Dear Reviewer 1,

The authors sincerely appreciate your valuable comments and suggestions to help improve the manuscript for the second time. We have revised the manuscript titled "Estimating the Snow Density using Collocated Parsivel and MRR Measurements: A Preliminary Study from ICE-POP 2017/2018 ". that was submitted to ACP (Atmospheric Chemistry and Physics) on 3 January 2024. Based on your suggestions, we have put substantial effort into additional analysis. The manuscript has been thoughtfully revised regarding the comments from all reviewers.

Both reviewers are concerned about the maximum ice fraction assumption and the bulk water fraction retrieval. Both reviewers suggest providing more investigations of assuming the maximum ice fraction and deemphasizing (or not overstating) the bulk water fraction retrieval. A sensitivity study of half-maximum ice fraction assumption has been applied and compared with PIP to address reviewers' concerns about bulk water fraction retrieval. The results indicate that the bulk density retrieved from the half-maximum ice fraction assumption is consistently lower than PIP retrievals. On the other hand, the bulk density retrievals from the maximum ice fraction assumption perform better in agreements with PIP than those from the half-maximum ice fraction assumption. The authors also deemphasize the performance of the retrieved bulk water fraction and discuss its uncertainty more in the revised manuscript by adding a discussion paragraph.

Moreover, the discussion of the retrieved density-particle size relationship has been revised in the manuscript. Each study's particle diameter definitions vary due to diverse measuring instruments and principles. The discussion does not intend to emphasize the difference in the density-particle size relationship. Instead of converting various particle diameter definitions, the particle diameter remains as proposed in each study. The definitions of particle size of each study are summarized in Table 4 of the revised manuscript as well.

The manuscript has also been revised carefully following the reviewer's suggestions on English wording and typos. The authors would like to express our sincere appreciation for the comments. The added or modified sentences in the revised manuscript are in red for your convenience. The point-to-point replies to every comment have been prepared in the following. For your convenience, the reply is arranged as follows,

Reviewer's comments

Response

Revisions in the manuscript

We would appreciate any feedback on the revisions.

General comments

G1: In the first round of reviews, both reviewers raised the issue on the credibility of the method's ability to quantify the liquid and ice volume ratios. While the density retrieval comparison with PIP brings confidence to the presented methods density retrievals that are linked with the liquid water fraction analysis, the choice of maximum vi is not evident but remains somewhat arbitrary in my view. The assumption of dry snow in Huang et al. (2010) is reasonable since they analysed falling snow in temperatures well below freezing. Clearly, the same assumption is not valid in mixed-phase conditions or rain. It is not evident that a "similar" assumption would be valid near melting temperatures that are present in some of the case studies presented in the manuscript. While the novel density retrieval method is well demonstrated, I suggest the authors would be careful with the confidence of the wording when presenting the results of the liquid fraction retrievals. In my view, the validity of the assumption of maximum ice fraction is less than "confirmed", at present. It is not demonstrated in which conditions such assumption would be valid and if the validity would break, e.g., near some temperature threshold. This should be at least noted in the discussion. Further, I suggest adding alternative density retrievals to Fig. 15 using a different assumption on liquid-solid volume fractions to demonstrate the effect on the method's performance.

Reply: To address reviewers' concerns about the maximum ice fraction assumption and the bulk water fraction retrieval, the authors intend to provide a rational justification for the maximum ice fraction assumption. A half-maximum ice fraction sensitivity study has been applied and compared with PIP. The concept of "retrieving" bulk water fraction has also been deemphasized in the revised manuscript per the reviewer's suggestion.

There are two reasons for choosing the maximum ice fraction in the proposed bulk density retrieval algorithm. The first reason is to ensure the "maximum bulk density" is derived. As shown in Fig. 2b, the maximum ice fraction is associated with maximum bulk density. Choosing a lower value of ice fraction subsequently obtains a lower bulk density value. The second reason is that the maximum bulk density with maximum ice fraction assumption has much better agreements of the density-derived SR to the Pluvio observed SR.

Moreover, the retrieved bulk density is in good agreement with PIP retrieval. As per the reviewer's suggestion, a sensitivity study of the half-maximum ice fraction assumption is conducted in the revised manuscript. The results indicate that the retrieved bulk density from half-maximum ice fraction is consistently lower than PIP retrieval. On the other hand, the bulk density retrievals from the maximum ice fraction assumption perform better in agreements with PIP than those from the half-maximum ice fraction assumption. The quantitative consistency of retrieved bulk density from maximum ice fraction to PIP gives authors more confidence in the maximum ice fraction assumption. The sensitivity study results are summarized in section 5.2 of the revised manuscript as shown in the following.

Please see Lines 389-402 of the revised manuscript.

5.2 The sensitivity of maximum ice fraction assumption to the bulk density retrieval

The bulk snow density is determined from possible combinations of vi/vw, and the maximum bulk density with maximum ice fraction (vi) is selected in the proposed algorithm. This maximum ice fraction assumption has been applied to the entire ICE-POP data. As shown in Fig. 2b, choosing the bulk density with minimum ice fraction (e.g., vi=0) leads to the maximum value of vw and minimum bulk density. However, the particle is unlikely to be composed only of water and air. A sensitivity study of selecting a different water/air/ice combination is conducted. The half-maximum ice fraction is selected to derive the retrieved bulk density. As shown in Fig. 15, the retrieved bulk density from the half-maximum ice fraction (red dots) has systematically lower values than the maximum ice fraction (blue dots). The bulk density retrievals from the half-maximum ice fraction have significant discrepancies compared to PIP retrievals.

On the other hand, the density retrieval from the maximum ice fraction assumption has good agreements with PIP retrievals (gray dots). The consistency of retrieved bulk density from the maximum ice fraction to PIP provides more confidence in the assumption of maximum ice fraction. However, the maximum ice fraction assumption may not be valid in a mixed-phased condition when the ice particles melt at a nearly freezing temperature environment. Further investigation is needed in the future study.

As both reviewers suggest, the revised manuscript also deemphasized the performance of the retrieved bulk water fraction. An additional discussion section (section 5.5) on its uncertainty is added in the revised manuscript. The following discussion has been added.

Please see Lines 440-457 of the revised manuscript.

5.5 The retrieval uncertainty of bulk water fraction

The performance of retrieved bulk density has been quantitatively validated by comparing collocated Pluvio-derived SR and PIP-derived bulk density. On the other hand, quantitative validation of retrieved bulk water fraction is not available due to the limitation of instrumentation. No instrument is capable of directly measuring the bulk water fraction. This study's retrieved bulk water fraction is considered qualitatively reasonable according to the case studies of the 28 February and 7 March 2018 events and the statistical analysis of warm-/cold-low events over coastal and mountain sites (section 4.3–4.5). The distinct bulk density and bulk water fraction retrievals of coastal and mountain sites are revealed. The results indicate that the winter precipitation systems of coastal sites with warmer and moister environments have higher bulk density and bulk water fraction than mountain sites.

The composition of water/ice/air fraction determines the bulk density. The retrieved bulk water fraction will differ if a different assumption is made when selecting possible bulk density. Therefore, the performance of the retrieved bulk water fraction is partially linked with bulk density retrieval. As shown in Fig. 15a, both the proposed algorithm and PIP capture the fast transition from the mixed-phase ($\rho_{bulk} \approx 1.0$ g cm^{-3}) to dry snow ($\rho_{bulk} \approx 0.1$ g cm^{-3}). Given the absence of direct measurements of bulk water fraction, the consistency between the retrieved bulk density from the two algorithms is indirect evidence of the qualitative reasonableness of the retrieved bulk water fraction. Combining multiple sophisticated instruments (e.g., 2DVD, PIP, SVI, MASC) and developing a more comprehensive technique can improve our understanding of the critical microphysical characteristics of particles. Further investigation of the particle composition ratio of air/ice/water fraction in different environments is needed.

In the conclusion, the performance of the proposed method is deemphasized as well. Please see Lines 481-482 of the revised manuscript.

The consistency of the retrieved bulk density to collocated PIP suggests that the proposed algorithm performs decently in this study.

G2: Referring to discussion raised by Referee #2's questions on compensating for gauge undercatch due to wind, it is recommended adjust for undercatch even with shielded gauges when measuring snow. See e.g. Kochendorfer et al. (2018). I recommend either applying a correction function or simply stating that no correction was applied. It could induce a bias in the order of 10%. Since the precipitation rate is provided only for reference, I consider this only a minor issue.

Reply: The undercatch adjustment is not applied to the Pluvio data. We have stated that "no under-catch adjustment is applied" in the revised manuscript. Please see Lines 192-193.

Specific and technical comments

L38-39: Suggest "On the other hand, in a warm environment, the melting process induces higher fall velocity due to increased density and aerodynamic effects."

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Lines 38-39.

L99: Does "double windshields" refer to double-Alter windshields?

Reply: The information on the double windshields of each site has been provided in the revised manuscript. Please see Lines 100-102 of the revised manuscript.

The Pluvios at MHS, BKC, and GWU were equipped with a double windshield with inner Tretyakov and outer Alter shield. The Pluvio at YPO was equipped with a Belfort double alter windshield.

L215-216: I'm worried about the lack of transparency in how much data was omitted from the analysis by this visual examination. Could you provide a statistic on this? Further, I suggest marking the omitted data and analysis results in Figures 5, 7-11, e.g., with a grey mask.

Reply: The retrieved bulk density subjected to the attenuation effect is shown by a grey mask in the revised manuscript. Please see Figures 5, 7-11 of the revised manuscript.

L148: As I understand it, in the T-matrix simulations, you assume a standard deviation of 20° for the canting angle of spherical particles. Referring to my comment on the previous round of reviews, I still fail to understand what is the definition of a canting angle of a spherical particle and how is it relevant?

Reply: As introduced in the manuscript, the proposed algorithm assumes a symmetric sphere particle. The definition of a spherical particle's canting angle is irrelevant. The values of the canting angle do not affect the reflectivity from the T-matrix simulation of a symmetric sphere particle. The canting angle affects the reflectivity simulation as the axis ratio 0.5 is applied in the discussion section (section 5.4). The description has been revised to improve the clarity.

Please see Lines 148-150 of the revised manuscript.

The shape of the hydrometeor is regarded as a symmetric sphere since the Z_{HH} measurement of the hydrometer was observed from the bottom of the snow particle by vertical pointing MRR. No canting angle is considered.

Please see Lines 425-426 of the revised manuscript.

A sensitivity investigation assuming the particle axis ratio of 0.5 and the mean and standard deviation of the canting angle are 0° and 20°, shows that about 1.5 dBZ variation of MRR reflectivity can be induced.

L288: Suggest "relatively lower" to 'lower'. Comparison is always relative.

Reply: The "relatively lower" has been revised to "lower" per the reviewer's suggestion. Please see Line 295.

L296, L438: It is incorrect to say that the different sites would represent differrent synoptic environments. Synoptic scale is in the order of 1000km, while the sites seem to be within 100km of each other. The term "mesoclimate" would be more fitting.

Reply: The term "synoptic" has been revised to "mesoclimate" per the reviewer's suggestion. Please Lines 303 and 478.

L306-308: Not completely sure if I understood this sentence. Did you mean that the finding of decreased bulk density is supported by the decrease in average fall velocity?

Reply: Yes, the manuscript intends to indicate that decreased bulk density is supported by the decrease in average fall velocity. In order to improve the manuscript's clarity, the sentence has been revised. Please see Lines 313-315.

The decrease of averaged fall velocity between 08 to 19 UTC on 7 March (Figs. 12a, b) and 19 UTC to 03 UTC on 8 March (Figs. 12d, e) is consistent with the decreasing density in MHS and BKC sites.

L408: It's unclear to me what is meant here. Do you mean that the agreement with density derived from PIP would be worse with a different assumption?

Reply: Choosing the maximum ice fraction in the retrieval algorithm ensures the maximum bulk density is derived. As shown in Fig. 2b, the maximum ice fraction is associated with maximum bulk density. Choosing a lower value of ice fraction subsequently obtains a lower bulk density value. The maximum bulk density with maximum ice fraction assumption has much better agreements of the density-derived SR to the Pluvio observed SR. Moreover, the retrieved bulk density has good agreements with PIP retrieval. As per the reviewer's suggestion, a sensitivity study of the ice fraction assumption is conducted in the revised manuscript. The results indicate that the retrieved bulk density from half-maximum ice fraction is consistently lower than PIP retrieval. The

consistency of retrieved bulk density from the maximum ice fraction to PIP provides more confidence in the assumption of maximum ice fraction.

Please also see the reply to General Comment 1(G1).

L409-411: Suggest "Given the absence of direct measurements of bulk water fraction, the consistency between the retrieved bulk density from the two algorithms serves as indirect evidence of the reasonableness of the retrieved bulk water fraction."

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Lines 452-454 of the revised manuscript.

L413: "mixing-phase" to 'mixed-phase'.

Reply: The "mixing-phase" has been revised to "mixed-phase" per the reviewer's suggestion. Please see Line 385.

L414-416: Suggest "Despite various potential factors that could compromise bulk density retrieval from collocated MRR and Parsivel instruments, the uncertainty study indicates that observational errors have a reasonably low effect, maintaining acceptable performance."

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Lines 436-438 of the revised manuscript.

Table 3: How is "Mean of Pluvio" defined? What are the units?

Reply: "Mean of Pluvio" indicates the mean values of SR from available comparison data for each site. Please see Line 462 of the revised manuscript.

Figure 2, L628: By definition, the value of Z_HH does not change on (along) its contours. Please rephrase.

Reply: The sentence has been removed to avoid confusion. Please see the Lines 486-487 of the revised manuscript.

Figures 5d, 9d-11d: Why does the measured temperature sometimes remain constant for extended periods of several hours? E.g., in Fig. 5d, between 13 and 17 UTC, the temperature reading seems to be stuck at -1°C without any fluctuation. Could you give a short explanation for this behavior? If it is a measurement error, remove the erroneous parts from the figures.

Reply: During ICE-POP, only the MHS site is equipped with WXT520. The temperature data of other sites are from the collocated POSS (Precipitation Occurrence Sensor System). In the previous manuscript, incorrect temperature data was utilized in Fig. 5. The correct temperature data is used in Fig. 5 of the revised manuscript. In Figs. 9-11, some constant temperatures can be seen. The trend of the temperature helps interpolate the density change. The authors would like to keep it.

Figure 14: Is the percentage on the color bar integrated over time or particle volume?

Reply: The percentage on the colorbar is integrated over time.

Figure 14, L731-732: In my understanding, "number density function" refers to the function that describes also the shape of the PSD. Hence, I suggest using the term "number concentration" here, instead.

Reply: The “number density function” has been revised to “number concentration” in the revised manuscript.

Dear Reviewer 2,

The authors sincerely appreciate your valuable comments and suggestions to help improve the manuscript for the second time. We have revised the manuscript titled “Estimating the Snow Density using Collocated Parsivel and MRR Measurements: A Preliminary Study from ICE-POP 2017/2018 ”. that was submitted to ACP (Atmospheric Chemistry and Physics) on 3 January 2024. Based on your suggestions, we have put substantial effort into additional analysis. The manuscript has been thoughtfully revised regarding the comments from all reviewers.

Both reviewers are concerned about the maximum ice fraction assumption and the bulk water fraction retrieval. Both reviewers suggest providing more investigations of assuming the maximum ice fraction and deemphasizing (or not overstating) the bulk water fraction retrieval. A sensitivity study of half-maximum ice fraction assumption has been applied and compared with PIP to address reviewers' concerns about bulk water fraction retrieval. The results indicate that the bulk density retrieved from the half-maximum ice fraction assumption is consistently lower than PIP retrievals. On the other hand, the bulk density retrievals from the maximum ice fraction assumption perform better in agreements with PIP than those from the half-maximum ice fraction assumption. The authors also deemphasize the performance of the retrieved bulk water fraction and discuss its uncertainty more in the revised manuscript by adding a discussion paragraph.

Moreover, the discussion of the retrieved density-particle size relationship has been revised in the manuscript. Each study's particle diameter definitions vary due to diverse measuring instruments and principles. The discussion does not intend to emphasize the difference in the density-particle size relationship. Instead of converting various particle diameter definitions, the particle diameter remains as proposed in each study. The definitions of particle size of each study are summarized in Table 4 of the revised manuscript as well.

The manuscript has also been revised carefully following the reviewer’s suggestions on English wording and typos. The authors would like to express our sincere appreciation for the comments. The added or modified sentences in the revised manuscript are in red for your convenience. The point-to-point replies to every comment have been prepared in the following. For your convenience, the reply is arranged as follows,

Reviewer’s comments

Response

Revisions in the manuscript

We would appreciate any feedback on the revisions.

############ Opening comments #############

I do still have a substantial concern about the method used to decompose the bulk density into an ice volume fraction ("bulk ice fraction", vi) and a liquid volume fraction ("bulk water fraction", vw). The authors do not provide a physical basis for the approach they use. Instead, they use what seems to be an ad-hoc requirement to obtain the smallest possible bulk water fraction given the ZHH and the retrieved ρbulk.

It is clear from equation (2) that ZHH is a function of ρbulk, so I think the part of the study related to determining ρbulk is reasonable. But it is also clear from equation (2) that ZHH provides no information that could be used to distinguish bulk ice and water fractions. From equation (1), the best that can be obtained is a linear relationship between vi and vw. An error in vw could be compensated by an offsetting error in vi to give an accurate ρbulk. Thus an accurately-retrieved ρbulk does not indicate or imply that an estimated vw is correct.

This concern could be addressed if the authors can provide a rational justification for the approach they have taken. Perhaps there are reasons that they have decided to select the solutions that provide minimum vw. Why is it desirable to choose the minimum vw solution? Note my comment below for lines 164-171 of the revised article. If they have sound reasons and can elaborate on those in the methodology, that would address this concern.

If the authors are unable to do this, I think the proper approach would be for the authors to deemphasize their claim of "retrieving" bulk water fraction and instead state that their analyses are for one possible approach to selecting the bulk water fraction.

Reply: To address reviewers' concerns about the maximum ice fraction assumption and the bulk water fraction retrieval, the authors intend to provide a rational justification for the maximum ice fraction assumption. A half-maximum ice fraction sensitivity study has been applied and compared with PIP. The concept of "retrieving" bulk water fraction has also been deemphasized in the revised manuscript per the reviewer's suggestion.

There are two reasons for choosing the maximum ice fraction in the proposed bulk density retrieval algorithm. The first reason is to ensure the "maximum bulk density" is derived. As shown in Fig. 2b, the maximum ice fraction is associated with maximum bulk density. Choosing a lower value of ice fraction subsequently obtains a lower bulk density value. The second reason is that the maximum bulk density with maximum ice fraction assumption has much better agreements of the density-derived SR to the Pluvio observed SR.

Moreover, the retrieved bulk density is in good agreement with PIP retrieval. As per the reviewer's suggestion, a sensitivity study of the half-maximum ice fraction assumption is conducted in the revised manuscript. The results indicate that the retrieved bulk density from half-maximum ice fraction is consistently lower than PIP retrieval. On the other hand, the bulk density retrievals from the maximum ice fraction assumption perform better in agreements with PIP than those from the half-maximum ice fraction assumption. The quantitative consistency of retrieved bulk density from maximum ice fraction to PIP gives authors more confidence in the maximum ice fraction assumption. The sensitivity study results are summarized in section 5.2 of the revised manuscript as shown in the following.

Please see Lines 389-402 of the revised manuscript.

5.2 The sensitivity of maximum ice fraction assumption to the bulk density retrieval

The bulk snow density is determined from possible combinations of vi/vw, and the maximum bulk density with maximum ice fraction (vi) is selected in the proposed algorithm. This maximum ice fraction assumption has been applied to the entire ICE-POP data. As shown in Fig. 2b, choosing the bulk density with minimum ice fraction (e.g., vi=0) leads to the maximum value of vw and minimum bulk density. However, the particle is unlikely to be composed only of water and air. A sensitivity study of selecting a different water/air/ice combination is conducted. The half-maximum ice fraction is selected to derive the retrieved bulk density. As shown in Fig. 15, the retrieved bulk density from the half-maximum ice fraction (red dots) has systematically lower values than the maximum ice fraction (blue dots). The bulk density retrievals from the half-maximum ice fraction have significant discrepancies compared to PIP retrievals.

On the other hand, the density retrieval from the maximum ice fraction assumption has good agreements with PIP retrievals (gray dots). The consistency of retrieved bulk density from the maximum ice fraction to PIP provides more confidence in the assumption of maximum ice fraction. However, the maximum ice fraction assumption may not be valid in a mixed-phased condition when the ice particles melt at a nearly freezing temperature environment. Further investigation is needed in the future study.

As both reviewers suggest, the revised manuscript also deemphasized the performance of the retrieved bulk water fraction. An additional discussion section (section 5.5) on its uncertainty is added in the revised manuscript. The following discussion has been added.

Please see Lines 440-457 of the revised manuscript.

5.5 The retrieval uncertainty of bulk water fraction

The performance of retrieved bulk density has been quantitatively validated by comparing collocated Pluvio-derived SR and PIP-derived bulk density. On the other hand, quantitative validation of retrieved bulk water fraction is not available due to the limitation of instrumentation. No instrument is capable of directly measuring the bulk water fraction. This study's retrieved bulk water fraction is considered qualitatively reasonable according to the case studies of the 28 February and 7 March 2018 events and the statistical analysis of warm-/cold-low events over coastal and mountain sites (section 4.3–4.5). The distinct bulk density and bulk water fraction retrievals of coastal and mountain sites are revealed. The results indicate that the winter precipitation systems of coastal sites with warmer and moister environments have higher bulk density and bulk water fraction than mountain sites.

The composition of water/ice/air fraction determines the bulk density. The retrieved bulk water fraction will differ if a different assumption is made when selecting possible bulk density. Therefore, the performance of the retrieved bulk water fraction is partially linked with bulk density retrieval. As shown in Fig. 15a, both the proposed algorithm and PIP capture the fast transition from the mixed-phase ($\rho_{bulk} \approx 1.0$ g cm^{-3}) to dry snow ($\rho_{bulk} \approx 0.1$ g cm^{-3}). Given the absence of direct measurements of bulk water fraction, the consistency between the retrieved bulk density from the two algorithms is indirect evidence of the qualitative reasonableness of the retrieved bulk water fraction. Combining multiple sophisticated instruments (e.g., 2DVD, PIP, SVI, MASC) and developing a more comprehensive technique can improve our understanding of the critical microphysical characteristics of particles. Further investigation of the particle composition ratio of air/ice/water fraction in different environments is needed.

In the conclusion, the performance of the proposed method is deemphasized as well. Please see Lines 481-482 of the revised manuscript.

The consistency of the retrieved bulk density to collocated PIP suggests that the proposed algorithm performs decently in this study.

########## Line-by-line comments on new revision ###############

L 28: Do you specifically mean liquid water content here? Do you instead mean just water content, since remote sensors observe both ice and liquid hydrometeors.

Reply: To improve the clarity of the manuscript. The “liquid water content (LWC)” has been revised to “liquid/ice water content (LWC/IWC)” as per the reviewer’s suggestion. Please see Line 28.

L 38-39: Since density is not related to the aerodynamic process, maybe rewrite this as ... induces higher density as well as higher fall velocity by the aerodynamic process.

Reply: The sentence has been revised according to both reviewers' suggestions. The revised sentence is as follows. Please see Lines 38-39 in the revised manuscript.

On the other hand, in a warm environment, the melting process induces higher density as well as higher fall velocity by the aerodynamic process.

L 107: The word minute by itself in English is often used to mean small or tiny. I suggest using one- minute instead, which has the desired meaning of a sample of length one minute of time, here and at other locations in the paper.

Reply: The “minute Parsivel data” has been revised to “one-minute Parsivel data” per the reviewer’s suggestion. Please see Line 109 in the revised manuscript.

L 111: Is the ICEP-POP that is used here intentional, rather than ICE-POP?

Reply: The typo has been corrected. Please see Line 113 in the revised manuscript.

L 144-147: If each hydrometeor is truly regarded as a symmetric sphere and ice and water are assumed to be evenly distributed within the particle, canting angle is not relevant - the scattering properties will not change with respect to any rotation of the sphere. Why are canting angles considered? Were the particles not actually symmetric spheres? Please enhance this description to be clear and correct about what is being assumed for the calculation of the scattering properties.

Reply: As introduced in the manuscript, the proposed algorithm assumes a symmetric sphere particle. The definition of a spherical particle's canting angle is irrelevant. The values of the canting angle do not affect the reflectivity from the T-matrix simulation of a symmetric sphere particle. The canting angle affects the reflectivity simulation as the axis ratio 0.5 is applied in the discussion section (section 5.4). The description has been revised to improve the clarity.

Please see Lines 148-150 of the revised manuscript.

The shape of the hydrometeor is regarded as a symmetric sphere since the Z_{HH} measurement of the hydrometer was observed from the bottom of the snow particle by vertical pointing MRR. No canting angle is considered.

Please see Lines 425-426 of the revised manuscript.

A sensitivity investigation assuming the particle axis ratio of 0.5 and the mean and standard deviation of the canting angle are 0° and 20°, shows that about 1.5 dBZ variation of MRR reflectivity can be induced.

L 164-171: This description of the methodology is the point of my most significant concern with the study. To obtain distinct vi and vw, the authors make an ad-hoc choice to pick the solution with the maximum ρbulk and vi. The justification they provide is that this is similar to Huang et al. (2010), which assumes the particles are only ice and air. My opinion is that this justification is not sufficient to allow a claim that vw is being retrieved.

Reply: Please see the reply to the opening comment. Also, the following sentence is added to the revised manuscript.

Please see Line 172 of the revised manuscript.

The impact of ice fraction assumption on bulk density retrieval will be investigated in the discussion section.

L 172-173 and 188: Per the statements by the authors here, the validation approaches that are being used are to validate the retrieved bulk density, not the bulk water fraction.

Reply: The study validates the proposed method's retrievals using the "bulk density" related parameters SR and Vz. A direct comparison of the bulk water fraction is not available. The sentence has been revised to improve the clarity.

Please see Line 173-174 of the revised manuscript.

Since a direct comparison of the bulk water fraction is unavailable, this study will use two approaches to evaluate the bulk density derived from the proposed method.

L 184-185: Reflectivity-weighted velocity (for comparison to radar Doppler velocity) is more often seen calculated from PSDs as

$$V_Z^{\rho bulk} = \frac{\sum \sigma_{bk}(D_i)\, V(D_i)\, N(D_i)\, dD_i}{\sum \sigma_{bk}(D_i)\, N(D_i)\, dD_i} \quad (4)$$

where $\sigma_{bk}(D_i)$ is the backscatter cross-section for particles in size bin i. It's not clear here what is meant by Z(ρbulk,D). Please add some description of Z(ρbulk,D), how it is calculated and whether your formula gives results that are the same as this more typical formula. If not the same, the comparisons of $V^{\rho bulk}$ and V^{MRR} may be of concern.

Reply: The authors have examined the calculation of Vz and confirmed that the calculation of the Reflectivity-weighted velocity utilized the $\sigma_{bk}(D_i)$ rather than the Z(ρbulk,D). The manuscript has been revised to improve clarity. Please see Lines 185-186 of the revised manuscript.

L 196: Per the reference, Kim et al. (2021), equation (6) gives the volume-weighted mean diameter, not the mass-weighted mean diameter. The Kim et al. statement seems correct, since equation (6) gives the ratio of the fourth moment of the PSD to its third moment.

Reply: In Kim et al. (2021), the "characteristic diameter, $D_{m'}$" is defined as the following equation.

$$D_{m'} = \frac{\int_{D_{min}}^{D_{max}} D^4\, N(D) dD}{\int_{D_{min}}^{D_{max}} D^3\, N(D) dD} \quad (6).$$

The authors concur with the reviewer's suggestion. To improve the manuscript's clarity, volume-weighted mean diameter (D_v) is replacing the D_m in the revised manuscript. Please see Lines 198-200 of the revised manuscript. Also, the Fig. 13 has been revised.

L 211: I think this should be ... and CPO are slightly lower.

Reply: The typo has been revised. Please see Line 215.

L 220: Regarding various measurement issues that induce inconsistency, please be more explicit by stating what are these issues.

Reply: As the reviewer suggested, the sentence has been revised to state those issues explicitly. Please see Lines 224-227 of the revised manuscript.

For example, Battaglia et al. (2010) indicated Parsivel's fall velocity measurement error due to the internally assumed relationship between horizontal and vertical snow particle dimensions. The low SNR of MRR reduces Vz measurement quality. In addition, the sampling volume discrepancy increases the Vz inconsistency.

L 264: Please check Figure 5. I do not see a gray area.

Reply: The figure has been corrected. The gray area representing the data with MRR attenuation effect has been shown in Fig. 5, 7-11. Please see the revised manuscript.

L 291-292 and 295-296: I think these lines overstate the interpretation of Figure 12 somewhat. I agree that the distributions in Figure 12 do show changes in fall velocity-diameter relationships. It is probably OK to say that the particular changes in the relationships are consistent with increases in ρ_{bulk} which could be associated with increases in bulk water fraction resulting, for example, from melting of particles. But I believe it is an overstatement to say that gradual increases in density, as well as the bulk water fraction can be found in the V (D) distributions in Figure 12 (L291-292) or that the retrieved bulk density and bulk water fraction reveal distinct V (D) relations (L295-296).

Reply: The authors intend to indicate that changes in fall velocity-diameter relation are consistent with bulk density and bulk water fraction increases. The sentence has been revised to not "overstate" the interpretation of Fig. 12. Please see Lines 298-299, and Lines 302-303 of the revised manuscript.

Original L 291-292:

Gradual increase of density, as well as the bulk water fraction, can also be found in the distribution of fall velocity versus the diameter from MHS, BKC, to the GWU sites (Fig. 12).

Revised: Lines 298-299 of the revised manuscript.

Gradual increase of density, as well as the bulk water fraction, can also be found consistent with an increase in the distribution of fall velocity versus the diameter from MHS, BKC, to the GWU sites (Fig. 12).

Original L295-296:

Overall, the retrieved bulk density and bulk water fraction successfully reveal distinct fall velocity-diameter relations of each site due to the different synoptic environments.

Revised: Lines 302-303 of the revised manuscript.

Overall, the retrieved bulk density and bulk water fraction qualitatively reveal distinct fall velocity-diameter relations of each site due to the different mesoclimate environments.

L 303: I'd suggest transitioned rather than transited.

Reply: The "transited" has been revised to "transitioned" per the reviewer's suggestion. Please see Line 309.

L 304: Should this be at other sites instead of as other sites?

Reply: The "as" has been revised to "at" per the reviewer's suggestion. Please see Line 311.

L 304-305: See my earlier comment regarding L 291-292. Saying that the V (D) relation is consistent with the bulk water fraction seems more appropriate.

Reply: Please see previous reply to L291-292 and 295-296. The authors intend to indicate that the changes in fall velocity-diameter relation are consistent with increases in bulk density and bulk water fraction. The revised manuscript has added one sentence to "not overstate" the relation.

Please see Lines 313-316 of the revised manuscript.

The decrease of averaged fall velocity between 08 to 19 UTC on 7 March (Figs. 12a, b) and 19 UTC to 03 UTC on 8 March (Figs. 12d, e) is consistent with the decreasing density in MHS and BKC sites.

L 326: See my earlier comment regarding L 196 and what is actually calculated by equation (6).

Reply: The authors concur with the reviewer's suggestion. The "characteristic diameter, $D_{m'}$" Kim et al. (2021) should be defined as volume-weighted mean diameter (D_v). In order to improve the clarity of the manuscript, volume-weighted mean diameter (D_v) is replacing the D_m in the revised manuscript. Please see Lines 198-200 of the revised manuscript. Also, the Fig. 13 has been revised.

L 334: Where does this relationship between D_m and D_0 come from? Is there a reference?

Reply: As mentioned in the previous revision, the bulk density comparison in Fig. 13 does not intend to emphasize the difference in the density-particle size relationship. The authors checked the earlier studies, as summarized in Brandes et al. (2007). The particle diameter definitions vary in each study. Instead of converting various particle diameter definitions, the particle diameter remains as proposed in each study. The density-particle size relationships and the particle diameter definitions are summarized in Table 4 of the revised manuscript. The manuscript has been revised to improve the clarity.

Please see Lines 341-346 of the revised manuscript.

Early studies, namely Magono and Nakamura (1965), Holroyd (1971), Muramoto et al. (1995), and Fabry and Szyrmer (1999), have documented various density-particle size relationships (Table 4 and Fig. 13). The particle diameter definitions vary in each study (Table 4). Instead of converting various particle diameter definitions, the particle diameter remains as proposed in each study. Despite distinct environmental conditions, instrumentations, and retrieval techniques, most of the particles in this study are consistent with the density-particle size relationship from previous studies.

L 359: See my opening comments and concerns along with the related line-by-line comments regarding the ability of the retrieval to determine bulk water fraction. This statement also falls under that concern and should be addressed.

Reply: Please see the reply to the opening comment. As per the reviewer's suggestion, the revised manuscript adds a sensitivity study and deemphasizes the claim of "retrieving" bulk water fraction.

L 366: While Battaglia et al. do discuss Parsivel fallspeed errors, I don't believe they are discussed in Wood et al.

Reply: The reviewer suggested the reference to Wood et al. (2013) in the previous submission. Even though Wood et al. (2013) discussed the PSD observation error from 2DVD, authors consider both Parsivel and 2DVD to have similar measuring principles and share the same issue. In addition, the correction factor (CF) derived from comparing the collocated 2DVD and Parsivel in the MHS site is derived to discuss the Parsivel PSD uncertainty. The sentence has been revised to improve clarity.

Please see Lines 404-405 of the revised manuscript.

As indicated by the study by Battaglia et al. (2010) and Wood et al. (2013), Parsivel and 2DVD have various issues in snowflake particle measurement.

L 376: Especially since this approach of using CF is from personal communications and not from a published reference, the values of the particle size-dependent CF and the method by which its values are determined should be documented here, to allow the results to be reproduced.

Reply: The values of CF are summarized in Table 5 of the revised manuscript.

L 410-411: No, I don't think it is justied to say that since the bulk densities are in agreement with those from the PIP, the bulk water fractions are confirmed. ZHH is dependent on bulk density in a way that makes it not possible to discriminate the contributions of vi and vw. Since bulk density depends on both vi and vw, offsetting errors in vi and vw could still give a correct ρbulk.

Reply: Please see the previous reply to the opening comment. As per the reviewer's suggestion, the revised manuscript adds a sensitivity study and deemphasizes the claim of "retrieving" bulk water fraction.

L 413: Usually mixed-phase rather than mixing-phase.

Reply: The type has been corrected as per the reviewer's suggestion. Please see Line 385 of the revised manuscript.

L 416-417: See comment regarding L 410-411.

Reply: Please see the previous reply to the opening comment.

L 433: There appears to be an incomplete sentence here: The retrieved bulk density.

Reply: The incomplete sentence has been removed.

L 441: Again, see and address my overall comments regarding retrieval of bulk water fraction.

Reply: Please see the previous reply to the opening comment. The sentence has been modified, and one sentence has been added to deemphasize the retrieval of the bulk water fraction.

Please see Lines 485-486 of the revised manuscript.

Moreover, the proposed algorithm in this study provides a possible approach to estimating the bulk water fraction.

L 444: Usually unattended rather than unattentively.

Reply: The type has been corrected as per the reviewer's suggestion. Please see Line 484 of the revised manuscript.

General comments

Does EGU have a policy on including information about where to obtain the input datasets used for the study presented in the paper? Is a data availability statement required? In the acknowledgements, I note that the source of the PIP data is not mentioned.

Reply: The PIP data is provided by Dr. Tokay. Please see Lines 496-497 of the revised manuscript.