

Dear Referee #2,

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.

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: We have added a summary of the relevant assumptions to the manuscript. 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. S1. No essential difference is found from Fig. 8, indicating that the impact of water vapor assumptions on the retrieval accuracy is limited.

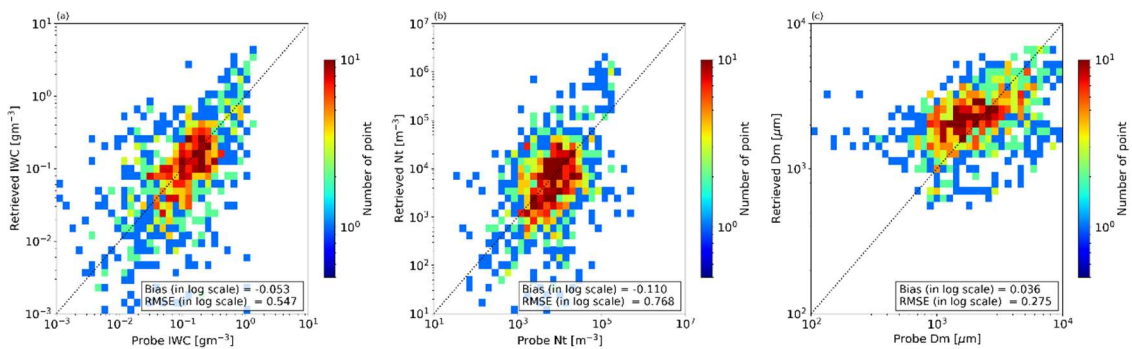


Figure S1: Same as Fig. 8, but assuming $RH = 75\%$ within clouds.

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.

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:

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.

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 S2–S6 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.

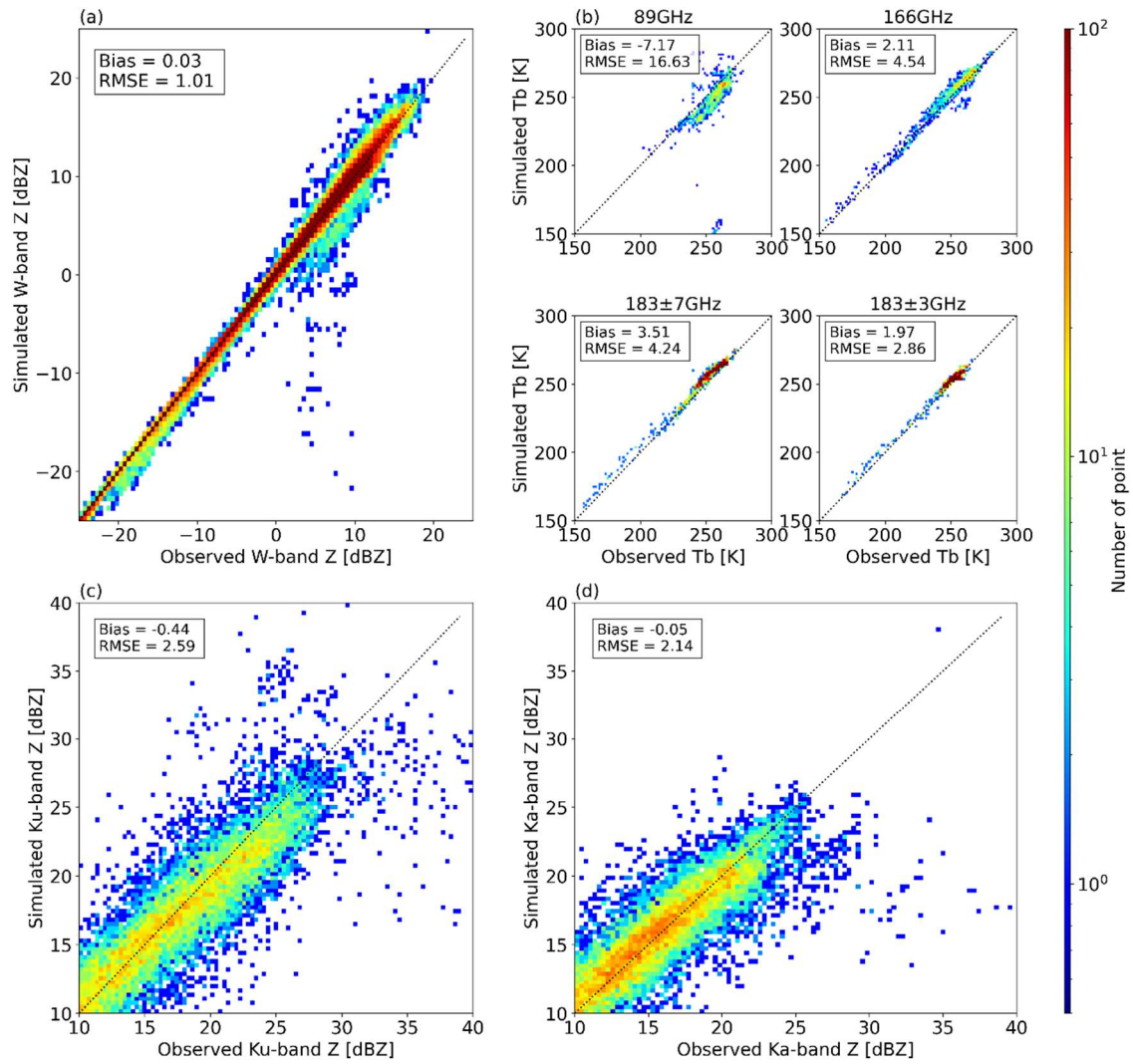


Figure S2: Same as Fig. 10 (assuming the mixed rosette–snowflake model), but for retrievals assuming the thick plate model.

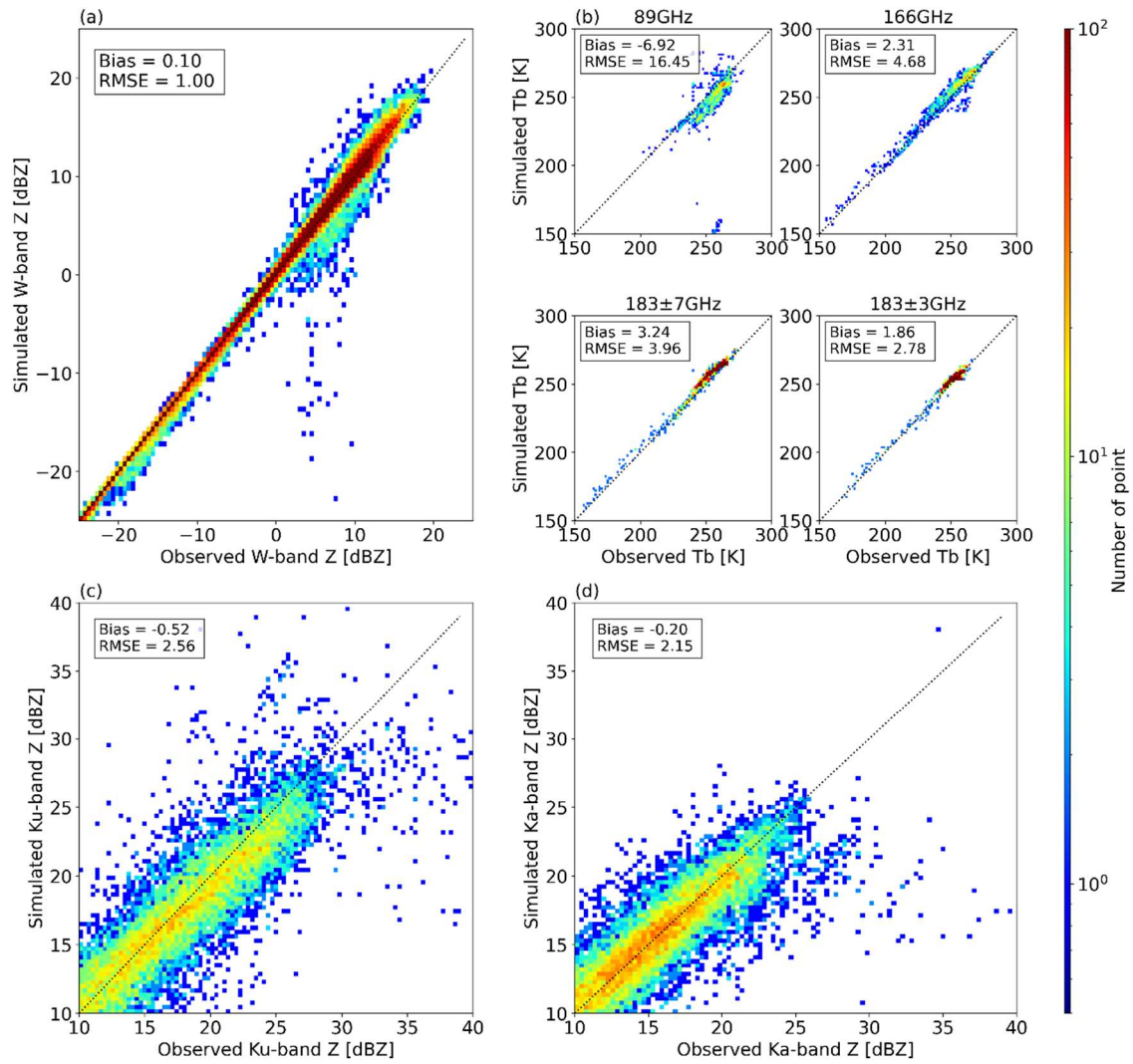


Figure S3: Same as Fig. S2, but for retrievals assuming the short column model.

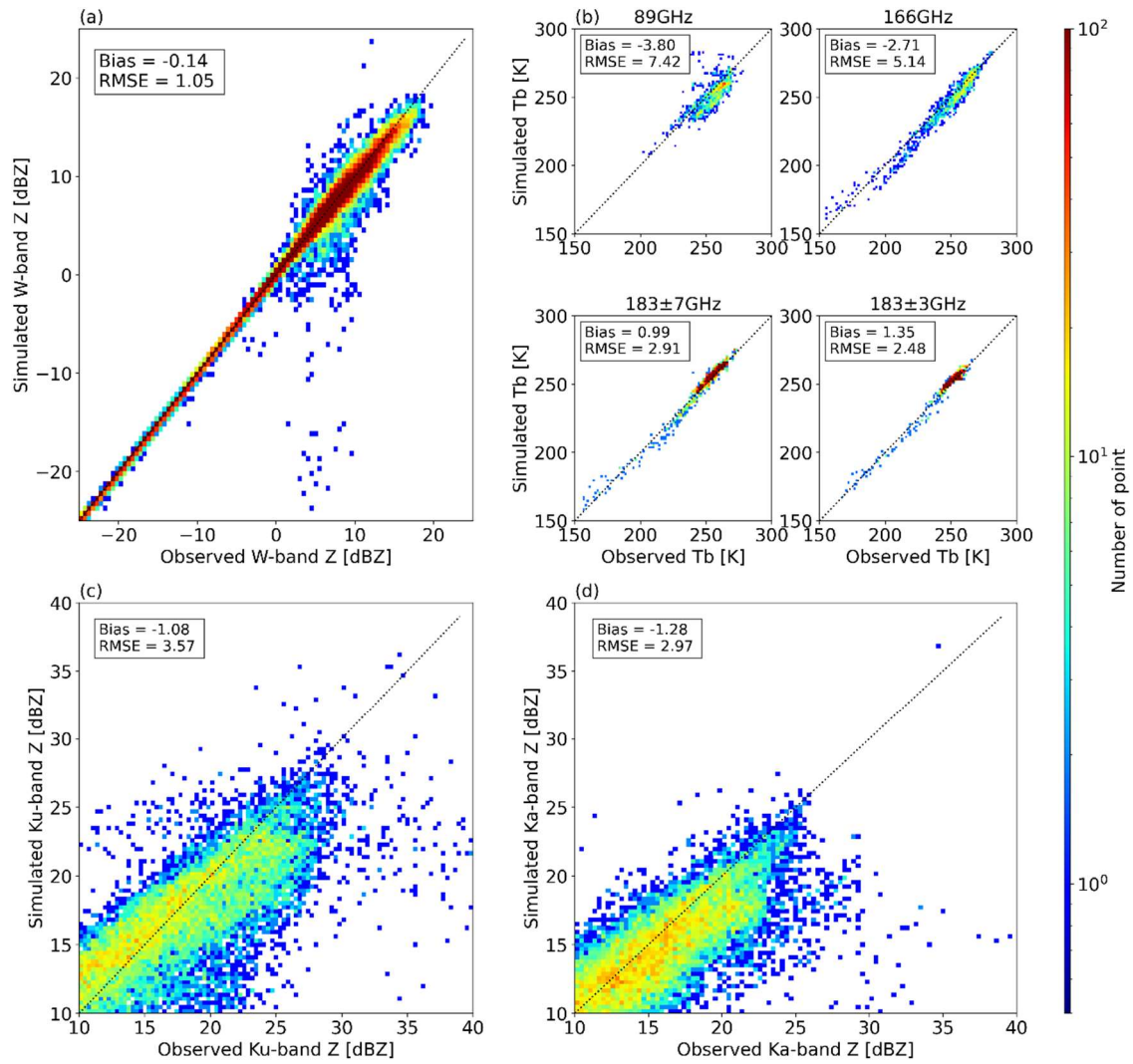


Figure S4: Same as Fig. S2, but for retrievals assuming the 6-bullet rosette model.

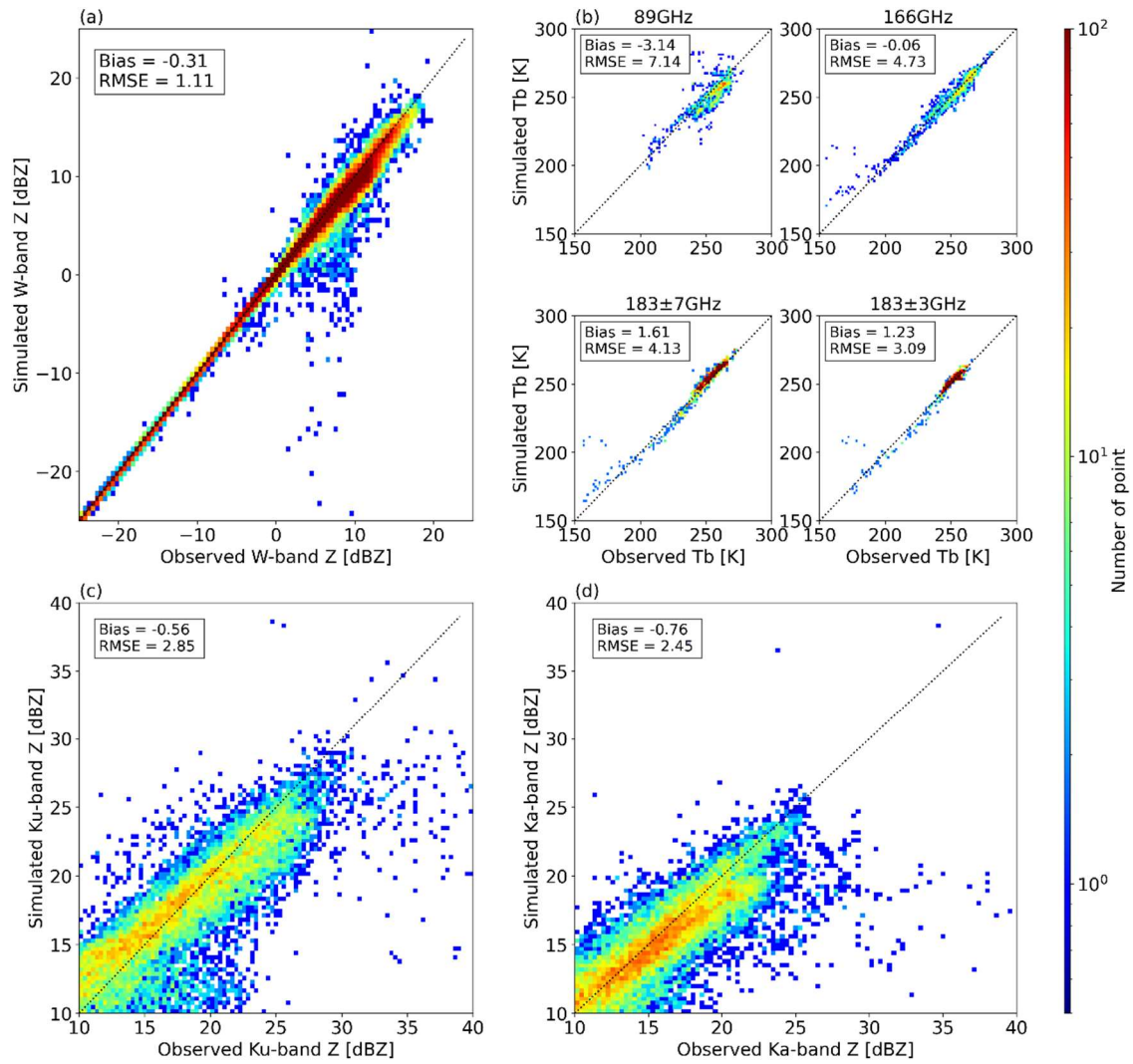


Figure S3: Same as Fig. S2, but for retrievals assuming the dendrite snowflake model.

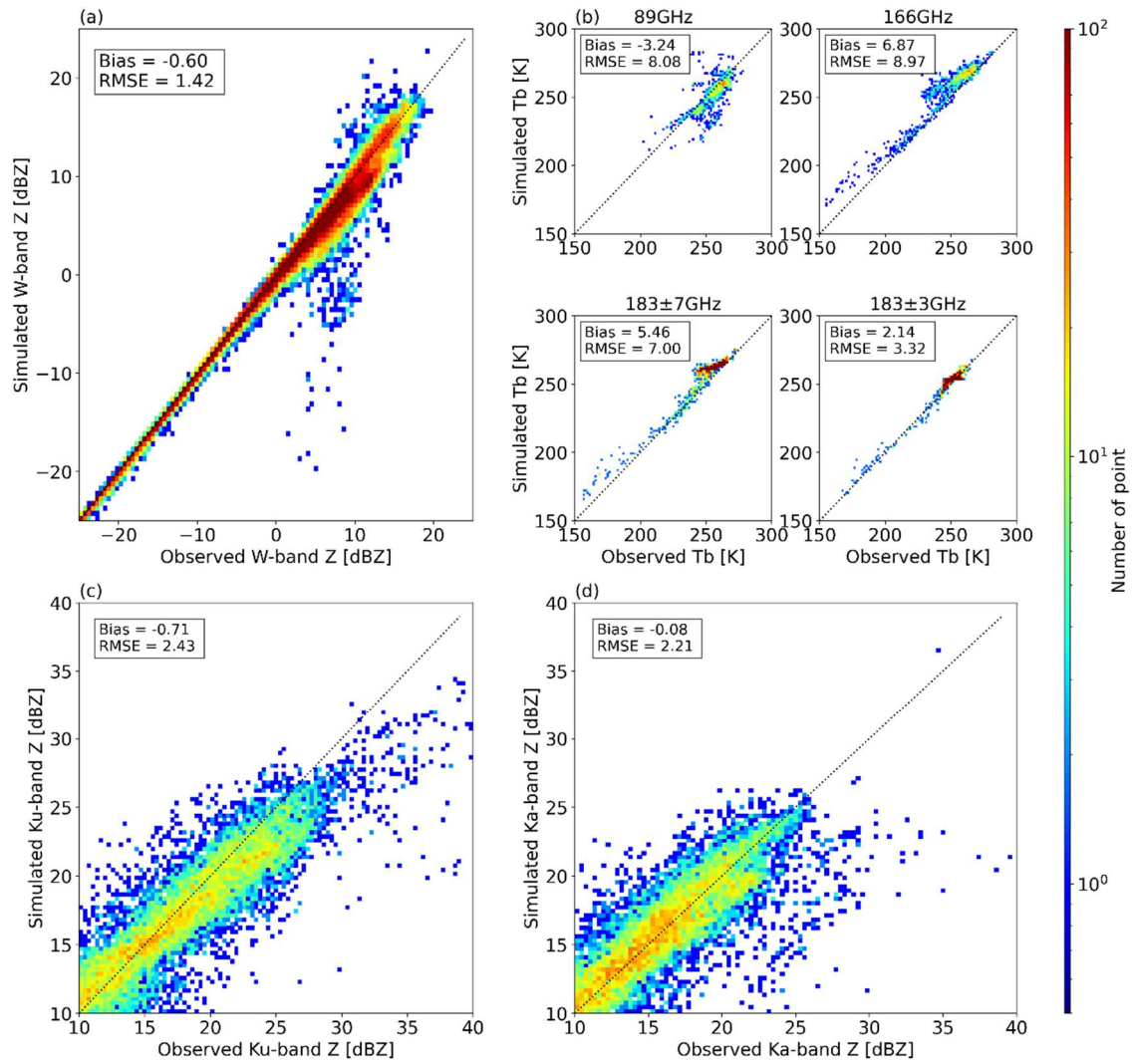


Figure S3: Same as Fig. S2, but for retrievals assuming the soft sphere model.

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.

- 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.

- 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.

- 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 Z_w . Therefore, an Optimal Estimation using only Z_w 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.