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Atmospheric Chemistry and Physics Discussions

Interactive comment on "Effects of ice crystals on the FSSP measurements in mixed phase clouds" *by* G. Febvre et al.

D Baumgardner (Referee)

darrel.baumgardner@gmail.com

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This manuscript would probably be better suited as a submission for Atmospheric Measurement Techniques, rather than ACP, and perhaps once it has been revised, the editors can choose to move it to AMT. As I was a reviewer who did the original technical assessment, it should have been my responsibility to make this recommendation at that time.

The study concerns the interpretation of measurements made with single particle light scattering spectrometers (OPC), equipped with inlets, when operated in clouds that contain ice crystals. This evaluation contributes to the ongoing evaluation that has seen a number of contributions that focus strictly on the potential for ice crystal fragments to be sampled as natural ice crystals or water droplets. The current study adds a

very valuable component to this ongoing assessment of the level of uncertainty that is contributed by having ice crystals in the environment, i.e. in the absence of shattering artifacts, how does an OPC respond to an ice crystal when it has been designed to interpret the intensity of scattered light with respect to spherical water droplets? As far as I know, only a single paper has addressed this issue, i.e. Borrmann et al. (2000) and much more is needed in order to use OPCs more effectively in clouds with ice. There are certainly cases where the spurious particles produced by ice shattering will swamp the signal such that no amount of data processing can recover useful information. There are, however, probably many other instances where ice is present but with very few crystals of sufficient size to cause problems with shattering. In these cases, much more information can be extracted once the response of the OPC is better characterized.

The current paper make a good start in the direction of characterizing the optical response of FSSPs to ice crystals, but falls short in a number of ways that I feel are too important to neglect and should be addressed before this paper moved to either the ACP or AMT stage.

First of all, there has yet to be a balanced paper written on the potential response of OPCs in clouds with ice. Given that this paper is entitled "Effects of ice crystals on the FSSP measurements in mixed phase clouds", it is important that it presents as many of the effects as possible related to how the FSSP responds to ice crystals. There are several different effects that need to be addressed in the current paper, in addition to improving upon the analysis of the effect that is discussed, i.e. missizing larger ice crystals as smaller water droplets.

So, aside from ice shattering, what are the effects that need to be addressed?

1) In mixed phase clouds, as a result of the Wegener–Bergeron–Findeisen (WBF) process, ice crystals will grow faster than water droplets, depending on the available water vapor and the relative humidity with respect to ice. The growth of the size distribu-

tion into a bimodal shape can be a result of frozen water droplets or small ice crystals growing more rapidly than the droplets. Can this be ruled out in the data set that is shown? The comparison with the PN of phase function derived from the FSSP, assuming some fraction of water droplets and ice crystals with mode between 25-35 um would help confirm or throw out this possibility. 2) The ray tracing calculations produce "average" scattering cross sections yet the OPCs do not measure ensembles of particles in random orientations but measure individual particles in individual orientations. Consider the following: the results of the Borrmann study and those of the current evaluation show that ice crystals are generally under-sized with respect to a water equivalent size. This is because the average orientation presents a geometric cross section somewhere between the maximum and minimum cross section. What if the flow through the FSSP inlet produces a velocity gradient that rotates the plates or columns into a preferential orientation so that as they pass through the sample area they aren't randomly oriented but all more or less showing the same geometric cross section? This is not at all out of the realm of possibilities. King (1986) showed conclusively that the shear in front of wingtip mounted PMS probes led to the preferential orientation of ice crystals so that plates appeared as columns. If this is the case as air flows into the FSSP inlet, it means that some fraction of the higher concentration, smaller ice crystals appear as larger particles that fall in the 25-35 bin because they present their largest cross section. This would explain why there is a secondary mode with higher concentrations than in the one or two channels lower.

This explanation seems like a more likely explanatation for the secondary mode, given that the natural size distributions tend to decrease exponentially with size, i.e. if this mode was coming from 55-80 um particles, the concentration of these would have to be of order 50 per liter, according to the distributions shown in Fig. 4. Yet from the CPI data, shown in the same figure, the concentration of crystals in this size range are on the order of 0.1 per liter. It doesn't seem consistent that this mode is being produced by larger particles that are much lower in concentration.

3) What is the sample volume for ice crystals versus water droplets? There have been suggestions that the depth of field for ice crystals larger than the nominal size of 50 um is much larger than the 2.5-3 mm for water droplets, due to the way that the FSSP qualifies particles. The bimodal peak could possibly be out of focus, larger ice particles, that are being qualified but since they are in the much larger, but less intense, portion of the beam, they are undersized. This can be tested in a number of ways. If this is the case, the concentration of particles in the 25-35 um range will be proportional to the slope of the distribution from 35-50 um. Secondly, all FSSP-100s have auxiliary channels of housekeeping information that can be used to test this hypothesis. The ratio of accepted to DOF rejected particles, will indicate if a larger than normal fraction of particles are being accepted or rejected. Secondly, the velocity accepted fraction will also indicate a larger than normal fraction of particles being accepted as within the most intense region of laser sample area. These are two parameters that need to be utilized in the current evaluation.

It is very important to emphasize here that the FSSP does not ever miss-size particles as long as the relationship between measured, scattered light intensity has been properly established. What the FSSP measures is the light scattered by a particle over a solid angle of +/- 4-12 degrees. This scattered light is the related to an equivalent optical diameter of a water droplet. When the FSSP measures the light scattered by an ice crystal and places this in a size bin, it is essentially classifying the ice particle with respect to the light scattered by a droplet with an equivalent optical diameter. For studies related to climate, i.e. to the evaluation of how cloud particles interact with radiation, there is no error in the measurement since, for example, a hexagonal ice crystal, with a major dimension of 80 um and minor dimension of 20 um, may have an optical diameter equivalent to a 35 um water droplet. Clearly its phase function will be quite different than a water droplet but from the perspective of forward scattering, the two are equivalent. If the goal is to derive the water content then this is a different issue, although it is very likely that the volume of a plate with these dimension would not differ significantly from that of an equivalent volume water droplet. To reiterate, there has been no “error” when an ice crystal is classified into a water equivalent size bin since the definition of “size” is nebulous to begin with when measuring irregular particles and classifying them by equivalent optical diameter has obvious advantages.

Below I list additional comments, questions and recommendations.

Abstract: Here and throughout the paper there needs to be a change in how the effects on the FSSP measurements are described. From the beginning the word “contamination” is used, i.e. “In this paper, we show that in mixed phase clouds FSSP-100 measurements may be contaminated by ice crystals . . .”. Yet the word contamination, according to the American Heritage dictionary, means “to make unpure or unclean by mixing”. This would possibly be a correct description of the effect on the measurements of spurious particles from ice crystal shattering but does not apply to the effect caused by mis-sizing due to asphericity. I think that a much better, and clearer, description would be “contribution to measurement uncertainties” , i.e. “In this paper we show how the presence of ice in cloud contributes to the uncertainties of measurements made with the Forward Scattering Spectrometer Probe (FSSP).

Abstract: Here and throughout references are made to shattering on the FSSP tips, but actually most of the fragments measured by the FSSP are from shattering on the inlet.

Page 7911, line 10: Spell out FSSP (and all acronyms) the first time.

Page 7911, line 22: “. . .seems to agree that the FSSP is a suitable probe only when the liquid phase is present..”. I don’t think this is quite correct. The community agrees that the FSSP is an accurate instrument for all water clouds but, given the lack of an alternative, accepts that the FSSP and similar instruments can be used in clouds with ice crystals with clear caveats that should be understood before interpreting the measurements.

Page 7912, line 8: “spherical” I think shoud be “near-spherical” or “quasi-spherical”.

Page 7914, line 9: “Experimental evidence shows that for particle diameters larger than about 100 μm, the number of shattered particles increases with the concentration of large particles”. .Actually, the 100 um threshold has never actually been established and is a number that is too often used with no hard evidence. This should not continue to be propagated in this paper unless the authors are aware of a study or publication that I don’t know about.

Page 7914, line 19: “. . .as 2 μm and 30 %, respectively.” These are only for water clouds.

Page 7916, line 17: Why are the angles of 3-15 used here and throughout? The nominal values for the FSSP-100 are 4-12 degrees.

Page 7916, line 24: The word “power” should probably not be used here since were are not talking about scattering per unit time. maybe “energy” would be more appropriate.

Page 7916, line 26: Change “lighted” to “illuminated”.

Page 7917, line 21: “Literature sometimes describes a typical behaviour of the FSSP in the presence of ice (mixed or iced clouds).” What does this mean?

Page 7917, Line 26: “. . .altitude, droplet concentration, liquid water content (LWC) . . .”. concentration and LWC are reversed in the figure. Page 7919, line 3: The phase diagrams are in the right not the left panels.

Page 7919, line 6: “The PSD. . .”. However the CPI shows large ice crystals. I don’t think that the CPI images are very useful shown as they are. There is a need a quantitative assessment of the fraction of water to ice, concentration of large ice crystals, etc.

Page 7919, line 14: “. . .seem to be correlated ; when the latter increases, 15 the former shows a similar tendency.”. Is this shown somewhere?

Page 7919, line 14: change “ration” to “ratio”.

Page 7919, line 15: “We define REX as the ratio of extinction due to ice particles alone (CPI data) to the total extinction (water droplets and ice crystals, PN measurements).” Move this definition before the use of REX.

Page 7920, line 22: “Our results clearly show that the second mode in the range 20–35 μm of the FSSP-100 size distribution is related to the presence of ice particles”. No, there is an association not a relationship. There is a very large difference between a relationship and an association with respect to cause and effect.

Page 7920, line 26: This is the first mention of the FSSP-300. This should be introduced in the section on instrumentation.

Page 7921, line 6: “…smaller secondary mode..”. The secondary mode is not that much smaller than "mode" in first channel. These distributions look quite different than those shown in Figure 4.

Page 7923, Figure 7: Use a more meaningful legend for the crystal types. The figure caption does not sufficiently explain the curves. These are averaged over all different orientations. What type of variation is there, i.e. there should be vertical bars indicating the range of scattering cross sections.

Page 7923, Line 21: “..no more than 15%..”. On average, perhaps, but when looking at variation, there could be a very different outcome.

Page 7924, line 17: How is Delta calculated?

Page 7924, line 22: Under or overestimated?

Page 7925, Section 5: I would remove this section entirely. First of all, the focus of the paper should be on identifying and evaluating all the effects of ice crystals on the FSSP except for shattering. Secondly, attempting to derive a shattering efficiency is fruitless given all the uncertainties related to this process. Why would the fragments all fall into the 25-35 um category? Why would you assume the fragments will spread uniformly across the sample volume? Why would you assume that 50% fall in and out of the

inlet? A very detailed modeling study is needed to examine these issues in detail and have no relevance in the current study.

Page 7928, Line 3: “The larger the amplitude of the second mode, the greater the ratio (REX) of extinction carried by ice particles to the total extinction (water droplets and ice crystals).” This is never shown quantitatively or even in a table or figure.

Page 7928, line 15: “The results suggest that the second mode peaked between 25 μm and 35 μm does not represent true size responses but likely corresponds to bigger aspherical ice particles.” No, as I discussed at the beginning, if the second peak is not a result of shattered particles, then it is a correctly measured equivalent optical diameter for a water droplet.

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