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Numerical study on the effect of charge separation at low cloud temperature and effective water content on thunderstorm electrification

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ABSTRACT

In the present study, a numerical model is used to evaluate the effects of low effective water content and low cloud temperature on graupel charging, charge structure and lightning activity in regions of thunderstorms. Two idealized cloud cases were simulated with MesoNH using different configurations of the main known parameterizations for noninductive charging involving ice crystal/graupel rebounding collisions. Simulations in regions with very low effective cloud water content were performed with the parameterization proposed in Mitzeva et al. (2006) based on the "Relative Growth Rate" hypothesis, while for simulations in regions with low cloud temperature, charge values from Avila et al. (2011) were used. Results showed that the inclusion of the charge separation at very low effective water content influences more the simulated cloud charge structure than does the inclusion of the charge separated at low temperatures. Also, the effect of the charge separated at very low effective water content is more significant when the original parameterization for non-inductive charging is based on the effective water content rather than on the rime accretion rate.

1. Introduction

The main mechanism responsible for thunderstorm electrification is the result of charge separation (independently of external electric fields) during rebounding collisions between riming graupel and ice crystals in the presence of supercooled cloud droplets, known as the non-inductive mechanism. Based on laboratory experiments (Takahashi (1978), Saunders et al. (1991), Brooks et al. (1997), Saunders and Peck (1998)) it was established that the sign and the magnitude of the charge transfer during a collision between a riming target (simulating a graupel particle) and an ice crystal depends on cloud temperature T and cloud effective water content EW (which is determined by the ability of the graupel to capture supercooled water droplets) or rime accretion rate RAR (which additionally includes the relative velocity V between the interactive ice particles, $RAR = EW \times V$). In general, graupel charges positively at high EW and negatively at low EW. During their laboratory experiments, Saunders et al. (1991) established that at very low effective water contents the charge sign was opposite to the polarity at higher EW. Furthermore, in these so-called 'anomalous zones' the charge magnitude was considerably higher in comparison to the remainder of the charge separation domain. On the other hand, the laboratory experiments of Jayaratne et al. (1983) showed that in the absence of cloud droplets, the separated charge during rebounding collisions between ice crystals and graupel is up to two orders of magnitude smaller than in the presence of cloud water. Therefore in numerical models usually it is assumed that there is no charge separation at cloud conditions with very low liquid water (below 0.01 g/m^3) content and at cloud temperatures below −40 °C, as at such temperatures aircraft in situ measurements in convective clouds reported the presence solely of ice particles. However, Mitzeva et al. (2006), investigated the effect of charging in cloud regions free of cloud droplets on the electrical charge structure of some simulated clouds. They proposed parameterizations for the charge transfer in the non-riming regions based on some theoretical assumptions. The first assumption relies on the "Sublimation/Deposition" hypothesis (Williams, 2001) for the charge separation, according to which if there is sublimation/deposition of vapour from/to the graupel surface, graupel charges negatively/positively, respectively. The second assumption is based on the "Relative Growth Rate" (RGR) hypothesis (Baker et al., 1987), according to which the ice surface growing faster by vapour diffusion charges positively. Results showed that charge transfer in non-riming cloud regions, even with two orders lower magnitude charge transfer compared with riming cloud regions, may influence the total cloud charge density, especially in the upper part of vigorous thunderstorm updraughts. Avila et al. (2011) performed new sets of laboratory experiments to determine the charge separation in laboratory cloud conditions similar to those occurring in glaciated cloud regions. The authors reported predominantly negative

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graupel charging in the temperature range −37 °C to −47 °C (at EW = 0.3 g/m^3 and RAR = 2.1 g/m^2 s) with estimated charge transfer per collision magnitude between 0.01 and 0.1 fC.

The aim of the present study is to investigate if the incorporation of the charging at low cloud temperatures and low EW in cloud models would affect considerably the electrical structure of simulated thunderclouds and their lightning activity. For this purpose, two idealized cloud cases were simulated with the 3D non-hydrostatic model MésoNH. For each cloud case, simulations in regions with very low effective cloud water content were performed using the parameterization proposed in Mitzeva et al. (2006) that is based on the "Relative Growth Rate" hypothesis; and using the Avila et al. (2011) charge values in the cloud temperature range between −37 °C and −47 °C. Results are compared with the corresponding simulations with zero charge transfer in cloud regions with low temperature and liquid water content. In the parameterization of cloud charging in regions with supercooled cloud water droplets all main known schemes for charge separations are used, based on laboratory results of Takahashi (1978), Saunders et al. (1991), Brooks et al. (1997), and Saunders and Peck (1998).

2. MésoNH model

The MésoNH is a non-hydrostatic mesoscale model which results from a joint development of Laboratoire d'Aérologie and Météo-France (http://www.aero.obs-mip.fr/mesonh/). The model integrates an inelastic system of equations that is able to simulate ideal and real atmospheric flows ranging from large eddy turbulent motion to the synoptic scale. The mixed-phase microphysical scheme in MésoNH follows the approach of Lin et al. (1983) that is a three-class ice parameterization coupled to a Kessler scheme (Kessler, 1969) used for the warm processes. The scheme follows the evolution of the mixing ratios of six water species: rv (vapour), rc and rr (cloud and rain drops) and ri, rs and rg (pristine ice, snow and graupel). The concentration of the precipitating particles is parameterized according to Caniaux et al. (1994). The pristine ice category is initiated by two heterogeneous nucleation processes: formation of ice embryos in a supersaturated environment over ice (deposition) following Meyers et al., 1992 and freezing of supercooled droplets. In the model, the secondary production of ice crystals or rime-splintering mechanism is following Hallett and Mossop, 1974. The homogeneous nucleation of pristine ice starts at temperatures lower than −35 °C. Ice crystals grow by water vapour deposition. The snow phase is initiated by autoconversion of primary ice crystals and it grows by deposition of water vapour, by aggregation through small crystal collection and by the riming produced by impaction of cloud droplets and of raindrops. Graupel particles are produced by the heavy riming of snow or by rain freezing when supercooled raindrops come in contact with pristine ice crystals. According to the heat balance equation and the efficiency of their collecting capacity, graupel particles can grow in dry and in wet mode (when riming is very intense and the excess of non-freezable liquid water at the surface of the graupel is shed and forms raindrops). At temperatures above 0 °C, ice particles melt into cloud and rain drops. Cloud droplet autoconversion, accretion and rain evaporation follow the Kessler scheme.

In the model, electric charges are carried by hydrometeors (cloud water, rain, pristine ice, snow, and graupel). The electrification scheme integrates the evolution of the mass charge density (qx in C kg^{-1}of dry air) which is closely related to the mixing ratio (rx in kg kg^{-1}) of the microphysical species x (Barthe et al., 2012; Pinty et al., 2013). The complete life cycle of the electric charges is simulated in the model with the charge separation, transfer, and transport, and the charge neutralization by lightning flashes. In the model, different parameterizations for charging are incorporated (Takahashi (1978), Saunders et al. (1991), Brooks et al. (1997), Saunders and Peck (1998), Tsenova and Mitzeva (2009, 2011)). Once electric charges are separated, they are transferred from particle type to particle type during the microphysical conversion processes (aggregation, autoconversion, melting…). At the same time, the charges are transported by sedimentation, advection and turbulence. When the in-cloud electric field becomes higher than an altitude-dependant threshold (Marshall et al., 1995), a lightning flash is triggered. The lightning flash scheme is based on observed morphological characteristics of the flashes as described in Barthe and Pinty (2007) and in Barthe et al. (2012) for the adaptation of the code to parallel computing.

Detailed information of physical processes included in the model version used for the present study can be found at: http://mesonh.aero.obs-mip.fr/mesonh/dir_doc/book1_m49_22nov2011/scidoc_p3.pdf

3. Parameterization of charge separation in thunderstorm

The analytical expressions of the charging rates relies heavily on the microphysical scheme:

$$\frac{\delta q_{xy}}{\delta t} = \int\int\left(\frac{\pi}{4}\right)\delta Q\left(1-E_{xy}\right)\left(D_x+D_y\right)^2\left(V_x-V_y\right)n_x(D_x)n_y\left(D_y\right)dD_x dD_y \quad (1)$$

where Dx and Dy are the diameters for hydrometeors x and y, respectively. |Vx − Vy | is the relative fall speed, nx and ny are the number concentrations of hydrometeors x and y, respectively, and Exy is the collection efficiency. The collection efficiency depends on the temperature and follows Kajikawa and Heymsfield (1989) for ice-snow and snow-graupel collisions, and Mansell et al. (2005) for ice-graupel collisions.

The expression of the charge exchanged is:

$$\delta Q = Bd^a V^b \delta q$$

where B, a, and b are constants depending on the size of small ice particles, on the relative velocity of the interacting ice particles, and on the sign of charge transfer and are tabulated in Saunders et al. (1991) and in Tsenova and Mitzeva (2009). For Takahashi (1978) data; δq is the charge determined from the parameterization scheme used for non-inductive charging.

For the purpose of the present study the following parameterizations as originals (orig) were used in the temperature range [−40 °C, 0 °C]:

1) SAUN1: charge separation values according to Saunders et al. (1991), calculated at EW >0.026 g/m^3, the equations for the charging in the 'anomalous zones' are not included.
2) SAUN2: same as SAUN1, but with included equations for the charging in the 'anomalous zones'.
3) BSMP1: charge separation values according to Brooks et al. (1997), calculated at RAR >0.078 g/m^2 s, the equations for the charging in the 'anomalous zones' are not included.
4) BSMP2: same as BSMP1, but with included equations for the charging in the 'anomalous zones'.
5) SAP98: charge separation values according to Saunders and Peck (1998), calculated at RAR >0.078 g/m^2 s.
6) TEEWC: charge separation values according to Takahashi (1978) calculated at EW >0.01 g/m^3 using the proposed in Tsenova and Mitzeva (2009) equations.

The inclusion of the charge separated at very low effective water content depends on the original parameterization. When parameterizations based on Saunders et al. (1991) results are used, for SAUN1 + RGR and SAUN2 + RGR parameterizations, additionally charging is included at EW < 0.026 g/m^3. Such additional charging is included for TEEWC + RGR at EW < 0.01 g/m^3. For the parameterizations based on RAR, (BSMP1 + RGR, BSMP2 + RGR and SAP98 + RGR) additional charge separation is included at RAR < 0.078 g/m^2 s. The charge separated at very low cloud water content is calculated by:

- when cloud water vapour is supersaturated with respect to ice (Si > 1), the charge acquired by graupel is $\delta q = -0.05$ fC.