Reviewer # 1

Summary:

The authors have made major modifications to the manuscript and have done a good job in addressing most of the points I raised in my review of the original submission. I have only a few comments that I think should be revised before it is ready for publication.

Response: Thank you for the positive feedback on our previous revision. We have carefully considered your additional comments and made further improvements to the manuscript accordingly. Please find our responses below:

Comments:

1. Regarding my original major comment #3, the authors conducted the simulation of polarimetric radar variables for a case of the mesoscale convective system (MCS). It is difficult to evaluate the ability of this radar forward operator to reproduce polarimetric radar signatures since only one moment of PPI snapshot is shown. What I cannot understand is why the authors did not apply the forward operator to the Typhoon case presented in the manuscript. I think the simulation results shown in the manuscript for the Typhoon case should at least include the simulated polarimetric radar variables if the authors claim this operator is a new forward polarimetric radar operator.

   Response: (1). Typhoon Haishen did not make landfall in China (specifically, it did not cross over the longitude of 130E). Consequently, there are no available ground-based radar observations from the Chinese radar network for this typhoon. This is the reason we did not conduct the simulation of polarimetric radar variables for the Typhoon Haishen.

   (2). To compensate for this, we have conducted a simulation case of Typhoon Doksuri, which made landfall in Fujian Province of China, at approximately 02:00 UTC on July 28, 2023. This simulation was based on the operational forecast provided by the CMA-MESO, initialized at 18 UTC on July 27, 2023. The CAM-MESO run was with a horizontal resolution of 3km and a vertical resolution of 51 layers, using the single moment microphysics scheme of WSM6. We conducted volume PPI simulations at the beginning of four consecutive hours prior to the landfall event, specifically at 23UTC on July 27 and 00UTC, 01UTC, and 02 UTC on July 28 (presented in Figure 1, Figure 2, Figure 3, and Figure 4, respectively). The observations for these simulations were obtained from the S-band polarimetric radar located in Xiamen (Z9592).

   The ZJU-AERO used its default settings, which are compatible with the WSM6, with the number of horizontal sub-beam quadrature points set to 3 and the number of vertical quadrature points set to 5.

The simulations presented in Figure 1-4 for multiple moments and multiple PPI sweeps, along with the previously included case of MCS, effectively demonstrate the capability of ZJU-AERO in reproducing polarimetric radar variables for the NWP model employing single-moment microphysics schemes. The case data has been included in the updated version of the demonstration sample data, which has been uploaded to Zenodo. Additionally, the results have been incorporated into the amended version of the user guide.

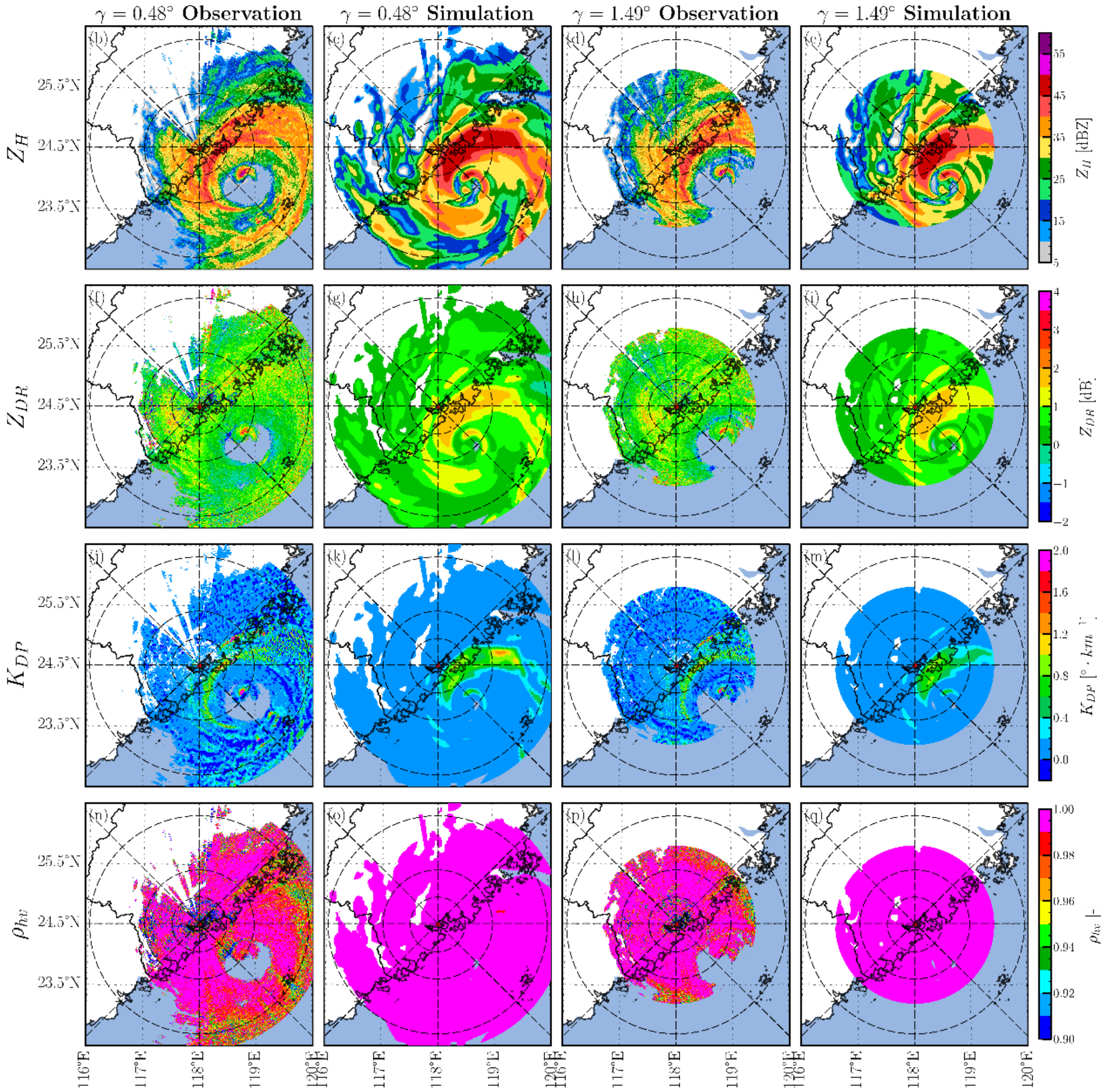

Figure 1: Comparison of observed radar variables on two PPI sweeps with their simulated counterparts using the ZJU-AERO. Columns 1 and 3 show the observed radar variables for PPI sweeps with fixed elevation angles of 0.48° and 1.49°, respectively. Columns 2 and 4 present the model equivalents, simulating the same radar variables by ZJU-AERO. The four rows show the following radar variables; horizontal reflectivity (Z_H), differential reflectivity (Z_{DR}), specific differential phase shift (K_{DP}), and co-polar correlation coefficients (ρ_{hv}). The simulations were conducted at 23 UTC on July 27, 2023.

There are several important notes for simulations in Figure 1-4:

(1). For the observed PPI sweep at the lowest fixed elevation angle (γ =0.48°), the sector of azimuth angles ranging from 315° to 360° experiences notable partial clutter beam-shielding effects. While the simulations are able to capture this phenomenon, the partial shielding effect is less pronounced compared to the observations. This discrepancy might be caused by the deficiency of the 3-km resolution topology map used in the simulations (the same topology map used by the CMA-MESO model).

(2). The simulations yield higher values for Z_H and Z_{DR} compared to the observations, while the simulations of K_{DP} are generally in good agreement. This indicates that the WSM6 single moment microphysics scheme has probably overestimated the effective radius of raindrops for tropical cyclones, which is also illustrated in Section 4.2 of the manuscript.

(3). The distinct melting layer signature observed in ρ_{hv} cannot be reproduced by simulations. This discrepancy is attributed to the lack of mixed-phased particles in the ZJU-AERO.

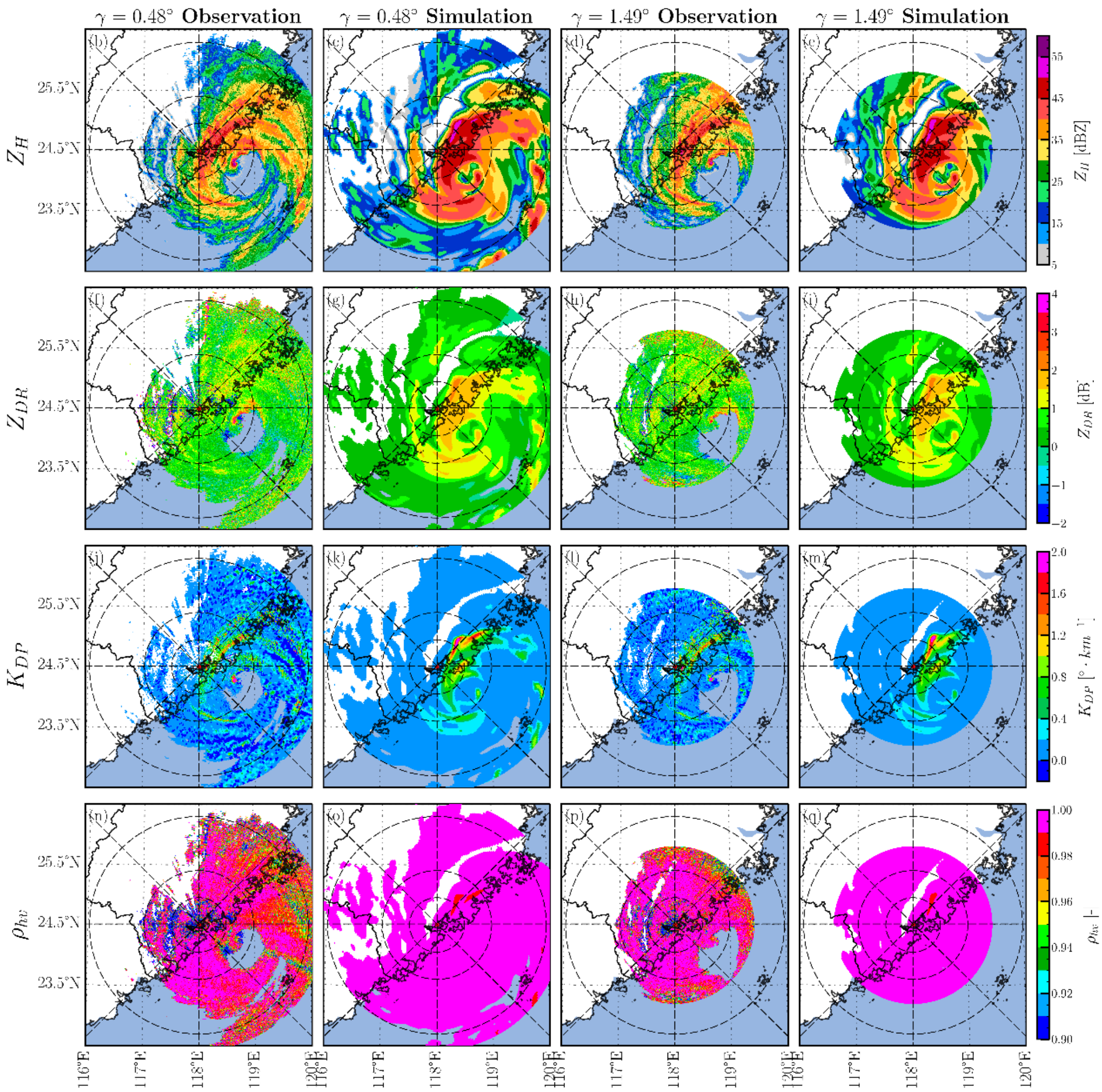

Figure 2: As Figure 1, but shows the observation and simulations at approximately 00 UTC on July 28, 2023.

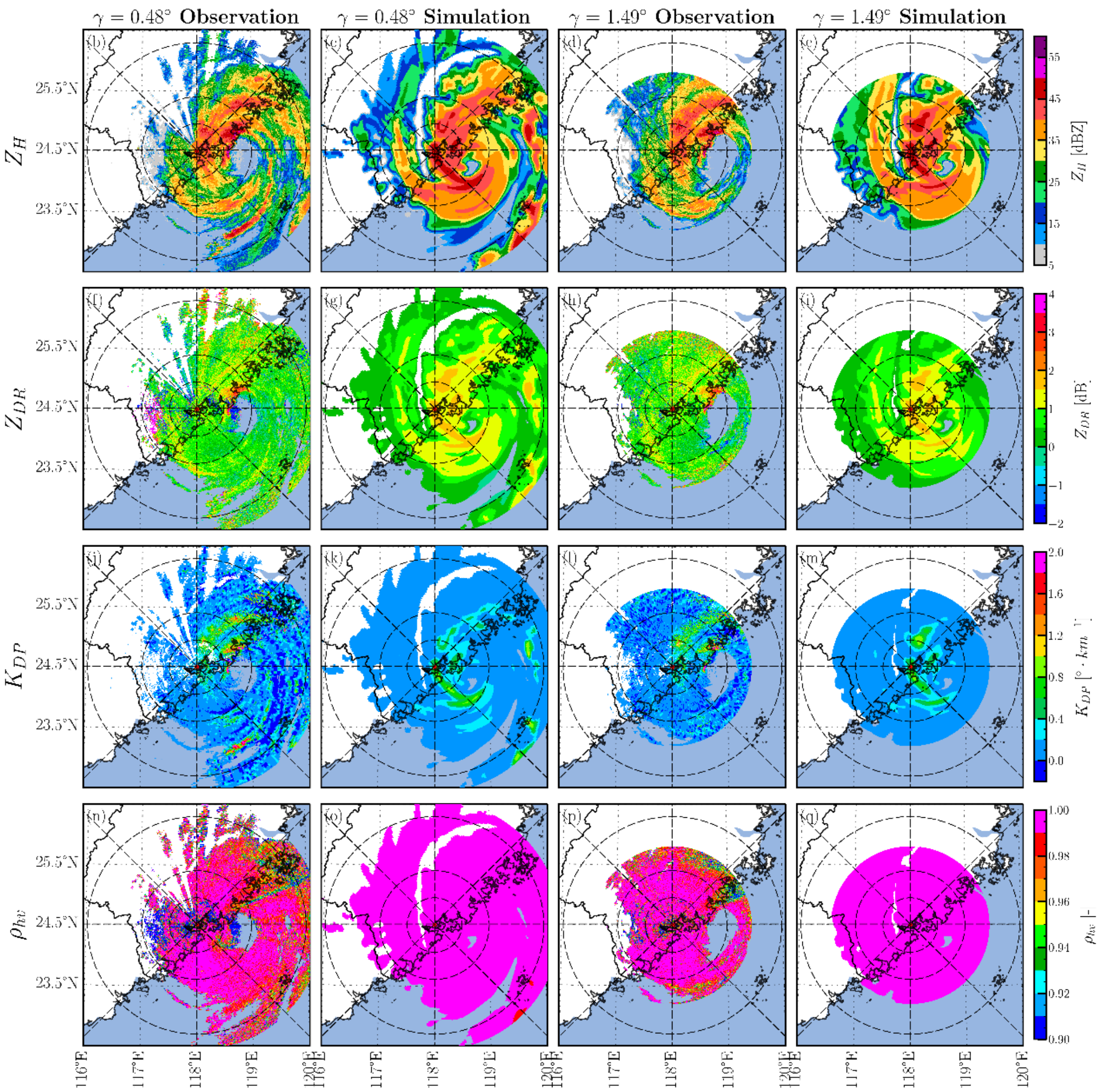

Figure 3: As Figure 1, but shows the observation and simulations at approximately 01 UTC on July 28, 2023.

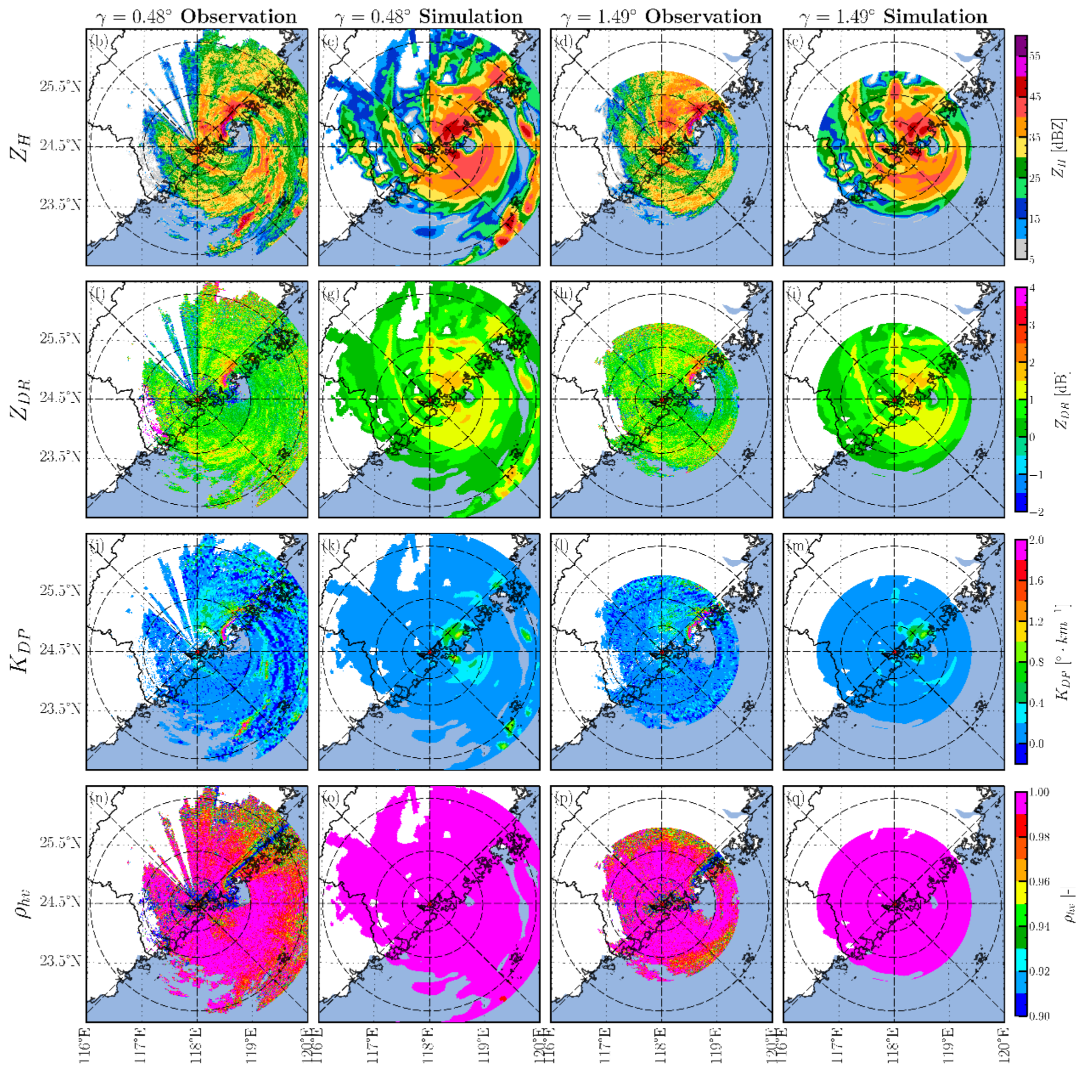

Figure 4: As Figure 1, but shows the observation and simulations at approximately 02 UTC on July 28, 2023.

2. For the response to my original minor comment #5, I still have no idea how the authors calculate the Z11, Z12, Z21, and Z22. This is also a common problem that occurs repeatedly in the 2.2 section. Authors always try to explain the details in the forward operator using more complex definitions from other people's articles. It is easy to get lost in some of the basic concepts and not get the specific approach of the forward operator. I suggested the authors should remove some nonsignificant definitions and formulas and reorganize the 2.2 section to give the readers a clear idea of what key variables need to be calculated and how to calculate when reproducing this operator.

Response: Thank you for your suggestions.

(1). We have reorganized Section 2.2, placing the basic details of FSA and BSA to Appendix C, and the equations of polarimetric radar variables to Appendix D.

(2). We have added specifications on how to calculate Z11, Z12, Z21, and Z22. Also, we have provided formulas for the extinction matrix elements (K11, K12, and K34), which are used in this study.

Reviewer # 2

General remarks:

The revision of the manuscript includes a number of clarifications that I appreciate. In my opinion, the ratio of presented content (or amount of text and figures) to scientifically interesting and novel content is quite high making it fairly tedious to read. Readability and tangibility, hence quality, of the paper could significantly improve in my opinion if the manuscript were purged from not-too-relevant or basic details (that were much better placed in the user guide) as already pointed out in the initial review.

The amount of present, though hidden-by-clutter, "core content" is sufficient for publication in my view, so rejection is uncalled for. And while I'd personally strongly recommend the authors to make the manuscript more concise, I leave it to the editor to decide how strongly to request that.

Response: Thanks for the suggestions. We understand the reviewer's concern about the writing style. To address the reviewer's concern (hopefully), we have reorganized Section 2.2, placing the not-so-relevant details of FSA and BSA to Appendix C, the equations of polarimetric radar variables to Appendix D. We hope those modifications can improve the readability of the paper.

Specific remarks:

1. L20: "database […] with a multi-layered architecture" – Here, it remains unclear what that might refer to, hence meaningless. I suggest to spend a few more words on this.

   Response: Good suggestion. We included the following words:

   "Specifically, three levels of databases are created that store the single scattering properties for different shapes at discrete sizes for various fixed orientations, integrated single scattering properties over shapes and orientations, and bulk scattering properties incorporating the size average, respectively.

2. L39f: "non-linear […] nature of the observation operator" – The challenge is not the operator nonlinearity, but the nonlinearity of the processes the operator describes.

   Response: Yes. We have reformulated the expression.

   "In essence, using radar data in the observation space is preferred over the model space due to the highly non-linear and non-unique nature of the processes that observational operator of polarimetric radar describes."

3. L48ff: I suggest to cover all mentioned RFOs in roughly the same detail (e.g. Zeng16 also provides a melting/mixed-phase particle scheme, makes use of Mie/T-Matrix-based bulk scattering lookup tables for speedy calculations and is online-coupled to the COSMO and ICON models).

   Response: Good suggestion, we have included those details.

   "Zeng et al. (2016) described an efficient radar operator that is online-coupled to the Consortium for Small-scale Modelling (COSMO) and Icosahedral Nonhydrostatic Weather and Climate Model (ICON) model, making use of Mie / T-matrix scattering look-up table of solid, liquid and melting (mixed-phased) hydrometeors, named as efficient modular volume-scanning radar forward operator (EMVORADO). Although the early versions of

EMVORADO focus on non-polarimetric radar variables, later developments on EMVORADO have enabled its capability on simulating dual-polarization variables and conducted sufficient evaluations (Trömel et al., 2021; Shrestha et al., 2022).”

4. L70: The meaning of both “accurate” and “multi-layered” in this context is not clear.

   Response: We have added a few explanations on “accurate” and “multi-layered”:

   “We utilize a semi-analytical scattering computation approach of T-matrix to ensure accuracy and features a multi-layered optical database that includes single scattering properties at discrete sizes and orientations, integrated single scattering properties over shapes and orientations, and bulk scattering properties incorporating the size average. Additionally, ZJU-AERO allows for flexibility in particle orientation and shape probability distribution tuning.”

5. L84: “The formulas […] are briefly presented” – Remove brief here; it’s fairly detailed.

   Response: Removed.

6. Fig1: This figure is only shortly mentioned in text, as far as I see without an actual clear purpose (“certain factors, such as beam-broadening, beam-bending, and beam-blocking among others (as shown in Figure 1)”). Remove it unless you give it a proper description/explanation and purpose.

   Response: We have added proper description / explanation to Figure 1 in the text of the manuscript.

   “The ZJU-AERO was developed to simulate the observable polarimetric radar variables for radar systems aboard on various platforms, including ground-based, space-borne, and potentially airborne radars in the future. The conceptual graph of the multi-platform radar operator is shown in Figure 1. While the physical principles of the weather radar detection process are universal, certain factors, such as beam-broadening, beam-bending, and beam-blocking among others (as indicated along the beam trajectory in Figure 1), which are critical to ground-based radars, are not equally important across platforms. For example, the beam-bending effect is typically negligible for space-borne radar due to large absolute elevation angles (usually 70~90°, as illustrated in Figure 1 for spaceborne radar) and shorter beam trajectories (usually < 20 km) below the model top, as compared to the ground-based radar (the trajectory can reach up to about 250 km). However, the simulations of space-borne and ground-based radars share consistent hydrometeor setting entries for snow/graupel, melting snow/graupel, and rain, such as the dielectric model, particle morphology (distribution), size distribution, orientation preference, and others.”

7. L130: “can also interface with the output of WRF NWP model” – what is the difference/add-on to the general NWP variable reading from external storage files from the 1st sentence in this module description?

   Response: Actually, there are only technical issues about adapting the forward radar operator to interface with the external grid data of another NWP model. For example, the projections of model horizontal mesh, the staggered vertical grid, the model variable mapping table, etc.

   We have added a sentence at the end of this module description to improve clarity:

   “Enabling ZJU-AERO to interface with grid data from another NWP model involves only

technical adjustments, requiring basic information about that NWP model's horizontal mesh (projections), vertical grid, and variable mapping table."

8. L131ff: This bullet point first suggests that trajectory are solved online (L131), then mentioning choice of (the same or a different?) online solver and an offline solver. Confusing.

   Response: Sorry for the confusion arises from mistaken formulation. We have fixed this inconsistency:

   "For ground-based radar (B1), users have the option of using an online trajectory solver that uses the temperature and humidity profiles above the radar site. Specifically, the atmosphere refractive index Na are determined from atmosphere temperature T, pressure P and water vapor mixing ratio Q. The trajectory is determined by a ray-tracing ordinary differential equation (ODE) solver (Zeng et al., 2014). Additionally,, ZJU-AERO offers an alternative option of using an offline 4/3R_E solver for ground-based radar in ZJU-AERO."

9. L137: "radar variables are averaged" – More precisely, that should be an integration.

   Response: Yes, we have reformulated the expression here:

   "The observable radar variables are calculated by integrating bulk scattering properties over the antenna patterns (as described in step 5) to obtain the final results (beam-broadening and beam-blocking are considered in this way)."

10. L167 & L173: Is the averaging (or integration) really done over the observable dual-pol parameters, specifically ZDR and rho_hv? This seems wrong since these variables are not additive.

    Response: Yes, the antenna pattern integrations are performed based on bulk scattering properties (<Z> and <K>) rather than dual-pol parameters. The procedure we described contains some mistakes. We have amended them:

    "5.2 Once the bulk scattering properties on each sub-trajectory gridpoint within each radar gate are available, the antenna pattern integration involves integrating the bulk scattering properties within the scanning volume of each radar gate.

    5.3 Then, the core module calculates the intrinsic polarimetric radar variables on each radar gate, based on the bulk scattering properties incorporating the antenna pattern integration presented in step 5.2. These radar variables include single-polarization reflectivities (Z_H for horizontal reflectivities), dual-polarization variables (Z_{DR}, K_{DP}, δ_{hv}, Φ_{DP} and ρ_{hv} for differential reflectivity, differential phase shift, backscatter differential phase and co-polar correlation coefficient, respectively), and attenuation variables (aH and aV for horizontal and vertical attenuation coefficient, respectively). The definitions of these variables can be found in Appendix D.

    5.4 For a detailed explanation of the intrinsic radar variables, please refer to Zhang (2016). In the final step of core module, the observable radar variables are obtained by taking into account the attenuation and phase shift accumulated along the beam trajectories."

11. L175: "procedures of steps 1-5 (excluding […]) are independent" – doesn't that imply, it's steps 2-5 only?

    Response: Yes. Done.

"The above procedures of steps 2-5 are independent for each single beam."

12. L266: What are the S^fwd?

    Response: We have added explanations to the superscripts of "fwd" here:

    "Here, the superscripts of "fwd" over matrix elements indicate that these are elements of the forward scattering matrix."

13. L358: "possibility-weighted averaging" – probability-weighted

    Response: Done.

14. L430: "various orientations" – Mishchenko refers to them (steps 1-3) as "fixed orientation" in contrast to orientation-averaged ones (step 4). Might be helpful to make use of this established terminology.

    Response: Good suggestion. We have substituted the invented terminology of "various orientations" as the established terminology "fixed orientation".

15. L435: "while for particles without axial symmetry or those that are inhomogeneous, we applied the invariant-imbedding T-matrix (IITM) code" – To which particles does this refer in the current state? According to later parts of the manuscript, IITM has been applied for the Chebyshev-shaped raindrops (which are actually both axial symmetric and homogeneous). For any others yet?

    Response: (1). Basically, those are the guidelines for selecting scattering computation approaches. However, there are exceptions when the EBCM approach suffers from numerical stability issues computing scattering properties of Chebyshev raindrops, for which we use the IITM approach instead. (2). There is no particle geometric model that is not axial symmetric or homogenous when the manuscript was finished. However, we have developed a melting particle model with inhomogeneous geometric specification in another paper for ZJU-AERO (under review), for which the guidelines of using IITM takes effect.

    (3). We have amended the formulation here:

    "The guidelines for selecting scattering computation approach are as follows: for both axially symmetric (i.e., the dielectric constant distribution of electromagnetic medium in spherical coordinates $\varepsilon(r,\theta,\varphi)$ is irrelevant with azimuth angle φ) and homogenous particles, we used the EBCM T-matrix code (Mishchenko and Travis, 1994), while for particles without axial symmetry or those that are inhomogeneous (or shapes that the EBCM approach suffer from numerical stability issues), we applied the invariant-imbedding T-matrix (IITM) code (Bi et al., 2013; Bi and Yang, 2014; Bi et al., 2022; Wang et al., 2023)"

16. L439f: Add reference to conversion formulas.

    Response: Done.

    "3. The forward and backward amplitude scattering matrices $\mathbf{S}_{\mathbf{FSA}}$ were then converted into the backscattering Mueller and extinction matrices, $\mathbf{Z}$ and $\mathbf{K}$, respectively (Mishchenko, 2014)."

17. L451ff: The sin(beta) does not really belong to the Gaussian probability distribution, but to the integration over polar angle (differently formulated: the sin(beta) has to appear in any integration over polar angle regardless of the purpose of that integration (compare e.g. phase function integration formulas) and of the probability distribution applied (compare e.g. formula

for total random orientation)). Moreover, Eq31 specifically gives a Gaussian around beta=0°

Response: Yes, sin(beta) should belong to the general form of the integration over probability distribution, regardless of the specific form of the probability distribution. We have amended the formulas:

"The integration in the Level A to Level B database conversion tool can be formalized as integration over canting angle β as follows:

$$\bar{\bar{\mathbf{X}}}(e)=\frac{1}{\pi}\int_0^{\pi}\sin(\beta)\mathrm{d}\beta\,\mathrm{p}(\beta)\bar{\mathbf{X}}(e,\beta),\mathbf{X}=\mathbf{Z},\mathbf{K} \quad (17)$$

Here $\mathrm{p}(\beta)$ *is the probability distribution of canting angle β. A Gaussian distribution in polar angle is often used to approximate the probability distribution of canting angle:*

$$\mathrm{p}(\beta)=\exp\left(-\frac{\beta}{2\sigma_{\beta}^{2}}\right) \quad (18)"$$

18. L467: "To improve the accuracy of raindrop modeling" – Since your paper is on radar forward operator, this is misleading. Make clear that this only refers to the geometric model of the raindrop, not to any radar modeling. Also, formulation seems to (wrongly) imply that you will do/develop these improvements.

    Response: Thanks for the suggestion, we have made it clear that we only improved the raindrop shape representation in the forward radar operator ZJU-AERO by using the established Chebyshev raindrop model, not any other modeling aspects, not developing the geometric model on our own.

    "To improve the accuracy of raindrop shape representation in the forward radar operator ZJU-AERO, it is essential to apply an established raindrop model that accounts for various effects such as the surface tension, hydrostatic and aerodynamic pressures, and static electric forces."

19. L468f: "By incorporating these factors, a more accurate representation of raindrop model" – more accurate geometric(!) representation of raindrop shapes (of real, observed shapes, not of a model!).

    Response: Thanks for the suggestion, it has been reformulated.

    "By incorporating these factors, a more accurate geometric representation of observed raindrop shapes can be achieved compared to the most commonly used spheroid model."

20. L524: Why inventing a new name for this, when it is nothing more than the attenuation cross section?

    Response: That is because "the SSP factor of a_h" is the name regarding the function of this variable, while in practice, it can be defined just as the extinction cross section of this particle. It seems be better to provide a consistent naming rule for those SSP factors (i.e., [z_h], [a_h]…) for clarity.

    We add a note that [a_h] is exactly the extinction cross section in the text to remind readers of this point.

    "Similarly, the SSP factor "[a_h]" for horizontal attenuation coefficient "a_h" is defined (the extinction cross section by essence)"

21. L528f: "describe how a particle with a diameter Deq affects the radar reflectivity" – It's not the

effect (i.e. a contribution) that is shown, particularly not when it later regards [Z_{DR}], but the equivalent radar parameter of a single, monodisperse particle of that size.

Response: Yes. We have amended the interpretation of those factors here:

"As shown by Eqs. (21) and (23), these factors ([z_h] and [a_h]) are equivalent radar parameters of radar reflectivity z_h and specific attenuation ah, respectively, for a single particle of size D_{eq}."

22. FigA1: Most of the caption does not describe what is seen in the figure, but explanation of theory or approach, hence belong in the manuscript text.

Response: Done. We have moved the sentences describing the theory or approach to the manuscript of this appendix:

"For space-borne radars onboard rain measurement satellite platforms, such as the Tropical Rainfall Measuring Mission/Global Precipitation Measurement/Fengyun3-Rain Measurement (TRMM/GPM/FY3RM), the trajectory of the radar beam can be treated without considering the beam-bending effects while still maintaining precision. The WGS84 coordinates of satellites, denoted as A (scLat, scLon, scAlt), in addition to the centre of foot-print, A1 (Lat, Lon), can be obtained through the satellite radar L1/L2 products thereafter referred to as swath files. These coordinates can then be used to calculate the local elevation angle of a given radar gate, C, using the knowledge of trigonometry in Figure A1(b). The length of segments H and RE can be computed by converting the (latitude, longitude, altitude) WGS84 coordinates to the Earth-Centre–Earth-Fixed (ECEF) coordinates. The range of radar gate AC is provided by the space-borne radar observation system in the L1 product of GPM/DPR known as "scRangeEllipsoid" (Iguchi et al., 2010). When neglecting the beam-bending phenomenon in the space-borne radar detection, the local elevation angle, e', can be expressed as e' = e-α in which e is the elevation angle on the satellite. The angle α could be determined using trigonometry, given that AC represents the range of the radar gate C."