Interactive comment on “Aerosol Effects on Electrification and Lightning Discharges in a Multicell Thunderstorm Simulated by the WRF-ELEC Model” by Mengyu Sun et al.

M. Sun et al.

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Reply to Referee 1

This work uses an advanced microphysical scheme coupled with a charging and discharge model to study the effect of pollution on microphysical and charging processes. The subject is of interest to readers of the Journal.

Yet, there is much work to be done to clarify the reasons for the differences between the continental and polluted case. I am also concerned that the results are not realistic in regard to how the cloud and rain water forms as the background conditions are changed. The authors offer explanations for why they do not, but they contradict themselves within the text.

I highlighted areas of text that were not grammatically correct or were unclear (in attachment). I also listed my comments here that are mentioned within bubbles in the attached text. Words are used describing results that require further explanation (e.g., what is a domain average? The authors stated that they did not use some of their results because they were not realistic). There is a lack of quantitative comparison. There are many highlighted areas and many comments.

I suggest the authors step back and ask themselves if the microphysical response to changes in aerosol concentration are consistent with other studies, including spectral (bin) microphysics studies, as well as observation!

They need to more clearly explain model simulation differences and add details where needed (see comments).

I do not see why Section 4.5 (Delay of First Flash) is its own section, coming well after the previous results that followed the storms through their different developmental phases.

Response:

We appreciate these valuable comments. We have studied them carefully and have addressed them in the revised manuscript. Below are the point-by-point responses to the reviewer’s comments.

120: No reference provided.

Response:

Thanks. We added citations as suggested: “**The special terrain condition with mountain in the northwest and ocean in the southeast (Qie et al., 2020), as well as heat island effect and elevated aerosol loading in the urban region (Zhang et al., 2013; Liu et al., 2018)…**” (Revised version, lines 122-125)

125: What is the context for stating "The maximum total lightning frequency even exceeded 1600 flashes (6 min)$^{-1}$ at the mature stage." How does the reader know this is a large number, considering system sensitivity varies from region to region.

Response:

Thanks for the reminder. We have revised the context to explain the intensity of this lightning activity and added references: “**The total lightning flashes of this case accounted for one-third of the total number of lightning flashes during the 2017 warm season (Chen et al., 2020).**” (Revised version, lines 129-130)

130: Where is the description of the model physics used, the domain grid spacing, etc? How long were the simulations run? How soon after the start of the simulations did the convection of interest occur?

Response:

Thanks for the comments. We have added the description of the model physics used in this study, as well as the related information of the simulations. (Revised version, lines 207-220)

135: Why are processes related to graupel growth the only ones mentioned? I was expecting to read more details about diffusional growth, interactions among particles, freezing, etc.

Response:

Thanks. We only previously mentioned graupel growth because that the predicted graupel density is variable. And that makes it possible for the single graupel category to represent a range of particles from high-density frozen drops to low-density graupel (Mansell et al., 2010). We have added more details of the two-moment bulk microphysics scheme. (Revised version, lines 137-149)

170: higher in the Beijing area than where else?

Response:

Thanks for this comment. We have added the hourly average mass concentration of $PM_{2.5}$ on 11 August 2017, and added related reference as follows: "**The hourly-average value of the observed $PM_{2.5}$ concentration before the thunderstorm initiation (more than 110 μg m^{-3}) is much higher than the 3-year mean $PM_{2.5}$ concentration (69.4±54.8 μg m^{-3}) in the Beijing area (Liu et al., 2018).**" (Revised version, lines 224-227, Figure 3)

180: should be: "should effectively delay..." There is no certainty here.

Response:

We agree to this suggestion and have corrected in the revised manuscript.

185: There are quite large differences in the simulated radar compared to the observed radar in terms of spatial coverage. The authors should say why, and explain why these large differences do not affect their results/conclusions. Also, can the authors hypothesize why the simulated stormed occurred 1.5 earlier than observed? This is quite a significant time difference.

Response:

These are good questions and comments. These comments contain 2 questions. We'll deal with them one by one.

(A) Regarding the differences in the simulated radar compared to the observation.

In order to explain these difference do not affect our results, we have made comparison of the radar reflectivity as a function of time, hourly peak rainfall rate, and the spatial distribution of precipitation between the observation and both simulations (revised version, Figure 5, 6, and 7). The comparisons show that the simulated distributions and spatio-temporal development of radar reflectivity and precipitation under polluted condition are in overall agreement with observations. In additional, we added related analysis in Part "**4.1 Radar reflectivity, precipitation and lightning flashes of multicell**" (revised version, lines 246-250; lines 255-273). With such information, the analysis of the physical processes is much appropriate for explaining the difference in the electrification and discharging in both simulated cases.

(B) Regarding why the simulated storm occurred 1.5 h earlier than the observation.

In our study, we use 3-hourly NCEP GFS data with resolution of 0.5 °×0.5 °and the WRF Processing System (WPS) to configure real-time simulations. The nesting technique from a domain with a resolution of 50 km×50 km to a domain with a resolution of 6 km ×6 km probably brings about instability of the simulations. Data assimilation was not applied to nudge the synoptic pattern toward the Global Forecast System (GFS) data. While assimilation of observational data can effectively improve the high-impact weather forecasting (Sun et al., 2014; Gustafssn et al., 2018). And the simulations began at 00:00 UTC on 11 August 2017, while the simulated thunderstorm formed at 09:18 UTC, which means the spin-up of the background aerosol is a little short (Lynn et al., 2020). These reasons probably result in the simulated stormed occurred 1.5 h earlier than observed. As mentioned above, we have made comparisons of radar reflectivity and precipitation, and the results show that the simulated distributions and spatio-temporal development of radar reflectivity and precipitation under polluted condition are in overall agreement with observations. These comparisons mean that the analysis of the physical processes is appropriate for explaining the difference in the electrification and discharging in both simulated cases. And we would improve our simulations in the future accordingly.

205: How is the variation of flashed in the P-Case better (more) consistent with the observation. No statistics are presented to prove this point.

Response:

Thanks for the comment. We have used predicted flash extent density (FED), as well as grid points (grids where the simulated electric field exceeds a breakdown threshold) to assess the lightning activity between both simulations and the observation (revised version, lines 185-188; lines 201-204). In addition, we have presented related analysis in Part "**4.1 Radar reflectivity, precipitation and lightning flashes of multicell**". (Revised version, lines 282-290)

240: In previous simulation studies, the authors note that more aerosols could be activated into cloud drops ... leading to larger cloud drop concentration. They claim that in this study no more cloud droplets could be created -- suggesting that the supply of moisture was limiting. However, this could be an artifact of the scheme, rather than physical reality. Moreover, in 255, the authors claim that warm rain process was delayed -- yet why should it be, since the cloud concentration (mass/) was just mentioned to be the same.

Response:

Thanks for the comment. This comment contain 2 questions. We'll deal with them one by one.

(A) Regarding the aerosols activated to cloud droplets.

In light of these comment, we have analyzed the radar reflectivity and precipitation (Figure 6, 7, revised version) at the beginning stage of the thunderstorm for the observation and both simulations. Since the observed radar reflectivity during 11:00-11:24 UTC is missing, so Figure R1 shows the radar echo before and after 11:15 UTC (09:45 UTC in simulations) for comparison. In the early stage of the thunderstorm, the radar echo for the P-case is relatively similar with these of the C-case. We realized that the area we chose in the initial stage was too small. The extra cell in figure 5j (initial version) probably because that the previous selected area did not include the cell in the C-case. Therefore, we have enlarged the region (shown in Figure 4d, revised version). The microphysics along with further electrification and lightning activities of this thunderstorm have been re-analyzed. With such improvements, we believe the analysis of the physical processes is much appropriate for explaining the difference in the electrification and discharging in both simulated cases. The results show that more aerosols could be activated into cloud droplets under polluted condition and more water vapor condenses onto these droplets. The related description has been modified in Part "**4.2 Microphysical properties of multicell**". (Revised version, lines 323-360)

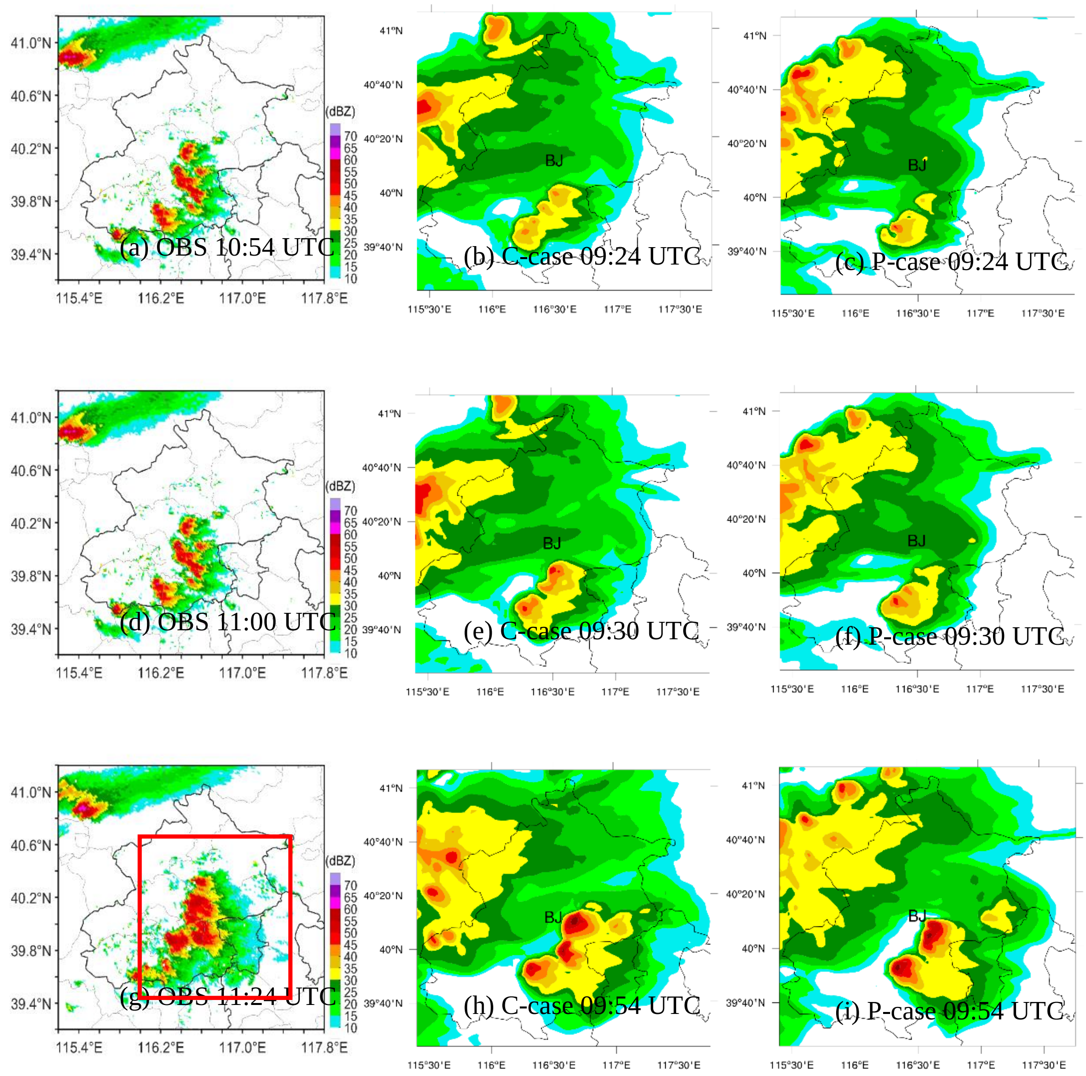

Figure R1 Radar reflectivity (unit: dBZ) between observation and simulation for the C- and P-cases, the simulation was earlier than observation about 1.5 h. (a), (d), (g) Observation at 10:54 UTC, 11:00 UTC and 11:24 UTC. (b), (e), (h) Simulation for the C-case at 09:24 UTC, 09:30 UTC and 09:54 UTC. (c), (f), (i) Simulation for the P-case at 09:24 UTC, 09:30 UTC and 09:54 UTC, respectively. The red rectangle in Fig. R2g denotes the region where the simulated results are analyzed in this study.

(B) Regarding the warm rain process.

We agree to the reviewer's comment. We have made the comparison of precipitation between the observation and both simulations (revised version, Figure 6, 7; lines 255-273), and found the warm rain processes was not delayed. We have deleted this sentence in the revised manuscript.

265: Moreover, latent heating profiles are similar in areas of cloud mass, again suggesting that warm processes were not delayed.

Response:

Thanks for the comment. Yes, the warm rain processes in this study were not delayed. And the temporal variation of the vertical profiles of peak latent heating has been added in Figure 12 (revised version) to make comparison of latent heat between both simulations during the whole duration of the thunderstorm. The latent heat shown in Figure 12 results from both condensation and freezing. In addition, related analysis has been added in Part "**4.2 Microphysical properties of multicell**". (Revised version, lines 327-329, 353-360)

260: Please add more up to date references.

Response:

Thanks for the suggestions and we have added related references as follows: "**Observations and simulations also found that the content of ice crystals could be greater under polluted condition, resulting from more condensation latent heat and strengthened updrafts (Khain et al., 2008; Koren et al., 2010; Wang et al., 2011; Zhao et al., 2015; Tan et al., 2017; Lynn et al., 2020).**" (Revised version, lines 341-344)

270: They state that the mass mixing ratio of graupel was relatively less in the P-case. This is contrary to the mentioned studies (more references could be added). They suggest that reduced raindrop freezing explains this, but previously mentioned that latent heating was the same. How can this be since latent heat is released from droplet condensation? Were the drop sizes smaller? Was there more snow?

Response:

Thanks for these questions. We will deal with them one by one.

(A) Regarding the latent heat.

For clarity, we have used the temporal variation of the vertical profiles of peak latent heating (Figure 12, revised version) to make comparison of latent heat between both simulations during the whole duration of the thunderstorm. The latent heat shown in Figure 12 results from both condensation and freezing. Related analysis have been modified in several parts, for example:

Lines 324-329: "**Under polluted condition, more aerosols could be activated into cloud droplets and more water vapor condenses onto these droplets, leading to large cloud water content and small droplet size (Lynn et al., 2007; Wang et al., 2011; Zhao et al., 2015; Jiang et al., 2017). Thereby, relatively more latent heat of condensation released in the P-case where large cloud water content exists, which can be seen in the vertical distribution of peak latent heat (Figure 12).**"

Lines 331-334: "**Under polluted condition, cloud droplets with smaller mean-mass radius are too small to be converted into raindrops. As a consequence, the rainwater mass mixing ratio is less in the polluted case compared to the continental one (Figure 10d).**"

Lines 371-373: "**In this study, the graupel content was higher in the C-case, probably owing to higher rainwater content and corresponding raindrop freezing.**"

(B) Regarding the drop size and snow contents.

We have added domain-averaged properties of different hydrometeors in Table 3 (revised version). The information of snow is shown in Table R1 and Figure R2. The size of raindrops in the P-case is larger, which is also be found in Wang et al. (2011), probably resulting from the melting of ice-phase particles. By collecting droplets and ice-phase particles, the aggregation of snow in the simulation is partially similar to the accretion of graupel (Zrnic et al., 1993; Ziegler et al., 1985). The snow content is also less in the P-case (Figure R2a, R2b), while there is no significant difference of domain-averaged mean-mass radius of snow between the P- (421.1 μm) and C-case (375.9 μm, Table R1). The single graupel category, which has variable density in the microphysical scheme, represents a spectrum of particles ranging from high-density frozen drops (or small hail) to low-density graupel (Mansell et al., 2010), therefore, could better represent mixed-phase processes. Since there is little difference of number concentration and mean-mass radius compared to the graupel and ice crystal, we would add these to the supplement if necessary.

Table R1. Domain-averaged Properties of Hydrometeors.

	Number Concentration (10^3 kg^{-1})		**Mean-mass Radius (μm)**	
	C-case	**P-case**	**C-case**	**P-case**
Cloud droplets	3930	7910	6.5	6.1
Rain drops	0.069	0.031	154.1	179.9
Ice Crystals	2280	3850	3235.8	2994.9
Graupel	0.028	0.012	322.4	479.5
Snow	4630	3880	375.9	421.2

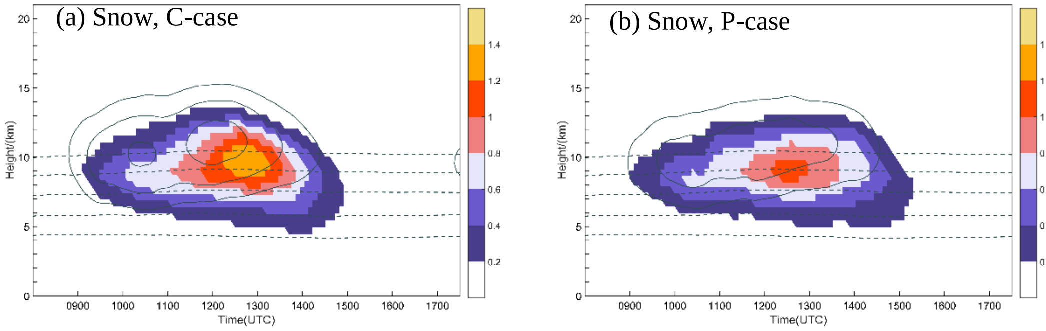

Figure R2 (a)-(b) Temporal variation of the vertical profiles of domain-averaged mass mixing ratio (g kg^{-1}, shaded) and number concentration (kg^{-1}, solid lines) of (a) snow in the C-case, (b) snow in the P-case. Contour levels in (a)-(b) for snow are 1.5×10^4, 3.0×10^4, 5.0×10^4 kg^{-1}. The 0 °C, -10 °C, -20 °C, -30 °C and -40 °C isotherms are shown by the dashed gray lines in (a)-(b).

280: The authors then note that the maximum amount of graupel in the mature stage is higher in P versus C, but don't explain why the results have changed.

280+ It is incorrect to claim that there are any appreciable differences in the dissipating stage, based on the numbers given.

Response:

Sorry for the ambiguity. The area we chose in the initial manuscript was too small, so the different stages could not be well matched in different cases. We have re-analyzed the microphysical processes after chosen a larger region (denoted in Figure 4d, revised version), so that the microphysical processes can be analyzed entirely. In the larger analyzed region, domain-averaged properties and related analysis of graupel have been added in Table 3 and Part “**4.2 Microphysical properties of multicell”** (revised version, lines 362-382).

295: The short paragraph is a conclusion, rather than a result.

Response:

Thanks for the reminder. We have rephrased this paragraph. (Revised version, lines 383-386)

305: How is dipolar charge structure more consistent with previous observations. Please tell the reader the difference between dipolar and simple dipoles/tripoles.

Response:

Thanks for this suggestion. We have added related references and the description of charge structure. (Revised version, lines 409-418)

310: negative charge region in which simulation?

Response:

Thanks for this reminder. We have clarified this sentence as follows: "**The negative charge region in the upper level (12-15 km) for the P-case resulted from collisions of graupel particles with smaller ice crystals and snow particles (Fig. 14d)**". (Revised version, lines 422-424)

320: Why do graupel and hail partices charge negatively?

Response:

Thanks for this comment. We have added related reference to explain as follows: "**According to Saunders and Peck (1998) non-inductive charging curve, graupel charges negatively within regions of relatively weak updrafts (< 5 m s^{-1}) and lower liquid water content (LWC), forming a negative charge region at 4-8 km in the P-case.**" (Revised version, lines 436-439)

340: Very hard to understand the sentence structure.

Response:

Sorry for the ambiguity. This sentence has been modified in the revised version, lines 452-454.

350: More recent references needed.

Response:

Thanks for this suggestion. We have added recent references as follows: "**Previous studies showed that larger vertical velocities were driven by increased microphysical latent heating. (Wang et al., 2011; Mansell and Ziegler, 2013;**

Altaratz et al., 2017; Fan et al., 2018; Li et al., 2019).” (Revised version, lines 335-337)

355:

"Considering that both cases have rather high CCN concentration, there would not be much difference between them in condensation." So, then what makes them difference. (By the way, I am not sure I believe this; more information is needed comparing mass, not just concentrations -- but we're still left with the question of why?).

Response:

Thanks for this question. For clarity, we have used the temporal variation of the vertical profiles of peak latent heating (Figure 12, revised version) to make comparison of latent heat between both simulations during the whole duration of the thunderstorm. The latent heat shown in Figure 12 results from both condensation and freezing. For the condensation latent heat, we modified the related analysis in Part “**4.2 Microphysical properties of multicell”,** for example:

Lines 323-329: “**Under polluted condition, more aerosols could be activated into cloud droplets and more water vapor condenses onto these droplets, leading to large cloud water content and small droplet size (Lynn et al., 2007; Wang et al., 2011; Zhao et al., 2015; Jiang et al., 2017). Thereby, relatively more latent heat of condensation released in the P-case where large cloud water content exists, which can be seen in the vertical distribution of peak latent heat (Figure 12).**”

For the frozen latent heat, the related analysis has been added as follows: “**the maximum of peak latent heat in the P-case occurs above 10 km at 09:30 UTC (Figure 12), indicating that more cloud droplets are lifted to the upper levels (< -40 °C) and converted into ice crystals at the beginning stage of the thunderstorm. … The high value of latent heat existed in the higher levels (above 10 km) reveals a large amount release of frozen latent heat. Previous studies also**

found that elevated aerosol loading contributed to the increasing frozen latent heat (e.g., Khain et al., 2005; Lynn et al. 2007; Storer et al., 2010; Li et al., 2017)."(Revised version, lines 349-357)

365: Section 4.5: Why is it a separate section and not integrated within the text?
370: "In the meanwhile" refers to when?
390: What simulation becomes much larger at 9:30 UTC?

Response:

Thanks for the comment. As mentioned before, we re-analyzed the microphysics along with further electrification and lightning activities of this thunderstorm, in the region denoted in Figure 4d. The re-analyzed results still suggest that under polluted condition lightning activity is significantly enhanced, while the delay of the first discharging in the C-case is not obvious. And we would delete this part in the revised version.

405: Please discuss what are the microphysical processes effected.

Response:

Thanks for the comment. The discussion of microphysical processes have been added. (Revised version, lines 471-480)

415: Is that heat of fusion rather than latent heat?

Response:

Thanks for this question. The latent heat shown in Figure 12 (revised version) results from both condensation and freezing.

425: The paragraph beginning with "Compared to C-case" has a contradiction.

Shouldn’t ice and graupel grow more quickly due to coalescence? You just pointed out that “it was not noted.”

Response:

Thanks for this comment. As mentioned before, we re-analyzed the microphysics along with further electrification and lightning activities of this thunderstorm, in the region denoted in Figure 4d. The re-analyzed results still suggest that under polluted condition lightning activity is significantly enhanced, while the delay of the first discharging in the C-case is not obvious. And we would delete related description in the revised version.

675: Figure 5: How are these vertical profiles calculated -- over what volume?

Response:

Thanks for this question. We have clarified as follows: “**Figure 10a-10h show the temporal variations of the vertical profiles for different hydrometeors. For each quantity, the mass mixing ratio and number concentration of hydrometeors are averaged horizontally over the analyzed region at a given altitude.**” (Revised version, lines 312-315).

685: Please better define "domain" in the figure caption of Figure 6.

Response:

Thanks for reminder. We have defined “domain” as “**the impacts of aerosol on lightning activity will only be evaluated in the southeastern Beijing area (39.4 °N-40.6 °N, 116.0 °E-117.5 °E, shown in Fig. 4d; here on, 'domain' for short)**” (revised version, lines 252-254) and denoted in the Figure 4d (revised version).

695/705: Figure 7 and 8: the word "main" is not clearly defined. Might differences also be shown?

Response:

Thanks for reminder. We have clarified in Figure 14 and 15 as: “**simulated variables**” (revised version).

710: What is "the location shown in Fig. 2?"

Response:

Thanks for reminder. We have clarified in Figure 16 (revised version).

References

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