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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.

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The subject of the well written and structured paper is well within the scope of AMT as it provides new tools and data for the correct use of an (already established) instrument for snowflake measurements called "Multi-Angle Snowflake Camera" (MASC). For this purpose, the authors use a combination of numerical simulations based on an Euler-Lagrange approach and field based measurements. The main findings are guidelines for the correct usage of the above mentioned MASC, which I consider a substantial contribution to further investigations of snowfall measurements. Event though the article is quite good in my

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opinion and I would not argue with the main findings, I have some remarks. (Disclaimer: Please note that I am not an expert in precipitation measurement and my expertise mainly is in fluid and particle dynamics and the simulation thereof. So if there are points regarding especially the meteorological topics that I did not get right, please do not hesitate to object/improve.)

Major remarks:

1) The description of the CFD simulation setup should be a bit more detailed: What is the total number of cells? (Table 1 seems to give a wrong information about this, as the cells would be much larger as they seem in Figures 1(c)-1(e)) Have there been any examinations on grid independency?

We have added more details to the description as follows (note Table 2 corresponds to Table 1 in the original manuscript, while Figure 11 corresponds to Figure 1):

"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."

Please specify the boundary conditions.

We have added the following specifications to the simulation description:

"The boundary conditions for velocity are a flat velocity profile at the inlet; slip conditions at top, bottom, front, back and outlet surfaces; and a no-slip condition at the object (MASC). Zero gradient pressure fields are applied at all boundaries."

Please justify why potentially important forces acting on particles in turbulent/shear flows are neglected (lift force, pressure gradient force)

We have rearranged the sections and wording in the title (as suggested by Reviewer #2) to reflect that the observations analysis is the featured part of our work, and that the relatively simple simulations serve only a supporting role. We have added the following to the conclusions section:

"Relatively simple simulations were carried out here to support the findings of the observations analysis. We used only a single set of particles with limited, 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, as well as other forces that have been neglected in this work and a turbulent dispersion model."

Where are the starting positions of the particles? (could be included e.g. in one of the figures 1(c)-1(e))

We have expanded the description of initial positions in the text as follows:

"The particles fall downward at an initial velocity of $1\,\mathrm{m\,s^{-1}}$ from an initial height of $3\,\mathrm{m}$ above the MASC in the $-z$ direction under the force of gravity, reaching an average terminal velocity of $1.05\,\mathrm{m\,s^{-1}}$ well before encountering flows perturbed by the MASC. Initial particle positions are ∼2 to 20 m away from the MASC in the upstream horizontal direction, depending on the flow velocity. These initial positions were evaluated to ensure they fell into the center of the aperture."

2) Furthermore, I would suggest using more particles and particles of different size and shape according to the different riming classes seen in the measurements. And, as the influence of turbulent wind on the collection characteristics

is examined, a model for turbulent dispersion should also be included. The finding that fall velocity is reduced with increasing wind speed could maybe have been made without the particle simulation part by just looking at the fluid velocities inside/above the collection area. If so, the particle simulations might as well be left out and more detailed particle simulations would be something for further work.

Although we neglect some of the details as you point out, we feel that it is still necessary to show the influence of the perturbed flow on the mean fall speed of a set of particles with which to compare the MASC measurements. As stated above in response to #1, we have rearranged the sections and wording in the title (as suggested by Reviewer #2) to reflect that the observations analysis is the featured part of our work, and that the relatively simple simulations serve only a supporting role. We have added the following to the conclusions section:

"Relatively simple simulations were carried out here to support the findings of the observations analysis. We used only a single set of particles with limited, 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, as well as other forces that have been neglected in this work and a turbulent dispersion model."

3) As in principle the dependence of the collection efficiency on particle dynamic properties is investigated, I would suggest to include some thoughts on and references to general particle dynamics. Namely, there is the particle Stokes number, defining the ability of particles to respond to sudden changes in the carrier fluid's velocity. It is proportional to the product of particle density and the square of the diameter. Aggregates with comparatively low densities would have a low Stokes number, indicating that they follow the flow better than more dense aggregates. Additionally, bodies moving through fluids tend to orient in a manner that the drag is maximised. For oblate particles this would mean that their "plane"

is oriented perpendicular to the flow direction. With these two principles a lot of the paper's findings can be explained quite well.

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

4) Regarding the orientation of particles: As non-spherical particles tend to arrange themselves in some preferential angle to the flow, the concept of determining their orientation seems questionable even for medium wind speeds between 1.5 m/s and 5.0 m/s, as the flow above and inside the measurement region seems to be heavily influenced by the device. What are the authors' views on this?

This is why we deemed it necessary to show orientations in even lighter winds (i.e., wind speeds as low as $< 0.5\,\mathrm{m\,s}{-1}$ in Fig. 12 from the original manuscript). This figure shows not only what the preferred orientation angle is such light winds, but also how sensitive the larger, low-density aggregates are.

Minor remarks:

Section 1: L46f: suggested change from "characterize" to "were used to characterize" or similar

Fixed as suggested

L58f: Isn't the collection region cylindrical or circular, not ring-shaped?

This has been changed to a "hollow, decagonal-prism-shaped collection volume" to more accurately describe the shape of the collection region.

L58ff: I would suggest to include some information about the different parts' positions in Fig. 1a)

Added information about parts' positions as follows (note that Fig. 11 corresponds to Fig. 1 in the original manuscript):

"The system's casing houses three cameras focused on a point at the center of the collection volume 10 cm away, with each camera separated by 36° (for more details, see Fig. 1 from Garrett et al. (2012). A coupled system of directly opposing near-infrared emitters and detectors (attached to the decagonal prism in Fig. 11(a)), vertically separated by 32 mm, detect falling hydrometeors larger than approximately 0.1 mm in maximum dimension (Garrett & Yuter, 2014). This triggers the cameras and three high-powered LEDs located directly above on top of the casing (see Fig. 11)."

L70ff: Maybe the number of references can be reduced, where possible?

We removed all Garrett et al. references that had already been cited and added "e.g.," to show that this is a subset of relevant references.

L90f: also include influence on riming degree among "fall speed, fall orientation,

and size distribution"?

Added as suggested

Section 2: Please specify more clearly: It seems that first a steady state simulation with simple-Foam is done, and afterwards particles are tracked through a "frozen" flow field, but it is not actually mentioned.

The following statement was added to the CFD description: "The flow is allowed to reach steady-state prior to tracking particles through a 'frozen' flow field."

L96: Which solver? Maybe simpleFoam should be mentioned here already.

Wording in this paragraph has been rearranged to correct this and mention simpleFoam earlier.

L100: simpleFoam instead of simpleFOAM

Corrected

L115: Please specify the drag coefficient function.

We have updated the text to state, "The drag coefficient $C_D(Re_p)$ is defined as $C_D = (24/Re_p)(1 + Re_p^{2/3}/6)$ for $Re_p \leq 1000$ and $C_D = 0.44$ for $Re_p > 1000$"

L115 & L117: Re **should be** Re_p

Corrected

Fig. 2: I would suggest writing "wind directions" instead of "wind vectors". What crosssection is meant? Maybe the plane for the arrows? Please specify. A more detailed view of the results inside/around the measurement section would be nice, as it would be possible to examine the wind speed there more detailed. Is it possible to show some exemplary particle path lines? (additional images could be included as supplementary material)

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We have updated the caption to state:

"Simulated wind field around the MASC with undisturbed winds set at $1\,\mathrm{m\,s^{-1}}$ towards the positive y–direction. Color represents the vertical wind speed v_{f_z}, and arrows show wind directions on the y–z plane. The plane in which the arrows are located is aligned with the center of the aperture on the y–z plane, and x–positive points out of the page."

In response to the request for a figure showing examples of particle trajectories from two reviewers, we will add at least one figure to show this in the revised manuscript. Attached is a preview for a flow of $1\,\mathrm{m\,s^{-1}}$:

Fig. 3 and Fig. 4: Please indicate where the data is sampled.

We have added the statement, "Data are sampled at the center of the aperture" to each of these captions.

L130: "in the k-ω-SST closure model"

Corrected

Section 3: L137: "the angle between D_{max} and the local horizontal" should be "the angle between the major axis and the local horizontal"

Corrected as suggested and also clarified the definition of maximum dimension in the preceding sentence to say that it is defined as the length of the major axis

L143: Is the average of the three images the best guess for the actual orientation angle? How "stable" is the detection of orientation angles for rimed particles, as they might have no clear major axis?

We have added to the discussion section:

"The average of the three images is not the best guess for the true orientation angle in all cases. For example, depending on the azimuthal orientation with respect to the central camera, the particle's major axis may not be resolved entirely. However, Jiang et al. (2019) showed that the azimuthal orientation is correlated with the wind direction, with particles' major axes tending to align with the wind direction. In our case, this would imply that the major axis is often oriented such that it cannot be entirely resolved by any of the three cameras. More work needs to be done to investigate the limitations of the MASC-determined orientation angle."

Fig. 6(b) might be dropped in my opinion

We have decided to keep this as no other reviewers commented on it, and we feel it adds some clarification through an additional perspective

L171: Why were the PDFs adjusted with a Gaussian kernel and how do the original data look?

Added to the end of the Hydrometeor observations – methods section:

Results are presented here in the form of probability density function (PDF) estimates, calculated using a kernel density estimator of the form

$$\hat{f}(x_0) = \frac{1}{n_s h} \sum_{i=1}^{n_s} K\left(\frac{x_0 - x_i}{h}\right) \qquad (1)$$

where x_0 is a real value of the distribution being estimated, x_i is a random sample from the distribution, n_s is the sample size, and h is the bandwidth (Wilks, 2011). The Gaussian smoothing function is $K(x) = (2\pi)^{-1/2} \exp(-x^2/2)$ for a random variable x, and h is optimized according to Bowman & Azzalini (1997) to produce a smooth curve.

Table 3: In the regime of $U_{sfc} \leq 5\,m/s$: Are the data for smaller U_{sfc} also contained in values for larger U_{sfc}? (e.g. is the data of $U_{sfc} \leq 0.5\,m/s$ also in $U_{sfc} \leq 1.0\,m/s$?)

Yes and we have added the following clarification to the table's caption: "Less restrictive wind speed categories (e.g., $\leq 5\,\mathrm{m\,s^{-1}}$) include data from more restrictive categories (e.g., $\leq 1.5\,\mathrm{m\,s^{-1}}$)"

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L187f: If something different is simulated, then it should not be compared to that. There seems to be a significant difference between the measurements and the simulations. Please include some discussion about this difference.

This comparison statement has been removed and the following paragraph has been added to the discussion:

"For unshielded MASC measurements, the simulations demonstrated that the separation of flow leads to an upward flow velocity component above the aperture, which tends to decrease the mean fall speed of particles falling into the aperture. The mean value of the fall speeds measured by the unshielded MASC shown in Fig. 5(b) ($U_{sfc} \leq 5\,\mathrm{m\,s^{-1}}$) is $0.55\,\mathrm{m\,s^{-1}}$, which is similar to the simulated mean of $0.47\,\mathrm{m\,s^{-1}}$ for ambient wind speeds of $5\,\mathrm{m\,s^{-1}}$ in Table 3. However, the mean MASC-measured fall speed for $U_{sfc} \leq 1.5\,\mathrm{m\,s^{-1}}$ from Fig. 5(c) is only $0.60\,\mathrm{m\,s^{-1}}$, whereas the corresponding simulation-determined mean fall speed is $\sim 0.95\,\mathrm{m\,s^{-1}}$. This is a result of the Gaussian distribution of particle fall speeds from the simulations (not shown) not matching the observations, where distributions tend to either heavily favor the low-fall-speed mode or are bi-modal for light winds ($U_{sfc} \leq 1.5\,\mathrm{m\,s^{-1}}$). Therefore, while the primary effect of perturbed winds slowing particle fall speeds is well represented in the simulations, the details appear to be more complicated in reality."

Fig. 10: The low fall speed mode seems to be less prominent ($U_{sfc} <= 1.0$ and $1.5\,m/s$) or even vanishes ($U_{sfc} <= 0.5\,m/s$) for aggregates. Is there any explanation for this?

It is not clear to us why this is the case. One idea is that the spectrum of aggregate fall speeds is less susceptible to broadening by turbulent eddies, but this would need to be investigated in a separate work.

Section 4: As metioned above, please include some discussion of the simulation results and how they compare to the measurements. As mentioned in major remarks, I suggest including some of these thoughts: Falling objects tend to

orient in maximum drag conditions, which matches the findings here. (compare L196ff) As aggregates seem to have smaller fall velocities than particles of the other two categories, they should be oriented more vertical to orient in maximum drag conditions when experiencing the same horizontal wind speeds. This again matches with the findings. (compare L201) Aggregates are more prone to get blown away by the surface winds as they have comparatively low Stokes numbers and high surface-to-density-ratios in comparison to more rimed particles. (compare L205ff)

As mentioned above, 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.”

L236: “enhanced are reduced” should read “enhanced or reduced”

Corrected

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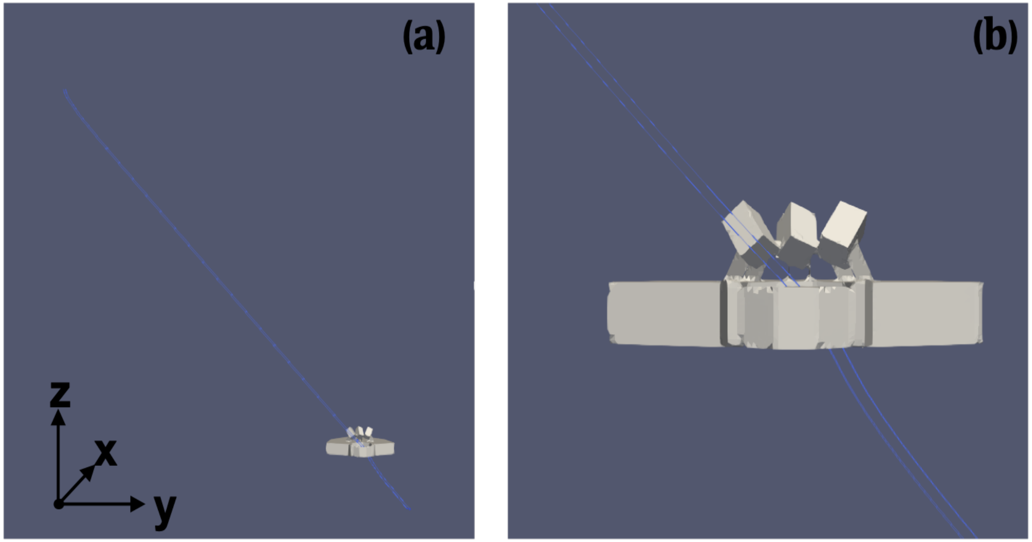

Fig. 1. Simulated particle trajectories for wind speed of 1 m sˆ-1

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