Response to Referee #1

General comments:

This manuscript investigated the effect of electric charges and atmospheric electric fields on the size distribution of cloud droplets numerically. The authors concluded that electric charges and fields enhance the collision efficiency of small droplets. My main concern of the manuscript is the novelty. As far as I understand, the manuscript does not specify clearly how different the study is from the one of Khain et al, 2004. The novelty should be stated clearly in the abstract and conclusion as well as in the introduction. Especially, the introduction needs to be improved substantially. This manuscript can be improved if the authors can summarize the open questions in previous studies and address them in their study. By such a treatment, the authors can place their contribution in a more general context. Overall, this manuscript does not satisfy the novelty requirement of the ACP journal. Major revision is needed before it can be considered for publication.

Response:

We thank the reviewer for pointing out that the novelty of this study should be more addressed in the manuscript. The Introduction of the manuscript is now completely rewritten. Now the Introduction summarizes the previous work on cloud electrification, the physical mechanism of the electrostatic induction, the effect of electrostatic induction on droplet collision efficiency, and the subsequent effect on precipitation formation. Now the rewritten Introduction is shown below in red fonts. The other parts of the manuscript has also been substantially revised, but not shown here.

This study is motivated as the aerosol-cloud interaction study regarding climate change has been widely carried out. It has been confirmed by both observational studies and modeling studies that increased aerosols can result in more numerous but smaller droplets, hence slower collision-coalescence process, and suppressed warm-rain precipitation process. Since cloud electrification has been found for both thunderstorms and warm clouds, and electrification can increase the possibility of collision-coalescence, as described in the revised Introduction of this manuscript, it is worthy of investigating whether the electrostatic effects can mitigate the aerosol effects. This kind of study has not been performed. Previous studies of electrostatic effect such as Khain et al. (2004) focuses on weather modification, including rain enhancement and fog elimination. Here we are interested in finding out to what extent the electrostatic effect can mitigate the aerosol effect.

To investigate the electrostatic effect vs. aerosol effect on droplet collision-coalescence, we purposely choose an initial droplet size distribution function based on Bott (1998), i.e., Equation 13 in the original manuscript. This distribution function has two parameters: liquid water content and averaged size of droplets. We set the liquid water content as constant (1 g m^{-3}) and vary the averaged size of droplets in the initial size distribution ($\bar{r}$ = 15, 9, and 6.5 μm) to represent the effect of aerosols on cloud microphysics. These settings give an initial droplet number concentration of 70, 325, and 850 cm^{-3}, respectively. As suggested by Reviewer #3, description of droplet number concentration is added to the manuscript. The electrostatic effect is then investigated for the three cases.

Here is a simple example to compare the electrostatic effect vs. the aerosol effect: When there is no electric charge and field, the case with initial $\bar{r}$ = 15 μm can develop a significant second peak in the size distribution through collision-coalescence in less than 30 min, while it takes about 60 min for the $\bar{r}$ = 9 μm case to develop a similar second peak. This represents an aerosol effect. When considering the electric charge and field effects, it only takes about 45 min for the $\bar{r}$ = 9 μm case to develop a similar second peak (as can be seen in Figs. 7 and 8 in the original manuscript). The aerosol-induced precipitation suppression effect is mitigated by the electrostatic effects. We emphasize on this issue in various places in the revised manuscript.

The Introduction now reads as:

1. Introduction

Clouds are usually electrified (Pruppacher and Klett 1997). For thunderstorms, several theories of electrification have been proposed in the past decades. The proposed theories assume that the electrification involves the collision of graupel or hailstones with ice crystals or supercooled cloud droplets, based on radar observational result that the onset of strong electrification follows the formation of graupel or hailstones within the cloud (Wallace and Hobbs, 2006). However, the exact conditions and mechanisms are still under debate. One charging process could be due to the thermoelectric effect between the rimed and relatively warm graupel or hailstones with the relatively cold ice crystals or supercooled cloud droplets. Another charging process could be due to the polarization of particles by the downward atmospheric electric field. The thunderstorm electrification can increase the electric fields to several thousand V cm^{-1}, while the magnitude of electric fields in fair weather air is only about 1 V cm^{-1} (Pruppacher and Klett 1997). Droplet charges can reach $|q| \approx 42r^2$ in unit of elementary charge in thunderstorms, with the droplet radius r in unit of μm according to observations (Takahashi, 1973).

Liquid stratified clouds do not have such strong charge generation as in the thunderstorms. But charging of droplets can indeed occur at the upper and lower cloud boundaries as the fair weather current passes through the clouds (Harrison et al. 2015, Baumgaertner et al. 2014). The global fair weather current and the electric field are in the downward direction. Given the electric potential of 250 kV for the ionosphere, the exact value of fair weather current density over a location depends on the electric resistance of the atmospheric column, but its typical value is about 2×10^{-12} A m^{-2} (Baumgaertner et al. 2014). The fair weather electric field is typically about 1 V cm^{-1} in the cloud-free air, but is usually much stronger inside stratus clouds, because the cloudy air has a lower electrical conductivity than the cloud-free air. There is a conductivity transition at cloud boundaries. Therefore, the cloud top is positively charged and the cloud base is negatively charged. Based on the in situ measurements of charge density in liquid stratified cloud, and assuming that the cloud has a droplet number concentration on the order of 100 cm^{-3}, it is estimated that the mean charge per droplet is +5e (ranging from +1e to +8e) at cloud top, and -6e (ranging from -1e to -16e) at cloud base. Other studies found different amount of charges in clouds. According to Tsutomu Takahashi (1973) and Khain (1997), the mean absolute charge of droplets in warm clouds is around $|q| \approx 6.6\, r^{1.3}$ (with units of e and μm for q and r, respectively). For a droplet with radii of 10 μm, it is about 131 e.

In general, charging of droplets can lead to the following effects on warm cloud microphysics. Firstly, for charged haze droplets, the charges can lower the saturation vapor pressure over the droplets and enhance the cloud droplet activation (Harrison and Carslaw, 2003, Harrison et al. 2015). Secondly, the electrostatic induction effect between charged droplets can lead to strong attraction at very small distance (Davis, 1964) and therefore higher collision-coalescence efficiencies (Beard et al. 2002). But Harrison et al. (2015) showed that charging is more likely to affect collision processes than activation, for small droplets.

The electrostatic induction effect can be explained by regarding the charged cloud droplets as spherical conductors. The electrostatic force between two conductors is different from the well-known Coulomb force between two point charges. When the distance between a pair of charged droplets approaches infinity, the electrostatic force converges to Coulomb force between two point charges. But when the distance of surfaces of two droplets is small (e.g. much smaller than their radii), their interaction shows extremely strong attraction. Even when the pair of droplets carry the same sign of charges, the electrostatic force can still changes from repulsion to attraction at small distance. Although there is no explicit analytical expression such as Coulomb force for the electrostatic interaction between two charged droplets, a model with high accuracy has been developed for the interaction of charged droplets in an uniform electric field (Davis 1964). Many different approximate methods are also proposed for the convenience of computation in cloud physics (e.g. Khain et al., 2004).

Based on this induction concept, electrostatic effects on droplet collision-coalescence process have been studied in the past decades. A few experiments show that electric charges and fields can enhance coalescence between droplets. Beard et. al. (2002) conducted experiments in cloud chambers and showed that even minimal electric charge can significantly increase the probability of coalescence when the two droplets collide. Eow et. al., (2001) examined several different electrostatic effects in water-in-oil emulsion, indicating that electric field can enhance coalescence by several mechanisms such as film drainage.

More numerical researches indicate that electric charges and fields can increase droplet collision efficiencies because of the electrostatic forces. Schlamp et al. (1976) used the model of Davis (1964) to study the effect of electric charges and atmospheric electric fields on collision efficiencies. They demonstrated that the collision efficiencies between small droplets (about 1~10 μm) are enhanced by an order of magnitude in thunderstorm condition, while collision between large droplets is hardly affected. Harrison et al. (2015) investigated the electrostatic effects in weakly electrified liquid clouds rather than thunderstorms. They calculated collision efficiencies between droplets with radii less than 20 μm and charge less than 50 e, with the equations of motion in Klimin (1994). Their results indicate that electric charges at the upper and lower boundaries of warm stratified clouds are sufficient to enhance collisions, and the enhancement is especially significant for small droplets. Moreover, they proposed that solar influences may change the fair weather current and droplet collision process, a possible pathway for affecting the climate system. Tinsley (2006) and Zhou (2009) also studied the collision efficiencies between charged droplets and aerosol particles in weakly electrified clouds, by treating the particles as conducting spheres. They considered many aerosol effects such as thermophoretic forces, diffusophoretic forces and Brownian diffusion.

As for the electrostatic effect on the evolution of droplet size distributon and the cloud system, few researches have been conducted. Focusing on weather modification, Khain et al. (2004) showed that a small fraction of highly charged particles could trigger the collision process, and thus accelerate raindrop formation in warm clouds or lead to fog elimination significantly. In their study, the electrostatic force between the droplet pair is represented by an approximate formula. The charge limit is set to the air-breakdown limit. The Stokes Flow is adopted to represent the hydrodynamic interaction, for deriving the trajectories of a pair of droplets. Harrison et. al. (2015) calculated droplet collision efficiencies affected by electric charges in warm clouds. But when simulating the evolution of droplet size distribution, the enhanced collision efficiencies are not used in this study. Instead, the collection cross sections are multiplied by a factor of no more than 120% to approximately represent the electric enhancement of collision efficiency. The roles of electric charges and fields on precipitation acceleration still needs to be studied.

The increased aerosol loading by anthropogenic activities can lead to an increase in cloud droplet number concentration, a reduction in droplet size, and therefore an increase in cloud albedo (Twomey 1974). This imposes a cooling effect on climate. It is further recognized that the aerosol-induced reduction in droplet size can slow down droplet collision-coalescence and cause precipitation suppression. This leads to increased cloud fraction and liquid water amount, and imposes an additional cooling effect on climate (Albrecht 1989). As the charging of cloud droplets can enhance droplet collision-coalescence, especially for small droplets, it is worth studying to what extent the charge effect can mitigate the aerosol effect on the evolution of droplet size distribution and precipitation.

This study investigates the effect of electric charges and fields on droplet collision efficiency and the evolution of the droplet size distribution. The amount of charges are set as the condition in warm clouds, and the electric fields are set as the early stage of thunderstorms. The more accurate method for calculating the electric forces is adopted (Davis, 1964). Correction of flow field for large Reynolds numbers are also considered. Section 2 describes the theory of droplet collision and stochastic collection equation. Section 3 and 4 present these numerical methods. Different initial droplet size distributions and different electric conditions are considered. Section 5 shows the numerical results of electrostatic effects on collision efficiency, and on the evolution of droplet size distribution. We intend to find out to what extent the electric charges and fields as in the observed atmospheric conditions can accelerate warm rain process, and how sensitive these electrostatic effects are to aerosol-induced changes of droplet sizes.

New references:

Eow, J.S., Ghadiri, M., Sharif, A. O., Williams, TJ.: Electrostatic enhancement of coalescence of water droplets in oil: a review of the current understanding, Chem. Eng. J., 84, 173–192, doi:10.1016/S1385-8947(00)00386-7, 2001

Tsutomu Takahashi: Measurement of electric charge of cloud droplets, drizzle, and raindrops, Reviews of Geophysics and Space Physics,11, 903-924, 1973

Harrison, R. G., Nicoll, K. A., Ambaum, M. H. P.: On the microphysical effects of observed cloud edge charging, Q. J. R. Meteorol. Soc., 141, 2690–2699, doi:10.1002/qj.2554, 2015

Beard, K. V., Durkee, R. I., Ochs, H. T.: Coalescence efficiency measurements for minimally charged cloud drops, J. Atmos. Sci., 59, 233–243., doi: 10.1175/1520-0469(2002)059<0233:CEMFMC>2.0.CO;2, 2002

Baumgaertner, A. J. G., Lucas, G. M., Thayer, J. P., Mallios, S. A.: On the role of clouds in the fair weather part of the global electric circuit, Atmos. Chem. Phys., 14, 8599–8610, doi:10.5194/acp-14-8599-2014, 2014

Harrison, R. G., Carslaw, K. S.: Ion-Aerosol-Cloud Processes in the Lower Atmosphere, Rev. Geophys., 41(3), doi:10.1029/2002RG000114, 2003

Wallace, J. M., Hobbs, P. V.: Atmospheric Science, Second Edition, Academic Press, 2006

Tinsley, B. A., Zhou, L., Plemmons, A.: Changes in scavenging of particles by droplets due to weak electrification in clouds, Atmos. Res., 79, 266 – 295, doi:10.1016/j.atmosres.2005.06.004, 2006

Zhou, L., Tinsley, B. A., Plemmons, A.: Scavenging in weakly electrified saturated and subsaturated clouds, treating aerosol particles and droplets as conducting spheres, J. Geophys. R., 114, D18201, doi:10.1029/2008JD011527, 2009

Klimin, N. N., Rivkind, V. Ya., Pachin, V. A.: Collision efficiency calculation model as a software tool for microphysics of electrified clouds, Meteorol. Atmos. Phys, 53, 111-120, doi:10.1007/BF01031908, 1994

Twomey, S.: Pollution and the planetary albedo, Atmos. Environ., 8, 1251-1256. doi:10.1016/0004-6981(74)90004-3, 1974

Main Comments

1. The authors concluded that electric charges and fields enhance the collision efficiency of small droplets. Is this new in the cloud physics field? If so, how different this study is compared with the one of Khain et al, 2004? Which open question does this manuscript address? The third paragraph (starting from Line 35) of the introduction part summarized the work of Khain et al, 2004, but didn't bring up the open question in Khain et al, 2004.

Response:

Thanks to the reviewer for asking these questions. It is not new that the electric charges and fields enhance collision efficiency of small droplets. Studies of Khain et al. (2004) and Harrison et al. (2015) already had this finding. In our study, we intend to compare the precipitation suppression effect due to increased aerosols and the electrostatic enhancement effect. We have revised the manuscript to emphasize on this issue.

Regarding the difference between our study and Khain et al. (2004), the two studies are different in many aspects. Firstly, Khain et al. (2004) focuses on justifying cloudy seeding via artificial charging process, for use in weather modification, while our study investigates to what extent the electrostatic effect mitigates the aerosol effect on the evolution of droplet size distribution. Secondly, the amount of electric charges on cloud droplets are extremely large in their study, and natural clouds probably do not meet that condition. In our study, however, the amount of electric charges and fields used in our study represent conditions in natural clouds such as warm clouds or the early stage of thunderstorms. Thirdly, simplified models are used for the electric force between charged droplets and for describing droplet motion in Khain et al. (2004). Our study uses more accurate models for electric force and droplet motions. Our study finds that electric charges and fields can accelerate precipitation under conditions in the real atmosphere and that the aerosol-induced precipitation suppression can be mitigated.

Reference：

Harrison, R. G., Carslaw, K. S.: Ion-Aerosol-Cloud Processes in the Lower Atmosphere, Rev. Geophys., 41(3), doi:10.1029/2002RG000114, 2003

2. The main conclusion of the manuscript is that electric charges and electric fields enhance the collision efficiency of small droplets pairs. The evolution of droplet size distribution with different initial radius is shown in Fig.7, 8, 10. To compare the evolution for different initial radii, I would suggest the authors to plot the size distributions in one plot at a single snapshot, i.e., plot r/r_0 at x-axis and n(x, t=15 min) of different r_0 at y-axis in one plot. This can help clearly demonstrate the conclusion.

Response:

We tried to plot droplet size distributions as suggested by the reviewer. The figures are shown below. The main problem is that collision-coalescence is significantly slowed down in the smaller r_0 cases. Therefore the time (t_0) required for a second peak to form in the size distribution is quite different for different r_0. For the three cases in this study, the time t_0 is about 30, 60 and 120 min, respectively. We use a normalized time, namely t/t_0, for 5 snapshots. Because both the radius and the time are normalized, information shown in the figures are not very straight forward. Therefore we prefer that Figures 7, 8 and 10 remain unchanged.

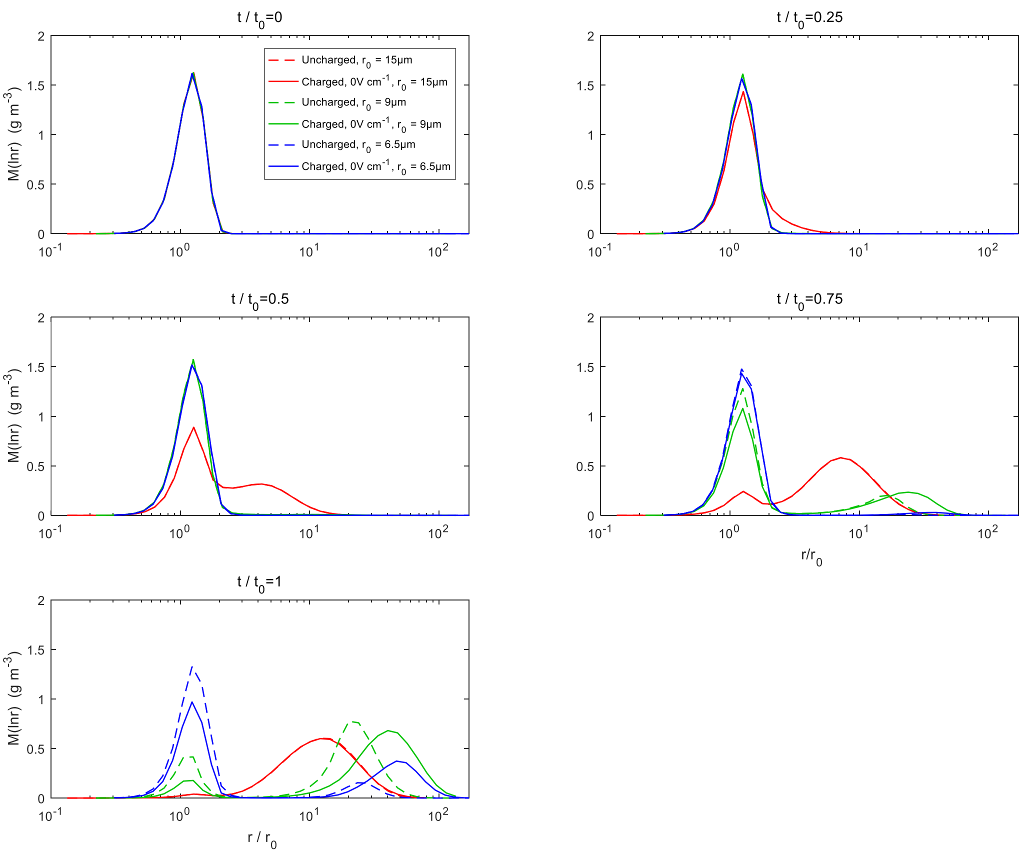

Figure 1. The evolution of normalized droplet size distributions. X-axis denotes the normalized droplet size r/r_0, where r_0=15, 9 and 6.5 μm separately. Different panels show different snapshots, i.e., at different normalized time t/t_0, where t_0=30, 60 and 120 min separately. Comparisons are made between uncharged droplets and charged droplets without electric fields.

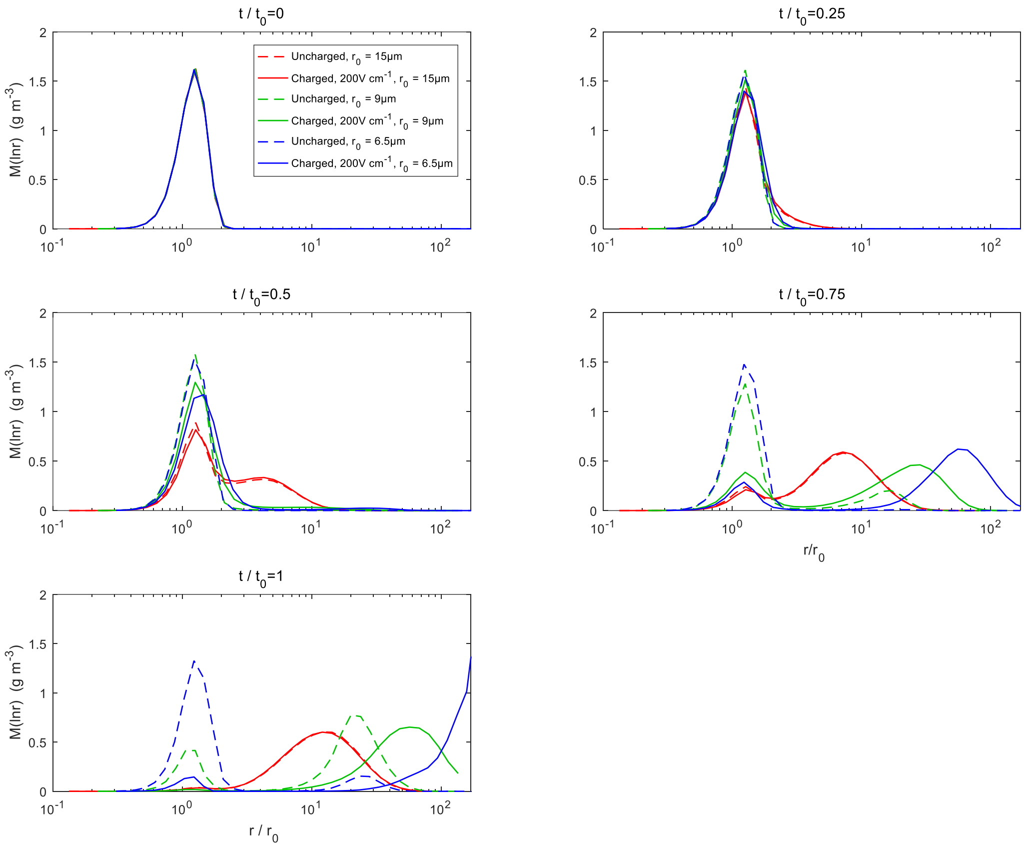

Figure 2. The evolution of normalized droplet size distributions. Comparisons are made between uncharged droplets and charged droplets with an electric field of 200 V cm^{-1}.

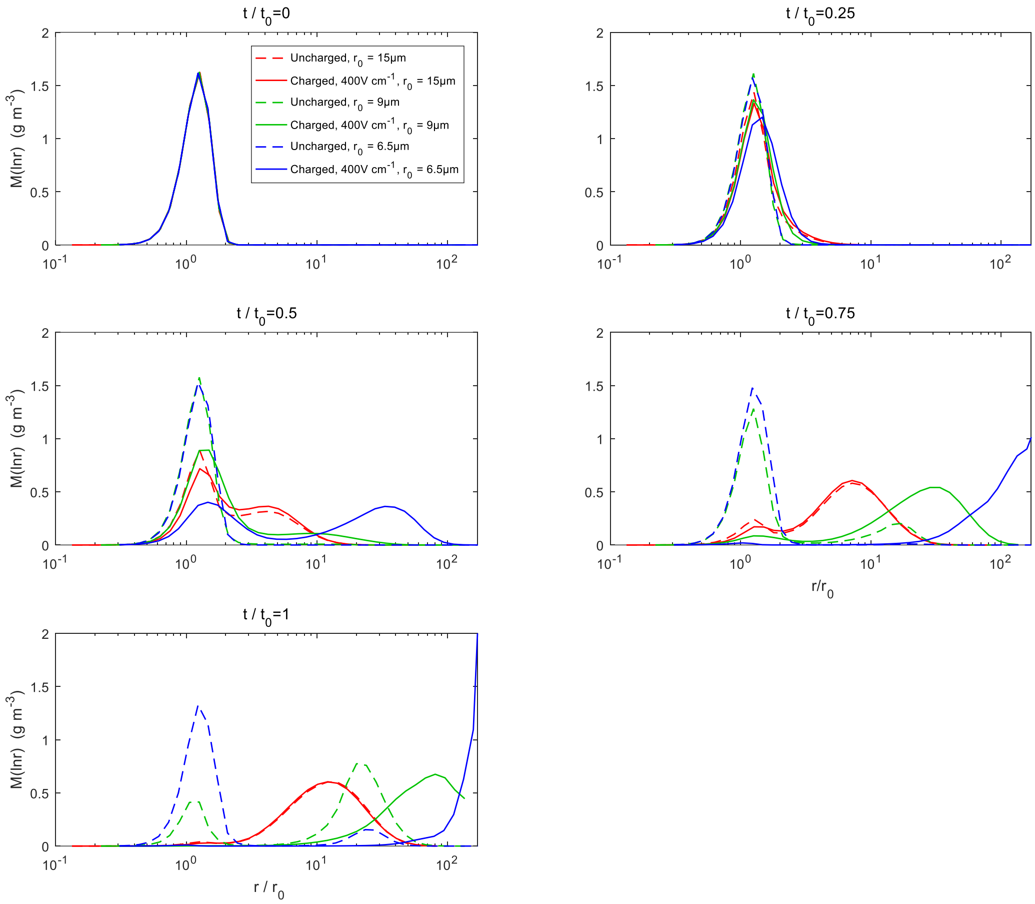

Figure 3. The evolution of normalized droplet size distributions. Comparisons are made between uncharged droplets and charged droplets with an electric field of 400 V cm^{-1}.

3. The authors mentioned the Navier-Stokes (NS) equation just above Eq.5. if you consider the backreaction from droplets to the flow, you can add the backreaction term to the NS equation. I don't see immediately why solving the N-S equation numerically with a low Reynolds number is difficult in this study.

Response:

We now realized that the sentence where N-S equation are mentioned is very misleading. In the revised manuscript, we have deleted this sentence in line 103 "Considering a sphere moving in a viscous fluid, the exact solution of the induced flow velocity field is to solve the Navier-Stokes equations. But the computation is too complicated in this study."

Solving the N-S equation is not difficult. However, the computation burden for the problem in this study would be heavy. With 37 size bins and 15 charge bins, the number of collision efficiency is on the order of 37×37×15×15. For each collision efficiency, about 10^4 steps are needed, including using the bisection method. It takes several days of computer time to derive all the collision efficiencies using the current method. Solving the N-S equation would be a much heavier computation burden.

4. How can I see from the terminal velocity curve in Fig.11 that the 5-um size droplet turns upwards?

Response:

Thanks for pointing this out. In Fig.11 of the original manuscript, y-axis is in logarithmic scale and stands for the absolute value of terminal velocity. Negative terminal velocity means upward motion. However, minus is not compatible with the logarithmic coordinate. We therefore plotted the absolute value of terminal velocity in Fig.11.

In the revised manuscript, we plot the negative terminal velocity in a separate panel, as shown below.

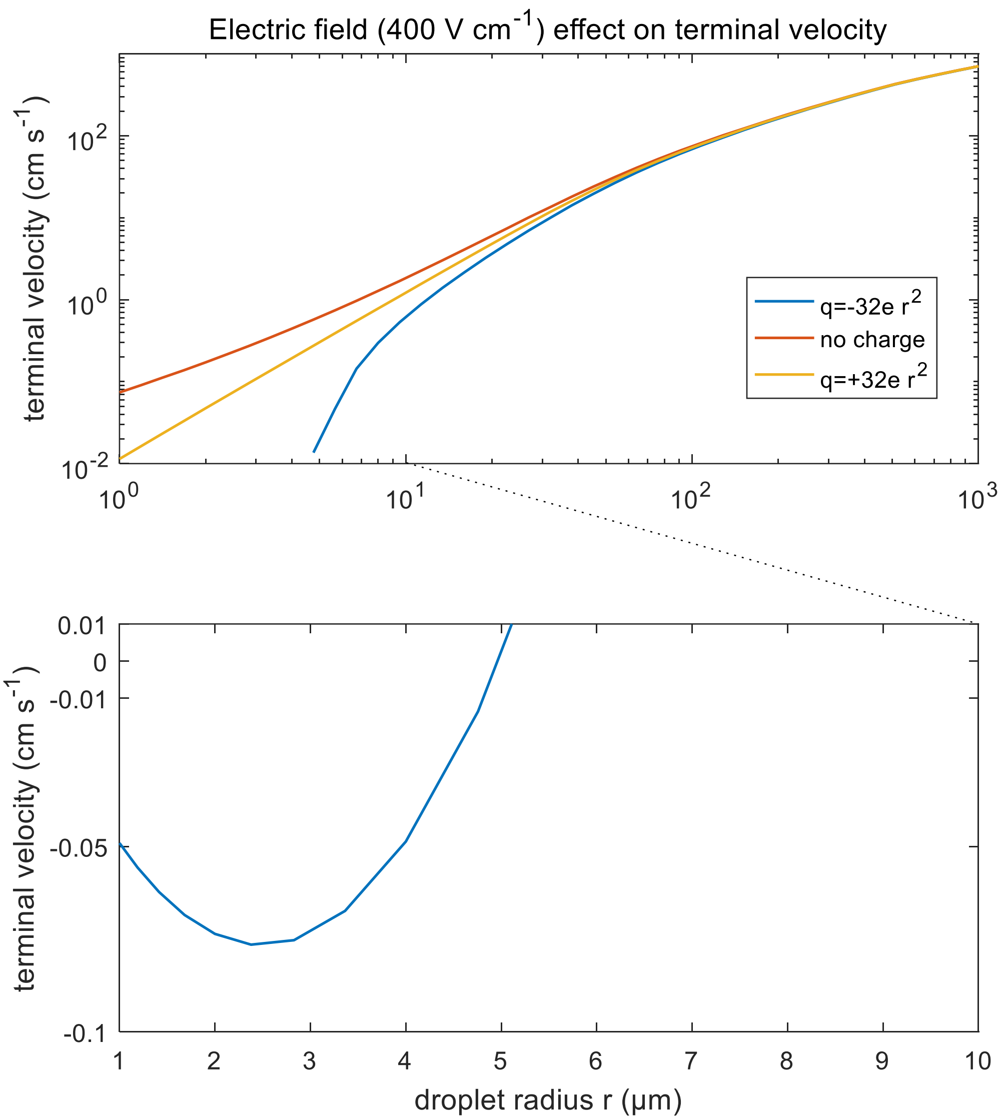

Figure 11. Terminal velocities of droplets in an external electric field 400 V cm^{-1}. Different lines denote different droplet charge conditions. It is seen that the terminal velocity of negatively-charged droplets smaller than 5 μm would turn upwards, which leads to the discontinuity of the lower curve in the figure.

Specific comments:

I would suggest the authors improve the English writing of this manuscript carefully across the paper. One way to improve the readability is to read the manuscript more carefully before submit it.

Response: Thank you very much for pointing this out. We have made substantial changes to the manuscript. The Introduction is completely rewritten. Most parts of Results and some descriptions of Methods are also rewritten. The writing of the paper is much more organized now.

1. Could it be an idea to use "droplet size distribution" instead of "droplet spectrum/spectra" so that readers from a different background (physics, astrophysics) can understand it? As you don't do any Fourier transform, right? What does the spectrum/spectra mean here?

Response: As the reviewer suggested, we have changed all the "spectrum/spectra" to "size distribution" in the manuscript, including text in figures. And it is true that we do not do any Fourier transform.

2. L10: a pair -> pairs. Changed.

3. L12: the cloud -> clouds. Please read through the paper and check if the same revision is needed. Changed and checked.

4. L22: in unit of um. We have corrected all of them.

5. L30: "this method" is unclear.

The sentence has been changed to "Schlamp et al. (1976) used the model of Davis (1964) to study the effect of …".

6. L36: used Stokes flow to represent. Changed.

7. L43: So -> Therefore. Changed.

8. L56: means -> represents. Changed.

9. L69: you already defined "/epsilon" just below Eq.2. So, the first sentence is a repetition and is misleading. You may also consider merge the two paragraphs, where E and /epsilon are discussed. Also, could you provide the expression of /epsilon?

Response:

Thanks for raising this question. Both E and ε are discussed in details now. We have revised line 59 "and ε is the coalescence efficiency" to "and ε is the coalescence efficiency, which represents the probability of coalescence when two droplets collide." The first sentence of line 69 has been deleted, and the paragraph of lines 69-73 has been merged with the paragraph above.

As for the expression of ε, it is just an empirical law (Beard and Ochs, 1984)

$$\varepsilon = (a-b)^{\frac{1}{3}} - (a+b)^{\frac{1}{3}} + 0.459$$

$$a = (b^2 + 0.00441)^{\frac{1}{2}}$$

$$b = 0.0946\beta - 0.319$$

$$\beta = \ln(r_2/\mu m) + 0.44\ln(r_1/200\mu m)$$

We now briefly explain this at the end of line 73:

The formula of coalescence efficiency ε is adopted from Beard and Ochs (1984), but this formula is only available for a certain range of droplet radii. In this study, however, a wide range of radii of r_1 and r_2 are considered. Therefore ε is limited between 0.3 and 1.0 in this study.

10. L73: used -> adopted. Corrected.

11. L85: What about "Momentum equation droplets"? Could you go through the paper and check "motion equation"? In physics, it is "the equation of motion".

Response: Thanks for pointing this out. We have gone through the paper and correct the following sentences.
Line 85: "Droplet motion equation" is changed to "Equations of motion for droplets"
Line 87: "In order to get the collision efficiency, the motion equation of droplets is integrated to get the trajectories of droplets" is changed to "In order to get the collision efficiency between a pair of droplets, the equations of motion are integrated to get the trajectories of the two droplets."
Line 89: "The motion equations for a pair of droplets…" is changed to "The equations of motion for a pair of droplets…"
Line 310: "The motion equation of droplets in the atmosphere is solved…" is changed to "The equations of motion for droplets in the atmosphere are solved…"

12. L88: the flow drag. Changed.

13. L92: velocity vector -> velocity. You may remove "relative to the earth". Changed.

14. L95: What does "The fluid property is treated as air" mean?
Response: We have changed "The fluid property is treated as air with temperature…" to
The fluid is air.

15. L100: I don't understand this paragraph. Do you mean that there are no droplet-droplet interactions? In English, it is very are to put two nouns together in a sentence. You may read through the paper and try to rewrite those, which can help improve the readability of the manuscript.

Response: Thank the reviewer for raising these concerns. Actually, the "superposition method" is a term in many papers of cloud physics, including our references. We should make a detailed explanation and move it to section 3.1, because the second term on the right side of Eq. (4) just shows the "superposition method". The whole paragraph is rewritten, and moved to line 97:

The hydrodynamic interaction of the two droplets is derived by the second term on the right side of Eq. (4), which assumes that each droplet moves in the flow field induced by the other one moving alone, and it is called "superposition method" in cloud physics. We just consider the interaction between one droplet and the fluid field induced by the other droplet. In fact, it is not the exact solution, but the accuracy is acceptable and it significantly simplifies the calculation. This method has been successfully used in many researches of calculation of collision efficiencies (Pruppacher and Klett, 1997). Wang et. al. (2005) improved the superposition method to ensure that the superposition of 2 droplets' stream functions also satisfy the no-slip boundary condition.

16. L105: The nomenclature of the Reynolds number is unique here. It is "Re". How do you define your Reynolds number here? I know in some atmospheric books, "N_Re" was invented.

Response: Actually N_{Re} is widely used. We chose to use this instead of Re because Re can be misleading when it appears in an equation, especially in an equation like Eq. 6 in the manuscript. The two letters in Re can be mistakenly thought as distance R and elementary charge e.
The Reynolds number is defined in line 109

$$N_{Re} = \frac{2rv\rho}{\mu}$$

And it should be defined at the first time it appears. Therefore, line 105 is changed to

…depends on Reynolds number $N_{Re} = \frac{2rv\rho}{\mu}$, where ρ is the density of the air, and μ is the dynamic viscosity of the air.

17. L115: a function. Changed.
18. L131: a complex mathematical problem in physics. Changed.
19. L146: the sign. Changed.
20. L147: it is obvious that. Changed.
21. L169: are not included. Changed.
22. L171: In thunderstorm conditions. Changed.
23. L173: approaches -> is close to. Changed.
24. L176: to the certain mass bins -> to mass bins. Changed.
25. L239: by a factor of about. Changed.
26. L249: evolution of the droplet size distribution. Changed.
27. L291: nearly not -> hardly. Changed.
28. L291: and difference -> and the one. Changed.

29. L294: to the observation. Can you add the reference as well?

Response: As suggested, we have added "according to Tsutomu Takahashi (1973) and Pruppacher and Klett (1997)" after line 294 "…to the observation". The results of observation in several previous researches are shown in Chapter 17.4.2.1 of Pruppacher and Klett (1997) .

Reference:
Tsutomu Takahashi: Measurement of electric charge of cloud droplets, drizzle, and raindrops, Reviews of Geophysics and Space Physics,11, 903-924, 1973

30. L326: Do you mean "the observed atmospheric conditions"? What does "real" mean here?

Response: Yes. As suggested, we have changed line 326 "…represent the real conditions in the atmosphere" to "…represent the observed atmospheric conditions."