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Atmospheric Measurement Techniques Discussions

Interactive comment on "Numerical simulations and Arctic observations of surface wind effects on Multi-Angle Snowflake Camera measurements" *by* Kyle E. Fitch et al.

Kyle E. Fitch et al.

kyle.fitch@utah.edu

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The manuscript investigates the aerodynamic impact of the particles' fall speed measured by a Multi-Angle Snowflake Camera (MASC) using field measurements and Computational Fluid Dynamics (CFD) simulations. It compares the fall speed PDF measured by the MASC and the K-band radar located at the same site. The distribution of fall speed differs from the two instruments and the numerical simulations suggested that the fall speed measured in strong winds ($>$ 5 m/s) would record slower falling particles when not shielded. Similar results were found using the simulations. Overall, this study helps to improve the quality control

procedure of the MASC data and contributes significantly to the field of snowfall measurement. It fits well in this journal as it improves the methodology to be used to quality control MASC data. The manuscript is very well written and clear. The figures are also clear and well described in the caption. I have, however, a few main and minor comments should be considered before publication.

Main comments

1. The manuscript gives the impression that the main point is the CFD simulations where it would have been used to study the collection efficiency or to develop transfer function to adjust the MASC measurements. After reading the manuscript, the CFD simulations are used only to explain the field measurements. Given that, I think that the authors should add a methodology section after the introduction that explains the approach taken in this study, which includes the field measurements and the simulations. It may also be useful to present the measurements before showing the results from the simulations.

We agree and have decided to present observations first in addition to changing the title to "Arctic observations and numerical simulations of surface wind effects on Multi-Angle Snowflake Camera measurements" to make it more clear that simulations are supporting the observations and not the other way around.

2. More details should be given about the simulations conducted such as, for example, the number and shape of the mesh used.

We have modified the description as follows:

"The *snappyHexMesh* tool requires an existing base mesh to work with, which is generated from *blockMesh* and is represented in Table 2. For *snappyHexMesh*, two of the most important parameters are *nCellsBetweenLevels*, set to 3, and the *refinementSurfaces* level, which is set to a minimum of 4 and maximum of 5. This brings the total number of cells to 131,864 when the block is 4 m $\times$ 4 m $\times$ 5 m. These values were determined through analysis of grid independence. For *blockMesh*, the resolution of 25 cm $\times$ 25 cm $\times$ 25 cm provided the most efficient mesh for a fixed *snappyHexMesh*. The *snappyHexMesh* parameters were also determined through testing; lower values (e.g., *nCellsBetweenLevels* < 3 or *refinementSurfaces* level < 4) rendered the mesh too coarse to capture the interaction between particles and flow inside of the aperture, while larger values come at a much higher computational cost."

Did you use the integrated trajectory simulations or developed one?

We have clarified by adding the following sentence to the description of CFD simulations:

"The integrated, semi-developed *solidParticleFoam* is used to simulate particle trajectories, with gravity included to supplement the developed simulation."

Could you add a figure that includes examples of particles' trajectories?

We have added this to the CFD simulations section. Attached is a preview for a flow of $1\,\mathrm{m\,s^{-1}}$.

In Table 2, only one size of particle was used. For dry snow and aggregates, the fall speed does not change much with diameter according to Rasmussen et al. (1999). However, the fall speed of rimed particles can vary a lot with sizes. Why not use more particles' sizes? What would be the impact on your results? Why did you choose a diameter of 2 mm and not 1 mm?

We have added the following to the conclusions section:

"Here we used only a single set of particles with simple, yet representative characteristics to support observations analysis with simulated particle responses to MASC-perturbed flow. Future work could include a much more diverse set of particle shapes, sizes, and densities."

Please also describe in more details the simulations. For example, is there an

updraft as found in previous studies (ex: Colli et al. 2016a,b; Theriault et al. 2012) for the Geonor (shielded and not)? How do you explain that slower falling snowflakes fall is detected by the MASC in stronger winds? Add any other details that could help better understanding the results from the simulations.

We have modified and added the following statements to the CFD simulations text describing the simulated flow perturbed by the MASC as shown in Fig. 2 (which is now Fig. 12 in the revised manuscript):

"There is a clear separation of flow at the upstream side of the aperture, a relatively large upward component above the aperture at the upstream side, and a smaller downward component within the aperture. The fall speeds of particles carried into the aperture by the prevailing flow are decreased by this upward component of the flow, which increases with increasing wind speeds."

3. The simulation as well as the measurement shows that an unshielded MASC leads to a decrease of the fall speed. Can you add a brief explanation in the manuscript? It seems counter-intuitive as faster falling particles would tend to fall in the gauge in stronger winds.

In addition to the above statements added to the CFD simulations section, we have also added the following sentence to the conclusions:

"The simulations revealed that an upward component of perturbed flow at the upstream side of the MASC aperture increases in magnitude with increased wind speeds, and that this leads to decreasing mean particle fall speeds with increased horizontal wind speeds."

4. At lower wind speed, larger aggregates tend to be more detected by the MASC than at higher wind speeds. In theory larger ones would fall faster and would not be deflected. How do you explain this finding? Could it be because larger aggregates in strong winds would breakup? Or is it common to report large ag-

gregates in windy conditions at that site? Did you compare with the climatology of solid precipitation at that location?

We have added the following to the discussion section (note that Figs. 8 & 6 and Table 1 correspond to Figs. 12 & 10 and Table 3 in the original manuscript, respectively):

"Larger aggregates with negligible riming tend to be more susceptible than smaller, more dense particles to disturbance by surface winds and associated turbulence, with a tendency for a more vertical orientation (Fig. 8), slower fall speeds (Fig. 6), and lower frequency of occurrence with higher wind speeds (Table 1) than other riming classes. The Stokes number is defined as the dimensionless ratio of the particle relaxation time to its terminal velocity in still air v_t/g, and a characteristic time of isotropic, homogeneous turbulent flow. Snowflakes with low Stokes numbers tend to follow the flow, becoming trapped in the vortices with the orientation aligning with the local velocity gradient (Voth & Soldati, 2017). The implication is that large, low-density, aggregate-type hydrometeors with relatively small values of v_t compared to more heavily rimed particles have low values of the Stokes number and are more likely to follow the motions of any turbulent flow induced by the MASC aperture. This finding is consistent with prior work by Theriault et al. (2012) who showed that for a Geonor gauge inside a single Alter shield, higher-density, faster-falling hydrometeors are collected most efficiently."

Voth, G. A., & Soldati, A. (2017). Anisotropic particles in turbulence. Annual Review of Fluid Mechanics, 49, 249-276. https://doi.org/10.1146/annurev-fluid-010816-060135

Some minor comments:

1. Lines 5-7: This sentence mentions that the simulations are compared with observations. However, I understood that in this study that the catch efficiency of the instruments is not computed from the simulations and compared with the measured one. But the simulations are used to explain the decrease in fall speed measured in strong winds. This is related to major comment #1. It should be rephrased for clarity.

This has been reworded to state, "Here we present analysis of Arctic field observations with and without a Belfort double Alter shield and compare the results to computational fluid dynamics (CFD) simulations of the airflow and corresponding particle trajectories around the unshielded MASC."

2. Lines 45: Newman et al. (2009) also conducted CFD simulations in the vicinity of a snowflake video imager. Should probably add the paper to this paragraph. Newman, A. J., P. A. Kucera, and L. F. Bliven, 2009: Presenting the Snowflake Video Imager (SVI). J. Atmos. Oceanic Technol., 26, 167–179, https://doi.org/10.1175/2008JTECHA1148.1.

Added to the end of that paragraph: "CFD simulations were also analyzed for wind flow along the optical axis of a snowflake video imager, with eddies dissipating approximately 1 m downstream of the camera housing and only minor modifications to the wind field (Newman et al., 2009)."

3. Figures 7, 9, 11 and 13: Those figures compare data taken with an unshielded and a shielded MASC. Please clarify in the caption that the shielded and unshielded data were collected during two different periods.

Added to each of those figures' captions: "Unshielded and shielded MASC observations are from two separate periods: 29 November 2015 to 21 August 2016 and 22 August 2016 to 28 August 2018, respectively."

4. Lines 185: Usfc is defined. Could you explain it further and how it compares with standard measurements of wind speed at the instrument's height (or at 10 m)? I may have missed the explanation in the text.

We added the following clarifying sentence to the methods section: "The wind measurement is taken at a standard height of 10 m, which is estimated to be 5(9) m higher than the unshielded(shielded) MASC shown in Fig. 1(2)," where Figs. 1 & 2 correspond to Figs. 5 & 6 in the original manuscript.

5. Lines 189-194: The authors forgot to introduce figure 10. Only Figure 10c is referred to.

We have modified this sentence that begins on line 192 in the original manuscript: "When separated by riming class (Fig. 6), shielded MASC fall speed distributions show discernible differences only for the lightest winds," where Fig. 6 corresponds to Fig. 10 in the original manuscript.

6. Lines 200-201: Please clarify that sentence. I don't understand what you mean by 'more vertical'?

We have clarified the meaning in the sentence as follows:

". . .shielded MASC orientation angles tend to be larger for sparsely-rimed aggregates (Fig. 12), meaning their major axes are less frequently oriented within the horizontal plane."

7. Lines 224-229: For clarity, the authors could remind the reader that larger aggregates fall slower than the rimed particles as in Figure 10. We have modified the sentence as follows:

"Larger aggregates with negligible riming tend to be more susceptible than smaller, more dense particles to disturbance by surface winds and associated turbulence, with a tendency for a more vertical orientation (Fig. 8), slower fall speeds (Fig. 6), and lower frequency of occurrence with higher wind speeds (Table 1) than other riming classes."

Where Figs. 6 & 8 and Table 1 correspond to Figs. 10 & 12 and Table 3 in the original manuscript, respectively.

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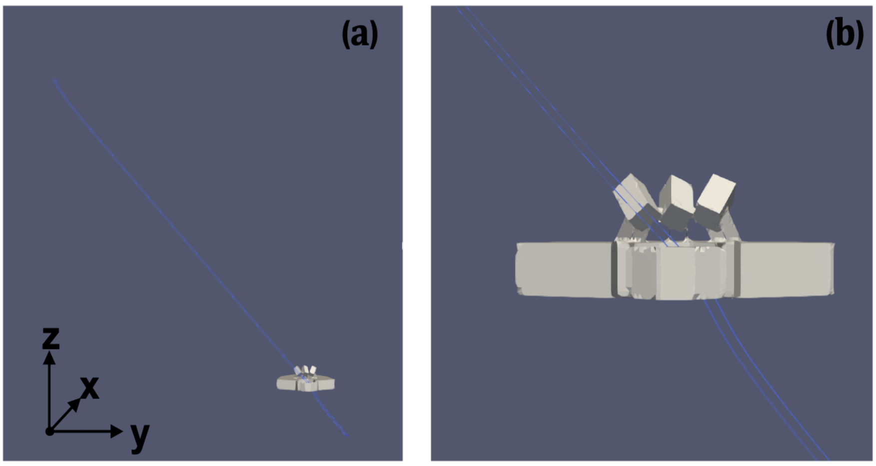

Fig. 1. Simulated particle trajectories for wind speed of 1 m sˆ-1