Response to the Referee 3 comments

RC#3:

General Comment

The manuscript compared three radar measurement based IWC retrieval methods (Z only based, Kdp only based, and Kdp and Zdr based) using X-band polarimetric observation and in-situ observation and demonstrated that the Kdp and Zdr based method can provide better IWC estimates. The retrieved IWC agreed very well with the observed IWC from the in-situ measurement. The methods are based on observations, and I would expect to extend the techniques to other places in future; however, the manuscript did not mention effectiveness of the methods for other cloud types at different locations. The subject and results of the manuscript are suitable for the scope of the journal. However, this manuscript lacked detailed descriptions about how to estimate coefficients. In particular, estimated coefficient values were not presented. Some figure captions lacked explanations. I recommend major revision in terms of comments below.

We thank the referee for his/her review and encouraging comments. Regarding the suitability of our method to other non-HIWC environments, we focused our analysis to HIWC environment so didn't speculate on if our result is applicable to other conditions. We are planning to extend our analysis of large dataset we accumulated in a recent projects and will report our findings once we complete the work.

As outlined in our responses the two other reviewers, we have made significant changes in the manuscript and added new figures and tables. We hope these changes make the paper easier to follow. Please find our responses to your specific comments as follows.

Specific comments

1. The manuscript lacked detailed descriptions about how to estimate coefficients (a1, b1, a2, and b2) and their values. Information below is at least needed:

1) The estimated coefficient values

2) Were the coefficient values estimated for each case or constant for all cases?

We thank the referee for pointing this out. In the revision, we have added texts to describe how to estimate the fitting parameters (in the caption of Fig. 5). Values of those parameters were estimated for each study cases are given in Table 2 of the revision. They were also computed for combined data of seven selected flights. The variability of those fitting parameters is briefly discussed in section 6.

3) How did you sample radar data? In-situ data was valid near the aircraft, while the radar could not collect data below a range of 1000 m from the aircraft. What are locations of the radar data used for the coefficient estimations? How did you match the radar data and the in-situ data? The sampling method may control the accuracy of the linear regression technique.

As provided in section 3.1, radar profiles were extracted at a horizontal distance of 1000 m from the aircraft. The data rate of the processed in-situ microphysics data is much lower than the radar data. Hence, the radar data were decimated to match with temporal resolution of the in-situ data (e.g. 1 s). At the Convair-580 average ground speed of 100 ms^{-1}, this results in a 100 m resolution along the flight line. The radar range resolution is 75 m and the data were not average over range.

4) How many cases (how many hours) were used for coefficient estimates?

It was 4.91 hours of data collection time (17699 data point at 1 s sampling period) for the seven selected cases.

5) Is there a dependency of the estimated coefficients on cases?

We do not see a dependency of the estimated coefficients over the study cases.

6) It is very worth to add a flow chart of the IWC retrieval technique.

We thank the reviewer for this good suggestion. However, we haven't added additional flowchart as we felt the processes of our analysis has been detailed in the revised manuscript. Also, it may be more adequate to have the flowchart of the IWC retrieval technique when we complete a work where additional steps are added to the technique to improve its performance further.

2. Details about the radar data are needed. What are the beamwidth, radar range gate spacing, and time resolution? Did the radar point at a fixed direction during the flights or scan some directions (in that case, what are the elevation and azimuth)? Did the radar sampling volume match the in-situ measurement sampling volume?

We thank the referee for this comment. We have added a table (Table 1 in the revised manuscript), which lists some important radar parameters. All the antennas of the X-band radar system are fixed. As mentioned in section 3, the radar data used in this study were sampled at 1000 m horizontal distance from the aircraft, whereas the in-situ data were measured right at the aircraft location. For in-situ probes, the sampling volume is much smaller compared to the radar sampling volume.

3. A more description about IWC from PSD is also needed. What D-M parameterization was used? How was it tuned using IKP2 measurements? Again, a flow chart of the IWC calculation should be useful. Did the image probes scan particles at a horizontal plane (parallel to the horizontal plane) or vertical plane (perpendicular to the horizontal plane)? Can the scan direction cause some errors in the IWC calculation?

IWC was calculated from composite 2DS+PIP PSDs based on $M = aD^b$ size-to-mass parameterization. We agree that a flowchart of IWC calculation should be useful but it is beyond the scope of this work and should be found in the IWC reference paper (Korolev *et al.* 2018). The coefficient a and b were tuned using a non-linear regression to find the best correlation between IWC measured by IKP2 and calculated from PSD. The coefficients a and b are determined by dominant particle habits, and therefore they may vary depending on type of clouds, temperature range and altitude were the particles were sampled. For the particle images sampled from the Convair580 during the HIWC campaign the best agreement between two ways of IWC measurements were obtained for a=7.0044e-12 and b=2.3. The laser beams of both PIP and 2DS probes used for particle image sampling were oriented vertically (the horizontal 2DS channel was not used). Such arrangement provides measurements of the maximum projection of particle images. The direction of scanning may affect assessment of IWC from 2D particle imagery. However, tuning of the a and b coefficients, which was employed in this study, compensates the effect of the direction of particle image sampling.

4. Is the technique presented in the manuscript valid for cases where graupel existed? Graupel particles generally have aspect ratio $\sim$1, which are not sensitive to Kdp or Zdr. Deep convective cases could include supercooled liquid droplets and heavily- rimed particles. Were there effects of supercooled liquid droplets and heavily-rimed particles in the cases used in the analysis? Was the case dependency of the proposed technique? More case descriptions would be needed to help understanding the case dependency.

As briefly mentioned in the manuscript, the fraction of flight segments with supercooled drops was <5%. Our data are also consistent with a multi-year and multi-aircraft observations of the HAIC-HIWC flight data that are detailed in FAA report (Strapp et. al, 2018). We didn't try to filter out those data points with supercooled drops in our analysis. Having said that we agree with the reviewer that the convective clouds we flew are likely consisted of heavily rimed particles and graupel at the convective cores of the storms we flew.

Our main goal is to investigate if adding polarimetric capability to operational pilot X-band radars allows to detect and avoid HIWC environment. In this regard, commuter aircraft typically avoid the convective cores based of high reflectivity values and other data. So our work and conclusion don't extend to convective core areas.

5. P. 14, lines 2-3: This sentence does not make sense to me. Please give more description about why Kdp can improve large aggregates effect, although it is sensitive small crystals. Just before the sentence, it was stated that (???) is more sensitive to the oriented small ice crystals." Why Kdp can improve large aggregates effect? How did you know the orientation of ice particles?

We agree with the referee on this comment. We've added information about K_{dp} and Z_{dr} as a function of MMD (Fig. 6) in the revised manuscript. The text also has been modified in the revised manuscript: "The large errors in the $IWC - Z$ estimator are due to the presence of mixtures of large aggregates and small ice crystal regions as indicated in the PIP images (not shown) in clouds. Large aggregates have a dominant contribution into the radar reflectivity, which explains the positive biases of the $IWC - Z$ estimates. On the other hand, the magnitude of K_{dp} in aggregates with MMD > 2 mm is usually smaller than 0.4 °/km and in small ice particles (MMD in the range 0.3 – 1 mm) is between 0.6 °/km to 1 °/km (Fig. 6a). It follows that estimators utilizing K_{dp} information may not have strong biases toward large aggregates in radar volumes like the $IWC - Z$ estimator."

6. P. 18 lines 10-11 "On the other hand,. . .": This sentence does not make sense to me. Why the modified IWC was less sensitive to the particles' shape and orientation, even though the Zdr constraint well worked for the IWC estimate?

We thank the reviewer for this comment. The sentence has been modified in the revised manuscript to have a better explanation: "On the other hand, the product $(1 - Z_{DR}^{-1})IWC$ already includes the particles' shape and orientation effects, thus, estimates based on it yield should better results."

7. Evaluations for mode error sources should be discussed; how could Kdp estimation resolution, Zdr bias, and in-situ instrument limitation (difference between IWCmeas and IWCpsd) affect the IWC retrievals?

We agree with the referee that the error analysis of the retrieval algorithms is important. In addition to the factors mentioned by the referee, errors in IWC retrievals also depends on the uncertainty of the fitting coefficients. A complete error analysis of the IWC retrieval is beyond the scope of this work. In the revised manuscript, we have added some text to discuss the retrieval uncertainty at typical values of K_{dp} and Z_{DR} in the HIWC regions (section 6, P21-22). In summary, standard deviation of IWC estimates at HIWC regions is about 0.6 g/m^3.

8. Fig. 12: I do not know the meaning of Fig. 12. Why can you see "the modified version of IWC is better replicated by a simple linear regression model" from this figure? "Modified IWC" is the just measured IWC scaled by Zdr. Why is this better replicated by a simple linear regression

model then measured IWC? In both Fig. 12a and Fig. 12b, it seems that there is ~50% variability in IWC at Kdp = 1. There is no significant difference between Fig. 12a and Fig. 12b. If you wanted to say that Eq. 13 can provide better correlations between IWC and polarimetric variables (Kdp and Zdr), this has been already shown by R^2 values in Fig. 5.

The Z_{dr} constraint is used to avoid large errors when $Z_{DR} \approx 1$. In general, Zdr values are not constant at different radar volumes; hence, $(1 - Z_{DR}^{-1})IWC$ is not a simply scaled version of IWC. We agree that the R^2 goodness of fit parameters in Fig. 5 already show that a linear regression fits $(1 - Z_{DR}^{-1})IWC$ better than IWC for the case of May 25. Figure 12 (now Fig. 14 in the revision) shows that the method also works well for other cases. In the revised manuscript, the sentence has been removed to avoid the confusion. We have also added estimated fitting coefficients for all the selected cases in Fig. 14 in Table 2 and discussed the variability in the coefficients in section 6.

9. "Modified IWC" is a confused phrase. In the manuscript, "modified IWC" represents the left hand side of Eq. 13. (1-ZDR^-1)*IWC. This is IWC scaled by [1-ZDR^-1], not actual IWC. Use an appropriate phrase through the text.

We completely agree with the reviewer. As it is also mentioned by another reviewer, "modified IWC" will confuse the readers. For a clear presentation, we have placed it with $(1 - Z_{DR}^{-1})IWC$ throughout the revised manuscript.

Minor comments

1. Did you do attenuation corrections for reflectivity and Zdr? Attenuation corrections may not be needed for pure ice precipitation, but it would be good to mention about this.

No, in this work, no attenuation correction was applied to reflectivity and Z_{dr} as it pointed out by the referee that in ice precipitation and at close range, attenuation at X-band is negligible. Some text has been added to section 3.1 as suggested.

2. Did you do calibrate Zdr values for systematic offset?

Yes, we did.

3. What was the window size for calculating Kdp? What is the special resolution of Kdp?

The window size for calculating Kdp in our algorithm is 31 and the original Kdp range gate spacing (before decimation) is 30 m.

4. P. 10, lines 1-2 "The radar estimates. . .": This sentence is unclear. Please add detailed descriptions.

We thank the referee for this question. It should read "The IWC estimates from radar data …". The sentence has been changed in the revision.

5. P. 10, line 8 (2): This feature is unclear in Fig. 4. Scatter plots of MMD, RHOhv and Zdr should be helpful.

The data shown in Fig. 4 are measured time series data so we do not have scatter plots of the parameters. Between 11:16:-6 and 11:21:46 UTC, RHOhv decreased and Zdr increased at MMD peaks.

6. P. 10, line 9 and p. 14, line 2: How did you know the orientation of small crystals? Kdp should also be sensitive to larger crystals with aspect ratio /= 1. How did you know the particle aspect ratios?

We agree that, in general, the orientation of ice particles is unknown and saying K_{dp} is only sensitive to small ice particle is not correct. The sentence in P10, L9 has been rewritten to remove this confusion. We have added a new figure (Fig. 6a in the revision) to show the typical values of the magnitude of K_{dp} as a function of MMD for all the data used in this work. In general, K_{dp} of large aggregates is smaller than that of small ice particles. The text in P14 has been revised to reflect this addition

7. P. 10, lines 10-11: In Fig. 5, it seems to me that the break point where Zdr started increasing and RHOhv deceased was at Kdp ~1.5 deg/km.

We agree with the referee. Corrected as suggested.

8. P. 10, line 20: I cannot see any blue line Fig. 5.

The line colors in Fig. 5 were changed from blue to black but not the text. We apologize for this confusion. The text has been corrected.

9. P. 10, lines 20-21: I cannot see measured IWC or modified IWC in Fig. 5.

In the revision, the measured IWC and $(1 - Z_{DR}^{-1})IWC$ (was "modified IWC") are in black.

10. Fig. 3b and Fig. 7b: Why is there a break line at 6-7 km range in reflectivity fields?

The break lines in those figures are locations of ground clutters which were filtered out. More information about the ground clutter contamination and filtering was given in section 3.1. In the revised manuscript, we have added some text to the figure captions to explain for those lines.

11. Please give height information for Figs. 3, 7, 9, 10.

Aircraft height information has been added for the figures as suggested.

12. Please give information about height, range, and temperature for Figs. 4, 5, 6, 8, 11, 13.

We have added a sentence in section 3.1 to indicate that in this work, the radar profiles were extracted at 1000 m from the aircraft for all the study case. The information of aircraft altitude and static air temperature for Fig. 4, 5, and 6 (May 26 case) is given in section 5.1 and for Fig. 8, and 11 (May 23 case) is given in section 5.2. The intervals of aircraft altitude and static air temperature for Fig. 13 (all study cases) are given in the Fig. 13 caption.

13. Unit of Kdp should be degrees / km through the manuscript?

We thank the referee for this question. It was a mistake. Correction has been made.

14. Fig. 5: What do red lines represent?

They are the linear fitting curves to IWC and $(1 - Z_{DR}^{-1})IWC$ data. Last paragraph in P10 has been modified to include this information.

15. Fig. 5: I confused ‘scatter plots’ with red and black dots. I guess that ‘scatter plots’ here meant color shades representing frequency distributions. I recommend using ‘frequency distribution’ instead of ‘scatter plot.’

We agree with the referee and thank for the comment. The caption has been changed as suggested.

16. Fig 5: missed (a), (b), and (c)

In the revised manuscript, all the figures have been checked and missing labels have been added.

17. P. 18 line 8: I cannot find ellipses in Fig. 11.

We apologize for missing ellipses in Fig. 11. They are now included in the revised figure.

18. Caption of Fig. 3: Delete “is”

The redundant word “is” has been removed from the Fig. 3’s caption.