Author responses to Reviewer 2

Format: The reviewers' comments are in black font while author responses are in red font. Text in red font italics indicates revised/added text in the revised manuscript.

We understand that reviewing this paper took a lot of time and effort, and we sincerely thank you for your comments that have improved this paper. Below are our responses to the general and specific comments:

Review of "Advances in CALIPSO (IIR) cirrus cloud properties retrievals — Part 1: Method and testing" by Mitchell et al.

The manuscript presents significant improvements to the retrieval method previously described by Mitchell et al. (2018). These include methodological refinements, incorporation of additional in-situ observations to develop new empirical relationships linking retrieval properties with CALIPSO observations, and benefits from recent improvements in the IIR and CALIOP operational products (version 4). The updated retrieval approach appears not only to show more precise results but also notably enhances sensitivity to tropical tropopause layer cirrus and polar stratospheric clouds. The method presented, following Mitchell et al. (2018), remains unique and built upon robust theoretical considerations. A major advantage over existing retrieval methods is that it does not rely on assumptions regarding the ice particle size distribution. It provides an extensive set of (interconnected) microphysical properties, such as the IWC, effective size De, extinction, and Ni. The latter is particularly valuable to the community, given the limited availability of such retrievals from satellite remote sensing. The authors provide thorough uncertainty evaluations, including the propagation of retrieval uncertainties and statistical comparisons with in-situ observations. I have no fundamental criticisms of the methodology itself. The study clearly falls within the scope of ACP, although, in my opinion, it could fit more naturally as a technical note. The retrieval methodology is robust, and the resulting product is highly valuable. While I have few specific concerns regarding the method itself, I do have several major general comments on clarifying the nature of the retrievals, the capabilities and limitations of the method, and aspects of its validation. I recommend publication after addressing the major revisions detailed below.

General comments:

1. The authors have thoroughly discussed uncertainties throughout the manuscript, including uncertainties propagated through operational CALIPSO products (sections 2.2.3 and 2.2.4) and indirect comparisons with in-situ measurements. However, the key conclusions related to these uncertainties are, in my opinion, not sufficiently highlighted in the current conclusions section. I suggest including a more comprehensive summary of this uncertainty analysis and explicitly outlining the method's limitations. Additionally, clearly defining optimal conditions for the retrieval's application would help users better understand how to effectively utilize or compare the dataset (e.g., for model evaluations). Specifically, aspects related to land/sea contrasts and impacts from snow and sea ice discussed in section 2, along with clarifications associated with the other points below, should be better highlighted in the conclusions.

Item (1) in the conclusion was modified and now reads (changes in italic):

"By expanding the sampling range to include optically thinner cirrus clouds ($0.01 < \tau < 3$) *over oceans*, the sampling has become more representative of all cirrus clouds *over oceans*. *The sampling over land, snow,* *and sea ice remains limited to thicker cirrus clouds having τ > 0.3 because of larger random uncertainties in IIR absorption optical depth retrievals*."

2. Operational product uncertainties are adequately discussed and identified as significant uncertainty sources in section 3.4. However, uncertainties stemming from in-situ-based parameterizations (e.g., regressions in Table 3 and relationships in Table 5) should also be acknowledged and discussed similarly, as they might be even more significant for this method. Section 4 provides climatological comparisons between retrievals and in-situ measurements, mostly confirming that in-situ measurements fall within the retrieval spread, except notably for Ni in tropical regions (Figures 17 and 18). I think the manuscript would greatly benefit from one or two detailed case studies, involving coincident satellite and in-situ observations (covering both tropical and mid-latitude scenarios). Such case studies should be feasible using the campaigns already discussed or the Krämer et al. (2020) dataset used for validation.

We added the following sentence in Sect. 3.4: "*Note that additional uncertainties in the X- β_{eff} relationships are difficult to estimate and are not included in this assessment.*"

Following also the recommendation by reviewer #1, a case study during the SPARTICUS campaign is now added at the end of Sect. 4.2, which now reads:

"The difficulty to directly compare IIR layer retrievals and aircraft in situ data is illustrated in the SPARTICUS case study shown in Fig. 21 for 30 March 2010. Following the CALIPSO track, the Learjet flew northwards (leg 1, triangles) with measurements at 11 km altitude 7 to 3 minutes before the CALIPSO overpass and then southwards (leg 2, diamonds) with measurements at 11.6 km altitude 6.5 to 8 minutes after. CALIPSO detected a single layer cirrus of top altitude near 12.6 km. The colors in panel a represent the altitude-dependent CALIOP extinction profiles scaled to IIR τ. The colors inside the triangles and diamonds indicate the PSD extinctions larger than 0.01 km^{-1} after averaging over a 30-s period. At the top of panel a is IIR layer α_{ext}, which was derived from τ and Δz_{eq} shown in panel b. As discussed in Sect. 2.2.5, Δz_{eq} represents the portion of a layer contributing the most to the cloud emissivity. The solid black line in panel a is the radiative altitude corresponding to T_r, which to a first approximation corresponds to the mid cloud altitude (see Fig. 7). IIR D_e in red in panel c (with vertical bars indicating $D_e \pm \Delta D_e$) is lower than the in situ values, which is explained by the fact that both legs were below the radiative altitude. That is, in the lower half of an ice cloud, mean ice particle size tends to be larger and N_i lower relative to the upper half due to diffusional growth and aggregation (e.g., Mitchell, 1988; 1994; Field and Heymsfield, 2003). Only a lower portion of the cloud was detected by the CloudSat radar (shown by the stars) between latitudes 36.5° and 36.78°. IIR D_e is the smallest (around 20 µm) south of 36.5° and north of 36.78° where there is no radar detection, indicating crystals smaller than about 40 µm. Moreover, the absence of radar detection outside this CloudSat domain (defined by the stars) indicates ice particles smaller than ~ 40 µm, revealing a vertical gradient in ice particle size. Regarding N_i (panel d showing $N_i \pm \Delta N_i$), the large IIR N_i values in red between 300 and 850 L^{-1} are explained by large N_i near cloud top. Regarding uncertainties, ΔN_i is overall equal to about 80 L^{-1} and its noticeable increase up to 300 L^{-1} in the northernmost part of the cloud is due to the decrease of τ. The same observation applies to ΔD_e which is between 3 and 11 µm. To summarize, while the vertically resolved extinction retrievals exhibit reasonable agreement with the in situ extinction measurements, the bulk cloud layer retrievals often do not exhibit similar agreement, and this appears to be due to vertical gradients in D_e and N_i and aircraft sampling location. This case study has been classified as ridge crest cirrus which have higher N_i than the other cirrus cloud classes described in Muhlbauer et al. (2014). In this regard, the retrievals here are consistent with this category of cirrus cloud."

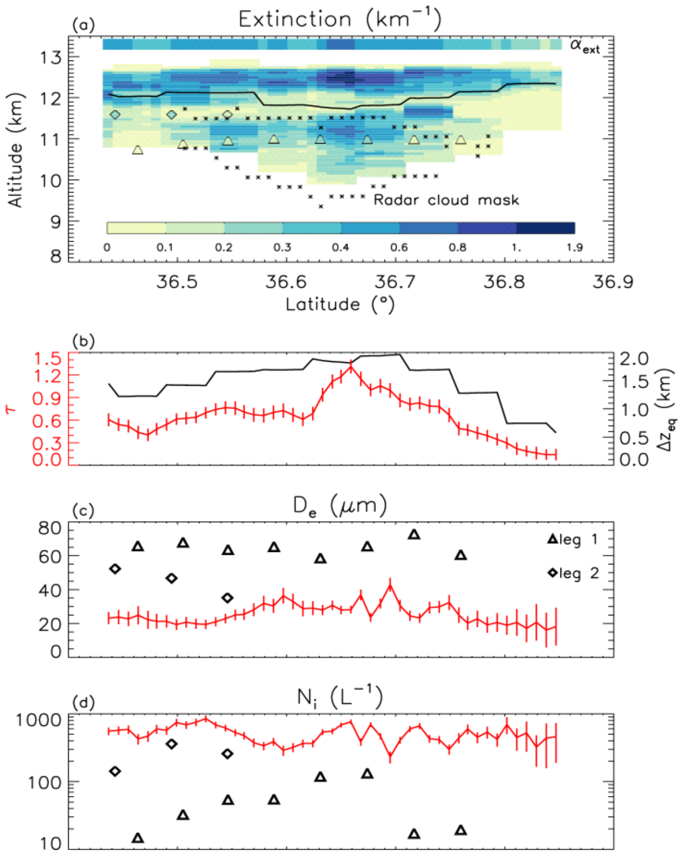


Figure 21. Comparison of IIR retrievals and in situ observations on 30 March 2010 during the SPARTICUS field campaign (CALIPSO granule 2010-03-30T19-27-25ZD). (a) extinction profile derived from the CALIOP lidar, IIR layer α_{ext}, and PSD extinctions in leg 1 (triangles) and leg 2 (diamonds). The stars denote the boundaries of the CloudSat radar GEOPROF cloud mask; (b) IIR τ (red) and Δz_{eq} (black, right axis); (c) IIR (red) and in situ (triangles and diamonds) D_e; (d) same as (c) but for N_i. The vertical bars in red in panels b-d represent the IIR estimated uncertainties.

3. It would also be beneficial to clarify what exactly the retrieved quantities represent. The IIR measurements inherently reflect vertically integrated quantities, weighted by emissions from various cloud layers. Section 2.2.5 briefly discusses these aspects in terms of equivalent layer thickness, but the implications for interpreting retrievals remain somewhat unclear. Typically, passive sensors retrieve integrated properties (IWP, optical depth), while this method retrieves parcel-scale properties (IWC, Ni, De, extinction). Clarifying whether the retrievals represent the entire cloud vertical extent or a specific altitude associated with the radiative temperature (Tr) is needed for proper user interpretation. Comparative case studies as mentioned in my comment #2 could involve CALIOP or DARDAR vertical profiles to clarify these points.

We clarified as suggested and modified Section 2.2.5 as follows:

1)Title was changed to "*IIR equivalent layer thickness, Δz_{eq} and radiative temperature*".

2)The first paragraph now reads: "*Even though the IIR is a passive instrument that retrieves layer integrated quantities such as cloud optical depth, the cloud boundaries information provided by CALIOP allows one to retrieve vertically resolved layer properties such as the layer extinction coefficient. However, the high sensitivity of CALIOP to cloud detection and the expected variability of extinction* *within the layer are such that only a portion of the cloud layer detected by CALIOP is "seen" by IIR. Thus, relevant for our retrievals is the IIR equivalent layer thickness, Δz_{eq}, which is estimated using the IIR in-cloud weighting function derived from the in-cloud 532 nm CALIOP extinction profile of vertical resolution, δz (Garnier et al., 2021a).*

3)Later in the section, we modified the text to clarify why the red and black curves have similar shape in panel a of Fig. 5 (new text in italic): "The first example in panel a is a TTL cirrus between 15.13 and 16.5 km observed in June 2010. Retrieved ε_{eff} is equal to 0.06 and the black and red curves have an almost identical shape *because the attenuation term in Eq. (12) is close to 1*".

4)The beginning of the last paragraph was re-written to note that T_r can be seen as a first approximation as the temperature corresponding to mid-cloud optical depth. It now reads: "*The examples shown in Fig. 5 illustrate that the IIR weighting function is in first approximation the CALIOP extinction profile normalized to the optical depth if the attenuation term in Eq, (12) is supposed to be close to 1 and ε(i) is approximated to the corresponding τ_{abs} in Eq. (13). This IIR weighting function is also used to determine the cloud centroid radiance and the corresponding radiative temperature, T_r, (Garnier et al., 2021a), which is given in red in each panel. The temperatures in black are T_{top} and T_{base} at the layer top and base altitudes, respectively. Because computing a centroid temperature would yield a temperature differing by less than a few tenths of a degree Kelvin (M2018), T_r can be seen as the temperature dividing the cloud optical depth into equal parts.*"

4. The retrieval method relies primarily on parameterizations derived from tropical campaigns, with only one mid-latitude campaign (SPARTICUS) providing somewhat less robust data due to reliance on 2D-S measurements and subsequent corrections. The question of the global applicability of the method should be addressed more explicitly, particularly in the conclusions, given the global applications discussed in Part 2 of this series. Clarifying whether significant limitations exist, such as for high-latitude regions, and advising users on potential constraints would be valuable.

The following sentences were added to the conclusion:

1)We added a new item (3) which reads: "*The computation of in situ β_{eff} used in the X - β_{eff} relationships was improved using mass-dimension relationships that appear more realistic.*"

2) For item (6), we added "*The X - β_{eff} relationships for the SPARTICUS synoptic and the TC4 anvil cirrus yield similar N_i retrievals (see Fig. 17)*."

3) The second paragraph under Conclusions now begins with: "*This study should be extended to more field campaigns, in particular at high latitude, to further investigate the variability in the X - β_{eff} relationships, which seems more important for D_e than for N_i*."

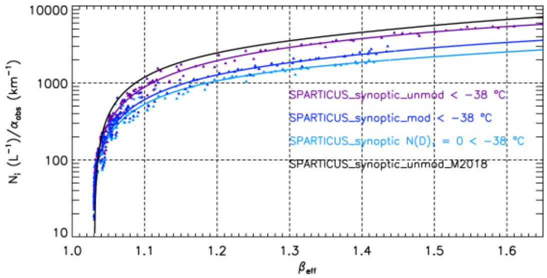
5. It would be informative to directly compare the performance of this updated retrieval method with Mitchell et al. (2018), perhaps through global maps or temperature-dependent analyses. Such comparisons would more clearly highlight the specific advancements made, aligning directly with the manuscript's title.

We agree that this discussion was missing. The manuscript was modified as follows:

1)Sect. 3.1 now also discusses the impact of using the EM2016 mass-dimension relationship.

- The title of this section is now: “Correction of the smallest bin of the 2D-S probes *and mass-dimension relationship*”.

- Figure 13 now includes the relationship for assumption (1), i.e. $N(D)_1$ unmodified, as derived in M2018 to illustrate that using the EM2016 relationship reduces N_i.



- The first paragraph now ends with: “*In addition, based on the findings presented in Sect. 2.4, we now use the EM2016 mass-dimension relationships*”.

- The beginning of the second paragraph reads (changes in italic): “It is instructive to examine the impact of *these changes* in terms of the N_i retrieval as described in Eq. (2). The field campaign dependence (and thus the 2D-S probe dependence) of N_i enters through the β_{eff} dependent terms in Eq. (2), namely through the N_i/A_{PSD} - β_{eff} and the [$1/Q_{abs,eff}$ (12 μm)] - β_{eff} relationships. From Eq. (2), the product of these two ratios is N_i/α_{abs} which is plotted in Fig. 13, showing the impact *of the mass-dimension relationships and of the* $N(D)_1$ assumption on the N_i retrieval. There are three assumptions: (1) $N(D)_1$ is unmodified, meaning the $N(D)_1$ measurement is correct, (2) $N(D)_1$ is modified, divided by 10.4 as discussed in Sect. 2.3, and (3) $N(D)_1 = 0$. These three assumptions were evaluated in Fig. 13 using 2D-S PSD data from the SPARTICUS field campaign measured at temperatures less than -38°C *using the EM2016 relationships. Assumption (1) as derived in M2018 is also shown in black, showing that using the EM2016 relationships (in purple) reduces retrieved* N_i.”

2) A new Section 3.5 entitled “Comparison with previous work” was added, which reads:

For comparison with the previous work (M2018), Figure 17a shows the N_i /α_{abs} ratio from the ATTREX-POSIDON (black), SPARTICUS (navy blue), and TC4 (red) relationships developed in this study vs. the N_i /α_{abs} ratio from SPARTICUS $N(D)_1$ unmodified established in M2018, which, out of the 4 formulations examined in M2018, yielded the largest N_i values (Fig. 5 in M2018). Also shown in Fig. 17a is TC4 $N(D)_1 = 0$ from M2018 (dashed orange) which yielded the lowest N_i values. We see that N_i from this study is about half N_i from M2018 SPARTICUS unmodified for both SPARTICUS and TC4 which are similar to M2018 $N(D)_1 = 0$, while ATTREX-POSIDON is half to two third. Panel b in Fig. 17 compares the D_e retrievals.

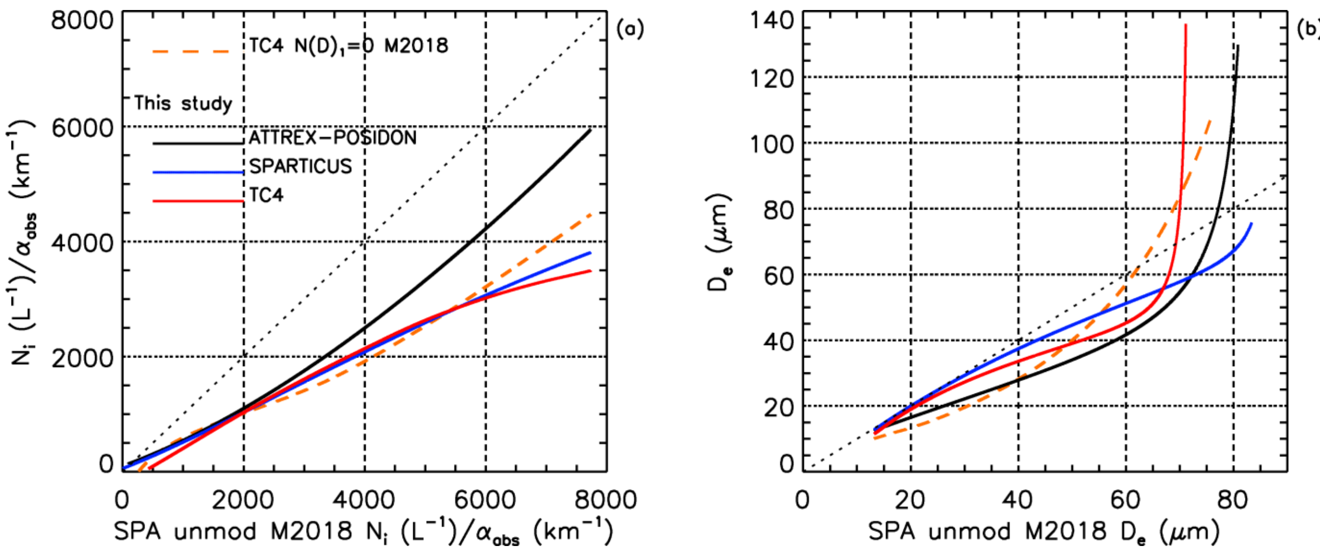


Figure 17. Comparison of (a) N_i and (b) D_e retrievals in this study (black: ATTREX-POSIDON, navy blue: SPARTICUS, red: TC4) and from TC4 $N(D)_1 = 0$ in M2018 (dashed orange) with retrievals from SPARTCUS $N(D)_1$ unmodified in M2018.

Specific comment 1. Given the extensive general comments, I have only one concise specific comment or rather a question: Section 2.2.5 illustrates the utility of the IIR weighting function to reconstruct CALIOP extinction profiles. Could similar reconstructions be feasible for IWC, De, and Ni profiles? While this clearly extends beyond the present study's scope, briefly mentioning this possibility as a potential future improvement in the conclusions would be beneficial.

The IIR weighting function is derived from the CALIOP extinction profiles at 532 nm which does not contain explicit microphysical information. Its application for estimating profiles of IWC, D_e, and N_i would require to also know the in-cloud variation of β_{eff}, which could be inferred from *a priori* assumptions regarding variations of D_e and further constrained by co-located radar observations when available. New text has been added near the end of Conclusions as follows:

This CALIPSO retrieval provides layer properties based on layer β_{eff} and the IIR weighting function derived from the CALIOP extinction profiles at 532 nm. Future work could aim at estimating in-cloud vertical profiles of IWC, D_e, and N_i. This would require knowledge of the in-cloud variation of β_{eff}, which could be inferred from a priori assumptions regarding variations of D_e further constrained by co-located CloudSat radar observations when available.