Review for: *Impact of ice multiplication on the cloud electrification of a cold-season thunderstorm: a numerical case study*

General comments:

Yang et al. investigate the role of three secondary ice production (SIP) processes in precipitation intensity, cloud electrification and discharge processes, within the context of a wintertime thunderstorm. The analysis relies on mesoscale simulations conducted using the Weather Research and Forecasting (WRF) model, coupled with a fast spectral bin microphysics (SBM) scheme. The employed SBM scheme was refined through the incorporation of state-of-the-art ice multiplication formulations, complemented by the integration of noninductive and inductive charging parameterizations.

This study contributes significantly to clarifying the complex interactions between ice microphysics – particularly the poorly constrained SIP processes – and cloud electrification. Despite its importance, the manuscript requires substantial revisions across the methodology, model evaluation and results sections, aimed at improving readability and enhancing the robustness of certain findings. It is recommended that the following aspects be revisited before publication:

Specific comments:

- In Section 2.2, I would recommend to explain the rationale behind selecting the specific microphysics scheme, specifying the ice and liquid hydrometeor species considered in the model, and providing information on whether this scheme has undergone evaluation in similar studies in the past.
- Regarding the implementation of the ice-ice collisional break-up (IC) and the shattering of freezing drops (SD), it is important to provide a more detailed description – especially if this is the first attempt to incorporate these parameterizations into the SBM scheme:
  - The physically-based parameterization of Phillips et al. (2017) explicitly considers the effect of ice habit, ice type and rimed fractions of the particles undergoing fragmentation. These parameters are not always described in models, and therefore certain assumptions have to be made. Please describe how these parameters are treated in the model and whether the scheme predicts the rimed mass fraction of colliding ice particles or if a constant value is prescribed. Given the demonstrated impact of the rimed fraction on the efficiency of the IC mechanism (e.g., Karalis et al., 2022; Sotiropoulou et al., 2021), you may consider assessing the sensitivity of your results to this parameter. Additionally, further clarification is needed regarding the

collection efficiencies of ice particles and whether all collisions between ice particles can lead to fragmentation and the generation of SIP particles.

- Please provide more details about the collisions considered in 'mode 1' of the Phillips et al. (2018) parameterization. Were collisions with ice nucleating particles (INPs) other than small ice particles taken into account? A brief description of the primary ice production mechanisms encompassed within the scheme would also be useful.

- To improve readability, please consider incorporating a dedicated paragraph (for example in Section 2) that outlines the various measurements utilized in this study, discussing any uncertainties and/or any post-processing applied to them. This applies to the radar observations (Figure 3), sounding data (Figure2) as well as the observed flash rates (Figure 6). Consider moving the information about the lightning observational dataset from the "Results" section (Lines 194-197) to the corresponding data paragraph.
- Please explain how the modeled composite reflectivity (shown in Figure 5) is derived. Which parameters (e.g., mass and concentration of ice and liquid hydrometeors) have the most influence on simulated reflectivity? In this way, the reader can better understand the changes caused when SIP is accounted for and you can better support your statement in Lines 251-252 "…the decrease in the sizes of these solid particles is **probably** the main reason of the weaker composite radar reflectivity in the 3SIP experiment".
- For improved visual comparison between model simulations (Figure 5) and radar observations (Figure 3), you may consider including all relevant subplots into a single figure. Also, ensure consistency in colorbar limits (dBZ) across visualizations.
- **Lines 176-178**: Here the reader is already wondering why activating SIP in the model leads to reduced modeled reflectivity. You could mention that this aspect will be elaborated upon in Section 3.2.
- **Lines 180-181**: "…the simulation with all the three SIP processes has the best performance comparing to the observation (Figs. 3b and 5j) ". The robustness of this statement can be enhanced by including additional statistics to complement the visual comparison.
- **Line 212**: consider using a more suitable transition sentence, especially since the charge structure will not be discussed in Section 3.2.
- **Line 218**: Please clarify the meaning of "strong correlation" in this sentence.
- With the model you have access to all production rates of important microphysical processes, like riming, aggregation, sedimentation, or the melting of graupel particles or snowflakes that could be used to support your statements throughout the text, such as Lines 218, 222, 259, 285, and 287.
- **Line 224**: Are you referring to the 'riming of cloud droplets and raindrops' rather than the 'rime-splintering process' here? Indeed, liquid hydrometeors that rime onto

graupel would typically increase its mass. However, if RS is activated, part of this rimed mass would then be transferred from the graupel to the smaller cloud ice particles.

- **Line 229-230**: Any idea why the enhancement of graupel/hail and ice/snow is followed by an increase in the cloud liquid water content (rain + cloud mass mixing ratios)? I would expect the opposite behavior, because of the Wegener–Bergeron–Findeisen (WBF) process.
- **Figure 7**: I would suggest superimposing the isotherms in this plot for better visualization of the RS temperature zone, melting layer, and temperatures where IC and SD are efficient.
- **Figure 8**: Please explain how averaged concentrations were calculated. Did you consider only in-cloud conditions? Instead of having separate plots for the number concentrations and sizes, it might be worth plotting the particle size distributions (PSDs) (i.e., d(N)/d(logD)). In this way, the reader would more easily identify both the ice enhancement caused when SIP is considered in the simulations, and the shift of the PSDs towards smaller sizes, which is crucial for capturing the correct radar reflectivity values.
- The discussion of Figure 8 in the last paragraph of Section 3.2, should be more quantitative. You mention that SIP processes can "**slightly** enhance" or "**slightly** decrease" the ice-particle or liquid-particle concentrations, respectively. Please try to quantify the ice enhancement caused when SIP is included in the model compared to the noSIP sensitivity simulation. This is an important information if you want to convince the reader of the importance of incorporating SIP processes in the model.
- In Section 3.2 or the "Discussion and Conclusions" section, consider including a discussion on the relative contribution of each SIP mechanism and a comparison of your findings with similar convective case studies from the literature.
- **Line 383-384**: The transition sentence does not have a clear connection with the rest of the paragraph.
- **Line 421**: You may want to refer to the new empirical parameterization for the sublimational break-up mechanism developed in Deshmukh et al. (2022). This mechanism has been found to be the second most dominant SIP mechanism in fast convective downdrafts (Waman et al., 2022).

<u>Technical corrections:</u>

- **Line 124**: I would suggest "**grid spacing**" instead of "resolution"
- **Line 169**: I would suggest "Model **evaluation**" instead of "Model validation"
- **Line 156**: "**correct representation**" (not representative)
- **Line 228**: "shown later", consider indicating the section where the subsequent discussion will take place. Similarly, for Line 233.
- **Line 233**: "reduced **by SIP**" (not by this SIP)

- **Line 257**: Section **3.3** (not 3.2)
- **Line 361**: Section **4 Discussion and Conclusions** (not 5)
- **Line 371**: **suggests** (not suggest)
- Please double check the reference provided for Mansell et al. (2010)

References

Deshmukh, A., Phillips, V. T. J., Bansemer, A., Patade, S. and Waman, D.: New Empirical Formulation for the Sublimational Breakup of Graupel and Dendritic Snow, J. Atmos. Sci., 79(1), 317–336, doi:10.1175/JAS-D-20-0275.1, 2022.

Karalis, M., Sotiropoulou, G., Abel, S. J., Bossioli, E., Georgakaki, P., Methymaki, G., Nenes, A. and Tombrou, M.: Effects of secondary ice processes on a stratocumulus to cumulus transition during a cold-air outbreak, Atmos. Res., 277, doi:10.1016/j.atmosres.2022.106302, 2022.

Mansell, E. R., Ziegler, C. L. and Bruning, E. C.: Simulated electrification of a small thunderstorm with two-moment bulk microphysics, J. Atmos. Sci., 67(1), 171–194, doi:10.1175/2009JAS2965.1, 2010.

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Phillips, V. T. J., Patade, S., Gutierrez, J. and Bansemer, A.: Secondary ice production by fragmentation of freezing drops: Formulation and theory, J. Atmos. Sci., 75(9), 3031–3070, doi:10.1175/JAS-D-17-0190.1, 2018.

Sotiropoulou, G., Vignon, E., Young, G., Morrison, H., O'Shea, S. J., Lachlan-Cope, T., Berne, A. and Nenes, A.: Secondary ice production in summer clouds over the Antarctic coast: An underappreciated process in atmospheric models, Atmos. Chem. Phys., 21(2), 755–771, doi:10.5194/acp-21-755-2021, 2021.

Waman, D., Patade, S., Jadav, A., Deshmukh, A., Gupta, A. K., Phillips, V. T. J., Bansemer, A. and Demott, P. J.: Dependencies of Four Mechanisms of Secondary Ice Production on Cloud-Top Temperature in a Continental Convective Storm, J. Atmos. Sci., 79(12), 3375–3404, doi:10.1175/JAS-D-21-0278.1, 2022.