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The Electrification of New Mexico Thunderstorms 1. Relationship Between Precipitation Development and the Onset of Electrification

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Aircraft, radar, and surface observations were used to study the relationship between precipitation development and the onset of electrification in thunderstorms which formed near or over the Magdalena Mountains of New Mexico. The study included storms which were electrically active as well as ones in which no electrical enhancement was observed. Electric fields inside these clouds showed negligible enhancement and did not exceed 1 kV m^{-1} until reflectivities at 6 km above mean sea level (msl) (about −10°C) exceeded approximately 40 dB_Z and cloud tops exceeded 8 km. The onset of electrification occurred during or immediately after convective growth within the cloud.

1. Introduction

During the summer of 1984, an experiment was conducted to study the development of small thunderstorms forming near or over the Magdalena Mountains of central New Mexico. One of the goals of the experiment was to investigate the onset of electrification in relation to the development of precipitation. There have been a number of previous studies in this region of New Mexico. *Workman and Reynolds* [1949] reported that in 12 clouds they first detected a radar return followed by a developing electric field with an initial electrical discharge of intracloud lightning occurring about 10 min after the initial radar return. *Reynolds and Brook* [1956] concluded that precipitation was a necessary but not sufficient condition for electrification and reported that radar detectable precipitation preceded the onset of electrification under the storm by as much as 30 min in one case. However, *Moore et al.* [1958], using tethered balloons, reported electric fields of 1 to 2 kV m^{-1} inside the clouds before the appearance of the radar echo. In another publication *Moore* [1965, p. 255]) in summarizing additional studies states, "the radar reflectivity of the rain echo in the cloud overhead immediately prior to the first discharge has always been less than a Z value of 2000 mm^6 m^{-3}...", i.e., 33 dB_Z. Details of the measurements are not presented, but we presume the techniques were similar to those reported by Moore et al.

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These previous results, which were presented about 30 years ago, have left some uncertainty about the relationship between the onset of electrification in these clouds and the development of precipitation. We sought to enhance these previous observations and further understand the onset of electrification by using aircraft observations inside the cloud in conjunction with a multiple Doppler radar network to obtain electrical, cloud particle, and air motion measurements in addition to the radar reflectivity and surface electric-field measurements which had been made in the previous studies. This contribution reports the results of our findings on the co-evolution of the precipitation as detected by radar and the electric fields observed both at the surface and inside or below the clouds.

2. Observational Components

2.1. *Electric Fields Measured With Aircraft*

The aircraft measurements were made by the Explorer sailplane operated by the National Center for Atmospheric Research (NCAR) and owned by the National Oceanic and Atmospheric Administration (NOAA), and the Special Purpose Test Vehicle for Atmospheric Research (SPTVAR) operated by the New Mexico Institute of Mining and Technology (NMIMT) and owned by the Office of Naval Research. The sailplane normally released from tow in the updraft region below cloud base and ascended in the updraft continuously inside the cloud. It often reached altitudes of about 7 km above mean sea level (msl) and on a few occasions higher altitudes. (All altitudes in this paper are above mean sea level.) Sometimes the lift was sporadic and the sailplane would loiter in the cloud at nearly the same altitude for periods as long as 30 min. In most cases the sailplane was in cloud for periods of at least 15 min when the lift was good, i.e., the updrafts were sustained as the cloud was developing, and sometimes as long as 60 min when the cloud development was weak, followed by later vertical development. Thus, the sailplane was able to check for the onset of electrification inside the cloud for extended periods while the cloud and precipitation development was occurring.

The SPTVAR made repeated penetrations of the cloud at approximately the same altitude, usually at 4 to 5 km (slightly above cloud base), but on some occasions at altitudes of about 7 km. Thus, the measurements from its penetrations could be used to examine the temporal evolution of the field and also provide measurements of the spatial variation of the field.

Measurements of electric field in this paper are given in a right-handed coordinate system with the x axis in the direction of flight, the y axis directed out along the left wing and the z axis directed upward. The sign convention for the electric field is that negative charge above the airplane creates a positive vertical component of the electric field.

On the sailplane the vertical and horizontal components of field perpendicular to the line of flight were measured using a Kasemir-type rotating, cylindrical field meter mounted on a boom, forward of the center of the nose of the airplane. Due to the good symmetry of the sailplane geometry about this location, the response of the field meter to airplane charge was small. To further reduce the effect of charge, a "hump ring" [*Kasemir*, 1972] was attached to the boom just aft of the field meter to provide a local field distortion which just cancelled that due to the small airplane asymmetry. The location of this hump ring was adjusted after test flights until the measured electric field did not change during artificial charging of the airplane in flight. The field meter itself was calibrated by placing it between parallel plates with high voltage applied to generate a known electric field. Due to the location of the field meter well forward of the nose and the thinness of the sailplane in the vertical direction the vertical field measured by the field meter was assumed to be a good estimation of the component of the ambient field in that direction. The horizontal component was calibrated with the aid of airplane maneuvers, which allowed an empirical determination of the distortion factor (1.7) due to the long wings. Two separate sensitivities were recorded for each of the field components. The sensitive scale recorded fields from about $\pm$ 2 to 1200 V m^{-1} with an effective lower value of about $\pm$ 50 V m^{-1} set by baseline drift and electronic noise. The insensitive scale recorded fields from about $\pm$ 0.5 to 300 kV m^{-1}. The resultant electric field calculated from the two components measured on the sailplane is reported in this paper and is referred to as the "perpendicular electric field" or simply E_{perp}.

During sailplane operations in 1984 the cylindrical field meter performed as expected when the electric field was weak. However, often during the upper parts of the sailplane flights, the field measurements became noisy as the electric fields grew to approximately 20 kV m^{-1}. Sometimes the noise was small and the signal seemed believable. However, at other times the signal deteriorated to the point that it was no longer trustworthy. Over time periods of several minutes, trends could be seen between periods of noisy data, but their reliability was questionable. Since the performance of the instrument in weak fields did not appear to be affected by this difficulty we were able to detect and measure the onset and early development of cloud electrification with the sailplane. This noise did not influence any of the determinations of the onset of electrification made by the sailplane in this study, but does create uncertainty in the values of maximum fields measured from the sailplane.

We now fly a cylindrical mill which measures the induced voltage on the top, bottom, left and right independently so that the charge on the aircraft can be determined. From measurements with this new mill we find that the location ahead of the nose of the sailplane results in a strong intensification of the electric field at the mill. The periods of noise are associated with times when the sailplane is aligned with the ambient electric field, thus intensifying the electric field seen by the mill due to charge on the aircraft. To overcome this limitation, we are considering the installation of conventional rotating shutter type field mills on the fuselage aft of the wings of the sailplane. Experience with the SPTVAR has shown that such field mill placements are not prone to the noise seen on the sailplane.

The SPTVAR measures all three components of the electric field using five rotating-shutter field mills with four mounted around the top, bottom, port, and starboard sides of the fuselage aft of the wings, and the fifth mounted behind the vertical stabilizer facing aft. The SPTVAR mills are discussed in more detail in *Dye et al.* [1988]. The SPTVAR mill signals are recorded at four sensitivities; the two least sensitive ones are the most useful and are referred to as the insensitive and sensitive scales. In this study the vertical component of field, E_z, is used to document the time evolution of field development. The component E_z was calibrated by flying the SPTVAR very near an electric field meter carried by a tethered balloon beneath a weakly electrified cloud. We estimate the uncertainty in E_z to be about $\pm$ 15% in favorable conditions, i.e., when the local **E** at the mills is not strongly affected by ion plumes from corona discharges at metallic protrusions from the airplane. The minimum E_z that can be reliably determined on SPTVAR is about $\pm$ 100 V m^{-1} for the sensitive scale, while the maximum E_z measurable is about $\pm$ 275 kV m^{-1} for the insensitive scale.

2.2. *Surface Electric Field Measurements*

The network of five rotating shutter electric field mills which was established and has been maintained for many years by Charles Moore and Charles Holmes along the mountain ridge in conjunction with the studies at Langmuir Laboratory was also used in this project. The data are recorded on strip chart recorders and also on digital tape. Both the strip chart records and/or the plots derived from digital data were utilized in our analysis. The minimum field which can be resolved is 7 V m^{-1} on the digital tape and about 150 V m^{-1} on the strip chart recorder.

2.3. *Radar Reflectivity*

The Doppler radars involved in this project were the NCAR 5-cm-wavelength CP-3 and CP-4 and the 3-cm-wavelength NOAA C and D radars. The reflectivity measurements used in this paper for comparison with the time of initial electrification of the storms were exclusively from the CP-3 and CP-4 radars, which were situated on the plains about 17.5 and 23 km, respectively, from Langmuir Laboratory (Figure 1). On occasion a few NOAA C and D scans of the upper part of the storms were used to supplement the CP-3 and CP-4 measurements to better determine the radar cloud top. The minimum detectable reflectivity over the region of interest was 0 dB_Z or less from all four radars. The radar returns in this paper are calculated in the conventional way and are properly referred to as the effective radar reflectivity factor. For simplicity, we will simply refer to it as reflectivity in dB_Z.

The operating characteristics of the CP-3 and CP-4 radars are listed in Table 1. These radars have been used extensively in the meteorological community with frequent calibrations. The calibrations now and during the Socorro Project utilize the solar calibration technique discussed by *Frush* [1984] and *Pratte and Ferraro* [1989] to determine radar system gain, beam width, and noise bandwidth; daily calibrations using an injected test pulse of known strength document the stability and performance of the radar receiver/processor systems; and radar transmit power was continuously monitored. The user's guide to the NCAR CP-3 and CP-4 radars states an accuracy of system gain to ± 0.4 dB. The accuracy of the radar constant is considered to be better than ± 3 dB, including the uncertainty of nonuniform beam filling for meteorological targets.

The NOAA C and D radars were calibrated independently, but in a similar fashion and not as frequently. During the Cooperative Convective Precipitaion Experiment (CCOPE) conducted in Montana during 1981, the NOAA C and D as well as the NCAR CP-3 and CP-4 radars were calibrated using a metal sphere to determine the radar constant for all four radars. The solar calibration is now thought to be a better technique [*Doviak and Zrnic*, 1983] and is widely used. Comparison of reflectivities from CP-3, CP-4, and NOAA D for the New Mexico storms shows agreement to within 5 dB_Z, in the absence of strong reflectivity gradients, and better agreement for the maximum reflectivity at a given altitude and time. Reflectivities from NOAA C were found to be 10 dB_Z low compared to the other radars,

TABLE 1. CP-3 and CP-4 Radar Characteristics — New Mexico, 1984

Parameter	CP-3	CP-4
Wavelength, cm	5.45	5.49
Average transmitter power, dBm	55	55.3
Beam width, deg	1.02	1.12
System gain. dB	41	42
Pulse duration, ms	0.001	0.001
Minimum detectable signal, dBm	−102.3	−103.6
Range gate spacing, m	150	150

but in this study NOAA C measurements were used only to better define cloud top.

For the storms investigated in this study we have constructed time-altitude histories showing the maximum reflectivity at a given time and altitude within the entire storm, which is normally comprised of more than one cell. These profiles were constructed from volume scans of the storm which were usually taken at 3-min intervals with elevation and azimuth sweeps designed to optimize scanning of the entire storm. Contours of reflectivity shown in the time-altitude histories assume continuity during the 3-min intervals between sweeps at a given elevation and thus represent an interpolation over that interval. In almost all cases there is good continuity of features from one volume scan to another so that features seen in one sweep can be discerned and followed in the succeeding volume scan. Thus, the growth and decay of cells within the storm can be followed. If substantial changes in reflectivity occurred between two successive volume scans, there could be errors in our determinations of reflectivity at a given time and altitude. Particularly, for maximum reflectivity in the storm, which is what we used, it seems likely that this granularity introduces negligible errors.

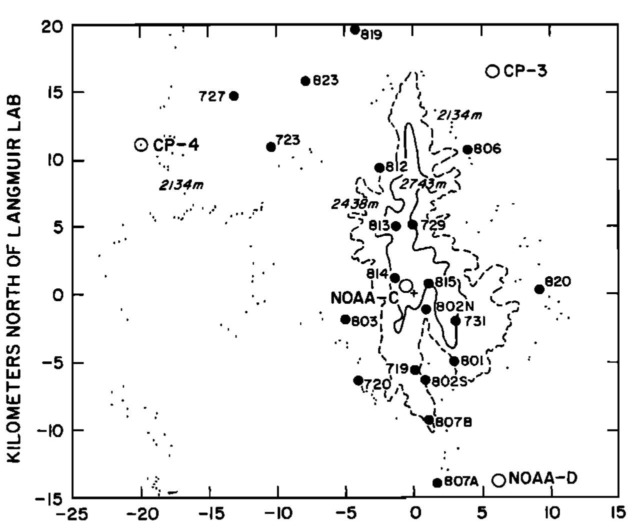

Fig. 1. The approximate locations at the time of initial electrification of the cores of the storms included in this study, with the month and day numerically indicated. Contours of constant terrain altitude of 2134, 2438, and 2743 m are as indicated.

2.4. *Rawinsondes*

Rawinsondes were released daily at 0730 MST from the Socorro airport, which is located 27 km east of the mountain ridge, and frequently from Langmuir Laboratory as well. On days with high potential for storm development sondes were also released at times when early storm formation seemed to be occurring, often between 1000 and 1100 (all times in this paper are Mountain Standard Time). The sondes were normally tracked through the tropopause using a conventional GMD tracking receiver. The rawinsondes and recording system were manufactured by A.I.R., Inc. (Boulder, Colorado).

2.5. *Aircraft Position*

Aircraft positions were determined using the NCAR multiple aircraft positioning system (MAPS) developed by *Johnson and Fink* [1982] in the NCAR Convective Storms Division. For this project, position information with a resolution of 20 m was recorded and displayed at Langmuir Laboratory in near real time about every 2 s. Comparisions of aircraft positions determined from MAPS with radar returns of the aircraft show that the positions relative to the radar echoes are accurate to 300 m or better with a precision of about 20 m.

2.6. *Time-Lapse Photographs*

Time-lapse photographs of the clouds were taken every 20 s from Socorro using a 16-mm time-lapse camera system operated by Charles Moore. These photographs were analyzed for some of the storms reported in this study by determining the displacement of the cloud top image above the image of South Baldy Peak. Radar data were used to estimate the range of the cloud turret from the camera site relative to the range of South Baldy Peak and thus provide a range correction in the calculation of the altitude of cloud top above South Baldy Peak. Cloud top and anvil blow-off toward the camera and difficulty in knowing which turret is being seen by the camera and consequently the range, can lead to substantial uncertainties and errors in the determination of cloud top. When the cloud top and range are well defined the analysis technique would give uncertainties of about 100 m. An error in range of 1 km would give an error in the cloud top determination of about 200 m.

3. CLOUD AND ENVIRONMENTAL CHARACTERISTICS

The observations reported in this study were made in convective clouds which formed near or over the Magdalena Mountains, a small, isolated range in central New Mexico. On a typical day, clouds begin to form over the mountains during midmorning as a result of the upslope motion of air induced by solar heating of the elevated and sloping terrain and/or by low-level flow of moist air toward the mountain. The vertical extent of the first cloud growth is often limited by weak, stable layers which gradually erode as the heating and convective action continue. When the cloud tops push past these stable layers, small thunderstorms often form with cloud tops ranging from 9 to 14 km. Cloud bases typically range from 3 to 5 km (+13 to 0°C, 700 to 600 mbar). For the most part the storms included in this study were the first storms to form over or near the mountain on a given day.

In New Mexico during the summer the winds aloft are typically very light with speeds of often less than 10 m s^{-1} from the surface up to 300 mbar. Hence the clouds often grow in a low-shear environment with values typically less than 10^{-3} s^{-1}. With light winds aloft the storms frequently remain attached to the mountain range or drift very slowly. The rawinsonde observations for days on which storms develop show instabilities at 500 and 600 mbar of 1 to 4°C. These instabilities give rise to vertical air motions in the clouds of 10 to 20 m s^{-1} and occasionally larger as seen in the sailplane observations.

Some of the storms are organized and have characteristics much like multicellular storms over the great plains with well defined areas of updraft and, near cloud base, downdrafts. Others are more cellular in nature with individual radar cells having horizontal dimensions of a few kilometers and relatively short lifetimes. The delayed vertical development and sometimes slow development of precipitation in these clouds provide opportunities to investigate the relationship between precipitation development and the onset of electrification over a wide range of reflectivities, cloud top heights (and temperatures), and cloud growth rates.

Microphysically, the clouds are continental in nature. The cloud droplet size distributions measured by the sailplane in regions containing cloud liquid water show typical droplet concentrations of a few hundred per cubic centimeter, mean droplet diameters 2 to 3 km above base of 15 to 20 μm, and usually the largest droplets to be less than 40 μm diameter. Raindrops are rarely observed at altitudes above the freezing level. When they are observed above the freezing level the evidence suggests that the drops were the result of the melting of graupel which fell from above and were recycled into the updraft much like the process reported by *Dye et al.* [1983] for a Colorado storm. The continental nature of the clouds, the appearance of the first radar returns from new cells at about −10°C (also reported by *Workman and Reynolds*, [1949]), and the appearance of graupel in the earliest stages of precipitation formation are factors which are indicative of the ice process of diffusional growth followed by riming being the dominant process of precipitation formation. However, a study conducted in this area during 1987 with the NCAR King Air showed the presence of 50-to 100-μm drizzle drops near the tops of a few clouds at temperatures of approximately −10°C before any ice was observed. The preliminary evidence suggests that coalescence may sometimes occur in the upper parts of these clouds, perhaps when the cloud bases are particularly warm.

4. DISCUSSION OF SEVERAL SPECIFIC CASES

During the observational period of July 14 through August 24, there were 20 storms on 18 different days which were used to study the relationship between the development of precipitation and the onset of electrification. The approximate locations of the core of the various storms near the time of the onset of electrification are shown in Figure 1. The locations of the four radars and of Langmuir Laboratory and altitude contours of the terrain are also shown in the figure. The coordinates of this figure and of all radar data presented in this paper are given in cartesian coordinates relative to Langmuir Laboratory and all altitudes are given in meters or kilometers above mean sea level.

For simplicity we will use the term "storm" to describe the different cases investigated in this study. In some cases the cloud system is indeed a thunderstorm, i.e., it produced precipitation and lightning and thunder. In the weaker cases the cloud would more properly be referred to as a cumulus congestus or cluster of cumuli congesti. We reserve the word "cell" to refer to a localized, individual area of updraft or radar echo embedded within the storm as a whole.

Among the 20 individual storms, there are cases with widely different characteristics. Some of the cases grew to intense thunderstorms quite rapidly. Others had periods of little growth followed by surges in growth with accompanying electrification. Yet others had only moderate growth rates, but did produce precipitation and did become electrified. Some of the moderate storms which did become electrified produced lightning while others did not. There were also a few weak storms which did not become electrified. Several cases are presented below to illustrate a range of storm types and various properties of the storms.

4.1. *August 3, 1984: A Moderate Storm With Delayed Electrification*

A summary of measurements from the August 3 case are presented in Figure 2. The time-altitude profile of reflectivity is displayed in the top panel, where the maximum reflectivity at a given time and altitude is shown. The altitudes of the sailplane as it ascended in the cloud and of the SPTVAR penetrations at about 7 km are superimposed on this profile. The visual top of the cloud which was determined from the time-lapse photographs is shown by dots at 2 1/2 min intervals. Although the aircraft were not necessarily in the highest reflectivity at any given time, most of the SPTVAR penetrations as well as the latter half of the sailplane ascent were in or near the highest reflectivities at that altitude. A PPI and RHI radar sweep of the storm nearest the time of initial electrification are shown in Figure 3 with the sailplane position at the time of initial electrification shown as a bold circle representing one loop in the sailplane spiral on the PPI and a bold line on the RHI.

The first radar detectable (0 dB_Z) precipitation formed in this cloud at about 6.3 km and −10° C at 1209 when the visual cloud top was about 8 km. For the next 10 min, the radar cloud top slowly increased to 7.5 km while the visual top slowly subsided. From about 1220 to 1230 a new area of growth a couple of kilometers to the northeast developed and pushed to 9 km. During this stage of growth the visual and radar top were the same within the error of the measurement. Precipitation associated with this new cell reached 40 dB_Z at 6 to 7 km in a small area. Beginning about 1237 the largest surge in growth, also slightly to the northeast of the older development, is apparent in the figure with the radar cloud top rising at 4 m s^{-1} up to about 12 km. The visual top shows a similar rise rate for the first 5 min. After about 1240 upper level outflows toward the camera obscure the turret top and the measurement is no longer meaningful. Reflectivities in this largest cell almost reached 50 dB_Z below the melting level. The sailplane ascent from 1230 to 1250 was within this new, main area of development. Thus, it is likely that the growth seen at cloud top near 1237 started at lower levels in the cloud near 1230.

The electric field measurements from the sailplane, the SPTVAR, and the surface are shown in the lower panels of Figure 2. Henceforth in this paper we shall refer to these measurements simply as "E", keeping in mind that for the sailplane we are referring to E_{perp} and for the SPTVAR and the surface — E_z. The measurements of E from the sailplane are shown for both the sensitive and insensitive scales. For the first 20 min that the sailplane was continuously in this cloud, both the sailplane and surface measurements showed no increase in E. Beginning at about 1235, E at the sailplane began to very slowly increase and E at the surface began to slowly change to a foul weather polarity. E at the sailplane and at the surface reached 1 kV m^{-1} at about 1243. The periodicity seen in the sailplane measurements between 1235 and 1245 is a result of the varying component of the horizontal field measured by the sailplane as it changed heading while continuously spiralling in the updraft. Although it is not apparent at the scale shown in the figure, E of about 0.5 kV m^{-1} was observed from the SPTVAR during its 1234 to 1236 pass. (The SPTVAR was out of cloud from about 1236 to 1245 to allow the sailplane to climb through the altitude of the SPTVAR.) Thus, the measurements from all three systems show the onset of electrification near 1235.

The core of the main cell of the storm was about 6 to 7 km from Langmuir Laboratory (LL) at the time that E began to build. As E grew the storm moved closer to LL. Thus, part of the increase in E seen at the surface is due to motion of the storm toward LL. The abrupt transitions in E seen on the

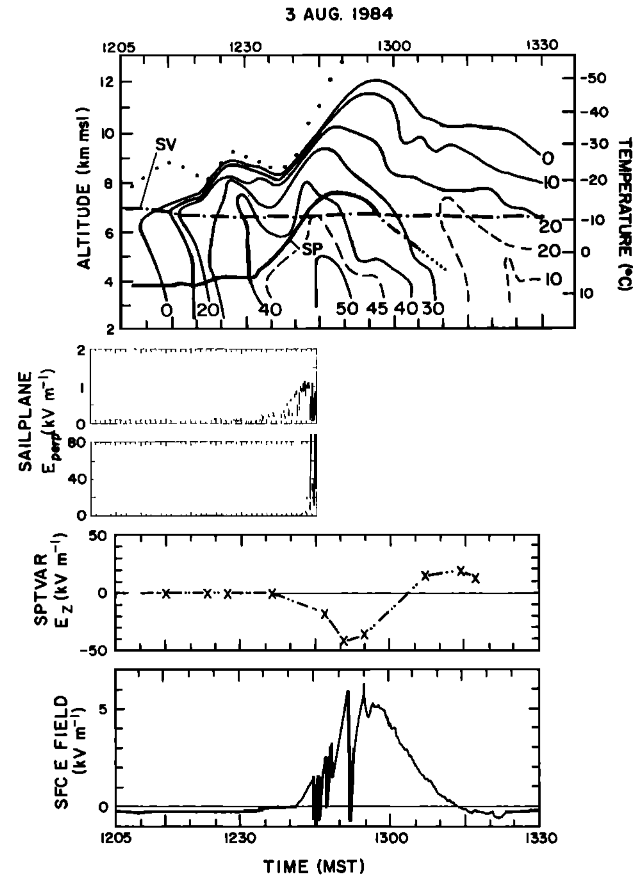

Fig. 2. Time-altitude profile of reflectivity for the August 3, 1984 storm, with the altitude of the sailplane (SP) and SPTVAR (SV) superimposed. The solid, bold line shows when the aircraft are in cloud. The altitude of the visual cloud top determined from the time-lapse photographs at 2 1/2 min intervals is shown by a series of bold dots at the top of the profile. Measurements of electric field from the sailplane, SPTVAR, and surface are shown in the lower panels. For SPTVAR, the graph shows the extreme value of E_z (either positive or negative) for each pass. The graphs for the sailplane and the surface E are the complete recorded functions.

surface record are an indication of lightning flashes. Because there were no other storms in the near vicinity it appears that this storm produced six lightning flashes. About 9 min elapsed between the time that E began to intensify and the first lightning discharge at about 1244. At about 1255 the SPTVAR and surface measurements show that the storm was beginning to decay electrically. This decay begins at about the time that the radar top begins to descend.

Radar detectable precipitation had been present in this cloud for up to 25 min before even the weak enhancement of E began, and more than 30 min before the rapid E intensification. The first slow increase in E began slightly after the time that 40 dB_Z was first observed at 6 km. The rapid intensification of E began near the time of the surge in growth associated with the main cell.

4.2. *July 31, 1984: An Electrically Intense Storm*

The time-altitude plot for the July 31 storm is shown in Figure 4. A PPI and a RHI radar sweep of the storm nearest the time of initial electrification are shown in Figure 5 along with the position of the sailplane. On this day the storm

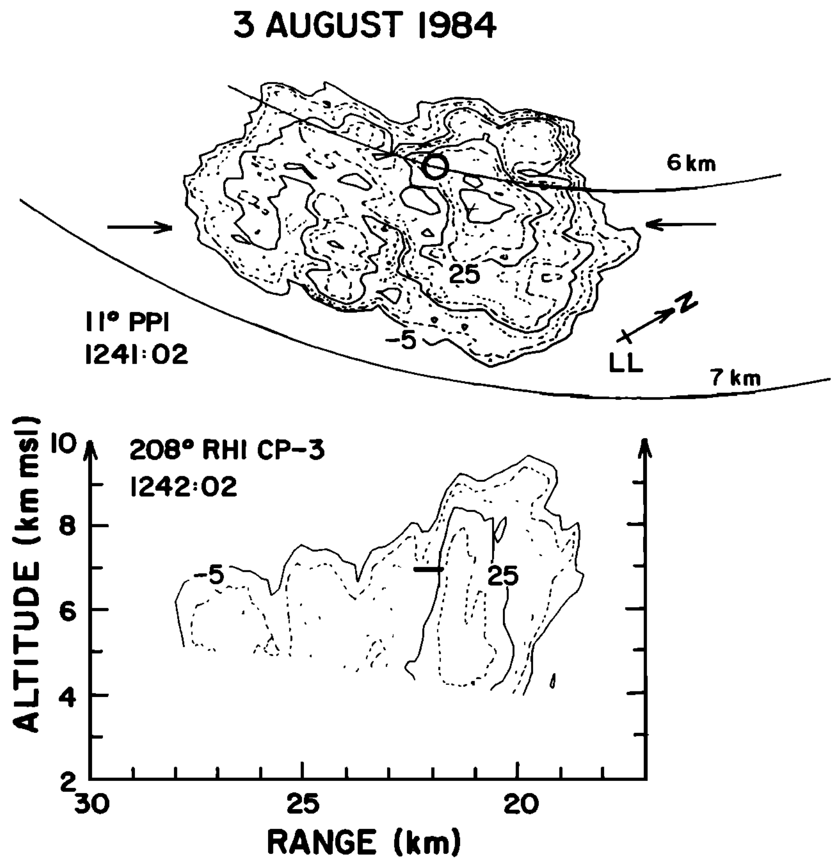

Fig. 3. Measurements of reflectivity from PPI and RHI radar sweeps of the August 3, 1984 storm near the time of initial electrification. The PPI measurements are from CP-4 with contour intervals of 5 dB starting at −5 dB_Z. The RHI contours start at −5 dB_Z but are at 10-dB intervals. The inward-pointing arrows near the PPI are along the direction of the RHI. The location of Langmuir Laboratory (LL) and north are shown near the PPI. The location of the sailplane spiral at the initial electrification is shown by the bold circle in the PPI and the bold bar in the RHI.

grew just to the southeast of LL with the core of the storm located about 3 to 4 km southeast of LL and the edge of the radar return just over LL at the time E began to intensify. The earliest growth produced visual tops to about 8.5 km with radar tops of about 7.5 km (−15 °C) and reflectivities up to 30 dB_Z at about 1025, the time of the first radar scan. No intensification in E was observed from this cell either at the surface or by SPTVAR which was making repeated passes just over the ridge near Langmuir Laboratory. At about 1055 the first 10-dB_Z return from a new cell appeared at about 6 km altitude (−10°C) with a visual top of about 9 km. The radar echo rose to about 7.5 km with the visual top at about 9 km and remained at that altitude until about 1115, when the radar top of the cloud began to rise at a rate of about 4 m s^{-1} reaching 13 km at 1200. The visual top began to rise at that same rate at about 1125 and remained nearly identical with the radar top until the anvil began to move toward the camera at about 1205. During its ascent inside the cloud from 1125 to 1132 the sailplane measured average updraft speeds of 7.5 m s^{-1} with peak values of 15 m s^{-1}. Reflectivities inside the storm increased to 50 dB_Z at 6 km altitude by 1135.

The first definitive evidence of enhanced E (about 0.2 kV m^{-1}) was seen at 1125:30 from the sailplane which had been almost continuously inside the cloud from when it entered cloud base at 1100. E at both the sailplane and the surface reached 1 kV m^{-1} at about 1127. During this early stage the SPTVAR was making passes over the ridge at about 3.3 km and was not in a good position to detect the initial enhancement, but enhanced E is evident from the SPTVAR by 1128:30. Unlike the August 3 case the electrification of the cloud proceeded very rapidly, producing lightning by about 1130, less than 5 min after the initial enhancement could be detected and only 3 min after 1 kV m^{-1} was observed. During the period that this storm was electrically active it produced over a hundred lightning flashes. At the time of the onset of electrification the reflectivity at 6 km was about 40 dB_Z and increasing and very active convection was occurring.

4.3. *August 1, 1984: An Electrified Cloud Without Lightning*

The August 1 storm was a small, isolated storm with one dominant cell that formed about 2 km east of LL but moved south at about 2 m s^{-1} so that at the time of initial electrification it was about 5 km south-southeast of LL. The first radar scan on this day at 1027 showed a small region of reflectivity extending from 5 to 7 km with a maximum of about 15 dB_Z a little above 6 km, suggesting that the first precipitation in this storm had formed only shortly before at about 6 km (Figure 6). The visual top at the time of the

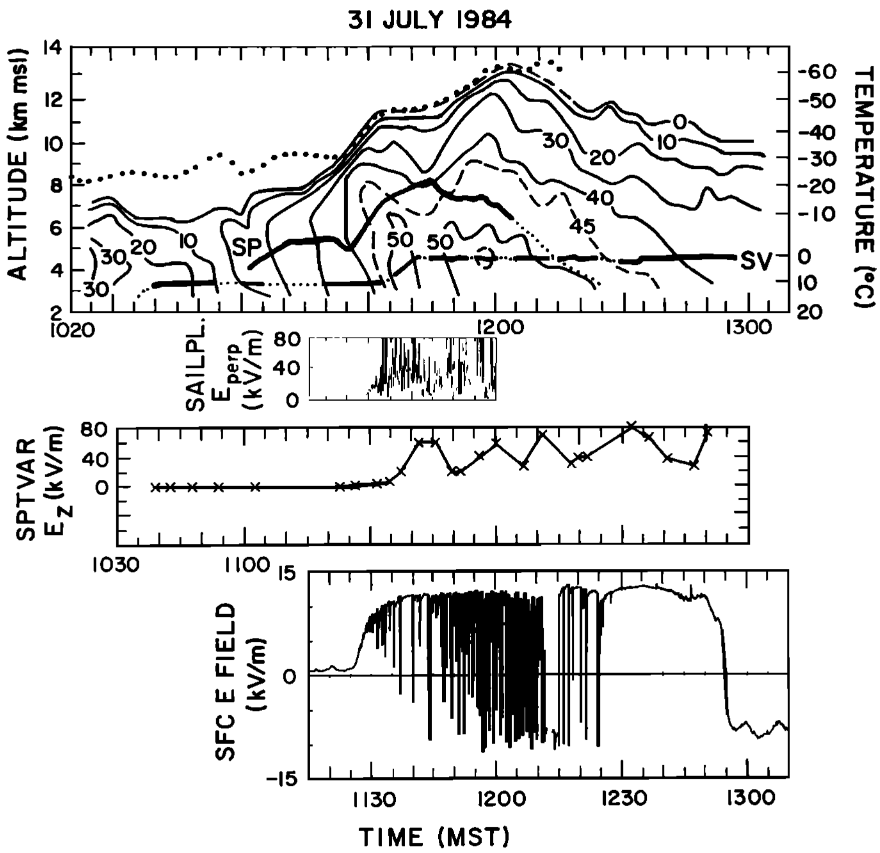

Fig. 4. As in Figure 2, but for July 31, 1984.

first radar scan was about 8 km and slowly grew to 8.5 km. This early growth gave way to the main development which is apparent in the time-altitude profile (Figure 6) starting at about 1040. Radar and visual tops rose to slightly above 9 km and reflectivities reached 45 dB_Z at 6 km altitude and 50 dB_Z at lower levels by 1047. Additional, weaker pulses of activity maintained the radar cloud top near 8.5 km with reflectivities of 40 dB_Z at 6 km until about 1105. The visual top appears to be slightly higher until 1127.

A PPI and a RHI radar sweep of the storm nearest the time of initial electrification are shown in Figure 7 with the track of SPTVAR superimposed. The SPTVAR made penetrations every 4 to 5 min back and forth below the cloud at 3.2 to 3.5 km from 1030 to about 1040, then slightly above cloud base up to 4.5 km altitude from 1045 until 1145. The passes started well before initial electrification and continued through the electrical decay of the storm. The first sign of electrical intensification occurred at 1051 when the SPTVAR observed E of 2 kV m^{-1}. The observed E increased to 30 kV m^{-1} at 1102 and decayed thereafter. No enhancement in E was seen in the surface data for this storm, apparently because the storm was too far from the surface field mill network. There was no distinct evidence of lightning discharges in the SPTVAR data.

4.4. *July 29, 1984: A Shallow Storm With Marginal Electrification*

Time-lapse photographs for this day show cumulus congestus clouds extending up to 7 km as early as 0900 with a chimneylike turret reaching to almost 9 km at 0935. By the time of the first radar scan from CP-4 at about 0943, the visual cloud top had decayed to about 8 km, but the reflectivity at low levels was 50 dB_Z and 35 dB_Z existed near 6 km (Figure 8). The first radar observations show the storm to be centered about 4 km north of LL with a diameter of about 6 km. As time progressed a rapid succession of new reflectivity cells only a couple of kilometers across formed on the southeast side of the storm within the previous reflectivity structure and gradually moved to the northwest at 1 to 2 m s^{-1}. By 0955 a new area of growth was also forming a few kilometers to the northwest of the main storm development. Radar tops extended to about 9 km for most of these cells. The time-lapse measurements shown in Figure 8 give higher cloud tops, but are probably in error due to uncertainty in determining range and because of motion toward the camera. The reflectivity structure of the various cells merged by 1000 to form a cloud mass consisting of many cells in a rather complicated structure which extended in the northwest-southeast direction at least 15 km. A PPI and a RHI radar sweep of the storm nearest the time of initial electrification are shown in Figure 9 with the position of the sailplane also shown. Although the NOAA C radar on top of the mountain clearly shows that the radar tops of this storm extended to no more than 9 km altitude, the storm developed unusually strong reflectivities with values below the melting level in excess of 60 dB_Z. The sailplane observations show the existence of millimeter-sized drops even at $-10°$C in the updraft of this storm.

Measurements from the sailplane, which was spiralling

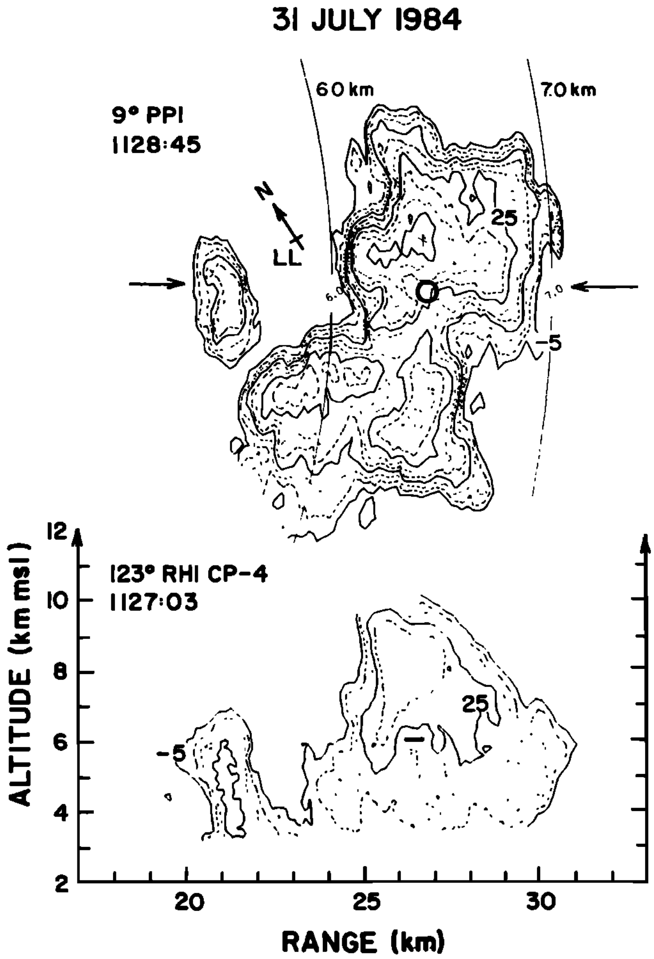

Fig. 5. As in Figure 3, but for July 31, 1984.

continuously in cloud from 0947 until 1004 and flying near the core of the storm until 1009, give indications of very slow field enhancement, but E did not exceed 0.2 kV m^{-1} until 0955. At this time E began to increase more rapidly, reaching 1 kV m^{-1} at about 0959. Reflectivities of 40 dB$_Z$ existed near 6 km altitude for almost 15 min before the observed E reached 1 kV m^{-1}. The largest E measured from the saiplane was about 25 kV m^{-1} just before the sailplane exited the cloud for the first time at 1010. The sailplane was flown back into the periphery of the storm on the southeast side and recorded E of 0.5 to 1 kV m^{-1} from about 1010 to 1025.

The SPTVAR started making passes near cloud base at about 0923. The earliest passes showed no enhanced fields, but the passes at 0942 and 0948 through precipitation suggest weak negative E of about 1 kV m^{-1} near cloud base. However, the measured E has the same sign and follows the pattern of the charge on the aircraft, which makes these measurements suspect. In any case E was weak and there is no evidence for a significant enhancement from the SPTVAR measurements during this period. The first unmistakable enhancement in E was seen during the SPTVAR pass from 1003 to 1005 which was above cloud base at 4.5 km altitude when E of about 1 kV m^{-1} was observed. The observed E increased to a maximum of 36 kV m^{-1} near 1019, when radar cloud tops were about 9 km. There was no evidence of lightning from this storm. However, at 1051 the surface field mill at Langmuir Laboratory showed the first of four discontinuities due to lightning from some distant storm.

4.5. *July 23, 1984: A Weak Storm With Little or No Electrification*

The first radar observations at 0934 (not shown) on this day showed the presence of a small storm about 10 km northwest of Langmuir Laboratory with reflectivities of 30 dB$_Z$ at low levels and radar tops to about 7 km. Time-lapse photographs were not available for this day. This first storm moved slowly to the northwest out of the area of good radar coverage and showed signs of weakening by about 1000. During the period of observation from about 0930 to 1000 the radar tops extended up to about 7.5 km and the maximum reflectivity attained at 6 km was about 30 dB$_Z$. The SPTVAR made two passes below this storm, but did not detect any enhanced E.

At about 1000 the sailplane entered the side of a new growing turret, embedded in a cluster of clouds, which was in approximately the same location as that of the first storm when it was first scanned by radar. This development, which became the main storm of interest on this day, did not contain radar detectable precipitation until about 1012 (Figure 10). Small and short-lived cells developed intermittently for over an hour on the east and southeast side of the storm as it also moved slowly to the northwest. The storm consisted of a clustering of small cells which developed and decayed rapidly to form a disorganized area of moderate reflectivity at low and middle levels which was about 10 km across. By about 1050 the storm had moved so far north that it was difficult for the CP-4 and CP-3 radars to scan, hence features at cloud top were difficult to resolve and the reflectivity contours in Figure 10 are incomplete. The highest radar top apparently extended to about 9 km near 1100. The maximum reflectivity at 6 km barely reached 40 dB$_Z$ for a brief period near 1037 and again at 1112.

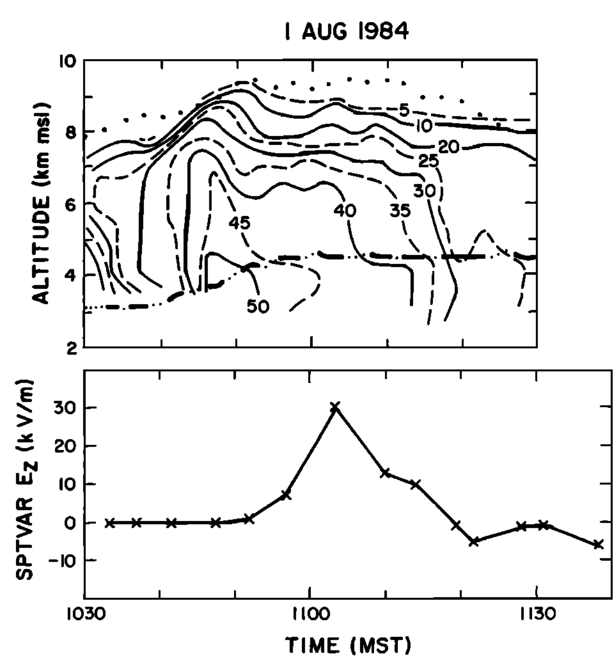

Fig. 6. As in Figure 2, but for August 1, 1984.

The sailplane was in this cloud continuously from 1000 to 1030, first in one area of updraft and then in another a couple of kilometers east of the initial ascent, including a period from 1024 to 1029 when the reflectivities from 6 to 8 km reached 30 dB_Z. The sailplane observations of E showed no indication of enhanced fields. At 1034 the SPTVAR started making repeated penetrations above cloud base at 4.5 km. One penetration at 1041 showed an E of 1 kV m^{-1} and another penetration at 1112 in another region of the cloud showed an E of 3 kV m^{-1}. This storm apparently was able to produce some very weak, but no sustained, electric fields.

5. Summary of Results

For convenience, we have arbitrarily defined the initial electrification (IE) of these storms as the time when E observed from either the surface, the SPTVAR or the sailplane reached or exceeded 1 kV m^{-1}. In a few cases (for example, August 3 and July 29 discussed above) we observed that E began to slowly build a few minutes prior to reaching 1 kV m^{-1}, but more frequently the increase was quite rapid. The term "initial electrification" implies the beginning of the presence of an electric field in the cloud, but in fact there are small fields present in the cloud at all times just as there are fair weather fields in a cloud free environment. Our instrumentation was not suited to investigating these small fields. The lower limit of sensitivity is approximately 50 V m^{-1} on the sailplane and 100 V m^{-1} on the SPTVAR. However, we can say that the measurements from the sailplane in the early stages of cloud and precipitation formation show fields of the order of 100 to 200 V m^{-1} or less, even when the sailplane enters cloud base in a strong updraft. As discussed below we have no evidence for fields in excess of 200 V m^{-1} until the precipitation process as deduced from radar observations has proceeded for tens of minutes and reflectivities at midcloud levels have reached about 40 dB_Z or greater.

We have directed attention to what is happening at the 6 to 7 km level (−10 to −20° C) because many researchers have observed that the −10 to −20° C level of the cloud seems tc be the preferred region of negative charge accumulation and have inferred that it is likely to also be an active region of charge separation. (See *Krehbiel* [1986] for a review.) There has also been a lot of interest in the noninductive ice-ice collision process as a mechanism for charge separation, and laboratory results have shown a reversal in the sign of the charge acquired by a rimed target at temperatures between −10 to −20° C (near −20° C by *Jayaratne et al.* [1983] and −10° C by *Takahashi* [1978]). Thus, it is of considerable interest to know the particle composition and reflectivity of the storms in this −10 to −20° C region while the storm is becoming electrified.

An overview of the results for the 20 storms which were examined is listed in Table 2 according to the calendar day with the Julian day shown in parenthesis. The time of the initial electrification and the source of this information (SFC = surface, SV = SPTVAR, and SP = sailplane) is shown in the second column. The next two columns show the elapsed time between the first detection of 10 and 40 dB_Z at 6 km altitude and the occurrence of initial electrification. For the cases examined there was a minimum of 16 min and a maximum of more than an hour of time between the occurrence of 10 dB_Z in the storm at 6 km and the initial electrification.

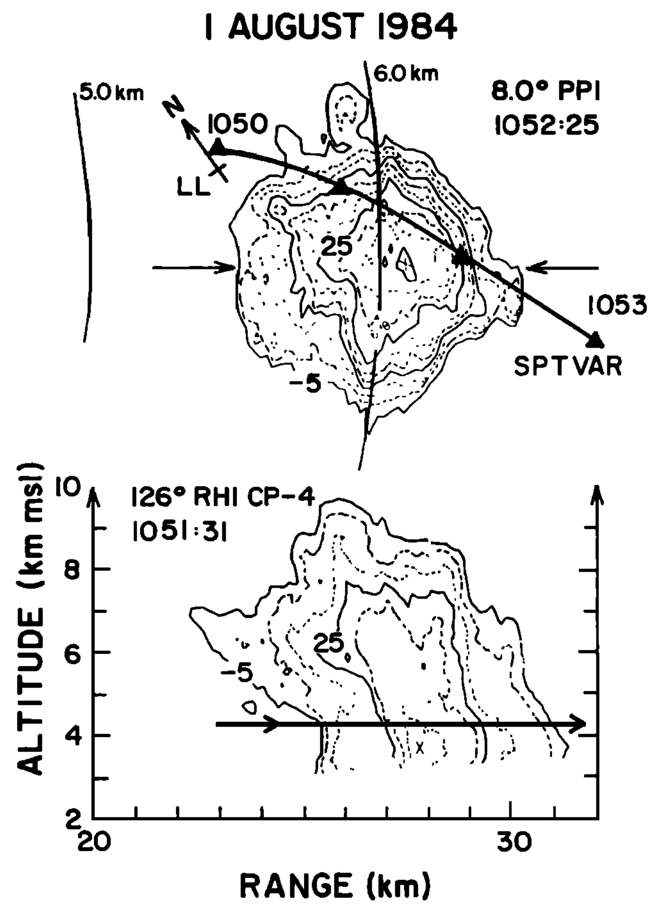

Fig. 7. As in Figure 3, but for August 1, 1984. The track of the SPTVAR is shown with solid triangles indicating 1-min intervals beginning at 1050:00 MST.

In most cases even 40 dB_Z was present at 6 km prior to initial electrification. The fifth column shows the reflectivity at 6 km (Z_6) at the time of initial electrification. In all cases the reflectivity was very near 40 dB_Z or greater. The sixth column shows the maximum reflectivity at 6 km observed anytime during the storm. There were several cases with reflectivities of 50 dB_Z or greater at this altitude.

The maximum electric field (E_{max}) observed at any time in the storm, the time of the first observed lightning (usually detected from the surface measurements), and the approximate number of lightning flashes from the storm with no attempt to differentiate between cloud-to-ground and intracloud discharges are shown in the seventh, eighth, and ninth columns. Maximum fields greater than 30 kV m^{-1} were frequently observed with the largest being 95 kV m^{-1} measured by the SPTVAR on July 27. (As noted in section 2.1, the largest fields measured from the sailplane are not entirely reliable.) Fourteen of the storms produced some lightning, four became electrified without producing lightning, and two had no electrification above our limit of detection. For several of the storms the time between the initial electrification (by our definition, 1 kV m^{-1}) and the first lightning is very short. For example, this time difference for the July 31 case is only 2 min.

The last three columns show the observed radar cloud top at the time of initial electrification, the highest radar top during the storm history, and comments on when the initial

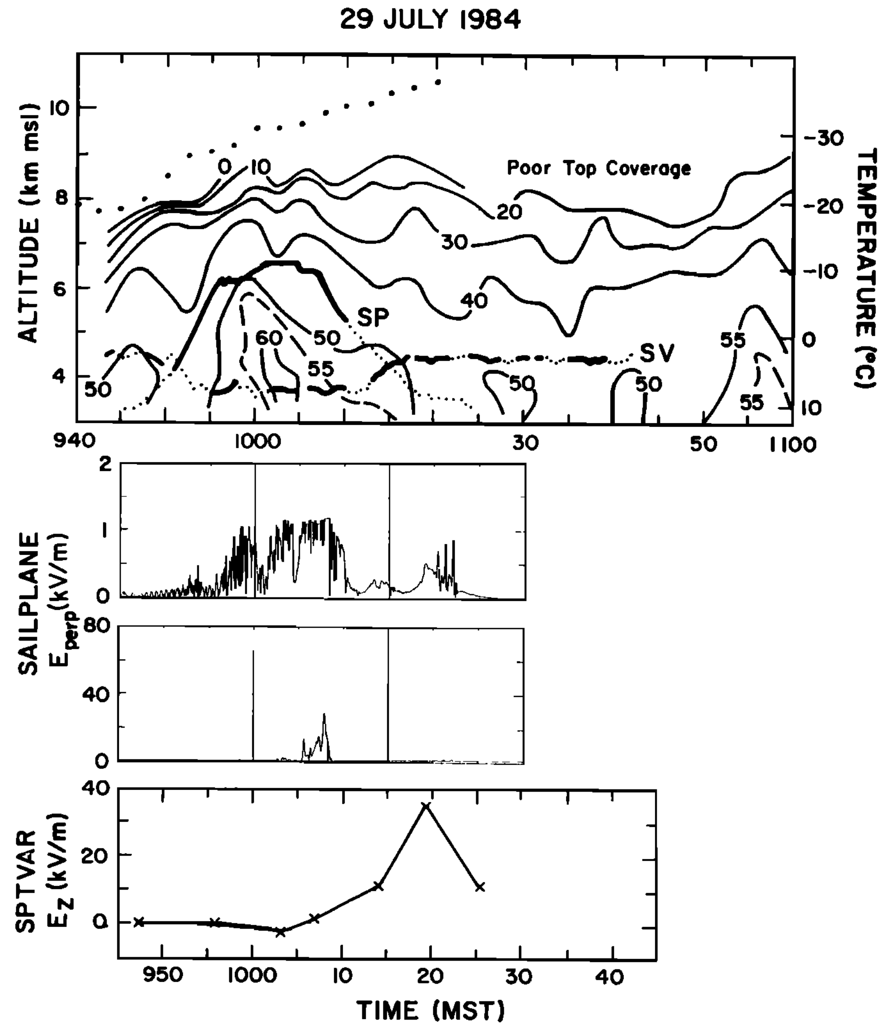

Fig. 8. As in Figure 2, but for July 29, 1984.

electrification occurred relative to the what the cloud was doing dynamically, i.e., was either the visible or radar cloud top growing, was it at its peak altitude or was it decaying? The two storms for which no or minimal electrification was observed had radar cloud tops extending to 8 km above sea level. All storms which did become electrified had cloud tops of at least 8.5 km. Furthermore, all storms which did become electrified had radar tops of at least 8 km at the time of initial electrification, except for the one SPTVAR pass on July 23 at 1041 which had a cloud top of 7.5 km. (The radar tops for July 23 are somewhat uncertain after about 1030 because the radar coverage of the top of the storm was not good due to the proximity of the storm to the CP-3 and CP-4 radars and because the storm was out of the field of view of the camera.)

Thirteen of the storms (fourteen if July 23 is included) became electrified at a time when growth was occurring in the cloud, thereby indicating the presence of updrafts in the cloud at the time of initial electrification. Three storms became electrified at or near the time that the cloud reached its highest radar top or at a relative maximum in cloud top at the end of a period of growth. There were two cases which did not become electrified and one storm (August 19) for which it was not possible to determine the convective state of the cloud at the time of initial electrification. Thus, the storms examined in this study were or very recently had been convectively active at the time that the storms began to show enhanced electric fields. On the other hand there were many periods of cloud growth and convective activity during which the clouds did not show enhanced electric fields.

The time-lapse photgraphs were not analyzed for all cases, but those which were (Figures 2, 4, 6, and 8) lead us to believe that the radar tops provide good characterizations of cloud top and convective development during the mature part of the storm. In agreement with the more comprehensive study of *Knight et al.* [1983] for clouds in northeastern Colorado, we found that during the early development of the storm the visual tops were higher than the radar tops, but within the error of the measurements, as the cloud matured the radar and visual tops became the same.

One of the reviewers of this manuscript suggested that there might be a difference in the initial electrification of those storms which formed directly over the mountains and those which formed over the plains. We investigated one possibility of a difference by segregating the storms at the time of initial electrification shown in Figure 1 into three categories: (1) storms with reflectivity cores over terrain of 2743 m (9000 ft) or higher, (2) storms with cores over terrain from 2438 m (8000 ft) to 2743 m, and (3) all remaining storms. Table 3 presents the reflectivities at 6 km at the time of initial electrification (fifth column from left in Table 2) for the storms in the three separate categories. There does not appear to be a difference in the reflectivity at 6 km at the time of initial electrification for these three categories.

6. CONCLUDING REMARKS

All of the 20 storms which we examined have shown the development of precipitation leading the onset of electrification of the storm by at least 15 min. In several cases convective activity and precipitation were present for many tens of minutes prior to the onset of electrification. In some cases the early electrification (before measured electric fields exceed about 1 kV m^{-1}) proceeded rather slowly (for example, August 3), while in other storms like July 31, electrification proceeded very rapidly even in the earliest stages. The rate of growth of electric fields derived from the sailplane measurements is discussed in a separate paper by D. W. Breed and J. E. Dye (The electrification of New Mexico thunderstorms, 2, Electric field growth during initial electrification, submitted to *Journal of Geophysical Research*, 1989).

In the storms which had enhanced electric fields, the electrification did not begin until nearly 40 dB_Z reflectivity or greater had been reached at 6 km or above. The more intense, vigorous storms such as July 31 produced 40 dB_Z more rapidly and also became electrified more rapidly. In storms which grew more slowly, but with cloud tops of 10 km or more such as the August 3 case, the onset of electrification occurred later relative to the 40 dB_Z reflectivity at 6 km. Still smaller storms with cloud tops which extended to only 9 or 10 km, did become marginally electrified but did not produce lightning unless cloud top exceeded 9.5 km. In the cases we examined it appeared that the radar top had to exceed about 8 km for the cloud to become electrified and had to exceed 9.5 km for lightning to be produced.

In previous studies *Reynolds and Brook* [1956] reported that the electrification of the New Mexico storms which they investigated followed the development of precipitation and also appeared to be associated with a surge in growth of the cloud. Our studies have also shown that the electrification follows precipitation development and also show, in most cases, that the electrification is associated with vertical growth. Sometimes the growth could be considered a surge but in others the growth was slow and the field enhancement was definitely not associated with explosive growth. However, the storms which were more active electrically (July 31 is a good example) did have very active convection occurring. There were also cases for which the initial electrification occurred at the end of a period of growth. Circumstantially, the evidence suggests that cloud growth, i.e., updrafts and active convection, is necessary for electric field enhancement to occur.

Our results differ with those of *Moore et al.* [1958] who reported electric fields of 1 to 2 kV m^{-1} inside the clouds before the appearance of radar detectable precipitation and *Moore* [1965] who said the reflectivity was never more than 2000 $mm^6 m^{-3}$ (33 dB_z) before the first discharge. Moore et al. sought to explain the difference between their observations and those of Reynolds and Brook on the basis that the earlier observations of electric field strength were made on the surface away from the cloud, not inside the cloud, and that the surface measurements at a distance

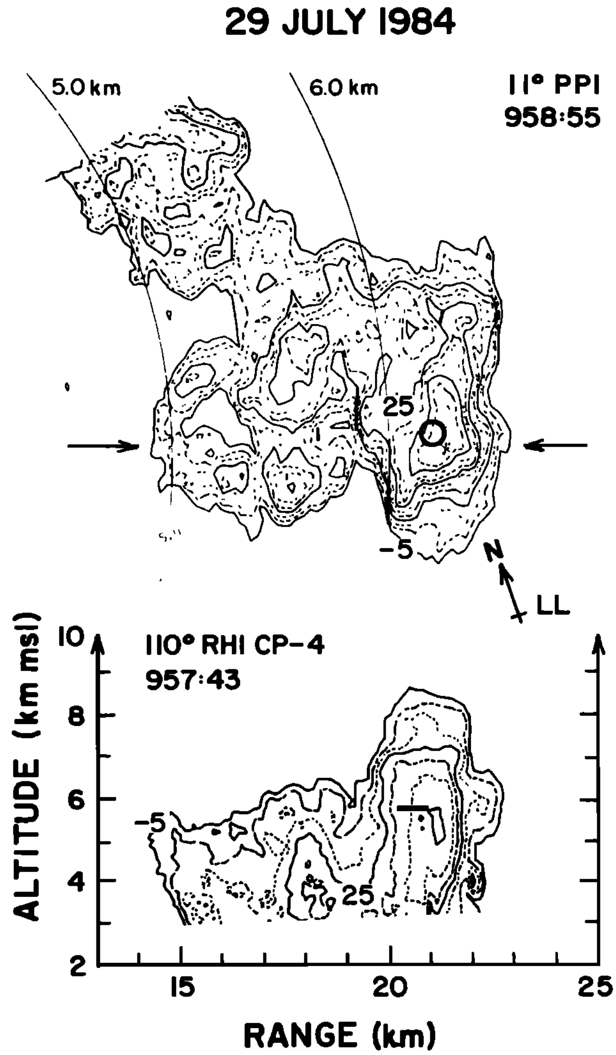

Fig. 9. As in Figure 3, but for July 29, 1984.

would be greatly attenuated by the distance and screening layers. Most of our observations of initial electrification were made either inside the cloud or directly below the base. We argue that measurements made either at the surface or by the aircraft directly below the cloud base formed by condensation would not be affected by screening layers because vertical air motions would transport charged particles away from the cloud base and not allow the screening layer to form. In a few of our cases, measurements from the surface or from SPTVAR were made somewhat away from the cloud but seldom farther than 5 km from the reflectivity core of the cloud. As can be seen in Figures 2 and 4 for August 3 and July 31 respectively, the time of the onset of electrification as detected by the aircraft is very similar (within a minute) to that detected at the surface below the cloud. This does not mean that the field did not vary as a function of distance from the cloud. It does mean, however, that in most cases once the intensification of the electric field began it was sufficiently rapid that the time at which either aircraft or the surface mills detected the initial electrification was not appreciably different, provided that they were reasonably close to (within approximately 5 km of) the storm.

The question of why our observations differ from those of

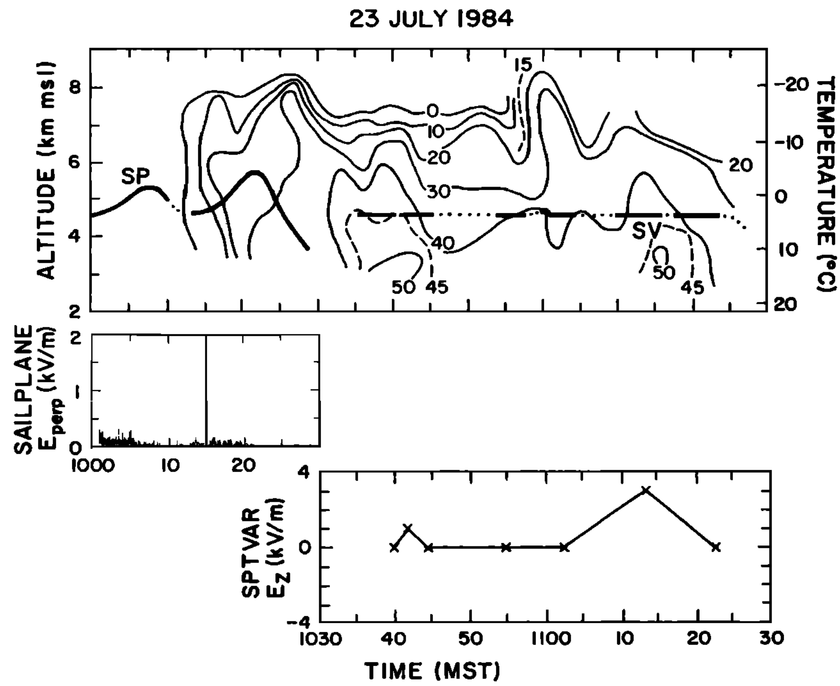

Fig. 10. As in Figure 2, but for July 23, 1984. Time-lapse photographs were not available.

Moore et al. [1958] remains. There are several possibilities. (1) One could attempt to explain it as a climatic change in cloud structure and properties. Perhaps coalescence was more prevalent in the clouds which occurred in New Mexico at the time of the earlier observations than now. Without detailed microphysical observations, which were unavailable then, it is not possible to pursue this possibility further, and even if coalescence was more prevalent it is not clear how this would influence the initial electrification of the storms. (2) Even though our sample of clouds from 1984 has a wide variety of cloud types, we may have missed clouds which show initial electrification before significant radar reflectivity. (3) Our measurements may be in error. However, we have tried to be careful. The reflectivities from independently calibrated radars, NCAR's CP-3 and CP-4 and NOAA's D, agree quite well and electric field measurements from several sources (instruments on two airplanes and on the surface) give a consistent picture. (4) The earlier measurements may be in error. We have no basis for impeaching the earlier results, but from the available literature [*Moore et al.*, 1958] we cannot evaluate in detail the radar calibration nor the operation of the balloon-borne electric field meter. However, there is a detail in the measurements of Moore et al. which we find puzzling and which differs from our observations. Moore et al. discuss and show in their Figure 9 an increase of about 1 kV m^{-1} in the measured electric field strength as the tethered balloon enters the cloud base. In many clouds in our study the sailplane ascended up through the cloud base, and in all cases, including ones not emphasized in this paper, there was no evidence of any sudden increase in field strength at the cloud base. For example, the second panel of Figure 2 shows the measured E for the sensitive channel for August 3 during the period when the sailplane enters and is near cloud base. In this cloud, the sailplane first ascends into the cloud base at about 1209 and then hovers in and out of cloud base until 1214, at which time it encounters a stronger updraft and is carried firmly into the liquid water of the cloud. In Figure 2 we see that E is about 100 V m^{-1} and remains essentially constant from 1200, when the sailplane was still out of cloud, until 1230. Our hypothesis is that in the region of active condensation and updraft at the cloud base a screening layer could not form. The sailplane measurements support this hypothesis.

In this paper we have reported the reflectivity of these storms at the time of initial electrification, but reflectivity in itself does not uniquely describe the particle concentrations, sizes and states which are responsible for the radar return. *Dye et al.* [1988] describe two small regions of space charge during very early stages of electrification (on August 3 and August 15 1984) in which the locations of the space charge are near but do not coincide with the reflectivity maxima. Instead, the space charges are located where the collision rates are a maximum. Thus, reflectivity by itself is not a reliable indication of electrification.

If the hypothesis that an ice-ice collision process is primarily responsible for the electrification of thunderstorms is correct, it would be reasonable to expect the onset of electrification to occur at substantially different reflectivities in storms in different geographic regions, with different distributions of particle sizes and concentrations. *Williams et al.* [1988] for a storm in Florida report the first intracloud lightning when the reflectivity was about 35 dB_Z at the altitude of negative charge, a value which is near but somewhat lower than the storms studied herein. Observations by *Hallett et al.* [1978] in Florida clouds have shown high concentrations of vapor-grown ice crystals (up to 100 ℓ^{-1}) and high concentrations of graupel (in excess of 10 ℓ^{-1}), which are larger than concentrations typically observed over the high plains [e.g. *Dye et al.*, 1986]. If an ice-ice collision mechanism is indeed active, electrification might be expected to appear

TABLE 2. Summary of 1984 Initial Electrification Cases

	Time of IE[a]	Time of Precipitation before IE, min.		Z_6 at IE	Maximum Z_6	Observed $\lvert E_{max}\rvert$, kV/m[a]	Lightning		Radar Top, km		Comments
		10 dB$_Z$	40 dB$_Z$				First	Total Number	at IE	Maximum	
July 19 (201)	none	—	—	—	15	~0.2	none		—	8	No electrification
July 20 (202)	<1202 (SFC)[b]	>32	14	≳40	50	55 (SV)	1204	~50	~11.5	13	IE with top growth
July 23 (205)	1041 (SV)[c]	27	2	~36	~40	3 (SV)	none		~7.5	~9	Very weak electrification
July 27 (209)	1132 (SV)[c]	62	11	>40	46	95 (SV)	1149	>3[d]	>8	~10.5	IE with slow growth
July 29 (209)	0958 (SP)	>15	13	50	52	36 (SV)	none		9	9	IE with slow growth
July 31 (213)	1127 (SP,SFC)	>62	2	43	50	80 (SV)	1129	>100	10.5	14	IE with growth
Aug. 1 (214)	~1050 (SV)	27	9	41	46	60 (SV)	none		9.5	9.5	IE at maximum top
Aug. 2 (215)N	1048 (SFC)	>20	6	45	52	17 (SV)	1053	~11	~9	13.5	IE with growth
Aug. 2 (215)S	~1131 (SP)	~25	~10	51	52	~80 (SP)	?	3?	10.5	13.5	IE with growth
Aug. 3 (216)	1242 (SP)	26	12	40	43	40 (SP,SV)	1245	6	9.5	12	IE with growth
Aug. 6 (219)	none	—	—	—	12	<0.2	none		—	~8	No electrification
Aug. 7 (220)A	between 1218 and 1226 (SV)	>23	>8	~47	50	65 (SV)	≈1225	?	~10	12	IE with growth
Aug. 7 (220)B	1259 (SP)	23	1	44	50	>65 (SV)	<1306	?	10.5	11.5	IE with growth
Aug. 12 (225)	1118 (SFC)	>16[e]	>10[e]	42	51	55 (SV)	1134	~10	>10.5	~12.5	IE with weak growth
Aug. 13 (226)	0907 (SFC)	?[f]	?	~55	61	70 (SV)	0908	18	~11	12	IE with growth
Aug. 14 (227)	1136 (SP,SFC)	16	4	44	45	15 (SP)	none		9	9.5	IE near relative maximum
Aug. 15 (228)	1036 (SFC,SV,SP)	26	3	38	43	28 (SV)	1059	6	10	11	IE at maximum top
Aug. 19	1017 (SV)	>23	6	44	46	60 (SV)	1044	~10	>7.5	?	uncertain
Aug. 20 (233)	1136 (SFC,SV)	24	6	47	55	40 (SV)	1140	~50	12.5	14	IE with growth
Aug. 23 (236)	~1220 (SV)	25	~6	52	53	80 (SV)	1220	30	11	12	IE with growth

Abbreviations are as follows: IE, initial electrification (see text); Z_6, reflectivity at 6 km altitude; SFC, surface measurements; SV, SPTVAR measurements; and SP, sailplane measurements.

[a] Source is indicated in parentheses.
[b] Sensitivity reduced by distance from LL.
[c] Too far from LL for good surface data.
[d] Based on SPTVAR coverage, some could be missed.
[e] Radar coverage started after precipitation.
[f] Radar coverage started 3 min after IE; z_6 was already 55.

TABLE 3. Reflectivities at 6 km During Initial Electrification Over Different Terrain Altitudes

> 2743 m		2438 to 2743 m		All Others	
Date	dB_Z	Date	dB_Z	Date	dB_Z
July 29	50	July 19	No IE	July 20	>40
July 31	43	Aug. 1	41	July 23	~39
Aug. 2N	45	Aug. 2S	51	July 27	>40
Aug. 13	~55	Aug. 7B	44	Aug. 3	40
Aug. 14	44	Aug. 12	42	Aug. 6	No IE
Aug. 15	38			Aug. 7A	47
				Aug. 19	44
				Aug. 20	47
				Aug. 23	52

at lesser reflectivities in Florida than in New Mexico or the high plains. For the cloud investigated by *Dye et al.* [1986] in Montana the reflectivity at 6 km was about 45 dB_Z at the onset of electrification, much like we have found in this study in New Mexico. In both regions the clouds are continental in nature with high droplet concentrations and precipitation formation dominated by the ice process. In lieu of detailed observations of particles inside clouds, it would be of interest to know the reflectivity at the onset of electrification for a significant number of clouds in other geographic areas and for winter storms, as well. However, an active coalescence mechanism with many raindrops in the cloud above the freezing level, as reported by *Goodman et al.* [1988] in Alabama, would present a complication for this kind of comparison.

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