Responses to the Referee #1 Comments on

Technical note: Bimodal Parameterizations of in-situ Ice Clouds Particle Size Distributions

by Irene Bartolomé García et al.

The authors would like to thank both anonymous referees for their comments, that helped improved the manuscript and make it more comprehensible. In the following, the comments and questions of referee #1 are addressed one by one. A reviewed version of the manuscript is attached at the end with the deleted parts in red and the new additions in blue.

Answer to Referee#1 (RC1)

The comments of the referee are in black,
responses by the authors in blue,
changes in the manuscript text in light blue.

Review of a Technical note: Bimodal Parameterizations of in situ Ice Cloud Particle Size Distributions, by Irene Bartolomé Garcia and coauthors, submitted to EGUSphere.

This study uses a massive set of in-situ aircraft observations collected from high latitude to equatorial ice clouds and collected in the Julia data base to investigate the size distributions of the ice and mixed-phase clouds over a wide range of conditions. Figure 1 and the cloud descriptions nicely shows the locations of the sampling, which clearly shows where the clouds were sampled. The particle probes included the CDP, FCDP, and the NIXE-CAPS, which is a CAS and grey scale CIP. The acronyms for these probes are identified in the text. Normalized size distributions, derived as a function of the melted equivalent diameter are evaluated. The interpretation of bimodality draws heavily on the data from the small particle probes. It is shown that bimodal particle size distributions (PSD) fit the observations much better than a single mode.

I have several major comments that I would like the authors to consider. A few are as follows.

1. Are the actual size distributions bimodal?

   Not every single PSD is bimodal. Our idea that a combination of two PSDs might lead to a better representation of cirrus clouds retrieved from satellite observations bases on the comparison between means of numerous measured PSDs and those retrieved from satellite observations shown by Sourdeval et al. (2018) (see Fig. 2). The observed PSDs are from a part of the campaigns which are also now included in the PSD database.
   From the two panels in Fig. 2 the bimodality of the mean observed PSDs can be seen, the more the warmer the temperatures are (especially for T $>$ - 50°C). This is in agreement with other studies that analyzed in situ data, for example Jackson et al. (2015). In Fig. 2 it is also visible that the PSDs from the unimodal satellite retrievals deviate the more pronounced the bimodality of the observations is.

   Your assumed mass dimensional (m(D)) relationship is poorly constrained for small particles. This could affect your interpretation.

   In Afchine et al. (2018), we have tested the mass dimensional (m(D))relation versus a number of others (see Fig. 3 here) and also compared the resulting IWCs to IWCs from

total water instruments. The agreement of the IWCs was satisfactory, therefore, we are confident that the mass dimension relationship reproduces the IWC as well as possible within the given range of uncertainties.
For the smaller ice particles $\leq 100\,\mu$m), the mass dimension relation is increasingly close to spheres, which corresponds to all other m(D) relations summarized in Afchine et al. (2018) and also the newly proposed by Lawson et al. (2019), i.e. we use the best available knowledge.

2. I have attached a figure showing PSD measured with balloon-borne ice crystal replicators, with very high resolution, no particle breakup, and unequivocal detection of small particles. There is little evidence of bimodality. It would be interesting to see if your assumed mass dimensional relationship (based on Mitchell et al., 2010) could change this result.

   Please see the answers to points 1. and 3., we think that the explanations given there also answer this point.

3. I'm very uneasy about your use of the small particle probe data. Shattering is a serious concern. The CAS is known to yield PSD that have major contributions from shattering. This issue could certainly create the bimodality you find. This issue needs to be discussed in more detail, not just in the references cited.

   We agree that ice particle shattering played a role in earlier studies. However, the efforts made in the development and use of antishatter probe tips and particle interarrival time algorithms to minimize ice particle fragmentation have resulted in this effect no longer heavily distorting the microphysical properties of the PSDs. There are a number of publications on this issue, some of which we have cited in our manuscript. We do not feel that it is necessary to discuss the problem again in more detail, since it is 'state of the art' that shattering has been minimized as much as possible in advanced cloud probes. The following has been added to the manuscript (lines 116-120):
   As mentioned in Sect. 1, shattering of the ice particles during the measurements would increase the number of small particles and cause an artificial bimodality in the PSDs. However, as presented in the above references, major efforts were made in the development of antishatter probe tips and particle interarrival time algorithms that have resulted in a successful minimization of the shattering of ice particles. Therefore, we are confident that the bimodality present in the JULIA database is not due to distorted microphysical properties of the PSDs.

4. Lines. 122-124. Mass dimensional relationship. Some of your measurements are at temperatures considerably warmer than for cirrus. Is there some reason to think that you can apply the modified m(D) relationship of Mitchell to the warmer emperatures?

   The reason that we used the same m(D) relation at warmer temperatures is from the comparison of various m(D) relations in Afchine et al. (2018). There it can be seen that the difference between all relations is small, even when looking at relations derived for warmer temperatures. However, we are aware that the uncertainties of the derived IWCs are larger than at colder temperatures. This explanation is now included in the manuscript in Section 2.2.:
   The used *m* - *D* relation was compared in Afchine et al. (2018) with other *m* - *D*

relations from the literature and also with the measurements from total water instruments showing good agreement for cirrus clouds. For temperatures warmer than the cirrus range, we are aware that the uncertainties of the derived IWC are larger than at colder temperatures. However, we use the same *m - D*, since as shown in Afchine et al. (2018), the differences between the compared *m - D* relations is small, even when considering those derived for warmer temperatures.

5. Line 131 and Eq. (3). What is the advantage of using the melted equivalent diameter (from the measured PSD) versus the physical diameter. The former uses an assumed mass diameter relationship which may not be valid under certain conditions.

   The normalization method followed in our study and developed by Delanoe et al. (2005, 2014) (hereafter D05 and D14, respectively) is based on the normalization method presented by Testud et al. (2001) (hereafter T01) for raindrop spectra. We also followed this approach. Because of the high complexity of ice particles types and shapes compared to rain, D05 and D14 chose the equivalent melted diameter instead of the physical diameter of the ice particles to adapt the mathematical formulation of the method of T01 to ice PSDs. It can also be noted that m-D relations would be necessary to relate the PSD to properties like the IWC regardless of the definition of the diameter. Please see answers to points 1 and 2 considering the chosen mass diameter relationship and its adequacy to the analyzed clouds.

6. Eqs. (3) and (4). Is it valid to assume that the PSD extends from 0 to infinity, rather than a partial gamma? Does this affect the IWC?

   To compute the moments of the distributions we do not use the general continuous form, but the discrete form summing from the minimum observed diameter to the maximum (third term in Eq. (3)).

7. Normalizing as a function of N_{ICE}. The value of N_{NICE} is subject to considerable uncertainty and potential error.

   To normalize the PSD it is necessary to find a parameter to scale the size space and the concentration space. As shown by Lee et al. (2004), a PSD can be normalized by using combinations of moments, therefore the question is, which moments to choose. For the normalization we are not using the total ice number concentration, which corresponds to the zeroth moment, but a concentration metric that corresponds to the third and fourth moment. This parameter was selected as adequate (and less uncertain than N_{ice}) for the normalization process in D05 and D14 (in our manuscript Eq. (4)). These moments were carefully selected to make normalized PSDs independent of the ice content and the mean volume-weighted diameter.

8. Line 199. D05 and D14 use the Brown and Francis m(D) relationship. How will this affect your comparison with their normalized PSD.

   In Fig. 3, we plotted in addition to the m(D) relations shown in Afchine et al. (2018) that of Brown and Francis (1995). It can be seen that the mass around 100 μm is higher than those from the other m(D) relations. We suspect that in the more recent relations the underlying measurement techniques have improved. Furthermore, in D14, it is argued that the Brown and Francis m(D) was obtain primarily at temperatures between - 20 °C and - 30 °C and dominated by particles between 200 and 800 μm, so they update the study of D05 and use m(D) relationships derived from direct IWC measurements. Therefore, we consider that the Francis and Brown m(D) might not be the most suitable one for our study since we cover colder temperatures and smaller particles.

9. Lines 265-267. 'minimize the impact of shattering effects'. Down to 3 microns? This is difficult to agree with.

   In Fig. 4, we show exemplary the mean PSD of Flight#6 of the StratoClim aircraft campaign. The inlets of the CAS probe is modified and the CIP probe is equipped with antishatter tips (see Krämer et al., 2016). In the left panel, the PSD without IAT correction to exclude shattering is shown, the right panel presents the same data set but with IAT correction applied. Comparing the two PSDs it is visible that they are nearly identical. From our analyses, ice particle shattering is generally not very frequent in cirrus clouds, because often the ice crystal sizes are not large enough to cause severe fragmentation of ice crystals. Only liquid origin cirrus sometimes carry ice crystals large enough so that an IAT correction reduces notably the number of ice crystals. In our measurements, we found only very few such events.

Minor Comments.

I feel that the comments above and the few minor comments below are the ones that need to be addressed in the revised article. I'll identify more minor comments after I see the revised manuscript.

1. Line 3. based on aircraft in situ
   Modified

2. 8. consists of
   Modified

3. 71. What is the averaging time as that is the relevant time.
   We are not averaging, we use the PSDs for every second.

4. Eq. (2) what is the [m]
   It indicates that the units of the equivalent melted diameter are meters. To avoid confusion, [m] is deleted and it is explicitly indicated in line 140.

5. 149: remove studied
   Done

6. 176: "fast" to "strong"
   We would like to keep "fast" to use the same terminology as in Krämer et al. (2016, 2020) referring to updrafts.

7. 255. Parameterization
   Modified

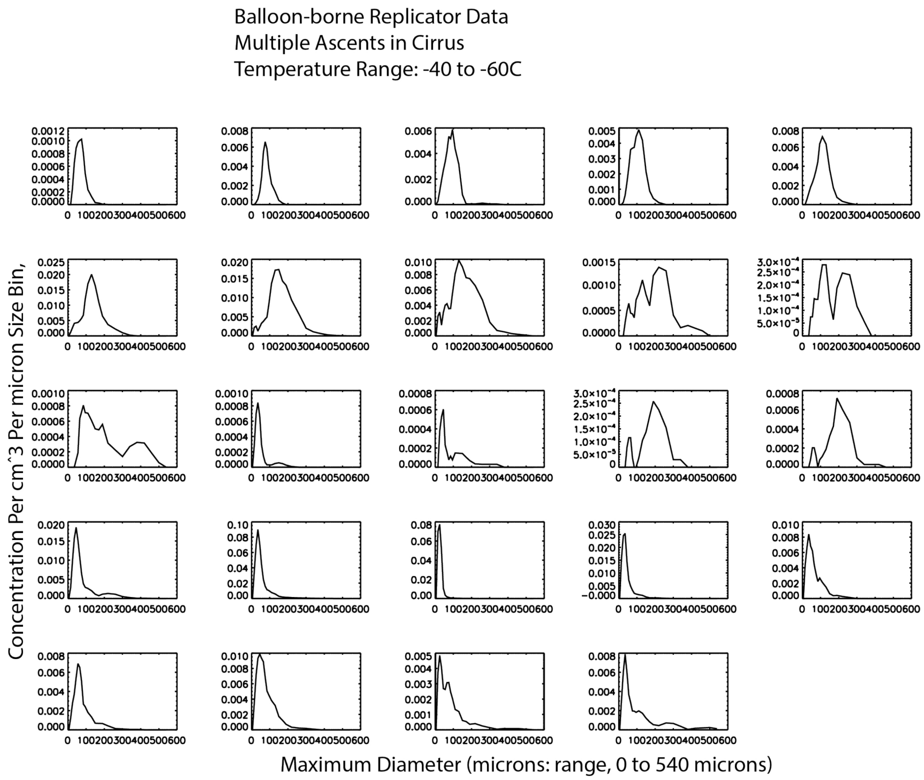

Figure 1:

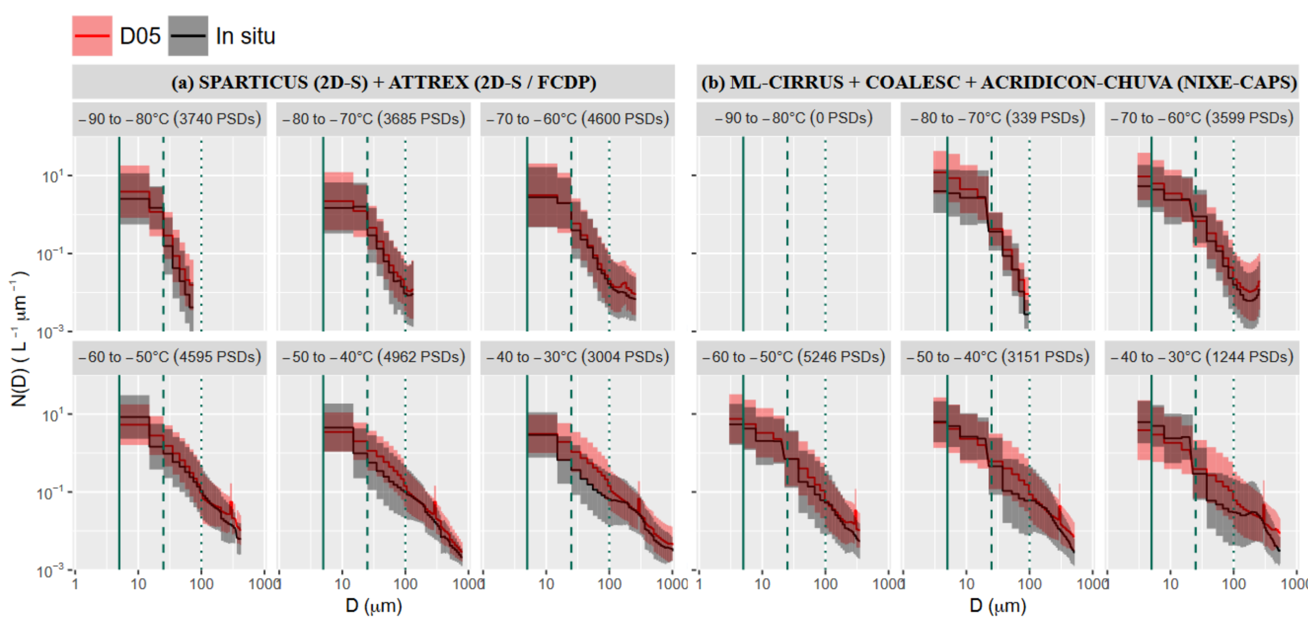

Figure 1. **(a)** Mean PSDs measured (black lines) during SPARTICUS and ATTREX, averaged per 10 °C temperature bin (from −90 to −30 °C). Black contours indicate one standard deviation around the mean. The mean and spread of one-to-one predictions by the D05 parameterization are similarly indicated in red. The total number of PSDs in each T_c bin is indicated in the panel heading and the relative contributions from each campaign can be deduced from Fig. S1. Vertical plain, dashed and dotted green lines indicate $D = 5$, 25 and 100 µm, respectively. The SPARTICUS data with $T_c < -60$ °C are ignored here to avoid contaminating FCDP measurements with uncertainties arising from the first size bins of 2D-S. **(b)** Similar to **(a)** but for the ML-CIRRUS, COALESC and ACRIDICON-CHUVA campaigns.

Figure 2: Figure 1 from Sourdeval et al., 2018, ACP

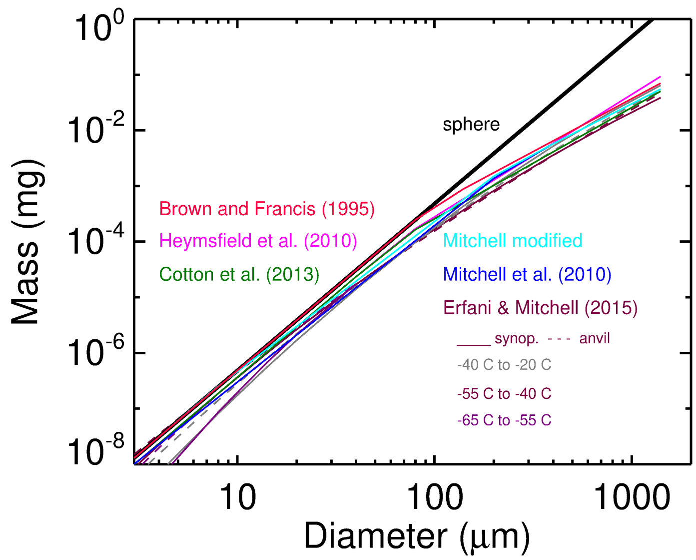

Figure 3: Afchine et al. (2018), Figure 8 (left panel) with the m(D) relation of Brown and Francis (1995) added.

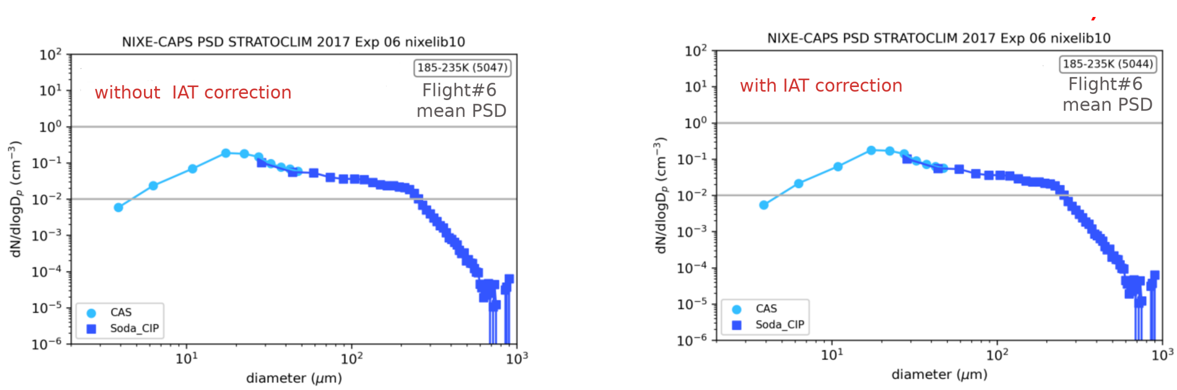

Figure 4: Mean PSD of Flight#6 of the StratoClim campaign. Left: without IAT correction, Right: with IAT correction.

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