acp-2022-136

Responses to reviewer 2

Highly supercooled riming and unusual triple-frequency radar signatures over Antarctica

F. Tridon, I. Silber, A. Battaglia, S. Kneifel, A. Fridlind, P. Kalogeras, and R. Dhillon

June 7th, 2020

We thank the reviewer for his efforts and time for reviewing the manuscript. All our point-to-point answers are highlighted in red below according to the following sequence: (i) comments from referees/public, (ii) author's response, and (iii) author's changes in manuscript.

General comments:

The manuscript well explained the techniques of the retrievals used in this study and entire methods of the measurements and retrievals and also evaluated the techniques well including uncertainties owing to observational limitations and assumptions used in the techniques. I really appreciate those descriptions; this helped to interpret the observed features. Figures are all beautiful at high resolution. I had expected more analyses and/or discussions about physics and characteristics of Antarctica, such as mesoscale, microphysical and dynamical processes, as the manuscript had been submitted to ACP (not AMT).

We agree that the title was a bit misleading because it was suggesting that we found a feature specific to the whole Antarctic continent. This is not the case and we cannot generalize our findings and verify their occurrence at other sites in Antarctica due to the lack of equivalent measurements. Therefore, we decided to change the title so that it describes the study more accurately, i.e. that we found a peculiar process at McMurdo station. Describing the mesoscale and dynamical processes of Antarctica (comment 1 below) is out of the scope of the study because it would require additional tools such as meso-scale modeling. Nevertheless, we think that ACP is the right journal because the aim of the paper is not to describe the technical details of a retrieval methodology but a previously undocumented physical process which we investigate both via observations and modeling.

Specific comments:

1) I expected a little bit more discussions and/or analyses for the following points at least:

   1.1) The analysis results from the Antarctica data were compared with data from only a site. Is this enough to discuss the characteristics of the Antarctic microphysics? Can you take into account other environments such as continental, maritime, coastal, arctic, mountain, etc.?
   (i) Such a request cannot be satisfied largely because of the lack of observations. Less than a handful of field campaigns with long term triple-frequency radar measurements have been conducted in the past (the main 3 being the ones mentioned in the paper: AWARE, BAECC and TRIPEX). This also limits our ability to examine the representativeness of our findings to the Antarctic continent. (iii) Therefore, we decided to change the title, abstract, conclusion and description of the results to reflect that we have indeed found a previously undocumented process at McMurdo station.

   1.2) What are the environmental characteristics of the site in terms of temperature (like lines 536-538), humidity, wind, vertical velocity, etc.?
   (ii) The general description of the environmental characteristics at McMurdo station during AWARE has already been the object of several papers. (iii) We have added the new section 2.1 to summarize these findings and we completed the Table 1 with mean values of temperature, relative humidity and horizontal wind for each case.

   1.3) Can the triply-frequency signatures be expected to be generalized for other sizes in Antarctica?
   (ii) We guessed that “sizes” was a typo and interpreted it as “sites”. It is conceivable that riming could occur at lower temperatures over the whole Antarctic continent due to the low aerosol concentration but this must be corroborated by observations at other sites. (iii) Like for comment 1.1, we no longer argue that this feature is present over the whole Antarctic continent.

   1.4) How can the fewer but larger supercooled liquid droplets (lines 144-146) contribute to riming? I guessed that fewer droplets could restrain riming since the chance of collision and accretion could be reduced.
   (ii) The increase of the size of the droplets can dominate the effect of their reduction in concentration because collision efficiency strongly increases when going from small cloud droplets (10µm) to slightly larger drizzle (30-40µm). As a result, the chance of collision and accretion depends mostly on the relative fall velocities between the cloud droplet and ice crystal, and on several aerodynamic effects (Pruppacher and Klett, 1997, Wang and Ji, 2000). (iii) We completed the manuscript with this explanation.

References:

Pruppacher, H. and Klett, J.: Microphysics of Clouds and Precipitation, Atmospheric and Oceanographic Sciences Library, Springer Nether-lands, 1996.

Wang, P. K., & Ji, W. (2000). Collision Efficiencies of Ice Crystals at Low–Intermediate Reynolds Numbers Colliding with Supercooled Cloud Droplets: A Numerical Study, *Journal of the Atmospheric Sciences*, *57*(8), 1001-1009

1.5) Seasonal variability (I know that the data were limited, though…).

(ii) Indeed, it is impossible to assess the seasonal variability of riming occurrence with only 3 months of data. Since the radars are zenith pointing and provide observations over a single location, several years of continuous observations would be necessary to provide a meaningful seasonal variability.

1.6) Line 528-530: Why the narrow rime ice PSD is characterized over polar regions?

(ii) As demonstrated in the model exercise, the narrow ice PSD generally requires a stable atmosphere and large droplets (which increase the riming efficiency). (iii) We modified the text accordingly:

"These features are often interpreted as riming signatures and pinpoint a relatively common atmospheric state over Antarctica that includes a rather stable atmosphere inhibiting turbulent mixing and high riming efficiency driven by large cloud droplets. We note, however, that the limited amount of the triple frequency dataset collected during AWARE does not allow drawing definite conclusions concerning the frequency of such events. "

1.7) Lines 536-538: Can you explain a little bit more why the DWR signatures can be characterized as a unique signature over Antarctica?

(ii) They are unique in the sense that they have not been observed in the previous triple-frequency datasets, which, even if those datasets are not numerous, cover a much longer duration than AWARE. (iii) It would not be reasonable to add the technical description of section 3.2 in the conclusion so instead, we added a line in section 3.2 emphasizing the fact that such features are unique. However, we admit that unique is probably too strong and we now use peculiar instead.

2) Please provide a bit more explanation about BAECC; location, period, radar frequencies, case descriptions... This should help to characterize the observed features in this study.
   (ii) (iii) We added a paragraph rapidly describing BAECC and providing references with more detailed descriptions of case studies.

3) This manuscript analyzed one 'extraordinary' case study. Does this represent the other cases listed in Table 1? Need descriptions of the generality of the results from the detailed analysis among the selected cases.
   (ii) The case study features riming signatures like the majority of the other

AWARE cases (i.e., increase in $DWR_{Ka,W}$ while the AWARE $DWR_{X,Ka}$ remains close to zero for data above the -15°C level), but at an extreme level (as written at the end of section 3.2, the case study has been selected because it features the strongest $DWR_{Ka,W}$). The results from section 3 and 4-5 could be considered as two independent studies (general occurrence of riming during the whole AWARE field campaign vs. study of the mechanisms leading to extreme riming signatures for a single case study) and this is why they are the object of two different paragraphs in the conclusion and summary. (iii) We think that this was already clear in the manuscript so we only slightly modified the transition between those two paragraphs in both the summary and the conclusion, and we better clarified what distinguishes this case study rather than referring to it generally as 'extraordinary'.

4) Line 215-216: This sentence did not make sense to me. Maybe a few more explanations would be needed.
(iii) We expanded the text to make this discussion clearer.

5) What could bring the situation of slightly pointing off-zenith?
(ii) Since we already explained in the original manuscrit what is the consequence of slightly pointing off-zenith in section 4.2 (“As a result, a small component of the horizontal winds is found along the pointing direction of the mis-pointing radar which explains the observed $dV_D^{Ka,W}$ difference”), we interpreted the question of the reviewer as what could be its cause.
Note that we are talking of very subtle mispointing (of the order of 1°). The only reason we are able to detect them is thanks to the high sensitivity and narrow beam widths of cloud radars. Even if it is done with great caution, it is a challenge to align the beams of the radars to such a precise direction. During BAECC, it was found that the mis-alignment of the radar beams was eventually due to the thawing of the soil where the container of one of the radars was installed. (iii) We think that this technical information diverts too much from the main results, so we did not include it in the manuscript.

6) Figure 6 and Figure 7 (now figures 8 and 9): The data points were distributed to a large range. I wondered how such grid points with low density data are significant.
(ii) Note that the values indicated are the absolute numbers ((iii) we modified the title of the colorbars from “n” to “counts” to make it clear). So, the bluish pixels correspond to less than 10 occurrences and they are indeed not significant, this is why we only try to match the yellow to reddish pixels. We could restrain the color scale to occurences larger than 100, but we wanted to show the whole data points in the selected area.

6.1) Please provide the total number of sample size.
(ii) (iii) We added the total number of points (about 130000) in the introduction of Fig. 8 (section 4.3).

6.2) Because of the noisiness, it seems to me that any lines from the particle models cannot represent the observation data for any plots.
(ii) It is true that multi-frequency radar observations are inevitably noisy not only because of the eventual radar volume mismatch, but also because of the intrinsic noisiness of radar measurements. But the main variability here is the natural variability due to the variety of microphysic processes occurring, the complexity of ice particles and the variability of ice PSD shapes (cf following comment 6.3). Therefore, the objective here is to find the scattering model which best match the observations in average.
(iii) We added a new paragraph in section 4.3 to better explain the methodology. We think that it is relatively clear that some theoretical lines match better the different density plots but to make the comparison more evident, we added the median and 10^{th} and 90^{th} percentiles of the density plot as function of $DWR_{Ka,W}$ (white lines in Fig. 8 and 9) to highlight the average trend and natural variability of the observations which can then be compared to the theoretical model lines.
Also, we have now estimated the noisiness of radar measurements for the configuration of the ARM radars during AWARE and we have added error bars in the top-right corner of Fig. 8 and 9 to illustrate them).

6.3) I supposed that the data to plot those figures came from the long time period (~4 hours), which period possibly included a variety of microphysical processes; not only riming, but also depositional growth, different degree of riming, aggregation, etc.. Those data could be plotted into a panel. So I was not sure of a meaningful of those plots; what is the purpose of overlaying the lines from the particle models; why the only selected particle types from models were plotted.
(ii) As it was indicated in the introduction of Fig. 8 (section 4.3), the histograms correspond indeed to the 9h to 13h period. (iii) We modified the text to make it more evident.
(ii) Indeed, the microphysic properties and processes involved during the 4 hours period are various. As explained in the reply to comment 6.2, the objective is to find the scattering model which best match the observations in average, and hence to detect, from the observed reflectivity signatures, the fingerprints of the dominant microphysical process in shaping the ice particles. Note that the main difference between these SSRGA-LS15-Bxxx models is the quantity of supercooled water accreted to the ice particle, i.e. the degree of riming, but during the generation of the ice aggregates, depositional growth and aggregation are intrinsically involved by the explicit simulation of the aggregation of monomers of various sizes. (iii) We added these explanations in section 4.3.

6.4) Because of those, it was unclear for me what is the 'unusual' triple-frequency signatures. It would help if the signatures were highlighted in the plots.

(ii) (iii) We added a magenta ellipse in figure 8 to highlight the unusual triple-frequency signatures and we expanded its description.

6.5) Lines 372-373 “At the top of the layer…” This sentence does not make sense to me. Please provide more explanation.

(ii) (iii) We replaced the sentence by “From 2.6 to 2.3 km, Dm strongly increases towards the ground, highlighting the layer where riming is most efficient and the probable top of the supercooled liquid layer”.

7) Line 428-429: Please explain this process more in details.

(ii) (iii) We modified the text:

“The location of this deep supercooled layer suggests that even if some vertical mixing did occur during this event, … it mostly took place at altitudes where the ice particle population did not yet experience rapid mass growth due to ice supersaturation conditions… and/or intense riming, thereby hindering PSD broadening.”

8) Figure 10:

8.1) Please highlight the location of the supercooled liquid layer

(ii) (iii) We added a blue-shaded rectangle to panel c representing the estimated supercooled cloud extent.

8.2) Add a plot and discussion of vertical velocity

(ii) The mean Doppler velocity signatures during the event are already discussed in sect. 4.2.2 and presented in Fig. 5, and since we do not think that another panel to the 10-panel Fig. 10 would add additional insights to the model results discussion, we prefer to leave the figure as is.

8.3) Why $Z_{Ka} < Z_W$ below 1 km?

We think that the low-level negative DWR is an additional potential result of radar misalignment (emphasized at low levels due to smaller radar volumes) as already discussed in the final paragraph of sec. 4.2 wrt the mean Doppler velocity differences. It is also possible that due to the strong low-level sublimation driven by the prevalent Foehn winds over the region, we are left only with very small ice particles that are more likely to be detected with the W band radar.

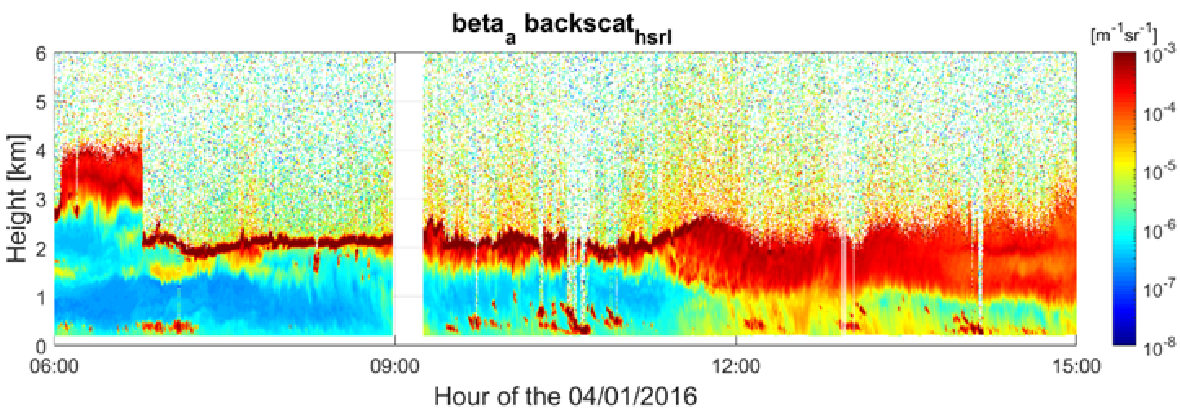
9) Lines 520-521: Does this mean the retrieval's error or radar forward simulator's error?

(ii) (ii) We refer to overestimation relative to the observations. We modified the text to:

“If model number concentrations are doubled prior to the forward calculations, reflectivity is overestimated relative to the observations (not shown).”

Technical comments:

- I really appreciate the high-resolution images; those included much information. However, sometimes I could not identify locations of what mentioned in the text; such as: Line 372 “reasonably homogeneous”; Line 416-417; Line 501 “W-band reflectivity intensification”
  L. 372: (ii) We don’t see how to highlight this because the entire retrieved fields are homogeneous. What we mean is that, if the retrieval were not robust, all pixels would appear independent and there would be no spatial coherence. (iii) We added “with good spatial coherence”.
  Line 416-417: see next comment
  Line 501: (ii) (iii): The reflectivity intensification from 3.5 to 2.1 km is rather evident in our opinion. Even though it was already indicated a couple of lines later, we now repeat the height range of the intensification for full clarity.
- Line 416-417: Which one is the supercooled cloud layer signature? The signature should be identified by a large gradient of backscatter, but I cannot see it well.
  (ii) In Figure 4a, only the reflectivity field is shown with superimposed black dots showing the cloud base as retrieved from the HSRL. In the inset of Figure 10a, the strong backscatter gradient is covered by the black dots. See below the full size picture of the measure backscatter in the time-height space of Figure 4 (the liquid cloud base gradient is clearly seen just above 2km between 7h and 11h, as indicated in section 4.2 of the manuscript). As noted in the caption of Figure 4, the cloud base height is an official ARM product which has been compared to other data products in Silber et al. (2018) and can be trusted.
  (iii) For full clarity, we added the reference to the PI product in the description of Figure 10 but we prefer not to add another panel in Figure 4 because Reviewer 1 already complained about too many panels.



Reference:

Silber, I., Verlinde, J., Eloranta, E. W., Flynn, C. J., and Flynn, D. M.: Polar Liquid Cloud Base Detection

Algorithms for High Spectral Resolution or Micropulse Lidar Data, Journal of Geophysical Research: Atmospheres, 123, 4310–4322, https://doi.org/https://doi.org/10.1029/2017JD027840, 2018.

- Sometimes it was unclear for me that which Ka-band radar (KaSACR or KAZR) was used to estimate DWR_X/Ka and DWR_Ka/W? I suppose that KAZR was used throughout the study; why wasn't Ka-SACR used? I expect that the use of Ka-SACR can reduce the beam mismatching error at least for DWR_X/Ka.
  (ii) As described in the Radar data processing section (section 2) and as indicated by the dataset citations, the KaSACR data is not used in this study. The main reason is the better sensitivity of the moderate sensitivity mode (MD) of the KAZR. The use of KaSACR data would indeed avoid the beam mismatch issue, but only where KaSACR SNR is high enough. Instead, we avoided the mismatch issue by using the differential spectral width and not the differential fall velocity. (iii) The choice of KAZR for its sensitivity was indicated in section 2.
- Table 1: Add a temperature range for each case.
  (ii) (iii) Done
- Just I was surprised that WACR had a huge offset in reflectivity (19 dBZ)… Was the sensitivity of the radar enough?
  (ii) We were also surprised by the huge offset of the WACR. The resulting sensitivity of the WACR was indeed lower than the sensitivity of the KAZR (as can be deduced by comparing the extent of the KAZR reflectivity field (Figure 4a) with the DWR_{KaW} field (Figure 4e)). This would be a problem if looking at thin ice clouds, but this does not prevent our analysis because we focus on thick clouds generating large ice crystals which lead to non-zero DWRs and significant signal to noise ratio (SNR). Furthermore, the large density of points with DWRs=0 in Figure 8 shows that a large amount of data is associated with a good SNR even if the ice crystals are not large enough to produce non-Rayleigh scattering.
- Figure 4e: Why is this plot dark?
  (ii) As was written in the text and the caption of Fig. 4, the shading allowed to highlight the Rayleigh reflectivity region at cloud top (non-shaded region) which is used to derive the two-way differential path-integrated attenuation.
  (iii) To make it more readable, we change this panel (Now Fig. 4c) and now, the shading actually indicates the Rayleigh reflectivity region.
- Line 213-214: I cannot identify vertical stripes. Can you add marks to the figure?
  (ii) It is not realistically possible to add marks to the figure because the vertical bands are present over almost the whole panels 4b and 4d. (iii) Instead, as suggested by the reviewer 1, we replaced the text to be more explicit by "vertical bands that alternate between more or less dark blue/red.
- Figure 9: How did you estimate the standard deviation from one profile?
  (ii) Standard deviation was probably not the right wording, we meant

uncertainties. The derivation of uncertainties is fully described in the retrieval methodology of section 4.5. Retrieving the uncertainties is the object of the 3rd point of the methodology: it is done via Monte Carlo propagation for parameters mu and Dm, and the errors of the other parameters are obtained via error propagation as described in the 4th and 5th points. (iii) In the caption of Figure 9, we replaced standard deviation by uncertainties and recalled how they are derived.