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DETAILED STORM SIMULATIONS BY A NUMERICAL CLOUD MODEL WITH ELECTRIFICATION AND LIGHTNING PARAMETERIZATIONS

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1. INTRODUCTION

A small multicell storm complex was observed on 28-29 June 2004 during the ThunderstormElectrification and Lightning Experiment (TELEX). Observation platforms included the KOUN polarimetric radar, a lightning mapping array (LMA), mobile radars, and soundings with electric field meters. The convection on this day was characterized by short-lived, shallow cells, a few of which grew sufficiently above the freezing level to electrify strongly and produce lightning. Analysis of polarimetric radar by Bruning et al. [2007] indicated that the warm rain (collision-coalescence) process was the dominant mode of precipitation formation, and that initial graupel in the lightning-producing cells formed from freezing drops. Inference from LMA-observed lightning showed an initial significant charge structure composed of main negative and lower positive charges (negative dipole) with associated negative cloud-to-ground lightning. Subsequent upper-level intracloud lightning indicated development of a significant upper positive charge region. A negative screening layer at cloud top was inferred from electric field meter data but apparently was not involved in lightning.

2. MODEL DETAILS AND INITIALIZATION

Electrification physics have been merged into a new version of the Collaborative Model for Multiscale Atmospheric Simulation (COMMAS). The single-moment 10-ICE scheme [Straka and Mansell, 2005] is available, but for this study a double-moment scheme with fewer categories was used. The two-moment microphysics scheme, an updated version of Ziegler [1985] and Zrnić et al. [1993], predicts mass and number concentration for five hydrometeor types (droplets, rain, ice crystals, snow, and graupel). Both the average mass density of graupel, allowed to vary between 300 to 900 kg m^{-3}, and the concentration of small cloud condensation nuclei (CCN) are also predicted. For this simulation, initial CCN concentration was set at $300(\rho_{air}/\rho_o)$ cm^{-3}, where ρ_{air} is air density and $\rho_o = 1.0$ kg m^{-3}.

The branched lightning parameterization of Mansell et al. [2002] was used, with charge neutrality of the channel structure nowmaintained by adjusting the electric potential of the channel [e.g.,Mazur and Ruhnke, 1998]. In Mansell et al. [2002], a simple height threshold (typically 2 km) was used to declare a flash to be a CG (i.e., the flash was not required to propagate all the way to ground). In the updated scheme, the potential at the tip must maintain the correct sign to be connected to ground, since the sign can change due to internal resistance and adjustment of the channel potential.

Electrification processes [Mansell et al., 2005] include parameterizations of multiple laboratory results of noninductive charge separation in rebounding graupel-ice collisions. Small ion processes such as attachment and drift motion are treated explicitly. A set of sensitivity tests found that none of the standard noninductive charge separation schemes described by [Mansell et al., 2005] was able to reproduce the charge and lightning development from lower dipole to full tripole that was inferred from LMA observations. Different schemes tended to result in either a lower or upper dipole structure. A hybrid scheme was developed that merged the parameterization of Brooks et al. [1997] for temperature $T > -15$°C with Saunders and Peck [1998] for $T < -15$°C. The hybrid scheme removed most negative charging to graupel for $T > -10$°C.

The maximum observed electric field magnitude exceeded 160 kV m^{-1} and was measured after lightning activity had ceased in the storm. Although this high field exceeds the relativistic runaway breakdown threshold, lightning was not initiated. Accordingly, the model threshold for initiation was set at 1.5 times the runaway threshold.

The horizontally homogeneous model environment was initialized from a 0000 UTC 29 June National Weather Service operational sounding. The sounding was modified to reduce convective inhibition (CIN) from 11.4 to 5.9 J kg^{-1}. The boundary layer moisture profile was adjusted to maintain slight stability in θ_v (virtual potential temperature), and CAPE increased from about 770 to 1000 J kg^{-1}. Simulations were performed in a 30-km by 30-km by 16-km domain with constant spacings of 250m in the horizontal and 150m in the vertical. Convection was initiated by an updraft forcing (acceleration) term that was applied for the first 30 minutes and then turned off. The forcing term had a maximum amplitude of 1.75×10^{-2} m s^{-2} and was applied in a spheroidal region in the center of the domain (horizontal radii of 8 km and vertical radius of 1 km, vertically centered at 1 km). Randomized thermal perturbations (maximum magnitude of 0.1K) were applied in a larger region to simulate natural fluctuations.

3. RESULTS

Modeled precipitation initiated as raindrops via stochastic collision-coalescence in high cloud water contents just below the freezing level, resulting in the first reflectivity (Fig. 1b, c). Raindrops lifted and growing in updrafts began freezing at temperatures around −10˚C to form graupel. Appreciable quantities of graupel appeared by 45 min (Fig. 1d). As graupel grew by riming, ice crystals were produced by rime splintering (Hallett-Mossop process) in the temperature range of −8 to −3˚C, and noninductive charge separation commenced. The first cell (45–55 min) produced a maximum $|E| < 44$ kV m^{-1} but no lightning (Fig. 2). A second, more vigorous cell produced more graupel, stronger electrification, and intracloud (IC) and negative cloud-to-ground (−CG) lightning flashes (Fig. 3).

In the first cell and the initial stage of the second cell, graupel gained mostly positive charge from rebounding collisions with ice crystals in the temperature range of −5 to −15˚C (Figs. 1e and 2, 45–68 min), with some negative gain at higher altitude. By 68min, the second cell had main negative and lower positive charge regions, as also inferred from the lightning in the observed cell. A positive charge screening layer also developed at the top of the cloud by ion attachment at this initial stage. This negative dipole structure in the simulated cell produced two IC flashes during 68–70 min.

The second cell deepened through 70min and graupel began charging negatively at higher altitude (Fig. 1e). A negative CG flash occurred just after 71min (Figs. 3 and 4), followed closely by an IC flash between the negative charge region and the newly developed upper positive charge region. Figure 4b also displays a negative charge screening layer at the top of the cloud, as was inferred from the observed electric field sounding [Bruning et al., 2007].

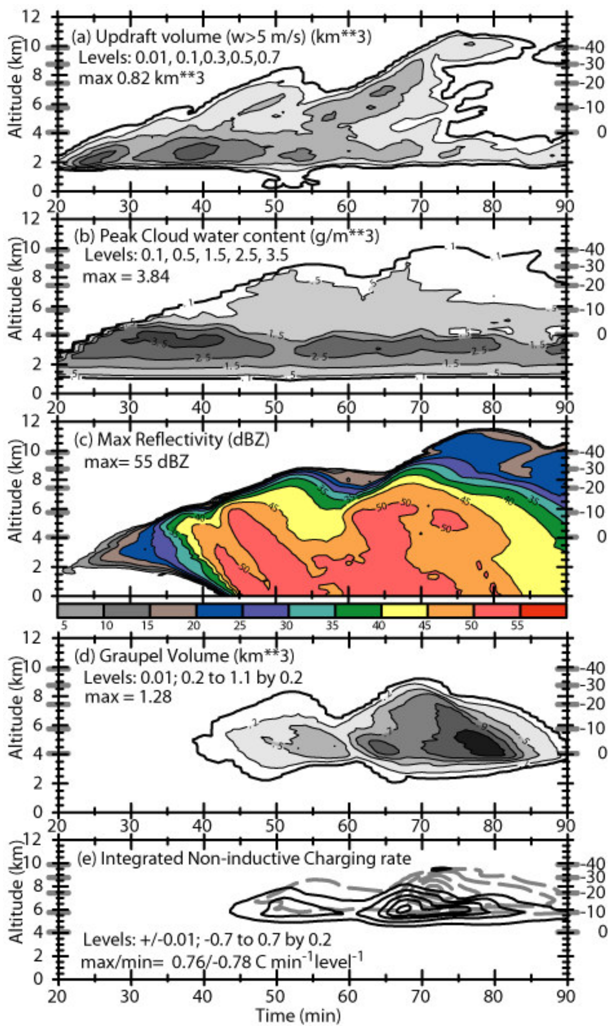

Figure 1: Time-height quantities: (a) Updraft volume per model level, (b) maximum cloud water content, (c) maximum reflectivity, (d) graupel volume per model level, and (e) horizontally-integrated positive and negative noninductive charge separation rates.

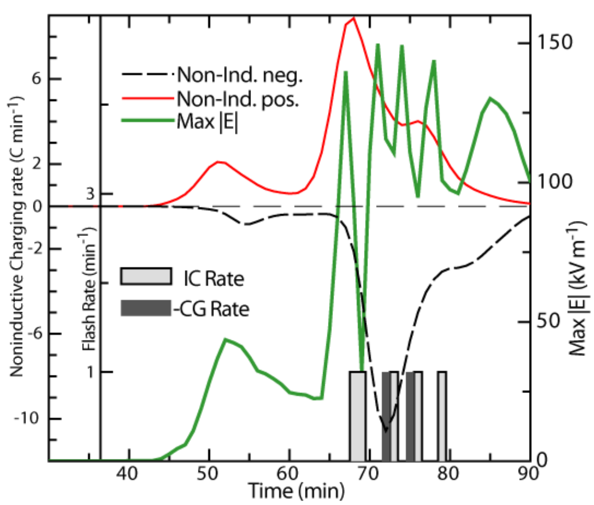

Figure 2: Domain-integrated noninductive charging rates, maximum electric field magnitude, and flash rates.

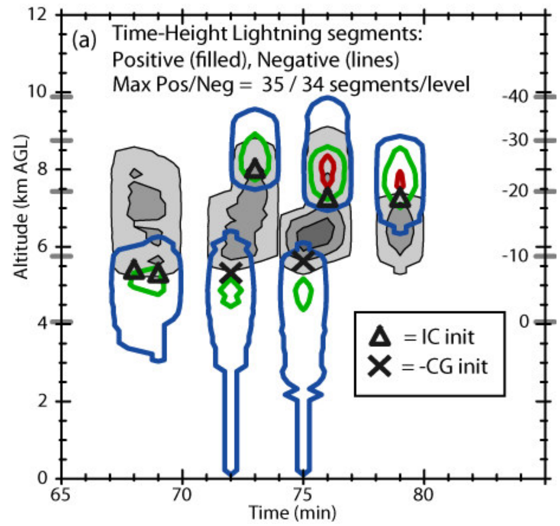

Figure 3: Time-height lightning channel segments per model level. Contour levels are 0.75, 10, and 25 segments per level.

The simulation produced a second −CG flash at 75 min, followed by two upper IC flashes. These last two IC flashes were lower in altitude than the IC flash at 73 min, following the descent of maximum reflectivity as the cell began to decay (Fig. 1c). Similar behavior was seen in the observed storm. After the final lightning flash at 79 min, the maximum electric field increased again to 130 kV m^{-1} at 85 min, but then decreased to 100 kVm^{-1} by 90 min (Fig. 2).

Inductive charge separation between graupel and small droplets was allowed, but integrated rates were at least an order of magnitude smaller than noninductive rates. We suspect that the effects are weaker than seen by Mansell et al. [2005] because the two-moment scheme properly accounts for depletion of droplet concentration, whereas the single-moment scheme assumes a constant droplet concentration.

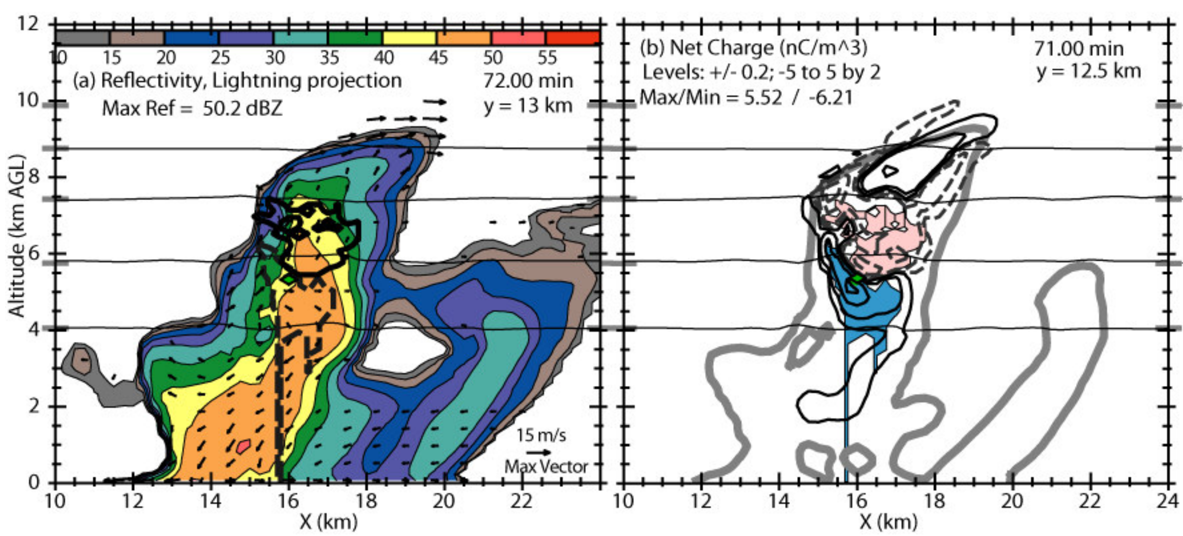

Figure 4: (a) Simulated reflectivity at 72min and −CG flash outline (solid line for positive leaders, dashed for negative). (b) Charge structure at 71min just before the −CG flash, with 25 dBZ contour (thick gray) and flash outline.

4. DISCUSSION

One of the notable features of the 28-29 June 2004 storm was that the first six lightning flashes were all –CG flashes, due to a vertical negative dipolar charge distribution in the lower part of the storm. In the model, however, the initial negative dipole charge structure resulted first in IC flashes, and a –CG flash did not occur until an upper positive charge region was forming. A sensitivity test found, furthermore, that when the CG threshold was reduced to 500m, the first –CG flash remained IC, and only the second original CG flash continued all the way to ground. Thus, although the model reproduced an initial charge structure consistent with observations, the initial flashes were IC, rather than –CG. Later in its lifetime, the observed storm did appear to produce at least one IC flash that 'failed' to become a –CG flash, but this was the exception.

A few possibilities may explain this discrepancy in the initial lightning. First, the lightning parameterization maintains a strong feedback between the positive and negative branches to maintain neutrality, which assumes that channels always maintain high conductivity. Many of the observed –CG flashes, however, connected to ground from the initial breakdown, which suggests that the fairly simple treatment of the model physics should be sufficient.

Second, the geometry of the charge regions perhaps could play a role. The simulated cell was narrower (about 3 km wide) and more isolated than the observed cell, which had a reflectivity echo about 5 km wide at first lightning. Although positive breakdown is not detected by the LMA nearly as well as negative breakdown, the first simulated flashes had positive breakdown extending higher than indicated by LMA data. Bruning et al. [2007] noted that the negative breakdown seemed to avoid and go around a region where radar data suggested wet or water-coated graupel was dominant. This avoidance suggests a weakly charged or charge neutral region with some positive charge around the sides. Initiation heights, on the other hand, suggest that proximity to ground was similar in both the simulated and observed storms.

More important than geometry could be an imbalance between the negative and positive charge regions. From previous laboratory and model results as well as a physical understanding, it is expected that lightning will be confined within charge regions when the charge regions carry roughly equal and opposite charge. In a simple dipole, lightning would initiate between the charge regions where the potential is close to zero. Therefore the potential of a leader may not be sufficiently biased to propagate down to ground. In the model, –CG flashes did not occur until the negative charge region was enhanced by charge separation at higher altitude, i.e., until the negative region carried more charge than the lower positive. This suggests that in the observed storm the negative charge region also carried more charge. The observed storm's negative region could also have become greater via negative charging of graupel at higher level, but that would require that the resulting upper positive charge region be too weak to be involved in lightning for at least 8min after the first –CG flash. Alternatively, the lower positive charge could have been dissipated by charge sedimentation and negative ion currents resulting from point discharge at the ground, which although both treated by the model, may have been underestimated, so that propagation of lightning was stopped from continuing to ground.

Simulations were made with two of the standard noninductive charging schemes, but neither resulted in satisfactory lightning behavior. The scheme based on data from Takahashi [1978] (TAKA) resulted in graupel gaining predominantly positive charge and a simple negative dipole structure for the full life of the storm. At lower temperatures (higher altitude), the cloud water content (CWC) was low enough that graupel continued to charge positively in the TAKA scheme. Ten flashes were produced, all of them IC flashes similar to the first two IC flashes in Fig. 3. The TAKA run produced no –CG flashes at all, and this suggests the hypothesis that the model needs the negative charge region to be stronger than the lower positive for –CG flashes to occur.

The noninductive scheme based on Saunders and Peck [1998] (SP98) had charge separation similar to Fig. 1e for $T < -15^{\circ}$C. At higher temperature (lower altitude), this scheme predicts negative charge to graupel at sufficiently low riming rates. Negative charging at $T > -15^{\circ}$C did occur to sufficiently negate positive charging and weaken the lower charge regions, thus preventing lightning from initiating at lower levels. The SP98 scheme resulted in 3 lightning flashes, all upper level IC flashes similar to the last two IC flashes in Fig. 3.

5. CONCLUSIONS

The basic behavior of the 28-29 June 2004 multicell storm was reproduced by the model, whose results support the interpretations previously made from observations alone: An initial negative-over-positive charge structure later evolved into a normal tripole structure. The question of how the initial −CG flashes were produced by the observed storm is left only partially answered: The model can predict an initial negative dipole charge structure with at least IC flashes, but seems to require an imbalance between the main negative and lower positive regions for −CG flashes to occur. Whether and how such an imbalance was achieved in the observed storm is uncertain.

Possible explanations for unsatisfactory results from the standard TAKA and SP98 schemes are proposed. Higher assumed CCN concentrations may have preserved higher CWC and perhaps caused more negative charging in the TAK scheme at lower temperature and more positive charging in the SP98 scheme at higher temperature. However, this also would inhibit the warm-rain process. In situ microphysical and electrical measurements are needed to provide insight into the conditions for thunderstorm charge separation.

Noninductive charge separation alone was found to be sufficient to produce strong charging at higher temperatures. Mansell et al. [2005] found this to be possible with the single-moment microphysics if higher ice concentrations were assumed. The vast majority of ice crystals at higher temperatures were produced by rime splintering, which can be more accurately predicted by the present two-moment scheme. Inductive graupel-droplet charge separation, on the other hand, was found to be less significant because of droplet concentrations were lower due to coalescence and collection by larger particles.

6. ACKNOWLEDGMENTS:

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7. REFERENCES

Brooks, I. M., C. P. R. Saunders, R. P. Mitzeva, and S. L. Peck, 1997: The effect on thunderstorm charging of the rate of rime accretion by graupel. *Atmos. Res.*, **43**, 277–295.

Bruning, E. C.,W. D. Rust, T. J. Schuur, D. R. MacGorman, P. R. Krehbiel, and W. Rison, 2007: Electrical and polarimetric radar observations of a multicell storm in TELEX. *Mon. Wea. Rev.*, **[in press]**.

Mansell, E. R., D. R. MacGorman, C. L. Ziegler, and J. M. Straka, 2002: Simulated three-dimensional branched lightning in a numerical thunderstorm model. *J. Geophys. Res.*, **107**, doi:10.1029/2000JD000244.

—, 2005: Charge structure and lightning sensitivity in a simulated multicell thunderstorm. *J. Geophys. Res.*, **110**, doi:10.1029/2004JD005287.

Mazur, V. and L. H. Ruhnke, 1998: Model of electric charges in thunderstorms and associated lightning. *J. Geophys. Res.*, **103**, 23299–23308.

Saunders, C. P. R. and S. L. Peck, 1998: Laboratory studies of the influence of the rime accretion rate on charge transfer during crystal/graupel collisions. *J. Geophys. Res.*, **103**, 13949–13956.

Straka, J. M. and E. R. Mansell, 2005: A bulk microphysics parameterization with multiple ice precipitation categories. *J. Appl. Meteor.*, **44**, 445–466.

Takahashi, T., 1978: Riming electrification as a charge generation mechanism in thunderstorms. *J. Atmos. Sci.*, **35**, 1536–1548.

Ziegler, C. L., 1985: Retrieval of thermal and microphysical variables in observed convective storms. Part I:Model development and preliminary testing. *J. Atmos. Sci.*, **42**, 1487–1509.

Zrnić, D. S., N. Balakrishnan, C. L. Ziegler, V. N. Bringi, K. Aydin, and T. Matejka, 1993: Polarimetric signatures in the stratiform region of a mesoscale convective system. *J. Appl. Meteor.*, **32**, 678–693.