

THUNDERSTORM ELECTRICAL MODELING – THE ORVILLE LEGACY

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1. INTRODUCTION

The study of thunderstorm electrification dates back to the time of Benjamin Franklin and his now-famous kite experiment (conceived in 1750 without the use of a kite and carried out in June 1752), wherein he demonstrated that thunderstorms, and lightning in particular, were electrical in nature. Credit should also be given to Frenchman, T. F. d'Alibard, who carried out Franklin's originally-conceived experiment in France in May of 1752. Subsequent research in the field was spotty, mainly involving refinements and duplications of Franklin's and d'Alibard's work.

In the 1850s and 60s Lord Kelvin (W. Thomson) established that the electrical state of the atmosphere could be represented as an electric field and introduced the electric potential and lines of force to help explain atmospheric electrical phenomena. He also established the first (and still operating) benchmark station in Kew, England for measuring the earth's electric field.

The next development came in 1898 when J. J. Thomson formulated the theory of ions. The fact that the atmosphere was not an insulator, but had a finite conductivity due to the presence of ions helped explain several previous observations including the relationship between the universal diurnal variation of the observed electric field and the frequency of thunderstorms. This also led to the development of theories concerning the electrification of thunderstorms. While many theories or variations on theories currently exist, only a few of the more prominent ones will be mentioned here. For more details the reader is referred to summary articles, such as those by Mason (1972), Latham (1981), Williams (1985), Beard and Ochs (1986), and Saunders (1993).

The first useful theory of charge separation proposed was that of Elster and Geitel (1913). In our present system of classification of electrification theories (convective, inductive, noninductive) theirs was an inductive theory wherein two electrically neutral, colliding drops are polarized in the ambient electric field. Upon collision, the contacting hemispheres having opposite induced charge, exchange charge (if the drops do not coalesce), leading to gravitational

separation of opposite charges giving rise to the electric field. The primary question regarding this theory is, how readily do drops colliding in an electric field separate rather than coalesce?

The next major contribution was that due to Wilson (1929) who proposed another inductive-type mechanism. Wilson proposed that polarized falling raindrops would preferentially capture ions of one sign while smaller cloud droplets would capture ions of the opposite sign followed by gravitational separation (the so-called Wilson effect). The sign of the charge attached to the hydrometeors is a function of the ion speed in the electric field relative to the fall speed of the drops. The various combinations for attachment were worked out by Whipple and Chalmers (1944).

Another contribution in the realm of inductive charging was that of Muller-Hillebrand (1954). Here, rather than water/water interactions, the author considered collisions between ice crystals and graupel particles in an electric field. While the probability of such collisions resulting in separation events is much greater than for water/water interactions, questions have been raised because of a relaxation time limitation on charge migration between interacting ice surfaces.

The so-called convective hypothesis was proposed independently by Grenet (1947) and Vonnegut (1953, 1955). In this theory the polarity of the thundercloud charge structure is determined by the initial electric field and space charge distribution at the time of cloud development. According to Vonnegut and Moore (1958), net positive ionic space charge is carried aloft in the developing cloud updraft creating a positively charged cloud through ion attachment to cloud droplets (the Wilson effect). As the positive cloud penetrates levels of higher conductivity, a current of negative ions from aloft leads to the formation of a negative charge layer at cloud top, which is carried to lower levels by cloud-edge downdrafts where it is entrained into the cloud leading to the formation of the classic positive-over-negative dipole. The final stage is the creation of an electric field at the surface strong enough to cause positive corona discharge leading to a feedback process.

The final major addition to charge separation

theories came as a result of the experiments of Reynolds *et al.* (1957) and is classified as a noninductive process (one in which the ambient electric field plays no role). In their experiments, Reynolds *et al.* found that there is substantial charge transfer between vapor-grown ice crystals and graupel particles that collide in a cloud of supercooled water droplets that are riming the graupel particle. They also found that when the supply of supercooled riming droplets was removed the charge transfer between the interacting ice crystals and graupel particles was reduced by orders of magnitude. From these experiments it was clear that the mixture of graupel, ice crystals, and supercooled droplets was necessary for significant charge transfer to take place. While the exact nature of the charge transfer at the micro-scale has not, to this day, been resolved, considerable additional laboratory work has been carried out, and this noninductive riming mechanism currently holds the favored position as the mechanism thought to be responsible for primary electrification in thunderstorms.

Thus, over a period of half a century, several different theories related to the separation of charge and the electrification of thunderstorms were developed. The question as to which one(s) are of primary importance was (and remains) the key question facing scientists in the field of thunderstorm electricity. Throughout the period of theoretical and laboratory work related to charge separation, observational studies were also undertaken. Much of the character of thunderstorms' electrical nature was revealed by these studies, but observational instruments and techniques were not adequate to make the crucial determination as to the efficacy of the various proposed mechanisms. With the advent of digital computers and the development of models of cloud growth a new avenue of approach was opened.

2. THE LEGACY

In light of the theories of cloud electrification noted above, some initial attempts at calculations related to charge distributions were undertaken. The Vonnegut/Grenet convective hypothesis was the first to be tested. Phillips (1967a, b, c) and Ruhnke (1970) used simple, quasi-static calculations of the charge accumulation within clouds subject to conductivity differences between clear and cloudy air. Despite the simplicity employed in the calculations, Ruhnke's results, in particular, turned out to be reasonably accurate for

non-precipitating clouds. However, none of these efforts included any consideration of cloud dynamics or microphysics. Since all theories of charge separation involved either or both of these considerations, the calculations were of limited utility. Dr. Orville, recognizing this, began the process of incorporating electrical effects within the context of dynamic cloud models.

Dr. Orville and his students had been developing two-dimensional (2D) models of storm and precipitation development for several years. In the summer of 1969, M. H. Smith traveled to Rapid City from the Univ. of Manchester, England to work on the problem of incorporating electrical effects into cloud models. The result of that collaboration was an unpublished report to the Office of Naval Research for Project THEMIS (Smith and Orville, 1970) that outlined the requirements for merging electricity with cloud growth in a multi-dimensional, dynamic cloud model. The premise of the report was the question, "Given a numerical cloud model..., what considerations are necessary to include electrical effects in the model?" One of the primary motivations for merging electrical effects with an existing dynamic and microphysical model was the recognized need for a platform to test various charge separation mechanisms, in particular the Vonnegut/Grenet convective theory, although the report stated that, "Possibly something can be said about sedimentation theories also...".

According to Smith and Orville, the general considerations for merging electrical effects into the model were deemed to include:

- 1) addition of electrical terms to the equations of motion (possible effects on dynamics) and terminal velocity calculations,
- 2) assurance of charge conservation,
- 3) the inclusion of small and large ions (positive and negative) as well as neutral aerosols,
- 4) the addition of diffusion and conduction of ions to cloud particles,
- 5) consideration of electrical effects on collection efficiencies and their effect on rain and hail production,
- 6) point discharge at the surface under strong electric fields,
- 7) vertical variation in small ion profiles and altitude-dependent recombination coefficients, and
- 8) an accounting for conduction currents above the cloud.

To account for these items Smith and Orville listed a number of variables and parameters that needed

to be added to the model. The principle dependent variables were:

- 1) large and small ion concentrations,
- 2) hydrometeor charge densities, and
- 3) the electric potential.

The secondary variables (dependent on the primary variables) were:

- 1) net total charge density,
- 2) the electric field,
- 3) the conductivity, and
- 4) current density.

The parameters that would be required were:

- 1) ion production rates and recombination coefficients (altitude dependent),
- 2) ionic diffusion coefficients
- 3) initial profiles of electrical variables,
- 4) neutral particle concentrations, and
- 5) hydrometeor number concentrations.

Although the information in this report was not published in the open literature, it became the basis for the first attempt to include electrical effects in a cloud model. Prior to and shortly after the preparation of the Smith and Orville report, two graduate students, J. E. Pringle and T. D. Stechmann, were recruited from the Electrical Engineering Dept. to undertake this modeling effort (both receiving M. S. degrees in Electrical Engineering for their work).

Pringle (1971) undertook the initial inclusion of electrical variables and parameters using the 2D, slab-symmetric model of Orville (1965) for non-freezing conditions (rain and cloud water only) with the intent of comparing convective and sedimentation theories. With respect to the additional variables and parameters listed above, all were included except: 1) recombination among large ions was ignored, 2) there was no charge transfer between cloud and raindrops, and 3) when attachment of ions to hydrometeors was included it was specified (as a function of the rate of change of the radius of the particle with a fixed percentage of the existing ions involved) rather than calculated from theory. Also, no influence of electrical effects on collection processes was attempted. The spacing used in the simulations was 500 m on a 10-km high by 5-km wide grid, with initial time steps of 30 s. In all, three cases were run. The first simulated small ions only with no attachment to hydrometeors. The second was the same, but with the addition of large ions. The

third arbitrarily prescribed the attachment of up to 40% of the existing positive ions to cloud droplets and negative ions to rain. The results from the first two cases showed only minor changes to the electrical state of the atmosphere, from which Pringle concluded that the convective mechanism was not of primary importance (the conclusion was correct, but the reason was not). The third case, with ions arbitrarily attached to cloud and rain, showed the development of relatively strong fields (to nearly 25 kV/m for the case presented) and large net charges. From this Pringle concluded that sedimentation theories (inductive and/or noninductive) might better explain cloud electrification and also noted that at fields about twice the value quoted above there was a small, but noticeable electrical effect on the downdraft.

Following on the research of Pringle (1971) was that of Stechmann (1972). Stechmann's work included the addition of ice particles to the model (cloud ice and "hail"), and the neutralization of charged rain and hail through: 1) the accretion of oppositely charged cloud water and ice within the cloud, and 2) the attachment of positive ions below cloud base using a rudimentary parameterization. The addition of the ice phase and the neutralization processes resulted in a considerable increase in the complexity of the calculations, in particular in accounting for the collection of positive ions by precipitation below cloud base. With these modifications the simulation showed electric fields on the order of 8 kV/m (with 30% of positive ions attached to cloud particles and 50 % of negative ions attached to precipitation), a factor of 3 less than those obtained by Pringle. An example of the results for: a) the total charge density, and b) vertical electric field component obtained by Stechmann, is shown in Fig. 1 at 89 min simulation time (positive values are partially shaded). Despite the shortcomings of the model, the expected charge dipole and electric field structure were produced (although this was guaranteed by the prescribed method of hydrometeor charging).

The first, and only, appearance of electrical model simulations in the reviewed literature bearing Dr. Orville's name as a co-author was Pringle *et al.* (1973). This was an update of the third class of simulations done by Pringle (1971), after some modifications to the model not involving electrical effects. The results were modified somewhat with maximum electric fields attaining 10 kV/m, requiring a larger percentage of attachment of ions to reach these values. The major conclusions from these efforts were that: 1) the fallout of charged precipitation is important in charge separation, 2) convection of ionic charge

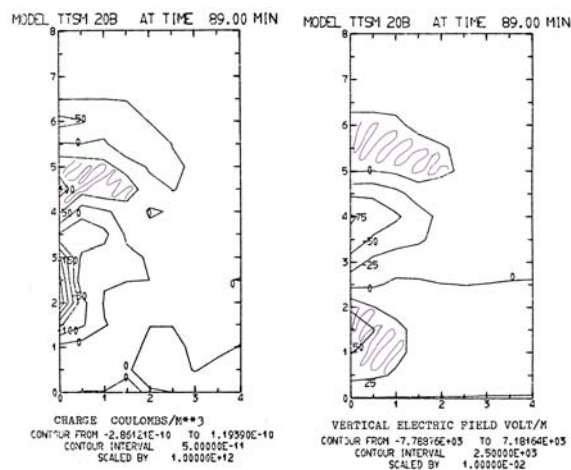


Figure 1 – a) Net total charge density, b) vertical electric field. Shading indicates positive values.

alone is not sufficient to separate large charges, 3) electrical forces in the vorticity equation produce negligible influences at the maximum fields obtained, 4) the life history of the electric fields parallels that of the cloud, and 5) the electric field magnitudes depend critically on the amount of charge carried by the cloud and/or rain particles. One other problem with the simulations undertaken in this period was the difficulty of obtaining initial profiles of the electrical variables that were stable under the numerical integrations. Although the appearance of Dr. Orville's name in the published cloud electrification literature ends at this point, his influence in the field did not.

In November 1974, Dr. Orville had the foresight to facilitate the hiring of Dr. Chin-Shan (Timothy) Chiu who had recently obtained his PhD (Chiu, 1974) from the New Mexico Institute of Mining and Technology working under Professor James Klett. Dr. Chiu had completed a study similar to that of Ruhnke (1970) using an analytical, steady-state, axisymmetric model to study convective charging (Chiu, 1974; Chiu and Klett, 1976). Dr. Orville, recognizing Dr. Chiu's potential in the area of thunderstorm electrical modeling, brought him to the Institute of Atmospheric Sciences (IAS) to continue the work initiated by Pringle and Stechmann. During his time at the IAS, Dr. Chiu developed a 2D, time-dependent, axisymmetric model that was a significant advance over the previous work, although it did not initially include the ice phase.

Chiu developed several improvements in the model representation of electrical interactions. First, he included an explicit accounting of the interaction of small ions with hydrometeors through diffusion (based on work by Gunn, 1954) and conduction (following Whipple and Chalmers,

1944 and Gunn, 1956). This eliminated the arbitrary assignment of ion charge to hydrometeors used in Pringle *et al.* (1973). In a similar vein, he accounted for hydrometeor charge neutralization/enhancement when coalescing interactions occurred. He also added an explicit representation of the inductive charging process between rain and cloud droplets based on theories developed by Latham and Mason (1962), Davis (1964), and Paluch and Sartor (1973). Finally, he solved the electrical initiation problem by deriving a self-consistent set of steady-state equations for the vertical profiles of ions and the electric field. The result of this work was a study of warm-cloud electrification by inductive charging submitted to the *Journal of Geophysical Research* in Nov. 1977. In a tragic accident, Dr. Chiu and his family died before the manuscript was published. Dr. Orville completed the revision process and the manuscript was published in Oct. 1978 (Chiu, 1978). At the time of his death, Dr. Chiu was also working on adding ice phase electrification to his axisymmetric model. As a tribute to that effort, Dr. Orville collected Chiu's notes and presented his theoretical approach as a conference paper (Chiu and Orville, 1978).

Chiu (1978) found that the application of inductive charging to a warm-rain cloud could result in strong electrification (10s to 100s of kilovolts per meter) depending on the assumed separation probability for drop-droplet collisions and the number of cloud droplets per unit volume. He also found that the frequently observed positive-over-negative dipole charge structure was reproduced as was the appearance of a lower positive charge center in the latter part of the simulations. Figure 2 shows a typical result for 300 cloud droplets cm^{-3} and a separation probability of 0.04. Shown in the figure are: a) the cloud water, b) the rainwater mixing ratios, c) the charge on rain, and d) the vertical electric field component. The largest electric field in this simulation was -583 kV/m . When separation probabilities of 0.02 were used, the field never exceeded -32.8 kV/m showing the sensitivity of the results to this important parameter.

There had been earlier modeling studies of inductive charging, such as those of Ziv and Levin (1974), Scott and Levin (1975), and Levin (1976), but those models were all of a steady-state nature. A steady-state model can predict the charging resulting from particle interactions, but does not account for the influence of changing cloud dynamics on the resulting charging. Chiu (1978) represents the first effort with fully coupled microphysics, dynamics and electrification.

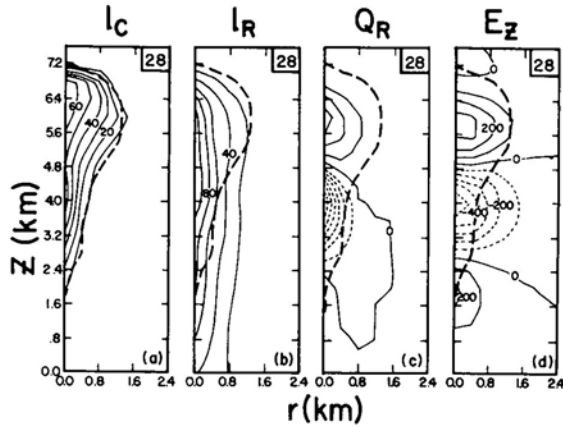


Figure 2 – a) cloud water, b) rainwater, c) rain charge density, and d) vertical electric field.

Takahashi (1979) conducted simulations with a model similar to Chiu's, except that the microphysics were described by multiple categories rather than as bulk quantities. Takahashi's results indicated that inductive charging in warm clouds would not lead to strong electrification. Apparently neither Chiu nor Takahashi were aware of studies by Jennings (1975) that showed inductive charging between rain and cloud droplets to be self extinguishing (the separation probability goes to zero) when the electric field exceeds 30 kV/m, indicating that strong electrification by inductive charging of warm clouds could not occur. Despite this, the adaptation of the processes mentioned above to the multidimensional, coupled model environment achieved by Dr. Chiu was a significant step forward for electrical modeling and came about as a result of Dr. Orville's mentorship.

During this period, I was working on my PhD at the State Univ. of NY at Albany under Dr. Richard Orville. I was developing my own 2D, slab-symmetric model of warm-rain electrification and was having trouble deciding on a final focus for my dissertation research, in addition to some problems with numerics. I was familiar with the work going on at South Dakota Tech and when Dr. Orville came to Albany to visit his brother, I was eager to meet with him. We met on a Saturday morning and discussed my modeling work for 4 hours. During that time Dr. Orville gave me suggestions for clearing up the problems I was having with numerical methods as well as suggesting an avenue of investigation, the effect of chaff-produced ions on the electrical state of a storm, that became the subject of my dissertation (Helsdon, 1979).

Because of his interest in weather

modification, Dr. Orville was aware of recent work done by Holitza and Kasemir (1974) and Kasemir *et al.* (1976) to test the feasibility of suppressing lightning by dispensing conducting chaff fibers in a thunderstorm and suggested that I focus my dissertation research on modeling the effects of chaff dispensed into the model storm. While I was aware that the water/water inductive process was unlikely to be a primary mechanism responsible for thunderstorm electrification, the mechanism could be used to create fields large enough to simulate ion production by chaff fibers distributed within the cloud and their effect on the strength of the electrification. In the last year of my research, the accident leading to the death of Dr. Chiu occurred and an advertisement to fill the vacant position was published. Dr. Richard Orville brought this ad to my attention and encouraged me to apply for the position, which I did. I was fortunate to be accepted and upon completion of my dissertation, I began working at the IAS in February of 1979 in close collaboration with Dr. Orville and Richard Farley, a collaboration that continues to this day.

Within the first year, we converted the model to run on NCAR computers and I submitted a manuscript based on my dissertation to the *Journal of Applied Meteorology* (Helsdon, 1980). The results showed that chaff seeding reduced the electric field in two ways: 1) directly by producing ions that neutralize charge on hydrometeors by conduction and convection, and 2) indirectly by reducing the electric field globally in such a manner to reduce the charge separation by induction throughout the cloud. Results also showed that early or late seeding achieved nearly identical overall results, although there were differences in the initial field variation. Figure 3 shows results from (A) early and (B) late seeding cases compared with a non-seeded case.

After the chaff seeding work was completed, rather than continue with the model that had been developed at Albany, we began adding the various charging mechanisms to the most recent version of the IAS cloud model (Orville and Kopp, 1977). In 1981 the Cooperative Convective Precipitation Experiment (CCOPE) was carried out near Miles City, MT. On 19 July a small, marginal (one recorded lightning flash) thunderstorm was well observed by aircraft and radar. Among the observations was a rather comprehensive set of electrical data obtained by the Desert Research Institute Aerocommander and the NCAR sailplane (Gardiner *et al.*, 1985; Dye *et al.*, 1986). The development of the Storm Electrification Model (SEM) reached the testing phase after the

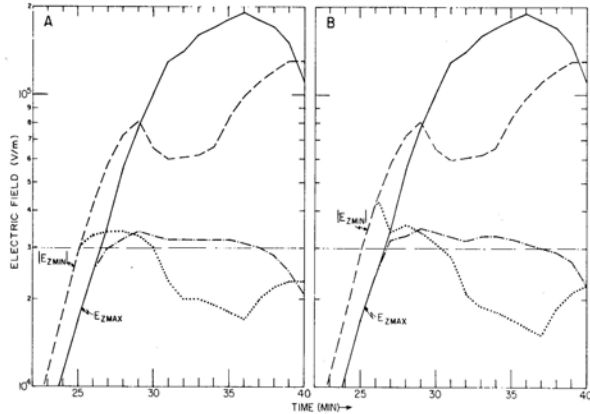


Figure 3 – A) Maximum positive (solid - control, dash-dot - seeded) and negative (dashed - control and dotted - seeded) vertical electric field component for early seeding. B) Same for late seeding. Chaff corona threshold 30 kV/m.

conclusion of CCOPE and we decided that the 19 July storm would be a good case to test the model. Up to this point all other electrical model simulations had been run on generic soundings and compared with generic results. We simulated the 19 July storm and made a direct comparison between the model results and observations both electrically and non electrically. The first results of this work were presented at the VIIth International Conference on Atmospheric Electricity (Helsdon *et al.*, 1984). This was the last paper concerning thunderstorm electricity that had Dr. Orville as a co-author.

Although Dr. Orville's direct participation in the modeling of thunderstorm electrification ended at this point, his interest continued and his legacy was established. This legacy is three-fold. First, he, along with M. H. Smith, outlined the requirements for including electrical calculations in a multidimensional, coupled dynamic and micro-physical model. Second, along with J. Pringle and T. Stechmann, he was the first to actually incorporate a rough parameterization of electrification into such a model and begin to study electrification mechanisms. Third, he mentored the next generation of modelers (Chiu and Helsdon) whose primary focus would be the electrical aspects of thunderstorm modeling. So, despite the fact that his name is not prominent in the electrical modeling literature, his influence and inspiration have been paramount in making electrical models an accepted tool in research concerning thunderstorm processes.

3. PROGRESS

In the same time frame, results from the first three-dimensional (3D) model including electrical parameters were published (Rawlins, 1982). He included bulk-ice microphysics and a simple non-inductive ice/ice scheme along with an inductive scheme. The main problem with this model was that the uniform 1-km grid spacing made the results of limited use (electrical features of observed storms often vary on length scales less than this). Takahashi (1984) also expanded his warm-rain 2D model to include the ice phase and the non-inductive mechanism. He used a 200-m grid length, but the 8 km depth of the grid limited the results to shallow clouds. Both of these simulations were generic in nature.

We refined our simulations and published our results in 1987 (Helsdon and Farley, 1987a, b), concluding that combined inductive/noninductive charging produced strong electrification whereas either process on its own did not. Figure 4 shows the results of the 2D SEM CCOPE simulation at the time of the observed (and simulated) lightning flash. Shown are: (A) the net total charge density, (B) the electric potential, (C) the vertical, and (D) the horizontal electric field components. Super-imposed on each plot is a representation of the lightning channel, as calculated by the lightning parameterization scheme that was under development. Unfortunately, there was an error in the code for the noninductive-only calculation that caused the calculated electric field to be too low by a factor of about 4. Given that our parameterization of the noninductive scheme was crude, we did not pursue revised calculations, but worked on making the scheme more quantitatively accurate based on laboratory results.

The next phase in model development involved the representation of lightning. Charging schemes can produce strong electrification, as is observed in real storms. However, in simulations the build up of charge and the resultant electric field will continue unabated. In models that include small ions, this leads to high ion velocities that become the limiting element in the determination of the time step that must be used to maintain numerical stability (ion speeds of 50 to 100 m/s are common in fields over 100 kV/m). More importantly, in real clouds fields do not continue to build up, but are limited by the presence of lightning. Because of this, models without some representation of the lightning process are only useful for examining the early electrification of clouds (up to the time of first lightning). Several early attempts were made to approximate the effects of lightning in electrical models.

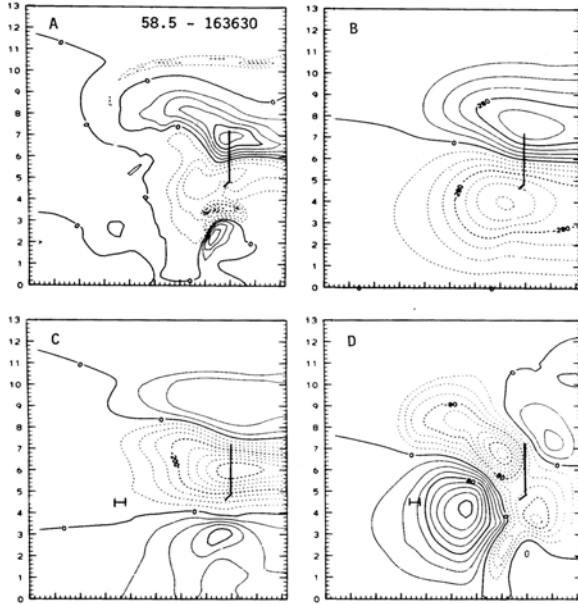


Figure 4 – A) net total charge density, B) potential, C) vertical, and D) horizontal electric field components. Solid-positive, dashed-negative. Lightning channel superimposed.

Rawlins (1982) applied a simple charge neutralization scheme (reduce the magnitude of positive and negative charges by 70% when lightning occurs) and a threshold of 500 kV/m for lightning initiation. Takahashi (1987) used a similar procedure in his model, with an initiation threshold of 340 kV/m, to study lightning locations. Other similar approaches were devised by Ziegler and MacGorman (1994) for their 3D kinematic model and Baker *et al.* (1995) for their 1D axisymmetric model. The shortcoming of this approach is that there are no physics attendant with the process, i.e., lightning is a function of arbitrarily specified parameters. We undertook to provide a physical basis for the incorporation of lightning within the model, by striving to produce an actual channel that would then manifest itself through the production of ions that would interact with hydrometeors in a physically consistent way.

Wu (1986) developed the parameterization based on the theoretical work of Kasemir (1960, 1984). The scheme uses the electric field as the parameter determining the initiation, propagation, and termination of the modeled channel. From theory, we calculate the charge density deposited along the channel and, thus, the influence of the channel on the subsequent electrical development through the conversion of this charge to small ions. This also allows the calculation of the total

charge transfer and the energy dissipation due to lightning in a physically meaningful way. The parameterization was developed for intracloud lightning, and needs modifications to the termination criteria to be suitable for calculating cloud-to-ground lightning. Although the underlying theory is 3D in nature, the scheme was originally developed for the 2D SEM.

The first simulated lightning channel is shown in Fig. 4 for the 19 July CCOPE simulation. The advantage of this scheme is that it is physics based. Charge neutralization is accomplished by the injection of ions created along the channel into regions of opposite charge taking the arbitrariness out of the process. This is shown in Fig. 5, taken from Helsdon *et al.* (1992) wherein the lightning scheme is outlined in detail. In Fig. 5 the net total charge density is shown (undisturbed in Fig. 4A) a) immediately after the discharge with the lightning-produced ions present as the opposite charges within the main positive and negative charge regions, b) 15 s later, and c) 30 s later showing the recovery of the original charge structure as the charge separation process continues to operate. In this simulation the threshold for lightning initiation was set to 400 kV/m. This method of representing lightning allows the possibility of the creation of charge regions by lightning, something that observations are now beginning to show occurs. Using this scheme and simulating the flight track of the NCAR sailplane that observed this storm, we were able to explain how the sailplane recorded only a horizontal electric field change when the observed lightning flash occurred and not a vertical field change (channel geometry in conjunction with aircraft observation altitude relative to the termination region of the discharge).

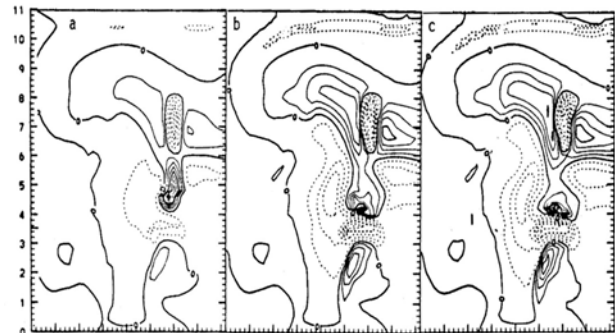


Figure 5 – Net total charge density showing lightning-produced ions a) immediately after, b) 15 s after, and c) 30 s after the discharge. Solid contours-positive charge, dashed contours-negative charge. 2D simulation of the 19 July 1981 CCOPE case.

Subsequent to the development of this physics-based representation of lightning for cloud models, other groups embraced the idea and improved upon it. Solomon and Baker (1996) used the concepts from Helsdon *et al.* (1992) to devise a scheme for their 1D axisymmetric model. Their improvement was to add the contribution of the channel charge to the electric field calculation, which influenced whether the flash was intracloud or cloud-to-ground. Mazur and Ruhnke (1998) developed a lightning scheme that determined propagation based on the total electric field at the leader tip (including the influence of charge on the channel) and determined termination based on the potential of the leader tip relative to the potential of the initiation point rather than using the electric field. Their lightning model was developed outside the context of a cloud model, however. MacGorman *et al.* (2001) expanded on concepts from Helsdon *et al.* by adding to their 3D model a randomization of the location of the initiation point around the maximum electric field region, addition of a consideration of the ambient space charge distribution in determining the propagation direction in regions with low electric field, and branching based on the number of grid points adjacent to the developing channel that support continued propagation as determined by the field/charge criteria. Mansell (2000) and Mansell *et al.* (2002), using the same 3D model as MacGorman *et al.* (2001), implemented a probabilistic dielectric breakdown scheme for lightning that developed branched channels using the electric field to determine the probability of continued propagation. The scheme is computationally intensive, but produces realistic looking channels and charge transfers.

The one limitation that pervades all of these lightning simulation schemes is that the channel is required to propagate between model grid points, so channel geometry is dependent on model grid spacing and channel "tortuosity" is limited to fixed angles. The next step in the evolution of lightning schemes is the removal of this grid point dependence for channel propagation. Sus (2001) and Helsdon and Sus (2001) developed a scheme that accomplished this goal by looking at the physics of the electron avalanche process at the tip of the developing leader. By choosing a random electron at the leader tip that fits certain criteria, random angles of propagation are obtained. Branches occur when more than one electron meets the propagation criteria. Also, the leader is assumed to develop in 50-m segments, removing the dependence on the grid spacing. Figure 6 shows the channel resulting from the

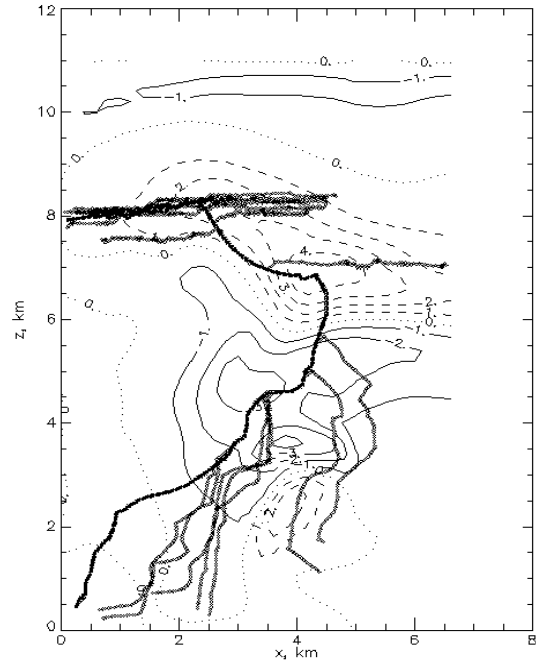


Figure 6 – Lightning channel (darker) with branches (light) superimposed over a charge distribution (dashed-positive, and solid-negative charge).

application of this new scheme in a 2D simulation. The removal of the grid point dependence makes the channel (and branch) geometry much more realistic. The scheme is also computationally intensive and is currently being adapted to the 3D SEM.

With respect to charging processes within thunderclouds, our effort at the IAS constitutes the primary work being done in this area. While early modeling work focused on the convective mechanism, recent observational studies (French *et al.*, 1996; Ramachandran *et al.*, 1996, among others) have indicated that noninductive charge transfers during collisions between ice crystals/snow and graupel in a supercooled riming environment are the most likely explanation for thunderstorm electrification. Regarding laboratory experiments related to noninductive charging, there have been two somewhat conflicting sets of results – those of Takahashi (1978, reconfirmed by Takahashi, 1999) and those of Saunders and colleagues at the Univ. of Manchester (e.g., Saunders *et al.*, 1991, although there have been numerous additional papers regarding laboratory work related to the Manchester experiments over the last decade). Both sets of experiments show the magnitude and sign of the charge transfer

during a non-coalescing collision are functions of temperature and liquid water content. However, there are differences between the two sets of laboratory results regarding the signs and magnitudes for the same temperatures and liquid water contents. While the underlying theory of how the noninductive mechanism operates still needs to be worked out, we used the 2D SEM to compare the results of a thundercloud simulation using the two sets of laboratory work. Helsdon *et al.* (2001) used the 19 July CCOPE cloud for the comparison and found that the laboratory results of Takahashi, as implemented by Randell *et al.* (1994), produced electrical structures that agreed better with observations than those of Saunders *et al.* (1991). The results suggested that the laboratory work of Takahashi might be a better representation of the noninductive charging process. However, more work needs to be done with respect to refinement of laboratory results, and model studies using the 3D SEM are required before any final conclusion can be reached.

Saunders (1993), in his review, suggested that model studies were still required to determine whether the convective mechanism could produce organized charge separation on timescales appropriate to the electrification of thunderclouds. Masuelli *et al.* (1997) undertook such a study, hoping to improve on the work of Chiu and Klett (1976). Using a 2D kinematic model with precipitation driven by dynamic (field-of-motion) output from a 3D model, they simulated a 10-min period of cloud growth and electrification by ion attachment. In contrast with the results of Ruhnke (1970) and Chiu and Klett (1976), they found the development of an opposite-polarity charge structure and orders-of-magnitude greater charges and electric field strengths, although still not to thunderstorm magnitudes. They suggested that their results needed to be checked using a more comprehensive, coupled model. Since these results were significantly different from earlier, simple simulations, we undertook to do a comprehensive evaluation of the convective hypothesis.

Helsdon *et al.* (2002) used the 3D SEM with an upgrade of the lightning scheme of Helsdon *et al.* (1992) to the 3D geometry to do a comprehensive comparative study of the convective mechanism vs. the noninductive mechanism for two storm situations – a weak storm (the 19 July CCOPE storm) and a severe hailstorm (the 1 July 1993 storm from the North Dakota Tracer Experiment (NDTE)). These two storms represent opposite ends of the dynamic storm spectrum. Each storm was simulated using

only the convective (ion attachment) process for electrification and, again, with the noninductive charge separation mechanism. As a diagnostic tool, we introduced a calculation of the conduction, convection, and point discharge components of the Maxwell current to help in analyzing the results. Results showed that the convective mechanism was capable of producing only weak and generally disorganized electrification of both storms, although the electrification of the NDTE severe storm case was stronger and showed characteristics of being a current generator for a brief period. In both cases using the noninductive scheme, strong electrification (and lightning in the NDTE case) were produced, consistent with the observed character of both these storms. Our results were consistent with those of Ruhnke (1970) and Chiu and Klett (1976) and did not support the charges and fields obtained by Masuelli *et al.* (1997). We concluded that the convective hypothesis, as envisioned by Vonnegut, was not capable of producing strong electrification in any type of storm situation. However, ion capture processes are important in the formation of screening layers in simulations and should be included in the model physics.

The Maxwell current analysis showed that both of the storms, with noninductive charging, acted as current generators. Figure 7 shows the a) convection and b) conduction current vectors in a south-north slice through the model domain at $X = 20$ km for the NDTE simulation at 20 min, 2 min after the onset of lightning. Note the scale vector length represents a current of 20 nA/m^2 for the convection current, but only 2 nA/m^2 for the conduction current. The convection current – the current carried by charged particles moving in the flow field (Fig. 7a) – shows a strong generator current (upward current flow as opposed to the downwardly directed fair weather current) throughout most of the cloud volume. There is some horizontal turn to the current vectors in the upper right portion indicating horizontal flow of charged hydrometeors into the anvil. The conduction current – the current carried by ions moving in response to the electric field (Fig. 7b) – also shows a strong current into the stratosphere as well as from the surface up to the base of the cloud, completing the connection between the surface, the cloud, and the upper atmosphere as part of the global circuit. The conduction current also shows a solenoidal character for currents that are off-axis from the core of the cloud. This is consistent with theory. The calculation of Maxwell current components has proven to be a useful tool in analyzing storm electrical evolution and will be

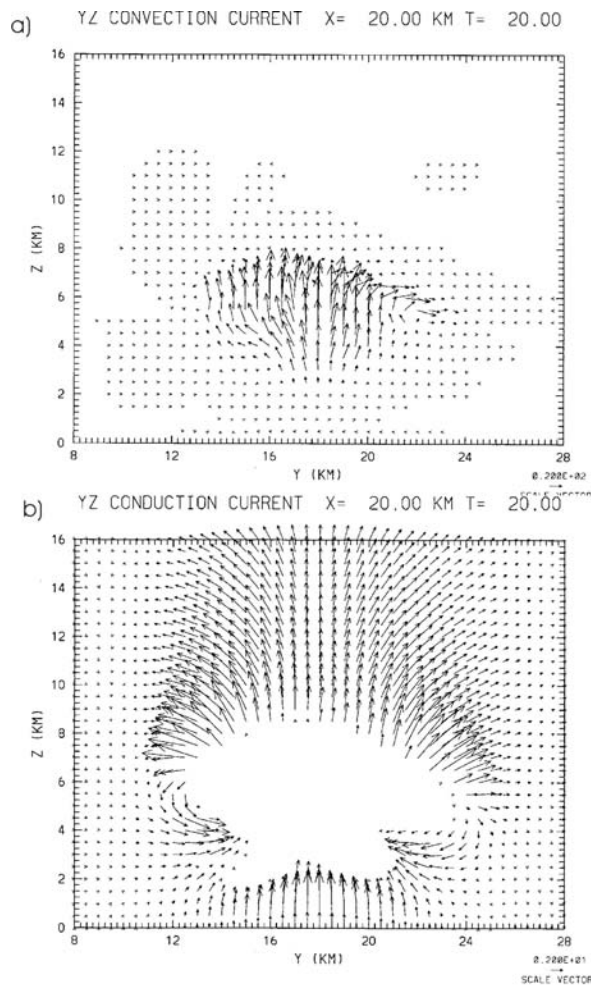


Figure 7 – a) convection, and b) conduction current density vectors in a 2D slice through the model domain at $X = 20$ km. Scale is 20 nA/m^2 in a) and 2 nA/m^2 in b).

further developed for use in subsequent studies.

The final area in which new work has begun is the use of the SEM to study certain aspects of atmospheric chemistry. Lightning is a source of nitric oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$) in the troposphere. Lightning directly produces NO through heating effects and the NO so-produced generates NO_2 by reacting with ozone. The presence of NO_x in the troposphere is important because it affects the tropospheric ozone concentration. Of the several sources of tropospheric NO (fossil fuel burning, biomass burning, soil microbial action, lightning, transport from the stratosphere, and aircraft production), the lightning source strength is the least well known. Most global and regional chemistry models now include a source term for lightning-produced NO_x , but there is an order of magnitude variation in the value used. Pickering *et al.* (1998) parameterized the production of NO_x

by lightning in the 2D Goddard Cumulus Ensemble model to arrive at vertical profiles that can be used in global models. However, assumptions about the distribution of lightning activity and the relative production between intracloud and cloud-to-ground flashes (intracloud production is assumed to be one-tenth that of cloud-to-ground flashes) as well as the fixed production rate per flash are limiting and strongly bias the results. While this approach to the problem has considerable merit, it needs to be checked against a more detailed calculation. The physics-based lightning scheme within our SEMs allows the more detailed calculations to be done. Zhang (2002) conducted a series of simulations with the 2D and 3D SEMs to test the ability of the models to predict the production and distribution of lightning-produced NO_x . The first simulation involved the 2D SEM as a proof-of-concept (Zhang *et al.*, 2003a) using the 19 July CCOPE storm as a base and simple suite of 4 chemical reactants (including NO, NO_2 , and O_3) and 6 reactions. Production of NO by lightning is assumed to be a function of energy dissipation by the lightning flash with NO produced at the rate of 9.2×10^{16} molecules/J (Borucki and Chameides, 1984). The results, with only intracloud lightning present, were in general agreement with observations, leading to an expansion of the chemistry module to include 9 reactants (CO, OH, HO_2 , CH_4 , and HNO_3 added) and 18 reactions within the context of the 3D SEM (Zhang *et al.*, 2003b). Figure 8 shows the results of the 3D simulation after 38 min and 18 lightning flashes. The top left panel is a 3D depiction of the remaining cloud and ice water contents forming the anvil, and to its right a 2D slice through the cloud. The bottom two panels show the NO mixing ratio (left) and the NO_2 mixing ratio (right). We note an asymmetric distribution of NO within the anvil and a plume of NO_2 to the surface. The primary concentration of NO_x remains within the core of the cloud. Mixing ratios of up to 2.5 ppbv of NO in the anvil agree with observations, but this simulation only produced 18 flashes, while observed storms typically are more active electrically.

The final step in the process was a simulation of the multicell, 10 July 1996 storm from the Stratospheric-Tropospheric Experiment: Radiation, Aerosols, and Ozone (STERAO) project using the same model configuration as in Zhang *et al.* (2003b). This storm was chosen for simulation because there were aircraft observations in the anvil for comparison with the simulated results (Stith *et al.*, 1999; Dye, *et al.*, 2000), there was a detailed analysis of the lightning activity (Defer *et*

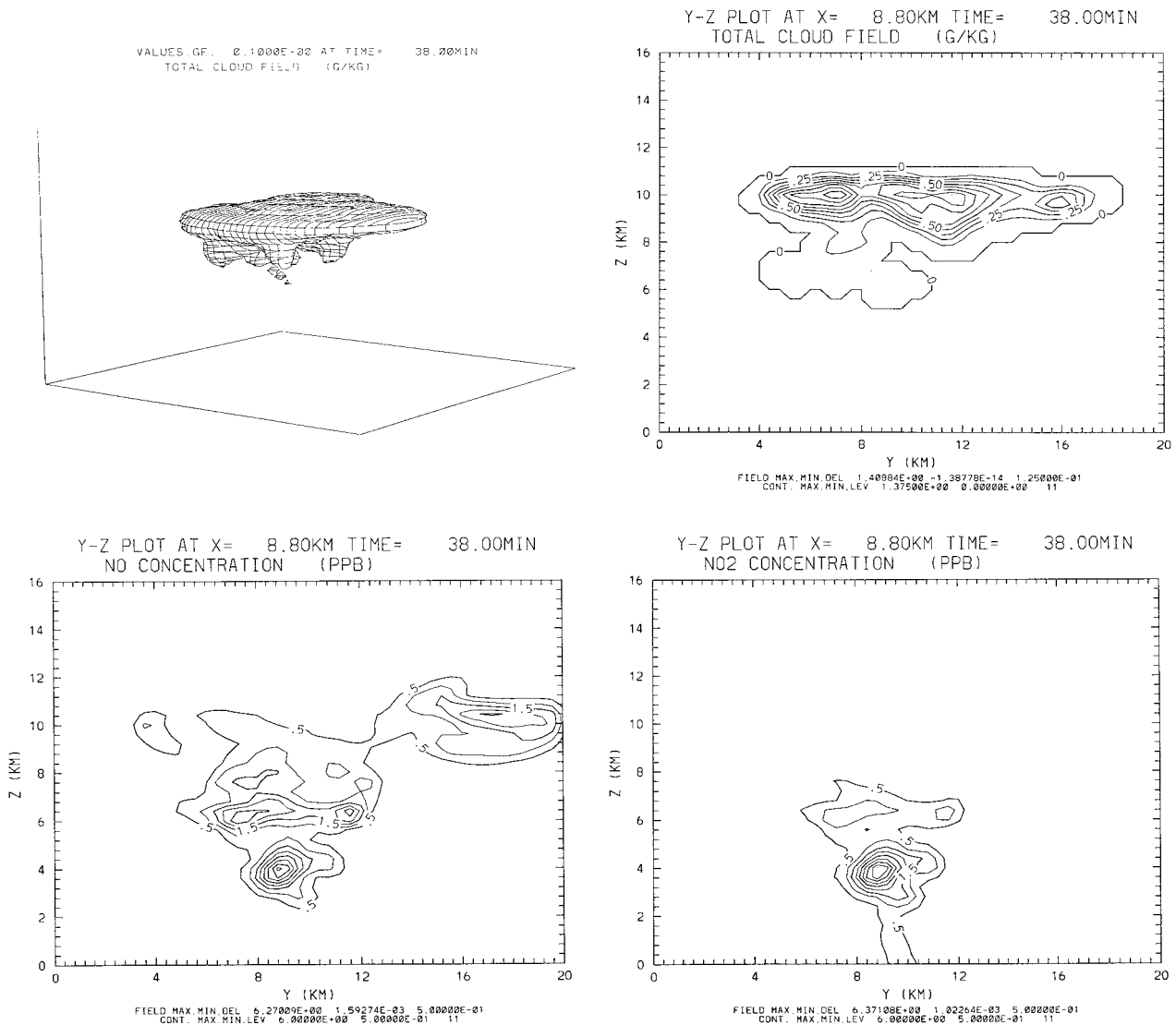


Figure 8 – 3D cloud depiction (top left) with 0.1 g/kg surface, 2D slice (top right) at X = 8.8 km through cloud, 2D slice through NO field (bottom left), and slice through NO₂ field (bottom right).

al., 2001), and it had previously been modeled (Skamarock *et al.*, 2000). The storm was also deemed suitable for simulation because the 3D SEM only computes intracloud lightning and the 10 July storm was dominated by such flashes (over 96% of total flashes were intracloud). The simulation was run for three hours of cloud growth and was initialized to produce three cells, following Skamarock *et al.* (2000).

The model generated 1003 discharges among the three cells while the observed, multicell storm produced around 1800 flashes over the same period (not counting short duration flashes, which are not well understood and not simulated with the current lightning scheme). Figure 9 shows the energy dissipation per flash (in units of

10^{10} J, top left panel) as a function of time during the integration and energy dissipation vs. charge transfer (top right). Also shown are 3D plots of the cloud (lower left), NO (middle), and NO₂ (lower right) mixing ratios at 90-min simulation time. These plots show that there is nearly an order of magnitude range in the energy dissipated by the simulated flashes. Also, the charge transfer and energy dissipation are correlated. These results are reasonable approximations to real intracloud lightning, although the energy dissipation is on the high side. The mesh plots show the three clouds midway through the simulation. Although all three clouds are still present, only the SE cloud remains electrically active. This is evident in the plot of NO mixing ratio, where the NO is only present in the

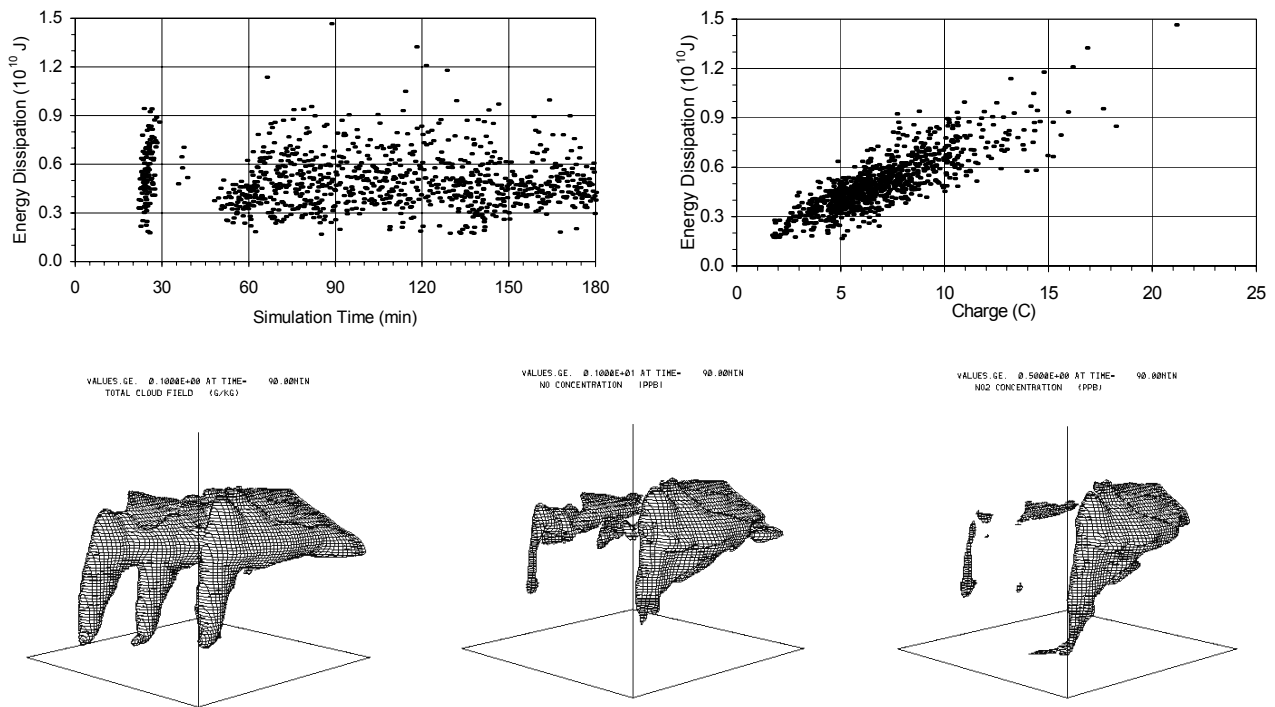


Figure 9 – Energy dissipation (10^{10} J) vs. time (top left), energy dissipation vs. charge transfer (top right), total cloud ≥ 0.1 g/kg (bottom left), NO mixing ratio ≥ 1 ppbv (middle), NO_2 mixing ratio ≥ 0.5 ppbv (bottom right) at 90 min for 10 July 1996 STERAO simulation.

SE cloud in significant concentrations. In contrast the NO mixing ratio is decaying following the cessation of lightning activity in the other two cells. This is even more evident in the NO_2 plot. Interestingly, there is a plume of NO_2 to the surface similar to that seen in the simpler 3D run shown in Fig. 8.

In general the model did a reasonable job of predicting the NO_x mixing ratios in a qualitative sense, but over-predicted the absolute values by about an order of magnitude. Zhang (2002) determined that there are several modifications that can be made to the model to bring the results in harmony with the observations without compromising the physics. Some of the more important modifications include addition of radiative transfer effects within the model cloud, using the breakeven field for lightning initiation rather than the breakdown field (Marshall *et al.*, 1995; MacGorman *et al.*, 2001), and adding a pressure (altitude) dependence to the NO production rate for lightning (Wang *et al.*, 1998). These modifications are currently pending.

As can be seen, much progress has been made in the 30+ years since Dr. Orville and his students and colleagues pioneered the inclusion of electrical effects in multidimensional, coupled

cloud models. Interestingly, since the initial work on the influence of electric forces on cloud dynamics and microphysics, little has been done in this area using more recent and more sophisticated models. The primary reasons for this are that early studies indicated potential effects to be small, there is lack of detailed information on how charges and fields might influence interaction coefficients (collision efficiencies, etc.), and the prevalent thinking (right or wrong) is that other areas related to cloud electrification are more worthy of study.

4. WHERE ARE WE NOW?

Currently there are two high resolution, coupled, 3D models – the SD Tech SEM and the Univ. of Oklahoma/NSSL model (as used by MacGorman *et al.*, 2001 and Mansell *et al.*, 2002), being used to simulate the electrification of storms. Both models have small ions, inductive and noninductive processes, and a lightning scheme. There are some differences between the models with respect to microphysics and lightning schemes, but for the most part they have similar capabilities. These models are state-of-the-art and are being used to address the critical issues

enumerated in the next section.

5. CRITICAL ISSUES

There are a number of issues that remain the subject of modeling studies in cloud electrification. I will list them here without going into great detail.

Charging Schemes

As noted above, the noninductive charging mechanism currently is considered by most atmospheric electricians as being primarily responsible for charge separation in clouds. However, the details of this mechanism have not been worked out to everyone's satisfaction and there continues to be disagreement between the results from different laboratories investigating the mechanism in cold chambers. Models can help in sorting out these details by applying the formulations to specific observed thunderstorm situations and determining which provides the best results. There has also been a resurgence of interest in the graupel/cloud water inductive mechanism as being of some importance in the development of the lower positive charge center of storms. This charge center is thought to promote cloud-to-ground lightning and its origin needs to be explained. The question of how charging mechanisms operate is also tied to the next item.

Storm Charge Structure – Polarity

Observations over the last 20 years have indicated that some storms appear to have a charge structure that is "inverted" with respect to "normal" storms, i.e., the main charge dipole exhibits a negative-over-positive structure (an oversimplification). These storms seem to be severe, contain large hail, and produce a high percentage of positive cloud-to-ground lightning flashes. The Severe Thunderstorm Electrification and Precipitation Studies (STEPS) in the summer of 2000 was undertaken to investigate these storms. Several good case studies were obtained and several hypotheses are "on the table" to offer an explanation for the observed charge structures. Numerical modeling is being used to try to sort out the processes responsible for the development of these storm charge structures. This highlights the necessity of having correct formulations for charge separation processes, as noted above. Thus far no model simulations have been successful in attaining the observed charge structures. This is a high priority item in the atmospheric electricity community.

Lightning Influence on Charge Structure

While the primary thinking is that charge separation mechanisms are responsible for the basic charge structure in thunderstorms, balloon and aircraft observations indicate that these structures in mature storms are more complicated than the simple tripole model. In early-storm observations, the evidence suggests that charge structures tend toward the tripole, but not so in more mature storms. Models with physics-based lightning schemes have shown that lightning can cause considerable charge rearrangement within storms. The question at hand is, does lightning merely travel through charge regions developed by charge separation processes, or is the lightning itself responsible for the developing charge structure in the mature stages of the storm? Models are one of the primary means of addressing this question.

Lightning Influence on Tropospheric Chemistry

As noted above, lightning is the least well quantified of the sources of NO_x in the atmosphere. The fact that it is injected directly into the troposphere at mid to upper levels, where it can influence ozone production, makes quantifying its production rate of great importance. Since this production term is being incorporated within global models with a range of values spanning an order of magnitude, it is essential that we determine the production rate more accurately. Field programs that investigate the lightning/ NO_x connection have been undertaken, but the results are difficult to put within the context of flash production rates. Modeling of NO production using models with explicit lightning physics can help to better quantify the amount and distribution of lightning-produced NO within developing storms and its transport and transformation through chemical reactions. Such modeling studies, undertaken within the context of observed storms, should help refine the production rates used in models without explicit lightning physics and ultimately improve our prediction of the ozone chemistry of the atmosphere.

Lightning Physics – Positive/Negative Leaders

There is much we do not know about lightning. Studies using instruments associated with rocket-triggered lightning have begun to reveal much about cloud-to-ground lightning and the attachment process. What remains less well understood is the virgin breakdown and in-cloud

propagation process. Such instruments as the Lightning Mapping Array (LMA), developed by P. Krehbiel and colleagues at the New Mexico Institute of Mining and Technology, are revealing more about these processes. What the LMA has revealed is that there is a definite difference in the breakdown process associated with positive and negative leaders, which attend the in-cloud portion of both cloud-to-ground and intracloud flashes. Also, we have little understanding of the branching process. This is another area where modeling, coupled with new observations can increase our knowledge. The new lightning scheme that we have developed attempts to model the breakdown process at the leader tip by considering random free electrons. The situation at the tip of positive and negative leaders is different. To this point all leader processes have been treated the same. We are now at the point where we can use the scheme to investigate different breakdown processes for oppositely charged leaders to see how channel formation and propagation differs. Channel behavior can be compared with data obtained by the LMA for verification purposes. The lightning scheme offers a method of coming to understand the formation of lightning channels more completely than ever before.

Models have advanced significantly with respect to complexity since 1970, just as our observing capabilities have increased. Modeling work, coupled with field observations and laboratory investigations have helped advance our understanding of the electrification of thunderstorms. In the process, as the sophistication of each component has increased, more detailed investigations have become possible. In truth, the more we have come to know, the more we realize how much there is left to understand. Modeling is an essential tool to help us continue to increase our understanding of thunderstorms and their place in the atmosphere.

6. FINAL COMMENTS

Although Dr. Orville is less recognized for his contributions in the area of thunderstorm electrical modeling than he is in the areas of cloud and precipitation physics, dynamics, and weather modification, nonetheless his contributions have been seminal. He established the protocol for inclusion of electrical effects in multidimensional models and was an advisor to those carrying out the first such modeling efforts. He was also a co-author of the first published work involving coupled thundercloud modeling. As important as this

research was, perhaps his most important contribution has been as a mentor and inspiration to those of us who have continued the work that he began, which has brought us to where we are today – where electrical models are providing insight into some of the oldest and most vexing questions associated with thunderstorms and opening up new avenues of investigation not thought possible only a few years ago. While he may best be remembered for his work in other areas, he stands as a pioneer in thunderstorm electrical modeling, and it is my privilege to recognize his legacy in this area.

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