



*Supplement of*

## **Evaluation of ice hydrometeor retrieval using multi-band radar and millimeter-wave radiometer measurements from the IMPACTS campaign**

**Keiichi Ohara and Hirohiko Masunaga**

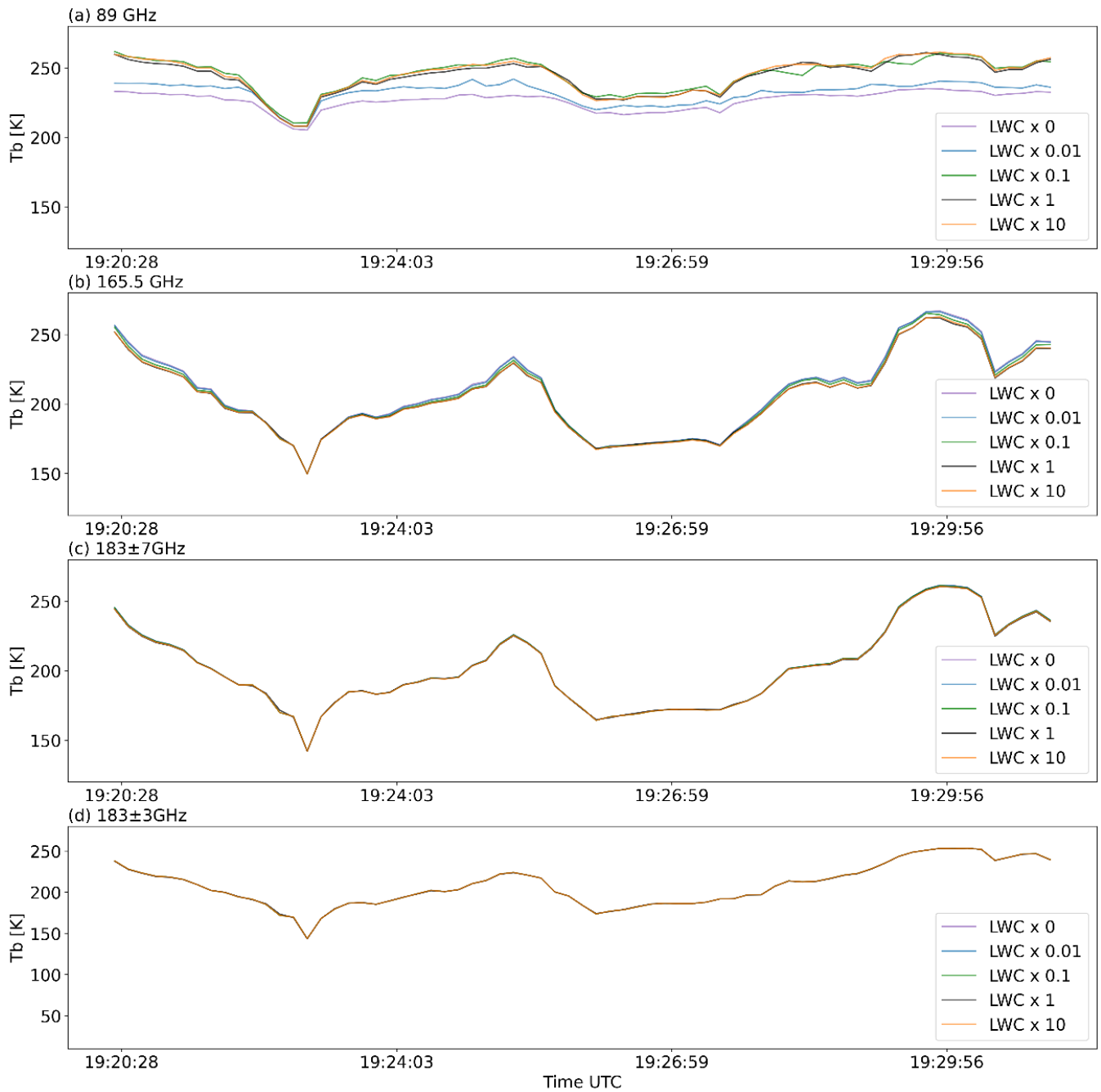
*Correspondence to:* Keiichi Ohara (ohara.keiichi@jaxa.jp)

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## Supplement

This Supplement evaluates the impact of uncertainties in LWC estimates, assumptions regarding water vapor, and temporal mismatches between remote sensing and in-situ observations on the retrieval accuracy.

- 5 In the current retrieval framework, the Ku-derived LWC is treated as a fixed input. Uncertainties in LWC estimates may potentially introduce systematic errors in the ice-hydrometeor retrieval. 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
- 10 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
- 15 unless LWC is unrealistically small. As a result, the signal is dominated by scattering from frozen particles, as in the high-frequency channels.



20 **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,  $183 \pm 7$  GHz, and  $183 \pm 3$  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.

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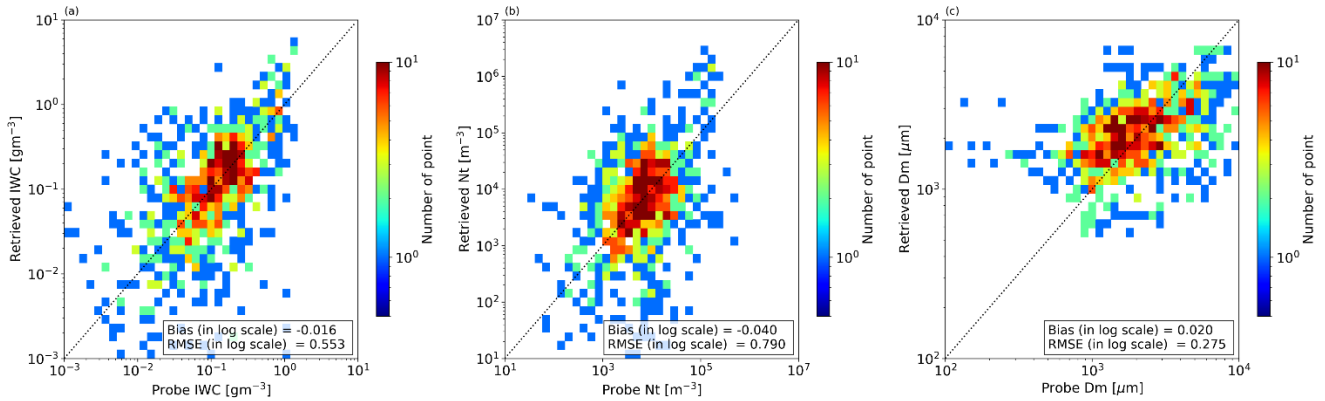
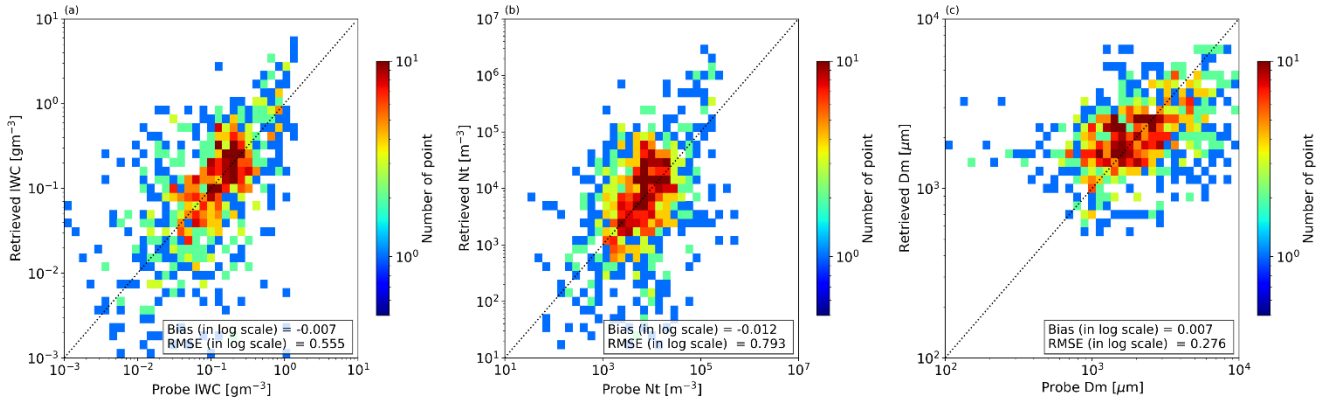


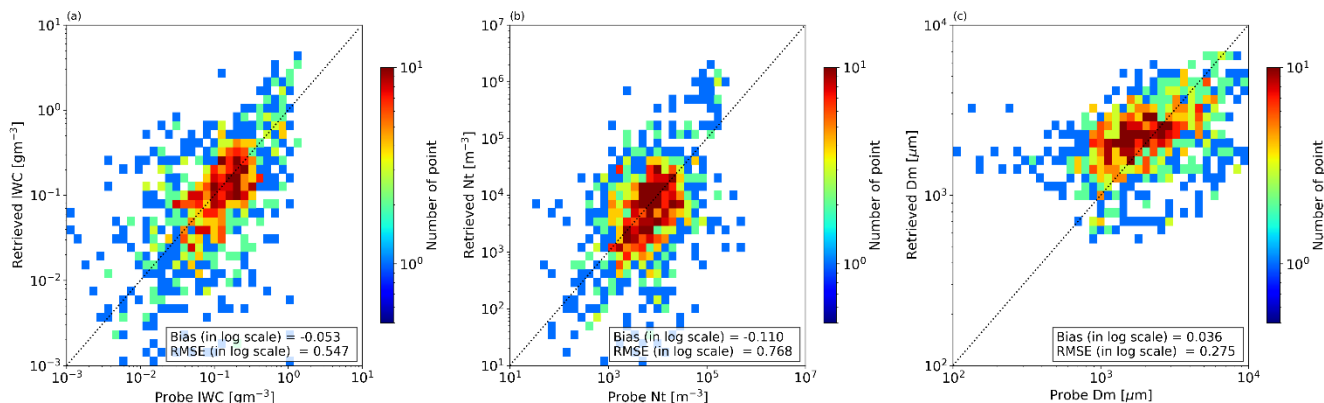
Figure S2: Same as Fig. 8, but assuming LWC scaled by a factor of 0.1.



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

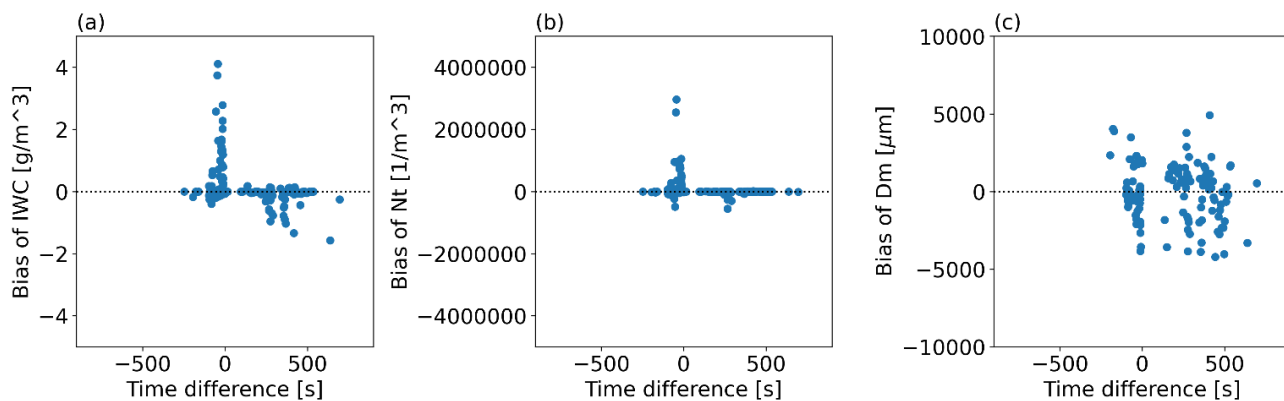
Nevertheless, uncertainty in LWC estimation may have a more pronounced impact on the ice-phase retrieval for non-precipitating clouds with an unexceptionally small LWC. To mitigate the uncertainty in LWC estimation, future work will extend the algorithm to simultaneously retrieve both liquid and ice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

High-frequency brightness temperatures are sensitive to water vapor, and uncertainties in relative humidity (RH) may affect the retrieval results. To assess this impact, a sensitivity test is conducted by assuming  $RH = 75\%$  within clouds and performed the same evaluation as in Fig. 8. The results are shown in Fig. S4. No essential difference is found from Fig. 8, indicating that the impact of water vapor assumptions on the retrieval accuracy is limited.



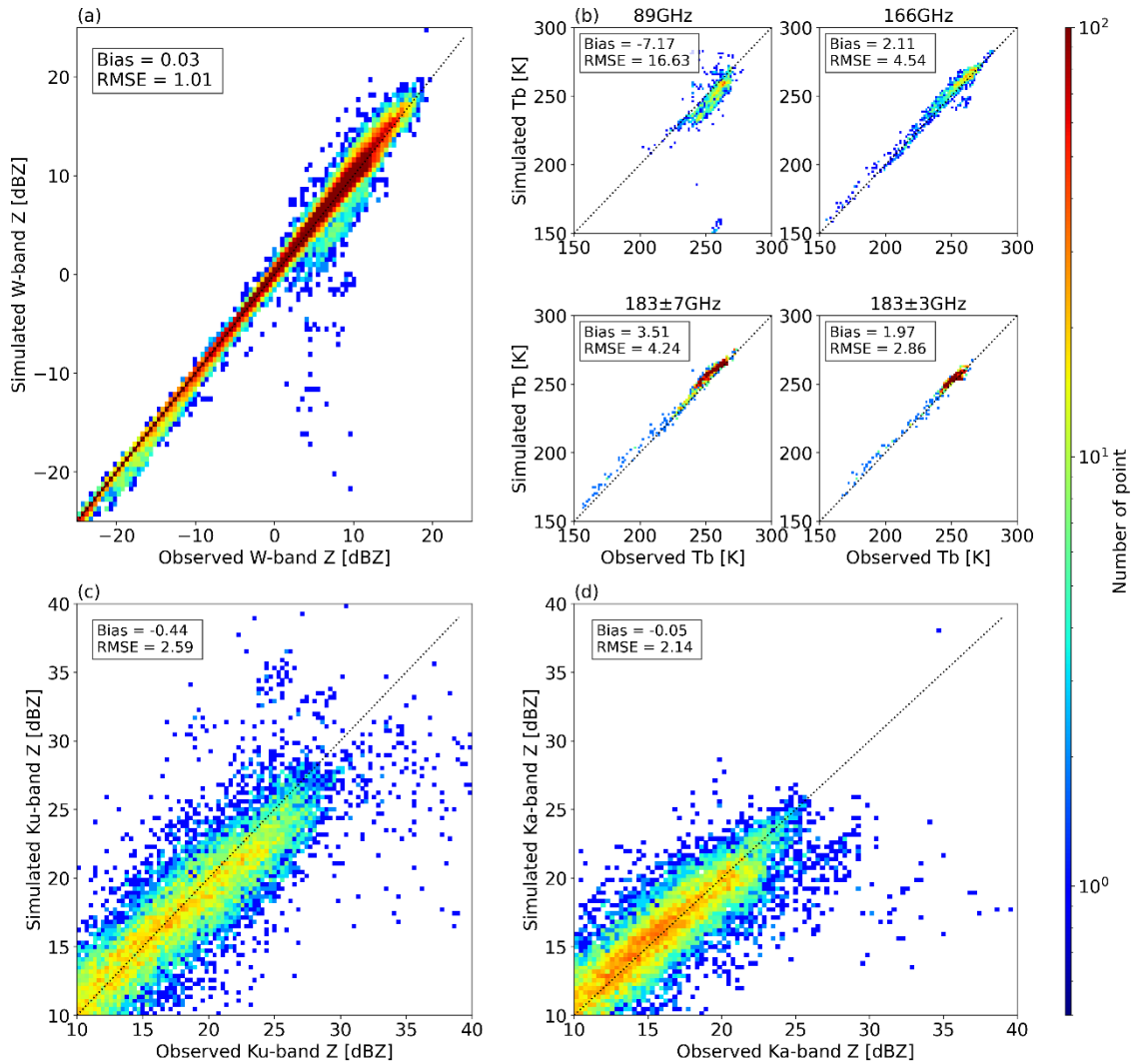
**Figure S4:** Same as Fig. 8, but assuming  $RH = 75\%$  within clouds.

Clouds can evolve even within 15 minutes. In particular, large hydrometeors can fall out quickly. The temporal mismatch between observations may affect the validation accuracy. Figure S5 shows 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). 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.



**Figure S5:** 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.

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.



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

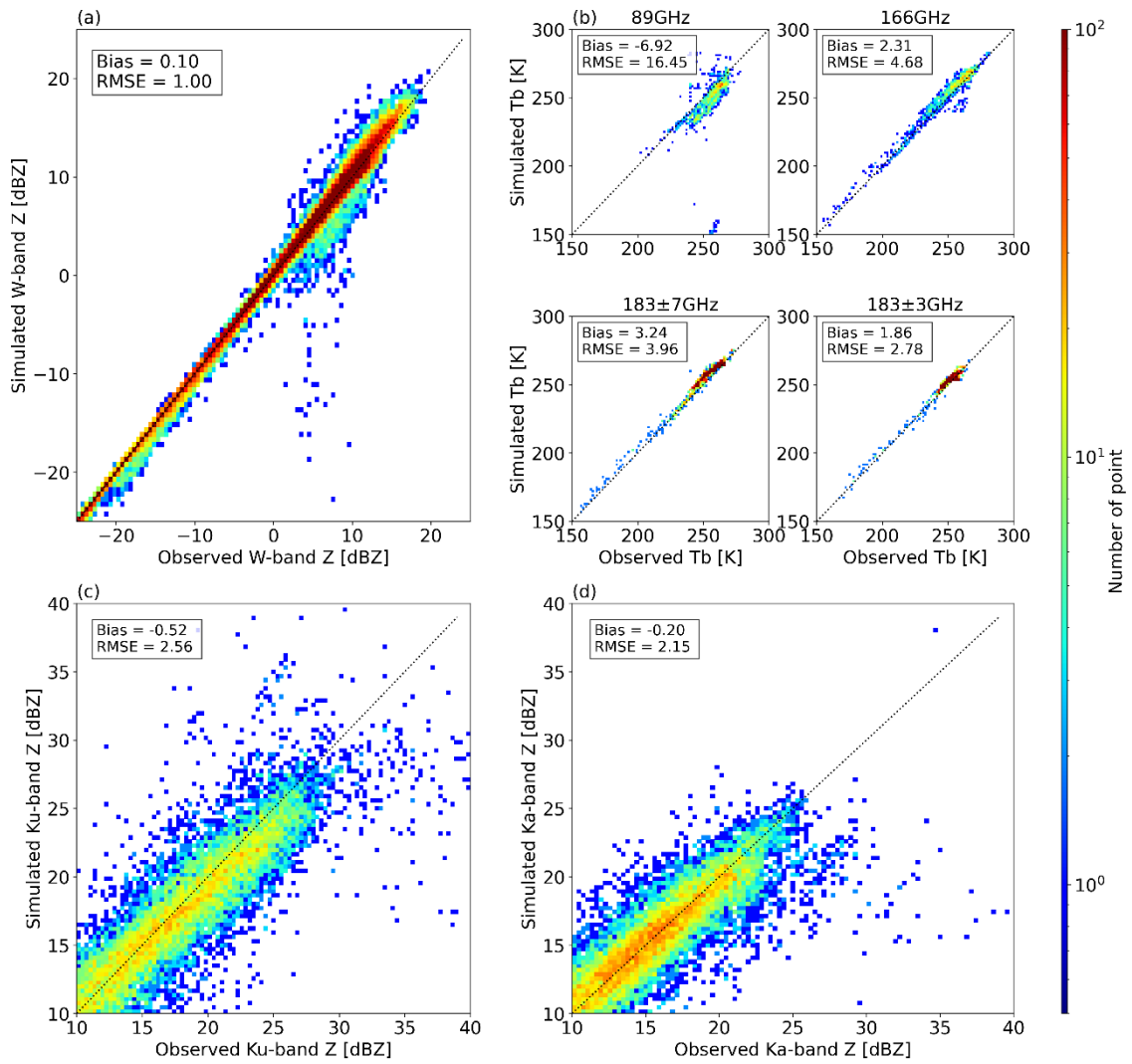


Figure S7: Same as Fig. S6, but for retrievals assuming the short column model.

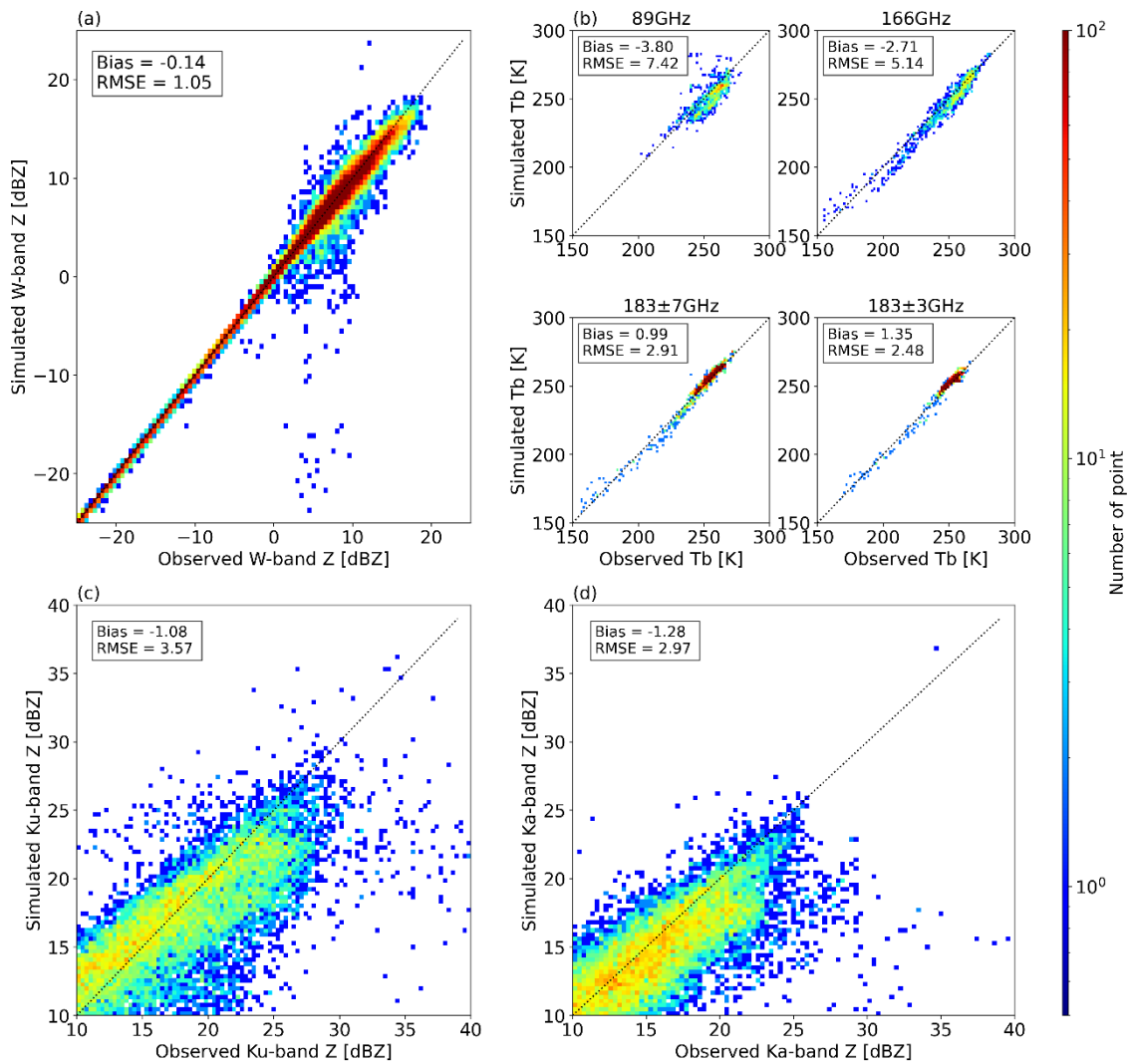
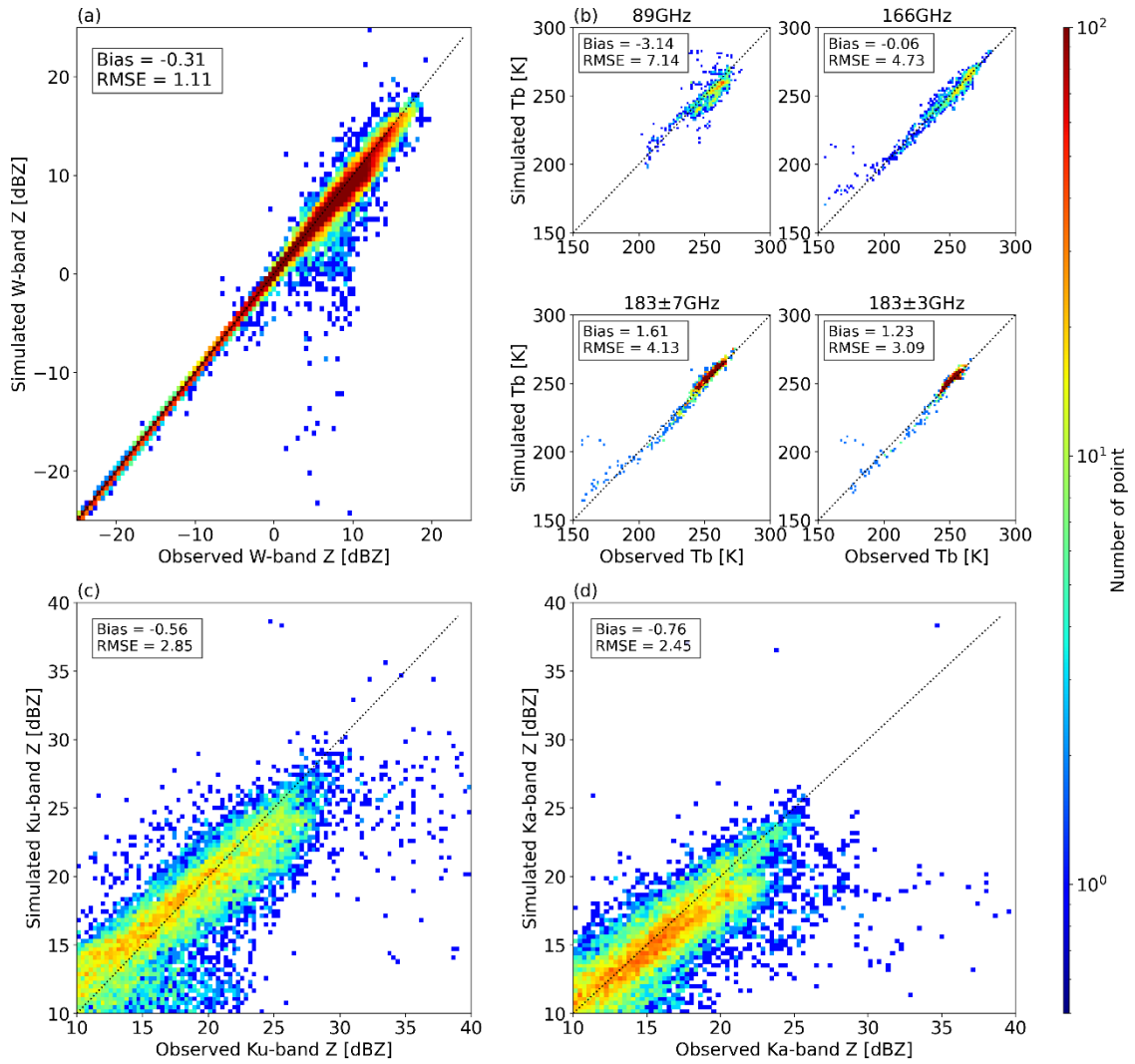


Figure S8: Same as Fig. S6, but for retrievals assuming the 6-bullet rosette model.



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

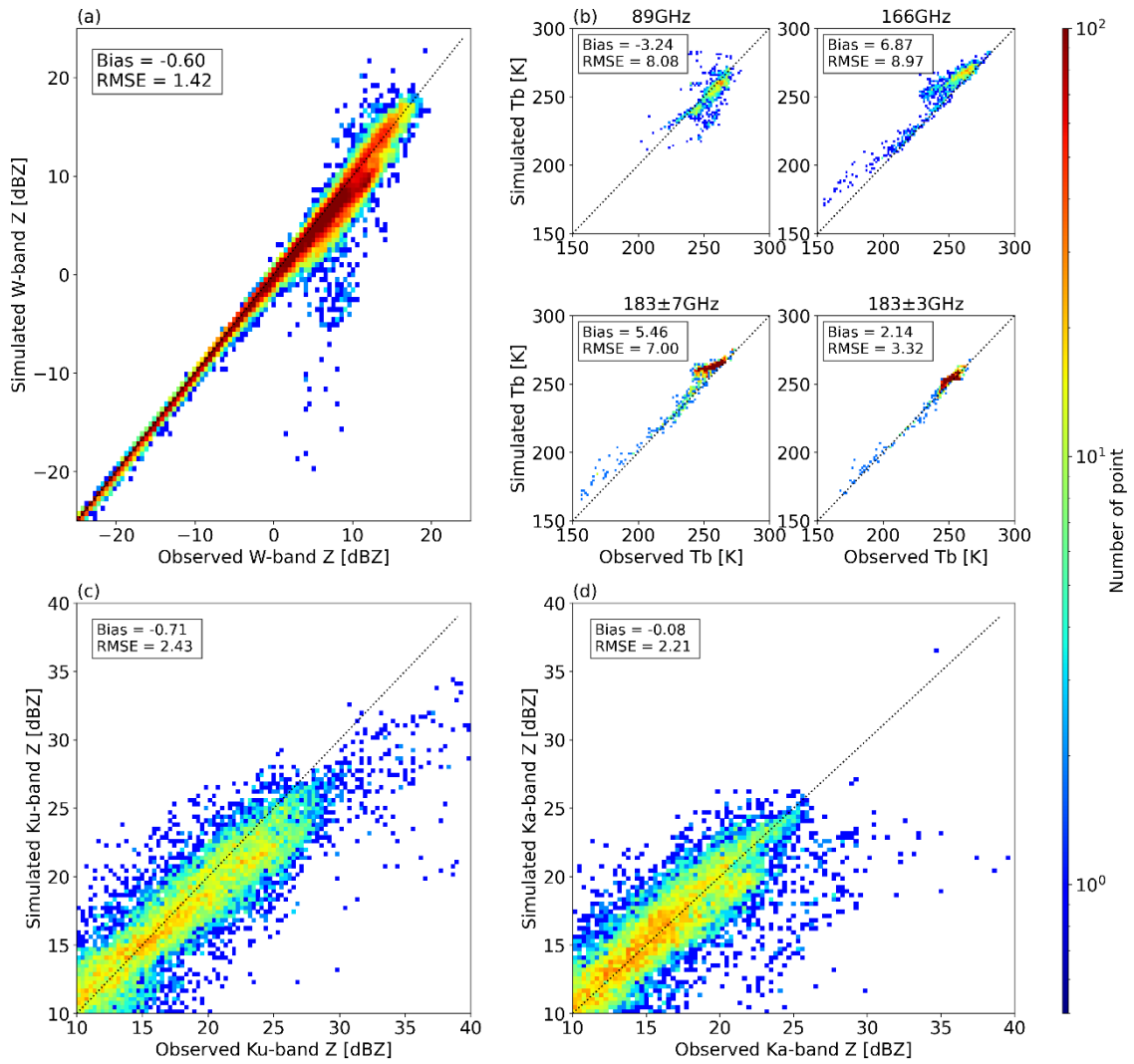


Figure S10: Same as Fig. S6, but for retrievals assuming the soft sphere model.