Radar Tests of the Precipitation Hypothesis for Thunderstorm Electrification

EARLE R. WILLIAMS

Department of Earth and Planetary Sciences, Massachusetts Institute of Technology

ROGER M. LHERMITTE

Rosenstiel School of Marine and Atmospheric Science, University of Miami

The contribution of falling precipitation to thunderstorm electrification is examined from an energy standpoint by means of radar measurements of precipitation. The gravitational power associated with falling precipitation is compared with estimates of the thunderstorm electrical output as a test of a causal relationship between these two quantities. The relative importance of the gravitational and electrical forces acting on precipitation particles is investigated by monitoring the stability of particle vertical motions to lightning-associated changes in electric field. The general absence of abrupt particle velocity changes is difficult to reconcile with the gravitational power determinations in electrically active storms unless the electrical energy contribution from convective motions is substantial.

1. INTRODUCTION

The electrical energy of thunderstorms is a result of the motion of charged particles against the local electric field. A specification of the nature of these particles is still unavailable, and the relative importance of precipitation and convection has yet to be quantified. The classical precipitation hypothesis (described in Mason [1971]) maintains that electrical energy results from the gravitational sedimentation of selectively charged precipitation particles, but with the exception of recent small scale measurements [Rust and Moore, 1974; Gaskell et al., 1978; Christian et al., 1980; Marshall and Winn, 1982] this hypothesis has not been tested. New approaches to quantifying the contribution of precipitation to electrification are afforded by meteorological radar, and are the subject of this paper.

Section 2 is concerned with the gravitational energy of thunderstorm precipitation which is available for electrification and with predictions for particle electric charge and terminal velocity when precipitation particles are falling with maximum efficiency. Incoherent radar measurements of precipitation-associated gravitational power and simultaneous estimates of electrical power in thunderstorms are presented in section 3, as one test of the precipitation hypothesis. These comparisons lead to the expectation that precipitation particle motions will be modified by electric forces if falling precipitation is the principal cause of electrification. A Doppler radar search for precipitation particle velocity changes at the time of nearby lightning discharges is described in section 4, as a complimentary test of the precipitation contribution.

2. THE ENERGY AVAILABLE TO PRECIPITATION MECHANISMS

2.1. Gravitational power, optimal charging, and maximum power conversion for falling precipitation. In the well-known treatment of the thunderstorm energy budget, Braham [1952] estimated that the gravitational potential energy of thunderstorm precipitation is a few percent of the latent heat energy. To investigate what constraints energy conservation places on the classical precipitation hypothesis, the required microphysical conditions necessary to maximize the conversion of gravitational to electrical power for falling precipitation are derived.

An upper limit to the steady state electrical power available from any precipitation mechanism is $MgV$, where $M$ is the total precipitation mass, $g$ is the acceleration due to gravity, and $V$ is the effective terminal fall velocity; this quantity is simply the rate at which the gravitational potential energy of precipitation is given up. Not all the available gravitational power may be converted to electrical power, but a realizable bound for electrical power may be determined by maximizing the current contributions of charged particles falling in local vertical electric fields.

The terminal velocity of precipitation particles as a function of their mass ($m$), charge ($q$), and the local vertical electric field ($E$) is given by Gay et al. [1974]:

$$V = \frac{\nu}{2r} (0.08) \left[ \frac{8(mg - qE)}{\pi \rho_v v^2} \right]^{0.8}$$

(1)

where $r$ is the particle radius, $\rho_v$ is the air density, $\nu$ is the kinematic viscosity of air, and $x$ is an empirical parameter dependent on the $Q$ number (the quantity in brackets on the right hand side of equation (1)).

This expression for particle velocity may be simplified considerably by comparing electrical and gravitational forces and nondimensionalizing the electric charge

$$q^* = \frac{qE}{mg} = \frac{qE}{(4/3)\pi r^3 \rho_v}$$

(2)

If the charge free terminal velocity, $V_0$, is approximated as being independent of nondimensional charge $q^*$ in view of the weak dependence of the empirical parameters $x$ and $Q$, a simplified expression for velocity is obtained

$$V = V_0 (1 - q^*)^{0.8}$$

(3)

The current contribution, $I$, of this falling particle is the product of charge and velocity

$$I = q^*V = V_0q^*(1 - q^*)^{0.8}$$

(4)

The electrical power will be greatest for any vertical electric field when this current contribution is maximized with respect to the nondimensional charge $q^*$.

$$\frac{dI}{dq^*} = 0 \quad q^* = 0.555$$

(5)
Solving for the optimum charge yields a value which is 56% of the balance charge and substitution in the velocity equation (1) shows that optimally charged particles will fall at about 52% of their charge-free terminal velocities.

The maximum fraction of gravitational potential energy which may be delivered as electrical power may now be calculated. This fraction $F$ is the ratio of electrical power $qEV$ to available power, $MgV_0$.

$$F = \frac{qEV}{MgV_0} = \frac{q*}{V_0}$$

Substituting the optimal values for $q*$ and $V/V_0$ into (6) yields the maximum achievable fraction of 0.29. This result is in effect the inefficiency imposed on all precipitation mechanisms by the second law of thermodynamics.

A maximum 29% of the gravitational potential energy of precipitation may be converted to electrical energy. A precipitation rate of 1 mm/hr corresponds to a gravitational power density of $2.7 \times 10^{-3} \text{ W/m}^3$. At a 29% conversion rate, we have a realizable limit on electrical power output of $7.9 \times 10^{-4} \text{ W/m}^3$ per mm/hr of precipitation rate. Since the electrically dissipative motions of the oppositely charged cloud particles have been ignored in this calculation, and since horizontal electric fields in which charged precipitation particle motion is also dissipative have not been treated, the bound just stated is undoubtedly quite conservative. As it stands, this result is a more severe constraint by a factor of three than the original estimate by Latham [1971] in his assessment of precipitation mechanisms.

The energy bounds on precipitation mechanisms derived in the previous section motivated a large-scale comparison between like parameters in actual thunderstorms. We sought to determine whether the available gravitational power associated with precipitation could adequately account for the observed electrification in all storms.

### 3. INCOHERENT RADAR MEASUREMENTS OF GRAVITATIONAL POWER

The energy bounds on precipitation mechanisms derived in the previous section motivated a large-scale comparison between like parameters in actual thunderstorms. We sought to determine whether the available gravitational power associated with precipitation could adequately account for the observed electrification in all storms. We noted earlier that the available gravitational power appears to be much less than the theoretical limit of 29%.

### TABLE 1. Compilation of In Situ Measurements of the Energy Contribution of Precipitation

<table>
<thead>
<tr>
<th>Investigators</th>
<th>$J$, nA/m$^2$</th>
<th>$E$, kV/m</th>
<th>$-J \cdot E$, W/m$^3$</th>
<th>$p$, mm/hr</th>
<th>Efficiency, (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rust and Moore [1974]</td>
<td>—</td>
<td>—</td>
<td>$3 \times 10^{-7}$</td>
<td>10</td>
<td>0.001</td>
</tr>
<tr>
<td>Gaskell et al. [1978]</td>
<td>2</td>
<td>50</td>
<td>$1.0 \times 10^{-4}$</td>
<td>22 ± 11</td>
<td>0.2</td>
</tr>
<tr>
<td>Christian et al. [1980]</td>
<td>2.5</td>
<td>7.5</td>
<td>$1.9 \times 10^{-3}$</td>
<td>15 ± 7</td>
<td>0.05</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>30</td>
<td>$3.6 \times 10^{-4}$</td>
<td>34</td>
<td>0.4</td>
</tr>
<tr>
<td>Marshall and Winn [1982]</td>
<td>40</td>
<td>30</td>
<td>$1.2 \times 10^{-3}$</td>
<td>27</td>
<td>1.6</td>
</tr>
</tbody>
</table>

The efficiency in Table 1 is calculated as the ratio of the electrical power density to the precipitation rate (gravitational power density). These efficiency estimates are probably all exaggerated since in most cases only the highly charged particles were detected electrically and counted in the determination of local precipitation rate. In all cases, the maximum local efficiencies are more than an order of magnitude smaller than the theoretical limit of 29%.

### TABLE 2. Radar Reflectivity, Rainfall Rate, Gravitational Power Density, and Precipitation Water Contents

<table>
<thead>
<tr>
<th>dBZ</th>
<th>$R$, mm/hr</th>
<th>$P$, MW/km$^3$</th>
<th>$M$, gm/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.34</td>
<td>0.92</td>
<td>0.02</td>
</tr>
<tr>
<td>25</td>
<td>0.83</td>
<td>2.3</td>
<td>0.05</td>
</tr>
<tr>
<td>30</td>
<td>2.0</td>
<td>5.5</td>
<td>0.12</td>
</tr>
<tr>
<td>35</td>
<td>4.9</td>
<td>13.3</td>
<td>0.27</td>
</tr>
<tr>
<td>40</td>
<td>11.9</td>
<td>32.3</td>
<td>0.59</td>
</tr>
<tr>
<td>45</td>
<td>28.8</td>
<td>78.4</td>
<td>1.33</td>
</tr>
<tr>
<td>50</td>
<td>70.0</td>
<td>190</td>
<td>2.98</td>
</tr>
<tr>
<td>55</td>
<td>169</td>
<td>461</td>
<td>6.70</td>
</tr>
</tbody>
</table>

$Z - R$ relation, $Z = 400R^{1.3}$; $Z - M$ relation, $Z = (2.1 \times 10^4)M^{1.43}$. 

$Z$ is the radar reflectivity, $R$ the rainfall rate, $P$ the gravitational power density, and $M$ the water content.
were counted as an estimate of the lightning discharge rate within the radar-scanned storm volume. The ohmic contribution to electrical dissipation within the cloud was neglected because it is probably small [Griffiths et al., 1974], and the dissipative contribution from external currents and field-driven cloud and precipitation particle motions were not included because they are unknown.

3.2. Results. The resulting flash rates and corresponding gravitational power estimates are plotted in Figure 1. Two points are plotted for each storm: The right-hand point designates the available gravitational power, and the left-hand point the maximum possible electrical power if precipitation is driving the electrification. The sloping lines in the top left relate electrical power to flash rate, for a fixed energy per flash as indicated.

The low flash rate storms tend to be widespread, shallow rain shower systems which produced occasional lightning. The high flash rate storms were of two types: frontal and air mass thunderstorms. For the low flash rate storms it is immediately apparent that the available gravitational power is more than adequate to account for their electrification. For increasingly active storms, the margin between electrical and gravitational power shrinks considerably. Noteworthy is the fact that a factor of 2 or 3 increase in available gravitational power (from the widespread rain shower systems to the active thunderstorms, for example) can result in an order of magnitude or more increase in electrical output.

The apparent global gravitational-to-electrical power efficiencies for three New England storms and one Florida storm are all a few percent or larger if a flash energy of $10^9$ joules is assumed.

The gravitational power calculations were most reliably performed on the Florida storm data, in which specific electrical power-producing storm cells could be identified and evaluated. The calculations for New England squall lines included all radar reflectivity contributions within a 10 km radius cylindrical volume in which lightning flash rates were estimated from single station electric field data. Orville and Spencer [1979], on the basis of satellite lightning observations, conclude that 1 flash/s in a 10 km $\times$ 10 km area is a reasonable value for an active squall line. Since the storm area over which we evaluated gravitational power (314 km$^2$) is more than 3 times this latter area, and because the reported flash rate of 1 s$^{-1}$ is 3 times larger than our largest estimates for New England (see Figure 1), it appears likely that apparent gravitational-to-electrical efficiencies are significantly larger than those recorded here.

Gravitational power values at times of maximum flash rate are plotted in Figure 1. Seldom do the times of peak flash rate and peak gravitational power coincide, and the temporal evolutions of these quantities are poorly correlated. This assertion is illustrated in Figure 2, where the evolution of these parameters is plotted for the August 13, 1978, Florida thunderstorm, which has also been the subject of another study [Lhermitte and Krehbiel, 1979]. In fact, the peak discharge rate at 1908 GMT is anticorrelated with total gravitational power.

To test the idea that a precipitation charging mechanism involving the ice phase is responsible for the electrification, the gravitational power above the altitude of 6 km has also been plotted in Figure 2. This quantity is well correlated with the electrical output, particularly at the time of the dramatic onset in discharge rate when both quantities increase by large factors. It is possible that the ice phase is playing a major role in the electrification or, alternatively, that the vigorous vertical air motion observed simultaneously by Doppler radar [Lhermitte and Krehbiel, 1979] is responsible for both the electrification and the rapid growth of precipitation particles at higher levels through accretion of supercooled water droplets.

These hypotheses may be tested further by examining the distribution of gravitational power with height in the storm. Figure 3 shows this distribution for the active storm just discussed at the time of peak discharge rate (~1908 GMT). Although radar reflectivity maxima are often observed aloft in active thunderstorms (and in this case as well), the integrated quantity gravitational power shows a marked decrease from midlevels (~5 km) to the cloud top. The gravitational power profile in Figure 3 resembles those from other thunderstorms in this study. Superimposed on this profile is the distribution of negative charge transfer locations in similar Florida storms [Jacobson and Krider, 1976].

The precipitation hypothesis holds that the positive dipole
structure of a thunderstorm is maintained by the descent of negatively charged precipitation particles in the central dipole region. If the negative charge transfer locations shown in Figure 3 are indicative of the lower (negative) end of the classical dipole, it is immediately obvious that only a small fraction (less than 10% in this case) of the available gravitational power of precipitation lies in the supposed generation region.

The bulk of the available gravitational power within the cloud lies below the inferred region of negative charge. Observations of precipitation particle charge transport in this region to date have shown mixed results. The studies of Gaskell et al. [1978] and Christian et al. [1980] have shown a tendency for negatively charged precipitation falling in upward directed electric fields, a dissipative configuration. Marshall and Winn [1982] have found positively charged precipitation (which they attribute to the effects of lightning) falling in upward directed fields, a generative configuration. Because upward directed fields (whose source appears to be predominant negative charge accumulation [Krehbiel et al., 1979; Winn et al., 1981]) are a consistent feature, the gravity-driven descent of positively charged precipitation in this region is necessary if precipitation is to account for thunderstorm electrification.

4. DOPPLER RADAR SEARCH FOR PRECIPITATION PARTICLE VELOCITY CHANGES

The measurements discussed in the preceding section indicate that depending on the energy per lightning flash, the estimated electrical power in active thunderstorms is an appreciable fraction of the gravitational power associated with precipitation. If the bulk of the electrical energy in thunderstorms results from gravity-driven precipitation, one may conclude immediately that the electrical and gravitational forces acting on the particles in question will be of comparable magnitude. Equivalently, one may conclude that the terminal velocities of precipitation particles will be modified appreciably by electrical forces, following the discussion in section 2.1.

Notwithstanding this energy argument, it is the prediction of currently popular precipitation charging mechanisms that electrical modifications in particle velocities will occur. Theoretical modeling of the induction charging mechanism have led to conclusions that "electrical forces in the cloud decrease the fall velocities of hydrometeors to a point at which ... precipitation is suppressed" [Levin and Ziv, 1974], and that rain particle terminal velocities can "decrease by a few meters per second in a region when the electric field strength grows beyond $2 \times 10^8$ or $3 \times 10^8$ V/m" [Chiu, 1978]. Illingworth and Latham [1977] conclude that substantial velocity modifications will occur for both the induction mechanism and the ice-ice charging mechanism in the high field regions of thunderclouds.

Furthermore, Schonland's [1950] hypothesis for the rain gush phenomenon is based on the sudden release of precipitation at the time of a lightning discharge: "With the passage of the flash within the cloud the electric charges momentarily disappear...and the rain...is free to fall."

For all of the above reasons, a Doppler radar has been used to look for changes in the velocities of precipitation particles at the time of nearby lightning discharge. The basis for all predicted velocity changes lies in the necessary reequilibration of forces (gravitational, electrical, and aerodynamic) when the electric force is modified abruptly as a result of the discharge. The response of precipitation particles to step function forcing has been studied by Hilst [1949], Wilson [1970], and Wang and Pruppacher [1977]. The predicted rapid response of these particles (a few seconds and less) make such velocity transitions distinguishable from the buoyant and advective velocity fluctuations which are common features in zenith-pointing Doppler radar data [Battan, 1980].

4.1. Methodology. Searches for velocity changes associated with the occurrence of nearby lightning were carried out as part of the TRIP (Thunderstorm Research International Program) experiments. A vertically pointing Doppler radar was operated on the mountain ridge at Langmuir Laboratory (3.2 km MSL) near Socorro, New Mexico, during the months of July and August in three consecutive summers (1979–1981). The operating characteristics of these radars and a summary of data acquisition procedure are included in Table 3.

During 1979, only a single radar range gate was available, situated at 6.8 km MSL in a region thought to be of im-

<table>
<thead>
<tr>
<th>TABLE 3. Doppler Radar Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Peak power</td>
</tr>
<tr>
<td>Beamwidth</td>
</tr>
<tr>
<td>Pulse width</td>
</tr>
<tr>
<td>Pulse repetition frequency</td>
</tr>
<tr>
<td>Data acquisition</td>
</tr>
</tbody>
</table>

Fig. 3. The vertical distribution of precipitation gravitational power for a Florida thunderstorm, which is typical of other storms, and the distribution of negative charge centers transferred by lightning in a number of Florida storms [Jacobson and Krider, 1976].
upward motion and post discharge downward motion. Electric field particle levitation is suggested by the pre-discharge upward motion and post discharge downward motion.

Figure 4. August 13, 1979, thunderstorm over Langmuir Laboratory. (a) Mean Doppler vertical velocity versus time at an altitude of 6.8 km MSL at the time (1421:54 MST) of a nearby lightning discharge. (b) Electric field at the ground near the radar versus time. Electric field particle levitation is suggested by the pre-discharge upward motion and post discharge downward motion.

tance in the production of charged precipitation [Krehbiel et al., 1979]. In addition to recording the Doppler signals on analog tape, one Doppler channel was monitored with an audio analyzer to check for lightning associated Doppler frequency changes in real time.

Substantial improvements in the 1980 experimental setup included multiple radar range gates spaced by 255 m, real time digital processing of the mean of the Doppler velocity spectrum at 150 ms intervals, and the real time color display of mean velocity and electric field. This latter feature permitted the instant recognition of substantial velocity changes.

The observations in 1981 were carried out at the same location and within 50 m of the radar for this discharge. To confirm further the proximity of the discharge to the radar range gate overhead, acoustic reconstructions of the thunder sources were examined for this event. The acoustic source heights clustered in altitude near the range gate, and the nearest identifiable source was displaced horizontally only 1500 m from the range gate.

Figure 5 shows evidence for more gradual variations of the downward vertical velocity which are well correlated with electric field changes. Such behavior still suggests a close coupling between the electric field and the motion field, but is less easily interpreted. These variations were observed within 1 km of the radar for this discharge. To confirm further the proximity of the discharge to the radar range gate overhead, acoustic reconstructions of the thunder sources were examined for this event. The acoustic source heights clustered in altitude near the range gate, and the nearest identifiable source was displaced horizontally only 1500 m from the range gate.

4.2. Results. Changes in Doppler velocity which were coincident with nearby lightning discharges were very infrequent. Three summers of experiments, a total of 38 thunderstorm days, and a total Doppler data recording time of 69 hours produced fewer than 10 coincidences. The electrical activities of these storms (as measured by flash rate) ranged from zero to 10 flashes/min and so spanned the range of values of the earlier New England storms (recall Figure 1). A conservative estimate of the number of lightning discharges occurring within 5 km of the radar during the data recording time is 1000. From these estimates, we infer a probability for observable velocity change of less than 1%.

This infrequency is consistent with the negative results reported by L. Battan (private communication, 1979) and by Zrnic et al. [1982].

Distinct associations between the Doppler velocity and the electric field at the ground which were observed are documented below.

The upward mean velocity shown in Figure 4 suggests a case of particle levitation in a strong predischARGE electric field which ends abruptly at the time of the discharge, thereby allowing the particles to move downward. The post discharge (downward) vertical velocity is consistent with the terminal velocity of precipitation particles in the form of graupel or small size hail, which suggests that vertical air velocity is not significant in the storm at this time. The fact that upward velocity is observed prior to the discharge suggests that the electrical forces exceed the gravitational forces acting on the particles. Equation (1) and reasonable assumptions about the magnitude of the field in the cloud lead to the conclusion that the precipitation particle charges at the time of the discharge were several hundred picocoulombs. The net particle motion appears to be electric field-driven just prior to the discharge and therefore cannot be contributing to the accumulation of electrostatic energy. It is, however, quite possible that gravity-driven generative motion was occurring prior to the onset of levitation, as well as following the discharge.

A rather large field change (~17 kV/m) was recorded near the radar for this discharge. To confirm further the proximity of the discharge to the radar range gate overhead, acoustic reconstructions of the thunder sources were examined for this event. The acoustic source heights clustered in altitude near the range gate, and the nearest identifiable source was displaced horizontally only 1500 m from the range gate.

4.2. Results. Changes in Doppler velocity which were coincident with nearby lightning discharges were very infrequent. Three summers of experiments, a total of 38 thunderstorm days, and a total Doppler data recording time of 69 hours produced fewer than 10 coincidences. The electrical activities of these storms (as measured by flash rate) ranged from zero to 10 flashes/min and so spanned the range of values of the earlier New England storms (recall Figure 1). A conservative estimate of the number of lightning discharges occurring within 5 km of the radar during the data recording time is 1000. From these estimates, we infer a probability for observable velocity change of less than 1%.

This infrequency is consistent with the negative results reported by L. Battan (private communication, 1979) and by Zrnic et al. [1982].

Distinct associations between the Doppler velocity and the electric field at the ground which were observed are documented below.

The upward mean velocity shown in Figure 4 suggests a case of particle levitation in a strong predischARGE electric field which ends abruptly at the time of the discharge, thereby allowing the particles to move downward. The post discharge (downward) vertical velocity is consistent with the terminal velocity of precipitation particles in the form of graupel or small size hail, which suggests that vertical air velocity is not significant in the storm at this time. The fact that upward velocity is observed prior to the discharge suggests that the electrical forces exceed the gravitational forces acting on the particles. Equation (1) and reasonable assumptions about the magnitude of the field in the cloud lead to the conclusion that the precipitation particle charges at the time of the discharge were several hundred picocoulombs. The net particle motion appears to be electric field-driven just prior to the discharge and therefore cannot be contributing to the accumulation of electrostatic energy. It is, however, quite possible that gravity-driven generative motion was occurring prior to the onset of levitation, as well as following the discharge.

A rather large field change (~17 kV/m) was recorded near the radar for this discharge. To confirm further the proximity of the discharge to the radar range gate overhead, acoustic reconstructions of the thunder sources were examined for this event. The acoustic source heights clustered in altitude near the range gate, and the nearest identifiable source was displaced horizontally only 1500 m from the range gate.

Figure 6 illustrates the velocity behavior in several radar gates when simultaneous perturbations were observed at the time of a lightning discharge. The most pronounced changes occurred in adjacent gates within 1500 m of the top of the radar cloud. A cursory look at the increases in downward motion at this time suggests that the particles were suddenly released when the electric field decreased. However, the large 8 m/s change at gate 25 (9.6 km MSL) would require the existence of large particles (D > 3 mm) to be consistent with this interpretation. The low radar reflectivity (13 dBZ) at this time, the rapid (<1 s) response time of the particles, and the fact that this gate is located near the top of the cloud all indicate that these targets are quite small (D < 1 mm) and therefore will have zero-field terminal velocities of at most 4 m/s. A more plausible interpretation is that these particles are field driven upward at ~4 m/s against a ~5 m/s downdraft prior to the discharge.
Fig. 6. Mean Doppler vertical velocity at selected radar gates in altitude subsequent to and following a lightning discharge in an isolated thunderstorm on July 6, 1980.
to the discharge and then approach the ground at the combined downdraft-terminal velocity of 9 m/s when the field collapses.

A downdraft need not be invoked to explain the smaller velocity increases in the adjacent gates 24 and 26 and in such a case it is possible that these targets are falling against the predischARGE electric field. Following the derivation in section 2.1, an upper bound on the rate of generation of electrical energy in each of these gates is (0.29)MgV where M is the precipitation mass per unit volume, g is the acceleration due to gravity, and V is the zero-field terminal velocity of the particles.

In gate 25 the particles were constrained to be field driven against gravity, and thus the predischARGE electric force exceeds the gravitational force acting on these particles. Recalling again the arguments in section 2.1, a lower bound on the rate of dissipation of electrical energy (\(\rho EV\)) is therefore MgV, where \(V\) is the field-driven velocity with respect to still air.

Since the radar reflectivities in these three adjacent gates are comparable, the mass densities \(M\) associated with the precipitation targets are closely matched. Summing the contributions of gates 24, 25, and 26 to electrical power, we have a lower limit on net dissipation of 20.29MgV - MgV = -0.42MgV. If the mass density corresponding to the radar reflectivity of 12-13 dBZ is \(10^{-2} \text{g/m}^3\) [Battan, 1973], we have a lower limit on net dissipation due to precipitation particle motion of \(1.6 \times 10^{-4} \text{W/m}^3\) within a substantial volume of the cloud.

Velocity excursions at lower levels of the cloud (gates 18 and 19) are insufficiently rapid to be attributed to an electric field discontinuity. These changes may be associated with the advection of inhomogeneities into the radar beam, but the coincidence with the time of the lightning remains a puzzle.

Radar gates have been examined for velocity changes at levels in the cloud where negative charge inferred to have been neutralized by lightning has been located in other studies [Jackson and Krider, 1976; Krehbiel et al., 1979]. No discernible velocity adjustments exist in gate 12 at a height of 6.3 km MSL. Nor are there apparent velocity changes in the heavier precipitation in the lower part of the cloud at gate 4 (4.2 km MSL).

A noticeable general feature of Figure 6 is the tendency for the standard deviation of the mean Doppler velocity estimate to be larger prior to the discharge than following it. This behavior may be attributed to either rapid fluctuations in the electric field prior to the discharge, or to an electric field broadening of the Doppler spectrum. If electric forces contribute significantly to the individual particle velocities, it is possible that in certain circumstances an increase in velocity spectral width will result when the electric field increases prior to a discharge.

Doppler spectra at vertical incidence recorded during 39 triggered lightning events within 50 m of the radar were not modified perceptibly. These discharges were often triggered during periods when natural lightning was entirely absent, and so it is possible that the electric field in the clouds overhead was less than that necessary for natural dielectric breakdown. Doppler effects attributed to the lightning plasma at these times were observed, and are reported elsewhere [Lhermitte, 1982].

Thunderstorms which were displaced from the mountaintop observatory were observed occasionally (~2 hours total observation time) with a fixed horizontal beam. No sudden changes in horizontal motion were detected at the time of lightning discharge.

5. DISCUSSION

The conclusions drawn from the results of the radar measurements depend critically on the energy transferred in a lightning flash, and this topic deserves some discussion. Hill [1977, 1979] thoroughly reviews work on this subject, but confines his attention to the energy dissipated per unit length in the return stroke channel. The interest here is in representative values for the total electrostatic energy given up by an entire flash.

The integration of electric field soundings within thunderclouds [Winn et al., 1978, 1981] yield cloud-to-ground potential differences of 1-2 \(10^8\) volts. Values for total negative charge transferred in New Mexico cloud-to-ground lightning range from 10 C [Brook et al., 1962] to 70 C [Krehbiel et al., 1979]. Because the negative charge transferred by lightning, \(\Delta Q\), is localized [Krehbiel et al., 1979] and because the cloud-to-ground potential difference is not annihilated by the discharge but is only reduced [Winn and Byerley, 1975], the electrostatic energy dissipated will be of the order of \(\Delta Q \cdot \Delta V\). The resulting range in energy is \(10^9\) to \(10^{10}\) joules. The energy associated with intracloud lightning is less well constrained at present, but comparable values are probably reasonable.

The inclusion of the lightning contribution alone in thunderstorm electrical power will make the latter estimate conservative, but probably not grossly so.

With a lightning flash energy of \(10^9\) joules, the estimated steady state electrical power for weakly electrified rain shower systems and some thunderstorms is as much as 2 orders of magnitude less than the gravitational power associated with precipitation. In such cases, energy conservation places no measurable constraint on the contribution of precipitation to electrification. That is to say that falling precipitation could account for all of the electrical energy and yet experience vertical velocity changes of only a few centimeters per second in response to lightning discharges. Because such velocity changes are very small in comparison with the width of the Doppler spectrum and with the standard deviation of the mean Doppler estimate at vertical incidence, these changes will not be detected in the experiment described.

Another set of thunderstorms in Figure 1 exhibited electrical power which was a substantial fraction of the available power associated with falling precipitation. For a flash energy of \(10^9\) joules, the apparent global gravitational-to-electrical efficiency is several percent. This efficiency is an order of magnitude greater than the small-scale estimates (Table 1), but by itself, this result still allows the possibility that all the electrical energy is derived from falling precipitation. If the estimated efficiency were uniformly distributed throughout the precipitation volume, the ratio of electrical to gravitational force and the fractional velocity modification would likewise be of the order of a few percent (recall equation (6)) and any velocity changes would be below the level of Doppler radar detection (~1 m/s).

On the other hand, regardless of the origin of electrical energy, there is no reason whatever to believe that the energy efficiency will be uniform throughout the volume of the cloud. Currently popular precipitation charging mechanisms are believed to operate most effectively in very specific altitude intervals [e.g., Latham, 1981]. Furthermore, data presented in this paper (Figure 3) indicate a close association between strong electrification and the existence of precipitation at upper levels in thunderstorms. If this precipitation is indeed the principal cause for the electrification, readily detectable velocity changes...
(several m/s) should occur frequently, since the gravitational power associated with precipitation at high levels is a small fraction of that for the entire storm (Figure 3). Very infrequent velocity changes were observed at high levels, but do not support the view that precipitation motions were responsible for pre-discharge accumulation of electrostatic energy.

The discussion thus far has focused on the energy adequacy of precipitation in accounting for electrification in the absence of detectable Doppler velocity changes. An alternative possibility is that the bulk of the electric charge in thunderstorms exists as ions, or resides on cloud droplets and ice crystals, which are not "seen" by centimetric radar, but which may be transported by air motions to generate electrical energy.

6. Conclusions

An examination of the contribution of falling precipitation to thunderstorm electrification with simple theory and with quantitative radar techniques has led to the following conclusions:

1. A maximum of 29% of the gravitational potential energy of precipitation may be converted to electrical energy. This result places a realizable limit on electrical power density of 7.9 \times 10^{-2} \text{ W/m}^3\text{ per mm/hr of precipitation rate.}

2. Efficient conversion of gravitational to electrical energy requires the modification of precipitation particle fall velocities of several meters per second.

3. Modest flash rate storms contain sufficient gravitational power associated with precipitation to account for their electrification as Brahm's [1952] estimate has shown. The totalitarian principle in physics ("That which is not prohibited, is compulsory") would lead one to conclude that falling precipitation makes a significant contribution to the electrification of such storms. The presently available generation evidence (Table 1) is consistent with the low apparent global efficiencies for electrically inactive storms (Figure 1).

4. Storms which are electrically active (several flashes per minute) may be producing electrical power which is of the same magnitude as the available gravitational power of falling precipitation. The analysis presented in this paper (Section 2.1), taken together with the available data (Figures 1–3), suggests that if precipitation is the major contributor to electrification in these storms, then the particles must be falling with high efficiency and must experience electrical modifications in their fall velocities. However, this last conclusion is not consistent with the general absence of velocity changes in the Doppler radar observations of electrically active thunderstorms.

5. The gravitational power associated with precipitation at upper levels (above 6 km) in thunderstorms is well correlated with the electrical output (Figure 2), but appears inadequate to account for the energy of electrification (Figure 3). The gravitational power structure of a thunderstorm is not entirely consistent with the classical, positive dipole-embodying, precipitation hypothesis, since the bulk of the gravitational power is not available for electrical power generation in the inferred central dipole region (Figure 2).

6. Fixed beam Doppler radar observations of overhead thunderstorms produced only a few distinct cases of precipitation particle velocity changes, though more than 1000 lightning discharges occurred within 5 km of the radar. For these few positive cases, it may be inferred that a volume of precipitation particles comparable with the radar pulse volume (several hundred m^3) is charged predominantly with a single polarity. The detected velocity changes occurred high in the observed storms (>6 km MSL) and in regions of weak radar reflectivity (<30 dBZ). The infrequent occurrence of increases in downward velocity at the time of lightning discharges does not support the view that precipitation motion is contributing to pre-discharge electrification, particularly in light of the earlier gravitational power analysis.

7. The marginality of precipitation gravitational energy and the general absence of precipitation particle velocity changes together are indirect evidence that the motion of charged cloudy air is a significant contributor to the electrical energy of thunderstorms.

Acknowledgments. We are greatly indebted to Bernard Vonnegut for suggesting and encouraging the use of Doppler radar in the described experiments. The staff at Langmuir Laboratory, and in particular Charles B. Moore, provided an extensive logistical base for the experiment in New Mexico which contributed immensely to its successful conduct during three summers. We are grateful to James Hughes of the Office of Naval Research and to Ronald Taylor of the National Science Foundation for expediting funding for the field experiments. The New England observations were made possible through the enthusiastic cooperation of Spiros Geotis and Frank Marks of the MIT Weather Radar group. Early discussions concerning gravitational energy with John Willett are gratefully acknowledged. Ted Madden offered the usual penetrating advice. This research was generously supported by a Hertz Foundation fellowship and was submitted by one author (E.R.W.) in partial fulfillment for the Ph.D. degree in the MIT Department of Earth and Planetary Sciences.

REFERENCES


Jacobson, E. A., and E. P. Krider, Electrostatic field changes pro-

R. M. Lhermitte, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, FL 33149.
E. R. Williams, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139.

(Received December 6, 1982; revised August 12, 1983; accepted August 30, 1983.)