1 Comments from reviewer 3

We would like to thank the referee for reading our manuscript and providing helpful feedback.

1.1 Specific comments

Reviewer comment 1

Line 69: Please include the time periods of these campaigns for completeness.

Author response:

We will include the requested information in the revised version of the manuscript.

Changes in manuscript:

- The sentence introducing the B984 flight will be modified to:

> **Changes starting in line 66:**
>
> The first considered flight, designated B984, ~~took place~~ was performed on 14 October 2016 as part of the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX~~, Schäfler et al. (2018))~~), which took place during September and October 2016 (Schäfler et al., 2018).

- The sentence introducing the C159 and C161 flights will be modified to:

> **Changes starting in line 71:**
>
> The two other flights, designated C159 and C161, ~~took place in March 2019 as~~ were part of the PIKNMIX-F campaign~~.~~, which took place in March 2019.

Reviewer comment 2

Line 107 and 108: Title 2.2 missing capital letter (In situ measurements). Also missing the capital letter in the first sentence of the paragraph below.

Author response:

We will correct this in the revised version of the manuscript.

Reviewer comment 3

Line 109: For completeness I would recommend a better description of what it is meant by "high-level" and the "lower parts" of in situ-sampling. Perhaps it makes more sense to introduce in-situ measurements before the analysis of the co-location of flight tracks.

Author response:

We agree with the reviewer that introducing the in-situ measurements before the analysis of the co-location of flight tracks does indeed improve the structure of the manuscript.

Changes in manuscript:

We will shorten and merge the paragraph starting in l. 112 with the paragraph starting in l. 108.

> **Changes starting in line 108:**
>
> The in situ measurements ~~of cloud hydrometeors were performed during the flights~~ that are relevant to this study are measurements of bulk ice water content using a Nevzorov hot-wire probe (Korolev et al., 2013) and PSDs recorded using DMT CIP-15 and CIP-100 probes, which measure size-resolved particle concentrations with resolutions of 15 and 100 μm, respectively. In situ measurements are available only for flights B984 and C159, which each consist of two parts: A high level run during which the aircraft flew above the cloud system to perform the remote sensing observations and a low level run during which the aircraft flew at lower altitude through the cloud to perform the in situ measurements. A detailed view of the ~~high-level runs and the corresponding in situ sampling paths~~ high and low level runs for the two flights are provided in Fig. 5. For flight C159, this view reveals a noticeable horizontal offset of 3 to 4 km between the ground ~~track~~ tracks of radar and radiometer observations~~and even larger deviations between the lower~~. Even larger deviations occur between certain parts of the ~~in situ sampling flight path and the high-level run~~low level run and the ground tracks of the remote sensing observations.

Reviewer comment 4

Line 130: Background properties of the atmosphere and the surface [. . .]

Author response:

We will correct this for the revised version of the manuscript.

Reviewer comment 5

Line 132-133: Although readers are referred to Pfreundschuh et al. (2020) for a detailed description of the retrieval, perhaps a better synergy between the text and table 2 would add to the description here regarding the parameters of the PSD for the different species.

Author response:

To improve the description of the retrieved PSD parameters as well as the following description of the retrieval, we will extend the paragraph describing the retrieval outputs to introduce the mathematical form of the PSD. The revised version of the paragraph reads:

Changes in manuscript:

> **Changes starting in line 131:**
>
> The output of the retrieval are two parameters of the PSDs of frozen and liquid hydrometeors as well as liquid cloud water content (LCWC) and relative humidity. ~~All~~ Hydrometeor PSDs are represented using the approach proposed by Delanoë et al. (2005): At each level in the atmosphere the concentration of hydrometeors with respect to the volume equivalent diameter D_{eq} is given by
>
> $$N(D_{\text{eq}}) = N_0^* F\left(\frac{D_{\text{eq}}}{D_m}\right) \tag{1}$$
>
> where F is a fixed function that specifies the shape of the normalized PSD and N_0^* and D_m are the retrieved parameters. The N_0^* parameter is retrieved in log space while D_m is retrieved in linear space. Relative humidity is retrieved in a transformed space based on an inverse hyperbolic tangens transformation and CLWC in log space. A listing of all retrieval targets and corresponding a priori assumptions ~~are listed~~ is provided in Tab. 2.

Reviewer comment 6

Line 136: [...] Atmospheric Radiative Transfer Simulator (ARTS, Buehler et al., 2018) is used [...]

Author response:

Since the ARTS acronym is introduced already earlier in the manuscript we will rewrite the sentence as follows.

Changes in manuscript:

> **Changes starting in line 135:**
>
> The latest stable release (version 2.4) of ~~the Atmospheric Radiative Transfer Simulator (ARTS , Buehler et al. (2018))~~ ARTS (Buehler et al., 2018) is used to implement the forward model used in the retrieval.

Reviewer comment 7

Line 145: "In the first one, the bulk properties". Use lower case in "in the first one [...]"

Author response:

We will correct this in the revised version of the manuscript.

Reviewer comment 8

Line 151: After the sentence that starts with "The updated values of [. . .]", for completeness perhaps the cloud ice PSD equation could be included in parentheses with the Dm, N0* and the shape parameter.

Author response:

The ice PSD equation in its complete form looks as follows:

$$N(D_{\mathrm{eq}}) = N_0^* \beta \frac{\Gamma(4)}{4^4} \frac{\Gamma(\frac{\alpha+5}{\beta})^{4+\alpha}}{\Gamma(\frac{\alpha+4}{\beta})^{5+\alpha}} (\frac{D_{\mathrm{eq}}}{D_m})^{\alpha} \exp\left\{ - \left(\frac{D_{\mathrm{eq}}}{D_m} \frac{\Gamma(\frac{\alpha+5}{\beta})}{\Gamma(\frac{\alpha+4}{\beta})} \right)^{\beta} \right\} \tag{1.1}$$

Due to its relatively bulky form and since we felt it does not contribute any useful information for the interpretation of the presented results, we chose not to reproduce the equation in the manuscript
However, in order to make the role of the shape parameters mentioned in the manuscript more clear we will rewrite the sentence in question and refer to the compact form of the PSD that will be included in the revised version of the manuscript.

Changes in manuscript:

The ~~updated values from Cazenave et al. (2019) are used as shape parameters of the distribution~~ normalized shape function F in Eq. (1) follows a modified gamma distribution shape using the parameters from Cazenave et al. (2019).

Reviewer comment 9

Line 152: single particle optical properties.

Author response

We will correct this in the revised version of the manuscript.

Reviewer comment 10

Line 154: "Since this is difficult". Please expand on this for completeness.

Author response

We will expand on the difficulty of choosing a particle model for ice hydrometeors in the revised manuscript.

Changes in manuscript:

> **Changes starting in line 154:**
>
> ~~Since this is difficult,~~ Due to the large variability of ice particle shapes in real clouds, it is unclear which particle habit should be chosen to best represent their radiative properties or whether such a unique best model exists at all. Hence, the approach taken here is to select a set of habits ~~has been chosen with which the retrieval will be run in order~~ and perform the retrieval with each of them. This will allow us to investigate the impact of the selected habit on the retrieval results.

Reviewer comment 11

Line 175: retrieved hydrometeor size distributions.

Author response:

We will correct this in the revised version of the manuscript.

Reviewer comment 12

Line 224: for which the best agreement.

Author response:

We will correct this in the revised version of the manuscript.

Reviewer comment 13

Line 286: typo in "For, flight B984 [...]". Move the comma please.

Author response:

We will correct this in the revised version of the manuscript.

Reviewer comment 14

Line 298: typo in "Secondly, the a clear backscattering"

Author response:

We will incorporate this suggestion in the revised version of the manuscript.

Reviewer comment 15

Line 349: Just comment here. I wonder if for a real scenario, with the complexities of the vertical differences in particle orientation, habit phase, etc, this would add to 20% in the resultant observations at nadir.

Author response:

This is certainly true. However, the point we were trying to make was to estimate the impact that neglecting particle orientation may have on the presented results. We were therefore interested only in an upper bound of the effect that particle orientation may have on the results in order to estimate the robustness of our results.

Reviewer comment 16:

Figure 10. The discussion mentions the large differentes for 243 GHz, however flight B984 shows smaller residuals at this channel than the other two channels. Is there anything to add to the discussion regarding this? Also, there are large differentes for 448 +- 7.2 GHz, specially for flight C159. Could you comment on that too?

Author response:

As we explain in the manuscript, we suspect that the larger residuals for flights C159 and C161 are caused by precipitation that is not observed by both sensors due to co-location issues. In addition to spatial co-location issues, flight C159 and C161 are affected by temporal co-location issues with delays of up to 30 minutes between the observations.
The initial version of the manuscript has not discussed the temporal co-location of the observations that differs significantly between the flights. For the revised manuscript we propose to add a new figure that displays the time delay between the radar and radiometer observations for the different flights. We will also extend the discussion of the residuals.
While the 448 $\pm$7.2 GHz channel may also be affected by this, the residuals look mostly random and are thus most likely caused by the increased thermal noise in this channel.

Changes in manuscript:

We will rewrite the discussion of the retrieval residuals.

- We will add the figure shown in Fig. 1.1 together with the description shown below to the the section the presents the radar observations.

> **Changes starting in line 90:**
>
> While the radar observations for flight B984 come from an airborne radar, the observations for flights C159 and C161 stem from a spaceborne sensor. The high velocity of the spaceborne sensor causes significant temporal delay

between co-located observations from the radiometers and the radar. Figure 1.1 displays the delay between co-located radar and radiometer observations with respect to the along-track distance for the three flight scenes. While the delays for flight B984 remain mostly within 5 minutes, they reach values exceeding 30 minutes for the two other flights.

- The presentation of the retrieval residuals will be extend as follows.

Changes starting in line 188:

Radiometer residuals for flight B984 are mostly within ±5 K ~~. For the two other flightsthe residuals are larger. Differences up to and~~ but larger for flights C159 and C161. For these two flights, residuals exceeding 10 K are observed ~~at~~ in the window channels up to 243 GHz as well as ~~in~~ the outermost channels around the absorption lines at 118 GHz and 183 GHz. Since these ~~correspond to profiles in which residuals of opposite sign are present~~ occur in profiles where precipitation is present and in which similar residuals can be observed in the radar observations, a likely explanation is that they are caused by ~~small-scale precipitation events that are missed by one of the~~ precipitation that is not observed by all sensors due to spatial and temporal co-location issues. Especially the large residuals in the 243 GHz channel for flight C161 at around 100 km along track distance may well be caused by the evolution of the convective cloud during the delay of almost 30 minutes that separates the radiometer and radar observations.

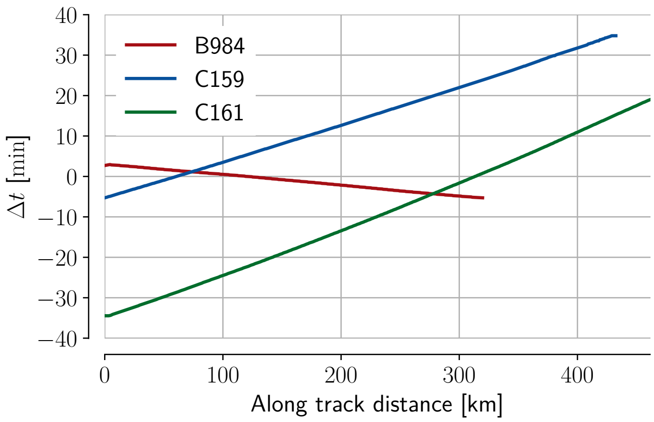

Figure 1.1: Delays between the co-located observations from radar and radiometers for the three flights.

Reviewer comment 17:

Figure A1: Have you looked at a similar figure for the other channels?

Author response:

We did indeed look at similar figures for other channels but focused on channels that were present on all flights, of which none showed any indications of a relationship between IWP and residuals. However, when revisiting these plots, we discovered an error in Fig. A1 from the manuscript, which showed residuals from the 325 ± 1.5 GHz channel instead of the 325 ± 3.5 GHz channel for flight B984. We will of course correct this for the revised version of the manuscript.
Moreover, upon closer inspection of the residuals in the different channels that were available for flight B984, we did discover signs of a potential effect of the assumed ice particle shape on the retrieval residuals. We therefore propose to include an additional figure with scatter plots for these channels in the manuscript.

Changes in manuscript:

- We will replace Fig. A1 with the corrected version shown in Fig. 1.2.
- We will include the figure shown in Fig. 1.3 in the manuscript.
- We will extend the discussion of the impact of the ice particle shape on the residuals as follows.

> **Changes starting in line 264:**
>
> In an effort to better separate a potential signal from the ice particle shape in the retrieval residuals, we have investigated the relationship between retrieved IWP and the residual for different channels. Most channels that were available on all flights do not show a clear sign of a relation between the particle shape and the residuals. As an example for those channels we provide scatter plots of the retrieved IWP and the channel residual for the 325 ± 3.5GHz channel in Fig. 1.2 in the appendix~~displays the relation~~. We did however identify two channels from flight B984 that may exhibit a potential signal from the ice particle shape in the residuals. The scatter plots for these two channels are provided in Fig. 1.3. For the 325 ± 9.5 GHz channel, all tested particles except the Large Plate Aggregate seem to manifest a positive correlation between IWP and ~~corresponding residualsin~~ the residuals. For the 243 ± 2.5GHz, the 6-Bullet Rosette, 8-Column Aggregate and Large Plate Aggregate exhibit a weak negative trend in the residuals, while it remains positive for the Large Column Aggregate and Evans Snow Aggregate. At least for these two channels the ~~325 ± 3.5GHz channel. This channel was chosen because it belongs to the channels displaying the largest differences between residual distributions for different particle habits (~~Large Plate Aggregate seems to stand out as the ice particle shape yielding the smallest residuals across the retrieved range of IWP values.
>
> We will adapt all other sections that discuss the ability of the sub-millimeter

> observations to constrain the shape of ice particles to take the this potential signal into account.
>
> Since the Large Plate Aggregate is the particle for which the best agreement between retrieved and in situ measurements was obtained, this may be viewed as an encouraging result indicating that sub-millimeter observations can, at least in combination with radar observations, be used to constrain the shape of ice particles in clouds. However, taking into account that these are observations from only one flight as well as the complicated statistics of the results from Fig. ~~11~~1.3, it remains unclear whether these findings are statistically significant. A potential confounding factor may be the impact of the a priori assumptions on these results. Since the retrieval balances the residual with the deviation from the a priori, this may lead to a worse fit for the softer particles (Large Column Aggregate, Evans Snow Aggregate) for which a much higher D_m must be retrieved for a similar scattering effect. While this effect may be desired in the retrieval to avoid the apparently excessive amounts of ice retrieved using these particle shapes, it is the combination of observations and a priori assumptions that constrains the particle shape and not the observations alone. We present these results here mainly for completeness and to serve as a potential basis for further investigation.

Reviewer comment 18:

Figure 14: How do these results translate to IWP? Perhaps a general summary of such a Figure could add to the discussion of Figure 14.

Author response:

The IWP along the in situ measurement path is mostly dominated by the high concentrations at the base of the cloud. This leads to a consistent overestimation of the IWP for the radar only retrieval. The combined retrieval exhibits large variability in the results but the Large Plate Aggregate and 6-Bullet Rosette yield the results closest to the in situ measurements.

Changes in manuscript:

- We will include Tab. 1.1 in the revised manuscript, which contains the in situ measured and retrieved IWP for flight B984.
- We will extend the discussion of the added value of the combined retrieval as follows.

> **Changes starting in line 327:**
>
> The tendencies observed for the retrieved IWC in Fig. 14 are even more pro-

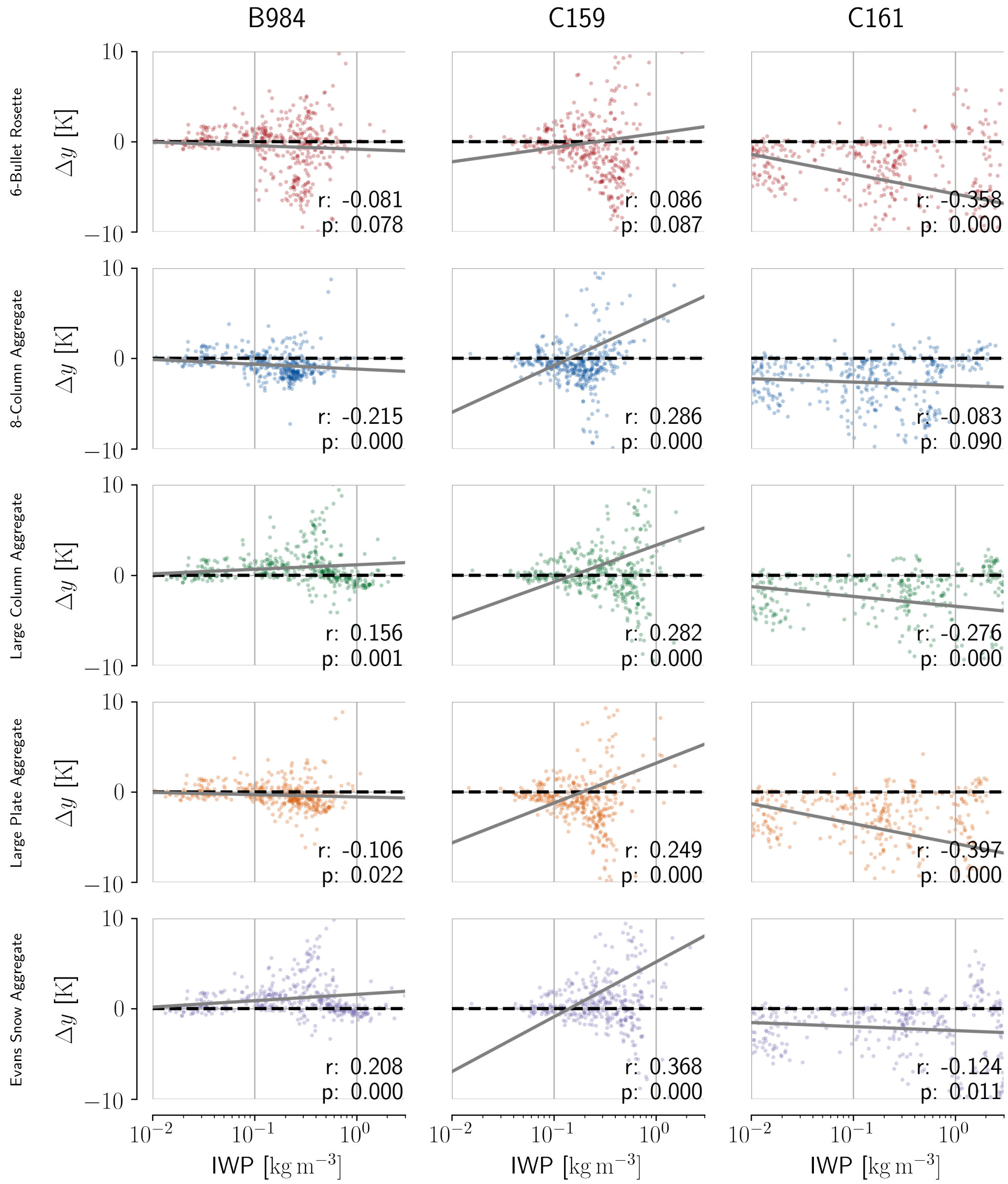

Figure 1.2: Scatter plots of retrieved IWP and corresponding residual in the fitted observations for the 325 ± 3.5GHz ISMAR channel. Each column displays the residual distributions for the five different particle habits. The gray line in each panel represents the regression line for the plotted data points. The text displays the correlation coefficient r and the p value of a two sided significance test for the slope of regression line.

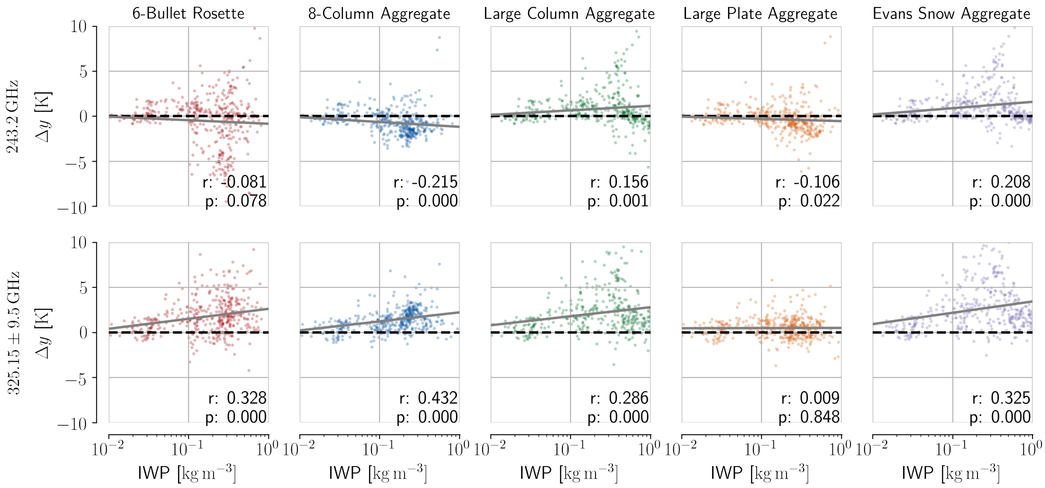

Figure 1.3: Brightness temperature residuals between true and simulated observations for two channels from flight B984. The first row shows the results for 243 ± 2.5 GHz channel, while the second row shows the results for the 325 ± 9.5 GHz channel. Columns show the results for the 5 tested particles shapes. The gray line in each panel represents the regression line for the plotted data points. The text displays the correlation coefficient r and the p value of a two sided significance test for the slope of regression line.

nounced when the IWP is calculated along the sampling path of the in situ measurements. The resulting retrieved IWP values are displayed in Tab. 1.1. The radar only retrieval systematically overestimates the reference IWP for all tested particle shapes. The combined retrieval leads to even stronger overestimation when the Large Column Aggregate or the Evans Snow Aggregate are used as ice particle shapes, while the 8-Column Aggregate leads to a strong underestimation of the true IWP. With the 6-Bullet Rosette and the Large Plate Aggregate as ice particle shapes the combined retrieval yields results that are closest to the in situ measurements. Thus, while the incorporation of passive observations increases the sensitivity to the representation of hydrometeors, it can help to improve the retrieval of IWP given that a suitable particle model is used in the retrieval.

Reviewer comment 17

Figure 15: I have a tough time with the gray of in-situ (sample)

Author response

The legend for Fig. 15 erroneously included an entry for gray lines that were labeled 'in situ (sample)'.

Table 1.1: Retrieved IWP along in situ flight path for flight B984 for the combined and radar-only retrieval.

	IWP [kg m^{-3}]	
Habit	Combined	Radar-only
6-Bullet Rosette	0.3362	0.4971
8-Column Aggregate	0.2383	0.6783
Large Column Aggregate	0.7868	0.4116
Large Plate Aggregate	0.3666	0.4664
Evans Snow Aggregate	0.7082	0.5073
In situ		0.3615

Changes in manuscript:

We will remove the entry from the figures legend. The corrected plot is shown in Fig. 1.4.

Reviewer comment 18

Figure 14 and Figure 15. Results are presented for flight B984, which uses the HAMP MIRA 35 GHz cloud radar. Could you comment on possible differences with CloudSat CPR were to be used.

Author response:

Although we did not investigate the effect of the radar frequency on the synergy between radiometer and radar observations in detail, we do not expect the results to change significantly if instead of the HAMP MIRA radar the CloudSat CPR were to be used. Although the higher frequency of the CloudSat radar should yield a relatively higher sensitivity to small particles, which may in crease the sensitivity to the assumed ice habit, the HAMP MIRA radar has the advantage of having higher absolute sensitivity. Furthermore, due to its lower frequency and airborne deployment, multiple scattering effects can be neglected for the MIRA radar, which is not the case for CloudSat CPR in a spaceborne configuration.
Regardless of the specific radar used, the main difficulty of determining ice concentrations in the cloud is that a radar only retrieval has only one piece of information per radar bin to infer the two moments of the hydrometeor distribution and thus has to rely on a priori information which cannot always accurately represent the properties of the observed hydrometeors.

Changes in manuscript:

We will add the following paragraph to the discussion of the added value of the combined retrieval.

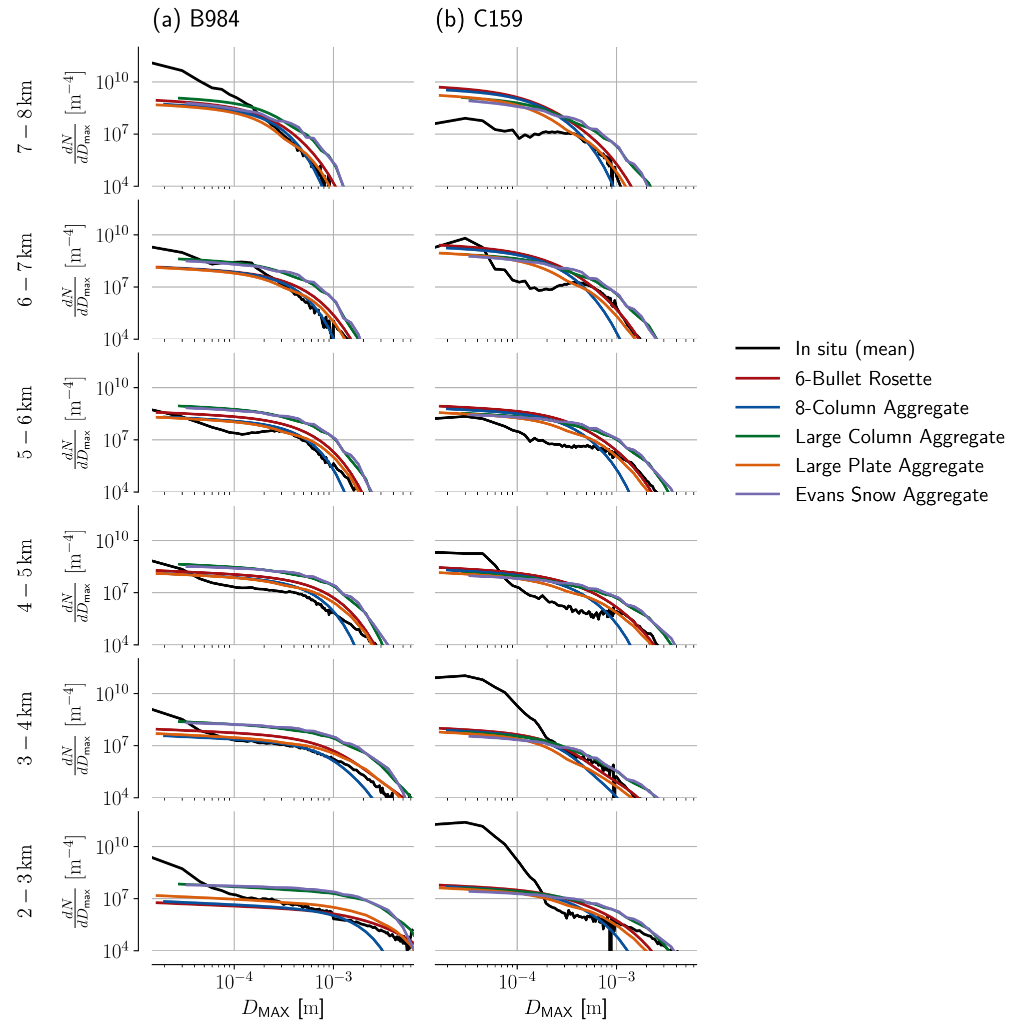

Figure 1.4: In situ measured and retrieved PSDs for flight B984 retrieved using the combined (panel (a)) and the radar-only retrieval (panel (b)). Each row of panels shows the mean of the in situ measured PSDs (black) together with randomly drawn samples of measured PSDs (light grey) for a given altitude bin of a height of one kilometer. Colored lines on top show the corresponding mean retrieved PSD for different assumed particle shapes.

Changes starting in line 319:

While these results were obtained for a Ka band cloud radar, we do not expect them to change much for a W band radar especially if it is spaceborne. Although the habit may have a stronger effect on the retrieval results of a W band radar due to its higher frequency, the underlying problem remains that the radar observations provide only a single piece of information per range bin. To retrieve the two moments of the hydrometeor PSD, the retrieval thus has to rely on a priori information which cannot accurately describe the distributions in all clouds.

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