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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.

Anonymous Referee #2

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General comments:

This is a nice study that effectively demonstrates the importance of complimentary instruments such as the FSSP-100 and the Polar nephelometer to increase understanding of mixed-phase and glaciated clouds, and to isolate potentially serious measurement and interpretation errors. I recommend that the article be published after mostly minor modifications.

I do believe that the authors have understated the potential effect of ice crystal shattering in their introduction and in subsequent analysis. In particular, Korolev et al. 2011 have shown that the response of the FSSP-100 in ice clouds can be almost entirely due to ice crystal shattering on the inlet tube, and this can be almost greatly eliminated by removing the sample tube, and using deflecting probe tips.

I also strongly recommend that the authors eliminate the paragraphs related to the estimation of the number of particle fragments produce by shattering crystals. The quantitative arguments are very weak and arbitrary in my opinion. For example, the concentration of particles > 100 μm on the CPI is used to estimate the number of impacting ice particles. This is totally arbitrary, and the size distribution shown in Figure 10 shows many more CPI particles below 100 μm. The MVD size of 310 μm is arbitrarily used to estimate the number of fragments per particle, where the concentration is lower than at any other arbitrary smaller size. And this all assumes that the CPI does not suffer itself from shattering. The inlet design of the CPI would lead the average reader to believe such shattering is likely to exist. Do the authors believe that the CPI is immune from shattering? If they do, they should state this in the paper with their justification. These shattering estimates detract from a paper where every other argument is reasonably convincing and supported by data. As a minimum the authors should greatly simplify this shattering argument, if they can, and provide realistic error estimates. I believe to do otherwise is misleading, and these estimates tend to get used in subsequent papers without the benefit of seeing how they were derived.

It is not always clear what the authors' objective is in identifying the effect of ice crystals on FSSP distributions. For example, they refer to the 'contamination' of the measurements by ice crystals. This is a bit tricky. In one earlier study referring to 'contamination', the intention was to quantify the liquid portion of the spectrum, so that ice crystals in fact 'contaminated' the liquid PSD. In this paper, the authors determine a technique to identify PSDs that are mixed-phase or glaciated, and the 'contamination' of mixed phase measurements they refer to is presumably not the simple presence of ice crystals, but their potential erroneous sizing and/or the augmentation by artefacts. For real crystals, the authors state that the sizing errors can be large if the crystals are smooth, but almost insignificant if they are rough. In figure 4 they report on concentration, area, and volume PSD errors for combined ice+liquid spectra, so I presume that the estimation of composite PSDs are considered of primary importance to their evaluation. In the specific comments, I have suggested some re-wording of certain sentences to address

the points in this paragraph that I hope the authors will consider. My first interpretation in early reading into the paper was that any measurement of ice crystals by the FSSP, even if it was corrected somehow, would be considered 'contamination'.

The text would benefit from editing by someone whose first language is English. In the specific comments below, I have only made such corrections if I think the meaning of the sentence can be misinterpreted. I have also added some more optional editorial suggestions at the end of this review that I believe would help improve the text.

Specific Comments:

Page 7910: lines 2-4 "In this paper, we show that in mixed phase clouds FSSP-100 measurements may be contaminated by ice crystals, inducing wrong interpretation of particle size and subsequent bulk parameters."

I think the use of "contaminated' is ambiguous here. Please consider the following:

"In this paper, we show that in mixed phase clouds FSSP-100 measurements may include both spurious measurements of shattered ice crystals and potentially incorrectly sized natural ice crystals, inducing improper interpretation of particle size and subsequent bulk parameters."

Page 7910: lines 16 "but likely corresponds to bigger aspherical ice particles".

Why likely? Could they not, according to your model calculations, be equally likely from rough or irregular ice particles with little size error? You imply the latter in the next sentence, in fact.

Page 7911: lines 25- end of paragraph I suggest you take out the section on the ice crystal shattering efficiency, or propose something less arbitrary. See general comment.

Page 7911: lines 7-9 Small change at end of sentence: "In situ measurement science uses quantitative types of probes in order to perform the particle size analysis of

hydrometeor range going from a few microns to a millimeter or more."

Page 7911: line 13. "especially when accurate measurements of cloud liquid water content (LWC) and droplet spectra are required".

I would suggest that you not make a statement implying that that FSSP provides accurate measurements of LWC. I would just state "especially when accurate liquid droplet spectra are required".

Page 7911: line 14. Should also add here:

Cober, S.G., and G.A. Isaac, 2012: Characterization of Aircraft Icing Environments with Supercooled Large Drops for Application to Commercial Aircraft Certification. J. Appl. Meteorol. and Climatol., 51. 265-284.

Page 7911: lines 21-24: "The scientific community of cloud physics (see the recent review on cloud in situ instruments by Baumgardner et al., 2011) seems to agree that the FSSP is a suitable probe only when the liquid phase is present, even if the discussion is not closed concerning the quantification of uncertainties in the evaluation of the LWC."

Do you mean above: "if only liquid phase is present" ?

Page 7912: line 2: Change "the shattering effects" to "the ice crystal shattering effects"

Page 7914: line 8 I don't think the problem is isolated to shrouded inlets. I think it is best to reword as following: Change: "on probes with shrouded inlet" to" by ice particle impacts on surfaces upstream of the sample areas"

Page 7914: line 9: "Heymsfield, 2007". I think you should put a full list of the references on ice crystal shattering at this point. Heymsfield (2007) is neither the original reference in this regard, nor the most encompassing. Some of them are already elsewhere in your paper, but there are several missing.

Page 7914, line 10: "The new generation of cloud instruments (CDP, CIP, 2DS,. .

.) are equipped with innovative shrouded inlets specially designed to reduce the shattering effects (Korolev et al., 2011) and provide information to separate real and artifact-shattered crystals (Field et al., 2003, 2006)."

The new designs are not for shrouded inlets, and I am not aware of a new design for the CPI. I would recommend the following:

"The new generation of cloud instruments (e.g. CDP, 2DS) are being equipped with innovative arms and leading edge tips especially designed to reduce the shattering effects (Korolev et al., 2011) and provide inter-arrival time information to further help separate real and artefact-shattered particles (Field et al., 2003, 2006, Lawson 2011)."

Lawson, R. P., 2011: Effects of ice particles shattering on the 2D-S probe. Atmos. Meas. Tech., 4, 1361-1381.

Page 7914: line 16: Change "The FSSP-100 instrument" to "The standard FSSP-100 instrument". There is also the extended range instrument that you mention later in the paper.

Page 7914, paragraph starting line 17: Korolev et al. (2011) show clear evidence that the FSSP number concentrations can be decreased by 2 orders of magnitude by removing the sample tube. This is not reflected in this paragraph. Obviously bulk parameters could be overestimated by more than 15-20% in this case. Maybe the Korolev examples are more extreme, but I don't think you want to minimize the effect of FSSP shattering here (with a sample tube installed).

Page 7914, last paragraph on CPI accuracy: Based on the results of Gayet et al., can the authors give a clear estimate of the shattering effects of the CPI, given that the 2DC is subject as well to shattering in this size range? You state that the CPI and 2D-C/2D-P have similar accuracy, but shattering on the 2DC at 100 μm can still be quite significant, according to Korolev et al. 2011.

This paragraph needs to be re-written so as to clearly state what uncertainties the

authors believe are in the CPI, and to what degree they think it suffers from shattering. The CPI results are used extensively later in the paper, and this reviewer believe that the there is no good evidence that CPI concentrations at 100 μm are immune from shattering effects.

Page 7915: line 15: "Indeed, Sassen et al. (1979) proposes an identification of phase clouds on the basis of their side scattering differences with water or ice particles."

Do the authors mean ""Indeed, Sassen et al. (1979) proposed identification of cloud phase on the basis of side scattering differences of water and ice particles"?

Page 7917: line 13: "Discrimination of liquid water clouds and mixed or iced cloud is a great challenge for a correct FSSP measurements analysis, but a hazardous process if only the FSSP probe is available."

Do you mean: "Separation of the liquid and ice components of the particle size distribution (PSD) in a mixed phase cloud, as well as quantitative estimate of the PSD of a glaciated cloud is a great challenge based on the FSSP probe alone." ?

Page 7917: line 20: "Literature sometimes describes a typical behaviour of the FSSP in the presence of ice (mixed or iced clouds)."

I don't understand this sentence. Can you please re-write?

Page 7918: line 3: "Without bulk water probe information during ASTAR, the consistency of the FSSP measurements was verified in liquid water clouds (i.e. g > 0.83) by comparing the extinction coefficient derived from the Polar Nephelometer data."

What does this sentence mean? Does it simply mean that the FSSP agreed with the PN in what was thought to be LWC clouds? If so, I would suggest substituting with:

"The consistency of the FSSP and PN data was determined by comparing extinction estimates from both probes in cloud sections thought to be dominated by liquid (i.e. g > 0.83)."

Page 7918: line 3: “The C100 profile indicates that ice particles are found even near the cloud top with rather a low concentration (_5 l−1),which then significantly increases (up to _40 l−1) at lower levels, with g-values of about 0.77.”

Are you saying that all, or the majority of particles > 100 um (C100) are identified as ice particles from the CPI imagery? It should be stated in the text, because it is not necessarily obvious to all readers that all large particle are ice particles.

Page 7919: line 7: “The close agreement between the PN measurements and the theoretical FSSP-100 values confirms this statement (seen as already on Fig. 2).”

How does it confirm that this is liquid cloud? Do you mean that the close agreement between the PN and the FSSP extinction supports that the PSDs are accurate? I don’t see the requirement for liquid cloud. Maybe I missed something here.

Page 7919: line 7: “Near the cloud top the particle phase is dominated by (spherical) liquid water droplets even if some ice crystals are detected (see Table 1 and Fig. 4a) as reported by Gayet et al. (2009).

What was reported by Gayet et al. 2009? Was it that the tops of these clouds are often dominated by liquid cloud with some presence of ice crystals? If so, please re-write.

Page 7919: line 17: “Conversely, the difference between the measured (PN) and theoretical (FSSP-100) phase functions at sideward scattering angles increases with REX values (see Table 1).”

This is not clear, and I am not sure what you are saying. Please re-write.

Page 7921: line 10: “Therefore a common feature is observed in the presence of ice crystals regardless of the probe version and airspeed”

Not exactly. Korolev et al. (2011) provide convincing data that this second mode is dominated by shatterers created by the sample inlet on the FSSP. So, FSSPs without a sample tube probably have a different behaviour, as would the CDP. Please reword.

Page 7924: line 23: “At the same time the asymmetry parameter remains within a deviation of 0.01 (Fig. 8b).”

It is not 100% clear to this reviewer how Fig. 8b that tells me this? REX below 0.2 is 25% of the way between b and c. I see a deviation of 0.02 for the same range on 8b. It is difficult to understand your point here. Maybe you should reword, and correct the 0.01 for 0.02 if I am correct.

Page 7925: line 17: Regarding the reference to Heymsfield (2007), if you want to quote the extreme situation for the FSSP, you need to quote Korolev et al. (2011), who found that ice crystal concentrations could be increased by up to 2 orders of magnitude by the sample tube of the FSSP. I am not sure if there are estimates of extinction increase or mass in that reference, but their data showed that there was almost no registration on the FSSP without a sample tube, and quite high concentrations with the simultaneous second probe with the sample tube. You need to consider this work in this paragraph.

Page 7925: line 20: You need to add Korolev et al. (2011) to the reference list here.

Page 7925: line 24: “There are no means of discriminating real and artefact ice particles related to the FSSP-100 secondary mode.”

Some FSSP probes have been modified to measure interarrival times, which helps in eliminating artefacts. This should be mentioned somewhere in the text, because the statement above is misleading. Also, the CDP has the particle-by-particle option, which gives the interarrival time, and it might be more commonly used than the FSSP in the near future.

Page 7925: line 26: “with new inlets specially designed” I think you mean “new arms and leading edge tips specially designed”

Page 7926: line 2: “Figure 9 gives convincing arguments showing that the number concentration of particles larger than 20 μm (hypothesized to be ice shattered-fragments measured by the FSSP) is related to the concentration of (natural) ice particles larger

than 100 μm"

Note that some readers could argue that particles measured in the size range smaller than 100 um may be positively correlated to concentrations larger than 100 um for natural reasons. For example, if the PSDs at any given point in cloud change only by mixing, you would just have scaled PSDs across the cloud, and a natural positive correlation. I think that the authors should make the point here if they think this correlation should not exist in natural clouds. In my opinion it is 'evidence', but not a 'convincing argument'.

Page 7927: line 11 to end of section: I suggest that the authors remove the entire argument on the estimation of the number of shattered particles. See argument in 'general comments'

Page 7927: line 22: "We show that in mixed phase clouds the FSSP measurements could be contaminated by ice crystals, inducing a wrong interpretation of the particle size and subsequent bulk parameters. Conversely, this contamination is revealed by a bimodal feature of the particle size distribution which could be a relevant indication of the presence of ice particles in mixed-phase clouds."

This comment is related to my discussion of the term 'contamination' in the 'general comments'. I find the use of the word 'contaminated' in your sentence is not clear. I prefer something like the following:

"We show that in mixed phase clouds FSSP measurements could contain errors, resulting from ice crystal artefacts or improper measurement of natural ice crystals, which affect the PSD and its bulk parameters. The presence of ice crystals in the mixed-phase PSD is identified by a characteristic bimodal feature."

Page 7928: line 25: "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."

Does this sentence contain an error? Did you not state in the text that rough ice crystals have almost the same size response as spherical drops? Could you change this to: "The results suggest that the second mode peaked between 25 and 35 um would not represent the true sizes of aspherical particles if they were present, especially if they were smooth" (and delete the following sentence)

Page 7928: line 20: "As for the number concentration measurements they are hampered by the unknown definition of the depth of field to aspherical randomly oriented ice crystals." Was this discussed earlier in the text? If not, it should not appear here first in the conclusions.

Page 7928: line 22: "There are no means of discriminating real and artefact ice particles related to the FSSP-100 secondary mode"

My comment is again to make the reader aware that inter-arrival time may help, and some modified FSSPs and some CDPs are equipped with this option

How about: "There are no means of discriminating real and artefact ice particles related to the FSSP-100 secondary mode without additional data such as interarrival time that is not commonly available, and even then results may not be conclusive."

Page 7928: line 22: I suggest you delete all the end of the paragraph starting with "We define the shattering efficiency .."

Other notes:

I did not see figs. 9a and 9b, just fig. 9.

Editorial suggestions:

Page 7911: lines 17, 18.

"The LaMP's activities in the area of aircraft icing and the implication of the FSSP in these studies give motivation to explore any situation capable of increasing the knowledge of FSSP behaviour." Change to: "The LaMP's activities in the area of aircraft icing

and the importance of the FSSP in these studies motivates exploration of any situation capable of increasing the knowledge of FSSP behaviour."

Page 7911: lines 18-20:

"This is useful mainly in order to calculate bulk parameter such as the liquid water content (LWC) and mean volume diameter (MVD) with minimum errors." Change to: "The objective is to calculate bulk parameter such as the liquid water content (LWC) and mean volume diameter (MVD) with minimum errors."

Page 7912: line14: "the size response" Change to: "the analysis of the size response"

Page 7912: line 24-25: "The conclusion always seems to be similar namely that it is difficult" to Change to: "They conclude that it is difficult to"

Page 7913: line 2: "measurements in Arctic mixed-phase clouds" Change to: "measurements using a data set for Arctic mixed phase clouds"

Page 7913: line 13: "to measure cloud particle properties" Change to: ", to measure cloud particle properties" (comma added)

Page 7913: line 16: "completed the ATR42" Change to: "were additional to the ATR42"

Page 7913: line 23: "extended" Change to: "additional"

Page 7914: line 2: Change "We recall that it includes" Change to: "The instrumentation package includes"

Page 7914: line 7: "could be hampered by" Change to: "may be compromised by"

Page 7914: line 15: "study, the effects of resulting" Change to: "study, but the potential effects of resulting"

Page 7916: line 1: "affected" Change to: "adversely affected"

Page 7916: line 6: "was yielded" Change to: "was present"

Page 7916: line 12: "were planned" Change to: "were conducted"

Page 7916: line 22: "Usually, water liquid spheres are used in Mie calculations" Change to: "Mie calculations assume liquid water spheres."

Page 7916: line 22: "As a consequence, particles" Change to: "Particle "

Page 7916: line 22: "of the lighted particle" Change to: "of the light-scattering particle"

Page 7917: line 1: "For the same geometric volume, aspherical particles scatter between 3_ and 15_ a light power that differs from those predictable using Lorentz-Mie theory (Borrmann et al., 2000)." Change to: "For the same geometric volume, light scattered by aspherical particles between 3 and 15 degrees differ from that predicted by Lorentz-Mie theory (Borrmann et al., 2000)."

Page 7917: line 4: "size ranging can be affected" Change to: to "instrument sizing can be affected"

Page 7917: line 5:

"leading to uncertainties in the bulk parameter calculation and mean diameter" Change to: "leading to uncertainties in the bulk parameter calculations (e.g. mean diameter, MVD, LWC etc.)."

Page 7917: line 9: "usable" Change to: "possibly effective"

Page 7917: line 12: "To resume, FSSP" Change to: "In summary, FSSP"

Page 7917: line 17: "Conversely, the shape" Change to: "However, the shape"

Page 7917: line 23: "in the mixed-phase stratiform cloud layer and yielded precipitations" Change to: "in the mixed-phase precipitating stratiform cloud layer"

Page 7918: line 17: "In order to evidence" Change to: "In order to reveal"

Page 7918: line 19: "addresses the top of the cloud layer" Change to: "corresponds to the top of the cloud layer"

Page 7918: line 21: " (d) relates precipitating ice crystals" Change to:" (d) corresponds to precipitating ice crystals"

Page 7919: line 21: "the second mode of the PSD is strongly marked whereas simulated" Change to: "the second mode of the PSD has a strong identifying feature, and simulated"

Page 7919: line 26: "ice crystals are more dominating the" Change to: "ice crystals increasingly dominate the"

Page 7922: line 17: "different realizations whereupon" Change to: "different scenarios where"

Page 7922: line 20: "We recall that surface roughness" Change to: "Surface roughness"

Page 7922: line 24: "domain of the rough influence" Change to: "domain of the roughness influence"

Page 7923: line 18: "an assessment of the size response" Change to: "an approximation of the size response"

Page 7923: line 18: "The rough aspect seems to play the crucial role in scattering studies. The difference between water and smooth ice crystal calibration is extremely large with an influence on the channel width. On the contrary, the scattering properties of a crystal with a deep roughness" Change to: "The crystal roughness seems to play the crucial role in its scattering properties. The difference between the water and smooth ice crystal size calibration is extremely large with an influence on the channel width. On the contrary, the scattering properties of a rough crystal"

Page 7924: line 5: "crystal pictures" Change to: "crystal images"

Page 7924: line 8: "Sensitivity studies deserve to be carried out in, this domain, although remain outside the scope of this paper" Change to: "Sensitivity studies should

to be carried out in the future in this regard, but are beyond the scope of this paper"

Page 7924: line 26: "a subsequent g-decrease" Change to: "a corresponding g-decrease"

Page 7924: line 28: "the ice crystals control" Change to: "the ice crystals highly dominate"

Page 7925: line 5: "an adequate modelisation" Change to: "an appropriate consideration"

Page 7925: line 7: "are in this case precious allies of" Change to: "provide crucial additional information for proper interpretation of"

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