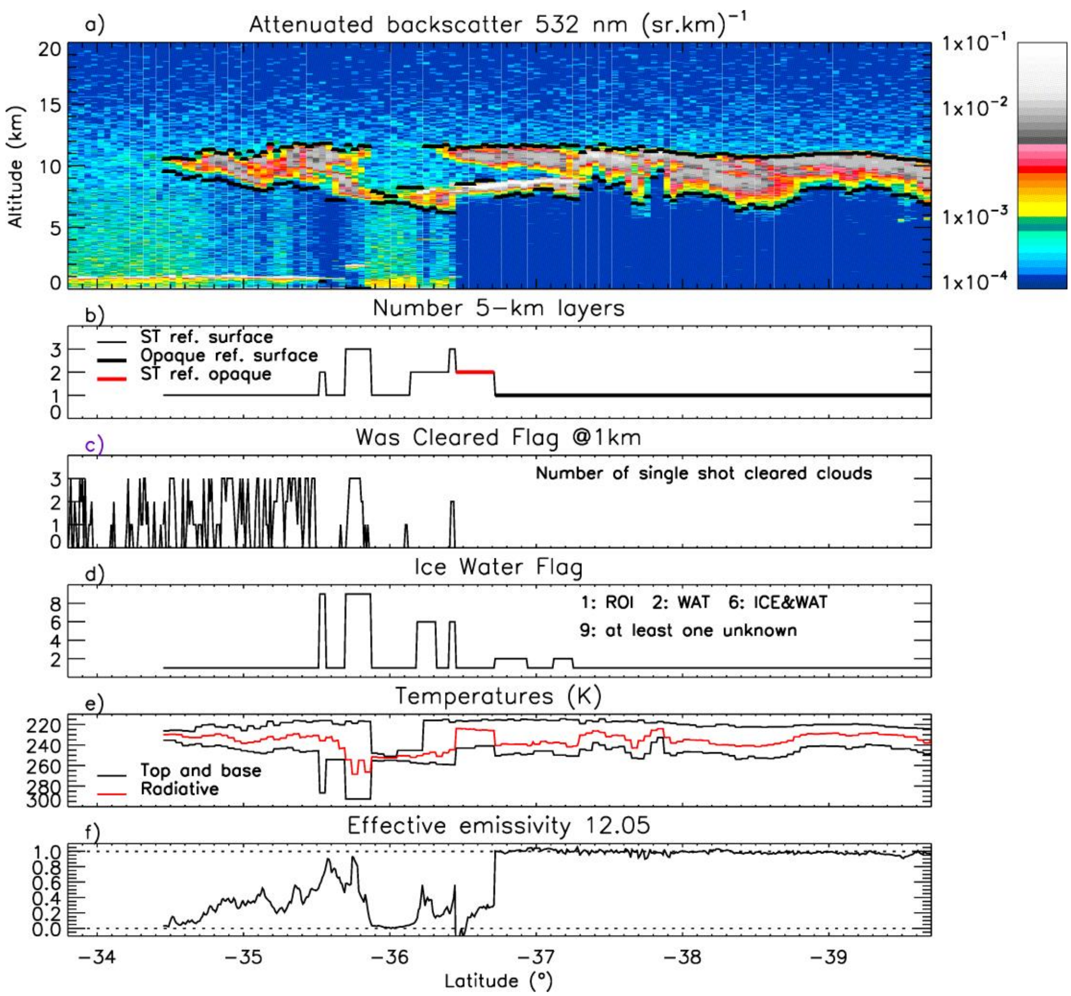
Response to anonymous referee #4

The authors are thankful to the referee for his/her thorough review of the paper.

Our responses are detailed below, and the manuscript has been revised accordingly. In the following, the reviewer's comments are in black, and our answer to each comment is in red.

The manuscript describes the updated version of the cloud retrieval products derived from the IIR instrument on CALIPSO. The manuscript is written well and contains some interesting results. However, as the paper aims to demonstrate the improved accuracy, some more comparisons with previously published results and some more discussion on the results is needed.
Some specific papers I suggest to reference are Kahn et al. (2018), King et al. (2013), Platnick et al. (2017) and Van Diedenhoven et al. (2020). Detailed references are below. Further specific comments are below.

Section 2: Please add a legend at panels c and d of Figure 1.
Done. The revised figure 1 is:



Section 3. Could you remind the reader what the ice model used for V3 was and also that change caused by the ice model are discussed in part I?
The following text has been added:

*"In V3, the LUTs were derived using single scattering properties of the "solid column" and "aggregate" crystal models from the database described in Yang et al. (2005), with no particle size distribution. We showed in Part I that everything else being equal, the size distribution introduced in V4 increases retrieved $D_e$."*

New reference:
Yang, P., Wei, H., Huang, H. L., Baum, B. A., Hu, Y. X., Kattawar, G. W., Mishchenko, M. I., and Fu, Q.: Scattering and absorption property database for non-spherical ice particles in the near-through far-infrared spectral region, Appl. Opt., 44, 5512–5523, https://doi.org/10.1364/AO.44.005512, 2005.

Section 3.4.1: Kahn et al. (2018) also found a similar difference in effective radius of semi-transparent and opaque clouds with similar, but slightly larger, sizes. For opaque cloud tops, the global statistics of Van Diedenhoven et al. (2020) show similar, but somewhat larger, mean effective sizes over ocean. Furthermore, King et al. 2013 and Platnick et al. (2017) show similar histograms with seemingly comparable results.
a)Note that the "non-opaque" clouds in Kahn et al. (2018) have emissivity < 0.98, and likely include our ST clouds and a very large fraction of our opaque clouds, because the term "opaque" in our study refers to clouds that are opaque to the CALIOP lidar. The CALIOP opaque clouds have emissivity typically > 0.8 and a lot of them have emissivity < 0.98 and are called "non-opaque" in Kahn et al. (2018). We added a reference to Guignard et al. (2012) who show variations of $D_e$ with effective emissivity.

The following text is added:

*"Median $D_e$ in opaque clouds is around 60 µm and the distributions peak at 50 µm. It is larger than in ST clouds, which is consistent with retrievals based on AIRS thermal infrared data (Guignard et al., 2012; Kahn et al., 2018)."*

New reference:

Guignard, A., Stubenrauch, C. J., Baran, A. J., and Armante, R.: Bulk microphysical properties of semi-transparent cirrus from AIRS: a six year global climatology and statistical analysis in synergy with geometrical profiling data from CloudSat-CALIPSO, Atmos. Chem. Phys., 12, 503–525, https://doi.org/10.5194/acp-12-503-2012, 2012.

b)We decided to reference Van Diedenhoven et al. (2020) in section 3.4.2 (see response to next comment), where Kahn et al. (2018) is referenced again.

c)We agree that comparisons with MODIS are important, which is why the paper includes a dedicated section (3.5) with comparisons of collocated MODIS and IIR retrievals for ST and opaque ice clouds. Platnick et al. (2017) is referenced in this section. We chose not to reference King et al. (2013) because we wanted to focus on comparisons with MODIS Collection 6.

As discussed in Section 3.5, IIR and MODIS retrievals typically do not cover the same range of optical depths. To clarify the range of optical depths covered by IIR, we added median $\varepsilon_{eff,12}$ and median $\tau_{vis}$ in Table 4. Furthermore, we added the following sentences in section 3.4.1:

*"The ST clouds are optically thin, with median IIR $\tau_{vis}$ of only 0.2 - 0.26."*

and

*"These opaque clouds have median $\varepsilon_{eff,12}$ equal to 0.95 at night but only 0.86 for daytime data, with median IIR $\tau_{vis}$ equal to 5.6 and 3.8, respectively".*

Section 3.4.2: I find Figure 9 interesting and strongly suggest to also include a similar figure with the opaque cloud results in the paper.

We followed the reviewer's suggestion and included a new figure (Fig. 10) for opaque clouds (all the following figures are renumbered). The new Figure 10 is:

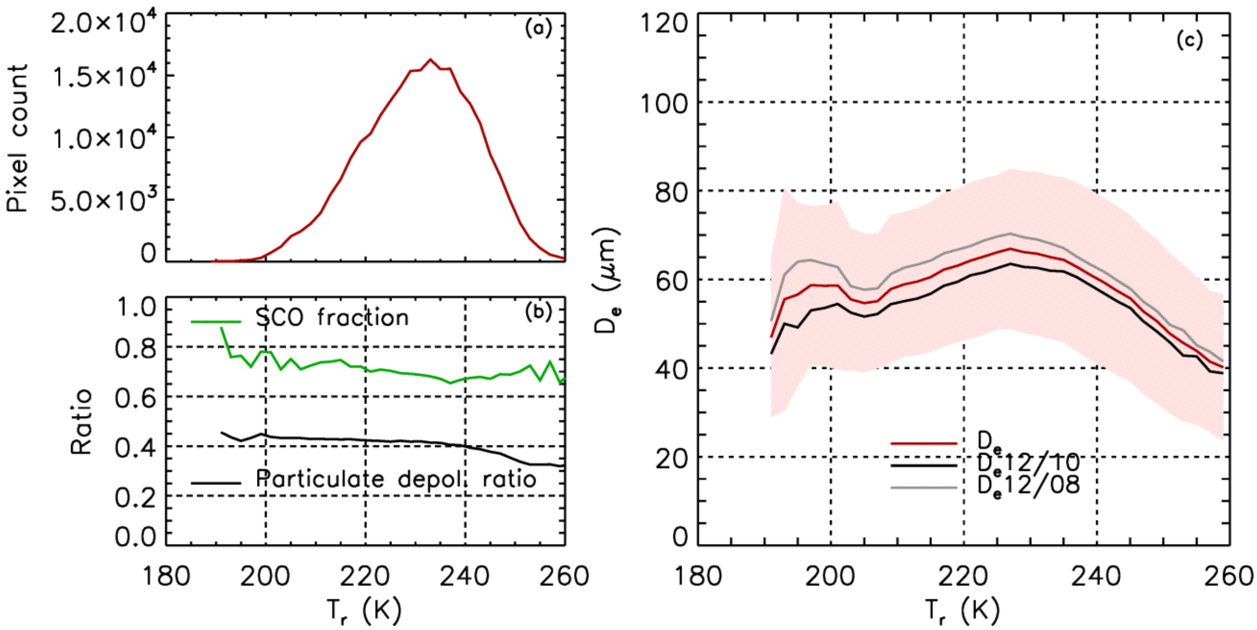



**Fig. 10: Same as Fig. 9 but for opaque clouds.**

Section 3.4.2 now reads as follows. The changes are in italic.

"Recall that $D_e$ is retrieved using the crystal model (SCO or CO8) that agrees the best with IIR in terms of the relationship between $\beta_{eff}$12/10 and $\beta_{eff}$ 12/08. As seen in Fig. 9, the SCO crystal model is selected in 80 % of the ST clouds of $T_r$ < 205 K. This fraction steadily decreases down to 60 % as $T_r$ increases up to 230 K (Fig. 9b) and remains stable above 230 K. This result is qualitatively consistent with previous findings using V3 (Garnier et al., 2015), and, as was discussed in this paper, both the IIR model selection and the mean CALIOP integrated particulate depolarization ratio (in black in Fig. 9b) indicate changes of crystal habit with temperature. *In opaque clouds (Fig. 10), both the IIR model selection and the CALIOP depolarization ratio between 200 K and 230 K are less temperature-dependent than in ST clouds*. The difference between mean $D_e$12/10 and mean $D_e$12/08 in black and grey in Fig. 9c is a measure of the residual mismatch between IIR observations and the selected model. We see two temperature regimes, that is, below and above 225 K, with a better agreement between IIR and the LUTs at the warmer temperatures. This suggests that the V4 models are better suited for warmer clouds and that they do not perfectly reproduce the infrared spectral signatures of colder clouds composed of small crystals. It is acknowledged that the highly variable ice particle shapes found in ice clouds (Lawson et al., 2019 and references therein) are likely not fully reproduced through the two models chosen for the V4 algorithm. It is further noted that the Clouds and the Earth's Radiant Energy System (CERES) science team is planning to use a two-habit model for retrievals in the visible/near infrared spectral domain (Liu et al., 2014; Loeb et al., 2018). This model would be a mixture of two habits (single column and an ensemble of aggregates) whose mixing ratio would vary with ice crystal maximum dimension, with single columns prevailing for the smaller dimensions. Interestingly, our findings appear to be consistent with this approach.

*In both thin ST clouds (Fig. 9c) and opaque clouds (Fig. 10c), $D_e$ increases with cloud radiative temperature until it reaches a maximum value around 250 K in ST clouds and 230 K in opaque clouds. Kahn et al. (2018) found that for clouds of emissivity smaller than 0.98, $D_e$ is maximum and around 50 μm at 230 K, which is consistent with our findings, keeping in mind that clouds with emissivity smaller than 0.98 are found in both our ST and opaque clouds. The increase of cloud average $D_e$ with cloud radiative temperature in ST clouds (Fig. 9c) is in general agreement with numerous previous findings (e.g. Hong and Liu, 2015).* The decrease *of $D_e$* between $T_r$ = 250 K and 260 K *for ST clouds* is possibly due to an increasing fraction of small liquid droplets in these prevailingly ice layers, which would be consistent with the fact that CALIOP integrated particulate depolarization ratio decreases from 0.37 to 0.30 (Fig. 9b). *Similar comments apply for opaque clouds for $T_r$ between 230 and 260 K. Using combined POLDER (POLarization and Directionality of the Earth's Reflectances) and MODIS data, Van Diedenhoven et al. (2020) found that $D_e$ at the top of thick clouds of optical depth larger than 5 is maximum at cloud top temperature equal to 250 K, rather than $T_r$ = 230 K for our opaque clouds. This discrepancy might be partly explained if the cloud radiative altitude is higher in the cloud than the cloud top derived from the visible observations, which could also explain that $D_e$ shown in Van Diedenhoven et al. (2020) is larger than in this study."*

Kahn et al. (2018) find similar variations of effective radius with cloud temperature for transparent clouds.
Our understanding is that they find similar variations for non-opaque clouds, that they define as clouds of emissivity < 0.98, which corresponds to our ST clouds and a large fraction of our opaque clouds.

For thick clouds, Van Diedenhoven et al. (2020) also show similar variations of effective radius with cloud temperature and find evidence that these size variations are related to variations in crystal growth rates. They also show a vertical variation of crystal shape, which may be consistent with the SCO fraction shown in the manuscript. Please show the statistics also for thick clouds and discuss how it compares to Kahn et al. (2018) and Van Diedenhoven et al. (2020).
We added a new Fig. 10 with results for opaque clouds as suggested and included a discussion (see above).

Since both habit and size vary with temperature, it may be interesting to investigate how habit varies with size. Again, such results can be compared to Van Diedenhoven et al. (2020) for thick clouds. Note that this is just a suggestion.
We are thankful to the reviewer for this great suggestion. We could carry out this type of analyses for a larger dataset for a future publication.

Section 3.5: Van Diedenhoven et al. (2020) found a vertical variation in ice asymmetry parameter that leads to a high bias in MODIS collection 6 ice effective radius for warm clouds. This may partly explain the larger differences between MODIS and IIR for the warmest ice cloud tops.
Again, we are thankful to the reviewer for this possible explanation.

Section 4.3.1: King et al. (2013) and Platnick et al. (2017) show similar histograms for liquid cloud tops. Please discuss the comparison.
We explain at the beginning of Section 4 that the water clouds selected for this study have centroid altitude larger than 4 km and that most of them are composed of supercooled droplets.

We added median $\varepsilon_{eff,12}$ and median $\tau_{vis}$ in Table 5 to highlight the range of optical depths covered by IIR retrievals. Furthermore, the following sentences are now added (the new Fig. 15 is the previous Fig. 14):

"*Note that the IIR retrievals shown in Fig. 15 are for a population of very thin water clouds: median $\tau_{vis}$ is only 0.9 in ST clouds and between 4 and 5 in opaque clouds*"

IIR histograms shown in Fig. 15 and MODIS histograms found in the literature for liquid cloud tops are for different populations of clouds. The IIR cloud population is composed of thin supercooled water clouds in the free troposphere, while the MODIS cloud population includes warmer and lower clouds of larger optical depth. Therefore, we chose to have a dedicated section where we show comparisons of collocated IIR and MODIS retrievals (Section 4.4). We chose not to reference King et al. (2013) because we wanted to focus on comparisons with MODIS Collection 6.

We added this sentence at the beginning of Sect. 4 to inform the reader that comparisons with MODIS are shown in a dedicated section:
"*Our results are presented in Sect. 4.1 to 4.3 and comparisons with MODIS are shown in Sect. 4.4.*"

Section 4.3.2: Although I'm not aware of any other published statistics of liquid drop effective radius as a function of cloud top height for (near-) global clouds, I find the decrease of effective radius with decreasing cloud top temperature a bit surprising. I would expect an increase of effective radius as, under an adiabatic assumption, drops grow as the clouds deepen. I do notice that MODIS results in Fig. 16 show the same variation. Please add some discussion about this in the text. Some more discussion
on how these results relate to other results would be good.
As mentioned earlier, the water clouds selected for this study have centroid altitude larger than 4 km, most of them are composed of supercooled droplets, and in section 4.3.1, we now give the range of optical depths for ST and opaque clouds in Table 5.
We could not find references with similar statistics for a similar population of clouds. We commented on the increase of $D_e$ with temperature by adding the following:

*"It seems that these thin clouds would not be associated with strong updrafts, and the increase of layer average $D_e$ with layer radiative temperature could indicate growth through vapor deposition. In addition, there is an increasing probability for supercooled droplets to freeze as temperature decreases and as their size increases."*