Response to Referee #2

General comments:

This manuscript studied the effect of electric charges and atmospheric electric fields on collision efficiency and the size distribution of cloud droplets numerically. The author concluded that electric charges and fields could accelerate large-drop formation in natural conditions, particularly for clouds with small droplet size. In my opinion, the manuscript is not acceptable for publication in its present form. Some major corrections should be done to make sure that the results can be more appropriate.

Main points:

1. There are some errors in Eq. (3). The second term of the right hands of Eq. (3) should be the loss of droplets of mass m, however, the collection kernel is about droplets of mass mx and mass m-mx.

Response: Thanks for the reviewer's careful reading. We have changed the following expression in the second term on the right hand of Eq. (3):

$$K(m_x, q_x; m{-}m_x, q{-}q_x)$$

To

$$K(m_x, q_x; m, q)$$

2. Equation (7) describes the induced flow field u, however, Eq. (7) does not satisfy no-slip boundary for two interacting droplets. Specifically, in the superimposed induced flow field according Eq. (7), the fluid velocity on the surface of the droplet is not equal to the velocity of the droplet. The detailed description paper of the theory was published in Journal of the Atmospheric Sciences in 2005 (https://journals.ametsoc.org/doi/full/10.1175/JAS3397.1).

Response: Thanks for the reviewer's comment. We have made the corrections. The error was made when we typed the equations. Actually, the equations in our computer program are correct and satisfy no-slip boundary condition. We have made a thorough check to the equations. Lines 103 to 114 in the original manuscript now reads as:

The formulas to compute the flow velocity $\boldsymbol{u}$ are discussed in this section. We consider a rigid sphere moving with a velocity U relative to the viscous fluid. It is known that when the Reynolds number is small, the Stokes flow gives a concise solution of the stream function

$$\psi_s = U\left(\frac{1}{4\tilde{R}} - \frac{3\tilde{R}}{4}\right)\sin^2\theta \qquad (5a)$$

where $\tilde{R} = R/r$ is the normalized distance (R is the distance from the sphere centre, r is the droplet radius), θ is the angle between the droplet's velocity and vector $\boldsymbol{R}$ pointing from the sphere centre. U is the droplet velocity relative to the fluid, i.e., $U_1 = |\boldsymbol{v_1} - \boldsymbol{u_2}|$ for droplet 1, and $U_2 = |\boldsymbol{v_2} - \boldsymbol{u_1}|$ for droplet 2. However, this stream function of the Stokes flow does not apply to the system with a large Reynolds number. It is needed to approximatively construct a stream function which 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. Hamielec and Johnson (1962, 1963) gave the stream function ψ_h induced by a moving rigid sphere, for large Reynolds numbers:

$$\psi_h = U\left(\frac{A_1}{\tilde{R}} + \frac{A_3}{\tilde{R}^2} + \frac{A_3}{\tilde{R}^3} + \frac{A_4}{\tilde{R}^4}\right)\sin^2\theta - U\left(\frac{B_1}{\tilde{R}} + \frac{B_3}{\tilde{R}^2} + \frac{B_3}{\tilde{R}^3} + \frac{B_4}{\tilde{R}^4}\right)\sin^2\theta\cos\theta \tag{5b}$$

where $A_1, \ldots, B_4$ are functions only of Reynolds number N_{Re} for each droplet. The method is valid for $N_{Re} < 5000$. But the solution deviates from the Stokes flow solution when $N_{Re} \to 0$ for small droplets. Therefore, this work adopts a smooth combination of ψ_h and Stokes stream function ψ_s (Pinsky and Khain, 2000)

$$\psi = \frac{N_{Re}\psi_h + {N_{Re}}^{-1}\psi_s}{N_{Re} + {N_{Re}}^{-1}} \tag{6}$$

which converges to stokes flow when $N_{Re} \to 0$. Then the induced flow field $\boldsymbol{u}$ is derived,

$$\boldsymbol{u} = -\frac{1}{\tilde{R}^2\sin\theta}\frac{\partial\psi}{\partial\theta}\hat{\boldsymbol{e}}_{\boldsymbol{R}} + \frac{1}{\tilde{R}\sin\theta}\frac{\partial\psi}{\partial\tilde{R}}\hat{\boldsymbol{e}}_{\boldsymbol{\theta}} = u_R\hat{\boldsymbol{e}}_{\boldsymbol{R}} + u_\theta\hat{\boldsymbol{e}}_{\boldsymbol{\theta}} \tag{7a}$$

where $\hat{\boldsymbol{e}}_{\boldsymbol{R}}$ and $\hat{\boldsymbol{e}}_{\boldsymbol{\theta}}$ are unit vectors in the polar coordinate (R, θ). It can also be expressed in the Cartesian coordinate (x, z) as:

$$\boldsymbol{u} = (u_R\cos\varphi - u_\theta\sin\varphi)\hat{\boldsymbol{e}}_{\boldsymbol{z}} + (u_R\sin\varphi + u_\theta\cos\varphi)\hat{\boldsymbol{e}}_{\boldsymbol{x}} \tag{7b}$$

where the direction of $\hat{\boldsymbol{e}}_{\boldsymbol{z}}$ is downward, the same as gravity. φ is the angle between the droplet's velocity and $\hat{\boldsymbol{e}}_{\boldsymbol{z}}$.

Both Stokes and Hamielec stream functions satisfy the no-slip boundary condition, i.e., the fluid velocity on the surface of the droplet is equal to the velocity of the droplet. Hamielec stream function is no-slip because those functions $A_1, \ldots, B_4$ in Eq. (10) satisfy $A_1 + 2A_2 + 3A_3 + 4A_4 = 1$ and $B_1 + 2B_2 + 3B_3 + 4B_4 = 0$, as long as the droplet is considered as a rigid sphere (Hamielec, 1963). These relations ensure that $u_\theta = -U\sin\theta$ at the surface of the droplet. Note that u_θ is the velocity of the fluid at the surface, and $U\sin\theta$ is the tangential velocity of the droplet surface. This equation ensures the no-slip boundary condition.

In our study, the adopted stream function is a linear combination of Stokes flow and Hamielec (1963) flow field, because the latter one works well for a wide range of Reynolds numbers up to 10^3. Both Hamielec and Stokes stream functions satisfy the no-slip boundary condition.

In addition, the superposition method used in our study does accord with Eq. (19) and (20) in Wang and Ayala's paper in 2005 (https://journals.ametsoc.org/doi/full/10.1175/JAS3397.1) based on the Stokes flow.

Reference:

Wang, L. P., Ayala, O., Grabowski, W. W.: Improved Formulations of the Superposition Method, J. Atmos. Sci, 62(4):1255-1266, doi: 10.1175/JAS3397.1, 2005

3. Fig. 4 gives the initial spectrum mass distribution in 2D grids of bin. For charged clouds, the initial charge is distributed symmetrically, as shown in Fig. 4b: 14% with charge +1r^2, 14% with charge -1r^2, 22% with charge +0.5r^2, 22% with charge -0.5r^2, and 28% with no charge. What is the principle determining the abovementioned charge ratio? Is there any observation data to prove the charge ratio?

Response: We thank the reviewer for raising these questions. The ratio in the original manuscript is an approximation of 2:3:4:3:2, but it is arbitrarily chosen. The basic idea was to let the droplets distribution over charge bins mimic a normal distribution, and also to satisfy electric neutrality $\bar{q} = 0$.

In fact, there are some observations on mean charges of droplets, as can be seen in Figure 1 below (from Pruppacher and Klett, 1997). But there is no observational data for the kind of charge ratio that we used. Now we use a Gaussian distribution in the revised manuscript to describe the droplet distribution over the charge bins.

Lines 199-202 have been revised and it reads as follows in the revised manuscript:

To simulate an early stage of the warm-cloud precipitation, we need to distribute the droplets in each size bin to different charge bins, so that these droplets have different charges. Since there is little data on this, we assume a Gaussian distribution,

$$N(q) = \frac{N}{\sqrt{2\pi}\sigma} \exp\left(-\frac{q^2}{2\sigma^2}\right)$$

where N is the number concentration in the size bin, and σ is the standard deviation of the Gaussian distribution in that bin. $N(q)$ represents the number concentration of droplets with charge q. This distribution satisfies electric neutrality $\bar{q} = 0$. For different size bin, droplet number concentration N is different. We purposely set the standard deviation σ to be different for different size bins. For larger size, the charge amount is larger, based on $\overline{|q|} = 1.31\ r^2$ (q in unit of elementary charge and r in μm) as stated in the Introduction. Therefore, we set larger standard deviation σ for the larger size bins.

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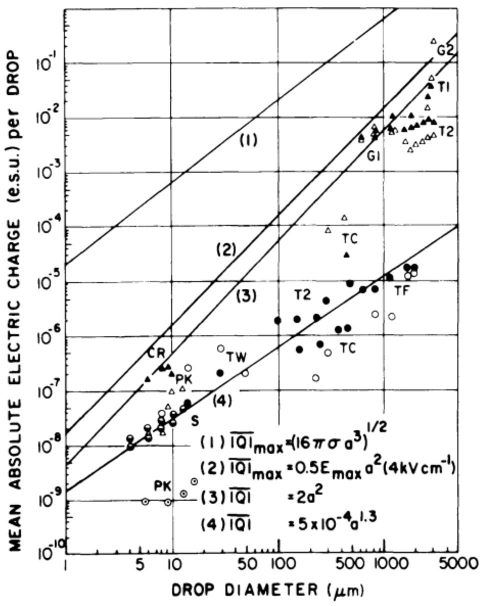
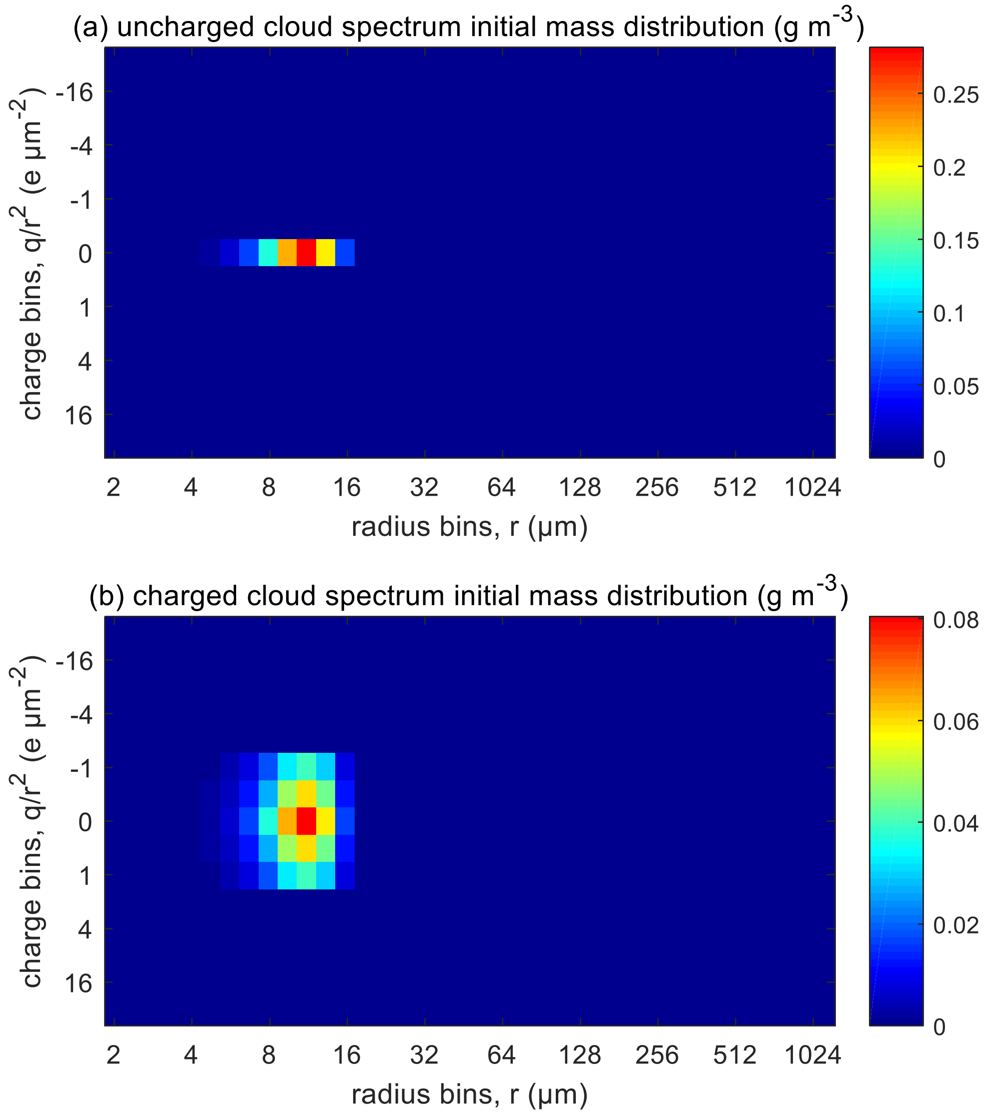


Fig. 17-2. Mean absolute electric charge on cloud and raindrops. Round symbols indicate warm cloud cases, triangular symbols indicate thunderstorm cases; solid symbols indicate negative charge, open symbols indicate positive charge. PK Phillips and Kinzer (1958), S Sergieva (1959), CR Colgate and Romero (1970), TW Twomey (1956), TC Takahashi and Craig (1973), T*1* Takahashi (1965), T*2* Takahashi (1972), TF Takahashi and Fullerton (1972), G*1* Gunn (1949), G*2* Gunn (1950). (Adapted with changes from Takahashi (1973).)

Figure 1(Appendix). Observational data for the relationship between droplet charge and radius

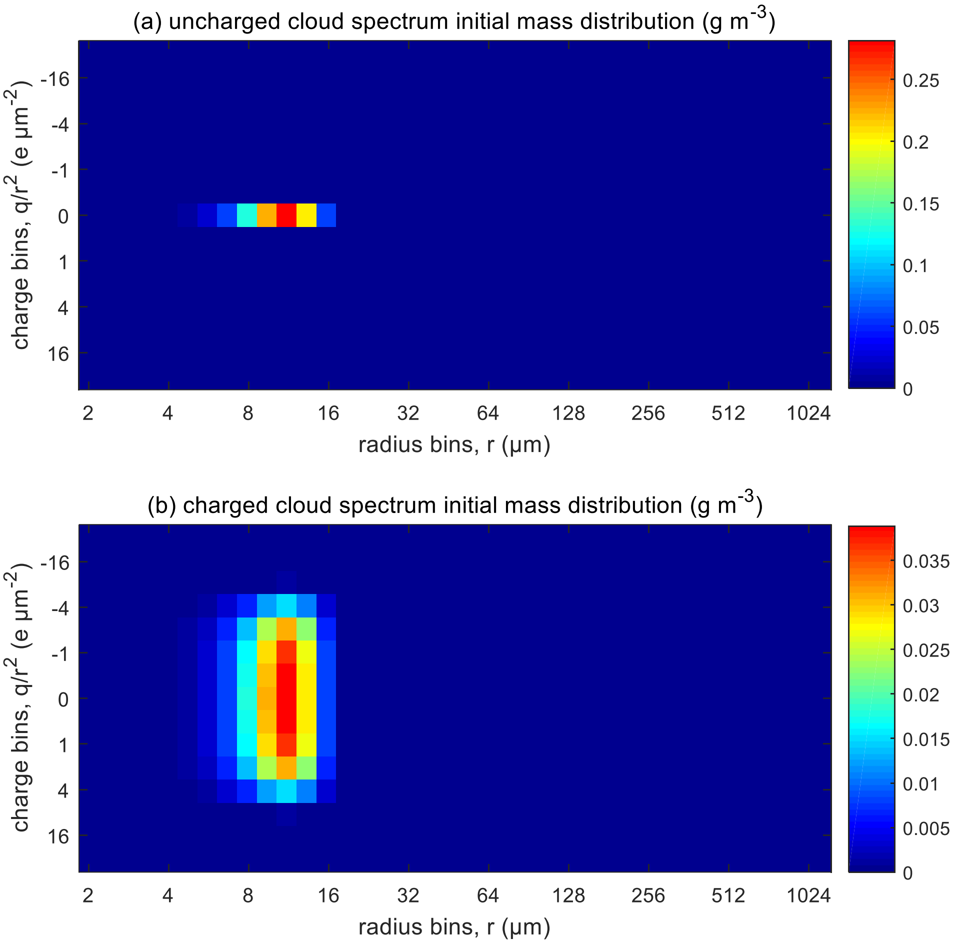
(Pruppacher and Klett 1997). Our new setting $\overline{|q|}$ = 1.31 r^2 (q in unit of elementary charge and r in μm) approaches line (4) around $r \approx 10$μm, which is the weakly electrified warm cloud case.

New simulations using the Gaussian charge distribution have been performed. Figs. 4, 7-10 in the original manuscript are now replaced with the new simulations, and comparisons are shown below. But the changes in results are not significant. Therefore, discussions in section 5.2 basically remain unchanged.



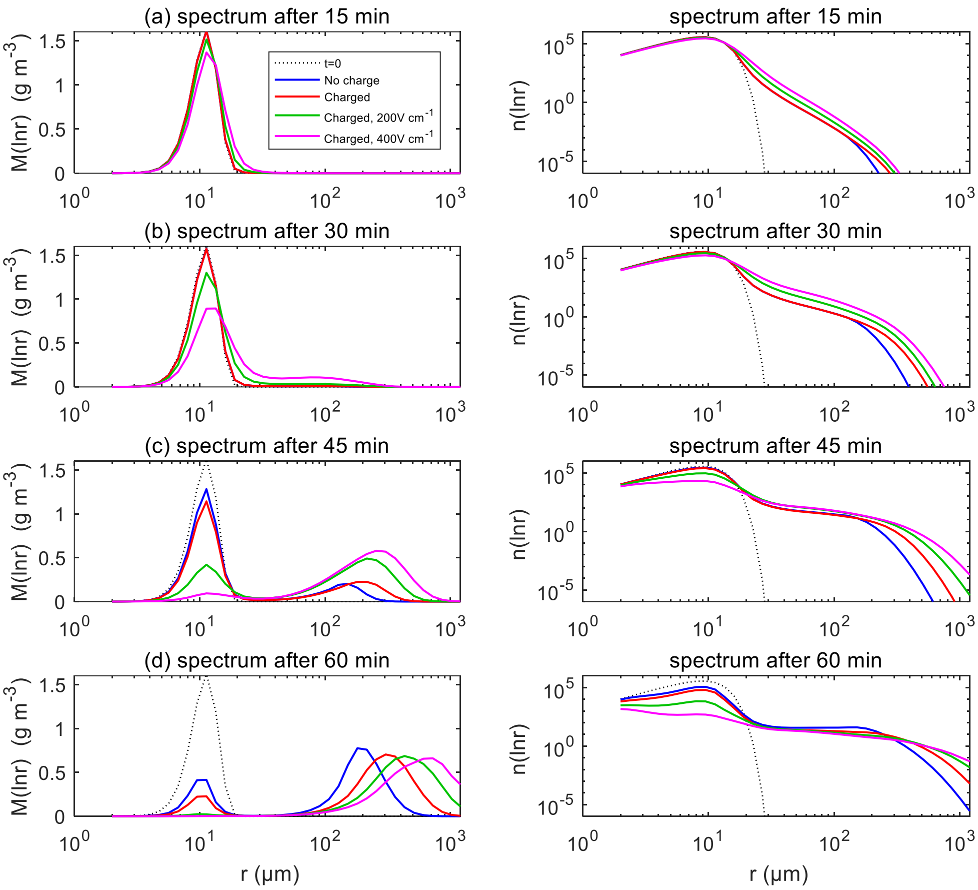
(Figure 4 in the original manuscript)

Figure 4. The initial droplet mass distributed over the size and charge bins. Colours stand for water mass content in the bins (in unit of g m^{-3}). (a) Uncharged droplets (b) charged droplets.



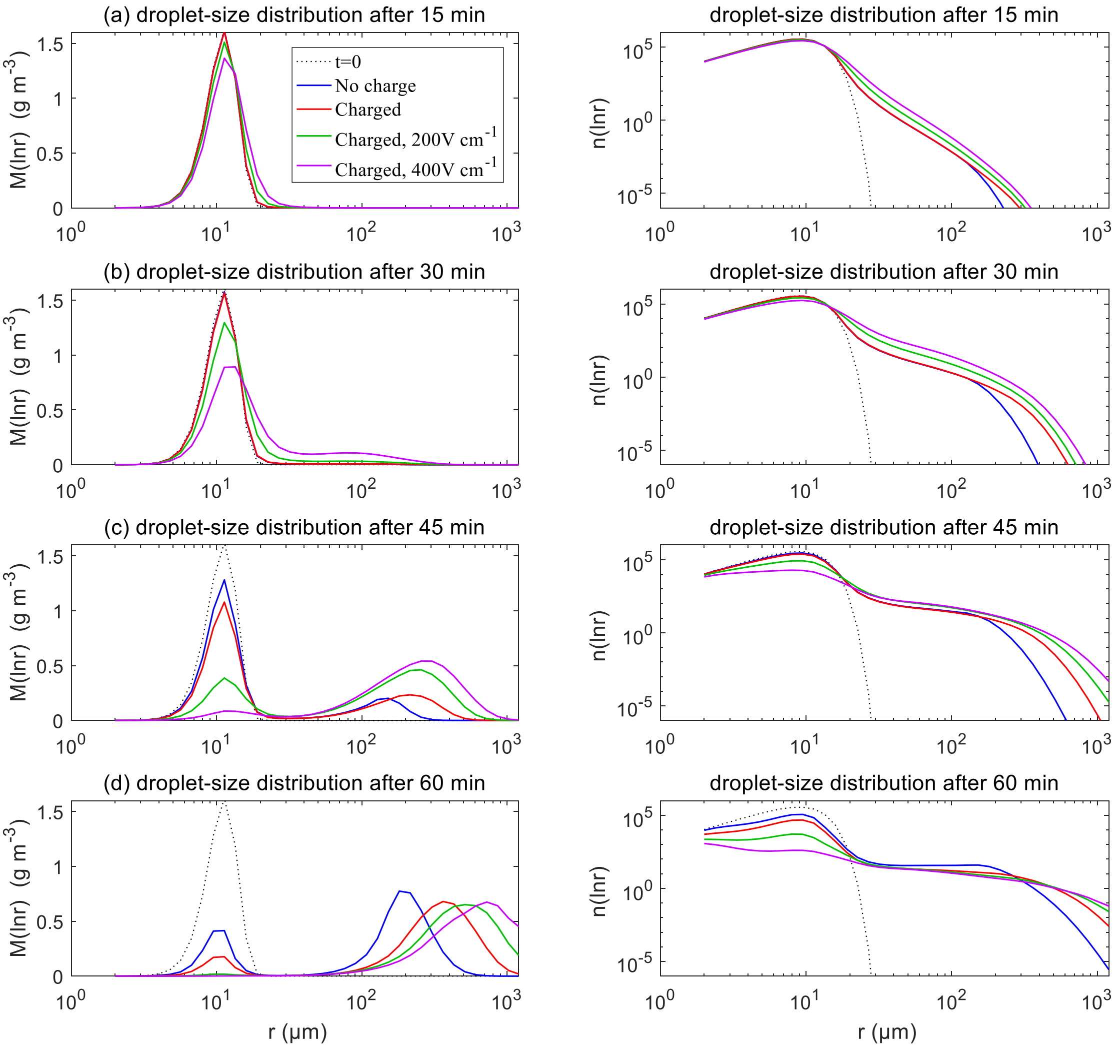
(Figure 4 in the revised manuscript)

Figure 4. The initial droplet mass distributed over the size and charge bins. Colours stand for water mass content in the bins (in unit of g m^{-3}). (a) Uncharged droplets (b) charged droplets.



(Figure 8 in the original manuscript)

FIG. 8. The evolution of the droplet size distribution with initial $\bar{r}$ = 9 μm.



(Figure 8 in the new manuscript)

FIG. 8 (it is Figure 10 now). The evolution of the droplet size distribution with initial $\bar{r}$ = 9 μm.