ELECTRIFIED 1D CLOUD MODEL: INVESTIGATION OF THE AMAZONIAN MONSOON AND DRY-TO-WET SEASONAL CONDITIONS FOR CONVECTION

P4M.8

Rachel I. Albrecht [1 *]
Carlos A. Morales [1]
Maria Assunção F. S. Dias [1,2]
Walt Petersen [3]

[1] University of São Paulo, São Paulo, Brazil
[2] Centro de Previsão de Tempo e Clima, Cachoeira Paulista, Brazil
[3] University of Alabama, Hunstville, Alabama

1. INTRODUCTION

The Amazon region presents a unique spatial and temporal rainfall variability. The precipitation in this area is modulated by the intrannual and intraseasonal oscillations, such as the seasons of the year, and the monsoon period, respectively. During the monsoon at the Southwest Amazon (December-March), convective systems are driven by the zonal wind direction from easterly (break periods) to westerly regimes, which are associated to the penetration of stationary frontal systems from the extratropics, the South Atlantic Convergence Zone (SACZ) (Rickenbach et al., 2002). Therefore, the wet season is characterized by periods of the presence of SACZ (SCAZP), where the convective systems are more “maritime” in nature (green ocean – Williams et al., 2002), and periods of the absence of the SACZ (non-SACZP) where the convective systems are more stronger, and then present continental characteristics (Cifelli et al., 2002). Prior to the onset of the monsoon season, the Southwest Amazon experience the dry-to-wet phase (September-November), characterized by extreme continental conditions (Williams et al. 2002; Morales et al., 2004).

The continental and maritime behaviors of the convective systems at this region along the year modulate the lightning records, with a maxima in both transition periods, that is, in both the onset and break periods of the monsoon, with the first one representing the major maxima (Williams et al., 2002). Therefore, these characteristics of number of lightning for a thunderstorm in different periods of the year are driven by the large-scale and thermodynamic conditions of the atmosphere. This effect works on the updraft strength given by the larger cloud buoyancy (also known as Convective Potential Available Energy – CAPE, and Convective Inhibition Energy - CINE), which leads to stronger continental updrafts, invigorating the ice microphysics favorable to charge separation and lightning.

The rainfall variability also regulates the agriculture management at some Amazonian regions where the forest was replaced by crops and flock. During the dry-to-wet season, local farmers prepare the pasture by burning it. These fires release high quantities of aerosols to the atmosphere, contributing to the increase of the cloud condensation nuclei (CCN). This increase is an important additional parameter for characterizing the convection prior the onset and at the onset of the wet season, known as the aerosol hypothesis (Rosenfeld., 1999; Williams et al., 2002): “Air drawn from the clean (polluted) boundary layer will contain a small (large) number of large (small) droplets. Active coalescence and rainout of the cloud prevail in the warm portion of the maritime cloud, leading to the depletion of liquid water form the colder mixed phase region. A dominance of diffusional droplet growth and suppressed coalescence prevail in the continental CCN-rich clouds, preventing rainout and allowing liquid water to ascend to the mixed phase region where it can contribute to the growth of graupel particles and catalyze the process of charge separation by ice particle collisions.”

Another feature that can determine local convection at Southwest Amazon is the topography. Machado et al. (2002) found that the diurnal march of the convection during the wet season began at the elevated hills (~400 m of height) presented at Southwest Amazon.

Knowing the fact that the lightning records are strongly dependent on season of the year, this paper presents a preliminary work on the investigation of the contribution of each of these effects (large-scale conditions, thermodynamics, topography, and aerosols) on the thunderstorm life cycle of local convection over Southwest Amazon.

To held this investigation, we can count on the TRMM/LBA and RACCI. Another useful instrument is numerical modeling, to simulate the ambient conditions of where the thunderstorms was formed. Therefore, this paper is focused on the preliminary work of electrification of cloud particles in a 1D cloud model.

2. MODEL AND DATA DESCRIPTION

One-dimensional cloud models have been criticized for exhibiting inconsistencies when tested against real situations. However, their relative simplicity and low computational requirements make these models still valid for several applications. For example, 1D cloud models are useful for studying the implementation of new processes into microphysical cloud

* *Corresponding author address:* Rachel I. Albrecht, Department of Atmospheric Sciences, Univ. São Paulo, São Paulo, SP 05508-090 Brazil; e-mail: rachel@master.iag.usp.br

parameterization, while three-dimensional cloud models remain computationally cumbersome and expensive for studies that require many model simulations. These facts illustrate the continuing desirability to obtain a one-dimensional cumulus model that is internally consistent and captures the essence of cloud structure (Ferrier and Houze, 1989; Cheng and Sun, 2004).

The cloud model used in this work is based on a cumulonimbus convection of the dynamic model of Ferrier and Houze (1989), coupled with ice classes of Ferrier (1994) and a parameterization of electric charge transfer between classes of hydrometeors by Takahashi (1984). In the following subsections, there is a brief description of the model equations and governing physics.

The behavior of a parcel of moist air in a cloud is described by an equation of motion, thermodynamic equations, and continuity equations. This 1D cloud model is formulated in cylindrical coordinate system and is axial symmetric, with variable radius. The model predicts cloud-averaged values of vertical velocity w, potential temperature θ, pressure perturbation relative to the large-scale environment, mixing ratios q_x and electric charge Q_x of x water classes: water vapor (v), cloud water (cw), rain (r), ice crystals (i), snow flakes (s), graupel (g) and hail stones (h, D>2 cm). The main input parameters are a thermodynamic profile (given by a radiosonde) and a lifting parcel forcing, such as a gust front. The prognostic equations for these variables can be found in detail at Ferrier and Houze (1989). For mixing ratios q_x, the sources and sinks of all possible microphysical interactions between the x water classes are illustrated in Figure 1.

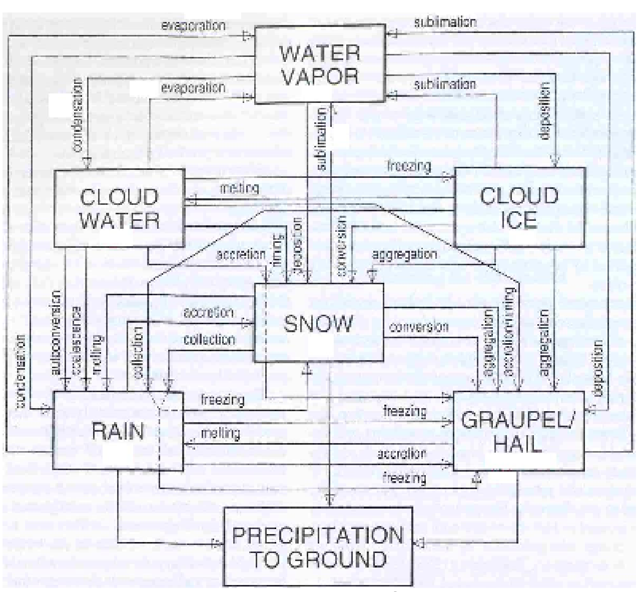

Figure 1 – Hydrometeor interactions for a model with six categories of water substances. Taken from MacGorman and Rust (1998).

The charging hydrometeor mechanism used in this 1D model is based on the noninductive mechanism of Takahashi (1984) laboratory study. The noninductive mechanisms are those that do not require a polarization of hydrometeors by an previous existing electric field. Of the various types of noninductive mechanisms that are possible, the graupel-ice mechanism is the only one thus far that detailed laboratory and modeling studies have suggested is capable of causing clouds to become electrified enough to be thunderstorms. Takahashi (1984) found that the magnitude and sign of the charge ($\delta\mu$) deposited on a graupel particle depended on temperature and liquid water content. Williams et al. (1994) also added the fact that charge transfers without the presence of an electric field can be possible due to the growth stage of hydrometeors (e. g., deposition, evaporation), the electrical double layer and the quasi-liquid layer (for details see MacGorman and Rust (1998) and Williams et al. (1994)).

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_N) of the Nth particle type of diameter D_N, that is

$$\frac{\partial Q_1}{\partial t} = \int\int K_{12} n_1(D_1) n_2(D_2)(\delta\mu) dD_1 dD_2 = -\frac{\partial Q_2}{\partial t} \qquad (1)$$

The collision kernel is the effective cylindrical volume for collision of particles 1 and 2, times the collision separation efficiency of these two particles K_{12} (which is the fraction of particles 1 in this volume that collide with particle 2 and separate from it), that is

$$K_{12} = \frac{\pi}{4}(D_1 + D_2)^2 |v_1 - v_2| \xi_{12} \qquad (10)$$

where v_1 and v_2 are particles 1 and 2 terminal fall velocities. The size distribution n_N is assumed to have an exponential distribution for graupel and snow, and since cloud ice typically has a narrow distribution, of sizes it can be approximated as a population with a single diameter D_i. For cloud ice, because D_i<<D_g and v_i<<v_g, the magnitude of sums and differences of these quantities can be approximated as D_g and v_g in (10). The terminal fall velocities can be approximated to power laws, such as $v_g = aD_g^b$, and the amount of charges transferred ($\delta\mu$) are taken from Takahashi (1984) work.

Once the model starts to electrically charge hydrometeors, it is necessary to include a lightning parameterization. A primary purpose of lightning parameterizations is to limit the electric field E magnitudes to observed values. Without a lightning parameterization, E would build to unrealistic large values, several times what is needed to cause electrical breakdown of air. Therefore, it is calculated 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*, which is the threshold electric field necessary for the average kinetic energy of an energetic electron (1 MeV) to remain constant as it gains energy from the electric field and loses energy to collisions Marshall et al. (1995). The breakeven electric field $E(z)$ (kVm^{-1}) decreases with altitude z (km), and contain a model of vertical distribution of the mass density of air, ρ_A (kgm^{-3}) (Marshall et al., 1995):

$$E(z) = \pm 167 \rho_A(z)$$
$$\rho_A(z) = 1.208 \exp\left(-\frac{z}{8.4}\right) \qquad (2)$$

At the current version of the model used in this work, there is just one lightning. The next step will be to include a scheme to reorganize electric charge hydrometeors and make several lightnings, reproducing then a thunderstorm life cycle.

3. RESULTS

The 1D electrified cloud model was initialized by thermodynamic conditions given by the radiosondes launched at the Rondonia state (Southwest Amazon) during the TRMM/LBA and RACCI field campaigns. These campaigns represent the wet (January-February 1999) and dry-to-wet (September-November 2002) large-scale conditions, respectively.

Figures 2 and 3 presents a compact description of the results obtained with the 1D electrified cloud model for the wet and dry-to-wet conditions, respectively. From the 167 radiosondes available from the TRMM/LBA field campaign, 26 were able to produce thunderstorms, while form the 165 RACCI radiosondes just 3 produced clouds with a dielectric breakdown. These first results reproduces satisfactorily the dominance of the seasonal large-scale conditions.

During the wet season, there is usually a more unstable and humid boundary layer than the dry-to-wet period. This can be seen by the very low CINE and very high CAPE during the wet season days, while during the dry-to-wet period there is the predominance of very high values of CINE and moderate CAPE. Therefore, with more instability and humidity, the wet season radiosondes were able to produce a larger number of thunderstorms. During the days of high CAPE and CINE ~0 together, it was produced the larger updrafts (> 25 m/s) at heights up to 8 km inside the cloud, which produced a great amount of iced particles and therefore also produced a rapid and efficient charge transfer and the consequent rapid breakdown (< 30 min), for example days 17, 21, 22 January and 07, 10, 12, 17 February (Figure 2).

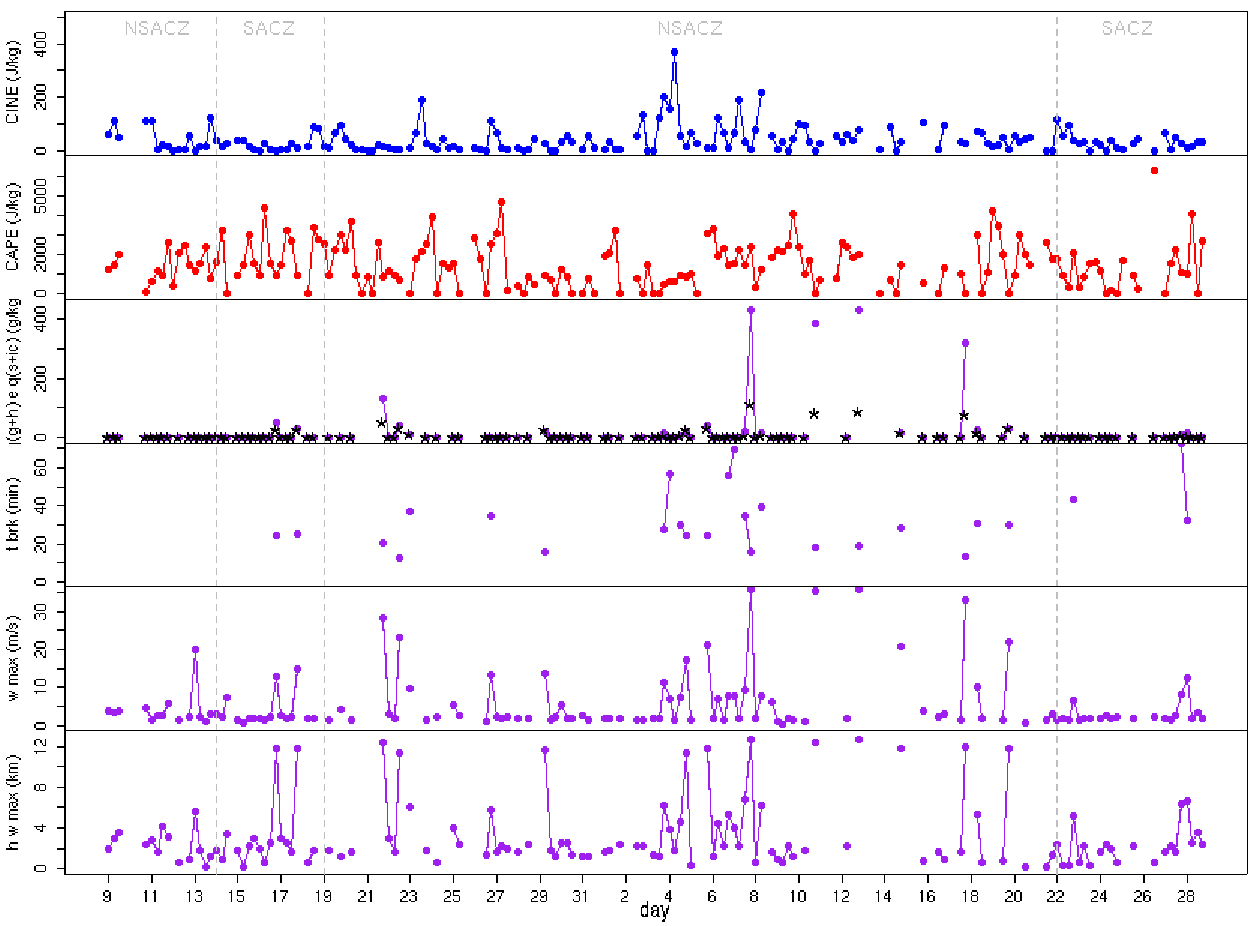

Figure 2 – CAPE, CINE, total mixing ratio of grapel+hail [q(g+h) - circle] and ice+snow [q(s+ic) - star], time of breakdown (t brk), maximum updraft simulated (w max) and its height of occurrence (h w max). Day starts at 09 January 1999 0000UTC and ends at 28 February 1999 1800UTC.

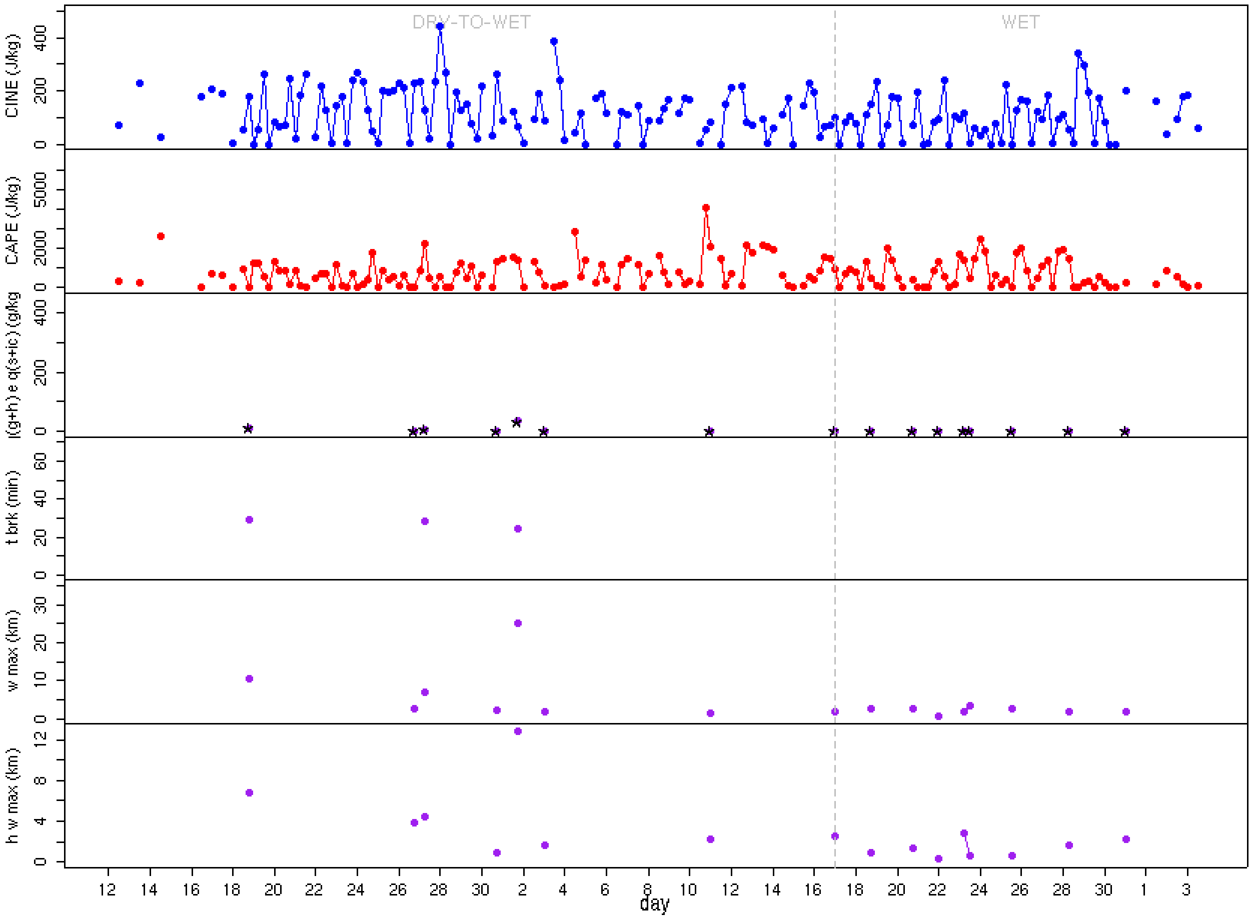

Figure 3 - CAPE, CINE, total mixing ratio of grapel+hail [q(g+h) - circle] and ice+snow [q(s+ic) - star], time of breakdown (t brk), maximum updraft simulated (w max) and its height of occurrence (h w max). Day starts at 12 September 2002 0000UTC and ends at 03 November 2002 1800UTC.

In the case of simulations with the dry-to-wet radiosondes, the CAPE values are not so high as for the wet season, but during this period it is observed the highest CINE values. Therefore, when the low level lifting parcel forcing (model gust front) were able to break the barrier impose by the CINE, a thunderstorm cloud is formed with maximum of updrafts up to 8 m/s at heights around 5 km. There is also the rapid ice formation and consequent charging of the hydrometeors with breakdowns around 30 minutes of simulation.

3.1 A case study

It is presented here a case study of one simulation with initial thermodynamic conditions given by a radiosonde launched at 18 September 2002 1800UTC, during RACCI field campaign (Figure 4). This specific day was chosen to represent a local convection situation, with minimum large-scale influences. That means that during this specific day there was a low convective fraction (0.29 – calculated using the reflectivity radar images, installed specially for the RACCI experiments), a reasonable number of lightnings detected by BLND† (104 lightnings) and a high CAPE (1207 Jkg^{-1}).

The first cloud droplets (q_i) were formed in 17 minutes of simulation and the first rain drops (q_r) appeared 8 minutes later, as it can be seen in Figure 5. Figure 5 shows the time versus height evolution of vertical velocity (w), variation of the large-scale potential temperature (θ), and the mixing ratio of the six types of hydrometeors considered in this model (q_x). The maximum of rain (q_r=7 gkg^{-1}) was obtained after 37 minutes of simulation, suggesting the contribution of melted hydrometeors (such as graupel and hail) to the achievement of this high value. Precipitation fallout occurred some minutes after the maximum of q_r (t=45 min). The maximum height of the top of the simulated cloud was ~12 km at t=48 min.

The cloud ice phase was initiated by graupel, ice crystals and snow flakes (t=26 min) due to rain droplets and water vapor that were carried by updrafts above the freezing level (T=0^{o}C, ~4.5 km of height). Only five minutes after the first ice particles were formed, hail is formed with a maximum mixing ratio of 3.8 gkg^{-1}.

† *Brazilian Lightning Detection Network*.

Graupels are smaller particles than hail, therefore they can be found at higher altitudes such as 10 km, while hail was confined bellow 8 km of height. The cloud updrafts reached high levels, above 8 km, initiating ice crystals nucleation. Ice crystals can grow by aggregation of other ice particles or rimming of supercooled cloud droplets, creating the snowflakes and graupels. The maximum of ice crystals mixing ratio(1.6 gkg^{-1}) was found some minutes before the maximum of snow (2.4 gkg^{-1}) indicating the presence of aggregation and rimming processes. The rapid ice crystals formation in ~ 9.5 km of height is responsible for a high quantity realize of latent heating. This can be seen at the maximum value of θ=1.5^{o}C at the same height and time of maximum q_i. The cloud stopped growing in 48 minutes of simulation, when it can be seen just downdrafts at all vertical profile. However, ice crystals, snowflakes and graupels persisted until the end of simulation, that is, not all the available water inside the cloud was precipitated.

The charge electrification of hydrometeors in ice phase occurred in a rapid and intense way as shown in Figure 6. 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 hail and the few ice crystals and snowflakes present at this level. The negative charging of graupel and hail, and the positive charging of ice crystals and snow at 4.8 km (T ~ -8^{o}C) is coherent with the laboratory work of Takahashi (1984) used in this model. Figure 6 shows the total charge (qnet) at the moment of the breakdown and also shows the vertical distribution of the breakdown and breakeven electric field chosen as the limit for lightning to occur. The lightning occurred at the moment of this instantaneous very high charging (t=28 min). As soon as there was a lightning, the model stopped to calculate the hydrometeor charge transferring, and the hydrometeor kept the same density charges from the moment of lightning to the end of the simulation.

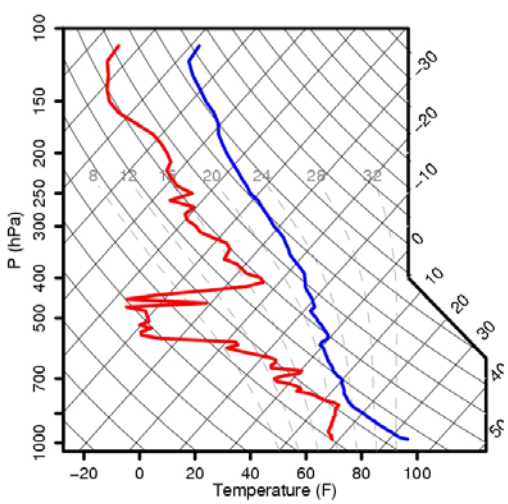

Figure 4 – SkewT-logP 1800 UTC 18 September 2002, Rondonia, Brazil. Temperature and dew point temperature are denoted by blue and red lines, respectively.

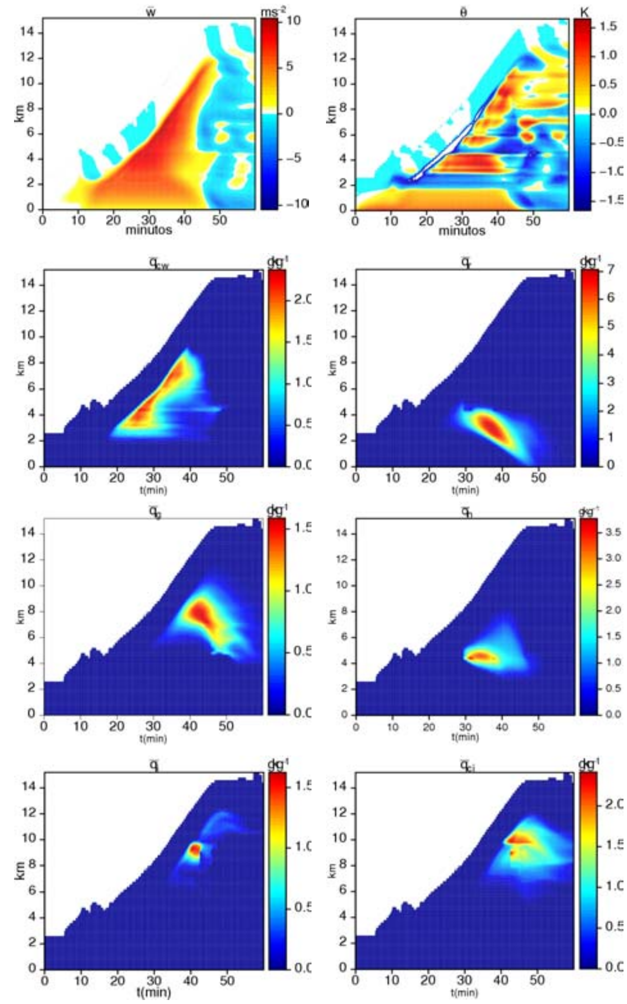

Figure 5 – Temporal evolution of vertical velocity (w), variation of the large-scale potential temperature (θ), and the mixing ratios of cloud water (q_{cw}), rain (q_r), graupel (q_g), hail (q_h), ice crystals (q_i) and snow (q_s) [From left to right, and top to bottom].

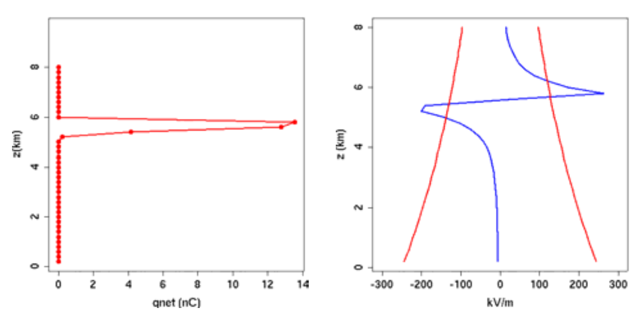

Figure 6 – (a) Electric field at the moment of lightning occurrence at the cloud model (t=28 min), and (b) vertical profile of model breakdown electric field, the breakeven electric field, Equation (11).

4. CONCLUSIONS

The cloud model with the dynamic formulation of Ferrier and Houze (1989) and microphysics of iced hydrometeors proposed by Ferrier (1994) reproduced satisfactorily the dynamics and microphysical processes considered. The initial condition reproduced by the temperature and humidity profiles is important for the formation and distribution of hydrometeors here simulated. Together with the low level forcing, these features have an important play in the rapid and efficient conversion of the available humidity into hydrometeors, and then in the charge transfer during collisions, producing reliable breakdown fields and so far lightning.

The main characteristics imposed by the large-scale conditions of the different seasons simulated were clearly seen, such as a more unstable and humid boundary layer of the wet season that leads to convection easily with a not so strong low level forcing, and the very stable boundary layer of the dry-to-wet period, being a strong barrier for the initiation of the convection. However, during the dry-to-wet period, a high CINE together with a moderate CAPE and a strong enough low level forcing, could break the stable boundary layer, and explode into a vigorous cumulonimbus. This feature can be the main reason for number of lightning records along a year. However, this will be still confirmed in the future step of this 1D electrified cloud model, the redistribution of charges after a breakdown, producing several lightnings and a complete thunderstorm life cycle.

The aerosol effect is also an issue to be explored with this model. This can be done by playing with the numbers of the functions that parameterize the water and ice species, making the same amount of mixing ratios to represent different hydrometeor spectra with more or less number of droplets/ice.

Another important part of this work is the identification of all days with only local convection in the region covered by the radars of RACCI field campaign, to study them throughout numerical simulations using this 1D cloud model. Identifying these days, it can be inferred the real effects of each possible forcing that influences cloud electrification: thermodynamic forcing (CAPE), aerosols (number of hydrometeors), topography (rising of low-level air parcels), and large-scale (seasons, divergence of air and humidity).

With a reliable parameterization to be used for continuously charge and discharge hydrometeors, the next step will be to insert a similar parameterization of electrification of clouds into the mesoscale model BRAMS, used in the University of Sao Paulo for weather forecasts. However, BRAMS is a three-dimensional model and therefore there will be also the possibility to calculate the trajectory of lightning discharges inside and outside the cloud [12]. Such study is necessary to develop a good understanding of observed relationships between lightning and storm properties that hold promise for nowcasting, storm warnings, lightning forecast, and the global impact of NO_x produced by lightning (which acts as a catalyst in reactions with ozone and so survives to continue affecting ozone concentrations).

5. REFERENCES

Cifelli, R., W. A. Petersen, L. D. Carey, S. A. Rutledge, and M. A. F. Silva Dias, 2002: Radar observations of the kinematics, microphysical, and precipitation characteristics of two MCSs in TRMM LBA. *J. Geophys. Res.*, **107**, 8077.

Ferrier, B. S. and R. A. Houze, 1989: One-Dimensional time-dependent cumulonimbus convection. *J. Atmos. Sci.*, **43**, 330-352.

Ferrier, B. S., 1994: A double-moment multiple-phase four-class bulk ice scheme. Pat I: Description. *J. Atmos. Sci.*, **51**, 249-280.

Cheng, S.-H. and W.-Y. Sun, 2004: An explicit one-dimensional time-dependent tilting cloud model. *J. Atmos. Sci*, **61**, 2797-2816.

MacGorman, D. R. and W.D. Rust, 1998: *The electrical nature of storms*, New York, Oxford University Press.

Machado, L. A. T., H. Laurent, and A. A. Lima, 2002: Diurnal march of the convection observed during the TRMM-WETAMC/LBA. *J. Geophys. Res.*, **107**, 8054.

Marshall, T. C., M. P. McCarthy, and W. D. Rust, 1995: Electric field magnitudes and lightning initiation in thunderstorms. J. Geophys. Res., **100**, 7097-7103.

Morales, C. A., L. A. T. Machado, M. A. F. Silva Dias, W. Amorim, M. E. B. Frediani, and R. I. Albrecht. 2004: Characteristics of the precipitating systems during the 2002 dry-to-wet field campaign in the Amazon region. XIII Brazilian Metorological Congress, Fortaleza, CE, Brazil.

Rickenbach, T. M., R. N. Ferreira, J. Halverson, D. L. Herdies, and M. A. F. Silva Dias, 2002: Modulation of convection in the southwestern Amazon basin by extratropical stationary fronts. *J. Geophys. Res.*, **107**, 8062.

Rosenfeld, D., 1999: TRMM observed first evidence of smoke from forest fires inhibiting rainfall. *Geophys. Res. Lett.*, **26**, 3105-3108.

Takahashi, T., 1984: Thunderstorm electrification – A numerical study. *J. Atmos. Sci.*, **41**, 2541-2558.

Williams, E. R., R. Zhang, and D. Boccippio, 1994: Microphysical growth state of ice particles and large-scale electrical structure of clouds. *J. Geophys. Res.*, **99**, 10787-10792.

Williams, E. and co-authors, 2002: Contransting covective regimes over the Amazon: implications for cloud electrification. *J. Geophys. Res.*, **107**, 8082.

Acknowledgements: *The authors would like to thanks the Fundação de Amaparo à Pesquisa do Estado de São Paulo (FAPESP) for the financial support of this work under the grant #04/09049-3.*