

Dear Referees,

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. A list of changes made in the manuscript (track-changes file) is described in red text. We hope that our explanations and revisions address all the concerns raised and meet the reviewers' expectations.

Referee #1

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 parameters (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 ($LWC \times 0.1$). However, the impact becomes negligible for LWC values greater than $LWC \times 0.1$. 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.

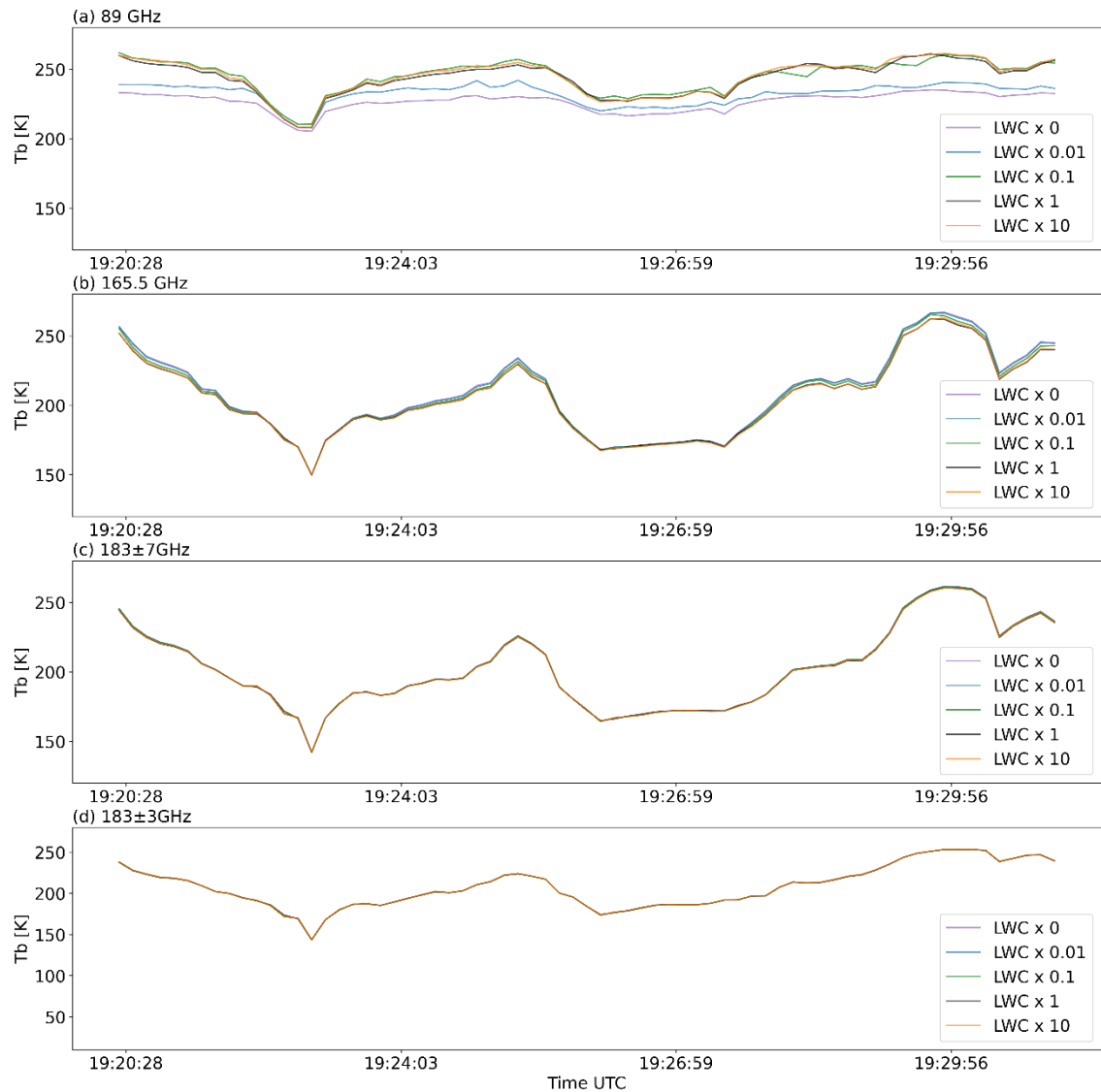


Figure S1: Sensitivity of simulated brightness temperatures to LWC scaled by constant factors (0–10) for the oceanic rainfall case presented in Figs. 2 and 7 of main text. Panels (a)–(d) correspond to 89 GHz, 165.5 GHz, 183 ± 7 GHz, and 183 ± 3 GHz, respectively.

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.

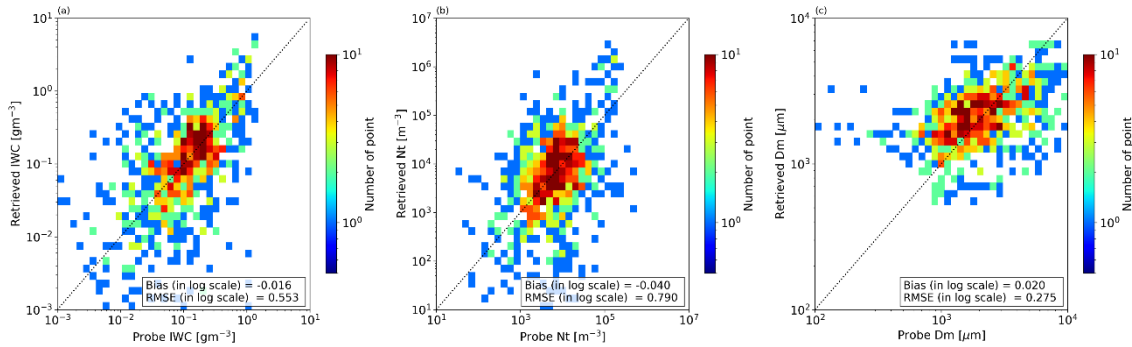


Figure S2: Same as Fig. 8, but assuming LWC scaled by a factor of 0.1.

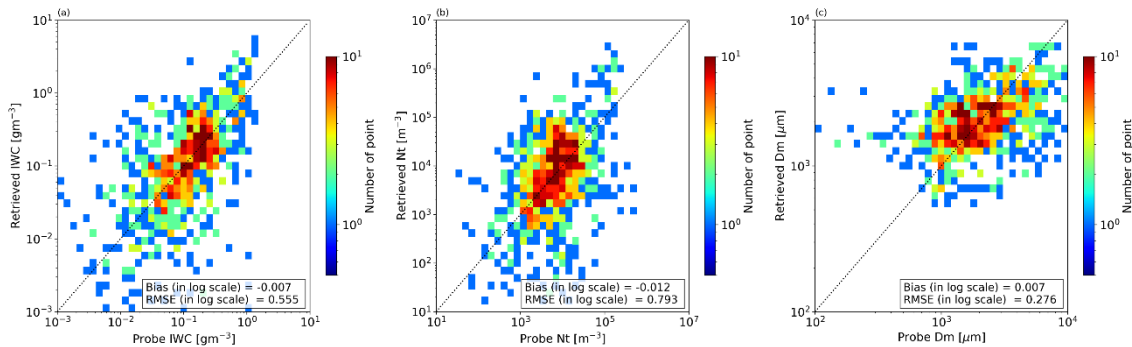


Figure S3: Same as Fig. S2, but with LWC scaled by a factor of 10.

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 (lines 225, 421-414 and the Supplement).

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 (lines 222-228).

Minor comments

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

Author response: The text has been corrected (line 33).

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 (line 53).

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. S4. 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 (lines 421-414 and the Supplement).

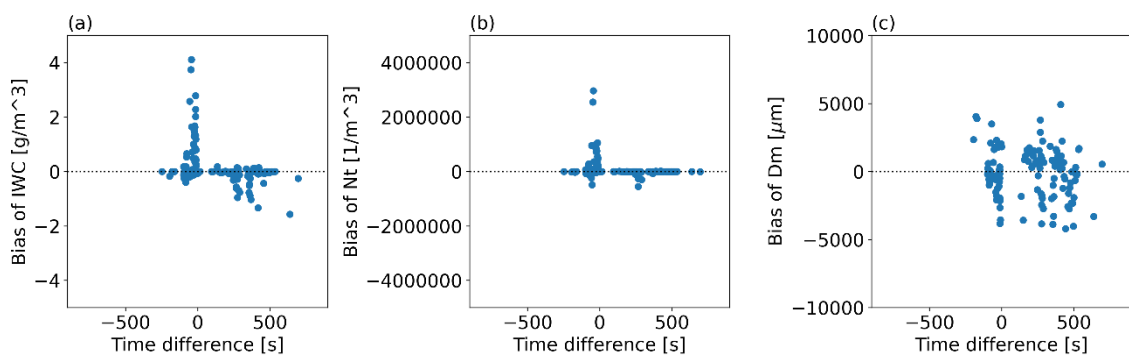


Figure S4: The dependence of the retrieval error on the matchup time difference between the ER-2 and P-3 observations for (a) IWC, (b) Nt, and (c) Dm.

- 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 (line 131).

- Line 131 "GoSMIR" should be "CoSMIR."

Author response: The text has been corrected (line 130).

- 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 173-174 and lines 346-348, 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 (lines 332-333).

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 Dm comparison described in Section 4.1. Please describe any benefit in adding the terminal velocity comparison to the Dm comparison.

Author response: As described in lines 478-481, 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 $A_r(D)$). (lines 478-479)

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 from ERA5 temperature 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 (lines 501-502).

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 (lines 503-509).

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 561-567).

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 (lines 553-553).

Referee #2,

General Comments:

General Comments 1:

- The manuscript would benefit from a discussion of the simplifying assumptions underlying the combined retrieval algorithm and how these assumptions may affect the results. For example, the algorithm currently does not retrieve temperature or water vapor, which will introduce forward-model errors in the passive microwave (PMW) observations. While some of these aspects are discussed in O25, it would be helpful to briefly summarize them here and refer to that work. Please also describe how surface emissivities are modeled.

Author response:

Temperature is prescribed from ERA5 hourly data and treated as a fixed auxiliary input. For water vapor, relative humidity (RH) is assumed to be 100% within cloudy/precipitating regions ($Z_w > -30$ dBZ), and is taken from ERA5 hourly data elsewhere ($Z_w < -30$ dBZ). As noted, high-frequency brightness temperatures are sensitive to water vapor, and uncertainties in RH may affect the results. To assess this impact, we conducted a sensitivity test by assuming $RH = 75\%$ within clouds and performed the same evaluation as in Fig. 8. The results are shown in Fig. S5. No essential difference is found from Fig. 8, indicating that the impact of water vapor assumptions on the retrieval accuracy is limited.

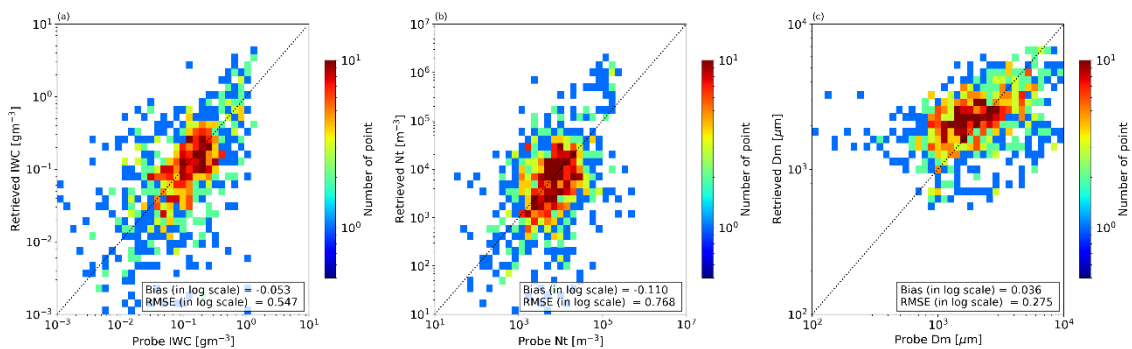


Figure S5: Same as Fig. 8 ($RH=100\%$), but assuming $RH = 75\%$ within clouds.

Land surface emissivity is modeled by the NESDIS microwave land emissivity model (Weng et al., 2001) implemented in the radiative transfer model in use (J-Sim). The emissivity is calculated assuming a vegetation fraction of 100%, soil moisture fraction of 50%, surface temperature from ERA5 hourly data, and zero snow depth in this study. These simplified assumptions may introduce errors in surface emissivity, particularly under conditions such as snow cover, which could affect primarily low-frequency brightness temperatures. However, the high-frequency channels (≥ 89 GHz)

used in this study are more strongly influenced by water vapor absorption and cloud/precipitation scattering, and thus have reduced sensitivity to the surface, suggesting that the impact is relatively small. Nevertheless, in dry atmospheric conditions at high latitudes, even high-frequency brightness temperature may be affected substantially by surface emission. In future work, we plan to refine the surface emissivity modeling by incorporating dynamic emissivity estimation methods for cloudy and precipitating regions, which may be critical for applications to global satellite observations.

We have added a summary of the relevant assumptions to the manuscript (lines 209-218, lines 421-424, and the Supplement).

Weng, F., Yan, B., and Grody, N. C.: A microwave land emissivity model, *J. Geophys. Res.*, 106(D17), 20115–20123, <https://doi.org/10.1029/2001JD900019>, 2001.

General Comments 2:

- The current results do not show a clear benefit of the triple-radar combined retrieval compared to the retrieval using only W-band observations. This may be related to the fact that the IMPACTS campaign primarily sampled winter storms, where Ku- and Ka-band observations may provide limited additional sensitivity. However, this point should be discussed explicitly, as the current results suggest that W-band + PMW observations may already be sufficient to retrieve ice microphysics with good accuracy.

Author response:

Figures 12 and 13 show that the combined use of triple-radar and microwave radiometer ($Z_w + T_b + Z_{Ku} + Z_{Ka}$) observations provides some benefit compared to the W-band radar-only case, but does not show a clear improvement relative to the combined use of W-band radar and microwave radiometer ($Z_w + T_b$) observations. As noted, the benefit of adding Ku- and Ka-band radar observations may be limited because 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 561-567).

General Comments 3:

- While the study shows that the mixed particle habit yields the best agreement with the in-situ measurements, an important scientific question is whether the available observations alone are sufficient to constrain particle habit. I therefore suggest adding a plot similar to Figure 9 that shows the bias and mean-squared error of the simulated PMW observations for the different habit assumptions.

Author response:

We agree that such an analysis is important. As pointed out, Ohara and Masunaga (hereafter O25) demonstrated that the consistency between simulations and observations depends strongly on the assumed particle habit in clouds with large IWP. Figures S6–S10 show comparisons between observations and simulations based on retrievals assuming several representative particle habits, in the same manner as Fig. 10. However, no clear differences in reproducibility were found among the different habit assumptions unlike in O25.

In the tropical deep convective systems analyzed in O25, the synergy of radar and radiometer observations appears to contain sufficient information to partially constrain not only the particle size distribution but also the particle habit. In contrast, the observational information related to particle habits appears to be limited for the midlatitude snowstorm cases observed during IMPACTS. This difference likely arises from differences in meteorological characteristics between tropical convective systems and midlatitude snowstorms, such as IWC, particle size, and water vapor conditions, which affect the sensitivity of radar and radiometer observations to cloud microphysical properties.

These findings suggest that, for midlatitude snowstorms, prescribing the particle habit assumption consistent with in situ observations may be a more effective approach than attempting to constrain it solely from remote sensing measurements. This issue will be further investigated in future work when extending the algorithm to a global framework including both tropical and midlatitude systems.

The above discussion has been added to the manuscript (lines 466-474 and Supplement).

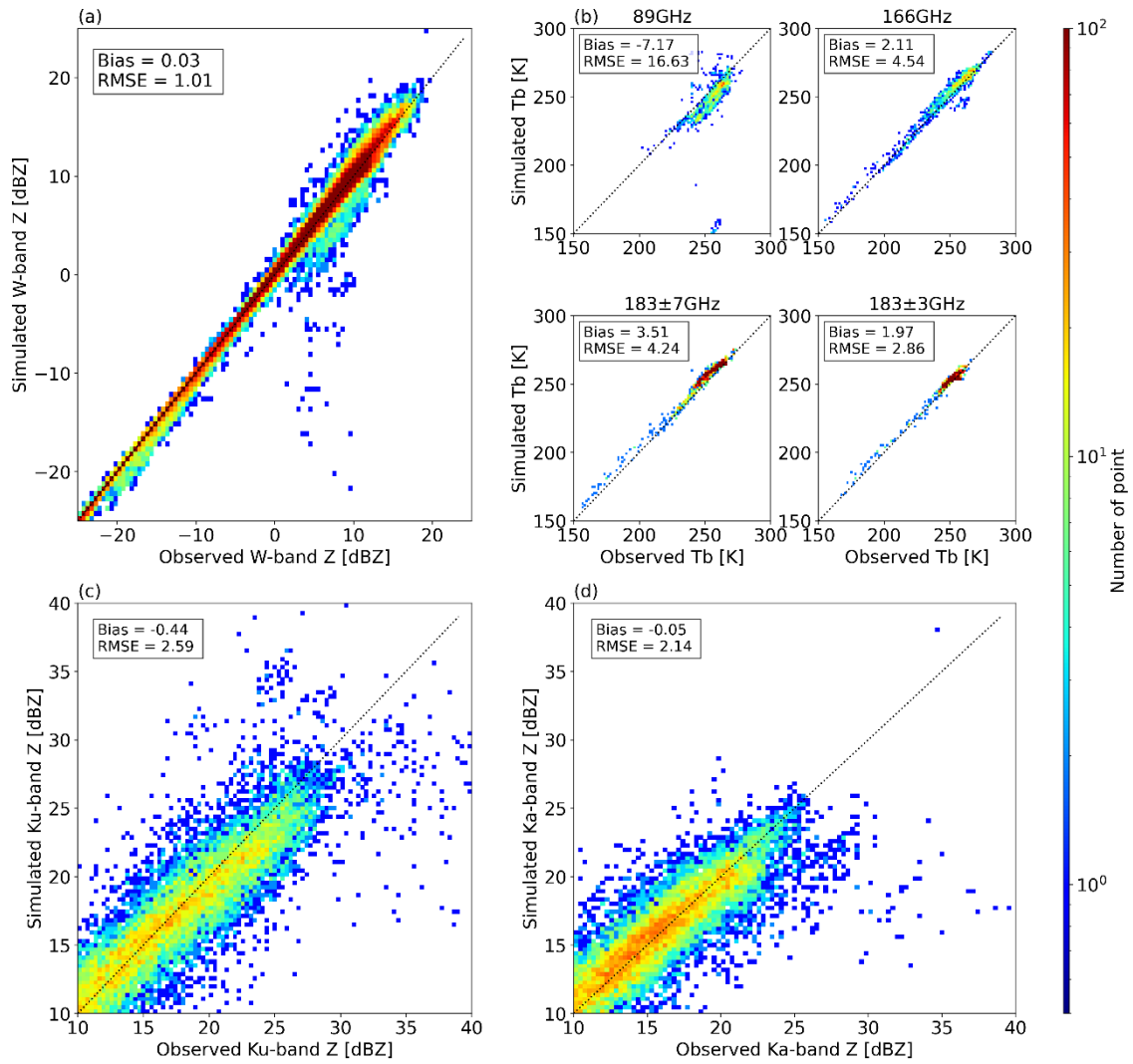


Figure S6: Same as Fig. 10 (assuming the mixed rosette–snowflake model), but for retrievals assuming the thick plate model.

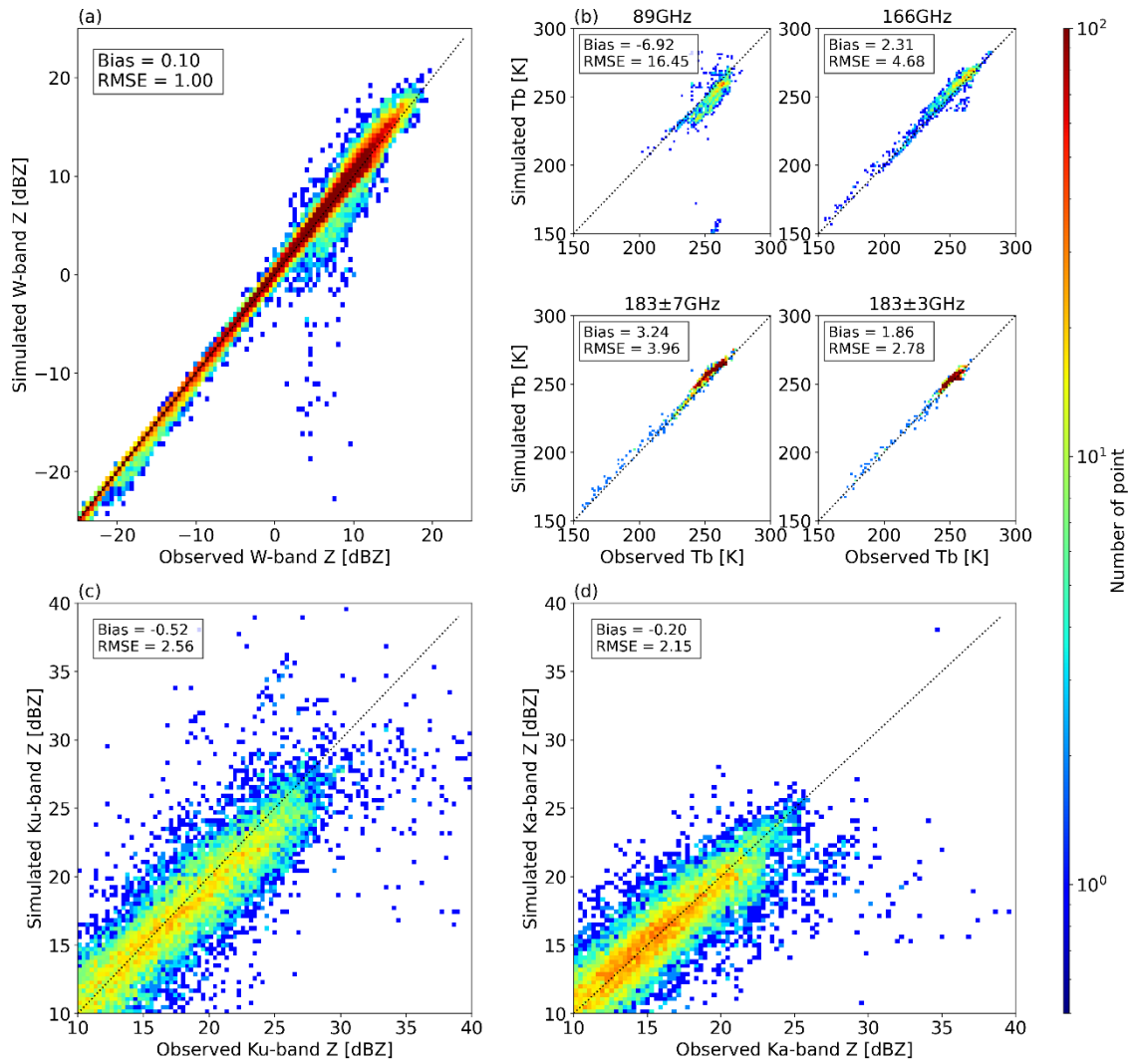


Figure S7: Same as Fig. S6, but for retrievals assuming the short column model.

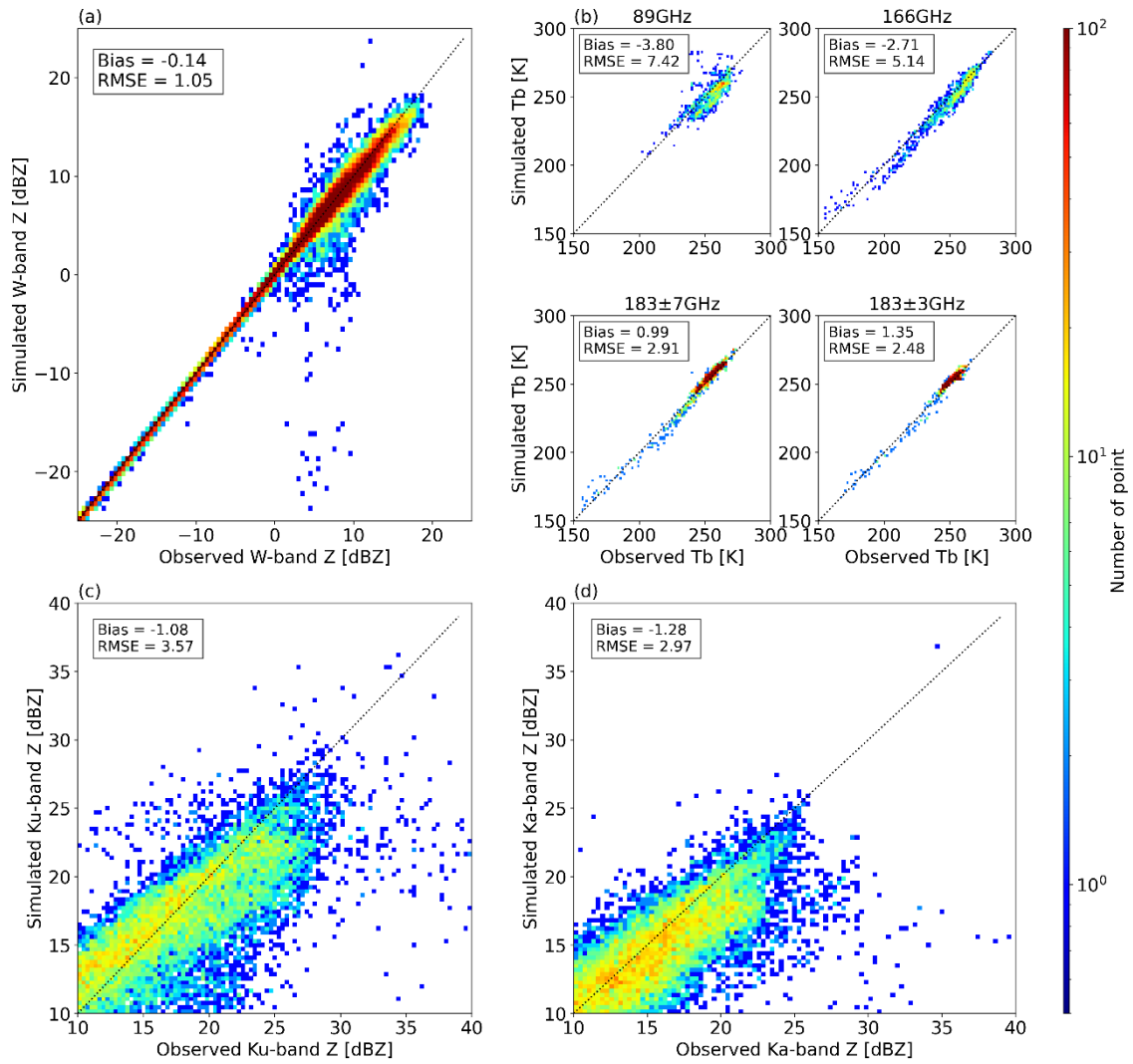


Figure S8: Same as Fig. S6, but for retrievals assuming the 6-bullet rosette model.

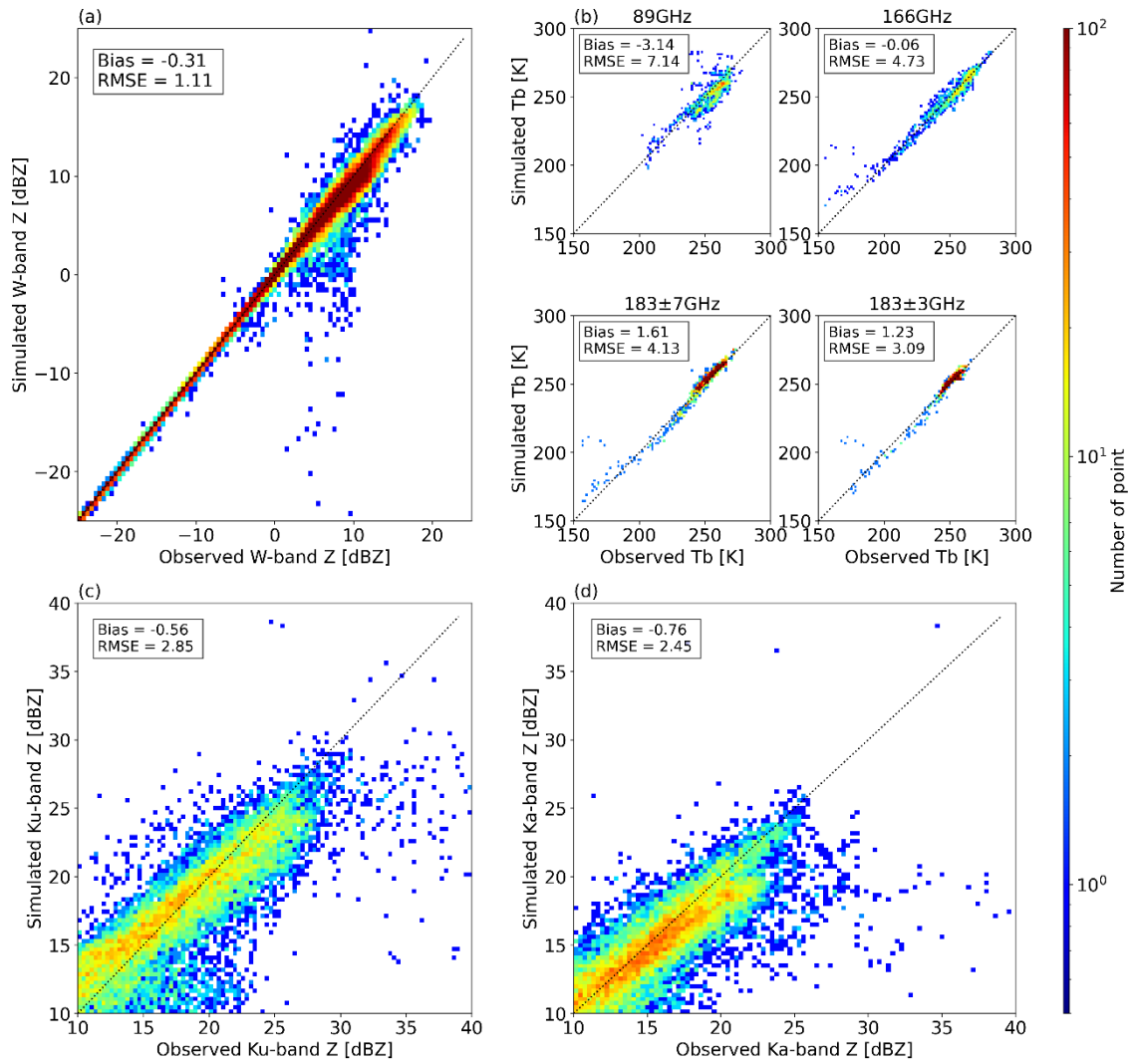


Figure S9: Same as Fig. S6, but for retrievals assuming the dendrite snowflake model.

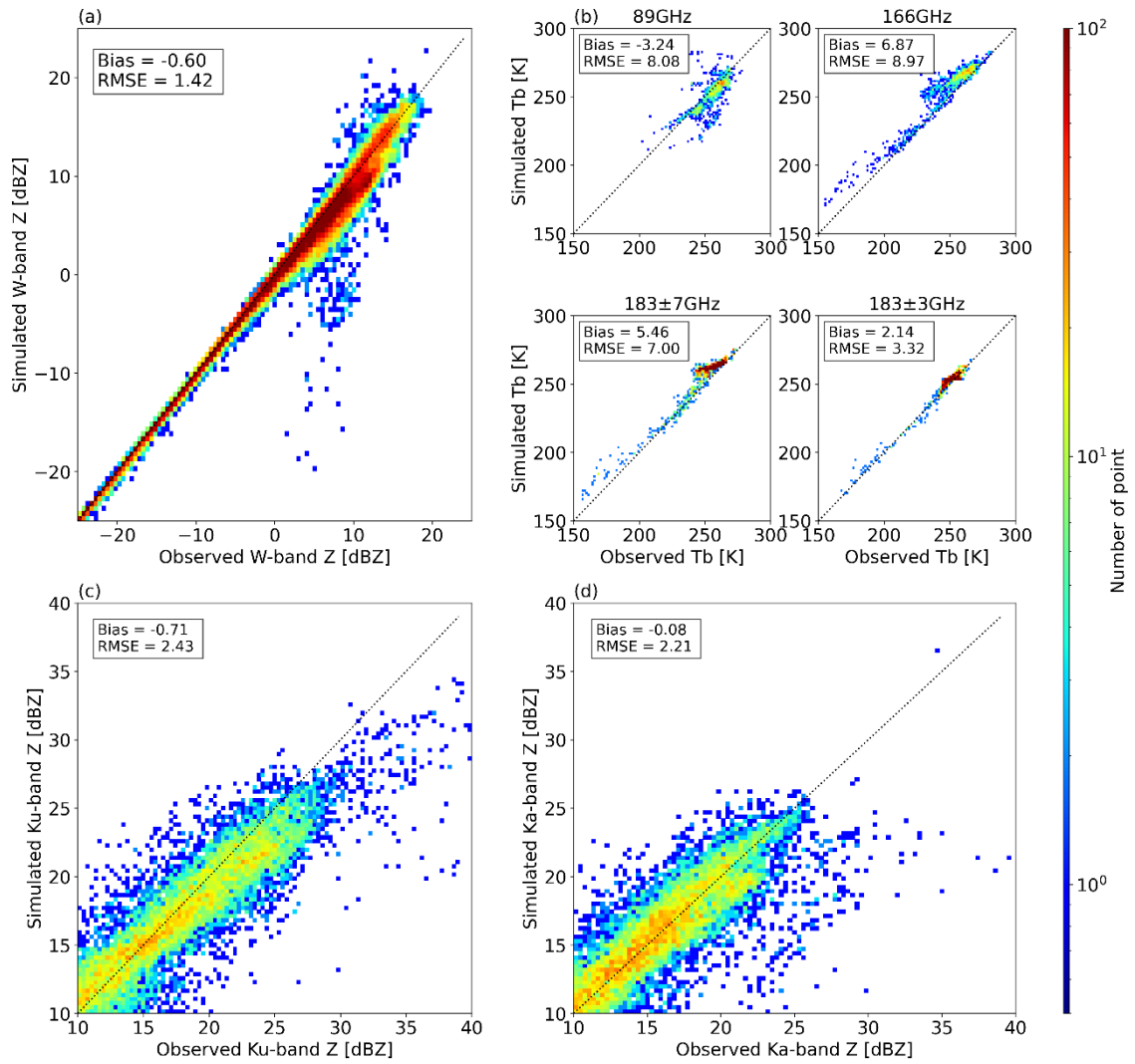


Figure S10: Same as Fig. S6, but for retrievals assuming the soft sphere model.

Specific Comments

- l. 117: It may be helpful to note that these correspond to the high-frequency channels of GMI, since GMI includes additional lower-frequency channels.

Author response: The sentence has been revised to explicitly clarify that these correspond to the high-frequency channels of GMI (line 115).

- Figure 2:

- Please increase the line width/marker size in panel (a), (b), (e).

- Please also increase the font size and use vector graphics or higher-resolution images to improve readability.

Author response: The layout of Fig. 2 has been revised, including adjustments to font size, line width, and marker size (Fig. 2).

- l. 374: In Fig. 2b, I only see one strong updraft that actually intersects the flight path. Could the observed biases simply result from the in-situ measurements being taken near the cloud base?

Author response: Thank you for this insightful comment. As pointed out, the observed biases may partly arise from the fact that the in-situ measurements were obtained near the cloud base. This point has been added to the manuscript (lines 398-401).

- l. 486: This statement appears to contradict the discussion in l.296. Please clarify.

Author response: The previous wording was not sufficiently clear. We intended to emphasize that, when attenuation effects are neglected, the initial estimate of the ice microphysical properties is already consistent with Zw. Therefore, an Optimal Estimation using only Zw observations can account for attenuation effects to some extent, but cannot reduce the uncertainty in λ assumed in the initial estimation. The sentence has been revised to clarify this point for the reader (lines 528-535).

We have carefully reviewed the manuscript and made the following minor corrections. None of these changes affect the analysis results.

- **Line 82:** The term “atmospheric reanalysis” has been revised to “ancillary,” as the data are not limited to atmospheric variables. Accordingly, “atmospheric” has also been removed from “atmospheric ancillary data” in Fig. 4.
- **Table 2:** The minus sign in $Z_w > -30\text{dBZ}$ was missing and has been added.
- **Figure 2:** A typographical error in the caption has been corrected.
- **Figures 3, 5, 6, and 7:** The layouts have been adjusted to improve readability.
- **Table 4:** The coefficient a_m for the soft-sphere model was incorrect and has been corrected. The correct value was used in the analysis, so the results are unaffected.
- **Equation (10):** The notation of the logarithm has been corrected.
- **Equation (13):** The notation has been revised to reflect that perturbations are applied to IWC and N_t in logarithmic space.
- **Equation (14):** The matrix notation has been revised to conform to AMT style.
- **Figure 10:** Additional information has been added to the caption.