Response to reviewer 1

We thank the referee for the time he/she has put on reading our manuscript and providing feedback. Based on the combined comments of the referees, we have decided to implement these general changes:

- We will switch to an airborne measurement set-up and the introduction section will be modified accordingly
- Text in the result section will be shortened significantly
- Redundant results for scene 2 will be placed in an appendix
- The selection of tested retrieval habits will be revised/changed

Below we respond to the main questions raised by the referee, and outline how we will revise the manuscript.

1 General comments

Reviewer comment 1

As noted in Section 4.2.4, the a priori assumptions do not describe reality very well. In particular, I suspect that the information content of Dm and N0* is highly dependent on the a priori assumptions of these two variables in the retrieval framework. Especially with a radar measurement, since Z is sensitive to both parameters over a wide range of the parameter space, the relative sensitivity and therefore information content will almost entirely depend on the relative constraints on these parameters imposed by Xa and Sa. As such it is imperative to accurately characterize these. I understand the choice to use the DARDAR constraints, but it's clear from the cross-section plots that the model ice particle concentrations vary over a much wider range than the roughly 2 orders of magnitude that Eq. 4 provides over a 220-272 K temperature range. So, when the retrieval results are compared to model "reality", it seems that a lot of N0* variability is folded into Dm and this is especially evident in Figures 13 and 14. My overall concern is that it is difficult to interpret some of the results when the model fields and the a priori assumptions differ so strongly.

Author response:

To avoid potential misunderstanding we would like to point out that the variation of the a priori mean with temperature, which is given by Eq. 4, does not limit the retrieved values of N_0^* to this range. How much N_0^* is allowed to vary around the a priori mean is determined by the covariance matrix. Since the standard deviation for $\log_{10}(N_0^*)$ at each grid point was set to 2 (c.f. Tab. 3), N_0^* is free to vary over several orders of magnitude in addition to the variation of the a priori profile.
Furthermore, the sentence in Section 4.2.4 was badly formulated and did not really express what we wanted to express there. The a priori assumptions are not generally bad for the model (after all the averaged results for the first scene are good). Rather, they are insufficient to accurately describe the (co-)variability of D_m and N_0^*.
Nonetheless, the point raised by the reviewer certainly remains valid: In absolute terms, the interpretation of the retrieval results is dependent on the a priori assumptions. We argue here, however, that by applying equivalent a priori assumptions in all retrievals, we can still derive conclusions on the benefits of the combined retrieval approach based on a relative interpretation of the retrieval results. Especially because our results indicate that the combined retrieval has to rely less on a priori assumptions than the radar-only retrieval, this can be an important advantage of the combined retrieval since if D_m and N_0^* could be constrained reliably a priori we would not have the uncertainties in the observational record of ice hydrometeors that we have today.
To address the issues raised by the reviewer we propose to make the following changes in the manuscript:

- To extend the discussion of the role of the a priori (around L. 491) and its impact on the results.
- To add a paragraph to the discussion of the limitations of the study (around L. 549) which clearly states that the retrieval results should not be interpreted in absolute terms
- To rephrase the sentence in Sect. 4.2.4 (L. 545) to stress that is refers to the Gaussian nature of the a priori rather then the a priori itself.

Reviewer comment 2

Forward model error is introduced when the different species present in the model microphysics are combined into one species and when different scattering models are used to represent the ice particles. That this is not represented in Se could lead to over-fitting and poor convergence (I suspect this is part of the reason why the normalized cost is much higher for the radiometer-including retrievals). It should be relatively easy to quantify this error by re-running the simulations with the retrieval assumptions(combining ice species, different scattering models), and I suspect that this error term would dominate the instrument noise term for many channels.

Author response

It is certainly true that the simplified forward model used in the retrieval introduces a forward modeling error and that it will likely dominate the sensor noise. However, we do not agree with the reviewer that this error was easy to quantify. First of all, the error will not be Gaussian and will depend on the cloud composition and the assumed particle shape, so that a more sophisticated error model would be required to describe the error accurately. Fitting such a model to the test scenes would likely yield overly optimistic results as this would mean making use of information which would not be available for real retrieval observations.
Because of these difficulties, we decided to not pursue this approach in the study. However, since this is an important point to mention, we will add a paragraph on this issue in the discussion.

2 Specific comments

Reviewer comment 1

Lines 85-88: I recommend the use of geographical spatial references (i.e.,north/south rather than left/right)

Author response

The proposed change will be adopted in the revised version of the manuscript.

Reviewer comment 2

Line 98 (also 176,252,449): Instead of vertical/horizontal (which are dependent on the convention used for plotting), I recommend the use of concentration/size tocharacterize the dimensions of the particle size distribution.

Author response

The proposed change will be adopted in the revised version of the manuscript.

Reviewer comment 3

Line 100: A few more details on the Milbrant and Yau microphysics sheme that are relevant to this study would be helpful here. For example: What is the assumed shape(functional form) of the particle size distribution, and what are the prognostic variables(e.g., number concentration, mixing ratio)?

Author response

We will follow the reviewers comment and add the requested information to the manuscript.

Reviewer comment 4

Line 135: Does the ARTS radar solver also provide analytic Jacobians?

Author response

Yes, it does. A sentence will be added to the description of the forward model to clarify this.

Reviewer comment 5

Line 187: "particles" should be "particle"

Author response

The sentence will be removed in the revised version of the manuscript since the information it conveyed was deemed irrelevant.

2.1 Reviewer comment 6

Line 198: Is Dm also only retrieved at these 10 points, or just N0* (and Dm retrieved in each radar range gate as in Grecu et al. 2016)?

Author response

D_m is actually retrieved at the resolution of the GEM model scenes. Since questions about the retrieval grids were also raised by the other reviewers, we will add an illustration of the grids applied in the different retrieval configurations to the manuscript.

2.2 Reviewer comment

7. Line 256: Actually, this is only one example of how the radar and radiometer measurements can be complementary. Even if the lines were parallel (and thus no information distinguishing size from concentration could be obtained), the radar still locates the cloud and describes its vertical structure. One can imagine a cloud of the same ice water path and particle size at two different heights having different brightness temperatures due to changes in the water vapor absorption above the cloud – having the radar information would provide increased information content about the ice water pathin this case than the radiometer measurement alone.

Author response

It is certainly correct that when a radar sensor is added to a passive observation system one of the advantages will be the increased resolution. However, what we are interested in are the advantages that neither of the two instruments can provide on its own. If it was only about vertical resolution, then the radar alone would be the ideal observation

system. In this sense, we do not consider the vertical resolution a synergy of the two sensors.
To make this clear, we will add an explanation of our definition of synergies between the active and passive observations to the section which discusses the complementary information content.

Reviewer comment 8

Table 4: Why are the values for GemSnow and GemGraupel different than in Table 1?

Author response

This was by mistake and will be corrected in the revised version of the manuscript.

Reviewer comment 9

Figures 7 and 8: I'm not sure why these are separate figures – it seems like all panels could fit on one page.

Author response

Figures 7 and 8 will be combined into a single figure in the revised manuscript.

Reviewer comment 10

Figure 10 is missing from the manuscript.

Author response

Figure 10 will be included in an Appendix to the revised manuscript with the rest of the analysis of the results from the second test scene.

Reviewer comment 11

Line 374: recommend using "represent" instead of "predict"

Author response

The proposed change will be adopted in the updated version of the manuscript.

Reviewer commene 12

Line 382: should be "reference" instead of "references"

Author response

This will be corrected in the updated version of the manuscript.

Reviewer comment 13

Line 414: How are the truncated PSDs (using GemSnow) represented in theforward simulations? Is total ice water content conserved? If so, how is it spread amongthe valid particle sizes – equally, or is the truncated mass allocated to the smallest size bin?

Author response

Total IWC is not conserved in the handling of PSDs. The point raised by the reviewer has been investigated by assessing the effect of the truncation on the water content of snow in the forward simulations. The results of the analysis are given in the figure below. As these results show, the effects of the truncation in the forward simulations are negligible. However, when the GemSnow particle model is used in the retrieval it can introduce significant errors. For this reason as well as another reviewers' comment regarding the choice of tested particles, the selection of particles to be used in the retrieval will be changed for the revised manuscript and the GemSnow particle will be replaced by a habit mix which uses the GemSnow particle for large diameters.

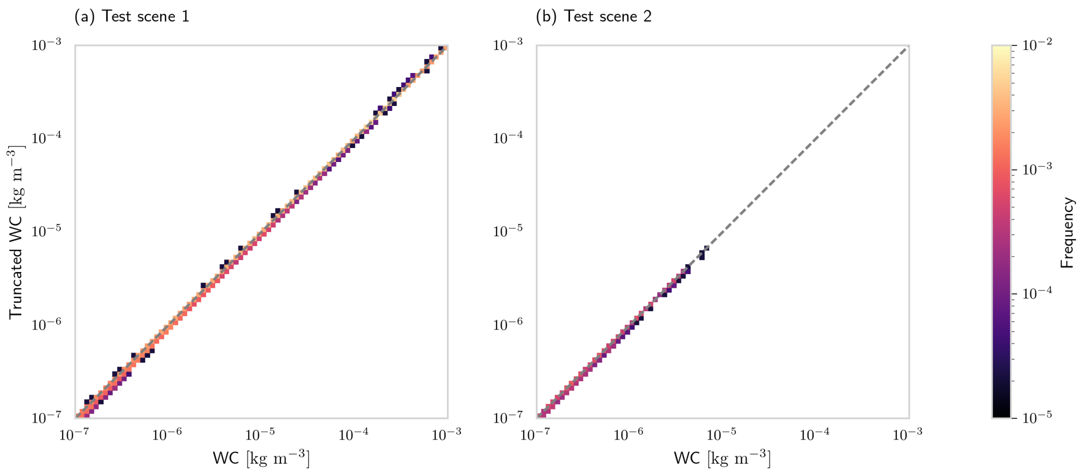

Figure 1: Joint distribution of truncated and full snow water content (SWC) for the two test scenes.

Reviewer comment 14

Figure 16: The figure labels/captions aren't clear if they refer to total liquid water content/path or just the cloud liquid water/path.

2.2.1 Author response

We will clarify that the contours refer to liquid cloud water content in the revised version of the manuscript.

Reviewer comment 15

Line 518: It's interesting that the Plate Aggregate provides the most accurate re-trieval results, even though it isn't similar to the models used in the synthetic measure-ment simulations. Does the decreasing density with size better replicate the combina-tion of high-density GemCloudIce (which tends to be present in high concentrations atsmall sizes) and lower-density GemSnow (which tends to be dominant at larger sizes)?

2.2.2 Author response

Unfortunately, we cannot give a definitive answer to this question. As panel (a) in Fig. 15 shows, the density of the LargePlateAggregate habit is actually lower than that of snow for large particle sizes. Moreover, the scattering properties certainly also play a role here. At this point we are therefore not able to postulate any direct causality between the particle density and the performance in the retrieval.

References

Buehler, S. A., Mendrok, J., Eriksson, P., Perrin, A., Larsson, R., and Lemke, O.: ARTS, the Atmospheric Radiative Transfer Simulator – version 2.2, the planetary toolbox edition, Geosci. Model Dev., 11, 1537–1556, https://doi.org/10.5194/gmd-11-1537-2018, URL `https://www.geosci-model-dev.net/11/1537/2018/`, 2018.

Milbrandt, J. and Yau, M.: A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description, J. Atmos. Sci., 62, 3065–3081, https://doi.org/10.1175/JAS3534.1, 2005.