Response to Reviewer 1

General comment:

The manuscript aims at developing more accurate microwave transfer models for ground-based microwave sounders, which are important and critical in applying its data from monitoring atmosphere condition continuously. The manuscript gives a complete answer to it with a clear description and logical writing.

Response:

We thank the reviewer for the positive evaluation of the manuscript and for recognizing the importance of developing an all-sky fast radiative transfer model for ground-based microwave radiometers. In response to the reviewers' comments, we have revised the manuscript extensively. We expanded the descriptions of the two instruments, including their calibration procedures, and provided more detailed information on the design and setup of the sensitivity experiments, including the ERA5 inputs, scene-classification procedure, and sample sizes. Section 3 was reorganized to consolidate all hydrometeor-sensitivity analyses and present them in a more coherent sequence. To address the reviewers' concerns regarding the reliability of the YKW-1 and YKW-2 observations and the origin of their channel-dependent O–B structures, we added MonoRTM clear-sky simulations as a high-accuracy reference. The close agreement between the ARMS-gb and MonoRTM clear-sky baselines indicates that the persistent baseline structures are unlikely to arise primarily from deficiencies in the ARMS-gb clear-sky radiative-transfer calculations, although the remaining instrumental, channel-characterization, collocation, and ERA5 background uncertainties cannot be fully separated. We therefore revised the discussion of potential error sources to provide a more cautious and accurate interpretation of the observed departures. In addition, the figures were updated, and the manuscript was thoroughly edited to improve its clarity and readability. Finally, the processed O–B datasets used in the evaluation experiments have been archived in a publicly accessible repository.

Comment 1:

Some expressions in the abstract need to be polished further, such as missing "of" *before "these instrument observe" in the second sentence, "correlation coefficient" instead of "correlation", and lacking some summaries on RMSE of ice, snow, and graupel.*

Response:

We thank the reviewer for these helpful suggestions. We have carefully polished the Abstract for grammar and statistical terminology. The sentence in Lines 12–14 has been revised to read:

"The Advanced Radiative Transfer Modeling System – ground-based (ARMS-gb) is a fast radiative transfer model specifically designed to simulate the brightness temperatures observed by these instruments."

Because the statistic reported in the manuscript is R^2, we now identify it using its correct statistical name, the coefficient of determination, rather than the more general term "correlation."

Species-specific RMSE values for ice, snow, and graupel cannot be uniquely determined from the field evaluation because multiple hydrometeor species coexist within the atmospheric profiles, and the resulting O–B departures represent their combined radiative effects. In addition, graupel was unavailable in the ERA5 profiles used for the field evaluation. We therefore avoid assigning the channel-level RMSE to individual hydrometeor species. Instead, the Abstract reports the overall improvements in hydrometeor-sensitive channels, while the individual effects of ice and snow are examined separately through the controlled sensitivity experiments in Section 3. The revised quantitative summary in Lines 21–25 reads:

"Compared with ARMS-gb v1.0, which neglects cloud effects, the root mean square error (RMSE) under cloudy conditions decreases by 1–2 K in the strong water-vapor channels, most notably at 30 GHz, where the coefficient of determination (R^2) increases from 0.34 to 0.71. In the weak oxygen band, where frozen hydrometeors have stronger scattering effects, the O–B decreases by 3–4 K. At 51 GHz, the RMSE decreases from 8.57 to 4.02 K, and R^2 increases from 0.43 to 0.85."

Comment 2:

The second sentence at Page 2 is not complete, which does not mention the contribution of cloud water, rain, ice, snow, and graupel to absorption.

Response:

We agree that the original description was incomplete. We have revised the text to distinguish gaseous absorption from hydrometeor extinction and to explicitly describe the contributions of cloud water, rain, ice, snow, and graupel through absorption and scattering. The revised text in Lines 36–39 reads:

"In the microwave region, gaseous absorption is primarily controlled by temperature, pressure, and water-vapor density. Under cloudy or precipitating conditions, hydrometeors, including cloud water, rain, ice, snow, and graupel, additionally contribute to the total extinction through absorption and scattering, thereby modifying the microwave opacity and the observed brightness temperatures."

Comment 3:

The colors in Figures 2, 5, and 7 are too low contrast to display the differences.

Response:

We thank the reviewer for this helpful suggestion. The color schemes of the relevant figures have been revised to improve contrast and readability. Figure 2 (Lines 136–137) now uses higher-contrast color scales to display the optical properties and the Mie－DDA differences. The original Figure 5, now renumbered as Figure 4 following the reorganization of Section 3 (Lines 258–261), uses clearly distinguishable colors for cloud liquid water, rainwater, cloud ice, snow, and their combined response. In Figure 7 (Lines 326–328), observations and simulations are distinguished by black and blue lines, while precipitation periods are indicated by neutral gray shading. For consistency, Figure 9 (Lines 362–363) was also revised using a blue–white–gold diverging scale centered at zero. The revised Figures 2, 4, 7, and 9 are reproduced below.

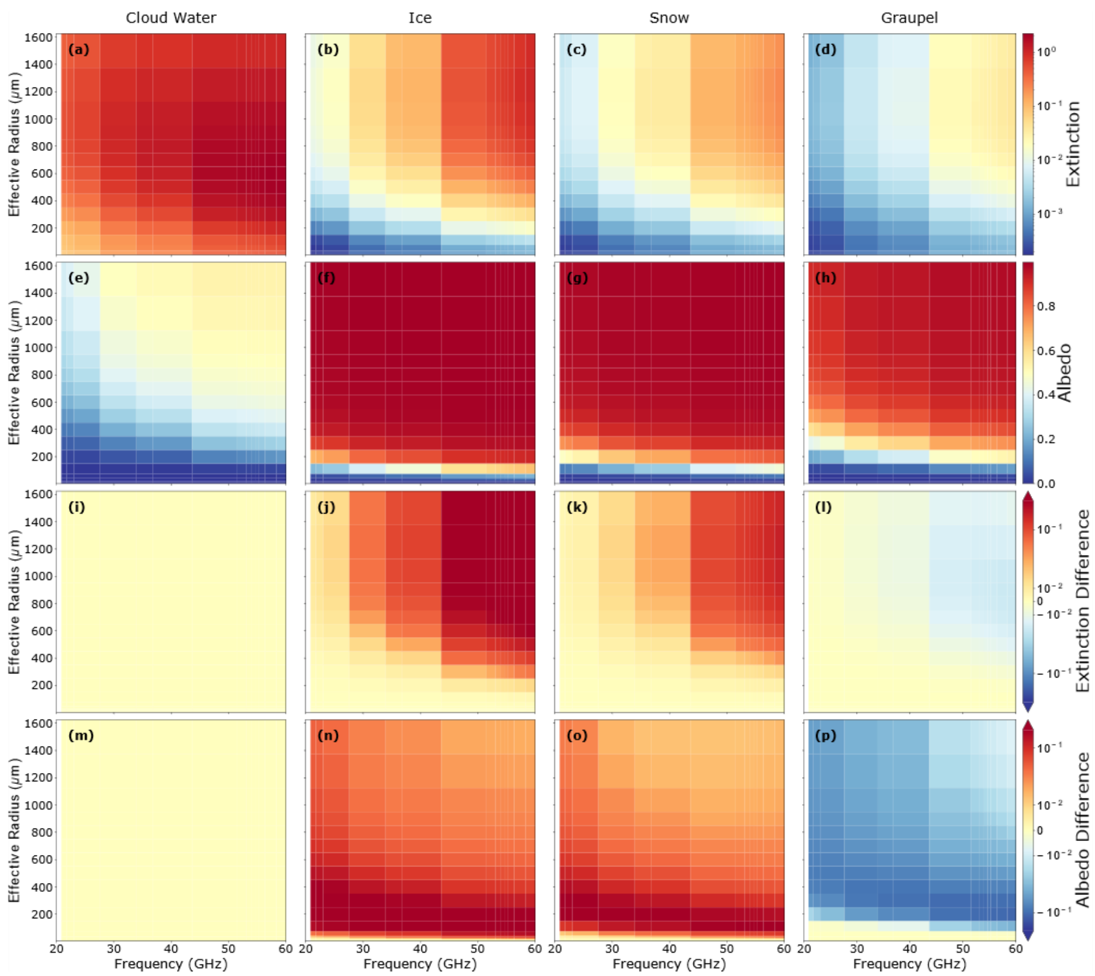

Figure 2: Scattering properties of the cloud particles. The top two rows (a-h) show the extinction coefficient and SSA of Mie, and the bottom two rows (i-p) show the corresponding difference between results computed from Mie and DDA.

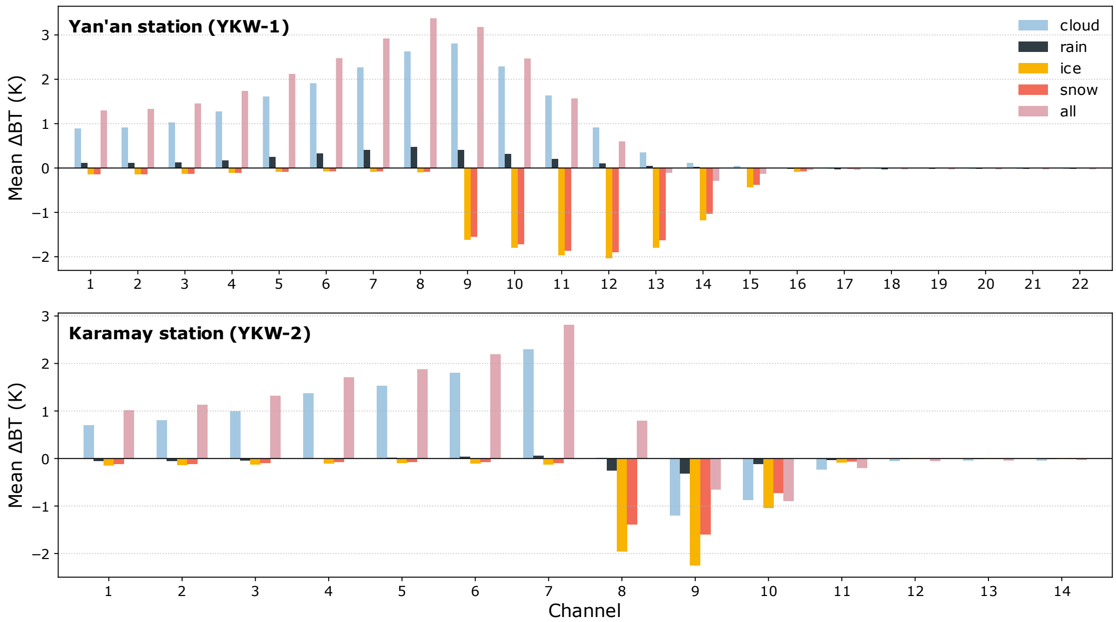

Figure 4 (formerly Figure 5): Mean hydrometeor-induced brightness-temperature responses (ΔBT) by channel for YKW-1 at Yan'an and YKW-2 at Karamay. The results are based on ARMS-gb v2.0 simulations driven by 2,135 and 2,845 hourly cloudy non-precipitating ERA5 profiles, respectively. Bars show the responses to cloud liquid water, rainwater, cloud ice, and snow included separately, together with the combined response when all four species are included. ΔBT is calculated relative to the corresponding clear-sky simulation.

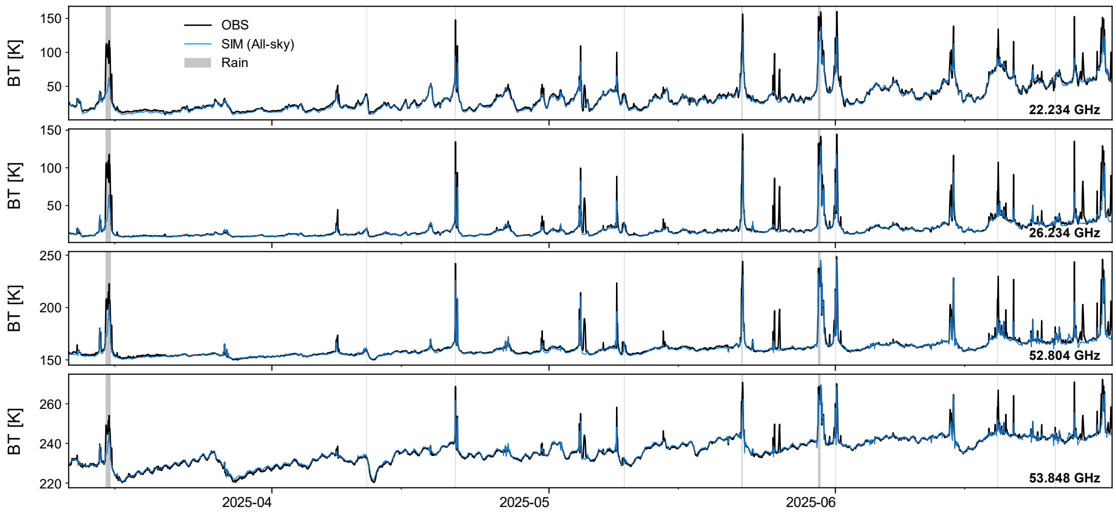

Figure 7: Time series of brightness temperatures observed by YKW-1 (black) and simulated by ARMS-gb v2.0 under all-sky conditions (blue) for four representative channels at Yan'an from 10 March to 30 June 2025. Gray shading denotes periods flagged as precipitation by the radiometer rain sensor.

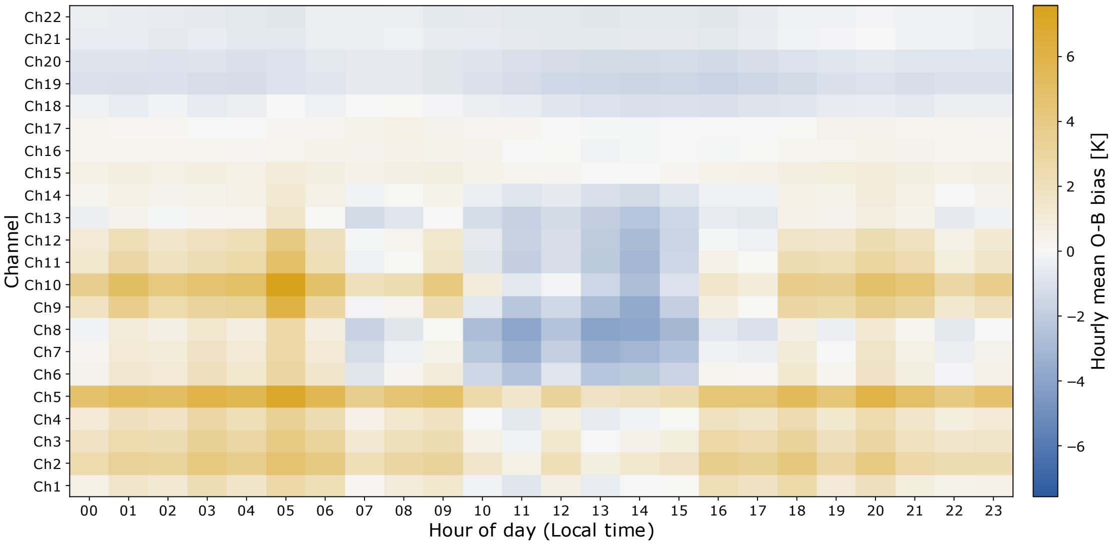

Figure 9: Diurnal variation of the mean O-B bias for the YKW-1 ground-based microwave radiometer at Yan'an station from January to June 2025. The time is shown in local time (UTC+8).

Comment 4:

What is the version of U.S. standard atmospheric conditions used in Page 9, and what is the rule on adding cloud liquid water, rainwater, ice, and snow into the profile?

Response:

We thank the reviewer for pointing out that the experimental configuration was insufficiently described. We have specified that the clear-sky background was taken from the U.S. Standard Atmosphere, 1976, and have clarified how each hydrometeor species was prescribed. The revised text in Lines 204–214 reads:

"To examine these microphysical dependencies under controlled atmospheric conditions, idealized single-species experiments were performed for YKW-1 using the U.S. Standard Atmosphere, 1976, as the clear-sky background. Cloud liquid water and rainwater were prescribed between 700 and 800 hPa, whereas cloud ice and snow were prescribed between 366 and 545 hPa. Only one hydrometeor species was included in each experiment. Two series of experiments were conducted to separately examine the effects of water path and particle size. In the water-path experiments, the layer-integrated water paths varied from 0.001 to 0.010 kg m^{-2} for cloud liquid water and rainwater and from 0.01 to 0.10 kg m^{-2} for cloud ice and snow. The effective radii were fixed at 50 µm for cloud liquid water and cloud ice and 500 µm for rainwater and snow.

In the particle-size experiments, the water paths were fixed at 0.001 kg m^{-2} for cloud liquid water and rainwater and 0.01 kg m^{-2} for cloud ice and snow, while the effective radii varied from 100 to 1000 μm. The hydrometeor-induced brightness-temperature response was defined relative to the clear-sky simulation as $\Delta BT = BT_{hydrometeor} - BT_{clear}$, and the resulting channel-dependent responses are presented in Fig. 3."

Comment 5:

Why are the differences of ice water content and snow water content in Figure 3c and 4d so great, if they are relevant to the height assumed of ice and snow appearances in the atmosphere?

Response:

We thank the reviewer for raising this point. The contrast between the cloud-ice and snow responses is not primarily caused by their prescribed height. In the idealized experiments in Figure 3, cloud ice and snow were placed within the same 366–545 hPa layer. However, the water-path experiments used different fixed effective radii: 50 μm for cloud ice and 500 μm for snow. The much stronger snow response therefore mainly reflects the stronger scattering associated with its larger particle size. In the particle-size experiments, where cloud ice and snow were assigned the same water path and effective radius, snow produced a slightly weaker brightness-temperature reduction, consistent with its lower bulk density and associated optical properties.

The original Figure 4 has been renumbered as Figure 5 following the reorganization of Section 3. Unlike the idealized experiments, its Jacobians were calculated using the vertical hydrometeor profiles from ERA5 rather than assuming a single fixed height. The different Jacobian magnitudes therefore reflect the combined influence of the ERA5 hydrometeor vertical profiles and the species-dependent optical properties assumed in ARMS-gb v2.0. We have clarified the physical interpretation in Lines 222–226:

"Cloud ice and snow generally produce negative ΔBT in the weak oxygen absorption band because particle scattering redirects radiation away from the viewing direction. Ice crystals generally have smaller effective radii than snow particles, and small ice crystals therefore produce only a weak brightness-temperature response, as evident in the water-path experiments. At the same effective radius, however, snow particles produce a slightly smaller reduction in brightness temperature than ice crystals, consistent with the lower bulk density and associated optical properties of snow."

Comment 6:

At Section 4, lines 243 to 245, it is not clearly stated if the vertical distributions of cloud liquid water, rainwater, ice water, and snow water contents are also taken from ERA5 reanalysis.

Response:

We thank the reviewer for pointing out that the source of the hydrometeor profiles was not sufficiently clear. Yes, the vertical distributions of cloud liquid water, rainwater, cloud ice, and snow were all obtained from the hourly ERA5 reanalysis, together with the temperature and humidity profiles. The ERA5 hydrometeor mass mixing ratios were converted into layer-integrated water paths at each model layer, thereby retaining their vertical distributions. Following the reorganization of the manuscript, this description has been moved from Section 4 to Section 3. The revised text in Lines 232–236 reads: "Hydrometeor effects were further examined under realistic atmospheric conditions using hourly ERA5 profiles collocated with GMR observations from January to June 2025. In addition to YKW-1 at Yan'an, the analysis included a second radiometer, YKW-2, at Karamay (45.37° N, 84.51° E). At both sites, ERA5 provided vertical profiles of temperature and humidity and mass mixing ratios of cloud liquid water, rainwater, cloud ice, and snow. The hydrometeor mixing ratios were converted to layer-integrated water paths before being supplied to ARMS-gb v2.0."

Comment 7:

At line 277, it mentions the calibration quality of the data at YKW-1 and YKW-2 is not consistently stable. How do you give the conclusion? Since the data quality are not consistent, why do you use the data for comparing?

Response: We thank the reviewer for this important comment. We agree that the original statement that the calibration quality of YKW-1 and YKW-2 was “not consistently stable” was insufficiently supported and could be interpreted as implying that the observations were known to be unreliable. We have therefore removed this statement and no longer attribute the clear-sky O–B departures to calibration instability alone. We have also added the available calibration information in Lines 129–130:

“Both YKW-1 and YKW-2 are subject to routine operational calibration using liquid nitrogen every six months, with a nominal calibration accuracy better than 1 K.”

Nevertheless, routine calibration does not guarantee temporally invariant measurement characteristics, because radiometric stability and channel-dependent biases may still vary with environmental conditions and the thermal state of the instruments. Before selecting the evaluation sites, we performed preliminary clear-sky O–B monitoring for all 12 GMR sites with available observations. YKW-1 at Yan’an and YKW-2 at Karamay were selected because their channel-wise clear-sky O–B series exhibited comparatively stable temporal behavior over the analyzed period. The site selection was based on this preliminary clear-sky quality assessment rather than on the subsequent performance of ARMS-gb v2.0 under cloudy conditions. These operational observations are also directly relevant to the intended application of ARMS-gb v2.0.

The evaluation does not assume that the observations or clear-sky baselines are error-free. To investigate the persistent baseline departures, we added MonoRTM as a high-accuracy clear-sky radiative-transfer reference. ARMS-gb and MonoRTM produced closely matching channel-dependent clear-sky O–B structures, with maximum differences of approximately 0.38 K at Yan’an and 0.30 K at Karamay. This agreement suggests that the ARMS-gb clear-sky calculation is unlikely to be the dominant source of the baseline departures, although the comparison cannot uniquely separate uncertainties associated with instrument calibration, channel characterization, collocation, and ERA5 background profiles.

The all-sky assessment therefore focuses on whether the cloudy-sky O–B approaches the corresponding clear-sky baseline for the same instrument and channel. This baseline-relative comparison limits the influence of persistent channel-dependent offsets when evaluating the additional hydrometeor treatment. The revised text in Lines 285–300 reads:

"Figure 6 compares the mean O–B departures for each channel at Yan'an and Karamay during April–June 2025. The cloudy-scene comparison includes ARMS-gb v1.0, ARMS-gb v2.0 with Mie- and DDA-based scattering treatments, and RTTOV-gb. To assess whether the persistent clear-sky baseline departures arose primarily from the ARMS-gb clear-sky radiative-transfer calculation, MonoRTM was used as a high-accuracy clear-sky radiative-transfer reference. The MonoRTM simulations used the same ERA5 profiles and GMR channel settings as ARMS-gb. Each channel was represented by 256 monochromatic calculations across its nominal bandwidth, and the resulting radiances were averaged to obtain channel-equivalent brightness temperatures. Following the selection of cloudy non-precipitating scenes and the removal of invalid records, 1,012 hourly profiles per channel and model were retained for Yan'an and 1,014 for Karamay. The clear-sky statistics used 402 valid profiles at Yan'an and 420 at Karamay, depending on the channel and model. The ARMS-gb and MonoRTM baselines exhibit similar channel-dependent structures, with maximum differences of approximately 0.38 K at Yan'an and 0.30 K at Karamay. This agreement indicates that the ARMS-gb clear-sky radiative-transfer calculation is unlikely to be the dominant source of the persistent baseline departures. The residual departures may also reflect uncertainties in instrument calibration, channel characterization, collocation, and ERA5 background profiles.

The difference between the cloudy-sky mean O–B and the corresponding clear-sky baseline provides an additional diagnostic of hydrometeor treatment. In the water-vapor and weak oxygen absorption bands, both ARMS-gb v2.0 configurations produce cloudy-sky departures closer to the clear-sky baseline than ARMS-gb v1.0."

Comment 8:

About the large error of exceeding 30 K in rain simulations at line 364, if the conditions on simulations are the same for MR measurements and the simulated BT? If the contributions from the rain cover are removed from the measured BT or included in the *simulated BT, since most ground-based MR are not suggested working at rain condition? The conclusion seems arbitrary and lack of proof for it, which should be further investigated in the coming version of the manuscript.*

Response: We thank the reviewer for this important comment. We agree that the original interpretation of the large O–B departures during precipitation was too strong. The measurement and simulation conditions are not fully equivalent during rainfall. ARMS-gb v2.0 represents atmospheric rainwater absorption and scattering using the hydrometeor profiles, whereas water deposited on the radome, raindrop impacts, and other near-instrument effects are not represented in the simulations. These effects were also not removed from the measured brightness temperatures. Therefore, the departures exceeding 30 K cannot be interpreted solely as errors in the atmospheric radiative-transfer calculation.

The precipitation cases are retained only to demonstrate the practical magnitude of rain-related contamination in GMR observations. They are not used for strict validation of ARMS-gb v2.0. We have clarified this scope in Lines 281–284:

"In this section, ARMS-gb v2.0 is evaluated against collocated GMR brightness-temperature observations. Clear-sky simulations provide channel-dependent O–B baselines, while the primary evaluation of the all-sky capability focuses on cloudy non-precipitating scenes. Precipitation cases are examined separately to characterize rain-contaminated O–B departures and are not treated as strict validation of the radiative transfer model."

We have also revised the discussion of Figure 10 to distinguish atmospheric rainwater effects from wet-radome and near-instrument contamination. The revised text in Lines 373–383 reads:

"These large departures should not be interpreted solely as atmospheric radiative-transfer errors. The simulations represent atmospheric rainwater absorption and scattering, whereas wet-radome and other near-instrument effects remain in the observations and are neither corrected nor represented in ARMS-gb v2.0. The observed and simulated conditions are therefore not fully equivalent during precipitation. Additional uncertainty arises from the representation of rainwater profiles and raindrop size distributions. Water deposited on the radome can also alter its effective microwave transmission and emission, while raindrop impacts and evaporation near the instrument may introduce further perturbations. Because these atmospheric and instrument-related contributions cannot be separated using O–B statistics alone, the precipitation cases are used here to characterize the practical magnitude of rain-contaminated departures rather than to provide strict model validation. Precipitation-affected GMR observations should therefore be used in retrieval and data assimilation only after applying rain-specific quality control, wet-radome corrections, and appropriate observation-error characterization."

The corresponding conclusion in Lines 403–405 has also been revised to read:

"During precipitation, GMR observations are affected by atmospheric rainwater, wet-radome effects, and other near-instrument processes, resulting in large and difficult-to-separate errors. Rain-affected observations should therefore not be used routinely in retrieval or data assimilation unless these errors are quantitatively characterized and explicitly accounted for."