A study of charge structure sensitivity in simulated thunderstorms

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Abstract

Two different thunderstorms are simulated by two distinct one-dimensional cloud models using four different parameterisations of the non-inductive mechanism of electric charging, based on laboratory studies. The results demonstrate that during the early (pre-lightning) stage of thunderstorm electrification, simulated charge density depends not only on the model charging parameterisation employed, but also on the specific representations of the kinematics and microphysical characteristics of the model itself. Though no conclusions are drawn regarding the physical suitability of the charging parameterisations themselves, the analysis indicates that the most significant differences between the simulated charge structures of the clouds produced in each particular model are the result of different distributions of model cloud characteristics and of the type of parameterisation of the microphysical processes. The study reveals that it is too early to make any conclusion regarding which, if any, of the existing parameterisation schemes are better suited to the realistic simulation of electrical charging in real clouds.

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Non-inductive charge transfer

1. Introduction

In the scientific community, there is a general consensus that the non-inductive mechanism plays a major role in thunderstorm electrification. This basic physical behaviour of this mechanism has been observed in numerous laboratory experiments (Reynolds et al., 1957; Takahashi, 1978; Jayaratne et al., 1983; Saunders et al., 1991, and others) which demonstrate that substantial charge is transferred during rebounding collisions between ice crystals and graupel pellets growing by the accretion of supercooled cloud droplets. However, several of the laboratory measurements (Takahashi, 1978; Saunders et al., 1991; Brooks et al., 1997) found different functional dependencies between the magnitude and sign of separated charge as related to liquid water content (LWC), effective water content, and/or in-cloud temperatures. Using various schemes for the numerical simulation of cloud electrification, studies by Solomon and Baker (1993), Brooks et al. (1997), Scavuzzo et al. (1998), Helsdon et al. (2001), Mitzeva et al. (2003), Mansell et al. (2005), Barthe and Pinty, (2007) and others show that the non-inductive mechanism can make a significant contribution to the dipole or tripole structure of simulated clouds during thunderstorm development. However, analysis of the numerical simulations provides conflicting conclusions. For example using Takahashi (1978) data, Scavuzzo et al. (1998) calculated a tripolar charge structure, while the model simulations by Altaratz et al. (2005) developed a dipole. The formation rate of a positive dipole in the Helsdon et al. (2001) thunderstorm study was lower when the Saunders et al. (1991) laboratory data were incorporated in the model in comparison with that of the Takahashi (1978) data, which is in contrast to the results presented in Altaratz et al. (2005).

Since the electrification depends on microphysical and dynamical properties, one possible reason for the discrepancy between the conclusions is that different thunderstorm cases were simulated. However, the discrepancy may be also due to the different manner of incorporating laboratory data because
of the manner in which specific physical features are implemented in each of the numerical models used for the thunderstorm simulations. The aim of the present study is to make use of a simplified and inexpensive to run 1-D modelling framework, to reveal:

- The effect of the choice of model used for the simulation
- The effects of different laboratory-based parameterisations of non-inductive charge transfer included in the numerical models
- The effects of the microphysical and dynamical properties of the simulated thunderstorms.

To facilitate the above, two different cloud cases are simulated by two different 1-D thunderstorm models using 4 laboratory-based parameterisations of non-inductive graupel-ice charge separation.

Conclusions regarding the impacts of cloud models, parameterisations of charge transfer or cloud microphysics and dynamics are derived based on the inter-comparison between charge density distribution (normal or inverted dipole, maximum magnitude and height of positive and negative charge density, etc.) obtained in various numerical simulations. Here it is worth noting that this study is not intended to provide conclusions regarding the physical suitability of the charging parameterisations themselves. We choose to use 1-D models because of their relative simplicity in terms of representing the relevant physical processes. In fact, 1-D models provide an excellent laboratory for studying the response of highly parameterised charging schemes to the changes made in parameterised microphysical processes. It is more reliable to compare the details in different non-linear schemes depending on many parameters using just one-dimensional cloud model rather than 3-D models.

2. Cloud models

In this section, we present a brief description of the two cloud models used for the thunderstorm simulations including the four different parameterisations of non-inductive charge transfer.

The first cloud model (hereafter denoted as M1) is the same as that described in Mitzeva et al. (2003). The second model (hereafter denoted as M2) contains the same dynamics core as Ferrier and Houze (1989) with ice and charge transfer parameterisations developed in Petersen (1997) and Albrecht et al. (2006).

2.1. Model descriptions

As structured in the M1 model, convective clouds are composed of active and non-active cloud masses (Andreev et al., 1979, see also Mitzeva et al., 2003). The active mass is modelled by successive spherical thermals ascending above cloud base, while the non-active cloud region is formed by thermals that have previously risen and stopped at the level where their velocity is zero. One can speculate that the ascending thermals represent the updraught region of convective clouds, while non-active masses represent the environment surrounding the updraughts. The model uses bulk microphysical parameterisations with five classes of water substance — water vapour, cloud water, rain, cloud ice, and precipitating ice (graupel).

The cloud droplets are formed by condensation; raindrops form by autoconversion of the cloud droplets and grow by collision and coalescence with cloud drops (Kessler, 1969). Ice crystals originate by activation of ice nuclei in supercooled cloud droplets, their concentration being given by Fletcher (1962). Homogeneous freezing occurs below −40 °C. Graupel forms by the freezing of rain drops (Bigg, 1953), contact nucleation of ice crystals and rain droplets (Cotton, 1972) and conversion of ice crystals (Hsie et al., 1980). Ice crystals grow by deposition and riming. Hail grows by deposition and coalescence with cloud and rain drops. Evaporation of rain drops and melting of graupel during their descent (Farley and Orville, 1986) as well as recycling, is included. The cloud drops and ice crystals are assumed monodisperse and have negligible fall velocities and so move upward with the air. Particle size distributions for the precipitation species (rain drops and graupel) are parameterised using inverse exponential distributions of the general form \(N(D)=N_0 \exp(-\lambda D)\), where \(N_0\) is the intercept of the distribution and \(\lambda\) is the slope (a function of both the intercept and mixing ratio of the species). The \(N_0\) values used in the model simulations are in the range of values given in Pruppacher and Klett, 1978. Precipitation fallout is calculated in the same manner as in Cotton (1972) and comprises that portion of raindrops and graupel that have terminal velocities greater than the updraught speed. The recycling of precipitating particles is possible in the model through the incorporation of the mass of raindrops and graupel falling out from the upper ascending successive thermals.

In the cloud model M1 ice crystals and small graupel in ascending thermals, together with larger falling graupel, are the electric charge carriers. The charging rate per unit volume of model cloud from rebounding collisions between ice crystals and graupel is calculated as in Mitzeva and Saunders (1990).

\[
\frac{dQ_i}{dt} = \frac{\pi}{4} E_s D_s^2 V_n N Q_d D_s = -\frac{dQ_i}{dt}
\]

where \(dQ_i\) and \(dQ_g\) are graupel and ice crystal charging rates, respectively, \(E_s\) is the event probability (for SKM and BSMP parameterisations (see Section 2.2), \(E_s=0.3\) based on Keith and Saunders (1989) while for \(T_{\text{orig}}\) and \(T_{\text{hybrid}}, E_s=1\), \(D_s\) is graupel diameter, \(n\) and \(N\) are ice crystals and graupel concentrations respectively, and \(V\) is graupel velocity defined in M1 by

\[
V = \left( \frac{4 g \rho_a D_s}{3 C_D \rho_a} \right)^{0.5}
\]

where \(C_D\) is the drag coefficient, and \(\rho_a\) and \(\rho_s\) are the graupel and air densities. \(Q\) is the separated charge during rebounding collision between graupel and ice crystals. The equations used in both models for the parameterisation of \(Q\) are given in Section 2.2.

Charge may also be transferred from one category to another as mass is transferred. For example, when a fraction of mass melts to rain, the same fraction of the graupel charge...
is extracted from the graupel and is transferred to the rain category. Changes in charge density occur in ascending thermals also due to the entrainment of non-active cloud regions and cloudless air, the loss of graupel by fallout and the incorporation of graupel fallen from upper levels.

The net (total) charge density in the updraughts of clouds is established by summing the charges on the ice crystals and on the graupel in the ascending thermals. The charge carriers in the non-active cloud region are ice crystals, which remain in the stationary and diffusing thermals; their net charge is changed in proportion to the dilution of ice crystal content due to diffusion and entrainment. During their descent, graupel particles charge by rebounding collisions with ice crystals in the non-active cloud mass or in the ascending thermals and they may be incorporated into ascending thermals when their terminal fall speed is smaller than the updraught velocity of the ascending thermals.

The second model (denoted as M2) is based on the work of Ferrier and Houze (1989), Petersen (1997), and Albrecht et al. (2006). This model is formulated in a cylindrical coordinate system and is axially symmetric, with a variable cloud radius. The microphysical processes utilise a bulk parameterisation similar to that of M1, however they include seven classes of water substances — water vapour, cloud water, rain, cloud ice, snow, graupel and hail. The continuity equations for each hydrometeor species include a combination of parameterisations taken from Lin et al. (1983), Rutledge and Hobbs (1983) and Ferrier (1994) using continuous collection and diffusional growth. As in M1, particle size distributions for the precipitation species are parameterised using the inverse exponential distributions of the form \( N(D) = N_0 \exp(-\lambda D) \). The values of \( N_0 \) for the snow category were allowed to increase as a function of temperature to a maximum value of \( 10^7 \) m\(^{-4}\) to reflect enhanced aggregation efficiencies at warmer temperatures, while for rain, graupel and hail were held constant. Selection of individual \( N_0 \)'s for each simulation were based on the sensitivity tests, observations and previous modelling studies such as Lin et al. (1983), Rutledge and Hobbs (1983), Ferrier (1994), and Krueger et al. (1995). Cloud water and cloud ice species were assumed monodisperse and to possess a negligible fall speed. Terminal fall speed relationships for precipitation were formulated as a function of particle diameter in power-law form and integrated over the particle size distributions to provide requisite mass-weighted fall speeds.

The major source of ice-particles (or mass) is primary ice-nucleation. Primary ice-nucleation is parameterised using the Meyers et al. (1992) nucleation scheme, which treats ice-nucleation as a combined function of the ambient temperature and ice-supersaturation. A time-splintering scheme is also represented in the model using the laboratory results reported in Hallett and Mossop (1974) and is formulated similarly to Gordon and Marwitz (1981) and Cotton et al. (1986). Homogeneous nucleation of ice from cloud water also occurs at temperatures \( \pm 40 \) °C.

All dependent variables are defined as a deviation from their environment values and horizontally averaged profiles of the quantities within the cloud. The model predicts cloud-averaged values of the vertical velocity, potential temperature, pressure perturbation relative to the large-scale environment, mixing ratios \( q_v \) and charge densities \( Q_q \) of water classes: water vapour, cloud water, rain, ice crystals, snowflakes, graupel and hailstones.

The charge densities \( Q_q \) represent the electrical charge residing on hydrometeor species \( x \). It is assumed that ice crystals, snowflakes, graupel and hailstones are capable of carrying electrical charge. The charge transfer between two hydrometeors \( (x \ and \ y) \) is:

\[
\frac{dQ_x}{dt} = \pi \frac{3}{4} \int \left[(D_x + D_y)^2 - V_x - V_y \right] E_{xy} N_x N_y Q dD_x dD_y = -\frac{dQ_y}{dt}
\]

where \( E_{xy} \) is the collision–separation efficiency between particles \( x \ and \ y \), \( D_x \ and \ D_y \) are particles diameters, \( N_x \) and \( N_y \) are size distributions of particles \( x \ and \ y \), \( Q \) is the separated charge during rebounding collisions between particles \( x \ and \ y \), and \( V_x \ and \ V_y \) are terminal velocities calculated in M2 by the following empirical equations \([\text{m s}^{-1}]\) (Lin et al., 1983; Rutledge and Hobbs, 1983; Ferrier, 1994):

\[
V_x = a_x D_x^{b_x}, \quad \text{where} \quad a_x = 19.3, \quad \text{and} \quad b_x = 0.37 — \text{for graupel particles}
\]

\[
V_y = a_y D_y^{b_y}, \quad \text{where} \quad a_y = 140, \quad \text{and} \quad b_y = 0.5 — \text{for hailstones}
\]

\[
V_i = a_i D_i^{b_i}, \quad \text{where} \quad a_i = 4.836, \quad \text{and} \quad b_i = 0.25 — \text{for snowflakes}
\]

\[
V_i = 0.1 — \text{for ice crystals}
\]

Similarly to M1, charge is also transferred from one category to another as water (liquid or frozen) mass is transferred.

2.2. Parameterisations of thunderstorm charging

The cloud electrification parameterisations are based on laboratory data for the non-inductive charge transfer between rebounding ice crystals and graupel in the presence of cloud droplets. In both models, the charge separation values are calculated in the temperature interval \([-40, 0\) °C], while at lower cold temperatures the charging is assumed to be zero (constrained by the requirement that some minimal supercooled water be available in the cloud environment in order for charge transfer to occur). Four different parameterisations are incorporated in both models:

1. SKM — the parameterisation is based on the equations presented in Saunders et al. (1991). According to these equations the charge transfer \( Q \) per separation event for graupel/ice crystal collision depends on crystal size \( d \) and relative velocity \( V \) following the equation:

\[
Q = Ad^aV^b q
\]

where \( A, a, \) and \( b \) are constants depending on crystal size and graupel velocity and are tabulated in Saunders et al. (1991); \( q \) depends on in-cloud temperature \( T_c \) and effective water content (EW). The effective water content is defined as the LWC effectively swept out by the path of a graupel particle, that is:

\[
EW = E_c LWC
\]

where \( E_c \) is the collection efficiency between graupel and water droplets, which is dependent on graupel velocity.
and the diameter of graupel and cloud droplets (Fonda and Herne, 1957).

2. BSMP — the parameterisation is based on the equations presented in Brooks et al. (1997). According to these equations the charge transfer $Q$ per separation event is given by Eq. (5), however $q$ depends on the rime accretion rate (RAR).

$$RAR = EWV$$

Fig. 1. SkewT–logP radiosonde diagram used for simulations for A) 19 July 1981, CCOPE, and, B) 29 June 1989, NDTP. Temperature and dew point temperature are denoted by bold and dashed lines, respectively.
where $V$ is the relative velocity between graupel and ice crystals.

3. $T_{\text{orig}}$ — the parameterisation is based on the data presented in Takahashi (1978). These data are included in the numerical models as a look-up table. The charging $Q$ depends on crystal size and relative velocity and is calculated as in Takahashi (1984):

$$Q = \alpha q$$

(8)

where $\alpha = 5 \left( \frac{d}{d_0} \right)^2 \left( \frac{V}{V_0} \right)$, $d_0 = 100$ µm and $V_0 = 8$ m s$^{-1}$ (based on Takahashi, 1984) and $\alpha$ is restricted to a value of 10.

4. $T_{\text{hybrid}}$ — the look-up table values for $q$ are used as for $T_{\text{orig}}$, however Eq. (5) was used in the calculation of $Q$ rather than Eq. (8).

In both models using both parameterisations based on Takahashi laboratory data, it was assumed that the charge separation values at temperatures lower than $-30 \degree C$ are the same as at $-30 \degree C$.

For the simulations using M2, similarly to other studies (for example, Helsdon et al., 2001; Mansell et al., 2005), it is assumed that the laboratory results are also valid for the interactions: graupel/snow, hail/ice crystals, and hail/snow. One can expect that this assumption is acceptable when the so called "hail" does not enter the wet growth regime at the calculated LWC. Due to the fact that our study reveals a significant difference between charge distributions simulated by M1 and M2 and that the above mentioned assumption may not be valid, the results of the simulations by a modified version of M2 (denoted as M2*) is additionally analyzed. The difference between the M2* and M2 models is that in M2* only charge separation during rebounding collisions between graupel and ice crystals is taken into account. In the simulations by M1, M2 and M2*, the charge transfer per separation event $Q$ is limited to less than 500 fC for positive charge and $\sim 200$ fC for negative charge in the SKM and BSMP parameterisations. In the case of Tak_orig and Tak_hybrid the corresponding limit of $Q$ was established at $\pm 100$ fC. The limit values were chosen based on the maximum values measured in the corresponding laboratory experiments for the separated positive and negative charges.

3. Numerical simulations and results

Both models were run using temperature and moisture profiles observed on July 19, 1981 (Fig. 1A) during the Cumulus Co-operative Precipitation Experiment (CCOPE cloud), near Miles city, Montana and also on 28 June 1989 (Fig. 1B) when a large mesoscale convective system with cloud), near Miles city, Montana and also on 28 June 1989. These facts do not restrict our study since our work is directed only to the examination of the most significant influences on model-simulated charge structures during the growth stages of thunderstorms (before first lightning) as a function of model type, non-inductive charge parameterisation, and microphysical and dynamical properties of the simulated thunderstorms. In the present study, it is accepted that the 'growth stage' of the simulated clouds extends until the appearance of intensive downdraughts.

The paper makes no conclusions regarding which specific charge parameterisation provides the most "realistic" charge distribution relative to the observed clouds. Thus, the simulated thunderclouds should only be considered as idealized model representations of clouds.

The forcing parameters necessary for simulations by M1 and M2 were chosen using a range of realistic values in such a way that both of the model microphysical and dynamical characteristics of a particular cloud were similar. Both models were initiated using the same thermodynamic profiles (air temperature and dew point air temperature) collected for the NDTP and CCOPE cases. The maximum time step $d_t$ in M1 was 5 s, decreasing when the updraught velocity $W$ was very high, in such a way that the spatial resolution $Z=Wd_t$ is no larger than $50$ m. In M2 the vertical resolution was fixed at 200 m and the minimum time step was 5 s, with smaller variations (less than 1 s), according to Ferrier and Houze (1989), to maintain model stability during intense convection.

Tables 1 and 2 show the microphysical and dynamical characteristics (maximum values of the cloud depth, updraught velocity, and liquid water, graupel and ice crystal contents) of the CCOPE and NDTP thunderstorms respectively, simulated by the M1, M2 and M2* models. Table 1 reveals that the simulated maximum values of cloud top height, models provide a rather rough approximation of the cloud dynamics, the simulation method is well suited to the study of the observed CCOPE cloud, because it was an isolated small cumulus cloud with maximum updraught speed between 10 and 15 m s$^{-1}$. The analyses of field measurements (Dye et al., 1986) reveal that during the early stages of the CCOPE cloud, negative charge accumulated near the 7 km ($\sim-20$ $\degree C$) level with positive charge located above negative charge (i.e., the presence of a positive dipole).

Since one-dimensional models are limited in their simulation of large mesoscale convective systems, the model results for the simulated NDTP cloud have to be considered as a simulation of an isolated cumulus cloud developing in the same environmental conditions. There is also no available information on the distribution of the electric field in the NDTP; Helsdon (1990) only reported a high percentage of positive cloud-to-ground lightning observed during the mesoscale convective system on 28 June 1989. These facts do not restrict our study since our work is directed only to the examination of the most significant influences on model-simulated charge structures during the growth stages of thunderstorms (before first lightning) as a function of model type, non-inductive charge parameterisation, and microphysical and dynamical properties of the simulated thunderstorms. In the present study, it is accepted that the 'growth stage' of the simulated clouds extends until the appearance of intensive downdraughts.

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<table>
<thead>
<tr>
<th>Cloud depth [km]</th>
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<th>Max cloud water content [g m$^{-3}$]</th>
<th>Max ice crystal content [g m$^{-3}$]</th>
<th>Max graupel content [g m$^{-3}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 3.9–11</td>
<td>18 at 10.5 km (23 min) at $-45 \degree C$</td>
<td>1.3 at 6 km (11 min) at $-13 \degree C$</td>
<td>1 at 8.8 km (21 min) at $-33 \degree C$</td>
<td>0.21 at 6.3 km (18 min) at $-18 \degree C$</td>
</tr>
<tr>
<td>M2 3–11</td>
<td>21 at 8 km (15 min) at $-35 \degree C$</td>
<td>1.12 at 5 km (10 min) at $-15 \degree C$</td>
<td>0.8 at 10.2 km (15 min) at $-35 \degree C$</td>
<td>0.5 at 6 km (13 min) at $-20 \degree C$</td>
</tr>
<tr>
<td>M2* 3–11</td>
<td>21 at 8 km (15 min) at $-35 \degree C$</td>
<td>1.12 at 5 km (10 min) at $-15 \degree C$</td>
<td>0.7 at 10.4 km (15 min) at $-35 \degree C$</td>
<td>0.29 at 6.4 km (13 min) at $-21 \degree C$</td>
</tr>
</tbody>
</table>

In M2, maximum ice crystal content is a sum of ice crystal and snow, and maximum graupel content is a sum of graupel and hail contents.
updraught velocity, liquid water, graupel and ice crystal contents of the simulated CCOPE thunderstorm by both models are similar, and in reasonable agreement with corresponding values measured in real clouds. In M2, crystal content represents the sum of ice crystals and snowflakes, and the graupel content is a sum of graupel and hailstone contents. Thus, in Table 1 it is apparent that the M2 * simulation produced almost the same maximum values of graupel content as the M1 simulation (0.29 and 0.21 g m\(^{-3}\), respectively). However, the M2 maximum simulated “graupel” contents (0.5 g m\(^{-3}\)) were twice that of the M1 model. Conversely, for the NDTP thunderstorm simulation (Table 2) the maximum graupel contents obtained

<table>
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<tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>M1</td>
<td>2.9–13</td>
<td>29.7 at 10.7 km (18 min) at (-55) °C</td>
<td>1.42 at 6 km (12 min) at (-10) °C</td>
<td>0.98 at 9 km (12 min) at (-35) °C</td>
</tr>
<tr>
<td>M2</td>
<td>2–13</td>
<td>29.2 at 11 km (17 min) at (-50) °C</td>
<td>0.9 at 5 km (11 min) at (-10) °C</td>
<td>0.54 at 9.8 km (16 min) at (-40) °C</td>
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<td>M2 *</td>
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<td>29.2 at 11 km (17 min) at (-50) °C</td>
<td>0.9 at 5 km (11 min) at (-10) °C</td>
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In M2, maximum ice crystal content is a sum of ice crystal and snow, and maximum graupel content is a sum of graupel and hailstone contents.

In Fig. 2, Net charge density \(\rho_{\text{net}}\) (nC m\(^{-3}\)) of the CCOPE thunderstorm simulations using M1 (first column), M2 (second column), and M2 * (third column) as a function of time (min) and height (km). Bold lines on dark (red) background are the positive charge densities, dotted (blue) lines on white background are the negative charge densities. The min/max values of simulated charge densities and the contour intervals are given on the plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2

Microphysical and dynamical characteristics of simulated NDTP thunderstorm by M1 (first row), by M2 (second row) and by M2 * (third row) models

<table>
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</tbody>
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with M2 (0.34 g m\(^{-3}\)) and M2\(^*\) (0.33 g m\(^{-3}\)) are almost the same and very similar to the maximum graupel content simulated by M1 (0.24 g m\(^{-3}\)). However, the maximum graupel content in the M2\(^*\) NDTP cloud occurs at significantly lower temperatures at higher levels (\(-39^\circ\text{C}, 9.2\text{ km}\)) than in the M2 cloud (\(-25^\circ\text{C}, 7.6\text{ km}\)) (Table 2). This is due to the hail particles in M2, which are larger than the graupel and cannot be lifted to higher levels. The M1 simulation of NDTP produced larger cloud water (1.42 g m\(^{-3}\)) and ice crystal (0.98 g m\(^{-3}\)) contents than the M2 model simulation (0.9 and 0.47 g m\(^{-3}\), respectively).

The net charge densities \(\rho_{net}\) (as a function of model time and height) of the CCOPE and NDTP clouds simulated by M1, M2 and M2\(^*\) using each of the 4 parameterisation schemes, are presented in Figs. 2 and 3, respectively. Fig. 2 shows that the M1 simulations (left column) lead to the formation of a positive dipole during some period of cloud development when the SKM, BSMP and T\(_{\text{hybr}}\) parameterisations were used for the CCOPE case. The tripole structure is formed between 17 and 20 min of simulation when the BSMP parameterisation is used by the M1 model. The charge is mainly positive in the cloud simulated by the M1 T\(_{\text{orig}}\) scheme, and a small negative charge centre is formed at a height of 6 km between 18 and 24 min. The charge density distribution in the cloud simulated by M2 CCOPE (middle column in Fig. 2) using SKM and BSMP has a more complicated structure — more than 3 layers of charge alternating in polarity are formed. The charge density simulated by T\(_{\text{orig}}\) and T\(_{\text{hybr}}\) schemes using M2 corresponds to a tripole between 12 and 18 min of model simulation. After 18 min, the cloud simulated using the T\(_{\text{hybrid}}\) scheme in CCOPE has a structure that corresponds to a positive dipole, while four charged regions alternating in polarity are formed in the M2 T\(_{\text{orig}}\).

Fig. 3. Net charge density \(\rho_{net}\) (nC m\(^{-3}\)) of the NDTP thunderstorm simulations using M1 (first column), M2 (second column), and M2\(^*\) (third column) as a function of time (min) and height (km). Bold lines on dark (red) background are the positive charge densities, dotted (blue) lines on white background are the negative charge densities. The min/max values of simulated charge densities and the contour intervals are given on the plots. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
Tables 3 and 4 show the maximum values of positive and negative net charge density in the CCOPE and NDTP thunderstorms respectively, simulated by the M1, M2 and M2* models. The maximum values of positive and negative charge density in the simulations of CCOPE thunderstorms by M2 using the four parameterisations of non-inductive charging are of the same order of magnitude (Table 3). Similar values are also obtained by M1 simulations using BSMP (~5.5/2.2 nC m⁻³) and SKM (~7.3/6.5 nC m⁻³) parameterisation schemes. However, the corresponding maximum values from the M1 model using T_orig and T_hybrid are an order of magnitude smaller (~0.04/0.79 and ~0.81/1.28 nC m⁻³, respectively).

The maximum values of negative net charge density in the cloud simulated by M1 CCOPE occurs at the same time (18–19 min) and height (about 6.5 km), corresponding to in-cloud temperatures of ~18 to ~20 °C, being independent of the parameterisation used for non-inductive charge transfer. The height and temperatures where the maximum values of positive net charge densities occur are approximately the same when SKM, T_orig and T_hybrid parameterisations are used in model M1. The main positive charge centre is located significantly higher (11 km) and at lower temperature (~57 °C) when BSMP was used in M1 for the CCOPE case. These results are in agreement with the field measurements of Dye et al. (1986), showing that the main positive charge centre is situated above the main negative centre. The height and temperature of the maximum negative and positive net charge values reached in the simulations of CCOPE using M2 are significantly different for different parameterisations of non-inductive charge transfer (second row in Table 3) relative to those of the same simulations using M1. The most remarkable difference is that the maximum values of the positive charge densities are at lower levels (higher temperatures) than the negative maxima when the CCOPE case is simulated by M2 using SKM and BSMP, i.e. the opposite of any results obtained by M1 and by M2 with T_orig and T_hybrid. These results do not agree with the observations of Dye et al. (1986).

Fig. 3 shows that simulations of the NDTP cloud using M1 (left panel) lead to the formation of a positive dipole when T_orig and T_hybrid parameterisations are used. A similar structure is obtained with the SKM parameterisation until 16 min of simulation, when a negative charge region is
formed above 10 km. Such a region is also obtained by M2, with the same charge transfer parameterisation, but in this case the lower negative charge region is thinner and below it there is a positive region. Simulations using M2 (middle panel of Fig. 3) with T_orig and T_hybrid parameterisations lead to the formation of a quadruple charge structure. Using BSMP parameterisation in M1, until 17 min of simulation, the main negatively charged region is between two positively charged regions. After that, a quadruple charge structure is formed. It can be seen that until 16 min of simulation the usage of SKM and BSMP parameterisations in M2 lead to the same charge structure in the NDTP simulated cloud, while M1 charge structure using SKM differs from the charge structure obtained by BSMP. The results also show that the use of M2 for the simulations of NDTP gives higher values for the total charge density than the simulations by M1, regardless of the parameterisation of non-inductive charge transfer included in the models. The use of T_hybrid gives the lowest values for maximum negative and positive charge densities by both models in the NDTP thunderstorm case.

The results presented in Table 4 reveal that the location of maximum values of net positive and negative charge density depend on the model (M1 or M2) as well as on the type of parameterisation used for charge transfer. The main positive charge centre is above the negative charge centre in the M1 NDTP thunderstorm simulation when BSMP and Tak_orig parameterisation are used. The same location of corresponding maximum values of positive net charge densities occurs in the M2 NDTP simulated cloud when SKM, T_orig and T_hybrid are used.

From the above analyses it is clear that differences between the charge density distributions in both M1 and M2 thunderstorm simulations, within some of the charge transfer parameterisation schemes, are significant, and it is also clear that the impact of these schemes on charge distribution depends on the cloud characteristics. To minimize the difference between M1 and M2 the modified version of M2 (denoted as M2⁎) was run using the same four charge transfer parameterisations. As was mentioned at the end of Section 2, the only difference between M2⁎ and M2 models is that in M2⁎ only rebounding collisions between graupel and ice crystals are taken into account.

The M2⁎ charge density distribution in the CCope and NDTP thunderstorms are shown in the third column of Figs. 2 and 3, respectively. Analysis of the results indicates that in some cases the M1 charge density is closer to the M2⁎ charge density rather than to M2: for example, the charge distribution in the CCope cloud using BSMP (first row of Fig. 2) and in the NDTP cloud using SKM (second row of Fig. 3). However, in other cases the charge distributions simulated by M1 are more similar to M2 rather than M2⁎: for example, charge distributions in the CCope thunderstorm using SKM (second row in Fig. 2). The results presented in Tables 3 and 4 show that in most cases the heights and temperatures of maximum net positive and negative charge simulations by M1 more closely correspond to the simulation of M2⁎ rather than to M2. For example, contrary to the results obtained by M2, the main positive charge centre is above the main negative simulated by M2⁎ for the CCope and NDTP clouds, with the BSMP parameterisation scheme in agreement with the corresponding simulation of M1. However, in some cases M2⁎ simulated the location of the main negative and positive charge centres approximately in the same position as M2, and different positions are obtained by M1 (for example, second row of Table 3).

4. Discussions and conclusions

The present study demonstrates that model-simulated charge structures during the growth stages of thunderstorms depend significantly on the particular models used and not only on the charging parameterisation and on the microphysical and dynamical properties of the simulated thunderstorms.

The effect of the parameterisations used for non-inductive charge transfer included in a particular cloud model noticeably influenced the results concerning thunderstorm electrification. For example, the maximum values of negative and positive charge density were smaller when the Takahashi (1978) data were used in the simulations by both models. However, this reduction of the charge values is different depending on the model used: it is more pronounced in the M1 simulations (one order of magnitude in the M1 CCope cloud) than in the M2 simulations. Similar to other studies (Helsdon et al., 2001; Mansell et al., 2005; Barthe and Pinty, 2007), there is also a difference in the charge structure formation of a particular simulated cloud using one and the same model, depending on the parameterisation of non-inductive charge transfer. This effect of parameterisation scheme depends also on the model used and/or on cloud dynamics and microphysics.

Comparisons between the different 1-D cloud model simulations using the same parameterisation reveal that the model dynamics and microphysics also significantly influenced the charge structure of the simulated clouds. The distinction between charge density distributions simulated by different cloud models is as noticeable as the difference due to the parameterisation schemes of charge transfer, and to different microphysical and dynamical characteristics of simulated thunderstorms. While the impact of the parameterisations of non-inductive charge transfer and the impact of cloud dynamics and microphysics on charge structure was expected and noted in many previous studies, the significant impact of a particular model used is puzzling. It has to be mentioned that in the M1 model there are non-inductive interactions only between ice crystals and graupel, while in M2 the non-inductive charging is a result of interactions between graupel/ice crystal, graupel/snow, hail/ice crystal and hail/snow, which certainly contributes to the difference in the results. The simulations using the modified version of M2 cloud model, M2⁎ (excluding non-inductive charging between graupel/snow, hail/snow and hail/ice crystals) confirm the above assumption. Moreover, the results by M2⁎ simulations are also different from the corresponding results obtained by M1 simulations. One possible reason for this is that although both models create approximately similar values (in the context of the model simulations) for maximum updraught velocity and water substances (liquid and solid), the modelled vertical distribution of these quantities is different and the charge structure is a sensitive function of the condensate and associated updraught profile differences. Additionally, the charge transfer is a sensitive (non-linear) function of graupel and ice crystal sizes, their
concentration and density, and their relative velocity, which are calculated in different ways in the respective cloud models. Our analysis reveals that in M2 the ice crystal concentration at $T = -20^\circ C$ is more than an order of magnitude larger than the corresponding value in M1. This implies that the separated charge for rebounding collisions between graupel and ice crystals will be an order of magnitude larger even if all other quantities in Eqs. (1) and (3) are equal. The structure of the 1-D cloud model and presentation of results may also contribute to the apparent effect of the model revealed in the study. The net charge density presented by the calculations of the M1 model is a combination of the total charge density in the updraft and non-active cloud regions. We think, in this manner, it is more correct to make a comparison of charge density distributions simulated by the M2 model.

The results also show that M1 is less sensitive to the charge transfer parameterisation scheme used in the simulations of the CCOPE case than in the simulations of the more dynamically active NDP case. On the other hand, M2 exhibits more sensitivity to the charge transfer parameterisations used in the simulations of both thunderstorms. For example the location of the negative and positive charge centres in the M1 CCOPE simulated cloud were almost the same for all the parameterisation schemes, and this is in fair agreement with the conceptual picture for charge distribution of the real CCOPE cloud given in Dye et al. (1986). Similar results are obtained by M2 using only the Tak_hybrid parameterisation scheme.

The simulations conducted in this study demonstrate that it is too early to make any conclusions regarding which, if any, of the existing parameterisation schemes are better suited to the realistic simulation of electrical charging in real clouds. Taking all of this into account, including the dependence of charge transfer on the liquid water content and the in-cloud temperature, representation of the sign and magnitude of the separated charge in non-inductive interactions between graupel and ice crystals, the importance of the relative velocity and sizes of the interacting particles (Saunders et al., 2006; Tsenova et al., 2007), as well as the cloud droplet size spectrum (Mitzeva et al., 1999; Avila et al., 1999; Pereyra and Avila, 2002) and on the saturation of water vapour in the cloud (Mitzeva et al., 2005; Saunders et al., 2006), it is clear that new parameterisations that take into account these new variables have to be included in the numerical models of thunderstorm simulations. Further laboratory experimentation related to the charge transfer occurring during interactions of graupel/snow, hail/ice and hail/snow under realistic cloud conditions are also needed.

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References

Albrecht, R.J., Morales, C.A., Silva Dias, M.A.F., Petersen, W., 2006. Applications of an electrified one-dimensional cloud model. 2nd Conference on Meteorological Applications of Lightning, Atlanta, GA.


