Dear Reviewer,

The authors sincerely appreciate your valuable comments and suggestions to help improve the manuscript. 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.

One of the major concerns of the proposed density retrieval algorithm using collocated MRR and Parsivel is lacking the uncertainty analysis. As per the reviewer's suggestion, we have performed substantial investigations of the retrieval uncertainty. The impacts of the measurement uncertainty of the Parsivel and the MRR on the bulk density retrieval are analyzed quantitatively. The measurement issue of Parsivel is also investigated to understand its impact on bulk density retrieval. The results are summarized in the revised manuscript as a Discussion section.

The MRR data quality issue has been examined per the reviewer's suggestion. The post-processed data have replaced entire MRR raw data by applying the algorithm from Maahn and Kollias (2012). All the bulk density, bulk water fraction, and reflectivity-weighted velocity retrievals have been recalculated. The figures have been revised as well.

The original purpose of utilizing reflectivity-weighted velocity to filter adequate retrieval is no longer needed and has been removed in the revised manuscript. The quality of the retrieval results have been greatly improved by applying the post-processed MRR data per the reviewer's suggestion. The low SNR MRR measurement has been removed. The comparison of reflectivity-weighted velocity is mainly used to identify the inadequate retrieval due to the attenuation effect on MRR reflectivity.

The performance of the retrieved bulk density has been validated by the snowfall rate (SR) from collocated Pluvio measurements and reflectivity-weighted fall velocity (Vz) from MRR. In addition to SR and Vz, the performance of the retrieved bulk density has been compared with the precipitation imaging package (PIP), a video disdrometer (Newman et al., 2009; Pettersen et al., 2020). The PIP was also deployed at the MHS site during ICE-POP 2018 (Tokay et al., 2023). The comparison of retrieved bulk density between the proposed algorithm in this study and PIP has shown good agreement with each other. The high consistency further confirms the performance of the retrieved bulk density. Since there is no direct bulk water fraction measurement for validation, the authors consider the validation of bulk density retrieval to PIP and Pluvio as "indirect" evidence to support the bulk water fraction retrieval.

The SR and Vz validation analysis shows that the algorithm can adequately retrieve the bulk density and bulk water fraction. The consistency of the retrieved bulk density to collocated PIP confirms the performance of the proposed algorithm in this study. The advantage of the proposed algorithm is that it utilizes collocated Parsivel and MRR, which are commercially available, commonly used, and robust instruments. The Parsivel and MRR can operate unattentively and need little maintenance. Further application of the proposed algorithm helps derive long-term observation data on snow properties. The authors believe the proposed algorithm can provide an alternative choice if sophisticated instruments (e.g., 2DVD, PIP, SVI, MASC) are unavailable.

The manuscript has also been revised carefully following the reviewer's suggestions on English wording. The authors would like to express our sincere appreciation for the comments. The point-to-point replies to every comment have been prepared. Please see the following replies. The added or modified sentences in the revised manual are in red for your convenience. We would appreciate any feedback on the revisions.

General comments

Do the authors see a possibility that the retrieved high values of bulk density and liquid fraction during periods of low reflectivity and precipitation rate could be, at least partly, an artifact from applying the method on observations of very weak precipitation? The retrieval seems somewhat unstable in these conditions which is not surprising considering factors such as low signal to noise ratio due to weak signal. Yet, the authors draw considerable attention to the retrievals of these periods of very weak precipitation. It is worth considering which disciplines would benefit from the microphysical retrievals of weak mixed phase precipitation (<0.5mm/h)? I would suggest either introducing a threshold for minimum reflectivity or precipitation rate where the method is applied, or otherwise critically reviewing the method's performance in weak precipitation, where the precipitation rate falls below the sensitivity of the Pluvios.

Reply: The retrieved bulk density and bulk water fraction as a function of density are shown in Figure R1. Most retrieved bulk density is obtained from MRR reflectivity from 10 to 30 dBZ. Some retrieval results with high bulk density and low MRR reflectivity can be found, but not frequent.

The quality of the retrieval results has been greatly improved by applying the post-processed MRR data as per the reviewer's suggestion. The low SNR MRR measurement has been removed. The authors intend to preserve as much data as possible by only eliminating the data with an attenuation effect on MRR reflectivity. The attenuated MRR reflectivity underestimates the retrieved bulk density and bulk water fraction.

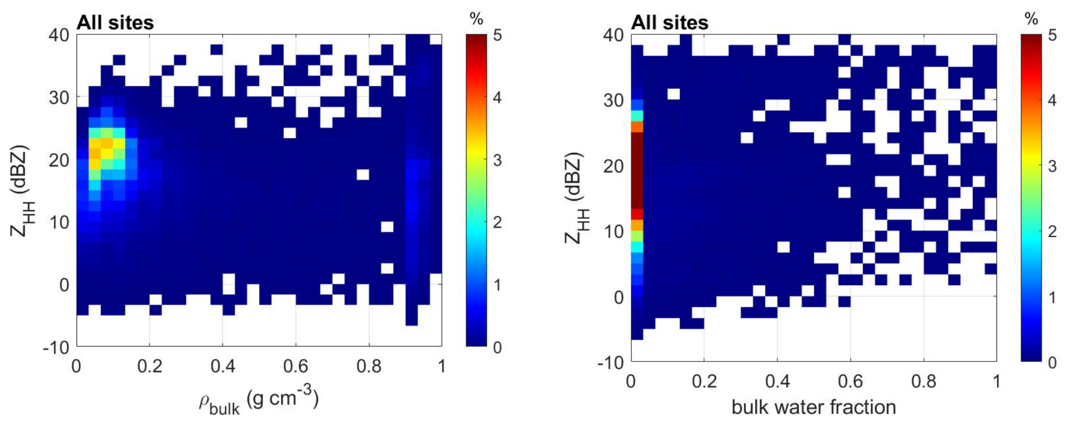


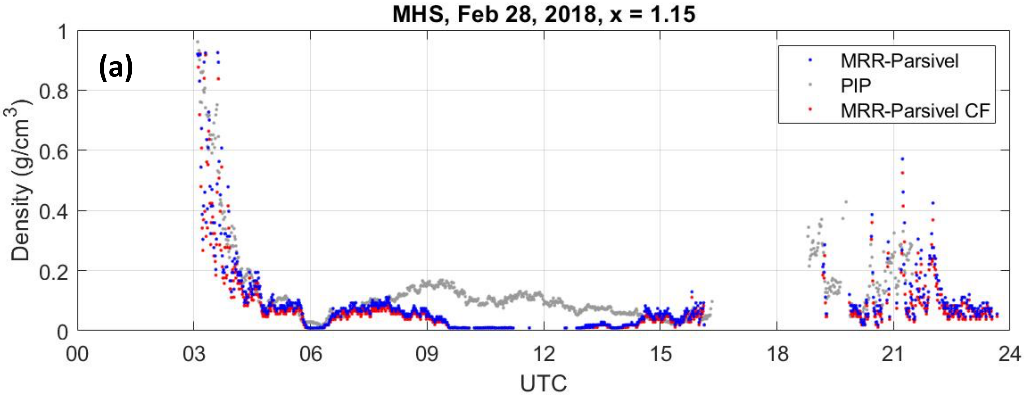
Figure R1: (a) The retrieved bulk density as a function of MRR reflectivity. (b) Same as (b), but for bulk water fraction.

I don't feel that the retrieval of v_w is adequately demonstrated in the case studies since there seem to be no time periods where there would be both a) agreement between derived and measured terminal velocity and b) notable precipitation intensity at the same time. It raises the concern how the method would perform in mixed phase situations with larger particles or higher precipitation rates. In my mind, the best way to address this would be to replace one of the case studies with another one that has significant intensity of wet snow, or discuss the possible limitations of the method's application.

Reply: The bulk water fraction is derived along with the maximum possible bulk density using the proposed method in this study. If a different assumption is made when selecting possible bulk density, the retrieved bulk water fraction will be different. Therefore, the performance of the retrieved bulk water fraction is linked with bulk density retrieval. Since there are no direct measurements of bulk water fraction, we will compare the retrieved bulk density from the proposed method and PIP. The consistency between retrieved bulk density from the two algorithms confirms that the retrieved bulk water should be reasonable.

As shown in Fig. R2(a), the retrieved bulk density values from the proposed algorithm and PIP gradually decrease from nearly 1.0 to 0.1 (g cm^{-3}) between 03 and 06 UTC. Both algorithms capture the transition from the mixing-phase to dry snow. Please see Figure R2. The manuscript has been revised to include a discussion of bulk water fraction retrieval. Please see Line 398-417.

In Figure 14, the coastal sites (BKC and GWU) were associated with higher retrieved bulk water fraction. The environment parameters, including temperature (^{0}C) and vapor pressure (hPa), show that the coastal sites have higher temperatures and more water vapor. Please see Lines 339-357.



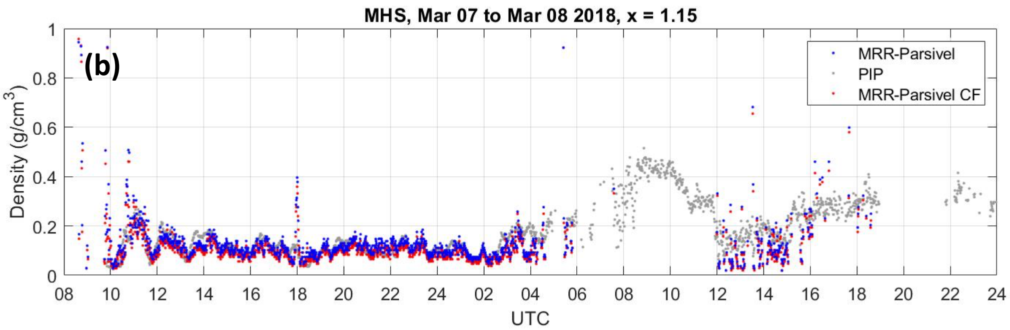


Figure R2: (a) The retrieved bulk density from collocated MRR and Parsivel. The blue dots are retrieved from CF-adjusted PSD. The red dots are from the original PSD. The gray dots are the retrieval from PIP. The case is 28 February 2018. (b) Same as (a), but for case 7 March 2018.

In the presented case studies, it seems like non-zero v_w values only occur when bulk density is nearly saturated at over 0.9 g/cm. I'm concerned whether this is physically reasonable especially given the assumption of spherical particles. This raises the question whether, effectively, the liquid fraction would act as a kind of an overflow buffer in the calculations when density alone cannot explain the reflectivity values. This could rise from the assumption of maximum ice volume fraction (v_i). Or could it be explained with the drizzle-like nature of the precipitation during the v_w signals? This concern could be dispelled with a counter example.

Reply: The assumption of the particle shape has been discussed in the revised manuscript. Please see Lines 386-397.

As the reply to the previous comment, the bulk water fraction is derived along with the maximum possible bulk density in the proposed method in this study. The performance of the retrieved bulk water fraction is linked with bulk density retrieval. Since there are no direct measurements of bulk water fraction, the consistency between retrieved bulk density from the two algorithms confirms that the retrieved bulk water

should be reasonable. Please see Figure R2. The discussion of bulk water retrieval can be found in Lines 398-417 of the revised manuscript.

The manuscript lacks discussion on the implications of assuming spherical particles. This might be significant consideration given the wide range of different particle habits and their shapes and preferred falling alignments.

Reply: The discussion of the assuming spherical particles has been included in the revised manuscript. Please see Lines 386-397. The particle shape assumption for falling velocity and reflectivity calculation has been discussed. Please see Lines 218-221.

Since the manuscript considers the liquid fraction, it would be worth showing or at least mentioning if melting layer signals were detected in the MRR observations.

Reply: Most cases in this study have surface temperatures near zero or lower than zero degrees. As shown in Figures 5 and 7-11, there is no pronounced bright-band signature from MRR radar data.

The viewpoint in the manuscript is more technical and focuses less on microphysics. As such, the topic is suitable for ACP but might be even better suited for AMT. This is a possible consideration for resubmission after revisions.

Reply: The manuscript contains the retrieval technique description and the retrieval result analysis. The retrieval technique is demonstrated by substantial bulk density analysis and water fraction evolution. The features of these bulk properties of warm-low and cold-low events are also investigated.

Specific comments

The title refers to snow density, but retrievals are attempted for snow, mixed phase precipitation and light drizzle. If liquid fraction plays an important role in the revised manuscript, it would be good to be reflected in the title.

Reply: The majority of the particles in this study are snow. The algorithm estimates bulk water fraction value, and the mixing phase of snow can be subsequently differentiated from dry snow. As the bulk water fraction equals one, thus the particle is considered a drizzle or raindrop. Hence, the main objective is to estimate the snow bulk density, including dry and wet snow.

The title indicates this is a preliminary study. Are the authors working on a more comprehensive analysis? Worth mentioning in the discussion.

Reply: The proposed method has been introduced and applied to ICE-POP 2018 data. The analysis also shows that the algorithm can adequately retrieve the bulk density and bulk water fraction. The advantage of the proposed algorithm is that it utilizes collocated Parsivel and MRR, which are commonly used and robust instruments. The Parsivel and MRR can operate unattentively and need little maintenance. Further application of the proposed algorithm helps derive long-term observation data on snow properties. The discussion has been added to the revised manuscript. Please see Lines 441-447.

L42: This sentence seems to suggest that riming and melting are the only processes affecting snow density. While these are important, one should not forget that, e.g., the primary particle habit and aggregation have great impact, too.

Reply: The aggregation process has been added to the revised manuscript. Please Lines 31-33.

L59: As one of the selling points of the new density retrieval method is the use of robust intsruments that require little maintenance, perhaps it would be good to mention studies that use, e.g., PIP or Parsivel for density retrievals. Such studies could be found, for example, by doing citation analysis on Brandes et al. (2007) and Huang et al. (2010), as referred to in the manuscript.

Reply: Per the reviewer's suggestion, the PIP (precipitation imaging package, Newman et al., 2009; Pettersen et al., 2020) was also deployed at the MHS site during ICE-POP 2018. Tokay et al. (2023) have utilized PIP to investigate the PSD parameters, including mass-weighted diameter and normalized intercept. The bulk density is estimated by Tokay et al. (2023) with various assumptions. The PIP retrieved density was generated from the assumption that D_{max} = 1.15 D_{eq}, and the mass derivation included was based on Bohm (1989). The time series of retrieved bulk density from the proposed algorithm and PIP are shown in Fig. R2. The consistency between retrieved bulk density from the two algorithms confirms that the retrieved bulk water should be reasonable. Please see Lines 398-413 in the revised manuscript.

In addition, the MASC (multi-angle snowflake camera) is also introduced in the revised manuscript. Please see Lines 59-62.

Section 2: Details about the ambient temperature measurements are missing, in particular, the types of the instruments or sensors used. The temperature measurements, while not part of the main retrieval methods presented, should be of great interest for the reader as an indication for melting and other microphysical processes.

Reply: The temperature measurements were derived from collocated AWS (Vaisala WXT520). The comparison between the temperature measurements from AWS and PARSIVEL has shown that WXT520 has better performance. The Parsivel data had a significant bias in the Parsivel temperature data. The information on the temperature sensor has been added to the revised manuscript. Please see Fig. 5, 7-11.

Section 2: I would like to see basic information about the Pluvios used such as make, orifice size and shielding.

Reply: The Pluvios are OTT Pluvio² - Weighing Rain Gauge. All of the Pluvios were equipped with double windshields. The Pluvio at the MHS was within the DFIR (double fence intercomparison reference) in addition to the double shield. All the sites investigated in this study have no taller trees or buildings near the MRR antenna and Parsivel. The environmental conditions of all sites are introduced in the revised manuscript; please see Lines 92-103.

L130: What is meant by a canting angle when referring to spherical particles?

Reply: The discussion of non-spherical particles has been introduced in the revised manuscript. Non-spherical and spherical particle measurements are different when MRR looks upward. However, the orientation of the non-spherical particle is assumed to be isotropic and homogeneous. A sensitivity investigation assuming the particle axis ratio of 0.5 has been conducted. The results show that about 1.5 dBZ variation of simulated reflectivity can be induced due to the assumption of particle size.

A random error of MRR reflectivity with a standard deviation of 1.2 dB is introduced into the retrieval algorithm to imitate the particle assumption and MRR measurement uncertainty. The overall standard deviation of bulk density retrieval uncertainty is about 0.025 (g cm^{-3}) for a given MRR reflectivity uncertainty of 1.2 dB. The bulk water fraction retrieval has the same feature, and the uncertainty is about 0.041. Please see the Discussion section in the revised manuscript.

L133: Why was this temperature range chosen for the simulations? Is it physically reasonable to simulate mixed-phase precipitation in -10 degrees Celsius, for example?

Reply: The temperature is set to 0^0C in the T-matrix simulation. The sensitivity test of temperature is shown in Fig. 1. The results indicate that the reflectivity simulation is insensitive to particle temperature. Please see Lines 150-155.

L147: I failed to find references to liquid water fraction from Huang et al. (2010). They seem to just assume particles to consist of ice and air. Either I missed it, or this reference could be more accurate.

Reply: Huang et al. (2010) assumed that a mixture of snow contains only ice and air. Please see page 642 of Huang et al. (2010), "To calculate the backscattering properties of the particles measured by the 2DVD, we consider snow to be a mixture of ice and air.".

The manuscript has been revised to improve the clarity. Please see Lines 167-168.

L263: "The particle size was" to 'Maximum particle size ranged from'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Lines 276-277.

L279: Since there are many sites involved in this study, it could be useful to have a small map showing their locations.

Reply: This study is part of a series of studies of ICE-POP 2018. Many published papers contain such information. The authors would like to use references to provide such information to keep the manuscript concise. "The instruments were located in nineteen sites across the Gangwon region on the east coast of Korea (see Kim et al. 2021 for detailed information of each site)." Please Lines 93-94.

L315: "number density function" to 'number concentration'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Lines 325-326.

L331: How is mean bulk density calculated here? Is it integrated over the total volume?

Reply: The mean bulk density is replaced by the median value of bulk density. The median value is obtained for each site. Please see Line 341.

L334: Since rain was not excluded from the retrievals, we are now talking about the mean bulk density of mixed precipitation instead of snow. As the densities of rain and snow are quite different, the mean value is easily driven by the fraction of rain, masking the possible signal from snow properties.

Reply: The number concentration of the retrieved bulk density is shown in Fig. 14. Both dry snow and mixing-phase events are shown in both warm-low and cold-low events.

The median values of the retrieved bulk density of each site are shown in Fig. 14a,b. The temperature (^{0}C) and water vapor pressure (hPa) measurements from nearby mountain and coastal AWS sites are collected and summarized in Fig. 14e. The warm-low events have warmer and moister conditions compared to cold-low events. The warm- and cold-low events in the coastal area have similar mean temperature values. On the other hand, the water vapor pressure increases significantly from cold-low to warm-low events. The mountain area has similar features but with higher temperature increments and fewer increments of water vapor pressure. Please see Lines 339-357.

L345: This sentence seems to suggest that the density of snow has an impact on the weather. It's unclear to me what was meant here. Please rephrase to clarify.

Reply: The sentence has been revised. Please see Lines 419.

L526: "The ZHH variation with vw is much less than that with vi". I think, the opposite is true.

Reply: It should be "On the contours of Z_{HH}, the Z_{HH} variation with vw is much less than that with vi." The sentence has been rephrased; please see Lines 628.

L560: What does the "shaded area" refer to in Fig. 5c?

Reply: The "shaded area" refers to the MRR reflectivity profile. The sentence has been revised to improve the clarity. "The time series of MRR Z_{HH} vertical profile (dBZ) from the third gate (0.45 km) to the 5 km." Please see Fig. 5 and 7-11.

Figures 5d, 9d-11d: There seem to be flat parts in the temperature measurements, where the measured value does not seem to change even for a fraction of a degree. These look like a measurement errors, perhaps gaps in the measurements. This raises concerns about the quality of the temperature measurements. The measurements should be checked and erroneous values omitted from the analysis. If there is a cause for concern about the quality of the measurements, it should be discussed in the manuscript.

Reply: The temperature measurements were derived from collocated AWS (Vaisala WXT520). The comparison between the temperature measurements from AWS and Parsivel has shown that WXT520 has better performance. The Parsivel data had a significant bias in the Parsivel temperature data. The information on the temperature sensor has been added to the revised manuscript. The scale range of the temperature in Fig. 5, 7-11 is also improved for clarity.

Figure 6: The integration times in these figures are quite long. For example, in Fig. 6b, there seem to be multiple modes in the (D, v) distribution. Because of the long integration time, it is unclear if these modes are co-existing or if the dominating particle type is evolving over time. Have the authors considered analyzing the particle properties such as (D, v) distribution in shorter time intervals?

Reply: The authors did examine shorter time intervals for (D, v) distribution. The (D, v) distribution showed better differentiation between dry and mixing-phase snow. Both Fig. 6 and 12 can illustrate the transition of the mixing phase to dry snow. Considering the number of the figure and keeping the manuscript concise, we would like to maintain the current format of Fig. 6 and Fig. 12.

Technical comments

L10: Authors should choose between the spellings "disdrometer" and "distrometer". Currently, mixed spelling is used for this word in the manuscript.

Reply: The "distrometer" has been revised to "disdrometer".

L27: Since riming refers to a process and not a hydrometeor type, change "riming" to 'rimed particles'.

Reply: The "riming" has been revised to "rimed particles". Please see Line 27.

L73-74: The readability of this sentence could be improved by rephrasing.

Reply: Please see Lines 81-82. The sentence has been revised: Subsequently, the measurement of Z_{HH} weighted fall velocity (V_Z) from MRR is compared with the calculated V_Z from the derived bulk density and Parsivel PSD measurement.

L121: The authors probably meant 'modified FROM Huang et al. (2010)'.

Reply: The typo has been corrected. Please see Lines 138.

L142: "as the increasing" to 'with increasing'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 161.

L178: "examined with" to 'compared with'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 193.

L186: "four with Pluvio" to 'four of them equipped with a Pluvio'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 200.

L196: "consistency of" to 'consistent'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 209.

L232: Full stop after "shown in Fig. 5"

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 347.

L267: "relatively weaker" to 'weaker'. There are also other instances of using "relatively" with a comparative in the manuscript. I advice against this.

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 280. Other similar comparatives have been revised as well.

L274: "precipitation system" to 'precipitation'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 283.

L303: "has a more consistent relation" to 'is more consistent with the relation'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 314.

L345: "microphysics processes" to 'microphysical processes'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 419.

L353: "Consistency" to 'Inconsistency'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 425.

L361: The manuscript could be more consistent with how dates are written: with or without ordinal indicators.

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 431.

L501: "blue lines" to 'blue', as there are also other symbols than lines.

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 603.

L524: "DSD" to 'PSD'

Reply: The sentence has been revised as per the reviewer's suggestion. Please see Line 624.

L569: "derived" to 'shown'

Reply: The sentence has been revised as per the reviewer's suggestion. Please Line 669.

Figure 5d: "MRM" to 'MRR' in the y-axis label.

Reply: The typo has been corrected. Please see Fig. 5d.

Figure 6c: label (c) missing from figure

Reply: The typo has been corrected. Please see Fig. 6c.