General comments:

This study evaluates the simulation of radar variables (Z_H and Z_{DR}) by the polarimetric radar observation operator of Jung et al. (2008) using the power-law fitting and direct integration methods for scattering calculations. This study is interesting for the polarimetric radar data assimilation. However, both the fitting and direct integration methods presented in this manuscript have their own inherent problems, which have already been addressed or improved by Jung et al. (2010), Dawson et al. (2014), Putnam et al. (2019), and Zhang et al. (2021). In short, the fitting method fails to accurately simulate the polarimetric radar signatures, as demonstrated in the manuscript results. Based on the operator of Jung et al. (2008), Jung et al. (2010) developed more accurate and generalized operators using the direct integration method for both rain and ice hydrometeors. Nevertheless, these operators are complex and require computationally expensive numerical integration over the particle size distribution. Subsequently, Putnam et al. (2019) modified the operators of Jung et al. (2010), introducing precomputed lookup tables to increase computational efficiency with some sacrifice to accuracy, and demonstrated their application in assimilating real ZDR (Putnam et al. 2021). However, the operators modified by Putnam et al. (2019) are still computationally expensive and difficult to use in data assimilation, especially in variational assimilation. Zhang et al. (2021) developed a set of parameterized operators based on the numerical integration of the scattering weighted by the particle size distribution. It is challenging to balance the computational efficiency and accuracy of the observation operator within data assimilation systems.

I really appreciate the authors' efforts in exploring a challenging path toward the effective assimilation of polarimetric radar observations. However, I would strongly encourage the authors to find new avenues rather than retreading ground that has already been explored.

We sincerely appreciate the reviewer's considerate comments regarding the inherent issues identified in previous studies, as well as for the valuable suggestions pointing to potential new research directions. To the best of our knowledge, however, the limitations of the power-law fitting approach—particularly the issue of unreasonable negative Z_{DR}—have not been explicitly addressed in the existing literature. Despite this deficiency, power-law fitting–based operators continue to be employed in recent studies (e.g., Kabasawa et al., 2018; Lee et al., 2026). Since the bias of the background directly leads to physically unreasonable outcomes after data assimilation, it is essential to highlight such systematic biases and to ensure that their limitations are well recognized by the research community. Although the polynomial fitting method addressed by Zhuang et al. (2021) can alleviate the negative Z_{DR}, it still exhibits uncertainties in representing Z_{DR}, particularly for wet snow and for extreme value in the real case simulation. Furthermore, since the polynomial fitting is applied after numerical integration, it is needed to first evaluate whether the integration-form operator provides sufficient accuracy under the meteorological conditions in Taiwan before applying the polynomial fitting. While we acknowledge the importance of systematically comparing different operators and discussing their respective strengths and weaknesses, we believe that explicitly identifying significant biases and preventing potential misuse of existing approaches is both necessary and timely. By clarifying these issues, our study aims to provide guidance toward more appropriate choices and to improve the physical consistency of observation operators. Consequently, the background simulations and associated error structures can be made more reliable prior to data assimilation.

Major comments:

(1) Introduction: I suggest that the authors systematically review the development of polarimetric radar observation operators, highlighting the respective strengths and weaknesses of different operators in both simulation and assimilation.

Response: We would additionally address the development of observation operators in the revised manuscript. As this study primarily focuses on the differences between power-law fitting approach and the numerical integration approach, we will provide a more in-deep comparison between these two types of operators. The novel method, polynomial fitting method addressed by Mahale et al.(2019) and Zhang et al.(2021), would be briefly depicted in the manuscript as well. The melting model also plays an important role in the observation operators, and it is necessary to modify the melting model toward the observation. Such modification could be found in Dawson et al.(2014) and Zhang et al. (2021). However, because the present study mainly targets the raindrop-dominant region below the melting layer, the remodeling of the melting model would be discussed only briefly. We will try our best to describe the evolution of the operators and point out how important the different steps are.

(2) Methodology: The manuscript appears to employ the direct integration method only for the raindrop. It is unclear how the manuscript handles ice-phase particles (snow and graupel/hail) and mixed-phase particles (wet snow and wet graupel/hail). A fair comparison should use the same method for all hydrometeor species. Additionally, the sacrifice of accuracy in the fitting method is unavoidable. Therefore, the authors need to clarify the computational advantages of this approach. If the fitting method provides neither improved efficiency nor adequate accuracy, then what is the rationale for using it instead of the direct integration method?

Response: We thank the reviewer for highlighting the computational advantages of the fitting-based approach. Based on our experiments, replacing only the raindrop-related term with the numerical integration formulation can reduce the overall computational cost by approximately 80%, resulting in a substantial acceleration of the simulations. However, this modification simultaneously introduces a pronounced negative Z_{DR}. In this study, the overall structure of the observation operator follows Jung et al. (2008), while the fitting coefficients are adopted from You et al. (2020), for both liquid-phase and ice-phase terms. Since the purpose of our article is addressing the unavoidable negative Z_{DR} in simulating the raindrop-related terms, we intentionally keep other components of the operator unchanged. This design allows us to isolate the impact of modifying a single term and to clearly highlight the resulting differences. For sure, it is always an important issue that how to well simulate the ice-phase related term inside the operator, and our team would try hard to set up and examine the ice-phase term; these efforts are on the process and we would like to see the results of using the integration form for all hydrometeor species.

(3) Results: The authors need to present the spatial distribution of the polarimetric radar variables simulated by different methods, including both horizontal and vertical cross-sections. In section 5.3, the authors used the fitted Dmr from the radar variables as a reference "observation" for comparison. However, it is unclear what

the purpose of such a comparison is when the “observations” themselves do not represent the truth. Why are the radar variables not compared directly?

Response: The spatial distribution of the dual-polarization radar variables would be presented in the manuscript after the revision. In section 5.2, the simulation of the polarimetric radar variables have been validated by the observed data. However, since dual-polarization radar variables are not prognostic variables in numerical models, during model updating, model state variables can only be adjusted through their correlations with dual-polarization parameters. These correlations are derived from ensemble model simulations, and it remains unknown whether the same relationships can be described by observations. To assess whether these correlations are reliable, microphysical observations can be used—beyond radar measurements—for verification. Yet, the lack of three-dimensional in-situ microphysical observations poses substantial challenges for such validation. Lee et al. (2019) developed fitted relationships using microphysical observations and radar data, aiming to describe long-term statistical connections between radar variables and observed microphysical quantities. Using these retrieval formulas, we can estimate microphysical characteristics from radar observations in regions lacking in-situ measurements. These estimated characteristics can then be used to validate real-case analyses, helping determine whether the microphysical structures—composed of model forecast variables within the analysis fields—become more consistent with observation-derived characteristics after data assimilation within the radar-covered region. In other words, we aim to assess whether the relationships between dual-polarization radar variables and microphysical parameters become more similar to those fitted from observations.

Reference

Dawson, D. T., E. R. Mansell, Y. Jung, L. J. Wicker, M. R. Kumjian, and M. Xue: Low-Level ZDR Signatures in Supercell Forward Flanks: The Role of Size Sorting and Melting of Hail, Journal of the Atmospheric Sciences, 71, 276-299, doi: 10.1175/jas-d-13-0118.1, 2014.

Lee, M.-T., P.-L. Lin, W.-Y Chang, B.K Seela and J. Janapati: Microphysical characteristics and types of precipitation for different seasons over north Taiwan, J. Meteorol. Soc. Jpn., 97(4), 841–865, doi: 10.2151/jmsj.2019-048, 2019.

Mahale, V. N., G. Zhang, M. Xue, J. Gao, and H. D. Reeves: Variational retrieval of rain microphysics and related parameters from polarimetric radar data with a parameterized operator. J. Atmos. Ocean. Technol.,36(12), 2483−2500, doi: 10.1175/JTECH-D-18-0212.1, 2019.

Jung, Y., G. Zhang, and M. Xue: Assimilation of Simulated Polarimetric Radar Data for a Convective Storm Using the Ensemble Kalman Filter. Part I: Observation Operators for Reflectivity and Polarimetric Variables, Monthly Weather Review, 136, 2228-2245, doi: 10.1175/2007MWR2083.1, 2008a.

Jung, Y., M. Xue, G. Zhang, and J. M. Straka: Assimilation of Simulated Polarimetric Radar Data for a Convective Storm Using the Ensemble Kalman Filter. Part II: Impact of Polarimetric Data on Storm Analysis, Monthly Weather Review, 136, 2246-2260, doi: 10.1175/2007MWR2288.1, 2008b.

Kawabata, T., T. Schwitall, A. Adachi, H.-S. Bauer, V. Wulfmeyer, N. Nagumo, and H. Yamauchi: Observational operators for dual polarimetric radars in variational data assimilation systems (PolRad VAR v1.0), Geosci. Model Dev., 11, 2493–2501, doi: 10.5194/gmd-11-2493-2018, 2018.

You, C. R., K. S. Chung, and C. C. Tsai: Evaluating the Performance of a Convection-Permitting Model by Using Dual-Polarimetric Radar Parameters: Case Study of SoWMEX IOP8, Remote Sensing, 12, 3004, doi: 10.3390/rs12183004, 2020.

Zhang, G., J. Gao, and M. Du: Parameterized forward operators for simulation and assimilation of polarimetric radar data with numerical weather predictions. Adv. Atmos. Sci., 38(5), 737−754, doi: 10.1007/s00376-021-0289-6, 2021.