.12, l.22).

10. *P 10 L 9: it is not clear why the authors decided to remove exactly 80 data points (images?) from the training dataset.*

We removed 80 points to have exactly balanced classes in the training set, as explained on p.12, l.5-9.

11. *P 13 L 9-10: How do the authors justify the choice of having 10%*

The choice of the quantiles 10 and 90% is indeed somehow arbitrary. This means that we assume about 10% of images not corresponding to pure precipitation or blowing snow, which appears reasonable from the bottom plot of Figure 9. It should also be noted that this threshold can be adapted to the user's need/objective. This is now mentioned in the text (p.15, l.17-19):
This value is qualitatively supported by the distribution shown in Figure 9. It can be changed by the user to be more (increasing it) or less (decreasing it) strict on the classification as pure blowing snow or pure precipitation, depending on the intended application.

12. *P 13 L 15-17: The authors computed an index of mixing for each image as well as an index average among the 3 images with a given time identifier. Can the*

authors comment on the variability of the value of the index among the 3 images for a given time? Is their classification methods providing consistent results among the 3 cameras for a given time? What are the reasons for the potential differences between the images?

As mentioned on p.15, l.26-27, the values of the normalized angle from the three views can be averaged to characterize a given triplet with a single normalized angle value (used in Figure 13 for instance). In addition, we computed the range (defined as max - min) for each triplet and it appeared limited (median of about 0.08 in Davos and 0.05 in Dumont d'Urville). This was added in the text (p.15, l.27-29):
The median of the range (max - min) covered by the ψ values from the three individual views is about 0.08 in Davos and 0.05 at Dumont d'Urville, indicating a limited variability between the three views.

13. *P 13 Table 3: as mentioned later in the text (P 15 L 12-13), it would be really relevant for the reader to provide as well the percentages expressed in terms of time. The percentage in terms of images are difficult to interpret since they depends on the image frequency that changes with time.*

As the MASC is not regularly sampling in time (falling particles trigger the instrument), there is no direct link between the percentage of images and the percentage of time.

Technical comments

1. *P 2 L11: the references should be written (Palm et al, 2011) and (Gossart et al., 2017)*

Done.

2. *P 10 L 4: the signification of the variables used in Eq 2 should be given in the text.*

Thanks for spotting the issue, we have added the definition of the variables and also moved equation 2 earlier the text (p.11, l.5-7).

3. *Figure 2: it would be interesting to show the period selected as blowing snow and precipitation on the upper graph of Fig. 2 Maybe add lines showing the median values of wind speed and MASC image frequency that were used to identify the different events.*

Figure 2 is now Figure 3. In the top plot of Figure 3, we indicated the days (as individual time steps would not have been visible) during which the blowing snow and precipitation images were selected. We also used different markers for blowing snow and precipitation point sin the bottom plots.

4. *Figure 2: please indicate at which height above the surface the wind speed is taken.*

The anemometer at Dumont d'Urville was at 10 m above the ground. This is now mentioned in the caption of Figure 3.

5. *Figure 3: it is very difficult to identify the blowing snow particles due their size. Could the author insert a zoom over a specific region of the image containing*

blowing snow particles? It would be also useful to include a scale on the images to allow the reader to better estimate the size of particles.

Figure 3 is now Figure 4. We have changed the last panel to improve the visibility of the particles in the MASC images. The dimension of the image in pixel and size was been added in the caption.

6. *Figure 4: a scale would be also useful on the images.*

See previous item.

7. *Figure 7: the labels and legends on the graphs are hard to read and should be made larger.*

Figure 7 is now Figure 8. We are sorry for this, the labels and legend font size has been increased.

8. *Figure 12: mention from which field campaign are taken these data.*

Figure 12 is now Figure 15. The data were taken from both locations, as now indicated in the caption.

9. *Figure B1: It would be interesting to better highlight on the binary image the artifacts*

As this figure is in an appendix, we decided to focus on the consistency in the color scheme to better illustrate the different steps of the processing on MASC images.

Reviewer 2

1. *Perhaps it is not crucial, but I am a bit anxious that advanced knowledge of statistics are required to follow the whole contents of this manuscript. In fact, classification procedures are explained considerably careful and I have also learned a bit with the textbook. However, it was still far from satisfactory to follow all of them. They are highly professional and large number of technical terms appears. I appreciate very much if the authors kindly consider the readers who are not so familiar with statistics.*

   We have added text in Section 3.2 and Section 4 to better describe and explain the approach for readers who are not experts in classification and machine learning.

2. *Probably it is a good idea to add following two references, such as in the introduction part. Naaim-Bouvet, F. et al., Detection of snowfall occurrence during blowing snow events using photoelectric sensors, CRST, 106, 11-22, 2014. Nishimura, K., and Nemoto, M., Blowing snow at Mizuho station, Antarctica, Philosophical Transactions of the Royal Soc. of London, A, 363 1647-1662, 2005. The former tried to measure the snowfall amount under the blowing snow condition and the latter showed the snow particle size distribution with SPC and mentions the possibility to detect snowfall.*

   We thank the reviewer for these relevant references, that were added (p.2, l.19-20).

3. *Page 2, Line 6: "The present study focuses on ... more than 2m above ground."*

This means when the measurements height is getting lower or much higher, new criteria for classification should be set at each time?

As indicated in the conclusion (p.23, l.12-15), there is no guaranty that the fitted GMM (and subsequent classification) is fully relevant for MASC images collected in a potentially very different population of blowing snow particles. We therefore recommend to retrain the algorithm if this is the case.

4. *Page 2, Line 22: I wonder the resolution of 33.5 μm is enough to detect the small particles? It is well known that as the position is getting higher, smaller particles will be dominant in the blowing snow. Although the minimum bin in Figure 12 looks 100 μm, measurement in Antarctica indicates diameter less than 100 μm shows the maximum even at the height of 10 cm (Nishimura, K., and Nemoto, M.: 2005).*

We agree with the reviewer that the MASC resolution (and the image processing) result in the fact that the small blowing snow particles cannot be seen by the MASC. We however think that it is still relevant to be able to distinguish blowing snow and precipitation images at a high temporal resolution. Text has been added at the end of Section 5 to compare size distributions derived from MASC and from SPC (p.19-22).

5. *Page 2, Line 34: I am a bit anxious whether manually-built validation set is satisfactory accurate. Possible error included should be also discussed.*

AS in many applications, the reference data set cannot be totally free of any error. But we did our best to be strict in the manual identification, and this type of

manual classification is a standard approach in machine learning. We added a specific mention of this possible remaining uncertainty in the text (p.5, l.21).

6. *Page 3, Line 13: Same questions listed above. Subsets of pure precipitation and pure blowing snow images were manually selected. I appreciate the authors' efforts very much, but is it perfect?*

   See previous.

7. *Figure 1: Not only the pictures but also a schematic picture of MASC which shows the basic will be helpful.*

   A subsection presenting the MASC was added (Section 2.1, p.3-4).

8. *Page 4, Line 5: Explanations about the MASC should be done before "2. Data sets". Particularly, it should be mentioned here that images are captured when the motion of particles are detected in the field of vision. Otherwise, readers are not able to recognize the meaning of "MASC image frequency" and the importance as one of the descriptors.*

   See previous item.

9. *Figure 3: I don't understand what do you mean by this figure, probably because I did not follow the procedure precisely. Yellow points shown in "Raw image" and "Median filter" do not corresponds to the blowing snow particles? Then, no particles are shown in the "Binary image"; that is blowing snow particles disappear in the final image. Is this correct? On the other hand, precipitation*

particles remain in the final image as shown in Figure 4?

We are sorry that the figures were not well readable. We have updated these figures (now Figure 4 and 5) to improve the contrast and make the identified (blowing sow or precipitation) particles more visible.

10. *Figure 4: This figure looks similar to Figure B1. Are there any different meanings? Figure caption of B1 is much clearer than the one of Figure 4. Same explanation should be done in Figure 4 as well.*

Figure B1 illustrates a case for which the median filter is not able to remove all background features because of fast changing background conditions, justifying the use of an additional filtering to obtain the final binary image.

11. *Page 10, Equation (2): Notations of D, T and μ(?) should be defined. I suppose μ(?) is not the same as the one in equation (1). Please note that some of the symbol are not readable in the review.*

Thanks for spotting the issue, we have added the definition of the variables and also moved equation 2 earlier the text (p.11, l.5-7).

12. *Figures 5, 6, 7, 8, 9 and 12; Please make the label of both axes much lager and clearly. It is hard to recognize what is specified respectively.*

We have increased the font size for labels and legends in the different figures.

13. *Page 13, line 20: Perhaps "850'000" should be expressed as "8.5x10^4".*

Done.

14. *Page 13, line 24: Similar particle size distributions are found Nishimura and Nemoto (2005) as well. However, the measurements with SPC revealed that the population of smaller particles than 100 μm shows the maximum.*

We have added text at the end of Section 5 about the comparison with SPC measurements from the literature (p.19-22).

15. *Page 13, line 18; In accordance with the procedures newly introduced in this manuscript, MASC images are classified and results are shown in Figures 9 and 10, and Table 3. Are they reasonable and are there any specific features derived with this analysis? Have you got any new findings? In other words, what sort of contributions you could achieve to the geophysical and cryospherical research field? Or, you would like to remain in just the introduction of the methodology?*

The primary goal of this manuscript is to introduce the proposed methodology to derive information about blowing snow from the MASC. We provide illustration from two contrasted data sets (Alps vs Antarctica) in order to evaluate if the outcome makes sense (and it does!). We also compare the obtained statistics on blowing-snow particle size to reference information from the literature to illustrated the limitations of the proposed approach, mainly related to the too-coarse resolution of the MASC to fully capture the entire size range of blowing snow. This is now clearly mentioned in the text (end of Section 5 and 6).

16. *Figures 6 and 8: No explanations were found in the text. Further, in general, descriptions about the figure are rather brief both in figure captions and text. More detailed explanation is recommended, that will be help to deepen the understandings.*

We have added text in Sections 4 and 5 to better describe these figures and their analyses.