Answer to Reviewer # 2

The authors thank the reviewer for his pertinent and helpful comments on the paper and they are grateful for his review which is always rather time-consuming and cumbersome. The manuscript has been modified according to the suggestions proposed by the reviewer. The remainder is devoted to the specific response item-by-item of the reviewer's comments :

1. Ice Particle Size and Concentration Measurements

The authors use the FSSP 300 and CPI probes to determine ice particle concentrations and the associated size spectra. These probes suffer from ice particles bouncing and shattering off their inlet tubes and the measurements can be totally destroyed by this artefact. Because of the long sampling tube of the CPI, it is particularly susceptible to this problem. Airborne and laboratory high speed camera images show ice crystals bouncing off probe surfaces and going forward into the airstream and even crossing streamlines in the horizontal direction (Isaac et al., 2006; Korolev et al., 2011). Korolev et al. (2011) provide a clear example of how standard FSSP measurements, without modification for artefact mitigation, can be completely destroyed by this problem, especially when large particles (> 500 μm) are present, which appears to be the case here.

The reviewer is right in underscoring that the 'non-modified' cloud probe measurements obtained during the CIRCLE2 campaign suffer from ice particles shattering. There are no direct means to estimate effects or errors on such in situ measurements. In the present study, we carefully considered this problem and the only method we have is to compare measurements from different techniques and to refer to previous results in the literature.

It is conceivable that the effects of shattering depend on the design of the probe inlet as exemplified by Isaac et al. (2006) and Korolev et al., (2011) from laboratory high speed camera. The extinction coefficients are inferred from the FSSP-300 + CPI and from the Polar Nephelometer probes, which all have very different inlet designs (for instance, inlet diameters of 40, 23, and 10 mm, respectively). The hypothesis that the shattering of large ice crystals affects the FSSP-300+CPI and PN measurements in the same way, or with a same efficiency, appears unlikely. This is supported by the consistency of comparison results between extinctions calculated from two different techniques (FSSP-300 + CPI and PN) as displayed in Appendix B (see Fig. B1.b) for the data obtained in the convective cell. This would appear unlikely if artefacts dominate the measurements in this case.

Referring now to recent works, Korolev et al. (2011) conclusively demonstrate the effects of ice shattering-contamination on particle size distribution measurements from modified and no-modified probes. Large ice particles were found to produce a higher level of contamination, whereas when maximum particle sizes were < 500 μm, the effect was significantly reduced. Because the largest ice particle sizes measured being about 300 µm, it is likely that the standard FSSP measurements are not significantly affected by the ice shattering contamination during the sampling of the convective cloud.

The FSSP-300 was designed as an aerosol measurement probe assuming spherical particles with a refractive index of 1.58. It is not clear from the reference given, Febvre et al. (2009), how the probe was calibrated to detect and size ice particles. However, Fugal and Shaw (2009) show corrections that are necessary to adjust FSSP measurements, which are *normally used to detect liquid drops, assuming the ice particles are shaped like droxials resembling a faceted sphere. The corrections are substantial but there is no indication that the authors have made such calculations. The definition of the sampling area of the CPI is difficult which is why the 2D-C probe is used to fit the spectra. Since the particles in this case were unusual, and the 2D-C probe was not functioning, it would be difficult to assess the possible errors because presumably a standard sampling area from previous cases was used in the calculation. One cannot fit using the FSSP measurements since the liquid versus ice correction was not made.*

The FSSP-300 with the 2D-C / CPI and Polar Nephelometer probes were intensively used onboard the DLR Falcon aircraft during several experiments devoted to cirrus and contrail observations: INCA (2000), PAZI (2005), CIRCLE2 (2007), CONCERT(2008). The FSSP-300 was designed as an aerosol measurement probe assuming spherical particles with a refractive index of 1.58. Because the cirrus ice particles are mostly not spherical (as evidenced from Polar Nephelometer measurements with typical asymmetry parameter of 0.77) the size calibration for aspherical particles proposed by Borrmann et al. (2000) was considered (Gayet et al., 2002). Borrmann et al. (2000) calculated size bin limits for a refractive index of 1.31 using Mie theory (spherical particles) and using the T-matrix method (aspherical particles). Differences in the size response between the calibrations for aspherical and spherical ice particles are little for sizes smaller than 4 μm but then significantly increase with size. For instance the upper size limits of the channel 27 are 11.07 μm and 8.55 μm for spherical and aspherical ice particles. Shcherbakov et al. (JOAT, 2005) refined the upper size limit of last FSSP-300 channel (21.8 μm) in order to obtain a good agreement with the first channel of the 2D-C probe in terms of particle concentration, extinction and ice water content. The particles larger than 3 μm diameter have been considered for the parameter derivation assuming to be ice crystals with a density of 0.9 g cm-3. The above size calibration and hypothesis have been used for the FSSP-300 data during CIRCLE2.

The reviewer is right about the CPI sampling area since the particles in this case were unusual, the possible errors on measurements are difficult to assess, particularly for particles smaller than about 100 μm without other concomitant and reliable data. Nevertheless, the extinction and mass spectra behave quite ‘reasonably’ at the overlap between the FSSP-300 and the CPI as we will see below (section 3). These results show a rather coherent feature despite inherent large uncertainties on both probe measurements.

2. Particle Mass Calculations

Particle mass calculations are difficult because of the different and sometimes unusual shapes that ice crystals assume in the free atmosphere. The authors made an interesting observation of many small chain-like aggregate ice crystals. However, although no mention is made of the assumed shape for particles in the FSSP size range, they likely considered the particles spherical as was done in Febvre et al. (2009) which was referenced for the method. They used a mass-diameter relationship with values of the coefficients which are meant for small columns (Mitchell et al., 1990). Although they stated these values would be representative of the chain-like crystals present, no further justification was given. Both the definitions of shape for the FSSP and CPI measurements could lead to large errors in the calculated mass. The chain-like crystals must project different shapes on the 2D plane of the CPI, depending on their orientation, and this would lead to large errors in itself. So the estimate of a possible maximum error of 100% in mass seems optimistic.

In the particle mass calculation (as well as for the extinction and reflectivity) the contribution of both FSSP-300 and CPI data are considered. As indicated above for the FSSP-300 data, the ice particles are considered spherical with a density of 0.9 g cm-3, an extinction efficiency of 2.0 and are size-distributed according to the aspherical-particle probe response. Concerning the CPI data, several mass-diameter relationships (see among others Mitchell et al., 1990) have been tested in order to fit the observed crystal shapes (elongated columns, rimed elongated columns, …). The problem is that these relationships (as the most reported in the literature) have been established for particles larger than 200 μm. Indeed, they cannot be applied to our data set (in the convective cell) since most of the observed particle are smaller than 200 μm with the largest sizes of about 300 μm. Finally, the best compromise with regards to the few available relationships for smaller ice crystals and our observations of chain-like aggregate ice crystals was the small columns parameterisation. This parameterisation gives the best (or the least worst) agreement in extinction comparisons (see Fig. B1.b) and in extinction and mass spectra behaviours at the overlap between the FSSP-300 and the CPI as we will see below.

We agree that the chain-like crystals must project different shapes on the 2D plane of the CPI, depending on their orientation, and this would lead to additional large errors. The possible maximum error of 100% in mass mentioned in the paper refers to previous estimates for cirrus cloud FSSP-300/2D-C measurements (Gayet et al., GRL, 2002). Indeed, in the present cloud situation the maximum error on the mass could be much larger.

3. Ice Water Content and Reflectivity Measurements

It has been recognized that any future field work in high ice water content conditions at the tops of convective storms need direct measurements of ice water content (e.g. Davison et al., 2009, 2011). Calculating the mass from size distributions can give large errors as mentioned briefly above. Although the Nevzorov probe (Korolev et al., 1998) has been used for many years to directly measure ice water content, it is now recognized that the probe does not capture all the particles that impact (Isaac et al., 2006). Korolev et al. (2008) has estimated this error to be as large as a factor of 3 and has recommended using a modified version of the probe.

We successfully operated the Nevzorov probe on the French ATR42 research aircraft during the study of Arctic mixed-phase clouds. Unfortunately this instrument was not installed on the DLR Falcon aircraft during CIRCLE2. These data would reduce the uncertainties on IWC measurements from spectrometer instruments. A promising new probe ("Robust probe") has been specially designed to measure IWC contents up to 7 g/m3 at high airspeed (200 m/s) (W. Strapp, personal communication). The mounting of this instrument is viewed on the French Falcon aircraft for on going research projects on MCS clouds.

The authors show the number size distributions but not the mass and reflectivity distributions. It would be very useful to know the mass median size, and see how the mass and reflectivity spectra behave at the overlap between the two probes. Perhaps the FSSP measurements were not that important in the calculation. For reflectivity, just a few large particles can swamp the calculations and it is possible the maximum sizes were not measured with the CPI. A reflectivity versus size graph would help reduce that concern.

Figure R.2 displays the composite representation of the particles size distributions from the FSSP-300 and the CPI in terms of number concentration, extinction coefficient, ice water content and reflectivity (the FSSP contribution is not represented being not important, see below). The data correspond to mean properties of the overshooting cell between 13:08:15 and 13:08:40 UT. As expected, the results do not display a perfect agreement of the spectra behave at the overlap between the two probes for the three first considered parameters. These discrepancies are due to several and combined reasons, which have been discussed in details in the previous sections. The contribution of the FSSP-300 on the number concentration, extinction, IWC and reflectivity values are 90%, 42%, 11% and 2%, respectively.

We agree that a just a few large particles can swamp the reflectivity calculations as exemplified by the reflectivity distribution on Fig. R.2. The results show a poor statistical representation of particles larger than about 250 μm due to the CPI sampling volume. This is confirmed by the careful examination of the CPI ice-crystal images (recorded in the convection cell penetration), which did not reveal particles larger than 300 μm. Considering a subsequent underestimation about 30% of the reflectivity expressed in mm6/m3, this correspond to 50% on dBZ, a value which is within the error bars of the measured reflectivity.

4. Observations of High Ice Water Content

The authors show high ice water contents in the tops of these convective clouds, as high as 0.5 g m-3 as inferred from the spectra measured by the in-situ probes. This is not that unusual as some of the references provided by the authors indicate. However, several significant references were not included. Strapp et al. (1999) found maximum ice water contents in excess of 1.3 gm-3, and often sustained ice water contents in excess of 0.5 gm-3. Abraham et al. (2004) reported a broad area in extratropical cyclones that were higher than 1 gm-3. The ice water content values in these two papers are probably underestimates given what is now known about the performance of the standard Nevzorov LWC/TWC probe (Korolev et al., 2008). An early Royal Aircraft Establishment report by McNaughton (1959), which has been used for years to provide some guidelines to aviation on ice water content, describes measurements made in convective clouds near Entebbe, Singapore and Darwin with total water contents (probably mostly ice) exceeding 5 gm-3. Mazzawy and Strapp (2007) summarize these and other measurements in order to come up with "Appendix D – An Interim Icing Envelope" which defines a mixed phase/glaciated icing environment to be used by the aviation industry in certifying engines for operations in these conditions. However, our inability to accurately measure high ice water contents limits these measurements, and those of Gayet et al. Hopefully, when newer probes become more widely used, the measurements will be more accurate.

The references cited by the reviewer have been added in the text to underscore that high ice water content have already been observed several times in convective clouds. The authors thank the reviewer for the indication of several important papers they did not know up to date (particularly AIAA conferences).

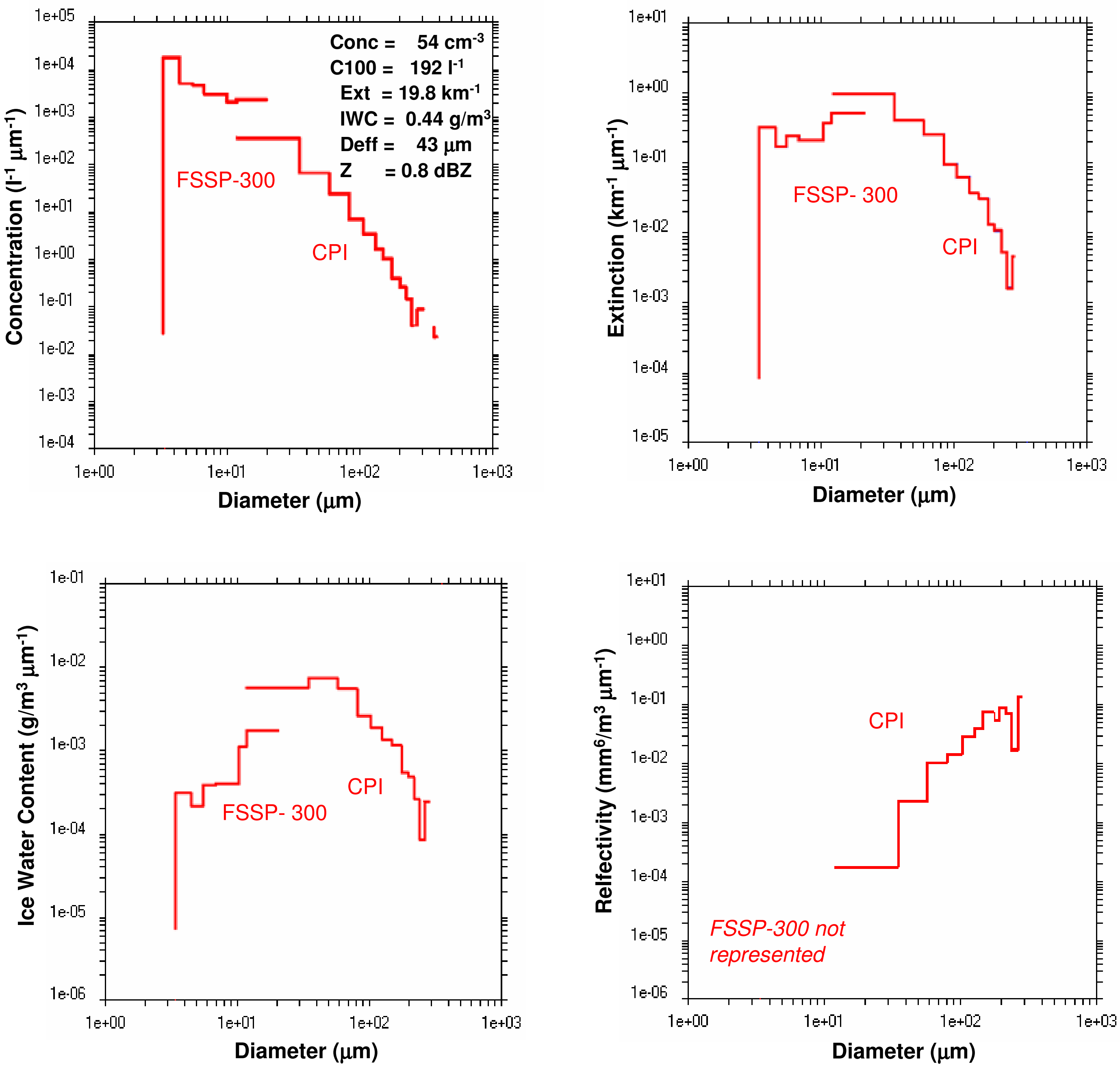
Conc = 54 cm-3
C100 = 192 l-1
Ext = 19.8 km-1
IWC = 0.44 g/m3
Deff = 43 µm
Z = 0.8 dBZ
FSSP-300
CPI
Concentration (l-1 µm-1)
1e+05
1e+04
1e+03
1e+02
1e+01
1e+00
1e-01
1e-02
1e-03
1e-04
1e+00
1e+01
1e+02
1e+03
Diameter (µm)
FSSP- 300
CPI
Extinction (km-1 µm-1)
1e+01
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
Diameter (µm)
CPI
FSSP- 300
Ice Water Content (g/m3 µm-1)
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
Diameter (µm)
CPI
FSSP-300 not represented
Relfectivity (mm6/m3 µm-1)
1e+01
1e+00
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
Diameter (µm)

Figure R.2