Final Report

THUNDERCLOUD ELECTRIFICATION
MODELS IN ATMOSPHERIC ELECTRICITY
AND METEOROLOGY

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ABSTRACT

There exist a variety of theoretical concepts and numerical models of thundercloud electrification, plus experimental data. Yet there is no consistent theory of the cloud electrification phenomenon. This is due in part to the physical complexity of the system. Even the most sophisticated models to date have addressed only portions of the problem. It is also relatively difficult to perform experiments and obtain not only accurate but sufficient data.

A survey is presented here of presently-available theoretical models. The models may be classified into three main groups: (a) "convection" models, (b) "precipitation" models, and (c) "general" models. The strengths and weaknesses of the models, their dimensionalities and degrees of sophistication, the nature of their inputs and outputs, and the various specific charging mechanisms treated by them, are considered.

The models in the convection group (e.g. Ruhnke, Chiu & Klett) assume air circulation patterns and liquid water content, and are concerned with charge separation due to combined effects of convection and conductivity gradients. They omit precipitation and microphysical interactions of ions and cloud particles, and usually assume a steady state. The models of the precipitation group (e.g. Kuettner et al, Illingworth & Latham, Tzur & Levin) also assume circulation patterns, but (as opposed to convection models) emphasize cloud particle and ion microphysics, and the development of particle size and charge spectra. The mechanisms of charge generation and separation considered are particle collisions and gravitational separation (for ice, both noninductive and inductive types), and the Wilson mechanism for ion attachment. The general models (e.g. Chiu, Takahashi) compute cloud dynamics and development of air circulation patterns and water distributions, describing the life cycle of the cloud in time. They include the microphysics of small ions, cloud particles and precipitation, and generally encompass the electrification mechanisms of both the convection and precipitation groups. The cloud dynamics, microphysics, and electrical effects are all coupled. The advantage of the general

models is in their more complete, consistent and detailed descriptions. Their disadvantages include the requirements of more detailed inputs that may be difficult to specify, and large computer expenditures.

In results obtained to date, the convection models predict no significant electrification enhancement based on conductivity gradients and convection alone, with the assumed air circulation patterns. However, the detailed structures and dynamics of the downdrafts and of possibly extremely thin charge layers at the cloud surfaces ("screening" layers) may be crucial to the operation of convective charge separation (e.g. Vonnegut's concept), but are not presently adequately treated by convection or general models.

Results of the precipitation models show that (a) the initial electrification can occur rapidly and stably through noninductive collision mechanisms involving ice, and (b) breakdown-strength electric fields can relatively easily be achieved subsequently through the collisional-inductive mechanism. A critical difficulty of the collision mechanisms is imprecise knowledge of relaxation times versus contact times, which can easily lead to overestimates of electrification. The general model results tend to support those of the precipitation models in emphasizing the high potential effectiveness of the collisional-inductive mechanism.

Among the existing model gaps are the following: None of the models is capable of handling thin screening layers, mainly due to coarse-grid-spacing limitations dictated by computer costs. (Details on scales under 100 m may be important.) Also, while the microphysics (charge and size spectra) are relatively sophisticated in 1-D models, these are relatively crudely treated in general models.

1. INTRODUCTION

There exist a variety of theoretical concepts and numerical models of thundercloud electrification, plus experimental data. Yet there is no consistent theory of the electrification phenomenon. This is due in part to the physical complexity of the system. Even the most sophisticated models to date have addressed only pieces of the problem. It is also relatively difficult to perform experiments and obtain not only accurate data but sufficient quantities of it.

A survey is made here of some of the presently available theoretical models. It is hoped that this type of information will be useful in (a) aiding the atmospheric-electricity-meteorology community in the selection of appropriate models of thundercloud electrification from among those available, and in building improved models, and (b) ultimately helping to answer the important question of how modeling and experimentation can be used for interpreting satellite or ground observations of atmospheric electrical phenomena in terms of the likelihood of severe storms and dangerous convection patterns.

A thundercloud electrification "model" as defined here is a (generally numerical) representation in time and space of a system of interacting components, consisting of combinations of the following (together with a set of assumptions):

1) air circulation/convection patterns (assumed in advance or calculated abinitio via dynamical equations).
2) cloud and precipitation particles or hydrometeors (size spectra and microphysics connecting 1 and 2).
3) small ions.
4) electric fields.
5) electromicrophysical processes (connecting 1, 2, 3 and 4).
6) cloud geometry and boundary conditions.

In general the implementation of a model consists of two stages. In the first stage the nonelectrical structure is established. This includes the air circulation pattern and the hydrometeor concentrations and size spectra. In the second stage the electrification (involving 3, 4 and 5 above) is added. With respect to the electromicrophysical processes, one of the two principal steps in the electrification process is the charging of the ice and water particles. The water (liquid or solid form) carries most of the charge in the cloud. The small ions in their free state (unattached) carry relatively little of the charge; they become quickly attached to the particles. The second principal step is the separation of this charge into positive and negative charge centers (possibly multiple). There have been proposed many possible electromicrophysical mechanisms for charging the particles (e.g. Chalmers, 1967), and a few for separating these charges (although charging and separation can also occur simultaneously). Not all of the possible charging and separating mechanisms have been studied by cloud modelers.

Of course, the cloud dynamics, microphysics and electrical effects are all coupled. This coupling is neglected in a simple model, but is taken into account in a sophisticated model.

The models may be generally classified into three main groups: (a) "convection" models, (b) "precipitation" models, and (c) "general" models. We will consider examples of each group, their strengths and weaknesses, their dimensionalities and degrees of sophistication, the nature of their inputs and outputs, the various charging mechanisms treated by them, and some key results.

In Secs. 2, 3, and 4 we consider, respectively, convection models (those of Ruhnke and Chiu & Klett), precipitation models (those of Kuettner et al, Illingworth & Latham, and Tzur & Levin), and general models (those of Pringle, Chiu, Helsdon, Libersky, and Takahashi). In Sec. 5 the Vonnegut and Telford-Wagner concepts of charge separation by convection are discussed. Sec. 6 presents a summary of the mechanisms and models considered. Experimental instrumentation relevant to the modeling is outlined in Sec. 7, and a number of final comments and suggestions comprise Sec. 8.

2. CONVECTION MODELS

A "convection" model typically uses as input the air circulation pattern and the liquid water content, as functions of the spatial coordinates (and possibly also of time). Also, a relationship between conductivity and liquid water content may be specified, avoiding the complexity of describing small-ion-and-cloud-particle microphysical interactions. Precipitation is also omitted. Two principal convection models considered here, namely, Ruhnke (1970, 1972) and Chiu and Klett (1976), are axially symmetric, deal with a simple cumulus convective cloud, and assume a steady state (based on the generally short free-air relaxation time compared with cloud lifetimes). The steady-state assumption precludes the simulation of the initial development of convective electrification. This last assumption, however, allows one to boil the number of equations down to two, namely, Poisson's equation and the current continuity equation, which may be solved for the two unknown functions (of two spatial coordinates), i.e. charge density and electric potential. This means that the boundary conditions must include specifications of the fair-weather charge density and electric potential. Without precipitation, the electrification (in steady state with fixed cloud boundary) depends only on the combined effects of conductivity gradient and convection.

One of the difficulties associated with the modeling of cloud electrification is that closed analytical descriptions attempting to treat such a complicated system require crude approximations and simplifications in order to make progress, with the result that although they may be useful for providing insights and indicating general trends and features, they are not likely to be capable of predicting the outcome of any particular experiment. For the latter purpose, relatively sophisticated numerical techniques appear to be required. We begin here with a relatively simple example of a numerical model.

2A. Ruhnke's Model (1970, 1972)

The model is that of Ruhnke (1970, 1972), which relates convection and cloud conductivity (the latter through water content) to charge distributions and electric-field distributions, in a non-precipitating cloud without charge-separating processes. The basic elements of Ruhnke's model are a spherical cloud (region of reduced conductivity in accord with a prescribed connection between water content and conductivity), plus an assumed circulation pattern, in this case a simple vortex, all within a superimposed fair-weather electric field. The two partial differential equations he solves in r,z coordinates are Poisson's equation and the current continuity equation, whose solutions yield the charge density and electric field distributions.

In the absence of convection (as well as additional charge-separating processes), a "positive" dipolar charge distribution appears, simply because of the gradients in conductivity within the fair-weather field. When the convection is added, it is found that the updraft causes a distortion of the dipole charge distribution, namely, unsymmetric decreases in the total separate amounts of positive and negative charge, such that the positive charge decreases more rapidly than the negative and the cloud has a net negative charge. The predicted unsymmetric dipole with excess negative charge appears to be consistent with some experiments in non-raining clouds. The main point is that without additional charge-separating processes the electric field inside or near the cloud is not enhanced with convection. The model is extremely limited because of its assumptions, but it appears attractive from the point of view that it may be extendable to include charge separation and other processes.

The advantage of this type of model is that one can assign arbitrarily spatial distributions of conductivities (equivalently, water content plus a connecting relationship) and air circulation patterns. This property could be useful if the required distributions were available from experimental data. As outputs, the model in its present form yields space charge and electric field distributions.

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2B. Model of Chiu and Klett (1976)

The Chiu-Klett model (developed by C-S. Chiu and J. D. Klett at New Mexico Tech, Socorro, NM) represents an extension of the Ruhnke model in several respects, as tabulated next:

Assumption	Ruhnke	Chiu & Klett
cloud geometry	spherical	Gutman model (Chiu and Klett, 1976)
circulation gometry	simple vortex (cloud in updraft)	Gutman model (updraft within, downdraft at edge)
currents	conduction + convection	conduction + convection + diffusion
conductivity	function of liquid water content	function of liquid water content + electric field

The results of Chiu and Klett are similar to those of Ruhnke's earlier and simpler model: no significant electrification occurs based on conductivity gradients and convection alone, in steady state.

It should be noted that none of the existing models to our knowledge (including Ruhnke and Chiu & Klett) is capable of handling thin charge-screening layers at the cloud edges (mainly because of coarse-grid spacing limitations), so that possible contributions of the effects/transport of such layers to the convective electrification process are presently unknown.

Although the Gutman cloud model circulation and liquid-water patterns appear somewhat peculiar relative to common expectation (see Chiu and Klett, 1976), this model nevertheless is claimed to be in fair agreement with some cumulus observation (of some 15-20 years ago). It is also more realistic than Ruhnke's, e.g., in generating an envelope of descending air at the cloud edge. The model (or one like it) is convenient to use, requiring as input few parameters, such as maximum updraft velocity, liquid water content, and cloud thickness. Obviously, more realistic circulation and liquid-water patterns are desirable as inputs to convection models. However, sufficiently detailed data for this purpose is difficult to generate experimentally. Some data has recently become available from multiple doppler radar measurements (Lhermitte and Krehbiel, 1979). However, we may also use theoretical data generated by sophisticated cloud models such as that of Chiu (1978) Takahashi (1979).

3. PRECIPITATION MODELS

A "precipitation" model is defined here as one that generates charges principally through collision and separation of hydrometeors. Relatively advanced examples of such a model are those of Illingworth and Latham (1977), Kuettner et al. (1978), and Tzur and Levin (1978, 1979). Simpler predecessors are those of Scott and Levin (1975) and Sartor (1967). These models are simpler than convection models in some ways, e.g. in assuming the circulation patterns and in ignoring conductivity gradients and, until very recently, small-ion effects as well (although conductivity currents may be parameterized in some precipitation models, e.g., Scott and Levin). The advanced precipitation models are similar to the convection models in that they require as inputs air circulation patterns and liquid water content. The earlier model of Scott and Levin has no spatial variation, and only a single liquid water content value. The Sartor model is not a model in the sense of the present study but is rather a "concept" in that it deals with the basic mechanism alone. The advanced precipitation models can be more sophisticated than the convection models in their treatment of particle microphysics. By avoiding detailed geometry, cloud dynamics, and air circulation calculations they may devote their resources to details of the time (and to a limited extent also the spatial) development of the particle size spectra, through collisions as well as through evaporation/condensation. The charges, governed by both collisional and small-ion effects, are usually averaged over particle-size classes, so that there is one value of mean charge per size class. By further and drastic simplification of the geometry and air circulation assumptions, however, particle charge spectra development can also be accommodated. Such simplifications are employed by the earlier precipitation models, for example, the infinite-parallel-plate-capacitor (IPPC) geometry where whole-cloud averages are treated without considering spatial variations (e.g., Scott and Levin, 1975).

Some examples of advanced precipitation models are given next.

3A. Model of Kuettner, Levin and Sartor (1978)

The model of Kuettner et al (1978) assumes a simple vortex circulation in steady state (with maximum updraft and vertical scale as parameters, similar to Ruhnke's except their model is two-dimensional slab, i.e.,x-y cartesian, geometry). Added to this is a linear vertical shear in the horizontal wind speed, which is allowed by the slab (as opposed to axisymmetric) geometry. The liquid water is assumed to vary linearly with altitude but with no defined cloud boundary. The model, as is typical of precipitation models, is concerned primarily with frozen precipitation particles or hydrometeors, especially their size and charge distributions. The advanced model of Kuettner et al includes the particle trajectories in x-y space, and their growth along these trajectories. The embryonic frozen hydrometeors are introduced at certain altitudes with fixed initial radius (e.g. 100 micron). They accrete cloud water or ice along their trajectories, at a rate proportional to their geometric cross-section, proportional to the relative velocity, i.e.,the difference between their velocity and that of the air (all small particles assumed to move with the air), and proportional to the liquid water content. The small ice particle or water droplet size is assumed irrelevant in this growth, but not in the charge generation. The assumption of geometrical cross-section for collection does not consider fluid-dynamic or electrical effects. For example, fluid-dynamical effects alone would significantly reduce the accretion rate.

The electrical charge separation occurs by collisions and subsequent separation between large (frozen precipitation) particles and small (cloud ice or water) particles. Kuettner et al consider two types of collisional (i.e., precipitation) charging mechanism:

(a) A thermoelectric effect for ice/ice collisions, and a Workman-Reynolds effect for ice/water collisions (between graupel and supercooled water droplets), with no external field required for either, which they call "noninductive charging," and

(b) Collisional-inductive (or "polarization-induction") requiring an external field, which they call "inductive charging," for which the initial field is the fair-weather field.

The average charge transferred per collision in the noninductive collisions is assumed to be 10^{-5} esu. The source of this value, which is about 50 times smaller than that suggested by Reynolds et al. (1957), is not given. Reynolds et al. propose that graupel pellets, falling through a mixture of coexisting ice crystals and supercooled droplets, will become warmer than the ice crystals and acquire negative charge as a result of rubbing contacts with the ice crystals. This is sometimes called the "Workman-Reynolds" thermoelectric effect.

Although the circulation and liquid water patterns are fixed, the precipitation charging is followed in time, as well the growth of hydrometeor sizes and charges. It is not clear from the paper, but one may infer that there are two classes of particle sizes: "small" particles (water and ice) of fixed size depending on altitude (concentration and water content specified), and "large" precipitation particles varying in size along their fall trajectories, so that at any altitude their distribution in sizes (size spectra) is given by the distribution in their trajectories. Particle charges are presumably averaged over the horizontal dimension at any altitude.

The growth rate of hydrometeor charge is proportional to the geometric cross-section, to the relative velocity, to the small-particle concentration, to the separation probability (e.g. 0.9 for ice/ice, and 0.015 for ice/water), and to a factor depending on the small and large particle charges, on the vertical component of the electric field and on the average rebound angle (an input) for the inductive charging. (It would seem that the field dependence of the inductive charging should involve the field component parallel to the relative velocity vector rather than the vertical component; using the latter implies vertical fall velocities only.)

The space charge at grid points is computed by summing the charges on large and small particles (essentially of opposite signs), and Poisson's equation is used to compute the field. A time-marching procedure updates charge densities and electric fields as functions of time, although the circulation and water content are stationary in space and time.

The results of the Kuettner et al calculation re-emphasize the charging results of precipitation models (inductive), namely, that breakdown-strength electric fields are relatively easily achieved. Their principal new results seem to be that the simultaneously-operating noninductive and inductive processes are synergetic in that the noninductive charging produces the proper charge-dipole polarity of the thunderstorm, rapidly and stably, but with weak electrification, while the inductive charging can generate the appropriate high field strengths.

Kuettner et al do not take into account electric forces on the cloud and precipitation particles, although the earlier model of Scott and Levin (1975) does, including levitation effects. Past charge histories of both types of particles (i.e., multiple collision effects) are taken into account.

An additional effect, apparently not yet treated in any model with particle collisions (but apparently considered by Takahashi (1979) and not included), is the influence of particle charges and the electric field on the collision rates.

This model was developed at the National Center for Atmospheric Research (NCAR), Boulder, CO.

3B. Model of Illingworth and Latham (1977)

Another "precipitation" model belonging in the same class as the Kuettner et al (1978) model described above is that of Illingworth and Latham (1977), (developed at the University of Manchester Institute of Science and Technology, Manchester, England). This model improves on the earlier IPPC precipitation models. The improvement consists of defining a charging zone in the shape of a right circular cylinder within the cloud, with finite diameter W and finite height Z_m, whose bottom is above the surface of the earth, and which has within it a uniform vertical updraft of velocity U. This allows a description of the various dependent variables (vertical electric field = E, total space charge = ρ, precipitation space charge associated with raindrops or hailstones - both simply called "pellets" = ρ_p, pellet charge = Q, and the ratio Q/Q_{lim}, where Q_{lim} is the limiting charge a pellet may acquire by inductive charging in a given field E) as functions of height z along the axis. Radial variations are not considered (but are in the 2-D model of Kuettner et al). The charging zone is divided into a finite number of thin disks, for computational purposes.

The pellets are assumed to form at a steady rate within the zone and to grow as they ascend in the updraft. The top of the charging zone is defined to be the position where the pellets have achieved a balance diameter D_0 with terminal fall velocity V = U. The pellets (assumed hail for the main results of the paper) start to fall from this position towards the ground as a constant flux F, growing further by accretion of cloud water assumed to have a uniform mass concentration c and to consist of small cloud particles of diameter d and number density n. The pellet size is a function of altitude.

As they fall the pellets collide with the particles (where the latter are assumed to be ice crystals for the main results of the paper and are carried upwards steadily with the velocity U of the updraft). All collisions of hail with ice crystals are assumed to result in separation, with charge q being transferred between pellet and particle. Both "inductive" and "non-inductive" charging are considered, where "inductive" is defined as requiring the presence of an electric field. For <u>noninductive</u> charging, q is assumed to be a constant, and the authors have in mind the thermoelectric mechanism of Reynolds et al. (1957). The theory in this case depends on F, n, and q, but only through the product Fnq which can be specified as a single parameter. For <u>inductive</u> charging, q is an assumed function consisting of two terms, one proportional to E and the other propertional to Q, with analytically-derivable coefficients depending on d and D.

The theory in this case depends on the parameters F and nd^2, which the authors re-express in favor of the rainfall rate = P_m and a quantity α which for ice-ice is proportional to the average value of nd^2 over the cloud volume. For the inductive case, a starting field (fair-weather) is required. An additional input parameter required for both the inductive and noninductive cases is D_m, the pellet diameter at the bottom of the charging zone. The limiting charge Q_{lim} is obtained from the condition that $q = 0$. The Illingworth-Latham model assumes that, prior to collision, the particles are uncharged in an inductive encounter, and both particles and pellets are uncharged in a noninductive encounter. Illingworth and Latham justify this assumption on the basis that multiple collisions are unimportant. It should be noted that Takahashi's complex model (1979) with 59 size classes seems to indicate that multiple collisions and the neutralizing of previously-charged drops through the collisions may be important. However, Takahashi's model is restricted to warm clouds. In their noninductive charging encounters Illingworth and Latham use the Reynolds et al. (1957) value of 5×10^{-4} esu.

The authors investigate the time and vertical-spatial (no variation over the horizontal dimension) variations of E, ρ , ρ_p, Q, and Q/Q_{lim}, for inductive charging, for noninductive charging, and for combined charging with both mechanisms acting simultaneously, for various values of W, the cloud width. The latter parameter enters into the evaluation of E from the total charges (due to pellets and particles) within the disks. Its values range from 0.8 km to 6.4 km (including infinity which represents the IPPC model).

The results show that narrow clouds (W = 0.8 km) exhibit more complex electrical structures than wide clouds, although the rate of field growth is reduced. In any case the field growth rate is significantly less than that of the unrealistic IPPC model. The inductive and noninductive mechanisms give different electrical structures. The existing data is in some cases consistent with the one mechanism and in other cases consistent with the other, suggesting that both mechanisms may simultaneously be operating in general. The noninductive mechanism results in an early rapid field growth but with a relatively weak ultimate field, whereas the field growth due to the inductive mechanism starts slowly but later outstrips that of the noninductive process.

It is of interest to note that in comparing the inductive-alone case, noninductive-alone case, and combined case, the electric field at early times in the combined case is less than the electric field in the noninductive-alone case.

The foregoing results and conclusions are in many ways similar to those of Keuttner et al.(1978). It should be noted that both models neglect (a) consideration of contact time versus relaxation time, and (b) time-dependence of the circulation pattern. They also neglect small-ion effects.

The main advantage of the Illingworth-Latham model appears to be in its use of a simplified constant updraft, over a finite region. In this way it is simpler to use than the Kuettner et al model, which is 2-dimensional and requires an assumed circulation in 2-D with both updrafts and downdrafts. While the latter is in principal more realistic, the state of the art at present is such that we don't know what the "true" circulation should be. The Kuettner et al model, on the other hand, appears to be more straightforward to use regarding input parameters. Moreover, the simulation of pellet growth along trajectories in 2-D space seems more satisfying physically. However, the computer time requirements may be impracticably large. Not much information is given by Kuettner et al. on the numerical details of operation of their computer model.

3C. Model of Tzur and Levin (1978, 1979)

The Tzur and Levin (1978) model (developed at Tel Aviv University, Ramat Aviv, Israel) is geometrically a combination of both the Kuettner et al. (1978) model and the Illingworth-Latham (1977) model. The model is a cylinder with fixed r-boundary and moveable z-boundaries. All boundaries allow fluxes of ions, water vapor, etc. across them. The 2-D axisymmetric equations are averaged over radius at each altitude, which leads to the model's "1½-D" appellation by the authors. The growth, maturation and decay of the cloud (the motions of its upper and lower boundaries, and the 1-D distributions between) are followed in time. As in the case of the general models to be discussed, the inputs to this model include vertical profiles of temperature and humidity. Horizontal entrainment of dry air through the sides of the cloud is taken into account, this air being mixed over the cloud cross-section. This model is based on that used earlier by Asai and Kasahara (1967) for studying cumulus dynamics.

The cloud particle microphysics is quite detailed. The model uses 36 size classes or categories of water drops in the warm-cloud version (Tzur and Levin, 1978). The drops are followed in time and space as they grow from nucleation by condensation and stochastic collection. The effects of electrical forces on the fall of charged drops are included.

The electromicrophysics include inductive-collisional charging and small-ion attachment, the latter including ion diffusion to the drops, the Wilson mechanism, and production of large ions by evaporation of the drops. Ion generation by cosmic rays, and loss by recombination, are included. It is not clear from their paper how the charge spectra are defined, but presumably the drop charges are averaged within each size category.

The principal results of Tzur and Levin (1978) concern electrification of shallow and deep warm clouds. The shallow and deep clouds reach altitudes of 3.5 km and 8.0 km, respectively. The shallow cloud is weakly electrified, with the Wilson effect dominating the charging and the collisional-inductive charging remaining weak. In the deep cloud the collisional-inductive charging is dominant and produces strong fields, while the Wilson effect is relatively weak. With a cloud radius of 1.5 km, maximum field values of the order of 400 kV/m (i.e. breakdown strength) are obtained. With larger radii, larger fields are obtained.

A critical parameter is the separation probability. The fields obtained by the collisional-inductive charging are very sensitive to this parameter, which is very poorly known. The 400 kV/m maximum field intensity is obtained when the separation probability is assumed to be about 0.06. When this is reduced by a factor of 2, the maximum field intensity drops to the order of only 10 kV/m.

The authors have developed a second, expanded version of their model (Tzur and Levin, 1979) which includes ice microphysics and associated additional size categories. Ice particles grow by condensation and riming, with a stochastic formulation for collisions between ice-ice, water-water, and water-ice. In addition to collisional-inductive charging and the diffusional and Wilson small-ion attachment mechanisms, the authors have included the Workman-Reynolds noninductive charging mechanism for ice-water collisions and the thermoelectric noninductive mechanism for ice-ice collisions, as in Keuttner et al. (1978). The effects of relaxation time (and presumably also contact time) in collisional charging events are taken into account. (See also Scott and Levin, 1975).

The results obtained are in general agreement with the glaciated cloud results of Kuettner et al. (1978) and Illingworth and Latham (1977) discussed above. That is, the noninductive charging develops the field early and with the right polarity, while the inductive charging subsequently builds it up to strong values.

4. GENERAL MODELS

In this section we consider "general" electrification models, defined as including cloud dynamics calculations as well as distributions and electrical interactions among small ions, cloud particles and precipitation. The dynamics, microphysics and electrical effects are all coupled. To date general models have been developed in two stages: First, a cloud dynamics model exists or is developed, and then electrification is added. By a "cloud dynamics model" we mean a (generally numerical) representation in time and space (2-D or 3-D in general models) describing how a cloud develops, matures and dies. This representation consists of a system of simultaneous equations whose solutions describe, for example, air circulation/convection patterns, and temperature and water distributions as functions of space and time. The equations represent conservation and transport of mass, momentum, and mechanical as well as heat energy. The models simulate the interactions among the environmental airflow, the cloud air circulation, and the cloud microphysics. The latter generally includes activation of nuclei, growth of cloud droplets, ice crystals, raindrops and hailstones. Such models have been developed, for example, in two dimensions by H. Orville and his co-workers (Orville, 1965, 1968; Orville and Kopp, 1977), by Murray and Koenig (Murray, 1970; Koenig and Murray, 1976), and by Takahashi (1979), and in three dimensions by Klemp and Wilhelmson (1978), by Schlesinger (1978), and by Clark (1979). Essentially all of these present models are based on a common source, namely, the pioneering work of Ogura (Ogura, 1963; Ogura and Phillips, 1962).

The solutions sometimes depend sensitively on the initial and boundary conditions (e.g. the initial and ambient distributions of temperature, humidity and air circulation velocities). The cloud models can also in principle define cloud particle/precipitation size spectra and microphysical interactions as functions of space and time. The water substance has the forms of water vapor and particles. In most of the general models the cloud particles are divided into two classes, "small" particles that move with the air velocity, and "large" (precipitation-size) particles that have appreciable terminal velocities. The precipitation size spectrum is parameterized by assuming the sizes obey a Marshall-Palmer (exponential) distribution characterized by two parameters, and that the particles fall with their mass-weighted mean terminal velocity. An exception appears to be the Takahashi (1979) model which handles 59 size classes with discrete interactions, and this at every grid point, thus requiring large computer capacity.

None of the general electrification models discussed in this survey handles the ice phase. All are concerned with warm clouds. It should be noted that including ice with its microphysics described by many size classes with discrete interactions, as in the advanced precipitation models, or by extending Takahashi's approach to include ice, will severely tax present-day computers (e.g. even the NCAR Cray machine). Hence a parameterization (e.g. similar to Marshall-Palmer) may be effective. This can be based on computational data from simpler models with complex size-class interactions.

Addition of electrification to the model implies added equations for electric fields, space charge (or ion concentrations), and cloud droplet and raindrop charge spectra, as functions of space and time, as well as an electric force term in the cloud equation of motion (and possibly also a joule heating term in the heat equation). The electrical addition requires that the electromicrophysical processes be defined (Sec. 6).

Some examples of general models are discussed next.

4A. Models of Fringle et al (1973), Chiu (1978) and Helsdon (1979).

One of the most sophisticated general models available is the 2-D axisymmetric model of Chiu (1978) and its 2-D slab-symmetric extension by Helsdon (1979), developed for warm clouds, and based on the nonelectrical cloud dynamics models developed by Orville and his co-workers. In Chiu's model two charging/charge-separation mechanisms are treated, namely (a) collisional-inductive (or "polarization-induction") whereby large drops and small droplets colliding in the electric field rebound with opposite induced charges and separate via their different terminal velocities (simultaneous charging and separation without small-ion involvement), and (b) ion attachment whereby small ions are attached to cloud droplets by diffusion and conduction. In particular, the Wilson mechanism (Chalmers, 1967) causes a falling drop to acquire a net charge whose sign depends on the sign of the vertical electric field; in a positive gradient (positive charge overhead), a falling drop has a net flow of negative small ions into its surface.

The Pringle and Chiu models were developed at the South Dakota School of Mines and Technology, Rapid City, SD. The Helsdon model was developed at the State University of New York at Albany, Albany, NY; Dr. Helsdon is presently with the South Dakota School of Mines and Technology.

The Helsdon model is similar to Chiu's model, except that the geometry is slab-symmetric in 2-D x-z coordinates, and with added ionization sources due to chaff seeding. An advantage of the x-z geometry (as opposed to an r-z axisymmetric geometry such as Chiu's) is that it can include wind shear which could be important for cloud electrification. The electromicrophysics is discussed further below.

The Pringle model is a predecessor to those of Chiu and Helsdon. All three (Pringle, Chiu, and Helsdon) are based on earlier nonelectric cloud dynamics models developed by Orville and his co-workers (Orville, 1965; Orville, 1968; Orville and Kopp, 1977). These deal with the dynamical growth and development of convective cumulus clouds in 2-D slab geometry which enables them to treat multiple clouds as well. The equations describe the conservation and transport of air and water mass, momentum, and heat. The equations for small-ion, charged-water, space-charge, and electric-field distributions and time-evolution are added, together with specified charge-separation mechanisms.

In Pringle's model (preceding Chiu and Helsdon) the rain is arbitrarily assumed to acquire negative charge at a rate proportional to the square of the raindrop diameter (Marshall-Palmer distribution). The cloud droplets are, on the other hand, assumed to acquire positive charge, but are assumed monodisperse. This is based on the standard concepts of polarization-induction collisions and/or the Wilson mechanism in the fair-weather electric field. The model therefore ignores the microphysics of particle charging and charge transfers. A feature of the Pringle model, however, is its inclusion of both small and large ions.

Chiu's improvements on the Pringle model include the microphysics of the polarization-induction and Wilson charge-separation mechanisms, both associated with falling precipitation in the local electric field. The charge transfers, from small ions to drops and droplets, and from droplets to raindrops, are also included. The droplet charges and sizes have unique values at each point. Chiu shows that with polarization-induction the cloud can be strongly electrified, to the point where the charged raindrops are appreciably levitated by the field. (See also Ziv and Levin, 1974.) The high effectiveness of the polarization-induction mechanism for producting strong cloud electrification appears to be a common result of models which include precipitation (see previous section). Note, however, that the separation probability is not well known but critically controls the electrification. The arbitrarily chosen value of 0.04 assumed by Chiu for this probability easily produces breakdown-strength fields.

(The ice phase is not included in Chiu's model, but is being included in more advanced models under development by H. Orville and his co-workers. This work is currently underway at the South Dakota School of Mines and Technology, Rapid City, SD.)

4B. Libersky's Model (1979)

The Libersky model (1979) (developed by L. Libersky and A. Petschek at New Mexico Tech, Socorro, NM) is similar to Pringle's in that the geometry is 2-D x-z slab geometry. There is some rudimentary transport of small ions, but it is not clear how the liquid water becomes charged. The model does not include precipitation.

However, the nonelectrical cloud dynamics appears to be more sophisticated than that of any other general model to date. The model includes a more realistic description of turbulence (after Daly and Harlow, 1970); the turbulence is anisotropic and is associated more with buoyant instabilities than with shear in the mean flow. (As opposed to this, the Chiu model uses isotropic though nonlinear eddy diffusion, based on Smagorinsky's formulation.) Due to the anisotropy the vertical component of the Reynolds stress is much larger tnan the horizontal component, particularly near the cloud top. Because of the strong anisotropy (and inhomogeneity) of the turbulence, vertical mixing is favored near the cloud top, and large amounts of dry air are entrained into the upper cloud. The model was originally developed to compute mountain lee waves.

4C. Takahashi's Model (1979)

Takahaski's work (1979, and many previous Takahashi references cited therein) in both theory and measurement emphasizes the roles played by small ions and convection to a greater extent than the other models discussed here. Takahashi's model (developed at the University of Hawaii, Hilo) is 2-D axisymmetric, and is concerned with shallow warm clouds. The nonelectrical cloud dynamics appears to be as sophisticated as Chiu's (1978), yet seems to have been developed later than the electromicrophysics, the latter having been tested earlier using simpler (1-D, 1½-D) cloud models. An advance made by Takahashi over previous models is in his utilization of 59 size classes of cloud particles to model discrete interactions among the particles, at each grid point. This detailed formulation contrasts with Chiu's formulation utilizing effectively two size classes, the "small" cloud droplets and the "large" raindrops (parameterized as a Marshall-Palmer distribution). However, as in Chiu, the charges are averaged over each size class so that there is one mean value of drop charge for each size class. The Takahashi 59-class-size formulation, however, allows the description of multiple collisions that can account for partial neutralization of drops within each group during subsequent collisions.

The four electromicrophysical charging mechanisms treated by Takahashi (1979) are the following:

(a) ion attachment to drops by diffusion, with net charging by differential diffusion (Gunn mechanism).

(b) ion attachment to drops by the Wilson mechanism (conduction + convection).

(c) collisional-inductive ("polanization charging").

(d) ion-drop interaction during drop condensation and evaporation (IDIDDCE).

The first three mechanisms (a, b, c) are the same as those treated by Chiu. They are found by Takahashi to be all dominated by the fourth mechanism (d), for the shallow clouds of interest, within which the computed fields do not exceed 300 V/m and of which the cloud tops do not get higher than about 3 km.

While the first three mechanisms are well known (e.g., Chalmers, 1967; Chiu, 1978), the fourth appears recently to have been proposed by Takahashi (1973). In his experimental study (1973) using a copper sphere covered by a water layer, Takahashi infers from change-of-potential measurements that negative ions are preferentially absorbed on the liquid surface during condensation, and that positive ions are preferentially absorbed during evaporation. The coefficient measured for this type of charging is given by Takahashi for the negative charging during condensation, but is not clearly stated for the positive charging during evaporation. Moreover, the value used for the separation probability in the collisional-inductive charging computation of his 1979 paper is not evident.

It should be mentioned that Griffiths and Vonnegut (1973) question the validity of Takahashi's inferences regarding the transfer of charge in his (1973) charging experiments on the IDIDDCE mechanism.

By invoking his IDIDDCE charging mechanism, Takahashi's model can reproduce his observations of strong negative potential gradients (due to negative space charge that persists and dominates) near the ground, coexisting with simultaneous positively-charged drizzle and raindrops. (With the IDIDDCE "turned off" in the model, the positive rain, created by the evaporation mechanism at the top of the cloud, does not occur.) The negative space charge, in the form of excess small ions, is carried down by the downdraft associated with the positive raindrops.

The following comments may be made. Physically it is not clear why significant numbers of excess small ions can persist without becoming quickly attached to droplets. Moreover, there are aspects of this model that relate it to the convection charging group. Namely, small-ion charging is dominant and the downdraft carrying space charge occurs principally along the cloud boundary. It should also be mentioned that Takahashi's concept seems reminiscent of Vonnegut's concept (1955), to be discussed below, and the concept proposed by Wahlin (1973), namely, that droplets would tend through an electrochemical mechanism preferentially to capture the negative small ions in their vicinity while rejecting the positive ions. If this occurs the negative ions in an updraft would become attached to water in the lower part of the cloud, leaving the excess positive ions to be carried up to the upper part of the cloud and to become attached there.

5. ADDITIONAL CONCEPTS

The Vonnegut and Telford-Wagner Concepts of Charge Separation by Convection

In all of the models discussed so far the role of convection as a distinct mechanism for separating charges has been either ignored, as in the "precipitation" models, or essentially obscure, as in the existing "convection" models or even the "general" models. It is known that there is enormous energy associated with air motion in thunderclouds. According to a concept advanced by Vonnegut (1955), the major cloud charges reside on the small cloud particles, and air motions can easily separate sufficient positive and negative accumulations of charge to generate breakdown fields.

In the Vonnegut concept, positive charges are carried from near ground level upward by updrafts within the cloud to the top of the cloud, where they attract negative small ions from the clear air outside the cloud. The negative ions attach to cloud particles in a thin layer at the cloud surface, which are then carried by downdrafts down the outside of the cloud toward the base where they accumulate as a negative charge center. This accumulation results in strong fields at ground level, drawing out more positive ions by corona. These positive ions are carried upward by the updrafts to the accumulating positive charge center at the top of the cloud, and so the process continues to generate opposite charge centers. The Vonnegut concept visualizes the air motions as organized up-and-down circulations, and depends on ionic currents to generate the charges on the water, by attachment.

The concept of Telford and Wagner (1979) is a new one which depends on turbulent motion and entrainment of dry air, together with certain postulates. It postulates that there are small particles and large particles, and that the charges are somehow generated, with negative charges residing on the large particles, and positive on the small. The air entrainment, which occurs mostly at the cloud top, causes evaporation and cooling. The small particles evaporate quickly, releasing positive small ions, which are somehow swept away to attach to particles in neighboring air parcels. Meanwhile, the cold air parcel containing the large negative particles sinks, bringing the negative charges with it. The result is an accumulation of positive charge at the top of the cloud, and negative charge at a lower level (actually, it is argued that the lower level will be near the -10° C level). The negative charge is accumulated before substantial hydrometers begin falling out of the region.

The concept depends on turbulent mixing and transport, and is qualitative at present. This concept is appealing because convective turbulence and continual mixing seems to be a feature of thunderclouds, with an enormous energy content.

A difficulty with modeling either the Vonnegut or the Telford-Wagner concepts may be associated with the necessity for describing details of circulation and charge distributions with high spatial resolution (e.g. at the cloud edge for the Vonnegut concept, and adjacent small parcels of air with different motions for the Telford-Wagner concept). Present numerical models such as Chiu's (1978) or Takahashi's (1979) cannot resolve details on the order of 100 m or less (because of computer limitations), and these or smaller scales may be important in convection electrification.

6. SUMMARY OF MECHANISMS AND MODELS

Mechanisms

In the thundercloud electrification models we have considered, the following electromicrophysical charging mechanisms have been used:

Ion attachment

Wilson (falling hydrometeor polarized in electric field selectively captures small ions of sign opposite to sign of charge at lower end of hydrometeor; convection and conduction only, no diffusion)

Gunn (diffusion of small ions to hydrometeor, charge proportional to difference in positive-ion and negative-ion mobilities; no convection)

Takahashi (ion-drop interaction during drop condensation and evaporation; see Sec. 4C)

Collisional charge transfer

Collisional-inductive (a pair of colliding hydrometeors, polarized in an electric field while in contact, subsequently separate gravitationally with charge having been transferred; larger hydrometeor takes on negative charge; sensitive to probability of separation, as well as relazation time for ice-ice)

Ice thermoelectric and Workman-Reynolds (noninductive transfer of charge through temperature difference between surfaces of a pair of colliding hydrometeors)

Another possible collisional charge transfer phenomenon due to ice-ice collisions is that due to workfunction differences, suggested on the basis of experiments by Buser and Aufdermaur (1977). This may be an important alternative to the thermoelectric effect (Reynolds et al, 1957).

To the above mechanisms for producing charges in clouds that due to lightning should be added.

Models

We have considered three groups of models, convection, precipitation and general. Table 1 summarizes some of the key characteristics of the models, the names of the developers, their dimensionality, the source of their air circulations, and the electromicrophysical mechanisms treated.

TABLE 1. SOME EXISTING MODELS

Type	Developers	Dimension	Circulation/ Cloud Dynamics	Microphysics/ Electrophysics
General	Chiu/ Helsdon/ Orville	R-Z, X-Z	sophist. egs. of motion (water)	Gunn ions Wilson ions coll. - induct.
General	Pringle/ Orville	X-Z	sophist. egs. of motion (water)	simple: + = cloud droplets - = raindrops
General	Libersky/ Petschek	X-Z	sophist. egs. of motion/ anisotropic turbulence (water)	ion conservation
General	Takahashi	R-Z	sophist. egs. of motion (water)	Gunn ions Wilson ions IDIDDCE coll. - induct. (+ discrete spectra: 59 size classes)
Precipitation	Kuettner et al	X-Z	assumed circ./ vortex + shear (ice & water)	coll. - induct. thermoelectric/ Workman-Reynolds (+ discrete spectra)
Precipitation	Illingworth & Latham	"1-D", R-Z	simple updraft (ice & water)	coll. - induct. thermoelectric/ Workman-Reynolds
Precip-tation	Tzur & Levin	"1½-D", R-Z	sophist. 1-D (water)	coll. - induct. thermoelectric/ Workman-Reynolds (+ discrete spectra)
Convection	Chiu & Klett	R-Z	assumed circ./ Gutman model (water)	convection/ conductivity - gradient (no microphysics, no precip)
Convection	Ruhnke	R-Z	assumed circ./ simple vortex (water)	convection/ conductivity - gradient (no microphysics, no precip)

Under "DIMENSION" (dimensionality), "R-Z" refers to 2-D axisymmetry and "X-Z" refers to 2-D slab symmetry. "1-D" R-Z or "1½-D" R-Z refers to cylinder models with fixed finite radius. (In the 1½-D model, non-zero fluxes occur at the sides, and the top and bottom move in response to the dynamics.) Under "CIRCULATION/CLOUD DYNAMICS", "sophist." means sophisticated; "egs. of motion" means that the air circulation is calculated from the equations of motion; "assumed circ." means that the circulation is assumed; "water" means water only - no ice.

The following summarizes the types of inputs and outputs that are in principle associated with general models. (No model has all of these.)

INPUTS (Nonelectric)

Temperature (vs. altitude) 1-D
Humidity (vs. altitude) 1-D
Convection (airflow) patterns 2-D
Topography
Heat flux from the earth
Land vs. water

INPUTS (Electric)

Fair-weather electric field (vs. altitude) 1-D
Conduction current (vs. altitude) 1-D
Ion concentration (vs. altitude) 1-D
Ion mobility (vs. altitude) 1-D
Ion sources (vs. altitude) 1-D
(e.g., cosmic rays, ground corona)

2-D OUTPUTS (Nonelectric)

Airflow (velocity vector) patterns
Mixing ratio
Temperature
Humidity
Particle size spectra

2-D OUTPUTS (Electric)

Charge density (total, small ion concentrations, charges on liquid water, rain, ice)

Electric field (vector) patterns

Currents (conduction, convection, precipitation, lightning, corona)

7. SOME INSTRUMENTATION RELATED TO MODELING

Progress in understanding thundercloud electrification depends on strong interactions between modeling and experimentation: on the experiments to provide the data-bases, to check the predictions of the models, and to suggest improvements in the models, and on the models to provide insights, to demonstrate complex interrelationships, and to suggest further experiments. (An example of the latter is the prediction of the levitation effect which led to a doppler-radar experiment in TRIP-79.) The following outline indicates types of instrumentation, available and proposed, for obtaining in-cloud experimental data (as in the TRIP programs) related to the modeling described in this paper.

Air Circulation

Multiple doppler radar (ground-based)

Vertical velocity (airborne)
- variometer (NCAR sailplane, Markson Bellanca, ONR-NMIMT Schweitzer)
- inertial platform (DRI B-26)

Cloud

Precipitation
- radar (ground-based/airborne)
- Cannon camera (airborne)

Droplet/particle sizes and concentrations (airborne)
- Knollenberg FSSP (forward scattering spectrometer probe)
- Cannon camera
- Takahashi radiosonde microphone method

Electric Fields-Airborne (difficult inside clouds, particularly in heavy precipitation)

Field mills (Kasemir, Ruhnke, Christian)

Polonium probes (Markson, fair weather up to 10 kV/m)

Corona points (Markson, moderate to strong fields)
Winn's dipole (NMIMT, tethered balloon)
Few's corona radiosonde (Rice, free balloon)
RF, acoustic from breakdown regions?

Charges on Precipitation

Induction ring (UMIST, Schweitzer aircraft)
Insulated bucket (precip. current, tethered balloon; Takahashi radiosonde, free balloon)

Charges on Small Droplets

Insulated bucket (Takahashi radiosonde, free balloon)
Under development for airborne use (UMIST, Barker)

Ion Concentrations?

Very difficult inside clouds - very few ions

Currents Over Cloud Top?

Related to structure such as turrets (Markson)

Cloud Edge?

Radiometer method (Lhermitte)?

8. FINAL COMMENTS AND SUGGESTIONS

Among the charging mechanisms thus far studied in thundercloud models, the collisional-inductive mechanism appears to be the most powerful. Once started, the electric field growth is exponential. However, this mechanism is very sensitive to certain parameters, such as separation probability which cannot be too low (e.g. it is relatively low for water-water), and relaxation time (while in contact) which cannot be too long (e.g. it is relatively long for ice-ice). (Also, contact time cannot be too short.) Electrification levels also depend sensitively on the initial humidity-versus-altitude sounding. Ion attachment mechanisms such as Wilson's appear to be relatively weak, probably because the free ion populations tend to be depleted.

With respect to general models it may be noted that they have an advantage in principle over the simpler models, namely, in providing more complete, consistent and detailed descriptions of thundercloud electrification. The price paid for this advantage, however, is that they require more detailed inputs that may be difficult to specify realistically.

Stronger Interaction Between Modeling and Experiment

One possible aid in the interaction between sophisticated numerical modeling and experiment might be the availability of computer software for small (mini) computers with "plug-in" modules to predict electrification. The modules would represent various microphysical mechanisms. The input would include simplified but realistic airflow circulation patterns. Another possibility is that of "retrospective modeling" with electrification mechanisms. Again, on a small computer one could input well-documented circulation and cloud water distributions versus time obtained for real storms (e.g. Lhermitte's data), and predict fields, etc. These can be compared with measurements made on the same storm.

Modeling Gaps and Possible Improvements

One gap in modeling is evident from the fact that the microphysics can be more sophisticated in 1-D models than in general models because of computer limitations. Hence the results of 1-D calculations (complex size and charge spectra) might be parameterized for use in 2-D and 3-D models. Another gap is associated with screening-layer calculations. Due to the use of uniform-mesh grids the spatial resolution scale is no smaller than 100 meters or so, so that thin screening layers are predicted to be insignificant or nonexistent by general models. This may be contrary to reality, although the existence of screening layers is still controversial. The modeling remedy may be to use more sophistication in mesh techniques, e.g., non-uniform grids with high grid-point density concentrated densely in the vicinity of the cloud boundary and sparsely elsewhere. This could be accomplished with a "dynamic grid" that moves with the cloud boundary, such as the grid method employed by Parker and Zalosh (1973) in a calculation following curved shock waves.

An additional gap concerns electrical effects of charges and fields on microphysical interactions. One effect is that the electric forces will alter collisions between interacting hydrometeors. In present models the collision efficiency is assumed to be the geometric value unity associated with straight-line trajectories. Takahashi (1979) recognizes this possibility but ignores the effect on the assumption that it is negligible (which may be justifiable in his weak fields). A difficulty also occurs in the treatment of the electromicrophysics of ion attachment by simultaneous diffusion, convection and conduction. Chiu (1978), for example, assumes simple superposition of diffusion and convection-conduction. This is incorrect since these mechanisms are coupled nonlinearly. More rigorous electromicrophysical interaction calculations such as those of Parker (1977) for attachment of Brownian particles (e.g. also ions) to charged raindrops can be used to check the approximation.

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