LIGHTNING PARAMETRIZATION IN NUMERICAL MODELS: DESCRIPTION AND RESULTS FROM BRAMS AND AN 1D CLOUD MODEL

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Abstract - Numerical schemes of cloud electrification and lightning have been implemented into two numerical models at the University of Sao Paulo: the mesoscale Brazilian Regional Atmospheric Modelling System (BRAMS), and the one-dimensional cloud model of Ferrier and Houze (1989). Both cloud models have electrical charge separation based on non-inductive collisions between ice particles found in various laboratory studies. The resulting electric field is calculated at each time step and a lightning is triggered when this local field overcomes the break-even electric field. In the 1D cloud model, the lightning propagates bidirectionally (upward and downward), neutralizing charges along the channel until the electric field reduces to 15 kV m\(^{-1}\). In the BRAMS model, the lightning is propagated bidirectionally towards two main exceeding net charge regions until the magnitude of the electric field reduces to 20 kV m\(^{-1}\). At this point the lightning channel is branched into streamers where the total net charge density is greater then 0.5 nC m\(^{-3}\), and the charges are neutralized along the whole lightning path. These models were used to simulate thunderstorm conditions observed during the wet and dry-to-wet seasons of southwestern Amazon. Both models were able to simulate the literature known tripolar and dipolar structures of thunderstorms, and other more complicated multipolar structures.

1 INTRODUCTION

To explain how a thunderstorm become electrified has been a goal of laboratory experiments and field observations for several decades. Investigators had made substantial progress evaluating various electrification processes, and have found the non-inductive mechanisms of charging capable of producing maximum electric field magnitudes comparable of those observed in nature [1] [2] [3] [4]. However, observations of the electrical properties of thunderstorms remain unexplained because it is nearly impossible to sample adequately all processes important to thunderstorm electrification [1]: relevant scales range from properties of ions to particle trajectories; storms are complex and can change drastically in a few minutes, and measurements are limited because many regions inside the cloud are hostile to instrumentation, aircraft and balloons. Therefore, one powerful and possible instrument to test laboratory and theoretical hypothesis of thunderstorm electrification is the simulation of electrified clouds using numerical weather prediction models.

This paper presents the description and preliminary results of numerical schemes of cloud electrification and lightning implemented in two numerical models: the mesoscale Brazilian Regional Atmospheric Modelling System (BRAMS), and the one-dimensional cloud model of Ferrier and Houze [5]. In section 2, there is a brief description of both models, focusing on the microphysical processes of hydrometeors, electrification of clouds and lightning processes. Section 3 presents the preliminary results in modelling an electrified cloud, and in the last section we summarized the findings and offered discussion remarks and perspectives.

2 THE CLOUD MODELS

2.1 The one-dimensional cloud model

The cloud model used in this work is based on a cumulonimbus convection of the dynamic model of Ferrier and Houze [5], coupled with a four-ice category (4ICE) representation of bulk cloud microphysics by Petersen [6], described in Simpson et al., [7] and Keenan et al. [8]. The 4ICE scheme includes prognostic equations for cloud ice, snow, graupel and hail mixing ratios. In order to use the model for examining the microphysical and electrical evolution of convection, the addition of parameterizations for non-inductive collision charging of the precipitation, and lightning discharges. The model dynamics was not modified.

The cloud microphysics is based on exponential (rain, snow, graupel and hail) and monodisperse (cloud water and ice) distributions of the hydrometeors. The mixing ratio \(q_v\) of these particles \(v\) are governed by the continuity equation of mass, which can be expressed as a...
balance of the advection (ADV), turbulence (TURB), sources (SOUR) and sinks (SINK) of the hydrometeors:

$$\frac{\partial q_x}{\partial t} = \text{ADV}_x + \text{TURB}_x + \text{SOUR}_x + \text{SINK}_x$$ (1)

The advection and turbulence terms are governed by the model dynamics. The sources and sinks of $Q$ are the microphysical processes of formation, development and vanishment of cloud particles, such as condensation, evaporation, autoconversion, coalescence, breakup, rimming, acretion, etc. From all these processes, those that involve the interaction by collision-rebounds between ice particles accounts for the electification of the cloud. Similarly to the continuity equation of hydrometeor mixing ratios (1), the continuity equation for electric charge densities ($Q_x$) at the ice particles $x$ is:

$$\frac{\partial Q_x}{\partial t} = \text{ADV}_x + \text{TURB}_x + \text{SOUR}_x + \text{SINK}_x$$ (2)

where the advection and turbulence terms are also governed by model dynamics. The main sources and sinks of $Q$ are the collision-rebound between ice particles, where the non-inductive charging mechanism happens. Per unit time, the volume in which a particle $x=1$ of diameter $D_1$ collides with a particle $x=2$ of diameter $D_2$ is given by the collision kernel $K_{12}$, and number densities ($N_1$, $N_2$) of diameters $D_1$ and $D_2$, that is

$$\text{SOUR}_1 = \int K_{12} N_1(D_1) N_2(D_2) \delta \mu dD_1 dD_2 = \text{SINK}_2$$

$$K_{12} = \frac{\pi}{4} |D_1 + D_2|^2 |v_1 - v_2| \xi_{12}$$ (3)

where $v_1$ and $v_2$ are particles 1 and 2 terminal fall velocities. The collision kernel is the effective cylindrical volume for collision of particles 1 and 2 times the fraction of particles 1 in this volume that collides with particles 2 and separate from it (collision-separation efficiency, $\xi_{12}$), $\delta \mu$ is the magnitude of charge transferred during the collision based on laboratory measurements. In this work we use Takahashi [9] measurements, which found that the charge transferred to the graupel during a collision with an ice crystal is a function $f(LWC, T)$ of the liquid water content ($LWC$) and temperature ($T$), as shown in Figure 1 and mathematically expressed as

$$\delta \mu = f(LWC, T) \times \alpha, \quad \alpha = \frac{D_2}{D_b} \left| \frac{v_1 - v_2}{v_0} \right|$$ (4)

where $\alpha$ is a correction factor for the laboratory measurements conditions, which varies from 0 to a maximum of 10, $D_b=100 \mu$m and $v_0=8$ ms$^{-1}$.

Once the model starts to electrically charge hydrometeors, it is calculated the electrical field $E$ at each grid point and if any overpass an adopted limit, a lightning occurs. In this work, it was considered the breakeven electric field ($E_{\text{even}}$) [10]:

$$E_{\text{even}} = 1.208 \exp \left( -\frac{z}{8.4} \right)$$ (5)

where $z$ is the altitude height in km. When $E(z) > E_{\text{even}}(z)$, the cloud model parameterizes a lightning discharge, which is consisted of describing the lightning path and re-arranging the electrical charge by neutralizing an determined amount of charge.

The lightning path parameterization is adapted from the work of MacGorman et al. [11]. After found the grid point that exceeded the $E_{\text{even}}$, the leader is propagated bi-directionally towards the top and bottom of the storm, in all consecutive grid points where $E$ is higher than $E_{\text{even}}=15$ kVm$^{-1}$. Having the upper and bottom ends of the lightning, the leader extended four more grid points up and down to guarantee that lightning can also propagate into regions of very electric charges [11].

The charging neutralization is same as Ziegler and MacGorman [12], commonly used in various works [10] [13] [14]. According to Ziegler and MacGorman, the charge density added to the grid point for the neutralization is:

$$\delta Q_{\text{net}} = \begin{cases} Q_{\text{cor}}, & \text{if } Q_{\text{net}} < Q_{\text{th}} \\ 0, & \text{if } Q_{\text{net}} \geq Q_{\text{th}} \end{cases}$$ (6)

$$\delta Q_{\text{net}} = (Q_{\text{net}} - Q_{\text{th}}) f_p - \delta Q_{\text{cor}}, \quad \text{if } Q_{\text{net}} < Q_{\text{th}}$$ (7)

$$\delta Q_{\text{net}} = -(Q_{\text{net}} - Q_{\text{th}}) f_p - \delta Q_{\text{cor}}, \quad \text{if } Q_{\text{net}} > Q_{\text{th}}$$ (8)

where $\delta Q_{\text{net}}$ is the net charge density before the lightning, $Q_{\text{th}}$ is a threshold equal to 0.5 nCm$^{-3}$, $f_p$ is the fraction to be neutralized and equal to 0.33, and $\delta Q_{\text{cor}}$ is a correction to guarantee that same amount of negative and positive charges are neutralized.

Figure 1 - Charge gained by graupel colliding with ice particles as a function of temperature ($T$) and liquid water content ($LWC$) [9]-[LWC,T].
The continuity equation of the eight hydrometeors mixing ratios at the model is also based on the dynamical processes of advection and turbulence, and microphysical processes that determines their sources and sinks, just like the equation (1) in the 1D model. As in the first model, the collision-rebound between the ice particles are the processes of sources and sinks that accounts to the charge density separation in the model based on equation (2). These electrification processes were adapted from the work of Altaratz et al. [19] (CSU-RAMS) to the BRAMS version. The sources and sinks formulation for charge densities is the same as equations (3) and (4) except that the number concentration of ice hydrometeors is given by equation (9).

Once again, as the model starts to electrically charge hydrometeors it is calculated the electrical field $E$ at each grid point and if any overpass the $E_{\text{crit}}$ a lightning occurs. As a 3D model, $E$ is calculated by Gauss equation with the total charge density:

$$\nabla \cdot \vec{E} = \frac{Q_{\text{net}}}{\varepsilon_0} \quad (10)$$

where $\varepsilon_0$ is the dielectric constant of the air. The electric potential $\phi$ is given by

$$\vec{E} = -\nabla \phi \quad (11)$$

Then the electric field can be obtained resolving the Poisson equation:

$$\nabla^2 \phi = -\frac{Q_{\text{net}}}{\varepsilon_0} \quad (12)$$

The lower boundary of the grid domain is assumed to be null (Dirichlet condition) while the upper and lateral boundaries have the Neumann condition ( $\partial \phi / \partial n = 0$ ). The potential field is resolved using the extended lateral boundaries to increase the solution precision by decreasing the influence of spread charges that come from the boundary condition.

As in the 1D model, when $E(z) > E_{\text{crit}}(z)$ a lightning channel is parameterized. The lightning follows the electric field direction at the first step on the grid point where the lightning began, and is spread randomly towards the consecutive points where $E(z) > 0.95E_{\text{crit}}(z)$ or $Q_{\text{net}} > 0.5nCm^{-3}$, bi-directionally [11]. This process continues along the consecutive points until $E_{\text{crit}}=15$ kVm$^{-1}$. If one end of the lightning reaches an altitude below 2 km or reaches the air outside the cloud, the model detects a cloud-to-ground or a cloud-to-air
lightning, respectively, and the charge of the lightning channel is set to zero [12]. Otherwise, if both ends of channel terminate inside the cloud, a cloud-to-cloud lightnings is stated and the charge neutralization is done by equations (6) to (8) [12].

3 RESULTS

It is presented here a case study of one simulation using each of the models (1D and BRAMS) with initial thermodynamic conditions (vertical profiles of temperature $T$ and dew point temperature $T_d$) given by a radiosonde launched at Ouro Preto d'Oeste, RO, Brazil on 0600 UTC 24 September 2002 (Figure 2).

The 1D model was initiated with a low level profile of vertical velocity $w$ [5], which lifts the air to higher levels and initiate the cloud. The vertical profile of $w$ increases parabolically from 0 ms$^{-1}$ at the surface to 2 ms$^{-1}$ at $z=1$ km, during the first 30 minutes of simulation. The simulation was conducted for two hours with a time step of approximately 5 s [5], and the vertical resolution of the model is $\Delta z=200$ m. The charge electrification of hydrometeors in ice phase occurred in a rapid and intense way as shown in Figures 3. Charge transfer was confined to the mixed cloud phase (where there is the presence of ice particles and supercooled cloud droplets, ~−4.8 km of height) due to the collision-rebounding mechanism between ice particles presented at these levels. Ice crystals were mainly charged positively while graupel and snow were charged in both polarities. Positive charging of graupel occurred at low levels of height (~ 5 km) due to low temperatures (Figure 1). The charge transfer scheme was able to charge the particles in an amount that the electric field was high enough to breakdown the air rigidity, represented by the breakeven electric field in equation (4). The simulated cloud had a tripoar structure ($Q_{net}$ at Figure 3) and produced 12 intra-cloud lightnings.

BRAMS model was used in a single cloud simulation initiated by a heat font in the center of the grid during the first 28 minutes of simulation (2°C of amplitude at the first 6 vertical levels, which decreases with a radius of 20 km in x and y coordinates). The model grid had 30 points with $\Delta x=\Delta y=10$ km, and 33 points in $z$, with 100 m of resolution in the first level, increasing in a 1.2 rate until the maximum of 1km, with no topography. The simulation was conducted during a total time of 2 hours with a time step of 10 s. The simulation had a horizontal homogeneous initiation, that is the vertical profile of temperature, humidity and wind (set to zero) is the same for all grid points in $t=0$.

Figure 4 shows the vertical distribution and temporal evolution of the total mixing ratio ($q_t$ – the sum of all hydrometeor mixing ratios) and net charge density ($Q_{net}$) of the single cloud simulation with BRAMS, at the center of the grid ($x=y=150$ km). It can be seen that the model created a deep vertical cloud (with the top at $\sim$14 km of height), when the heat low level forcing terminated (30 min). The maximum updrafts $w$ occurred from 40 to 55 minutes of simulation, with values from 10 to 17.5 ms$^{-1}$, at 3 to 12 km of height (not shown). At this same time interval there was the maximum production of ice hydrometeors and, therefore, production of electric
charges some minutes later due to the collision-rebound between these particles.

At $t=50$ min the amount of charge generated by the model was sufficient to parameterize one single lightning. This moment ($t=50$ min) is presented in Figure 5. Figure 5 shows the spatial ($x$) and vertical distributions of the charge densities of the five ice hydrometeors, $Q_i$ (nCm$^{-3}$) (pristine ice, snow, aggregates, graupel, and hail), as well as the net charge density ($Q_{\text{net}}$), at the grid point $y=150$ km and $t=50$ min (when the lightning occurred). The lightning path is represented by the black continuous line at $Q_{\text{net}}$ panel.

Figure 4 – BRAMS simulation. Temporal evolution and vertical distribution of the total liquid water content mixing ratio ($q_l$) and net charge density ($Q_{\text{net}}$) at the grid point $x=150$ km and $y=150$ km.

Figure 5 – BRAMS simulation. Spatial and vertical distributions of the charge densities of the four ice hydrometeors, $Q_i$ (nCm$^{-3}$) (pristine ice, snow, aggregates, graupel, and hail), as well as the net charge density ($Q_{\text{net}}$), at the grid point $y=150$ km and $t=50$ min (when the lightning occurred). The lightning path is represented by the black continuous line at $Q_{\text{net}}$ panel.

Figure 6 – BRAMS simulation. Temporal evolution of the maximums of net charge density ($Q_{\text{net}}$), the electric field ($E$), and mixing ratios of graupel+hail, pristine+snow+aggregates, cloud water+rain (representing LWC), and vertical velocity ($w$) at the grid point $x=150$ km, $y=150$ km and $t=50$ min (when the lightning occurred). The dashed black line indicates the time when the lightning has occurred.

Figure 7 – BRAMS simulation. Vertical distribution of the cloud electric field ($E_{\text{cloud}}$) and the breakeven field ($E_{\text{breakeven}}$) at the grid point $x=150$ km, $y=150$ km and $t=50$ min (when the lightning occurred).
(\(q_{\text{gravity+snow-aggregate}}\)), cloud water and rain (\(q_{\text{cloud+rain}}\)), and vertical velocity \(w\). It can be seen that the maximum resulting charge (\(Q_{\text{net}}\)) happened 4 to 5 minutes after the maximum of the hydrometeors at the ice phase and 1 minute after the maximum of updraft \(w\). This shows that the model is responding adequately to the charge transfer parameterization, which is dependent on the hydrometeors velocity and mixing ratios [9]. It can also be seen that the maximum of \(Q_{\text{net}}\) generated a maximum electric field of \(E \sim 123\) kV/m, which overpassed the \(E_{\text{breakover}}\) considered as threshold, as shown in Figure 7.

4 CONCLUSIONS

Both 1D and BRAMS cloud models reproduced satisfactorily the dynamics, microphysical and electrical processes considered in the parametrizations proposed here. The 1D model was able to produce an electrical life cycle of a cloud with 12 intra-cloud lightnings. BRAMS however produced only one lightning. The major reason for this is the resolution of the grid simulated: 10 km of horizontal resolution is too coarse to reproduce charge transfer processes, which occurs in the scale of nano to micrometers. This coarse grid was a preliminary test, once the model has a good numerical stability with this type of grid. Future simulations need (and will be done) a finer grid (1 km to 100 m of horizontal resolution), or scale adaptations are needed to coarse grids like the one shown in this work.

This study shows that numerical weather models will be able, in a near the future, to predict lightning strokes.

5 REFERENCES


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