Anonymous Referee #2
The manuscript introduces a software (CR-SIM) for simulating ground-based radar and lidar observations, based on input from atmospheric models. The software itself is presented and several possible applications are demonstrated. Tools of this type are needed to e.g. plan measurement campaigns and evaluate models using real observations. Accordingly, there exist important objectives and the manuscript fits GMD well. As far as I can judge (with no direct experience of data of the type targeted by the software), the application examples are described sufficiently well. At least, the number of "use cases" is sufficiently high to convince a reader about the value of the software. On the other hand, I find the description of the features and limitations of the software too short. I fully understand that not all details can be considered (but are hopefully covered by the user guide), but basic facts should be clarified in the manuscript, acting as the entrance points for potential users.

We thank the referee for their time and consideration reviewing the manuscript. We have revised the manuscript addressing all comments. Please see our point-by-point responses to the referee's comments.

1. First of all, it should more clearly be expressed how CR-SIM relates to similar software. Is there any other software that can do the same things as CR-SIM? Is CR-SIM unique in any way? Further, the use of "Finally" on line 84 gives the impression that the review of other software is complete, but I strongly doubt that is the case. For example, Matsui, T., Dolan, B., Rutledge, S. A., Tao, W.- K., Iguchi, T., Barnum, J., & Lang, S. E. (2019). POLARRIS: A POLArimetric Radar Retrieval and Instrument Simulator. Journal of Geophysical Research: Atmospheres, 124, 4634–4657. https://doi.org/10.1029/2018JD028317
seems to have a similar scope as CR-SIM but is not mentioned.

Thank you for informing us about the paper to update the abstract citation originally used. In the revised manuscript, we refer to POLARRIS and this paper in Section 2 instead of Dolan et al. (2017) and added a sentence "Matsui et al. (2019) simulated polarimetric precipitation radar-based hydrometeor classification, vertical velocity, and rain rate from CRM output to examine uncertainties in the retrieval algorithms and model microphysical parameterizations using POLARRIS."

We also compare CR-SIM with other simulators in section 4. Please see our response to referee #1's specific comment #1.

We agree with the referee that there are many other radar simulators and thus the list of existing software in this manuscript cannot be all-inclusive. We removed the word "Finally" and added "For example" to the beginning of the third sentence in Section 2.

2. The output variables should be better defined. For the radar ones (Table 2) not even the units are given. The dielectric factor used in the conversion to reflectivity can be defined in different ways. Does CR-SIM allow different options, or what option is used? Equations or citations for the relationship between the scattering matrix elements and the output variables should be given (see e.g. Eqs. 1-16 in Matsui et al.).
It is said that propagation effects are not treated. What is included in the term "propagation effects"?

The radar observables are computed by integrating scattering properties over the discrete PSD using a constant bin size for each hydrometeor. We followed the microphysical parameterization of the selected microphysics scheme to retrieve the PSD. The complex scattering amplitudes of the 2 x 2 scattering matrix are pre-computed for equally spaced particle sizes and stored in the look-up tables using the Mishchenko's T-matrix code for single non-spherical particles. Using the calculated scattering amplitudes stored in the LUTs, we computed radar observables following Ryzhkov et al. (2011), using for an assumption of the orientation distribution. CR-SIM incorporates three options of the orientation distribution model which can be selected by the user. The composition of particles is accounted for in the scattering computations by an appropriate selection of the dielectric constant for different hydrometeor types. The dielectric constant of liquid particles is frequency- and temperature-dependent (Ray, 1972). Ice phase hydrometeors are assumed to be made of ice inclusions in an ice matrix and their effective dielectric constant is computed using the Maxwell-Garnet mixing formula (1904). The output Zhh is the equivalent radar reflectivity, in which computations, we adopt 0.92 as the value of dielectric factor for liquid water at centimeter wavelengths. This choice of the dielectric factor is dictated by convention to ensure that the definition of radar reflectivity reduces to form: $Z = \int N(D) D^6 dD$ for (spherical) liquid particles, where D is the droplet diameter and N(D) is the droplet size distribution function.

The above information has been added to section 2 in the revised manuscript. Because the equations of radar observables have been well described in Ryzhkov et al. (2011), we decided to not add them in the manuscript. The method is fully described in the Section 4.4 and 4.5 in the CR-SIM User Guide (ftp://ftp.radar.bnl.gov/outgoing/moue/crsim/docs/crsim-UserGuide-v3.3.0.pdf).

We also added units for each output radar variable in Table 2 (now Table 3).

We meant "propagation effects" as the total attenuation along a radar beam path. We include specific attenuation from all simulated hydrometeors (i.e., cloud droplets, cloud ice, rain, snow, and graupel for the analysis in the manuscript), but gaseous attenuation was not included. We added the information in section 2.3.

3. Are there any other limitations that should be mentioned? As far as I understand, attenuation due to gases is not considered. That should be a significant effect at 94 GHz. Would be good to clarify if the attenuation due to liquid cloud droplets is included in the attenuation terms. Is the surface assumed to be flat or curved? Is refraction of importance? Ice particles seem to be treated as spheroids consisting of a mixture of ice and air. Just the choice of mixing rule (that is not specified) causes modelling uncertainties.

CR-SIM treats hydrometer categories for which mixing ratio (and/or number density) are provided by the input cloud model using the selected microphysics scheme. At this stage, all ice hydrometeors (e.g., snow, ice, graupel, hail) are modeled as dielectrically dry spheroids i.e., assuming the dry growth of larger ice particles. Thus, the refractive index of ice-phase hydrometeors depends on relative mixture of air and solid ice and is computed using the Maxwell-Garnet mixing formula (1904). The LUTs of scattering properties incorporated in the current CR-SIM were created using the T-matrix method for selected assumptions regarding ice particle composition and shape. More complex electromagnetic scatters can be incorporated by adding LUTs of their scattering properties from different scattering calculation methods without any change to the code. We stated this in the revised manuscript in Section 2.1.

As in the response to the previous comment #2, we did not calculate gaseous attenuation in CR-SIM. We thank you for this suggestion. We will certainly add water vapor attenuation in a future version of CR-SIM.

In CR-SIM, the earth surface is assumed to be flat. This assumption is acceptable for shorter observation ranges. The description is added in section 2.3 in the revised manuscript. However, this could be a source of uncertainty for longer distances from the radar and/or for small model vertical grid spacings. We investigated the differences between the two assumptions (earth curvature + atmospheric refraction, and a flat surface). The figure below shows elevation angles at a height of 5.5 km AGL as a function of horizontal distance (right) and height at an elevation angle of 2º as a function of radar range (left). Here, the Earth's surface is represented using a sphere with a radius of 6370.0 km for red lines or flat for blue lines. The black lines represent the difference between the two assumptions. The difference in elevation angle is less than 1 degree for the horizontal distance less than 300 km at a fixed height. This is smaller than the elevation spacing of the scattering LUTs. At a fixed elevation angle, the difference in height is less than 1.4 km for the radar ranges < 150 km and is greater than 5 km at the radar range of 300 km. If the model vertical spacing is smaller than the difference, the error from the flat surface assumption could be significant. In the MCS simulation presented in the manuscript, the maximum radar range is 50 km for the X-band radars, and the model vertical resolution is approximately 250 m. For the shallow cumulus cases in the manuscript, the maximum radar range is 15 km and the model vertical resolution is 30 m. The differences at the maximum radar range for those cases are smaller enough than the model vertical spacings. However, we need to carefully configure the simulation settings considering the uncertainty. We thank the referee for their comment.

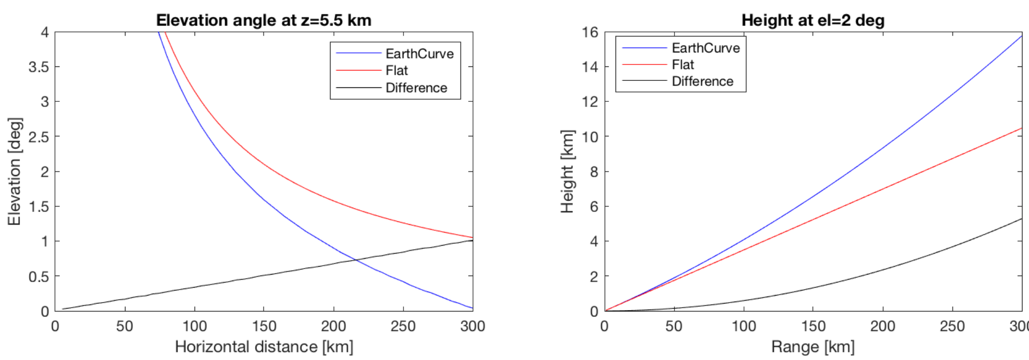

Figure 1: (Left) Elevation angle at a fixed height of 5.5 km AGL as a function of horizontal distance from the curved surface including the atmospheric refraction (blue) and flat surface (red) assumptions. (Right) Height at a fixed elevation angle of 2º as a function of radar range. Black lines represent the difference between the two assumptions. The curved surface is assumed to be a sphere surface with a radius of 6370.0 km.

4. As a user, you need an estimate on the overall modelling uncertainty. For example, are differences between real observations and simulations of 3 dBZ significant or not?

There are several sources of uncertainty in CR-SIM including particle composition and shapes, particle size, and canting angles for the calculations of the single scattering properties. We have investigated the uncertainties in some of these assumptions. The figure below shows statistical differences of simulated radar observables between two particle shape assumptions: spheroid ice (with an aspect ratio of 0.6) and spherical ice, using WRF+P3 model outputs. As expected, the aspect ratio assumption has the most influence on the polarimetric observables (i.e., Z_{DR} and K_{DP}). The influence is larger for the unrimed ice particles than for the partly-rimed ice particles.

As the referee pointed, the assumption of a flat Earth can also be an uncertainty source. Please see our response to the previous comment.

In addition, because CR-SIM ingests numerical model output, the assumptions in the microphysics schemes could also contribute to the uncertainty in CR-SIM. For example, the truncation of the edges of the PSDs (e.g., minimum and maximum sizes, size spacing) could affect CR-SIM results as pointed by referee#1. We added the settings of the PSD in Table 1 in the revised manuscript.

Since the input numerical model simulation itself can also include uncertainties, it is difficult to find an intrinsic uncertainty in CR-SIM by comparing the CR-SIM results with real observations. But comparisons with different radar simulator's results can help to understand this uncertainty. One CR-SIM user compared the CR-SIM simulated reflectivity with reflectivity from another simulator (Passive and Active Microwave TRANsfer, PANTRA) for the same model input data. He reported differences in reflectivity ranging from 0.5 to 2 dB probably due to a difference of the diameter spacing implemented in the simulators.

We plan to summarize the uncertainty analyses in a follow-up paper.

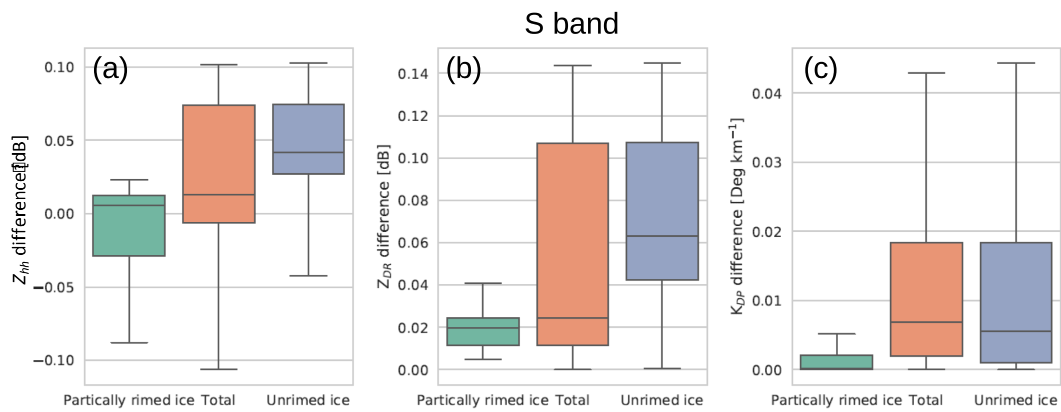

Figure 2. Box and whisker plots of the changes in (a) Z_{HH}, (b) Z_{DR}, and (c) K_{DP} by assuming spheroidal ice particles (aspect ratio = 0.6), compared to spherical particles (aspect ratio = 1.0) with a fixed canting angle of 0 degree at a radar frequency of 3 GHz. The results are shown for ice categories (partly rimed ice, unrimed ice, and total ice) predicted by WRF P3 microphysics scheme for the mesoscale convective system simulation. Lower and upper box boundaries are 25th and 75th percentiles, respectively, the lines inside the box are medians, and the outermost lower and upper lines are 10th and 90th percentiles, respectively. The radar elevation angle is 20º for all simulations.

I found the manuscript hard to read due to the high usage of acronyms. Consider if some acronyms can be avoided, or adding a table of acronyms.

Thank you for this suggestion. We added a section with a list of acronyms.

Specific comments:

Line 88: What do you mean with "quality-controlled" and how do you ensure it?

Here, we mean ideal values of radar observables without observational limitations such as sensitivity, minimum detectable value, or hydrometeor attenuation. We realized that “quality-controlled” was a confusing word and used “ideal” instead in the revised sentence.

Line 94: T-matrix and DDA are general methods to calculate scattering properties, not scattering datasets. Is there any scattering dataset that could be coupled to your model?

We modified the phrase to read “scattering methods.” We added a description of the possibility to couple with different scattering calculation methods in section 2.1. Different scattering calculation datasets can be easily incorporated by adding LUTs of their calculated particle scattering properties (e.g., Kneifel et al., 2017; Leinonen and Moisseev, 2015; Leinonen and Szyrmer, 2015; Lu et al., 2016) without any change to the code. Please also see our response to the referee #1’s specific comment #1.

Line 108: How is bulk density defined?

The bulk density used is as parameterized in the selected microphysics scheme, assuming spheroidal particle shapes. Change made.

Line 138: Do you get the fall speed from the models, or by an external expression? If the later, add a reference.

We calculate the fall speed following the same manner as in the selected microphysics scheme in the models (given on L159). The parameterization depends on the microphysics schemes that are described in the references in (the now) Table 2 in the revised manuscript.

Lines 153-154: I don’t get what you want to say what this sentence.

We revised the sentence to read “As expected, the lidar backscatter is significantly attenuated by cloud droplets, but the very high lidar backscatter at the interface between air a cloud can be used to detect cloud base height.”

Line 196 and elsewhere: I don’t think you can expect that all readers know the frequency of the radar bands (C, X, ...). At least define at the first usage of each band.

Thank you for the suggestion. We added the radar bands in text and figure captions.

Line 223: Start a new paragraph at "Figure 5 ..."

Done.

Line 238: "affects" -> "effects".

Done.

Lines 294-297: I could not understand this description.

We improved the paragraph. First, observation sites are randomly selected within the horizontal domain. Second, for each snapshot of the simulation, clouds over the observation sites are sampled as if the clouds are frozen in time and advected by the mean environmental wind. Thus, the columns are sampled along the direction of the horizontal wind over the advected distance (i.e. horizontal wind speed x 10 min), where the environmental horizontal wind at each snapshot is the mean horizontal wind across the simulation domain within the cumulus cloud layer (i.e., the layer between the mean cumulus cloud base and the maximum cumulus cloud top). Third and last, the CFP is estimated by varying both the number of observation sites and the integration period.

Line 331: Is CWRHI something built into CR-SIM, or done by external processing?

To simulate CWRHI accounting for radar beamwidth and range-gate spacing, a post-processing code is required. However, in the analysis by Oue et al. (2016), a CWRHI scan was referred to as a vertical cross section of CR-SIM simulated radar observables at the model grid. Figure 8 accounts for Z_{MIN} only. Details are described in Oue et al. (2016). To avoid the confusion, we revised the sentences in this paragraph.

Line 441: Is not the basic output from scanning radars in polar coordinates? If yes, is not this code essential to use CR-SIM and should then be fully integrated, as you claim that CR-SIM output "can be easily compared with real observations"?

The CR-SIM standard output is radar and lidar observables for all the cloud resolving model grid boxes accounting for elevation angles relative to a radar location, not polar coordinates that account for radar geometric characteristics such as beamwidth and radar range resolution to simulate scatters within the radar resolution volume. We describe this in Section 4 in the revised manuscript. The post-processing instrument model accounts for the radar sampling characteristics and outputs the observables in the polar coordinates. The post-processing code is now publicly available at the CR-SIM website (https://you.stonybrook.edu/radar/research/radarsimulators/) and also submitted to the Stony Brook University Academic Commons.

This feature facilitates the process of configuring any desirable observational setup with a varying number of profiling or scanning sensors and makes the gridbox-by-gridbox comparisons of the ideal radar variables easy.