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

General Comments:

Yang et al studied the role of three secondary ice production (SIP) mechanisms on cloud electrification in a simulated thunderstorm that was developed during the cold season. They implemented three major SIP mechanisms in the WRF model with fast SBM microphysics along with inductive and non-inductive charging mechanisms. Overall, the effect of SIP mechanisms on electrification is an important topic for the scientific community. However, in the current format, the paper needs major revision. Authors need to improve most of the sections including model validation, Analysis, implementation of SIPs, etc. I have enlisted specific and minor comments below.

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 the present study model validation is only based on spatial distribution radar reflectivity and temporal evolution flash rates. Since the study considers 3 major SIP processes, to what extent does the model agree with the observed number of concentrations of ice particles? How well does the model simulate the liquid water mass/content and vertical velocities? All these microphysical properties are of great importance for lightning. Comparison of some of these microphysical properties with the observation will be helpful for readers to understand the accuracy of the model. It will be good to compare the vertical distribution of radar reflectivity from the model with observations. If available, surface precipitation can be compared to show the robustness of model simulations.

Reply: We appreciate your comment, and we totally agree that comparing the modeled microphysics to observation is helpful for readers to understand the accuracy of the model. Unfortunately, we do not have any direct measurements of cloud microphysics (such as airborne measurements), and the surface station data is not publicly available. The radar has no dual-frequency products to retrieve microphysics. To better understand the performance of the model, we plot the contoured-frequency-by-altitude diagram (CFAD) of reflectivity, which can statistically show the difference in the frequency distribution of reflectivity at different heights between observation and model simulations. According to another reviewer's comments, a fourth secondary ice production mechanism by ice sublimational breakup has been added to our model (Deshmukh et al., 2022; Waman et al., 2022). The experiment with all four SIP processes included is named “4SIP”. As seen in Fig. R1, the maximum reflectivity is observed at about 4 km, which is the height of the melting levels. The modeled maximum reflectivity from the 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, but the 4SIP performs better than noSIP experiment. The observed reflectivity may be underestimated at low levels (Fig. R2) because the lowest elevation angle used in the radar measurement is 0.5 degree (please see more information on measurements in reply to comment 7) and the low-elevation beams are affected by ground clutters.

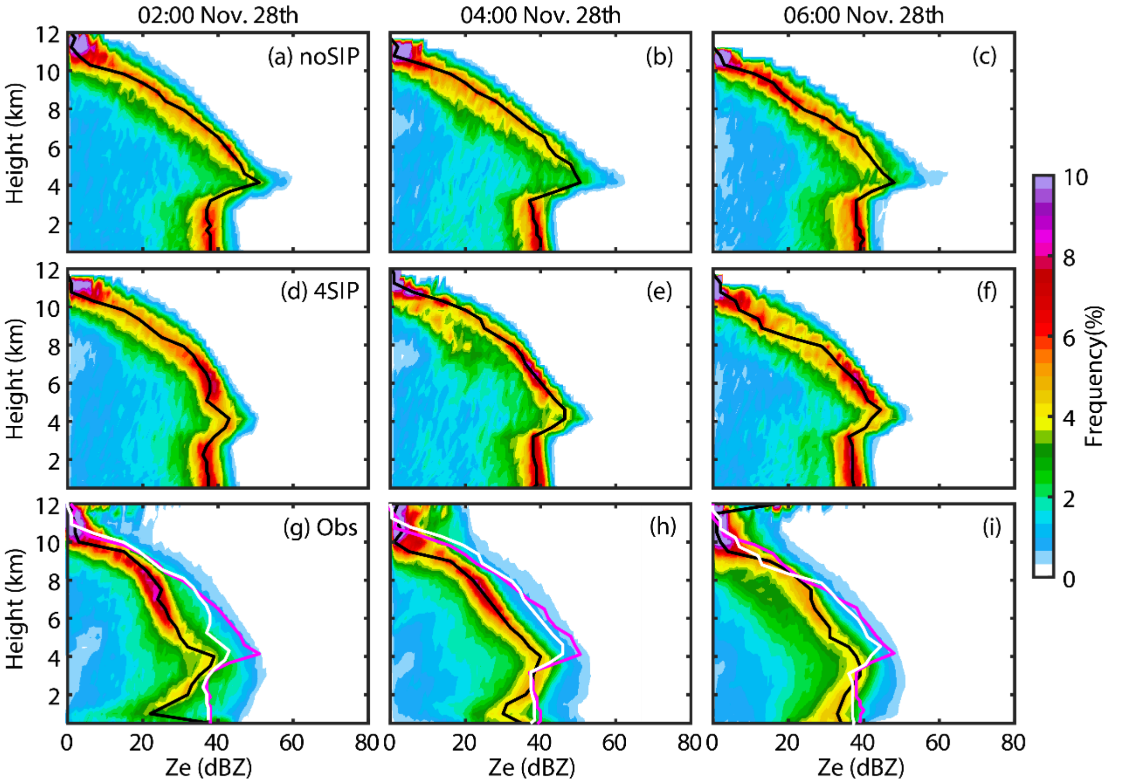

Figure R1. The contoured-frequency-by-altitude diagram (CFAD) of reflectivity from (a-c) noSIP, (d-f) 4SIP experiments and (g-i) radar observation. The black lines indicate the profiles of mean reflectivity, and the magenta and white lines in (g-i) are the mean reflectivity profiles from noSIP and 4SIP experiments.

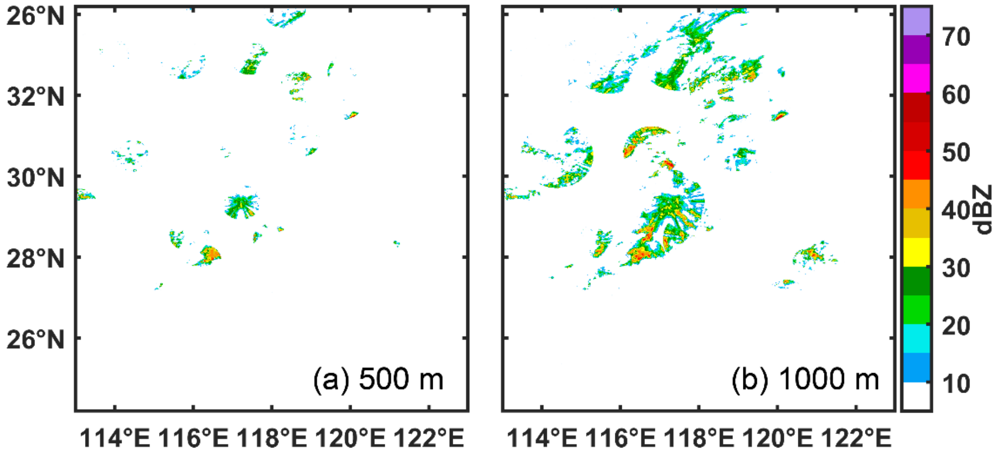

Figure R2. Observed radar reflectivity at (a) 500m and (b) 1000m a.m.s.l at 02:00, Nov. 28th.

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.

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.

2. Even with radar reflectivity plots, contour levels are different in observations and model, which makes it difficult to compare. To what extent does the simulated radar reflectivity is in agreement with observations when all SIP processes are active? It will be good to present some statistical analysis.

Reply: Thank you for your comment. The contour levels are revised, and the composite reflectivity of the model and observation are combined in one figure (Fig. R3). It is seen that the composite radar reflectivity in the 4SIP experiment is more consistent with observation. The statistical comparison can be seen in the CFAD of the radar reflectivity (Fig. R1), the noSIP overestimates the maximum reflectivity by about 7 dBZ, and this uncertainty is reduced after implementing the SIP processes. Both the noSIP and 4SIP experiments systematically overestimate the reflectivity, because the occurrence frequency of reflectivity that is greater than 30 dBZ is higher in the model.

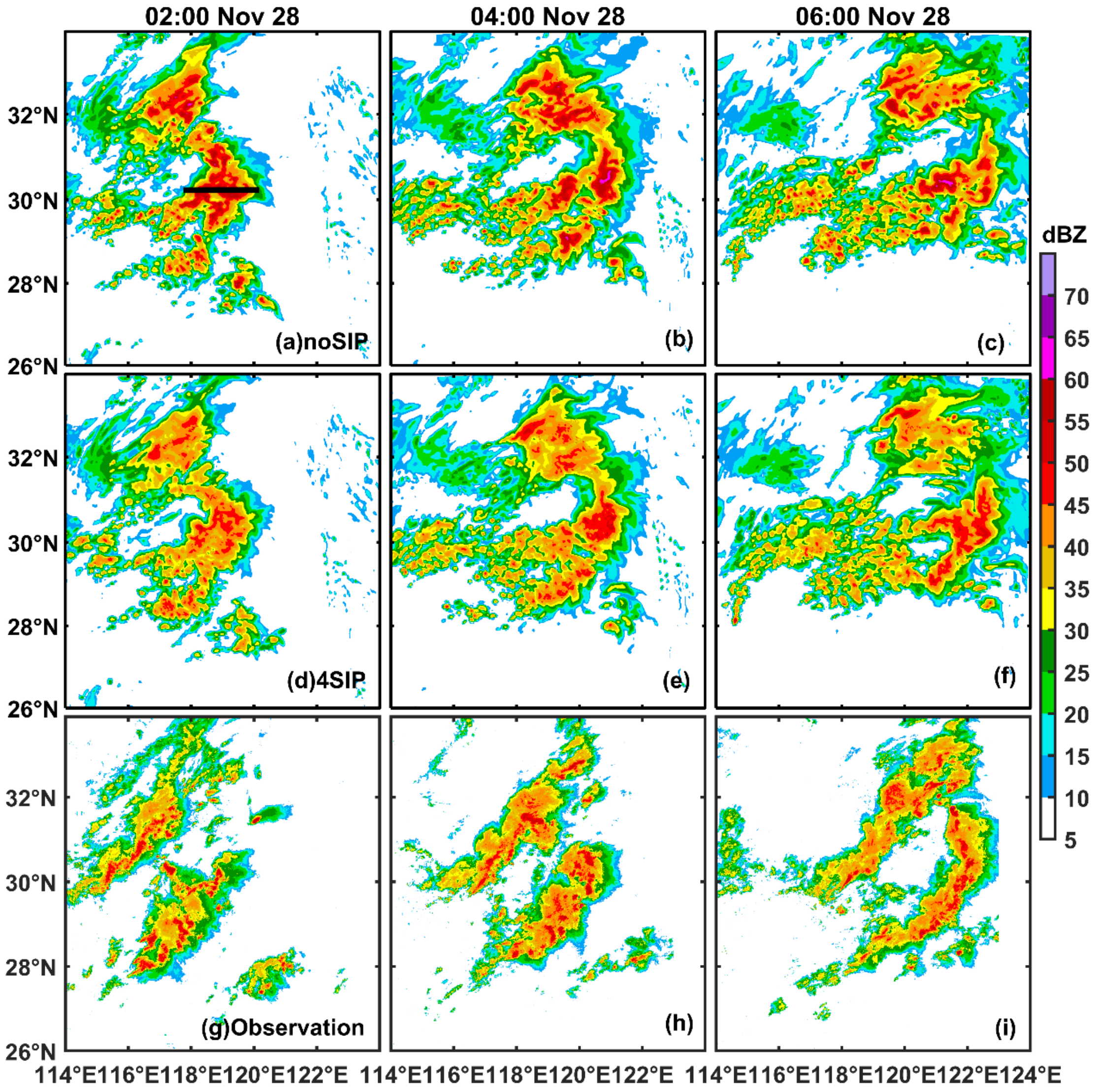

Figure R3. Composite radar reflectivity from (a-c) noSIP, (d-f) 4SIP experiment, and (g-i) observation at 02:00, 04:00, and 06:00, Nov 28th.

3. Based on my knowledge, in most of the previous studies, ice-ice collision is a major SIP mechanism in deep convective clouds when compared with rime-splintering and drop shattering (e.g. Phillips and Patade 2022). This is because rime-splintering and drop shattering are active over a limited range of temperatures. The authors need to mention the reasons behind less active ice ice collision in the simulated case. What are the factors that resulted in high secondary production by rime-splintering and drop shattering when compared with ice-ice collisions? What are the major differences in the microphysical processes of wintertime thunderstorms and summertime thunderstorms? There should be some discussion on the relative role of SIP in modulating ice number concentration and hence cloud electrification.

Reply: We appreciate your comment. The cloud electrification, in this case, is intensive around 00:00, when the graupel mixing ratio is high and the convection is deep (Fig. R4a). The enhancement of ice concentration by collisional breakup between ice crystals is mainly found after 01:00 when the ice/snow mixing ratio is high but the graupel mixing ratio is low (Fig. R5b and g). Cloud droplet concentration above the freezing level is also low after 01:00. Rime-splintering and drop shattering are active at relatively warm temperatures but throughout the entire life cycle. The relatively low graupel and droplet concentrations after 01:00 prevent the intensification of charge separation, this explains why collision between ice crystals has a weaker impact than rime-splintering and drop shattering on cloud electrification in this case. The ice-ice collisional breakup also enhances the ice concentration at temperatures warmer than -20 °C before 01:00, but the impact is weak due to the relatively low ice concentration in this period (Fig. R4g). Above -30 °C, the ice concentration is high but they are all small, thus the collisional breakup is insignificant. It is interesting to see that the ice concentration decreases in some areas (Fig. R5), in particular, the high-level ice concentration is reduced by more than 0.3 L^{-1} due to the rime-splintering and drop shattering, this is because the SIP enhances the cloud glaciation at low levels, and the cloud droplets that transport to higher levels for freezing are reduced.

Though the impact of the ice-ice collisional breakup is relatively weak on average, it does not mean this SIP process only has a minor impact everywhere. Figure R6 shows the cross sections (black line in Fig. R3a) of the mixing ratio, in which we can see that ice-ice collisional breakup clearly enhances the ice/snow mixing ratio, and the charge separation is also enhanced (Fig. R7).

The SIPs may have different impacts in different cases. Huang et al. (2022) analyzed the relative contribution of 3 SIP processes to ice generation using model simulations, they compared the modeled microphysics to airborne observation, and the results show shattering of freezing droplets dominates ice particle production at temperatures between −15 and 0 °C during the developing stage of convection, and ice–ice collisional breakup dominates at temperatures during the later stage of convection. Studies that investigate the impacts of different SIPs on cloud electrification are still limited. It will be interesting to see how changes in different environmental conditions (such as wind shear, cloud base height, and aerosol and INP concentrations) in different cases would influence the role of different SIPs. Based on this study, it is suggested that sufficient graupel is important for SIP processes to enhance cloud electrification. This discussion is added to the revised paper.

In many previous studies of summertime thunderstorms that occurred at a similar latitude (e.g., Caicedo et al., 2018; Shi et al., 2015), the main charging region is typically at 5-11 km a.m.s.l., and the freezing level is at about 5 km a.m.s.l, which are all about 1 km higher than the cold-season storm shown in this paper. Kitagawa and Michimoto (1994) found that wintertime thunderstorms generally have shorter periods of electrical activity and less frequent lightning than summer thunderstorms. In addition, they noted that the tropopause remains at 16 km in summer and drops to 10 km in winter, and the vertical extent of the atmospheric circulation is about half that of summer. This is the main factor that limits the convective activity of thunderstorm clouds in winter. Takahashi et. al. (2017) pointed out that winter thunderstorm clouds have lower liquid water content (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 occurrence of inverted charge structure of thunderstorms (Wang et al. 2021). This discussion is added to the revised paper.

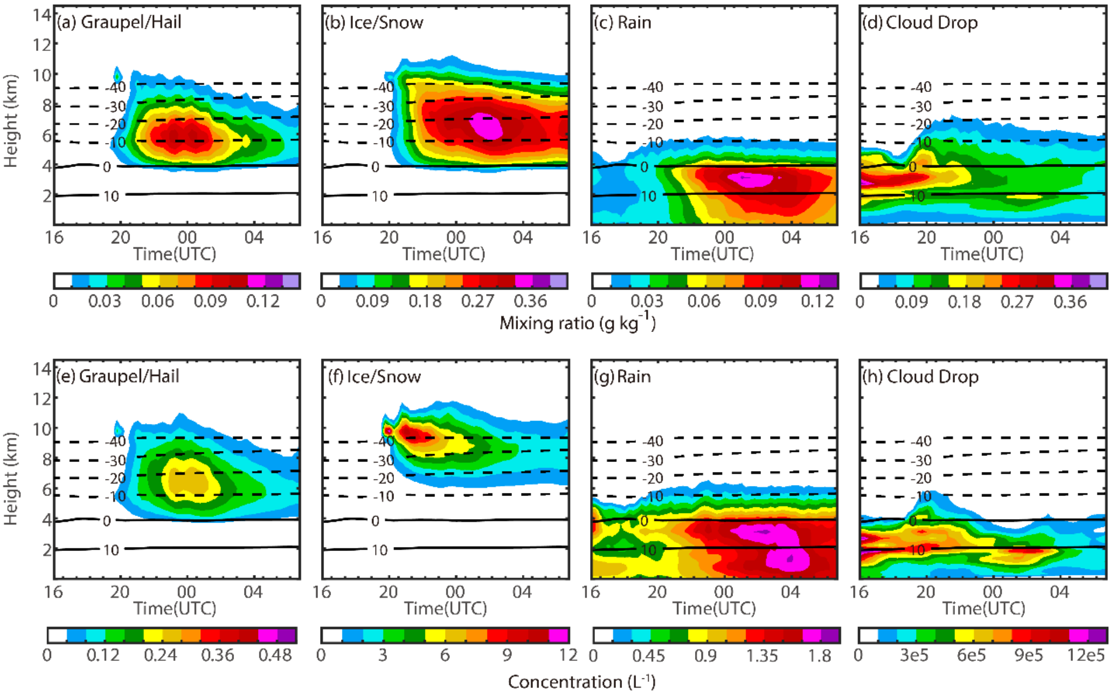

Figure R4. Temporal evolution of (a, e) graupel/hail, (b, f) ice/snow, (c, g) rain, and (d,

h) cloud drop mixing ratio and concentration in the noSIP experiment.

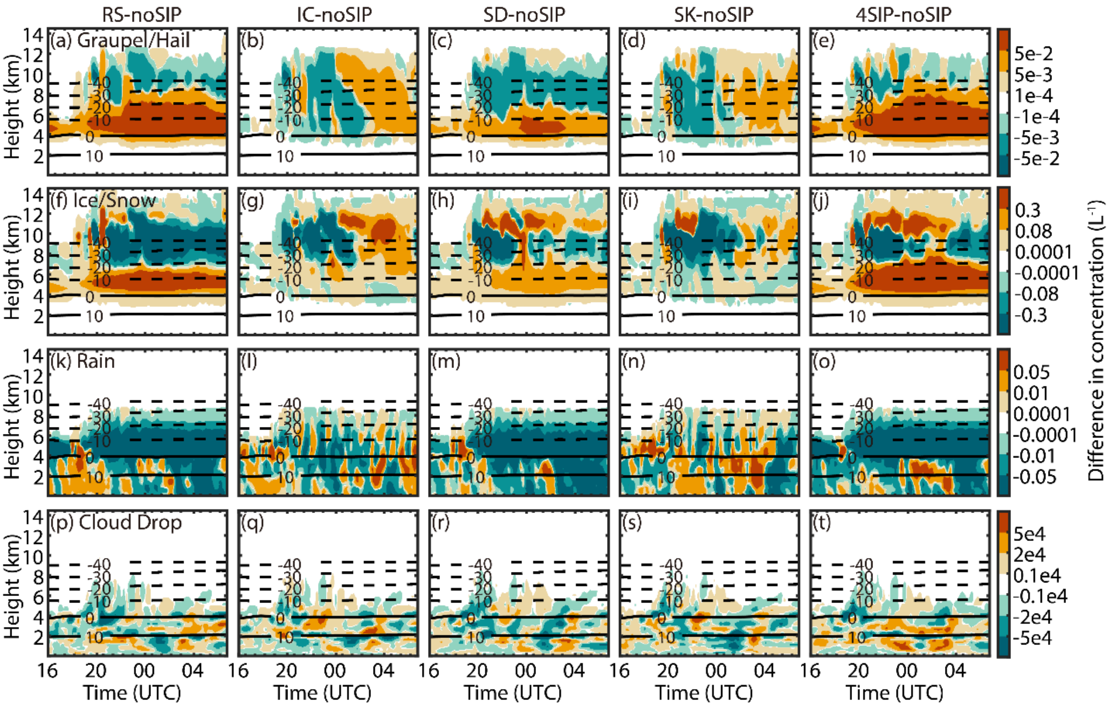

Figure R5. Differences in the number concentration of different hydrometeors between the experiments with SIP and those without SIP. (a, f, k, p) experiment with rime-splintering, (b, g, l, q), experiment with ice-ice collisional breakup (c, h, m, r) experiment with shattering of freezing drops, (d, i, n, s) experiment with ice breakup during sublimation, and (e, j, o, t) experiment with four SIP processes.

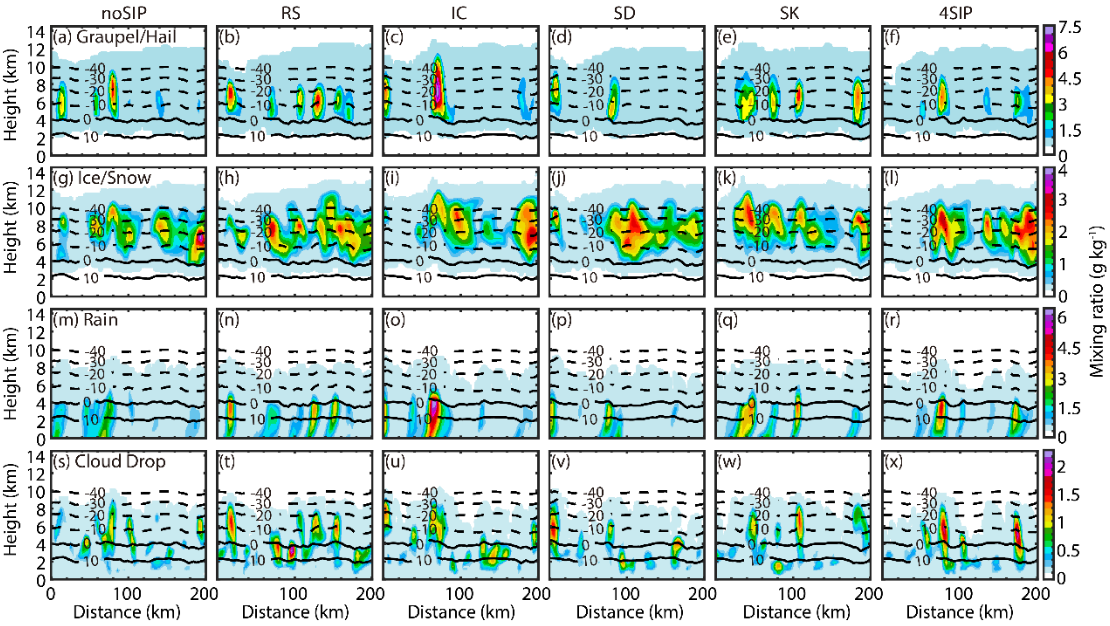

Figure R6: Cross sections of the modeled mixing ratio for (a)-(f) graupel/hail, (g)-(l) snow/ice, (m)-(r) rain and (s)-(x) cloud droplet at 01:00, Nov. 28th.

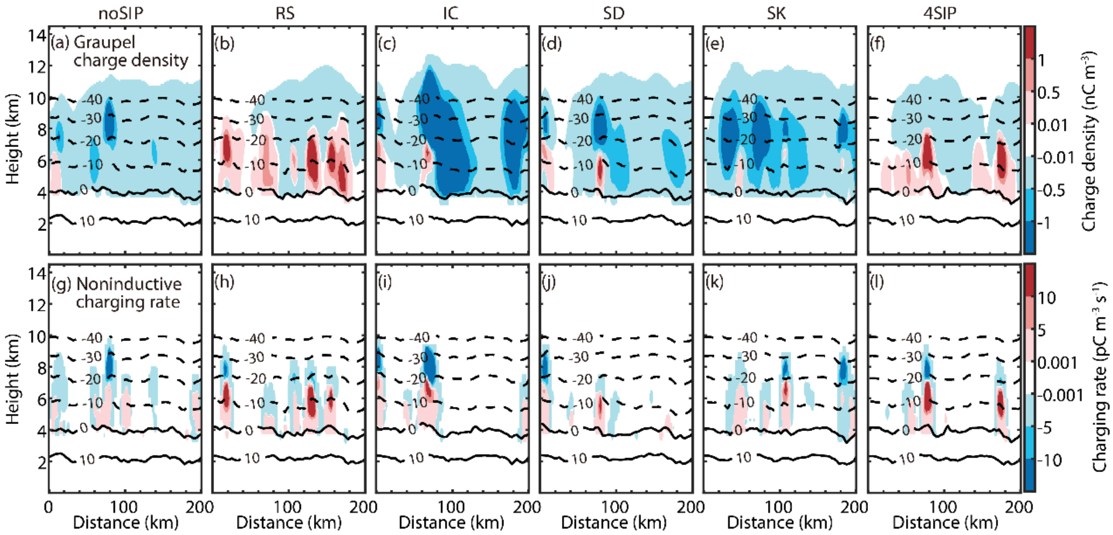

Figure R7: Cross sections of the modeled (a-f) graupel charge density and (g-l) noninductive charging rate at 01:00, Nov. 28th.

References:

Caicedo, J. A., Uman, M. A., and Pilkey, J. T. : Lightning Evolution In Two North Central Florida Summer Multicell Storms and Three Winter/Spring Frontal Storms. Journal of Geophysical Research: Atmospheres, 123(2), 1155–1178, https://doi.org/10.1002/2017JD026536, 2018.

Huang, Y., Wu, W., McFarquhar, G. M., Xue, M., Morrison, H., Milbrandt, J., Korolev, A. V., Hu, Y., Qu, Z., Wolde, M., Nguyen, C., Schwarzenboeck, A., and Heckman, I.: Microphysical processes producing high ice water contents (HIWCs) in tropical convective clouds during the HAIC-HIWC field campaign: Dominant role of secondary ice production. Atmospheric Chemistry and Physics, 22(4), 2365–2384, https://doi.org/10.5194/acp-22-2365-2022, 2022.

Kitagawa, N., and Michimoto, K.: Meteorological and electrical aspects of winter thunderclouds. Journal of Geophysical Research, 99(D5), 10713, https://doi.org/10.1029/94JD00288, 1994.

Phillips, V. T. J., and Patade, S.: Multiple Environmental Influences on the Lightning of Cold-Based Continental Convection. Part II: Sensitivity Tests for Its Charge Structure and Land–Ocean Contrast. Journal of the Atmospheric Sciences, 79(1), 263–300, https://doi.org/10.1175/JAS-D-20-0234.1, 2022.

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, 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.

4. It is important to show the rates of three SIP processes implemented in the model. Or at least the concentration of ice resulting from each SIP mechanism in 3SIP simulations can be shown. Time height evolution of ice particle number concentration from each of the SIP mechanisms will help to understand their relative importance in altering total ice number concentration. Authors have shown time height evolution of mass mixing ratios, however, changes in ice number concentration are very important as far as the role of SIP is concerned.

Reply: Thank you for your comment. The time height evolution of changes in ice number concentration is shown in Fig. R5. The ice production rate of the four SIP processes in the 4SIP experiment is better illustrated using cross sections, as the locations where secondary ice production is intense are different among the four processes. As seen in Fig. R8, the rime-splintering and drop shattering produce significant secondary ice in the core of clouds, where the graupel and rain mixing ratio are high, while the sublimational breakup of ice/snow is more intense near cloud edges or regions with relatively low reflectivity, probably because of the entrainment mixing and regional downdrafts. Ice-ice collisional breakup is more intense in regions with high ice/snow concentrations (Fig. R8b and R6l). The ice production rate by rime-splintering is the highest, and that by the sublimational ice breakup is the lowest, this substantial difference in the magnitude of the ice production rate is also true after averaging the entire cloud region, and it explains why the rime-splintering process has the most significant impact on the cloud microphysics.

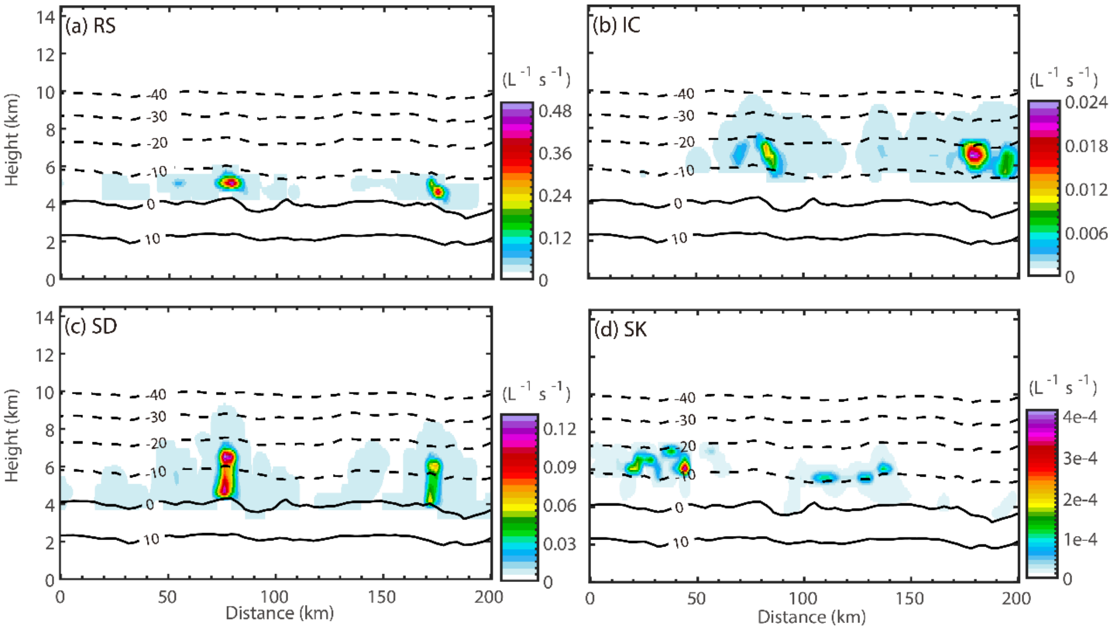

Figure R8: Cross section of the production rates of the secondary ice resulting from four SIP mechanisms. (a) experiment with rime-splintering (RS), (b) experiment with ice-ice collisional breakup (IC), (c) experiment with shattering of freezing drops (SD), (d) experiment with sublimational breakup (SK).

5. In Figure 8, temporal variation of ice/snow showed that there is not much effect of individual SIP process on ice/snow concentration, however when all SIPs were considered the concentration was boosted. What are the physical mechanisms behind it? I expect a significant increase in ice/snow concentration as a result of SIP in the simulations where a single SIP is considered if that mechanism is important.

Reply: Thank you for your comment. The original Fig. 8 was a display of averages over area and time, which lost some detailed information. Now we average only in cloud region. We can see that a single SIP process, especially by RS and SD, has clear influences on cloud microphysics (Fig. R5).

6. A few details of the implementation of SIP in the model are needed. What was the diameter of the tiny fragments that resulted from mode 1 in drop shattering? What kind of collisions were considered for collisional breakup mechanisms? In which category

the resulting fragments were added?

Reply: Thank you for your comment. Detailed information has been added in Appendix A of the manuscript. In our model, the tiny fragments are treated as the ice particles belonging to the first bin of the Fast-SBM scheme, which has a diameter of 4 micrometers (Khain et al., 2004). The collision between ice/snow and ice/snow has been considered in this paper. In this paper, except for the tiny fragments mentioned above, other fragments are added to the mass bins of the Fast-SBM scheme coinciding with their mass.

Reference:

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.

7. There is no information about the radar data e.g. which radar was used, what are the data corrections etc. Similarly, there is not much information available about lightning data.

Reply: We appreciate your comment. The following information is added to 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 are 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 and Southeast Asia. The lightning location algorithm 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 waveforms simulated using the Finite Difference Time-Domain (FDTD) technique. The lightning location error is 1-5 km (Li et al., 2022).*

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.

Reference:

Li, J.; Dai, B.; Zhou, J.; Zhang, J.; Zhang, Q.; Yang, J.; Wang, Y.; Gu, J.; Hou, W.; Zou, B, and Li, J.: Preliminary Application of Long-Range Lightning Location Network with Equivalent Propagation Velocity in China. Remote Sens. 14, 560, doi: 10.3390/rs14030560, 2022.

8. Line 378: if ice ice collision was less active what are the reasons behind the enhancement in the flash rate?

Reply: We appreciate your comment. In the original paper, the enhancement of flash rate by ice-ice collision is found between 22:00 Nov. 27th and 00:00 Nov. 28th. During this period, the graupel mixing ratio is enhanced (Fig. 7 in the original paper), and cloud electrification is enhanced by ice-ice collision (Fig. 12 in the original paper). In the revised paper, the parameters used in the ice-ice collisional breakup scheme are updated based on Gautam (2022). The result is different from the original one. As seen in Fig. R9, the flash rate has a similar magnitude in noSIP and IC experiments. In addition, as discussed in comment 3, ice-ice collisional breakup could be more important than the other SIP processes in some areas (Fig. R6 and R7). It is interesting to see such a significant difference in the original and updated IC experiments, suggesting it is important to use correct parameters in the scheme.

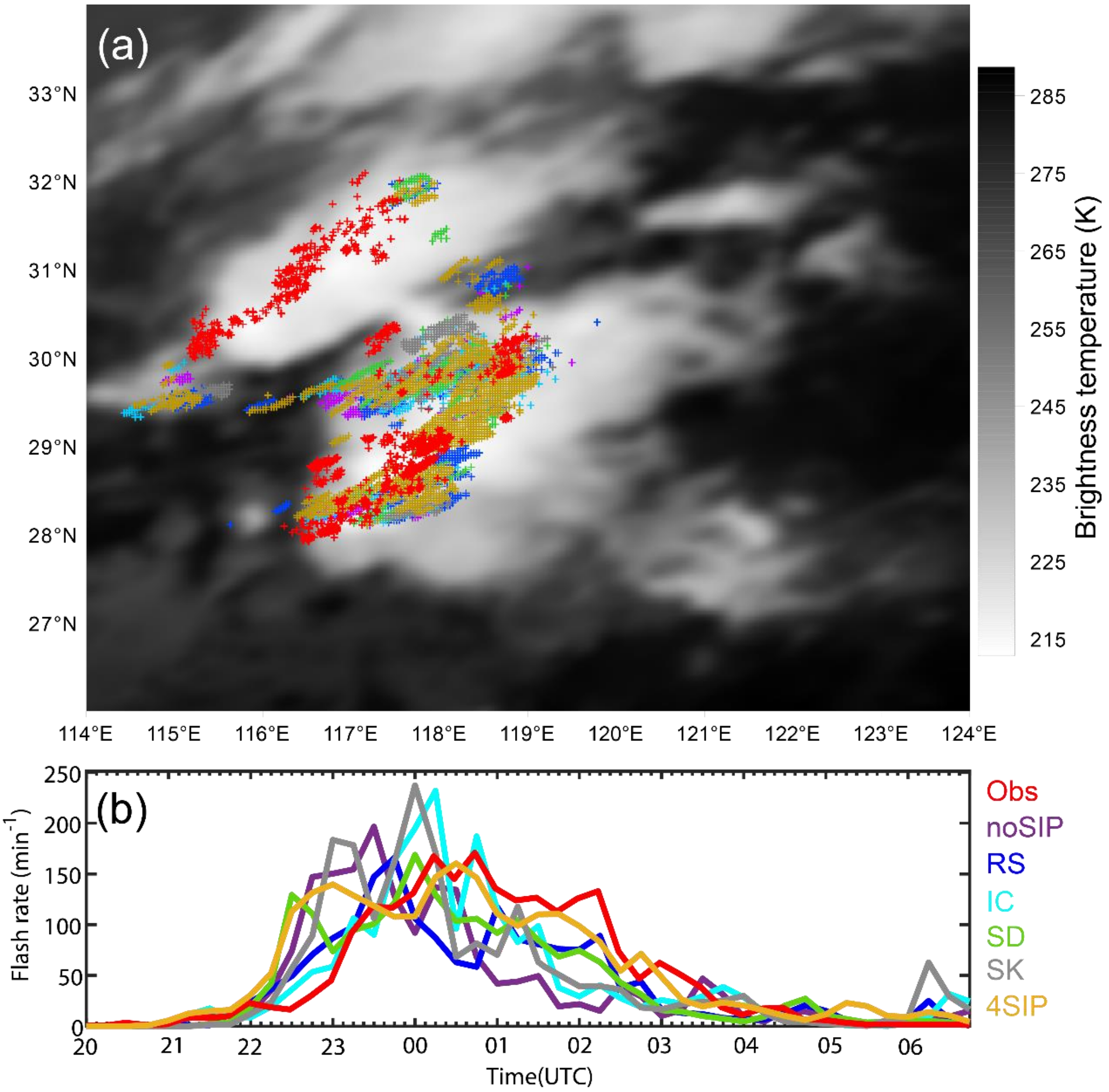

Figure R9. The (a) lightning location, and (b) time series of flash rate from observation and the six numerical experiments.

Reference:

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.

9. What are the mechanisms behind the improvement in the temporal distribution of flash rate in 3SIP simulations?

Reply: Thank you for your comment. According to Fig. R5, it is seen that the graupel mixing ratio (and concentration) is enhanced throughout the cloud life cycle, and the electric field is enhanced after 00:00, Nov 28th. Rime-splintering is the main mechanism that leads to the enhancement. This can be interpreted based on the equation of noninductive charging produced during the collision between graupel and ice crystal:

$$\frac{\partial \rho_{gi}}{\partial t} = \iint_0^\infty \frac{\pi}{4}\beta\delta q_{gi}\left(1-E_{gi}\right)\left|V_g - V_i\right|\left(D_g + D_i\right)^2 n_g n_i dD_g dD_i$$

Based on this equation, we can see the charge transfer is determined by three terms: 1) charge transferred during each collision between graupel and ice (δq_{gi}); 2) collision kernel between graupel and ice; 3) concentration of graupel and ice. δq_{gi} is determined by RAR, which is a function of liquid water content (LWC) and terminal velocity of graupel. With the addition of SIP, the LWC generally decreases (Fig. R5), and the diameters of ice particles decrease as well, leading to a decrease in RAR (Fig. R10), especially in RS and SD experiments. The collision kernel between graupel and ice is determined by the terminal velocity and size of graupel and ice, which also decreases after SIP processes are implemented. The concentration of graupel (n_g) and ice (n_i) increases due to the RS and SD processes, this explains the enhanced electrification by these two processes. Therefore, the higher graupel and ice concentration induced by RS and SD processes is the main reason resulting in the enhanced electric field, which leads to more flash rate after 00:00, Nov 28th.

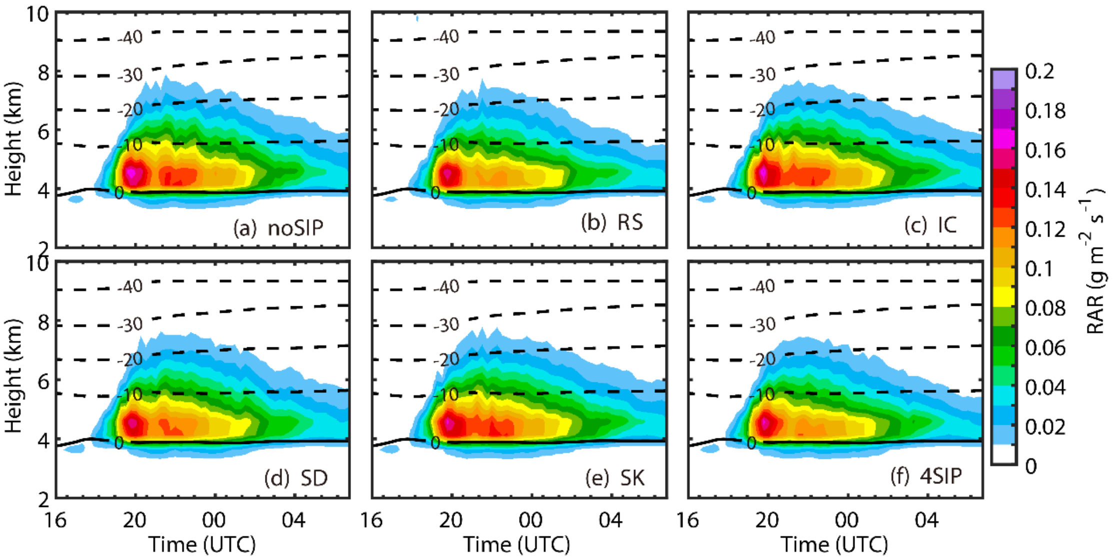

Figure R10: The time height averaged diagram of RAR. (a) experiment without SIP, (b) experiment with rime-splintering (RS), (c) experiment with ice-ice collisional breakup (IC), (d) experiment with shattering of freezing drops (SD), (e) experiment with sublimational breakup (SK) and (f) experiment with four SIP processes.

10. Authors should check the manuscript carefully for grammar and language corrections. In many places, articles are missing or not used properly.

Reply: We appreciate your comment and are sorry for the language errors. In the revised paper, we have carefully read through the manuscript and corrected grammatical errors.

Technical corrections/Minor comments:

1. What was the cloud base height and temperature of simulated clouds?

Reply: We do not have direct measurements of cloud base height. According to the sounding measurement and model simulation, the cloud base height and temperature are about 1 km and 12 °C.

2. Figure 1 captions: The time mentioned in the caption does not match that mentioned in the plots. Also, plots 1a and 1b are supposed to be 500 mb geopotential height, isotherms and wind barbs, but on plot b the mentioned height is 850 hpa. The same mistake is with plots c and d.

Reply: Thank you for your comment. This mistake has been corrected.

3. Figure 7: What are the averaging conditions for incloud points shown in time height plots?

Reply: We apologize for not explaining it clearly. The original figure in the manuscript shows the domain average time-height variation. In the revised paper, we only average the in-cloud area, which is identified using a total water mixing ratio (including all hydrometeors) greater than 10^{-6} g/kg.

4. Figure 7 captions: The names of sensitivity studies mentioned in the captions "SBM-0SIP Simulation; SBM-1SIP SimulationSBM-2SIP Simulation; SBM-3SIP" do not match the names on the plot. Please correct it according to the sensitivity tests mentioned in the text earlier.

Reply: Thank you for your comment and sorry for the mistake. It has been corrected in the revised paper.

Line 11: in a thunderstorm that occurred;

Reply: Thank you for your comment. This sentence is revised to "… in a thunderstorm that occurred …"

Line 11: are investigated …

Reply: Thank you for your comment. “is” is changed to “are”.

Line 40: correct lighting to lightning

Reply: Thank you for your comment. “lighting” is changed to “lightning”.

Line 55: Phillips et al. 2020

Reply: Thank you for your comment and sorry for the typo. It is corrected in the paper.

Line 67: studies that highlighted ….

Reply: Thank you for your comment, “that” is added in the sentence.

Line 95: warm moist ..

Reply: Thank you for your comment. “most” is changed to “moist”.

Line 111: Fig.3a not 2a

Reply: Thank you for your comment, and the figure number is corrected accordingly.

Line 113: Fig 3c not 2c

Reply: Thank you for your comment, and the figure number is corrected accordingly.

Line 124: Figure 4 not 3

Reply: Thank you for your comment, and the figure number is corrected accordingly.

Line 124: a two-way nested

Reply: Thank you for your comment, “a” is added before “two-way”.

Line 127: spin-up

Reply: Thank you for your comment. “spin up” is changed to “spin-up”.

Line 140: Incomplete sentence

Reply: Thank you for your comment. This sentence is changed to “At temperatures colder than -8 °C or warmer than -3 °C, the rime-splintering is inactive.”

Line 140: at temperatures colder than

Reply: Thank you for your comment. “temperature” is changed to “temperatures”.

Line 144: it can also be active …

Reply: Thank you for your comment. “be” is added in the sentence.

Line 204: change “With all the three SIP processes implement” to “With all implemented”

Reply: Thank you for your comment. “With all the three SIP processes implement” is changed to “With all implemented”.

Line 217: units should be g kg-1 and not g ks-1

Reply: Thank you for your comment. g ks^{-1} is changed to g kg^{-1}.

Line 232: there are …

Reply: Thank you for your comment. “there are” is changed to “there is”.

Line 235: graupel mixing ratio …

Reply: Thank you for your comment. “ratio” is added in the sentence.

Line 245: correct quicky to quickly

Reply: Thank you for your comment. “quicky” is changed to “quickly”.

Line 281: results in changes in the

Reply: Thank you for your comment. “result” is changed to “results”.

Line 318: delete the before that

Reply: Thank you for your comment. “the” is deleted.

Line 329: cross-section

Reply: Thank you for your comment. “cross section” is changed to “cross-section”.

Line 380: implemented

Reply: Thank you for your comment. “implemented” is revised.

Line 407: replace continued by continue

Reply: Thank you for your comment. “continued” is changed to “continue”.

Line 408: change falling to it falls

Reply: Thank you for your comment. “falling” is changed to “it falls”.

Line 414: change on to in

Reply: Thank you for your comment. “on” is changed to “in”.

Line 469: Define RAR and RARc

Reply: Thank you for your comment. RAR (riming accretion rate) and RARc (critical riming accretion rate) are defined in the revised paper.