

Dear Referee #1,

We would like to express our sincere gratitude to the reviewers for their careful reading of our manuscript and for providing valuable and insightful comments. We have carefully considered and responded to each point below and revised the manuscript accordingly based on these responses. We hope that our explanations and revisions address all the concerns raised and meet the reviewers' expectations.

Major comments

First of all, winter storms contain both thermodynamic phases, namely liquid droplets and ice crystals. The present retrieval framework allows an estimation of IWC and total number concentrations of ice crystals. The treatment of liquid droplets is minimal; LWC is derived from Ku-band radar reflectivity using an empirical approach, as briefly described in Lines 209-211. If the Ku-band-derived LWC is treated as a constant in the retrieval framework, two essential questions arise:

Major comment 1:

How are the potential biases and uncertainty of the LWC estimations incorporated into the retrieval framework, or is the LWC profile estimation treated as a truth with no uncertainty? If so, the retrieval framework may overfit the radar-radiometer measurements by compensating for potential biases in LWC by systematically biased IWC and total number concentration retrievals. This potential bias/uncertainty of LWC is particularly important to the effective use of microwave radiometer measurements, as these are sensitive to the presence of liquid droplets. The error associated with the LWC estimation propagates into the LWC and number concentration retrievals. I would like to see in the manuscript either a quantitative discussion regarding the impacts of LWC uncertainty in the retrievals or an integration of the LWC uncertainty in the retrieval system. Please see my minor comments #8 to consider performing the validation of LWC.

Author response to the major comment 1:

In the current retrieval framework, the Ku-derived LWC is treated as a fixed input. As pointed out by the reviewer, biases in LWC may potentially introduce systematic errors in the ice-hydrometeor retrieval. We conducted a sensitivity analysis to evaluate how uncertainties in the Ku-derived LWC influence both brightness temperatures and the retrieved ice microphysical properties.

Figure S1 shows the sensitivity of simulated brightness temperatures to LWC scaled by constant factors for the cases shown in Figs. 2 and 7. In this experiment, the retrieved ice microphysical properties (Fig. 7) are used as inputs to the forward simulations. The results indicate that LWC uncertainty has a negligible impact on brightness temperatures at frequencies above 165.5 GHz. This

is because these channels are strongly affected by water vapor absorption, resulting in limited sensitivity to the surface and lower atmosphere, while the signal is dominated by scattering from frozen particles in the mid- to upper troposphere.

At the lower frequency (89 GHz), the brightness temperature shows some sensitivity to LWC when the LWC is smaller than 0.1 times the reference value (LWC x 0.1). However, the impact becomes negligible for LWC values greater than LWC x 0.1. It follows that brightness temperature at 89 GHz and higher frequencies is radiatively saturated by a liquid cloud layer unless LWC is unrealistically small. As a result, the signal is dominated by scattering from frozen particles, as in the high-frequency channels.

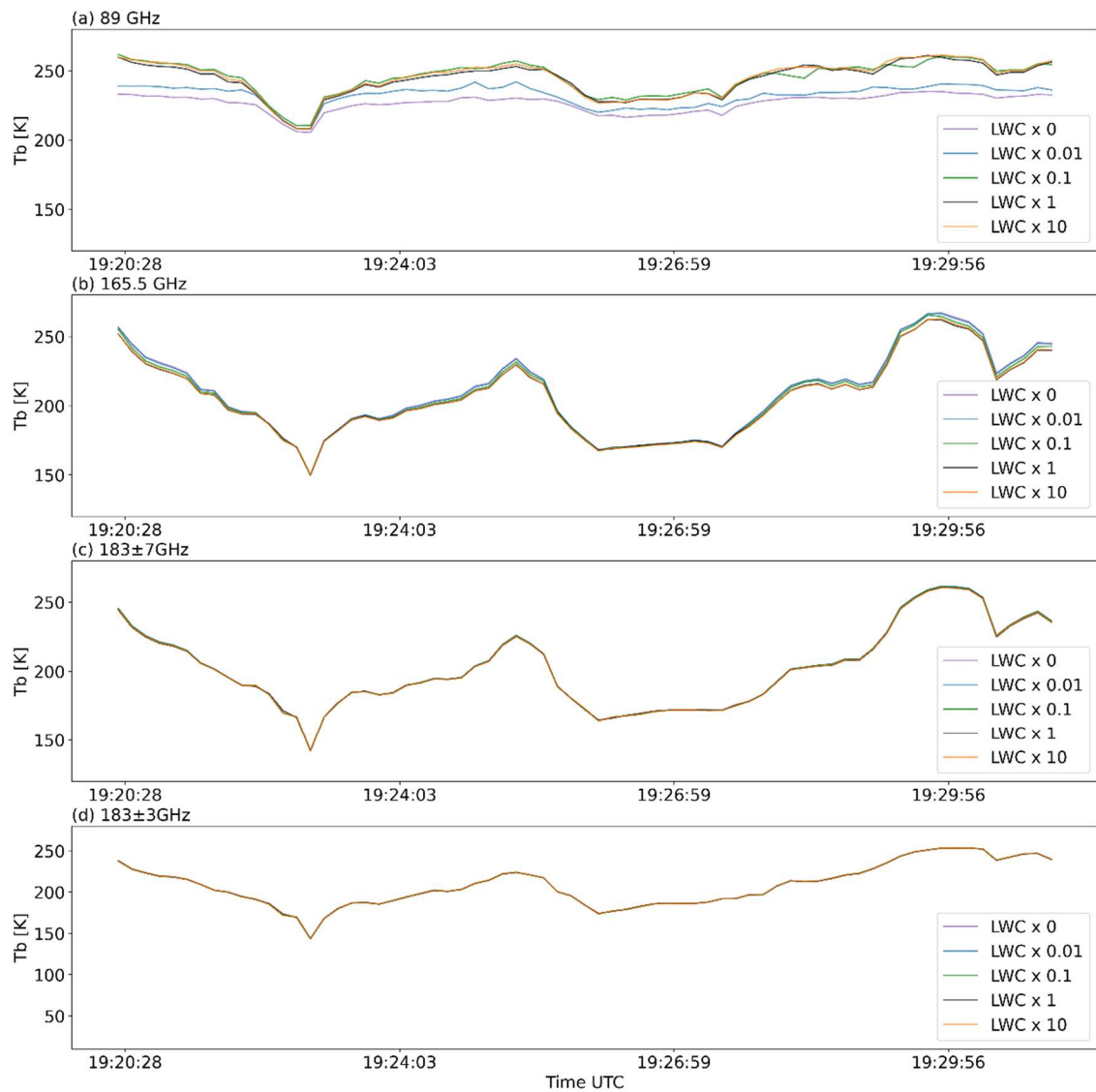


Figure S1: Sensitivity of simulated brightness temperatures to LWC scaled by constant factors (0–10) for the oceanic rainfall case presented in Figs. 2 and 7 of main text. Panels (a)–(d) correspond to 89 GHz, 165.5 GHz, 183 ± 7 GHz, and 183 ± 3 GHz, respectively.

Figures S2 and S3 compare the retrieved values with probe measurements when the LWC is scaled by factors of 0.1 and 10 for all IMPACTS cases, respectively. The results show that the uncertainty in LWC has a limited impact on the retrieval accuracy of ice hydrometeors for these cases. As summarized in Table 1, approximately half of the analyzed cases correspond to snowfall events, where liquid water is largely absent. Even in the remaining rainfall cases, most are associated with well-developed precipitation systems with cloud-top temperatures below -20 °C, suggesting the presence of sufficient liquid water. As indicated in Fig. S1, these conditions may explain the limited sensitivity of the brightness temperatures and ice-hydrometeor retrievals to LWC uncertainty.

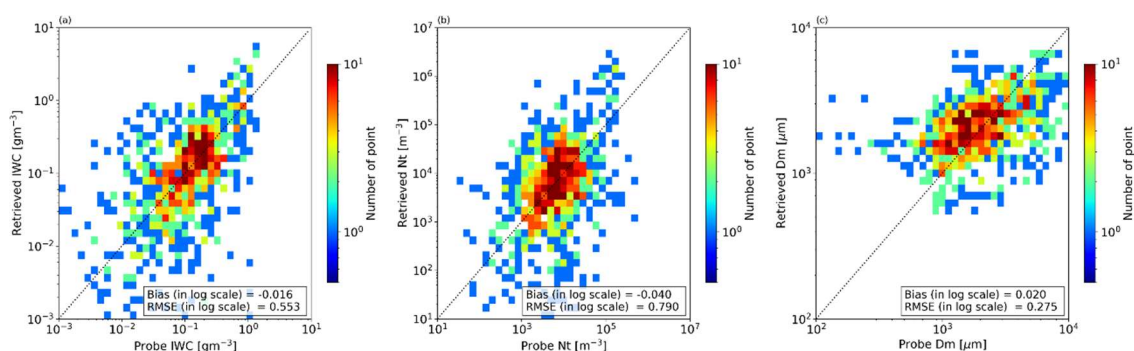


Figure S2: Comparison of retrieved ice hydrometeor properties with in situ probe measurements for the case where LWC is scaled by a factor of 0.1.

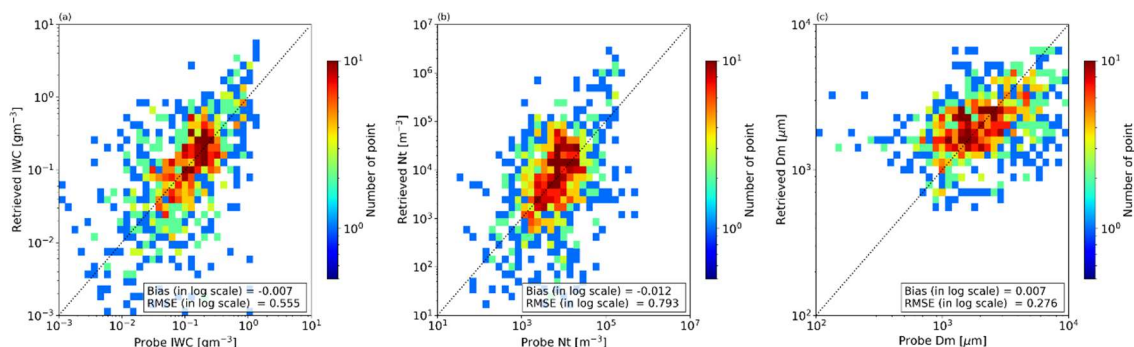


Figure S3: Same as Fig. S2, but with LWC scaled by a factor of 10.

Nevertheless, uncertainty in LWC estimation may have a more pronounced impact on the ice-phase retrieval for non-precipitating clouds with an unexceptionally small LWC. To mitigate the uncertainty in LWC estimation, future work will extend the algorithm to simultaneously retrieve both liquid and ice phases using a combined radar–radiometer approach.

The above discussion has been added to the revised manuscript.

Major comment 2:

Is the use of Ku-band-derived LWC self-conflicting with the W-Ka-Ku-Tb-based retrievals? Ku band radar reflectivity can be fully explained by liquid droplets through the Ku-LWC relationship. Then, the algorithm tries to explain Ku band radar reflectivity by considering both liquid droplets and ice crystals. I might not fully understand the retrieval framework. It would be at least helpful from the readers' perspectives to describe more details about the treatment of liquid droplets in the algorithm. Also, citing Masunaga (2022) is less helpful from the reader's perspective as it is a textbook with >400 pages. Instead, I suggest that the authors briefly describe the Ku-LWC relationship-based LWC estimation.

Author response:

In the present retrieval framework, liquid and ice particles are treated separately based on temperature from ERA5 hourly data. Specifically, hydrometeors at temperatures above 0 °C are assumed to be entirely liquid and are estimated solely using the Z_{Ku} -LWC relationship, whereas those at temperatures below 0 °C are assumed to be entirely ice and are retrieved using the proposed combined algorithm. Mixed-phase conditions are therefore not considered in the current algorithm, and thus the potential self-conflicting issue does not arise.

That said, we agree that the treatment of supercooled liquid water is a potentially critical limitation of the current approach and should be addressed in future work.

Additional details of LWC estimation have been added in Section 2.2, and the relevant sections of Masunaga (2022) have been explicitly indicated for the reader's convenience.

Minor comments

1. Line 33, “graupel and hail,” these should be plural.

Author response: The text has been corrected.

2. Line 54, “combined radar-lidar.” This should be “combined spaceborne radar-lidar,” as the airborne radar-lidar approach can profile in-cloud structures by flying through inner clouds, and ground-based radar-lidar can profile the lower portion of the clouds.

Author response: The text has been revised.

3. Lines 62-64: Figure 1b is the derivative of the 165.5 GHz brightness temperature with respect to a logarithmic IWC. This requires an IWC profile, but the corresponding description is lacking. Please clarify and explain how the IWC profile is obtained to compute the derivative.

Author response: As described in the caption of Fig. 1, the IWC profile is taken from the O25 retrieval (combined CloudSat–GPM), and is used to compute Jacobian $\frac{\partial T_b}{\partial \log(IWC)}$.

4. Lines 101-102: Clouds can evolve even within 15 minutes. In particular, large hydrometeors can fall out quickly, which may skew the validation results. I would suggest adding discussions regarding the potential biases in the comparison due to the time difference between the remote sensing and in-situ measurements.

Author response: To assess the potential effect of temporal mismatches, we examined the relationship between the time difference of the ER-2 and P-3 observations and the retrieval error (difference between retrieved and in-situ values), as shown in Fig. S3. No clear correlation was found for the IMPACTS cases analyzed in this study, suggesting that the matchup time difference is unlikely to systematically affect the retrieval accuracy. This discussion has been added to the manuscript.

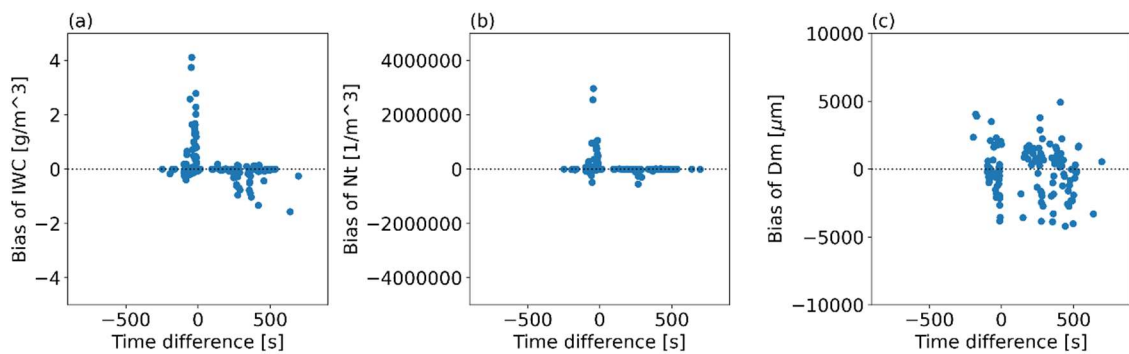


Figure S4: The dependence of the retrieval error on the matchup time difference between the ER-2 and P-3 observations for (a) IWC, (b) Nt, and (c) Dm.

5. Line 131 “... are averaged using a Gaussian weight.” How did you make an average of radar reflectivity? A simple average does not work as radar reflectivity is in a dBZ unit. These quantities should be converted into radar backscattering power, averaged, and then converted back to a dBZ unit. The current manuscript was unclear whether the radar reflectivity was appropriately averaged.

Author response: The averaging is properly processed, that is, the radar reflectivity is first

converted to linear units ($Z_w [\text{mm}^6 \text{m}^{-3}] = 10^{(Z_w[\text{dBZ}]/10)$), averaged, and then converted back to dBZ. This procedure has been clarified in the revised manuscript.

6. Line 131 “GoSMIR” should be “CoSMIR.”

Author response: The text has been corrected.

7. Lines 152-154: the 2D-S has a lower detection limit, and this probe misses lots of small hydrometeors, mainly liquid droplets but potentially small ice crystals that contribute to the total number concentration. Please elaborate on potential biases in in-situ measured PSDs and resultant impacts on the validation effort.

Author response: Given that probes such as the 2D-S have large uncertainties for particles smaller than 100 μm , as described in lines 174-175 and 343-345, the validation is performed using PSDs integrated over particles larger than 100 μm to derive IWC, Dm, and Nt. For consistency, the retrieved PSDs are also reconstructed and integrated over the same size range before comparison.

8. Table 3. I am wondering if P-3 aircraft deploy cloud probes that directly measure total water content (e.g., King probe) and both total and liquid water content (e.g., Nevzorov probe). This could provide a reliable dataset for the validation of the retrievals.

Author response: As noted in our response to the major comment, the current algorithm does not consider mixed-phase conditions. While measurements from the King or Nevzorov probes would provide valuable information for simultaneous IWC and LWC validation in mixed-phase clouds, this will be considered in future work when extending the algorithm to simultaneously retrieve both liquid and ice hydrometeors.

9. Lines 314-315: It seems that reading O25 is a prerequisite to reading this manuscript. I suggest the authors consider either inserting a sentence that guides the readers to read O25 in the Introduction or providing a summary of how covariance matrices are derived.

Author response: We have added a brief note in the manuscript to guide the reader to the relevant section of O25.

10. Section 4.1: Regarding the validation of the retrievals with in-situ measurements, did the authors make some averaging of the in-situ measured microphysical properties to match the large radiometer’s footprint, or are these treated as point measurements in the comparison?

Author response: As described in lines 159-160, the in-situ measurements are also averaged

within the radiometer footprint using a Gaussian weighting prior to comparison.

11. Section 5.1: The terminal velocities obtained from both cloud probes and the retrievals rely on a series of empirical equations (i.e., Eqs. 4-7). Basically, this is a comparison of the mean diameters between cloud probes and the retrievals through the lens of terminal velocity, and it does not add any information from the direct D_m comparison described in Section 4.1. Please describe any benefit in adding the terminal velocity comparison to the D_m comparison.

Author response: As described in lines 464-467, both probe-based and retrieved terminal velocities are computed using Eqs. (4)–(7). However, the treatment of the cross-sectional area $A_r(D)$ differs between the two approaches. It is directly measured by the probes, whereas it is prescribed based on the assumed particle model in the retrieval. Therefore, agreement in terminal velocity requires not only consistency in particle size (D_m) but also validity of the particle model (parameterization of $A_r(D)$).

12. Lines 460-461: V_d should not be used as a data-filtering criterion for the V_d plots. Suggest the authors use a different meteorological variable for a data-filtering criterion (e.g., temperature).

Author response: We have revised the analysis to use temperature from ERA5 hourly data for screening. In some IMPACTS cases, the 0 °C level did not coincide with the melting layer identified from Doppler velocity. To ensure the exclusion of liquid-phase conditions, the analysis was restricted to data with temperatures below –3 °C. These changes have been reflected in the manuscript.

13. Figure 11f: In this histogram, I would add the original V_d histogram, so that the readers can see how much 1) the width of the histogram is narrowed after a subtraction of estimated V_t , and the peak of the histogram is shifted from a non-zero peak toward zero.

Author response: The histogram of V_d has been added to Fig. 11f, and the corresponding discussion has been included in the manuscript.

14. Section 5.2: The manuscript lacks a sufficient discussion of the difference between Z_w+T_b and $Z_w+T_b+Z_{ka}+Z_{ku}$. I can see it only in Lines 512-514. It seems to me that adding Z_{ka} and Z_{ku} does not much improve the retrievals. Ka band and Ku band radar reflectivities should be sensitive to large ice hydrometeors that may be beyond the Rayleigh scattering regime at W-band frequency. I just suspect that only a trivial improvement by adding the two radar frequencies may be due to a self-conflicting assumption in the Ku band (related to my major comment). Please elaborate on the reasons.

Author response:

As also noted in the general comment by another reviewer, the benefit of adding Ku- and Ka-band radar observations may be limited because the midlatitude snowstorm cases are analyzed in this study, for which low-frequency radar reflectivity is not very sensitive to ice microphysics. As illustrated in Fig. 1, Ku- and Ka-band radars are primarily sensitive to relatively large frozen particles just above the melting layer, whereas high-frequency microwave radiometers are sensitive to a broader range of frozen particles extending to higher altitudes. The in situ observations by the P-3 aircraft were mainly conducted at altitudes where the radiometer retains sensitivity to ice particles, while the number of samples in deeper cloud layers was limited. This sampling characteristics may have contributed to the limited benefit of the triple-radar configuration.

The addition of Ku- and Ka-band radar observations is expected to provide greater benefit for cloud systems such as tropical deep convection that contain larger ice hydrometeors (e.g., hail and graupel). This aspect will be further examined using global EarthCARE–GPM coincident observations in future work.

The above discussion has been added to the revised manuscript (lines 541-547).

15. Figure 13: This plot is somewhat confusing. I am not certain how I can interpret the vertical axes. Is a positive value better than a negative value, or is any deviation from zero better?

Author response: Positive values on the vertical axis indicate an improvement in retrieval accuracy due to the combined use of sensors compared to the W-band radar-only retrieval, whereas negative values indicate a degradation in accuracy. This explanation has been added to the manuscript.