Response to comments by reviewers 1#:

Thanks very much for your careful reviewing. We will benefit impressively from your suggestions about writing and technique details.

After carefully reading the revised opinions, we have made targeted revisions after discussion. Specific revisions against each point are explained as follows. All the changed contents are highlighted in blue in the revised manuscript.

Specific comments:

● **The motivation of the study is not stated clearly to me. I think the aim of the authors is to present their forward modeling framework. If that is the case, the framework must either be described in more detail, or the code be made available. In the current state, the framework can't be reproduced from the descriptions in the manuscript (especially instrument specific aspects). Also it might help to give the framework a name, so that it can be referred to when used in the future.**

Response: Thanks very much for the valuable suggestion. Sorry for the unclear description. The focus is to present the W-band radar reflectivity uncertainty caused by cloud precipitation microphysical parameters and guide appropriate parameter settings in the forward modeling. We have rewritten the research objective.

"The radar reflectivity for the W-band is also sensitive to microphysical parameters like the particle size distribution (PSD) model and parameter, particle shape, orientation, and mass (Mason et al., 2019; Sy et al., 2020; Wood et al., 2013; Wood et al., 2015). A sensitivity analysis is essential for estimating the effects of these uncertainties on simulated radar reflectivity, and guiding appropriate parameter setting in forward modeling.

China has also begun its own spaceborne millimeter wave radar project. The National Satellite Meteorological Center plans to launch a cloud-detecting satellite, whose main load will be the cloud profiling radar (Wu et al., 2018). For development of spaceborne cloud radar, simulation research on cloud and precipitation detection can provide important theoretical support for the design and performance analysis of the system.

In this study, we quantify the uncertainty of different physical model parameters for hydrometeors contributing to radar reflectivity uncertainty via a sensitivity analysis, and present radar reflectivity simulations with optimal parameter settings, based on forward modeling for spaceborne millimeter wave (94 GHz, W-band) radar. Parameters included the particle size distribution (PSD) parameters, PSD model, particle density parameters, shape, and orientation. Using appropriate physical parameter settings, we present and compare the simulation results of two typical cloud precipitation scenarios with measured CloudSat results. Based on a sensitivity analysis of typical cloud parameters, and a demonstration of cloud precipitation cases, we show the radar reflectivity uncertainty caused by the physical modeling of hydrometeors while emphasizing the importance of assuming more realistic scattering characteristics, as well as appropriate density relations and PSD parameters corresponding to different cloud precipitation types."

● Further, the motivation of the sensitivity study and its relevance for the other parts of the paper is unclear to me. Quantifying uncertainties in radar reflectivity from varying PSD parameters, PSD models and particle shape and orientation has been done before in different studies as far as I'm aware. Maybe including a literature review in the introduction on this topic might be helpful to understand the importance of this step to the study?

Response: Thanks very much for the valuable suggestion. We have added more details about the importance of sensitivity analysis in the introduction.

"However, the particle shape, composition, orientation, and mass relation all affect the scattering characteristics. The radar reflectivity for the W-band is also sensitive to microphysical parameters like the particle size distribution (PSD) model and parameter, particle shape, orientation, and mass (Mason et al., 2019; Sy et al., 2020; Wood et al., 2013; Wood et al., 2015). A sensitivity analysis is essential for estimating the effects of these uncertainties on simulated radar reflectivity, and guiding appropriate parameter setting in forward modeling."

● I recommend reworking the description of the forward modeling framework. While Fig. 1 shows the "sub module structure", the figure is not described that well in the text. I think reworking section 2.1 with a step by step description of Fig. 1 could solve the issue. I am not sure if "submodule" is the right term describing the framework. Maybe the authors mean working steps?

Response: Thanks very much for the suggestion. Sub module here refers to the function module (similar to working step) in the forward framework. We have added more details and rewritten the section 2.1 with a step by step description of Fig. 1.

"The key points of each sub module are described as follows.

1) From CloudSat historical data and typical weather processes we obtained the cloud precipitation scene cases. According to the occurrence area and time, the corresponding National Center of Environmental Prediction Final (NCEP FNL) reanalysis data were obtained as the initial field in the WRF model.
2) The WRF model was used to simulate the distribution of all types of hydrometeors in these cases. In this research, we use version 4.1.2 of the advanced research WRF model (Skamarock et al., 2019). The WRF simulation results were then validated by using the real observation data.
3) Based on the hydrometeor mixing ratio of the WRF output and assuming certain microphysical parameters based on empirical information obtained from a large amount of observation data, the PSD of the hydrometeor particles were modeled.

4) The complex reflective index of different hydrometeors was calculated according to the particle phase and temperature. The scattering and attenuation characteristics of the hydrometeor particles were then calculated using the T-matrix method (Mishchenko and Travis, 1998). Meanwhile, the absorption coefficients of the atmospheric molecules, such as the water vapor and oxygen, were calculated based on the Liebe attenuation model.
5) The radar reflectivity factor was then calculated based on the atmospheric radiation transmission process and the scattering and attenuation coefficients of hydrometeors.
6) Through coupling with the instrument and platform parameters, the radar echo signal was calculated using the radar equation.
7) During the simulation process, the sensitivity analysis of typical cloud physical parameters was performed to guide the optimal microphysical modeling of the hydrometeors.
8) Finally, the simulation results were compared with observation data, such as CloudSat data, to validate the forward simulations."

- **The authors compare forward simulation results using "conventional" vs "optimized" settings. I am unsure what "conventional" and "optimized" refer to. Does conventional mean "typically included in radar simulators"? Also "optimized" might not be the best term to use, because it sounds like an optimization algorithm was applied, which is not the case if I understood correctly. (If I am wrong, then the optimization needs to be described more clearly!) It should be stated more explicitly what exactly the terms "conventional" and "optimized" mean and what settings (PSD parameters etc.) were chosen for the case studies. I recommend including e.g. a table listing all settings. Only stating "the PSD parameters were assumed based on the typical empirical values of land stratiform precipitation clouds" (L370) and referencing three studies is not sufficient to me. I would prefer this information to be explicitly stated in the paper rather than having to look up the cited studies and guessing which values were used.**

Response: Sorry for the unclear description. Thanks very much for your valuable suggestion. The word of "optimized" is ambiguous. The "optimized" has been modified to "improved". Also, we have added detailed PSD parameter information (the values of used PSD parameters) at L370 in the revised manuscript.

"For the stratiform case, the PSD parameters were assumed based on the empirical values of land stratiform precipitation clouds (Mason, 1971; Niu and He, 1995; Yin et al., 2011), in which the D_0 of cloud water was set to 0.01 mm, the D_0 of cloud ice was 0.02 mm, and μ was set as a constant of 1. As snow in stratiform clouds were mainly unrimed particles (Yin et al., 2017), a mass-power relation representative m=0.0075$D^{2.05}$ of unrimed snow (Moisseev et al., 2017) was used in the simulation, where D was the volume equivalent diameter. In addition, a melting layer model with a width of 1 km was assumed below 0 ºC and the PSD parameters of the raindrops were calculated according to the melting model.

The main difference between the conventional and improved setting is that the conventional setting does not consider the melting model, and the PSD parameters for rain were set as D_0=1 mm, μ=3."

A table listing all settings was not included, because most of parameters are the same. The main difference between the conventional and improved setting was the application of the melting model (the PSD parameters of rain were calculated from melting model in the improved setting, and the PSD parameters of rain were assumed according to the experience values in the conventional setting), and the varying mass relations for snow and graupel in the convective cloud.

● **When introducing models, software etc. the authors often omit citations. This is especially evident in paragraph L43-58 in the introduction, where citations for the discussed radar simulators QuickBeam, SDSU, G-SDSU as well as for WRF-SBM are missing. Further, citations for the described scattering models (Mie, T-matrix) should be included. I noticed some citations listed in the references don't appear in the manuscript. This should definitely be checked and corrected and might explain the missing citations.**

Response: I am very sorry for the carelessness. Thanks very much for pointing out. The citations in paragraph L43-58 and scattering models have been added now in the revised manuscript. Also, we have checked the references and citations one by one throughout this manuscript.

"In the design of the observation system and interpretation of cloud and precipitation observation data, forward modeling and simulation play a highly important role (Horie et al., 2012; Lamer et al., 2021; Leinonen et al., 2015; Marra et al., 2013; Sassen et al., 2007; Wang et al., 2019; Wu et al., 2013). QuickBeam is a user-friendly radar simulation package that compares modeled clouds to observations from CloudSat, but it cannot simulate mixed phase particles in the melting state (Haynes et al., 2007). The Satellite Data Simulator Unit (SDSU) developed by Nagoya University, Japan, is a satellite multisensor simulator integrating radar, microwave radiometer, and visible/infrared imager. Goddard Satellite Data Simulator Unite (G-SDSU) is a derivative version of the SDSU (Masunage et al., 2010). In addition to the basic functions of the SDSU, it can be coupled with high-precision National Aeronautics and Space Administration (NASA) atmospheric models, such as the Weather Research and Forecasting-Spectral Bin Microphysics (WRF-SBM). The Global Precipitation Measurement (GPM) satellite simulation is also based on the G-SDSU, which converts the geophysical parameters simulated by the WRF-SBM into observable microwave brightness and equivalent reflectivity factor signals of the GPM (Matsui et al., 2013).

The WRF model was used to simulate the distribution of all types of hydrometeors in these cases. In this research, we use version 4.1.2 of the advanced research WRF model (Skamarock et al., 2019). The scattering and attenuation characteristics of the hydrometeor particles were then calculated using the T-matrix method (Mishchenko and Travis, 1998)."

● I find the description of the CloudSat and MODIS data that was used lacking. The CloudSat product that was used should be described in more detail and a short overview of CloudSat (resolution, sensitivity) should be included. That could for example be done by adding a new section either after the introduction or after the model overview. Or including 1-2 more sentences in the introduction.

Response: Thanks very much for your suggestion. We have added the description of CloudSat data in the introduction, and the information of MODIS data in section 4.1.1.

"The CPR is a W-band, nadir-pointing radar system, with a minimum detectable signal of approximately -29 dBZ. The CPR footprint size is 1.4 km across-track and 2.5 km along-track, and the vertical resolution is approximately 500 m (Stephens et al., 2008).

The level-2 cloud product of cloud top temperature from MODIS with spatial resolutions of 5 km was used in the comparison."

● In section 2.2.1 N and D should be defined.

Response: The definition of N and D has been added now.

"where $N(D)$ is the particle size distribution, D is the volume equivalent diameter, N_w is the normalized intercept parameter, D_0 is the median volume diameter, ρ_w is the density of water, i.e. 1 g/cm^3, μ is the shape parameter, and Γ is the gamma function."

● What is the bin size of the hydrometeor model?

Response: The bin size for different hydrometeor is different, for example, the bin size for rain is 0.1 mm, and that for cloud water is 0.01 mm.

● For the mass-size parameters "mean" values are used in the study. It should be stated more clearly which literature values are averaged over. I recommend including a sentence like, "For a and b we took literature values from -list of studies- and calculated the mean". The units of a and b as stated in the text and should be included in the figure captions as well.

Response: Thanks very much for the valuable suggestion. The relevant information has been added in Figure 4.

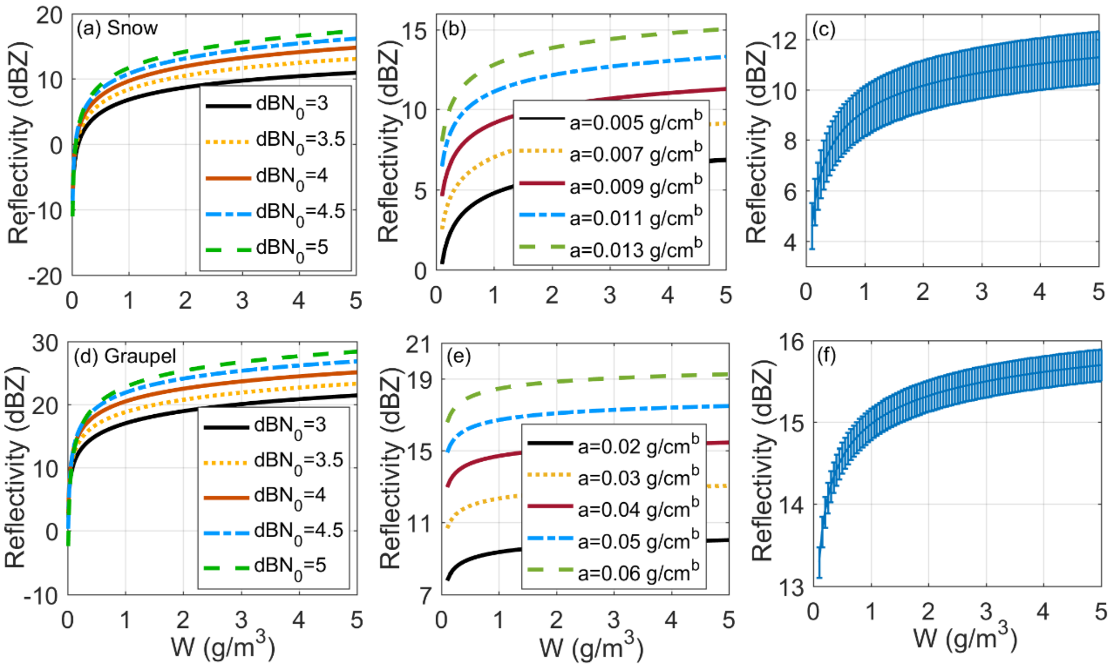

Figure 4: Impact of PSD parameters on radar reflectivity for snow and graupel. Variation in reflectivity for snow at (a) dBN_0 values of 3, 3.5, 4, 4.5, and 5 with a mean mass-diameter relationship of $m = 0.009D^{2.1}$, where D is in cm and m is in g; (b) prefactor a in mass-diameter relationship of 0.005, 0.007, 0.009, 0.011, and 0.013 g/cm^b, with exponent b of 2.1 and N_0 assumed to be 3×10^3 m^{-3} mm^{-1}; (c) mean value ± standard deviation of b, where the mean is 2.1 and standard deviation (SD) is 0.28, with a assumed to be 0.009. The vertical bars represent the SD of the reflectivity change caused by deviation from the mean value of b. Variation in reflectivity for graupel at (d) dBN_0 values of 3, 3.5, 4, 4.5, and 5 with a mean mass-diameter relationship of $m = 0.04D^{2.6}$, where D is in cm and m is in g; (e) prefactor a in mass-diameter relationship of 0.02, 0.03, 0.04, 0.05, and 0.06 g/cm^b, with exponent b of 2.6 and N_0 assumed to be 4×10^3 m^{-3} mm^{-1}; and (f) mean value ± standard deviation of b, where the mean is 2.6 and standard deviation is 0.16, with a assumed to be 0.04. The value range in a and b and the mean value are obtained from literatures, and the standard deviation of b are calculated according to the range and average of Gaussian distribution.

● Figures 9 and 11: To increase the readability of the figure, the hydrometeor types could be written next to the letters in the subfigures, similar to Fig. 6a,c,e.

Response: Thanks very much for the suggestion. The hydrometeor types have been added in the subfigures of Figure 9 and 11.

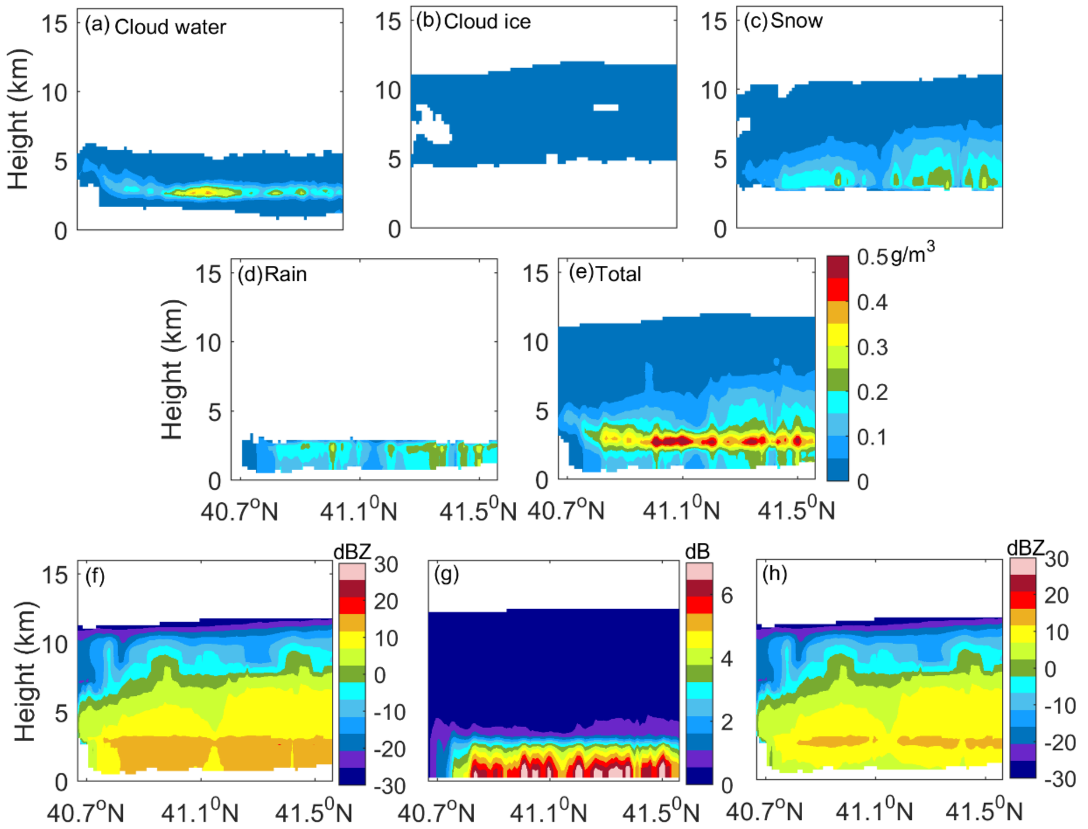

Figure 9: Latitude-height cross-section of the hydrometeor for the stratiform case simulated by the WRF for: (a) cloud water, (b) cloud ice, (c) snow, (d) rain, and (e) total hydrometeors. (f) Simulated unattenuated radar reflectivity with the total hydrometeors, (g) two-way attenuation, and (h) attenuated radar reflectivity. Owing to the Mie scattering effect, the unattenuated radar reflectivity did not decrease markedly at the bottom of the melting layer, whereas the bright band at the melting layer was highlighted due to strong attenuation in the rain region.

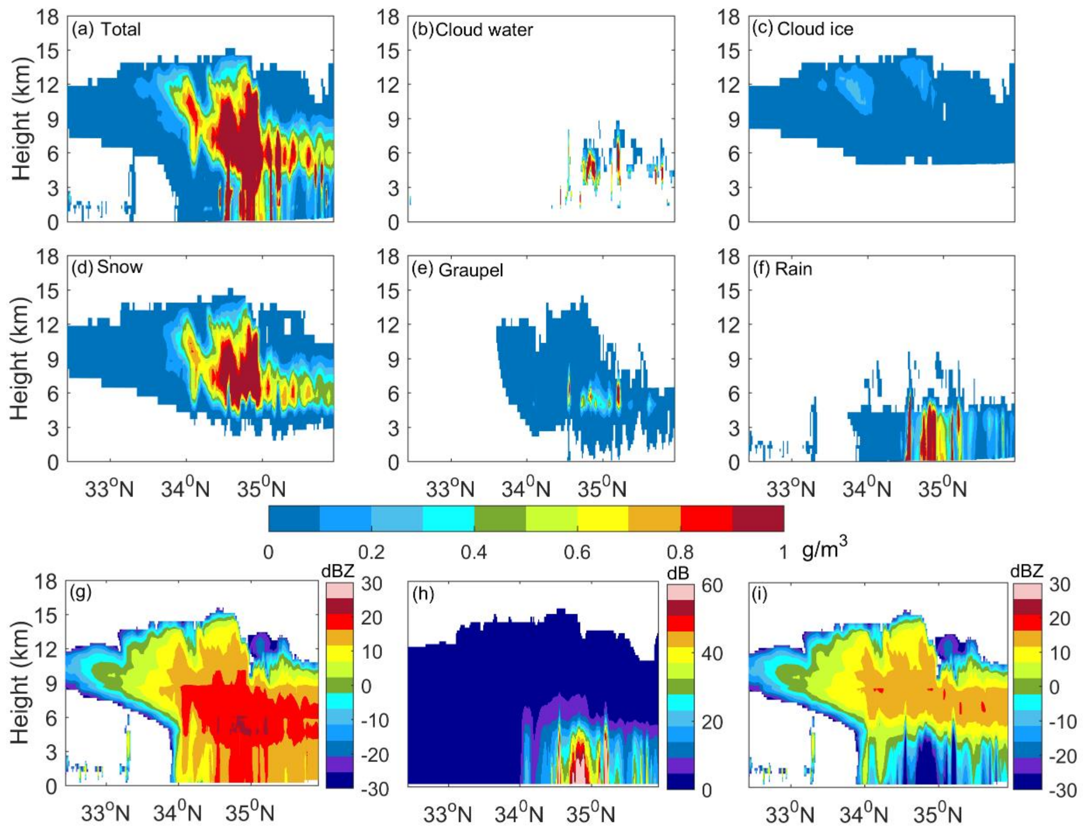

Figure 11: Latitude-height cross-section of the hydrometeor of the convective case simulated by the WRF for: (a) total hydrometeors, (b) cloud water, (c) cloud ice, (d) snow, (e) graupel, (f) rain. (g) Simulated unattenuated radar reflectivity with the total hydrometeors, (h) two-way attenuation, and (i) attenuated radar reflectivity.

Technical corrections

● L34: restructure sentence?

Response: Thanks for your suggestion. The sentence has been restructured. "The cloud radar platform mainly includes spaceborne, airborne, and ground-based radars."

● L35: typical → widely used

● L57: seriously → majorly (or omit)

● L62: I recommend starting a new paragraph beginning with "In this study.."

● L74: I think it should be a "," instead of "." This small typo resulted in me having a lot of trouble understanding the sentence.

● L93: then → further

● L115: omit "a" before D0

● L156: caused → formed

● L161: graupel → snow

● L196: which → and

● L174: prefactor a varies between

● L181: actual → in nature

● L192: omit "still"

● L310: omit "mainly"

Response: Sorry for the poor writing. Thanks for your suggestions. The corresponding expressions and sentences have been modified in the revised manuscript.

● L236-238: unclear sentence

Response: Thanks for your suggestions. The sentence has been rewritten. "During radar reflectivity calculation, a look-up table of backscattering and extinction cross-sections is established for reducing the calculation workload."

● L257-259: restructure sentence?

Response: Thanks for your suggestion. The sentence has been rewritten. "Figure 2 shows the radar reflectivity change with variations in the gamma PSD parameters for cloud water and rain. Cloud water particles are small compared to the radar wavelength, which is in the linear growth stage in the Mie scattering region."

● L320: appeared → becomes significant?

● L488: They → it?

Response: Thanks for the suggestion. "appeared" has been modified to "becomes significant". "They" has been modified to "it".

● Figures 2, 4, 6: Optionally, the different y axis scales of the subplots could be noted to avoid confusion.

Response: Thanks for the suggestion. The *y* axis in Figure 2 and 4 are for radar reflectivity, and the *y* axis scales are different for different hydrometeors. The *y* axes of the subplots in Figure 6 are for backscattering cross-section and corresponding radar reflectivity, and the *y* axis scales have been noted.

Thanks so much for helping us with the English. To edit the text further, we have paid another commercial editing service to polish our manuscript for the language. We would like to thank the reviewer for his/her significant effort to suggest changes for our manuscript.

Special thanks to the reviewer for the good comments and his/her patience.
