Reviewer's comments are in black, and responses are in blue.

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:

Reply: We appreciate your insightful comments. The paper has been revised accordingly and has been improved a lot. Please see our responses below.

Specific comments:

1. 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.

Reply: Thank you for your comment. The following information is added to the revised paper.

"Compared to bulk microphysics scheme, spectral bin microphysics (SBM) scheme has the advantage of calculating particle size distributions (PSDs) by solving explicit microphysical equations. It aims to simulate as accurately as possible cloud microphysical processes (Khain et al. 2015). In the fast version of SBM in WRF, the ice and liquid hydrometeor species include cloud droplet/rain, ice/snow, and graupel, each of them is represented by 33 doubling mass bins. It has been demonstrated that SBM performs better than bulk microphysics in modeling cloud microphysics in many

previous studies (e.g., Fan et al., 2012; Khain et al. 2015). However, SBM has not been widely used for studying cloud electrification (e.g., Mansell et al., 2005; Shi et al., 2015). Recently, Philips et al. (2020) implemented cloud electrification parameterization in the SBM in a cloud model, and they conducted an idealized simulation of deep convective clouds. The results showed the modeled charge structure and lightning activity are consistent with observations. However, cloud electrification has not been implemented in SBM in WRF for real case study before."

References:

Fan, J., L. R. Leung, Z. Li, H. Morrison, H. Chen, Y. Zhou, Y. Qian, and Y. Wang: Aerosol impacts on clouds and precipitation in eastern China: Results from bin and bulk microphysics. J. Geophys. Res., 117, D00K36, doi:10.1029/2011JD016537, 2012.

Mansell, E. R., MacGorman, D. R., Ziegler, C. L., and Straka, J. M.: Charge structure and lightning sensitivity in a simulated multicell thunderstorm. Journal of Geophysical Research, 110, D12101, doi: 10.1029/2004JD005287, 2005.

Khain, A. P., et al. : Representation of microphysical processes in cloud- resolving models: Spectral (bin) microphysics versus bulk parameterization. Rev. Geophys., 53, 247–322, doi:10.1002/2014RG000468, 2015.

Phillips, V. T., Formenton, M., Kanawade, V. P., Karlsson, L. R., Patade, S., Sun, J., Barthe, C., Pinty, J. P., Detwiler, A. G., Lyu, W. and Tessendorf, S. A.: Multiple environmental influences on the lightning of cold-based continental cumulonimbus clouds. Part I: Description and validation of model. J. Atmos. Sci., 77, 3999-4024, doi: 10.1175/JAS-D-19-0200.1, 2020.

Shi, Z., Tan, Y. B., Tang, H. Q., Sun, J., Yang, Y., Peng, L., and Guo, X. F.: Aerosol effect on the land-ocean contrast in thunderstorm electrification and lightning frequency. Atmospheric Research, 164–165, 131–141, doi: 590 10.1016/j.atmosres.2015.05.006., 2015.

2. 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:

Reply: Thank you for your valuable reminding. The detailed information is added in Appendix A of the revised paper as follows.

"The parametrization of ice–ice collisional breakup is developed by Phillips et al. (2017). The number of ice fragments produced during ice–ice collision is:

$$N_{IC} = \alpha A(M)\left\{1 - exp\left[-\left(\frac{C(M)K_0}{\alpha A(M)}\right)^{\gamma}\right]\right\} \quad (A3)$$

where $A(M)$ *is the number density of breakable asperities on the ice particle and related to the rimed fraction and the size of smaller ice particle,* $C(M)$ *is asperity–fragility coefficient that is set as* 3.86×10^4 *according to the cloud chamber experiment of natural ice particles (Gautam, 2022),* K_0 *is the initial value of collision kinetic energy,* γ *and* α *are the shape parameter and the equivalent spherical surface area of smaller particles, respectively.* $\gamma = 0.5 - 0.25\Psi$*, where* Ψ *denotes the rimed fraction, which is assumed 0.2 in this study. The tiny fragments are treated as the ice particles belonging to the first bin of the Fast-SBM model.*

The parameterization of shattering of freezing drops was developed by Phillips et al. (2018) based on laboratory experiments. If contact with a smaller ice particle, a supercooled drop may break and produce both big and tiny ice fragments, thus, the number of the ice fragments can be expressed using:

$$N_{SD\_1} = N_T + N_B \quad (A4)$$

$$N_{SD\_1} = F(D)\Omega(T)\left[\frac{\xi_T {\eta_T}^2}{\left(T-T_{T,0}\right)^2+{\eta_t}^2} + \beta T\right] \quad (A5)$$

$$N_B = min\left\{F(D)\Omega(T)\left[\frac{\xi_B {\eta_B}^2}{\left(T-T_{B,0}\right)^2+{\eta_B}^2}\right], N_T\right\} \quad (A6)$$

where, N_T *and* N_B *are the number of tiny and big ice fragments generated by a shattered drop.* $F(D)$ *and* $\Omega(T)$ *are the interpolating functions for the onset of drop shattering.* ξ_T, ξ_B, η_T, η_B, $T_{T,0}$, $T_{B,0}$, β, *are parameters determined based on datasets from previous laboratory experiments, which can be found in Phillips et al. (2018). The tiny fragments are treated as the ice particle belonging to the first bin of Fast-SBM model, which have a diameter of 4 micrometers (Khain et al., 2004). The mass of big ice fragments is* $m_B = 0.4m_{drop}$.

In addition, a drop may also break if contacting with a more massive ice particle. The number of ice fragments produced in this process is:

$$N_{SD\_2} = 3\Phi \times [1 - f(T)] \times max\left\{\left(\frac{k_0}{S_e} - DE_{crit}\right), 0\right\} \quad (A7)$$

$$f(T) = \frac{-C_w T}{L_f} \quad (A8)$$

$$S_e = \gamma_{liq} \pi D^2 \quad (A9)$$

where, γ_{liq} *is the surface tension of liquid drop,* k_0 *is the initial kinetic energy of the two colliding particles,* $f(T)$ *is the frozen fraction.* C_w *and* L_f *are the specific heat capacity of water and the specific latent heat of freezing, respectively.* $DE_{crit} = 0.2$*, and* Φ *is 0.3 according to James et al. (2021). All ice fragments are assumed to be tiny in this mode. The tiny ice fragments are added to the first bin of ice size distribution."*

References:

Gautam, M.: Fragmentation in graupel snow collisions. Master of Science dissertation, Dept of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden-, doi: http://lup.lub.lu.se/student-papers/record/9087233, 2022.

James, R. L., Phillips, V. T. and Connolly, P. J.: Secondary ice production during the break-up of freezing water drops on impact with ice particles. Atmospheric Chemistry and Physics, 21, 18519-18530, doi: 10.5194/acp-21-18519-2021, 2021.

Khain, A., Pokrovsky, A., Pinsky, M., Seifert, A., and Phillips, V.: Simulation of Effects of Atmospheric Aerosols on Deep Turbulent Convective Clouds Using a Spectral Microphysics Mixed-Phase Cumulus Cloud Model. Part I: Model Description and Possible Applications. Journal of the Atmospheric Sciences, 61, 2963–2982, doi: 10.1175/JAS-3350.1, 2004.

Phillips, V. T. J., Yano, Jun-Ichi, Khain, A.: Ice Multiplication by Breakup in Ice-Ice Collisions. Part I: Theoretical Formulation. J. Atmos. Sci., doi: 10.1175/JAS-D-16-0224.1, 2017.

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, 3031–3070, doi: 10.1175/JAS-D-17-0190.1, 2018.

- 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.

Reply: Thank you for your comment. The parameterization of Phillips et al. (2017) has more detailed physical processes than ours. In WRF fast-SBM, cloud ice is divided into high-density graupel and low-density ice/snow. This model does not distinguish between ice and snow, nor does it differentiate between graupel and hail (Khain et al., 2009). This is now clarified in the revised paper.

In our model, the rimed fraction is set as 0.2. And the results of sensitive experiments for different rimed fraction values (0.2 and 0.4) are shown in Fig. R1 to Fig. R4. Figure R1 and R2 show the mixing ratio and number concentration for different rimed fractions. It can be seen that with a rimed fraction of 0.4, there are more graupel particles before 02:00, Nov. 28th. The mixing ratio and concentration of snow particles is also enhanced. As shown in Fig. R3, a larger rimed fraction leads to a slight increase in the charge density on graupel and snow. For the total charge density (Fig. R4), the upper-level negative charge and middle-level positive charge region is enhanced. This is added in the discussion section in the revised paper.

The collection efficiency of ice/snow is the product of collision efficiency and coalescence efficiency. The collision efficiency is obtained based on the Bohm's theory (Bohm, 1992a, 1992b) and the superposition method in Khain et al. (2001). The coalescence efficiency is parameterized in Khain and Sednev (1996), which can be expressed using:

$$E_{coal} = \min\,[1, \frac{e}{e_i} \max\,\{0, a + bT_c + cT_c^2 + dT_c^3\}]$$

where e is the vapor pressure, e_i is the saturation vapor pressure with respect to ice, a, b, c are constant coefficients. As described in Phillips et al. (2017), the number of fragments per collision is associated with the number density of breakable asperities, asperity–fragility coefficient, particle surface area, initial value of collision kinetic energy as well as shape parameter, which indicates that not every collision can lead to fragmentation.

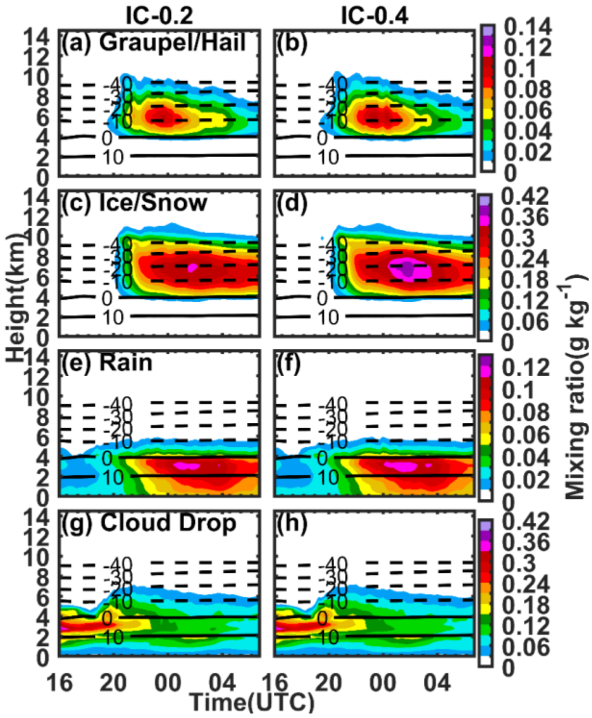

Figure R1: The mixing ratio of (a) and (b) graupel/hail, (c) and (d) ice/snow, (e) and (f) rain and (g) and (h) cloud droplet of ice-ice collisional breakup process for different rimed fraction. The rimed fraction of the left column is 0.2 and that of right column is 0.4.

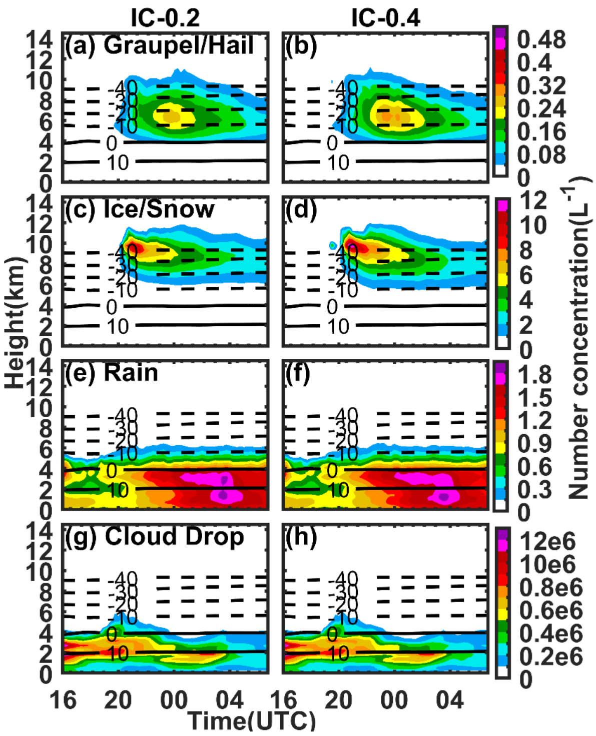

Figure R2: The same as Fig. R1, but for number concentration.

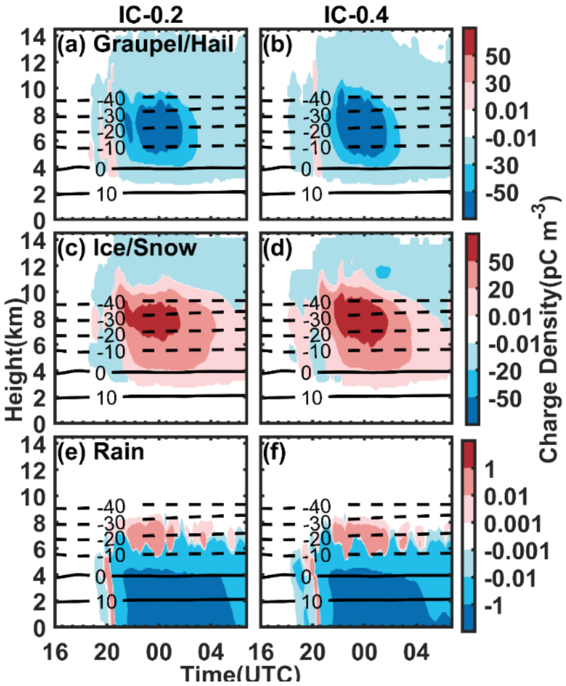

Figure R3: The charging density in IC experiment for different rimed fraction. The rimed fraction of the left column is 0.2 and that of right column is 0.4.

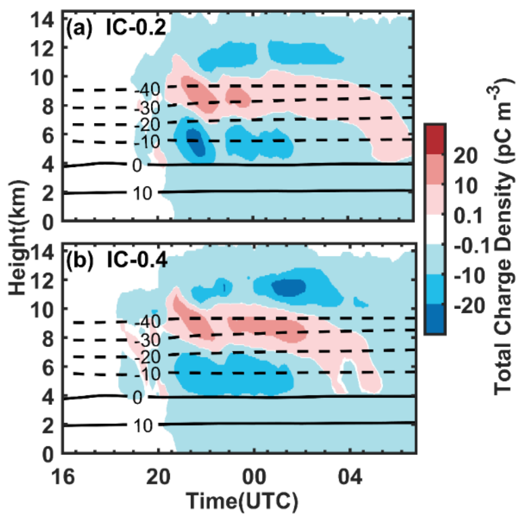

Figure R4: The total charge density in IC experiment for different rimed fractions. The rimed fraction of (a) is 0.2 and that of (b) is 0.4.

References:

Böhm, J. P.: A general hydrodynamic theory for mixed-phase microphysics. Part II: collision kernels for coalescence. Atmos. Res., 27, 275-290, 1992a.

Böhm, J. P.: A general hydrodynamic theory for mixed-phase microphysics. Part III: Riming and aggregation. Atmos. Res., 28, 103-123, 1992b.

Khain., A, Sednev, I.: Simulation of precipitation formation in the Eastern Mediterranean coastal zone using a spectral microphysics cloud ensemble model. Atmos. Res., 43, 77-110, 1996.

Khain, A., M. Pinsky, M. Shapiro, and A. Pokrovsky: Collision Rate of Small Graupel and Water Drops. J. Atmos. Sci., 58, 2571–2595, https://doi.org/10.1175/1520-0469(2001)058<2571:CROSGA>2.0.CO;2, 2001.

Khain, A., Leung, L. R., Lynn, B., and Ghan, S.: Effects of aerosols on the dynamics and microphysics of squall lines simulated by spectral bin and bulk parameterization schemes. Journal of Geophysical Research, 114(D22), D22203, https://doi.org/10.1029/2009JD011902, 2009.

Phillips, Vaughan, T. J., Yano, Jun-Ichi, Khain, and Alexander: Ice Multiplication by Breakup in Ice-Ice Collisions. Part I: Theoretical Formulation. Journal of the Atmospheric Sciences, 2017.

- 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.

Reply: Thank you for your professional comment. The "model 1" collision represents the collision between frozen drops and smaller ice crystals. The collisions with ice nucleating particles (INPs) are not considered in this SIP process. The default primary ice nucleation parameterizations implemented in SBM in WRF are used. The immersion freezing is parametrized according to Bigg (1953). The deposition/condensation nucleation is represented using the parametrization of Meyers et al. (1992), which is a function of saturation ratio with respect to ice. The contact freezing is also developed in Meyers et al. (1992), which is a function of temperature.

References:

Bigg, E. K. : The formation of atmospheric ice crystals by the freezing of droplets. Q. J. R. Meteorol. Soc., 79(342), 510–519, doi:10.1002/ qj.49707934207, 1953.

Meyers, M. P., P. J. DeMott, and W. R. Cotton: New primary ice nucleation parameterizations in an explicit cloud model. Journal of Applied Meteorology., 31, 708– 721, doi:10.1175/1520-0450(1992)031<0708:NPINPI>2.0.CO;2, 1992.

3. 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.

Reply: Thank you for your comment. The following descriptions are added in the paper: *"Radar reflectivity can be used to illustrate the intensity of the storm. The radar data used in this study is a gridded product generated based on 32 S-band radars operated across southeast China. For each radar, the detection radius is 230 km, the range resolution is 250 m and the beamwidth is 1°. The radar finishes a volume scan every 6 minutes consisting of 9 elevation angles (0.5°, 1.5°, 2.4°, 3.4°, 4.3°, 6.0°, 9.9°, 14.6° and 19.5°). The data recorded by these radars were interpolated into a Cartesian grid with a horizontal resolution of 1 km and vertical resolution of 500 m based on the Cressman technique.*

In addition, the lightning location and flash rate is evaluated using observation. The lightning location data is obtained based on the very low frequency (VLF) lightning location network (LLN) in China developed by Nanjing University of Information Science and Technology (Li et al., 2022). VLF-LLN was established in 2021 and has 26 stations distributed across various regions in China. The detection area covers the entire China as well as parts of East Asia and Southeast Asia. The lightning location method is developed based on the time-of-arrival (TOA) method, and the arrival times of each lighting-induced pulse at different stations are obtained by matching the recorded waveforms to the idealized waveform established using the Finite Difference Time-Domain (FDTD) technique. The lightning location error is 1-5 km.

Moreover, the NCEP reanalysis data is used to investigate the synoptic conditions, the sounding measurements at Fuyang, which is conducted every 12 hours, is used to investigate the thermodynamic conditions, and the brightness temperature (TBB) on FY2H satellite that is developed in China is used to illustrate the cloud coverage.

4. 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".

Reply: Thank you for your comment. For each grid point, the maximum radar reflectivity among all layers is used as the composite reflectivity. The size of particles has the most influence on simulated reflectivity, which is calculated for a wavelength of 10 cm.

5. 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.

Reply: Thank you for your comment. The subplots of simulated and observed radar reflectivity with the same color bar have been combined in the revised manuscript.

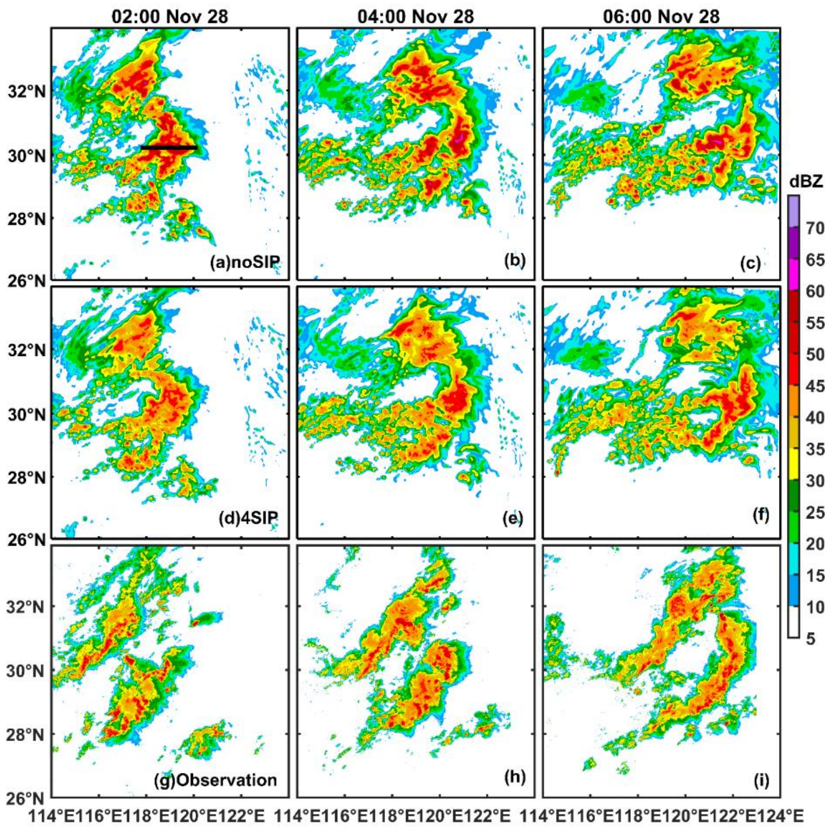

Figure R5: The simulated radar reflectivity and observed reflectivity. (a, b, c) simulated reflectivity of the experiment without SIP process, (d, e, f) simulated reflectivity of experiment with four SIP processes, (g, h, i) observed reflectivity. The black horizontal line in (a) shows where the cross sections were made.

6. 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.

Reply: Thank you for your comment. According to your suggestion, a sentence is added to indicate this aspect will be elaborated upon in Section 3.2.

7. 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.

Reply: We appreciate your comment. According to this comment and a comment by another reviewer, we plot the contoured-frequency-by-altitude diagram (CFAD) of reflectivity, which can statistically show the difference in the reflectivity at different heights between observation and model simulations. According to your comment, ice sublimational breakup has been added to our model as the fourth secondary ice production mechanism (Deshmukh et al., 2022; Waman et al., 2022). The experiment with all four SIP processes included is named "4SIP". As seen in Fig. R6, the maximum reflectivity is observed at about 4 km, which is height of the melting levels. The modeled maximum reflectivity from noSIP experiment is larger than observed by about 7 dBZ, this is also seen from the map of composite reflectivity in the paper. With SIP implemented, the maximum reflectivity decreases and is more consistent with observation. The mean reflectivity profiles in both the noSIP and 4SIP experiments are systematically larger than observed as the occurrence frequency of reflectivity greater than 30 dBZ is higher, but the 4SIP performs better than noSIP experiment. The observed reflectivity maybe underestimated at low levels because the lowest elevation angle used in the radar measurement is 0.5 degree (please see more information of measurements in reply to comment 3) and the low-elevation beams are affected by ground clutters (Fig. R7).

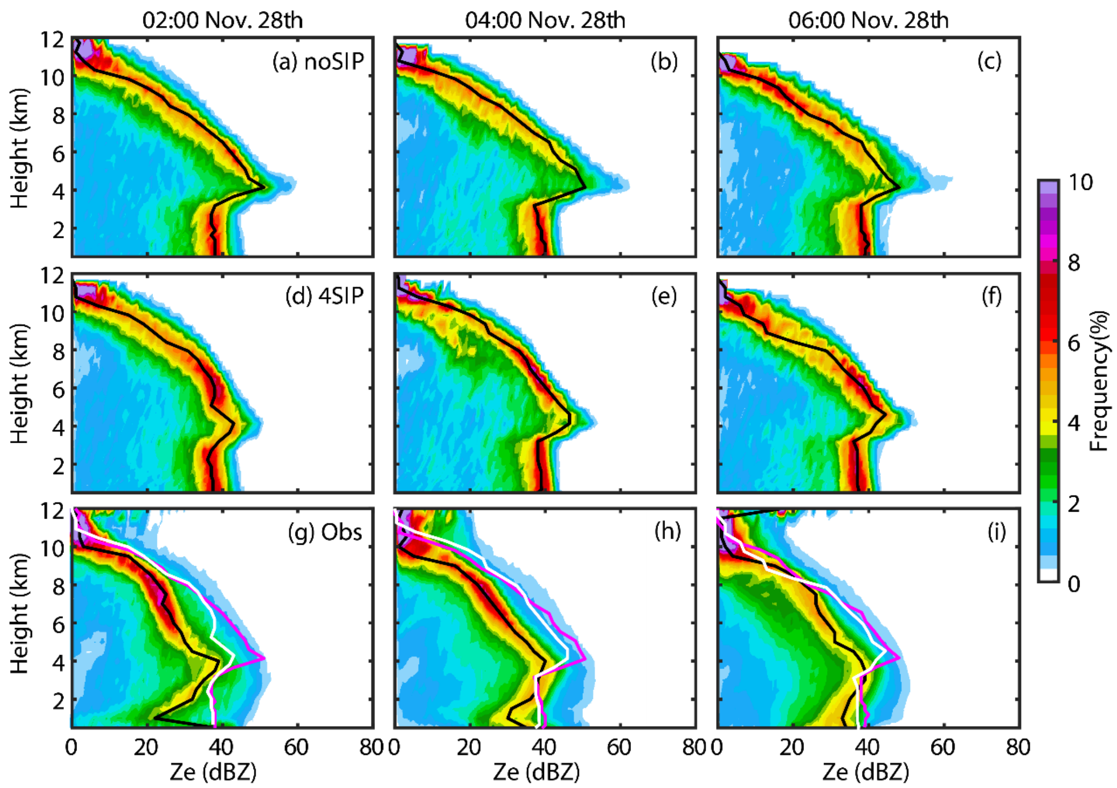

Figure R6. The contoured-frequency-by-altitude diagram (CFAD) of reflectivity from (a-c) noSIP, (d-f) 4SIP experiments and (g-i) radar observation. The black lines indicate the profiles of mean reflectivity, and the magenta and white lines in (g-i) are the mean reflectivity profiles from noSIP and 4SIP experiments.

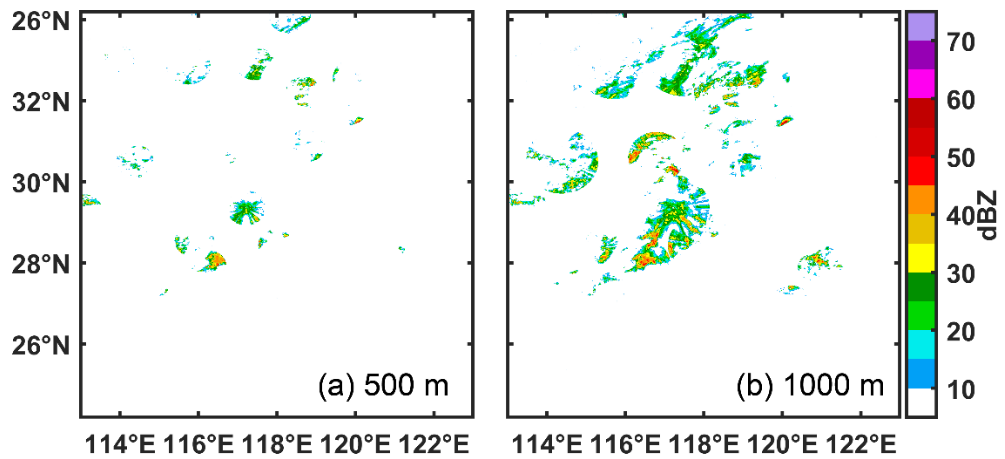

Figure R7. Observed radar reflectivity at 500m and 1000m a.m.s.l at 02:00, Nov. 28th.

8. Line 212: consider using a more suitable transition sentence, especially since the charge structure will not be discussed in Section 3.2.

Reply: Thank you for your comment. According to your suggestion, the transition sentence has been revised.

“The various SIP processes may have different impacts on the cloud microphysics.”

9. Line 218: Please clarify the meaning of “strong correlation” in this sentence.

Reply: Thank you for your comment. The temporal evolution of the rain mixing ratio is consistent with that of snow, suggesting the melting of snow contributes significantly to the rain. This sentence has been revised in the paper.

10. 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.

Reply: Thank you for your comment. A simple melting procedure is used in the Fast-SBM model, which means that all ice-phase particles simply melt into water. This process is not a complex process carried out by particles at certain scales, but rather a simple transformation of the mass of ice-phase particles to liquid particles. Therefore, it is not sensitive to environmental parameters. The production rate of rime process, aggregation process and sedimentation process are shown in Fig. R8. The rime process occurs mainly between -10°C and 0°C, and the aggregation process occurs mainly in colder regions. The production rate of rime process is greater than that of aggregation process.

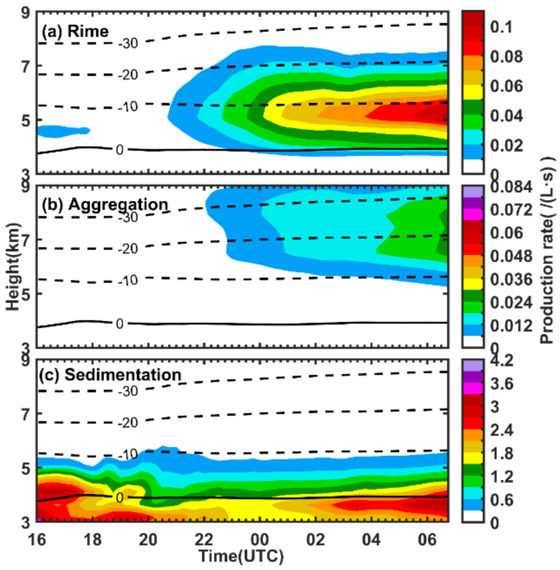

Figure R8: The production rate of (a) rime process, (b) aggregation process and (c) sedimentation process.

11. 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.

Reply: Thank you for your comment. The graupel mixing ratio is enhanced in the RS experiment compared to the noSIP experiment, indicating the secondary ice produced by rime-splintering enhances the riming in the cloud. This sentence is revised accordingly.

12. 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.

Reply: Thank you for your comment. The old Fig. 7 shows the domain average mixing ratio, which may be not suitable for investigation. Now we average the mixing ratio only in the cloud. According to the new results (Fig. R9), the rime-splintering and shattering of freezing drops enhance the graupel and snow mixing ratio. The ice-ice collisional breakup and snow breakup during sublimation enhance the ice/snow mixing ratio after 00:00, mainly above 6 km. We do see a decrease in LWC at temperatures colder than 0 °C after adding rime-splintering and shattering of freezing drops. In some areas below the melting level, the LWC may increase due to the enhanced snow concentration that fall from above. The enhanced snow concentration and mixing ratio by SIP does not provide stronger rain, due to their smaller sizes. This has been clarified in the paper.

13. 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.

Reply: Thank you for your comment. The isotherms have been superimposed in the figure in the revised paper.

14. 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.

Reply: The number concentrations shown in old Fig. 8 are the whole inner domain average value. In the revised paper, we average the concentration only in the cloud. We agree that PSDs can better show the shift of the PSDs towards smaller sizes. But unfortunately, since we use SBM, there are 132 3D variables in the PSDs of different hydrometeor species, this requires extensively more computer storage and much more cost for the data. For this reason, we only show the concentration and diameters.

15. 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.

Reply: Thank you for your comment. To provide better quantitative analysis, we plot the difference in mixing ratio and concentration between the simulation with SIP implemented and the noSIP simulation (Fig. R9 and R10). The graupel and ice/snow concentration are enhanced by rime splintering and shattering of freezing drops, mainly below 8km. The maximum increase, which exceeds 0.02 g/kg, is found between 00:00 and 04:00. If all four SIP processes work together, the ice/snow concentration is clearly higher than that without SIP. The rain concentration above the freezing level decreases due to the four SIP processes, suggesting a more significant cloud glaciation by SIP processes. These quantification results are added in the revised paper.

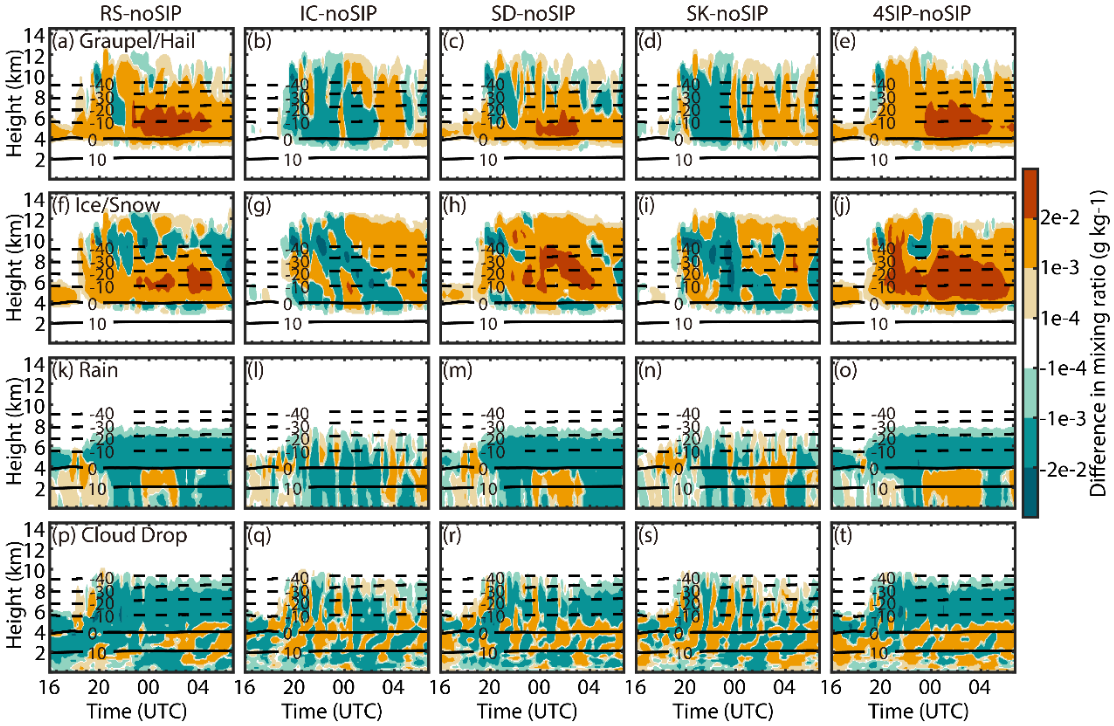

Figure R9: Differences in the mixing ratio of different hydrometeors between the experiments with SIP and that without SIP. (a, f, k, p) experiment with rime-splintering, (b, g, l, q), experiment with ice-ice collisional breakup (c, h, m, r) experiment with shattering of freezing drops, (d, i, n, s) experiment with ice breakup during sublimation, and (e, j, o, t) experiment with four SIP processes.

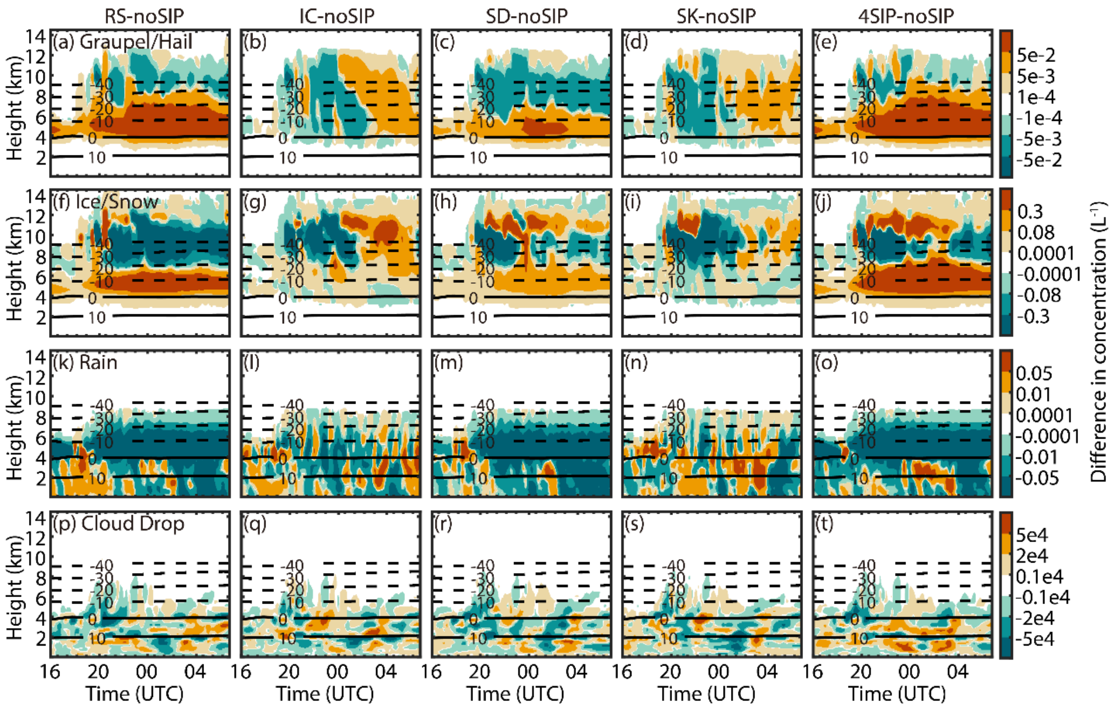

Figure R10: The same as Fig. R9, but for number concentration.

16. 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.

Reply: Thank you for your comment. The following discussion is added to the revised paper.

"*Different SIP processes have different impacts on the cloud microphysics electrification. The rime-splintering and shattering of freezing drops are active throughout the cloud life cycle but are limited to relatively warm temperatures. The cloud glaciation below 8 km is enhanced by these two processes, leading to lower LWC at higher levels. The low-level positive charging is significantly enhanced by them due to the higher graupel and ice/snow concentrations. The ice-ice collisional breakup is more active in regions with higher ice/snow mixing ratio, its average impact on cloud electrification is minor, while it could be significant in some areas in the cloud. The sublimational breakup of snow is more active near cloud edges or in downdrafts, and its average impact on cloud electrification is weak.*

Due to the scarcity of winter thunderstorms, there have been few modeling studies of it. Takahashi et al. (2019) studied the winter clouds in Hokuriku and found that lightning was generated in clouds with the following conditions: cloud top temperature less than -14℃, -10 ℃ isotherm is higher than 1.2 km, space charge greater than 2-3 pC/L, ice crystal concentration greater than 500 m^{-3}, and graupel concentration greater than 20 m^{-3}. According to the analysis above, the winter thundercloud studied in this paper satisfies all these characteristics. Takahashi et. al. (2017) pointed out that winter thunderstorm clouds have lower LWC and low cloud tops. In our simulation, the modeled LWC is typically lower than 1 g m^{-3}, which is lower than that reported in summer convections (e.g., Yang et al., 2016; Phillips et al. 2022). The lower LWC in wintertime convection indicates weaker riming, thus a lower riming accretion rate, which potentially leads to a higher possibility of inverted charge structure of thunderstorms (Wang et al. 2021)."

References:

Takahashi, T., Sugimoto, S., Kawano, T., and Suzuki, K.: Microphysical structure and lightning initiation in Hokuriku winter clouds. Journal of Geophysical Research:

Atmospheres, 124, 13,156–13,181, https://doi.org/10.1029/2018JD030227, 2019. https://doi.org/10.1016/j.atmosres.2015.05.006, 2015.

Takahashi, T., Sugimoto, S., Kawano, T., and Suzuki, K.: Riming Electrification in Hokuriku Winter Clouds and Comparison with Laboratory Observations. Journal of the Atmospheric Sciences, 74(2), 431–447, https://doi.org/10.1175/JAS-D-16-0154.1, 2017.

Yang, J., Wang, Z., Heymsfield, A., and Luo, T.: Liquid-ice mass partition in tropical maritime convective clouds. J. Atmos. Sci., 73, 4959-4978, doi: 10.1175/JAS-D-15-0145.1, 2016.

Wang, D., Zheng, D., Wu, T., and Takagi, N.: Winter Positive Cloud - to - Ground Lightning Flashes Observed by LMA in Japan. IEEJ Transactions on Electrical and Electronic Engineering, 16(3), 402–411, https://doi.org/10.1002/tee.23310, 2021.

17. Line 383-384: The transition sentence does not have a clear connection with the rest of the paragraph.

Reply: Thank you for your comment. We agree. In addition, this sentence is kind of repeating the rest of the paragraph. Therefore, it is removed in the revised paper.

18. 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).

Reply: Thank you for your comment. The sublimational breakup mechanism has been added in our model and its impact has been discussed in manuscript. All the related figures are updated. The results show the sublimational breakup of ice is more active near cloud edges or in downdrafts. On average, its impact on cloud electrification is weaker than the rime-splintering and shattering of freezing drops, but it could be significant in some areas.

Technical corrections:

• Line 124: I would suggest “grid spacing” instead of “resolution”

Reply: “resolution” is changed to “grid spacing”.

• Line 169: I would suggest “Model evaluation” instead of “Model validation”

Reply: “Model validation” is changed to “Model evaluation”.

• Line 156: “correct representation” (not representative)

Reply: “representative” is changed to “representation”.

• Line 228: “shown later”, consider indicating the section where the subsequent discussion will take place. Similarly, for Line 233.

Reply: Revised accordingly.

• Line 233: “reduced by SIP” (not by this SIP)

Reply: “reduced by this SIP” is changed to “reduced by SIP”.

• Line 257: Section 3.3 (not 3.2)

Reply: “Section 3.2” is changed to “Section 3.3”

• Line 361: Section 4 Discussion and Conclusions (not 5)

Reply: “Section 5” is changed to “Section 4”.

• Line 371: suggests (not suggest)

Reply: “suggest” is changed to “suggest”.

• Please double check the reference provided for Mansell et al. (2010)

Reply: The reference is revised to “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, 171–194, doi: 10.1175/2009JAS2965.1, 2010.”