

Response to the Referee 2 comments

This manuscript presents an assessment of ice water content (IWC) retrieval algorithms based on KDP only and combined KDP-ZDR observations using measured IWC from aircraft in-situ probes. Results show that both the KDP-only and combined KDP-ZDR method works much better than the reflectivity-based retrieval algorithms. Although KDP-only and KDP-ZDR combined IWC retrieval algorithms are not new concept, an algorithm derived from quasi-collocated in-situ measurement and radar observations is a good addition to the existing literature. Some sections of the manuscript lack details and are somewhat difficult to follow, especially section 2. Modifications to the manuscript are needed before it can be recommended for publication. Major concerns and questions that needed to be addressed are outlined below.

We would like to thank the reviewer for many constructive comments which helped improve the manuscript greatly. We have made many changes in the revised manuscript, and have added more references to improve the presentation of the manuscript. Please find our responses to your comments as follows.

General Comments:

1. Combining KDP and ZDR in IWC retrieval is not new concept. For example, Eq. (13) in the current manuscript is very similar to Eq. (29) in Ryzhkov et al. (1998). In my opinion, the authors should discuss more on the relationships and differences between the current study and the other more theoretical studies.

We agree that combining KDP and ZDR in IWC retrieval is not a new concept. As a result, we didn't really provide an in depth review. In literature, there are many different equations representing the relationships between IWC, Z , K_{dp} , Z_{dr} and parameters of the particle size distribution. We tested most of them and only focused on the methods (Kdp-only and (K_{dp}, Z_{DR}) combination) that work best for our data sets in the HIWC environment. We believe we have included enough review of the concept and we have also added a recent reference (Ryzhkov et al. (2018)) in the revised version of the manuscript.

2. Section 2 lacks detailed derivation and/or reference to existing literatures and is very difficult to follow. This section needs to be heavily rewritten. The author should provide detailed derivations or clearly refer to existing literatures for the equations. When doing so, the authors should make sure that the conventions of the equations are consistent.

In the revised manuscript, we have added references for each equation in section 2. Part of section 2.2 (P5) was re-written. Again, because the concept is not new, we did not include all the derivations that can be found in the literatures. Instead, we summarized the main findings which are important to our study.

We thank the referee for the comment on the inconsistency of the convention of the equations. We have corrected the errors.

3. The parameters (a, b) used in the Kdp only and Kdp-ZDR combined algorithm are obtained from linear fittings of data from 7 cases. By looking at Figure 12, it seems different values of (a, b) could be obtained if data from only one, or some of, the 7 cases are used in the fitting. What is the variability of the parameters (a, b)? How large the retrieval uncertainty will be due to the uncertainty in (a, b)?

In the revised manuscript, we have included the fitting coefficients for both methods in Table 2. The standard deviations for (a_1, b_1) for the K_{dp} -only method and for (a_2, b_2) for the (K_{dp}, Z_{DR}) method are (0.12, 0.33) and (0.032, 0.033), respectively. The uncertainty of the retrieval depends on the uncertainty in (a, b) and the values of K_{dp} and Z_{DR} . Typical values of K_{dp} and Z_{DR} for HIWC regions (MMD between 0.25 mm to 0.8 mm) are about 1 deg/km and 1.12 (or 0.5 dB) (from Fig. 6 in the revision). At those typical values, standard deviation of IWC estimates using (K_{dp}, Z_{DR}) is 0.6 g/m³.

Specific comments:

P2, L14: What is the conclusion of Ryzhkov et al. (1998)?

The conclusion of Ryzhkov et al. (1998) is briefly summarized in Section 2. In the revision, the text has been modified and a new reference (Ryzhkov et al. (2018)) has been added.

P3, L11 and L14: Which convention is used for the back-scattering matrices and forward scattering amplitudes?

It is in forward scatter alignment (FSA) convention. We thanks the referee for pointing this out. Additional text has been added to the revision to make it clear.

P3, L10 and L13: The radar observables, Zdr and Kdp, are usually integrated over a particle size distribution. Although Eq. (1) and Eq. (2) are OK if all the particles are of the same size and aspect ratio, this situation rarely happens. I think these equations can be removed since Eq. (5) and Eq. (6) are more general. Instead, the authors can discuss scattering properties in single particle level here.

We thanks the referee for this comment. The Eq. (1) and (2) are for n particles of same size D and axis ratio r . The purpose of including Eq. (1) and (2) is to show that large number ice particles (which is relevant to HIWC regions) can contribute to a significant K_{dp} . We'd like to keep those equations instead of including a discussion on the particle's scattering properties because this paper mainly focuses on an empirically derived estimator for IWC based on radar polarimetric parameters (K_{dp}, Z_{DR}) .

P3, L15-17: This sentence is confusing. I guess the authors mean that Zdr does not change with increasing number of small particles while Kdp increases with increasing number of particles. The authors may want to rephrase this sentence.

We agree with the referee. The sentence has been rephrased.

P3, L20: Is the permittivity of particle based on solid ice?

It is the relative permittivity of ice particles in the radar volume, which is unknown. An approximate relationship between relative permittivity and density of snow/ice particle can be found in Matrosov *et al.* (1996).

P5, Eq. (9-11): By using symbol for “approximately equal”, do the authors really mean “proportional”?

We thank the referee for pointing this out. The error has been corrected.

P5, Eq. (11): Derivation for this equation is needed. Also, Eq. (9) and Eq. (10) use integration over a PSD, why Eq. (11) only use one mass?

(please see the response after the next question)

P5, L7-9: Again, detailed derivation is needed. How to derive a closed form of IWC as a function of Kdp and ZDR? What does “particle mass variation is small within the radar volume” mean?

In the revised manuscript, we have removed Eqs (9)-(11) and revised the text in L7-9. We’ve also added a recent reference by Ryzhkov *et al.* (2018). Detailed theoretical derivation and discussion of the IWC approximations based on (K_{dp}, Z_{DR}) can be found in Ryzhkov *et al.* (1998, 2018); therefore, we decided not to include them in the paper.

P5, L19-20: What are the physical meanings of the constants b1 and b2?

We thank the reviewer for this question. Mathematically, the intercepts (b1 and b2) are mean values of IWC at $K_{dp} = 0^\circ$. Physically, we do not know their meaning. When the ice particle orientation uniformly distributed in a plane perpendicular to the radar beam, $K_{dp} = 0^\circ$ but IWC can be larger than zero.

P10, L7: What does “initial observations” mean? Should the “include” be replaced with “indicate”?

We have modified the text to remove the confusion. It now reads “From Fig. 4, it follows: ...”

P10, L8: “latter” is confusing. Better to clearly state which observations are weighted and biased towards Zdr.

The sentence has been modified as suggested.

P10, L20: No blue line in Fig. 5(c).

We thank the referee for pointing this error. It is now corrected.

P10, L7-12: Are the polarimetric variables K_{dp} , Z_{dr} , Z_h , and ρ_{hv} shown in Figure (4) measured at a specific distance from the airplane or averaged over a range? How about those shown in Figure (5) and (6)?

Those radar parameters were measured at a distance of 1000 m from the aircraft. The data were not averaged over the range but were decimated in time (along the flight path) to match with the temporal resolution of the in-situ data. Additional information on this has been included in the revised manuscript.

P13, L6: What are the coefficients (a, b) used for K_{dp} -only and (K_{dp} , ZDR) algorithms? Are same values used for the other case?

In study case May 26, the coefficients (a, b) for K_{dp} -only and (K_{dp} , ZDR) algorithms are (0.94, 0.7) and (0.12, 0.07), accordingly. The coefficients are different and are optimized for each case. We have added estimated coefficients for all selected flights in Table 2 and discussed on the variability of those coefficients in section 6.

P20, L12: I think the word “significantly” is too subjective and optimistic. For example, when $K_{dp}=1$, in panel (a), IWC varies by 50% of the maximum value (range 1 ~2 with maximum 2), and in panel (b), modified IWC also varies by 50% (range 0.15 ~0.3 with maximum 0.3). I would suggest remove the word “significantly”.

We completely agree with the referee. The word “significantly” has been removed.

Technical corrections:

P1, L9: Is the differential reflectivity here in linear scale or log scale?

It is in log scale.

P2, L10: Aydin and Tang (1995) should be (1997).

We apologize for the error. It has been corrected.

P3, L8: The book of Bringi and Chandrasekar (2001) has over 600 pages. Detailed page numbers or equation numbers are needed. The same for P3 L22 and other places.

We have added equation numbers in the book of Bringi and Chandrasekar (2001) to the revised manuscript.

P4, L26: IWC is not sensitive to shape and orientation sounds strange. IWC is independent of them. The authors may want to rephrase this sentence.

We thank the referee for this comment. This sentence has been revised. It now reads “For a given radar volume, if the orientation of the ice crystal changes, K_{dp} value changes (Eq. (7)) while the IWC of the radar volume is not.”

P11, Figure 3 caption: “Bottom panel is shows” remove “is”.

This typo has been corrected.

P13, Figure 5 caption: using two values (0.1 and 0.05 degree) and “respectively” for three panels is confusing.

The values are for the last two panels (panel b and c). The caption has been modified to avoid the confusion.

P13, L5: “blue” should be “black” for measured IWC.

The error has been corrected.

P14, L5: “estimations” should be “estimation”.

We thank the referee for pointing this error. It has been corrected.

P14, L5: The panels of Figure 6 are not labeled by ‘a’ or ‘b’. Same for Figure 11.

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

P15, Figure 6: Should vertical axis labeled as “Error” instead of “Bias”?

In this study, measured IWC is considered as ground truth, hence, the difference between estimated IWC from radar data and measured IWC is labeled as bias. However, we have corrected the second sentence in the caption of Fig. 6 in the revision: “Bottom panel shows estimation (~~errors~~) biases for the three estimators.”

P18, L8: No ellipses in Fig. 11a.

We thank the reviewer for pointing this out. Ellipses have been added to Fig. 11a (it is now Fig. 12 in the revision).