Response to referee #3 (in RC1)

RC: The article presents a method to be used as an operational retrieval to derive ice crystal number concentrations of pure ice clouds, Ni, (T < -30° C) from combined spaceborne lidar-radar measurements (CALIPSO-CloudSat) and a thorough evaluation using in situ data from five airborne campaigns. An example of application is shown via a case study, including Lagrangian transport modelling. An interesting result is that regions with stronger updraughts show peaks in Ni with particle sizes > 5micron in contrast to regions of mature cloud, as one would expect. At the end, geographical maps and zonal profiles of 10 years of Ni are presented and discussed for particles with sizes > 5micron and > 100micron. A follow-up paper will use these data in the framework of aerosol-cloud interactions. Ni is an essential microphysical parameter, which is recently used as a prognostic variable in climate models, and therefore it is important to have global observational constraints. The variable is also important for process studies. The combination of lidar and radar measurements, being part of the A-Train, allows to determine the vertical structure of clouds such as top and base of the clouds, cloud layering, as well as ice water content and effective ice crystal diameter. The attempt to derive ice crystal number concentration is relatively recent, as its determination depends on several assumptions (in particular a gamma-modified particle size distribution (PSD) and a specific ice crystal mass-maximal diameter relationship). The presented method is based on a direct constraint of the shape of normalized particle size distributions using lidar extinction and radar reflectivity from the operational liDAR-raDAR (DARDAR) products. 40000 in situ PSD's are used for an evaluation, investigating results separately for ice crystal sizes > 5, 25 and 100 micron, first for the prediction of PSD from N0* and Dm and then for retrieved Ni. The article is generally well structured and well written. I strongly recommend the publication of this article, after minor revisions.

AR: We thank the referee for all the insightful comments that have greatly helped us to improve the quality of the manuscript. Detailed responses to each of them are provided below.

Minor Comments

1. RC: 1) The methodology section 2 gains in clarity by integrating the content of section 2.1 into sections 2.3 and section 3.1, in particular as DARDAR products are data and the retrieved variables such as beta-ext, Ze and beta-ext are not defined. In that way the section on the representation of the size distribution gets section 2.1, in which the advantage of using scaled PSD's is described as well as the necessity to assume a certain m-D relationship and a certain shape of PSD. The new section 2.2 (Extracting Ni from DARDAR products) goes then further into detail how to extract Ni from the DARDAR products N_0^* and IWC. It should be clearly stated in the beginning that from N_0^* and IWC from DARDAR one deduces Dm and finally Ni. New Section 2.1: Be careful of replacing DARDAR by 'DARDAR retrieval (see section 3.1)'. Then a short description of the DARDAR products (like in initial sect 2.1) should be integrated into section 3.1. P4,l17-18 define beta-ext as (lidar) extinction and Ze as (radar) reflectivity

AR: We are grateful for these suggestions and fully agree with them, sections 2 and 3 have been edited accordingly. Sec. 2 now only focuses on describing the methodology and the DARDAR algorithm is described in Sec. 3.1. It can be noted that further technical details on DARDAR are now also provided in Appendix A.

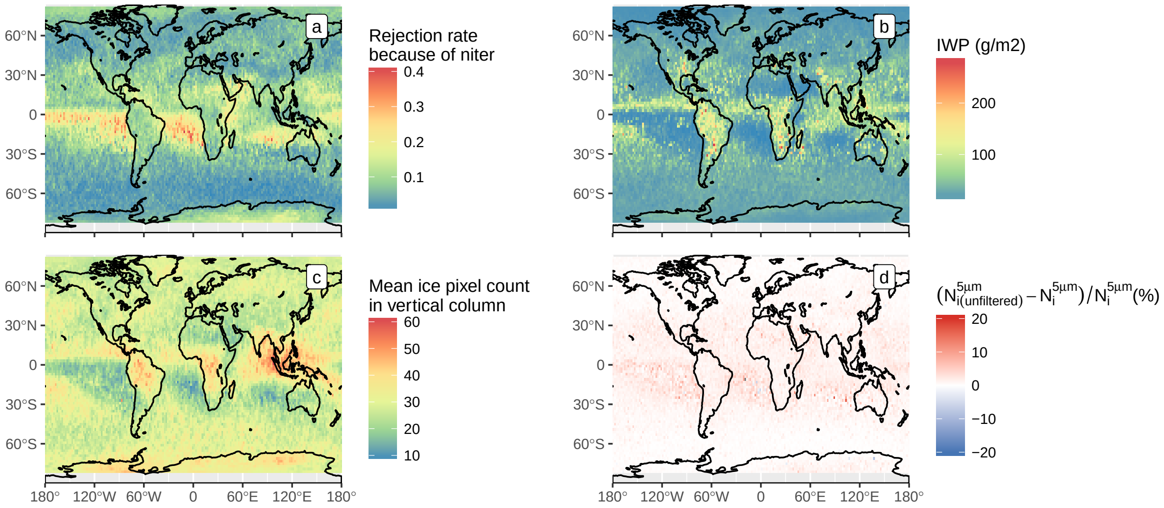

Figure 1: (a) Spatial distribution of the rejection rate associated with the $n_{iter} < 2$ filtering for pure ice clouds with $T_c <$ -30°C. These results correspond to one year of DARDAR retrievals (2008). (b-c) show the corresponding ice water path (IWP) and average number of ice cloud pixels in the vertical column (we recall that the height of a pixel is 60 m). (d) represents the relative difference on $N_i^{5\,\mu m}$ between -60 and -50°C that would be expected if the n_{iter} filtering was not applied.)

2. RC: 2) p 6, l22 it is stated that DARDAR retrievals of pure ice clouds for which the iterative retrieval converged too quickly are ignored. How many of these retrievals are these and can you explain which category of cases these are?

AR: We thank the referee for this comment as we had not yet looked into the distributions of rejection rates associated with the filtering based on iteration number. We agree that useful information could be contained there. It is reminded that this filtering is used to avoid pixels associated with a too quick convergence of the forward model with the observations, which could indicate a lack of information and therefore a strong reliance on a priori considerations. This is now further discussed in Appendix A of the revised manuscript.

The spatial distribution of this rejection rate for ice clouds with $T_c <$ -30°C is shown in Fig. 1 of this response. A strong latitudinal dependence of the rejection rate is noted, with less than 10% in the mid-latitudes and about 10 to 20% in the tropics. Rejection rates up to 40% are even seen in the north of oceanic subsidence regions of the South hemisphere. A high rejection rate in DARDAR retrievals in the tropics is not surprising as thick clouds with a complex microphysics are likely to be encountered there. However, Fig. 1(b-c) show that the highest rejection rates occur in regions where thin ice clouds with low IWPs are found, most likely retrieved from lidar-only conditions. It could therefore be that, for these thin clouds, a single iteration is sufficient for proper retrievals and we may be over-constraining the dataset filtering. This has never been investigated from DARDAR and would require further analyses to be verified and fully understood. We have nevertheless verified that this filtering actually has a small impact on the overall climatologies. Fig. 1(d) for instance shows the spatial distribution

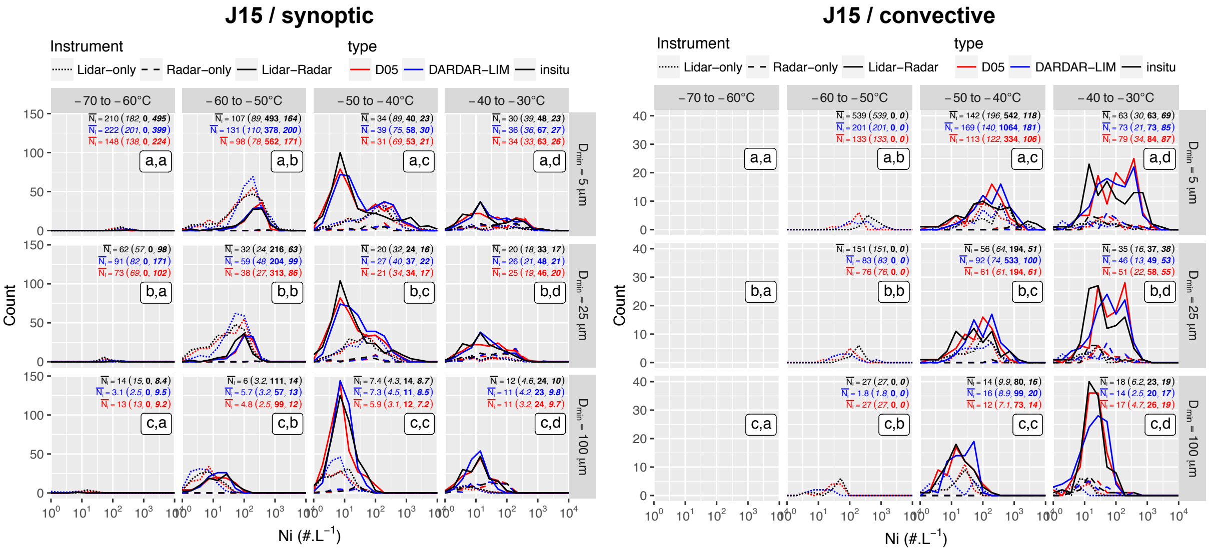

Figure 2: Similar to Fig. 4 of the revised manuscript. The PSDs have here been subsetted following the classification proposed for SPARTICUS by Jackson et al. [2015]. PSDs for synoptic and convective clouds are shown on the left and right panels, respectively.

of relative differences in $\mathrm{N}_\mathrm{i}^{5\,\mu\mathrm{m}}$ (in the -60 to -50°C bin) between 1-year climatologies obtained without and with applying the n_iter filtering. Differences smaller than 10% are typically found in regions where the rejection rate is the most significant. The bias is positive, which seems to indicate that thin cirrus higher $\mathrm{N}_\mathrm{i}^{5\,\mu\mathrm{m}}$ are ignored because of this filtering. It should be noted when comparing these results to Fig. 7(a-c) of the revised manuscript that relatively very low $\mathrm{N}_\mathrm{i}^{5\,\mu\mathrm{m}}$ values are found in regions where this bias is maximum. The n_iter filtering therefore does not have any significant influence on the results shown in this study. After careful consideration, we have chosen to keep the filtering as but we will keep in mind these analyses and results when producing future versions of the dataset (based on the next version of DARDAR cloud and mask products, which should soon be available). It can also be mentioned that all these filtering options will be provided together with the N_i dataset, which will hopefully be distributed co-jointly with the publication of this two-part study.

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3. RC: 3) The evaluation of the prediction of PSD's and Ni (using all field campaigns) and later for retrieved Ni (using coincident SPARTICUS measurements) is shown separately for different temperature intervals, which is important as ice crystal particles shapes differ with temperature. It would be very interesting to separate also anvils and synoptic cirrus, as m-D relations might be different. Is there enough statistics of the collocated SPARTICUS campaign measurements to compare Ni distributions of Fig. 5 for anvils and synoptic cirrus?

AR: We thank the referee for this interesting comment. It is a very good point that m-D relations might be different from different cloud types and this could subsequently affect the quality of our evaluation. As mentioned in Sec. 4.1.1, differentiating between different cloud types has not been attempted in this study for reasons of brevity and also because DARDAR does not make any distinction when assuming its PSD shape and m-D relation. It would nevertheless be interesting, following the referee's comment, to indeed verify if any specific issue occur when applying a basic differentiation, such as convective vs. synoptic clouds.

To do this, we have associated a cloud type to each PSD from the SPARTICUS dataset used in this study, based on the cloud classifications by Muhlbauer et al. [2014] and Jackson et al. [2015]. Fig. 2 of this response shows comparisons between the histograms of collocated SPARTICUS measurements (Fig. 5 in the original manuscript, Fig. 4 in the revised version) when distinguishing between the "convective" and "synoptic" classification by Jackson et al. [2015]. This classification is chosen here as it is more straightforward. Muhlbauer et al. [2014] offer numerous specific cloud classes, which for this application leads to subsets with a lower statistical significance. It can first be observed in Fig. 2 that convective clouds have higher $\mathrm{N_i}$ means, but are also much less occurrent than synoptic clouds during SPARTICUS. With respect to the quality of DARDAR-LIM retrievals no obvious bias or other issue can be noted in either cloud class. Differences are noted but it remains difficult to estimate if these are within the noise, considering the small number of statistics. Testing the impact of m-D relations would also require to disentangle the impact of a possible misrepresentation of the PSD shape in either of these two cloud classes. Finally, it should be kept in mind that these cloud classification are often very difficult to obtain and can be associated with large uncertainties as well.

For these reasons, and to avoid substantial additional descriptions and discussions in the manuscript, we have still kept analyses based on cloud types out of the revised manuscript. But we recognize the importance of this point and the strong interest to differentiate between cloud types to test the impact of the m-D relation but also the assumptions made on the PSD shape. This will be done in a future study that will focus on improving the PSD representation used for lidar-radar $\mathrm{N_i}$ retrievals.

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4. RC: 4) section 3.2.2: One specific ice crystal mass-maximum diameter (m-D) relationship is used to determine IWC from the PSD. Indeed, Delanoë et al. 2014 show that the uncertainty to the m-D relationship for the normalized PSD is less important when minimizing using lidar extinction and radar reflectivity. The uncertainty seems to increase if only the lidar extinction is used for the minimization (Fig. 9). As both measurements are complementary, there are clouds for which only the first (thin cirrus) or the latter (towards the base of thick cirrus) are available. We also know that the shape of crystals changes with temperature and Heymsfield et al. 2010 showed that the m-D relation for anvil ice clouds yield masses about a factor of 2 larger than for synoptic ice clouds. Erfani and Mitchell 2016 cite this result in their paper and write that their results showing a similarity in m-D expressions between these two cloud types might be an artefact if the ice particle masses for a given projected area are quite different between these types. The L16 m-D relationship was developed for midlatitude cirrus. So for tropical anvils the computed IWC might be biased. Did you test the IWC computed with the L16 m-D relationship with the measured IWC for tropical anvils (using SPARTICUS and ATTREX) ?

AR: We again thank the referee for this very good point. It is absolutely correct that, as shown by Delanoë et al. [2014] and mentioned by the referee here, uncertainties related to the m-D relation used on the normalized PSD are minimum when both lidar and radar are available. This should lead to smaller uncertainties on lidar-radar $\mathrm{N_i}$ estimates, as now discussed in the appendix of the revised manuscript.

The consequences on $\mathrm{N_i}$ could also be evaluated using the histograms for coincident flights shown in Fig. 2. However, it can be argued that the statistics are for the moment not sufficient

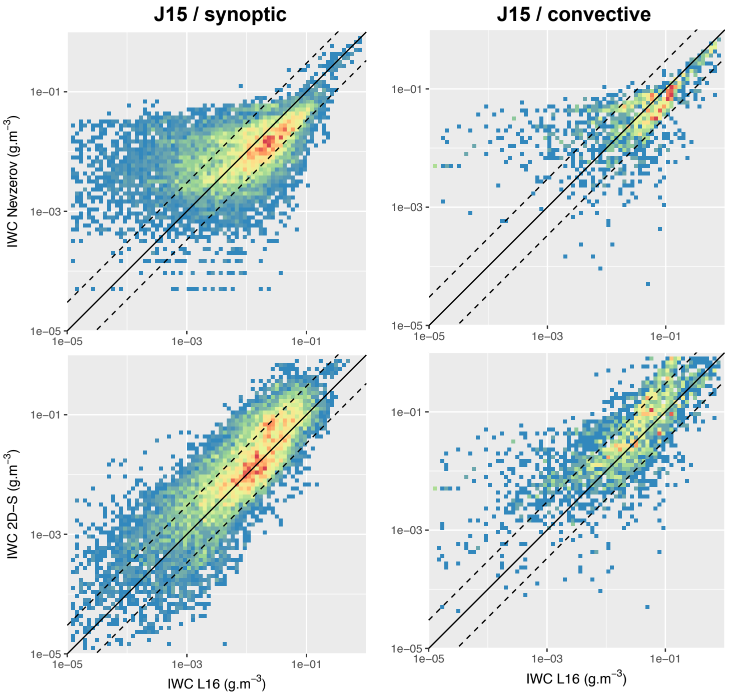

Figure 3: SPARTICUS IWC obtained from Nevzerov (first row) and 2D-S (second row) measurements, as function of L16 predictions based on the 2D-S PSD. The column indicate the cloud category based on Jackson et al. [2015]. A factor of 3 around the one-to-one line is indicated by a dashed line.

to draw any strong conclusions. The impact of m-D assumption will also need to be disentangle from the impact of the PSD shape assumptions, which largely dominate the observed differences. We nevertheless hope to extend this type of evaluation using additional flights coincident with the A-Train, in order to further dig into these issues in the future.

Regarding the use of L16, we have not performed comparison to SPARTICUS or ATTREX measurements in the context of this study, but evaluations of this m-D relation have been made in other studies. Afchine et al. [2018] has for instance shown that this relation should be applicable to tropical clouds, and that the influence of different m-D relations on IWC is small in the temperature range of cirrus. This is now further detailed in Sec. 3.2.2. To provide a more complete response to this comment, we have now analysed the consistency between L16 and SPARTICUS measurements. The classification by Jackson et al. [2015], discussed in the previous response, is used to differentiate between synoptic and convective clouds. IWCs are operationally provided from the 2D-S [based on an assumed area-mass relation; Baker and Lawson, 2006] as well as from bulk measurements from a Nevzerov probe. These comparisons are shown in Fig. 3. It appears that L16 overestimates by a factor of about 2 the IWC measured by the Nevzerov probe. This overestimation seems consistent between synoptic and convective clouds. The 2D-S IWC are in better agreement with L16, for either the synoptic of convective clouds. These results based on SPARTICUS are therefore in agreement with the conclusions by Afchine et al. [2018]. Unfortunately, the ATTREX IWC was not available in the version of the data used for this study and the same analysis could not be repeated. However, it can be noted that Thornberry et al. [2017] showed similarly good agreements between the 2D-S-based IWC and bulk measurements.

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5. RC: 5) Figs. 6 c and d of the case study present the trajectories as function of UTC. The relevant variable is the time difference which you show in brackets, and then the position on the map in Fig. 6a. If it is not too complicated, it might be clearer to present instead of UTC longitude.

AR: We thank the referee for this comment, adding the spatial coordinates would indeed add clarity to compare Fig. 6(c-d) to Fig. 6a (Fig. 5 in the revised manuscript). We have changed these figures so that the time difference is now used as the reference variable and the corresponding lat-lon coordinates for trajectories A and B are indicated in brakets.

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6. RC: 6) concerning Fig. 5, is it possible to get also De from DARDAR for this cloud ?

AR: This is a good point, DARDAR r_{eff} retrievals are now added in Fig. 6(d) of the revised manuscript and are briefly described in Sec. 5.2.

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7. RC: 7) The long descriptive text of the case study is sometimes difficult to follow. I suggest for example to move the analysis of the collocated air track comparison (Fig. 8) to a supplement.

AR: We fully agree with this comment, especially considering that the paper already is long and that thorough in situ analyses have extensively been discussed in the previous section. This figure aimed at comforting these results and show that DARDAR-LIM is capable of reproducing the spatial variability of N_i observed by the 2D-S. Following this comment, it has been moved to supplementary materials (see Fig. S7) and the discussion in Sec. 5.2 has been shortened accordingly.

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8. RC: 8) I would rename section 6 ‘Presentation of global Ni climatologies’ and 6.1 ‘Geographical distributions’. P21l5: ‘considered with caution’ instead of ‘cautiously considered’

AR: We thank the referee for this comment, Sec. 6 has been edited accordingly.

References:

A. Afchine, C. Rolf, A. Costa, N. Spelten, M. Riese, B. Buchholz, V. Ebert, R. Heller, S. Kaufmann, A. Minikin, C. Voigt, M. Zöger, J. Smith, P. Lawson, A. Lykov, S. Khaykin, and M. Krämer. Ice particle sampling from aircraft – influence of the probing position on the ice water content. *Atmos. Meas. Tech.*, 11(7):4015–4031, 2018. doi: 10.5194/amt-11-4015-2018.

B. Baker and R. P. Lawson. Improvement in determination of ice water content from two-dimensional particle imagery. part i: Image-to-mass relationships. *J. Appl. Meteor. and Clim.*, 45(9):1282–1290, 2006. doi: 10.1175/JAM2398.1.

J. Delanoë, A. J. Heymsfield, A. Protat, A. Bansemer, and R. J. Hogan. Normalized particle size distribution for remote sensing application. *J. Geophys. Res*, 119(7):4204–4227, 2014. doi: 10.1002/2013JD020700.

R. C. Jackson, G. M. McFarquhar, A. M. Fridlind, and R. Atlas. The dependence of cirrus gamma size distributions expressed as volumes in n0-λ-μ phase space and bulk cloud properties on environmental conditions: Results from the small ice particles in cirrus experiment (sparticus). *Journal of Geophysical Research: Atmospheres*, 120(19):10,351–10,377, 2015. doi: 10.1002/2015JD023492.

A. Muhlbauer, T. P. Ackerman, J. M. Comstock, G. S. Diskin, S. M. Evans, R. P. Lawson, and R. T. Marchand. Impact of large-scale dynamics on the microphysical properties of midlatitude cirrus. *Journal of Geophysical Research: Atmospheres*, 119(7):3976–3996, 2014. doi: 10.1002/2013JD020035.

T. D. Thornberry, A. W. Rollins, M. A. Avery, S. Woods, R. P. Lawson, T. V. Bui, and R.-S. Gao. Ice water content-extinction relationships and effective diameter for ttl cirrus derived from in situ measurements during attrex 2014. *J. Geophys. Res. Atmos.*, 122(8):4494–4507, 2017. doi: 10.1002/2016JD025948.