STUDY OF ELECTRIFICATION IN THUNDERSTORMS USING IN-SITU AIRCRAFT MEASUREMENTS

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ABSTRACT

The Convection and Precipitation/Electrification (CaPE) experiment was conducted in east central Florida from early July to mid August of 1991. One of the objectives of this experiment was to determine the meteorological and the electrical conditions in which lightning would occur. In addition, participants hoped to obtain observations to better understand how precipitation influences, or is influenced by, air motion and the role of precipitation and convection in electrification of the cloud.

One of the biggest questions among thunderstorm researchers has been whether the kinds of precipitation and cloud particles that grow in a storm cause the electrification, or whether convective motions themselves electrify storms without involving the precipitation particles. Two classes of hypotheses have been proposed in this context. Precipitation theories predict that the negative charge is being carried by precipitation particles, whereas in convective theories, negative charge is predicted to be carried by small cloud particles which are carried up by the convection within the cloud.

We are presenting results from the preliminary analysis of four research flights during this experiment. We find that larger electric fields coincide with regions having larger amounts of precipitation. The sign of the fields is consistent with negatively charged precipitation. In regions where the updraft is strong, precipitation is absent. These regions have higher cloud water content and lower electric field. Thus, our preliminary analysis shows that precipitation theories seem to be more consistent with observations.

INTRODUCTION

The Convection and Precipitation/Electrification (CaPE) experiment was conducted in east central Florida during the period 8 July to 18 August 1991. One of the objectives of CaPE was the determination of the meteorological and electrical conditions in which lightning can occur and also increased understanding of the initiation and propagation of lightning. The basic goal of our research is to understand the formation of precipitation in clouds in which both coalescence and the ice process are active, how precipitation development influences or is influenced by air motion, and the role of precipitation processes and air motions in electrification of clouds.

CaPE was a multi-agency project involving many organizations contributing instruments and know-how for collecting data. It involved simultaneous data collection from research aircraft, radars, satellite and surface mesonet stations. During the CaPE project, the South Dakota School of Mines and Technology, Institute of Atmospheric Sciences' T-28 flew 19 research missions. We have analyzed four of these flights. We will present a few examples of the aircraft data collected during CaPE and make a preliminary assessment of the mechanisms important in the electrification of Florida thunderstorms.

THEORY OF THUNDERSTORM ELECTRIFICATION

Understanding the electrification of thunderstorms and their dynamics and precipitation processes requires simultaneous observations of their dynamical, microphysical and electrical properties. The interior of the storm typically contains a dipolar charge distribution consisting of positive charge in the upper part of the cloud and negative charge below positive. These are the dominant accumulations of charge in the storm and are called the "upper positive" and "main negative" charges. In general, it is thought that small ice particles carry the positive charge, whereas precipitation particles carry the negative charge. The upper positive charge attracts negative ions to the top of the cloud from electrically conducting clear air from around the storm. The ions, which are produced by cosmic radiation, attach to small cloud particles at the edge of the cloud forming a negative screening layer that partially cancels or screens the interior positive charge from an outside observer.

Positive charge is also found beneath and inside the base of the cloud below the main negative charge. This is termed the "lower positive charge". Lower positive charge is carried by descending precipitation and occurs in localized regions known as "lower positive charge centers" (LPCC's) (Williams, 1989). A typical charge structure of a thunderstorm is seen in Figure 1 (adapted from Krehbiel, 1986).

In fair weather conditions, the atmospheric electric field at the Earth's surface has a negative value of about 100 to 200V/m. This is because the ionosphere is charged positively to a potential of about 300,000V with respect to the earth's surface. However, beneath a thunderstorm the electric field at the ground is often substantially higher, up to 10,000 V/m or more, and tends to be reversed in sign from fair weather conditions.

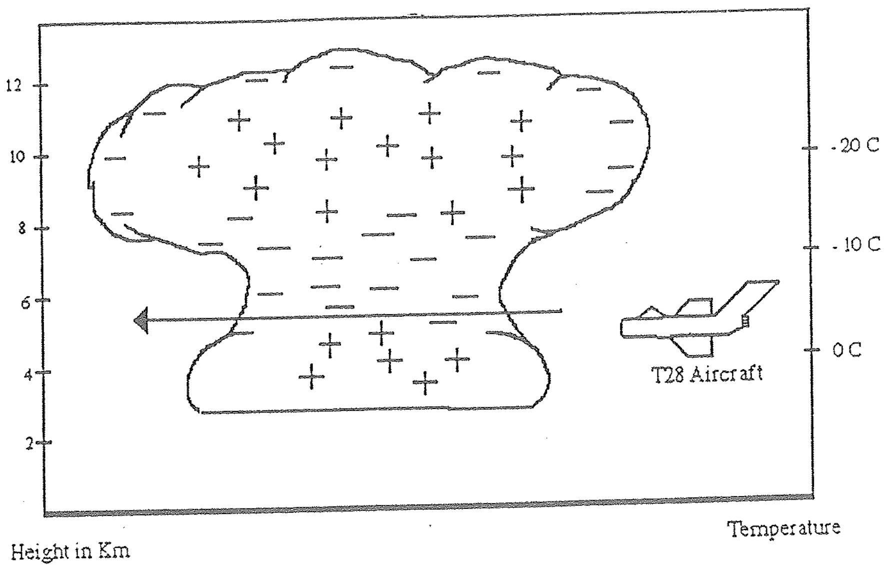

Figure 1. Charge structure of a typical thunderstorm.

The structure of a storm is often cellular in nature. A storm can consist of many convective cells with each individual cell contributing to the overall electrification of the storm.

One of the main questions among the thunderstorm researchers has been whether the kinds of precipitation and the cloud particles that grow in convective storms cause their electrification or whether the convective motions themselves directly electrify the storm without involving or requiring precipitation. Studies have indicated that the main negative charge is found in a relatively narrow range of altitudes at temperatures that vary between 0°C and -25°C (Simpson and Scrase, 1937; Workman and Reynolds, 1949; Reynolds and Neill, 1955). This has caused many researchers to focus on frozen precipitation as primary agent in the electrification process.

In precipitation theories, it is hypothesized that the relatively large frozen precipitation particles acquire negative charge by colliding with or shedding smaller ice particles. The smaller ice particles acquire a corresponding positive charge upon separation and are carried by the updraft into the upper part of the storm. The precipitation may rise or fall with respect to ground depending on the relative magnitudes of its fall speed and that of the updraft, but will separate from smaller particles in either case. Negative and positive charges are thus segregated onto large and small particles, respectively, and are separated by action of gravity to electrify the storm (see Figure 2(a)).

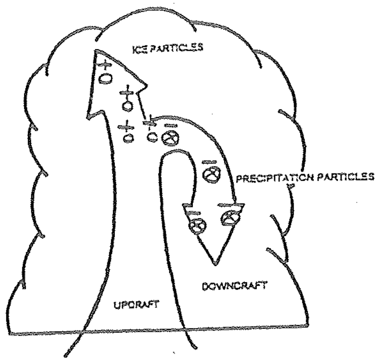

Figure 2(a).
Precipitation mechanism.

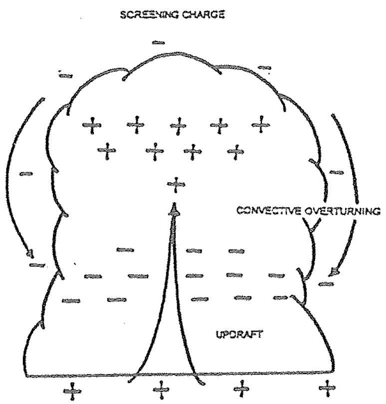

Figure 2(b).
Convective mechanism.

Two charging mechanisms can occur during this process, i.e., inductive and noninductive. In inductive charging processes (Chalmers, 1967), the existing electric field causes polarization of charge on the particles. On collision, charges are exchanged between the precipitation and cloud particles (see Gaskell, 1981). In the noninductive charging mechanism, there is no influence of the electric field. Both precipitation and cloud particles can be with or without charge. Once the collision occurs, they acquire charge depending on the temperature and cloud liquid water content. At lower temperatures, precipitation acquires a negative charge whereas smaller ice particles acquire a positive charge. For warmer temperatures, the signs are opposite.

Convection theories postulate that the positive and the negative charges are initially spatially segregated by the action of the fair weather field. The energy of electrification is derived directly from the convective motions of the storm, which transport charges of opposite sign away from each other. The hypothesis is that the screening charge at the cloud boundaries is carried downward by convective overturning to the level of the main negative charges and that this is the primary source of the main negative charge (Vonnegut, 1953).

The charges are expected to reside primarily on small cloud particles, with the net charge being either small or of a same sign as that of the cloud particles. This charge transport would be generative, i.e., negative charges would be carried downward away from the upper positive charge, increasing the electrical energy of the storm (see Figure 2(b)). An alternative possibility is that turbulent mixing folds the screening charge into the upper positive charge of the storm which would be dissipative, decreasing the electrical energy of the storm (Telford and Wagner, 1979).

ANALYSIS

The four flights which we selected for our preliminary analysis are listed below.

Date	Flight Time (start)	Flight Time (end)	Average Altitude	Hydrometeors
28-Jul-91	16:08	17:14	≈6200 m	graupel
29-Jul-91	17:29	18:41	≈5500 m	graupel, raindrop
31-Jul-91	13:33	14:26	≈5500 m	graupel, raindrop, snow
13-Aug-91	17:53	19:14	≈5500 m	graupel, raindrop, snow

We would also like to give a general overview of the instrumentation onboard T-28 research aircraft. These instruments have very specific ranges and uses as seen in the table below.

Variable	Instrument	Range	Accuracy	Resolution	Units
Total Temperature	Rosemount 102AU	[-30-+30]	[+/-0.5]	0.001	Celsius
Cloud Water	JW Liquid Water Content	[0-6]	[+/-20%]	0.0001	g/m**3
Cloud Droplet Concentration	FSSP Probe	[0-2000]	[+/-1%]		#/cm**3
Precipitation Concentration	2 D-P Probe	[200-6400]	[+/200]	200	micrometer
Electric Field	DC E Field Meter	[-200-+200]		0.01	kV/m

Next we give some examples of observations from within thunderstorms using these instruments. Figure 3 shows four variables measured by the T-28 during a penetration of a thunderstorm on a research flight on 29 July 1991. It can be seen that the aircraft encounters two convective cells (distinct updraft regions), at 18:03:00 and 18:03:45, respectively, which we will refer to as cell 1 and cell 2, respectively. Cell 2 is characterized by a large updraft speed of 22 m/sec and a very high value of JW liquid water content ≈4 g/m3 at the same time. This cell is very active and vigorous. However, note that the electric field for this cell is small, indicating that it is at either the center of the charges in the vertical or there are very few charged particles above or below it. The 2 D-P shadow count gives the rate at which the probe detects precipitation particles. For cell 2, there are insignificant amounts of precipitation. However, at time ≈18:03:20, large values of precipitation concentration can be seen in Figure 3. This time also coincides with downdraft or a negative vertical velocity. This region has a small negative value of vertical electric field. A possible explanation for this could be that the precipitation particles carrying negative charges are being carried down by the downdraft to levels below the aircraft. The temperature level at which this penetration was carried out was around -6°C, and the altitude for this penetration was around ≈5500 m.

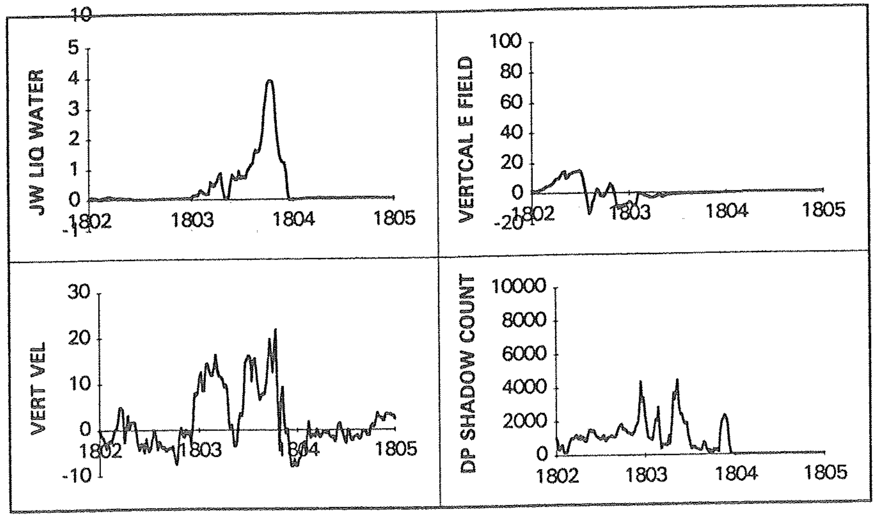

Figure 3. 29 July 1991 case. Starting from left to right at the top, panel 1 is JW liquid water content in g/m3; panel 2 is vertical electric field in kV/m; panel 3 is vertical velocity/updraft in m/s; panel 4 is 2DP shadow count in #/sec. The x axis has values of time plotted in hours and minutes.

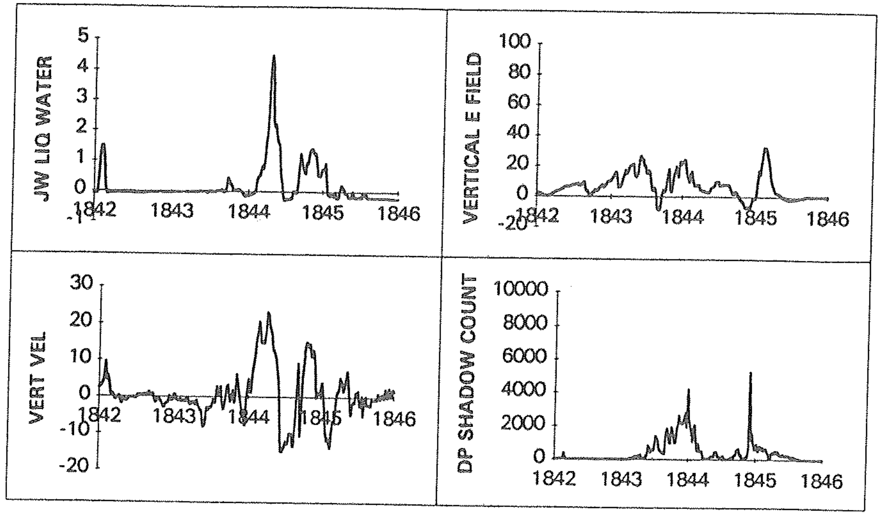

Figure 4. As in Figure 3, but for a 13 August 1991 case.

Figure 4 is an example of data from the research flight on 13 August 1991. This was the first penetration by T-28 through this storm system. The average temperature measured during this penetration by the aircraft was around -4°C. This penetration, like Figure 3, has an example of a young cell encountered at 18:44:15 with vertical velocity of 22 m/s and JW liquid water content of ≈4.5 g/m3. We do not see many precipitation particles in this cell. The vertical electric field associated with this cell is again small and is positive indicating negative charges above the plane or positive charges below. Another feature of this cell is that the updraft temperature is 2°C warmer compared to its surroundings, indicating that vigorous growth of this cell is continuing due to release of latent heat of condensation in the updraft.

Figure 5 is also from 13 August 1991 and is the second penetration through the same storm system after a gap of 8 minutes. The average temperature for this penetration as measured by the T-28 was ≈-4°C. It can be seen that the aircraft encounters a region of several updrafts and downdrafts, or in other words, cells which are much weaker and less defined as compared to previous examples. The JW liquid water content values peak within the region having updrafts at time period ≈18:52:00. However, these peaks are smaller as compared to the first and the second example. At this time, there is a small positive vertical electric field. At time period 18:54:15, we see that the T-28 encounters a region having large concentrations of precipitation and a coinciding high positive vertical electric field. We can also see that a vertical electric field of similar magnitude exists at ≈18:52:50, but with smaller precipitation content as compared to one seen at 18:54:15. One plausible explanation for this could be that the size of the precipitation particles is larger in the second episode because it is in a stronger downdraft. Also, our aircraft data are obtained at a single altitude. Microphysical conditions above or below the aircraft, which will influence the measured electric field, will not be known until further analysis of radar observations is complete.

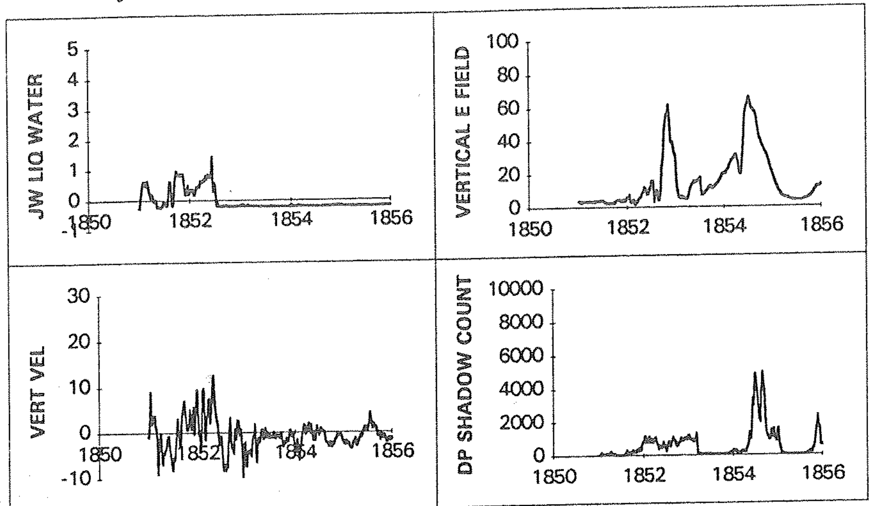

Figure 5. As in Figure 4, but for the next penetration.

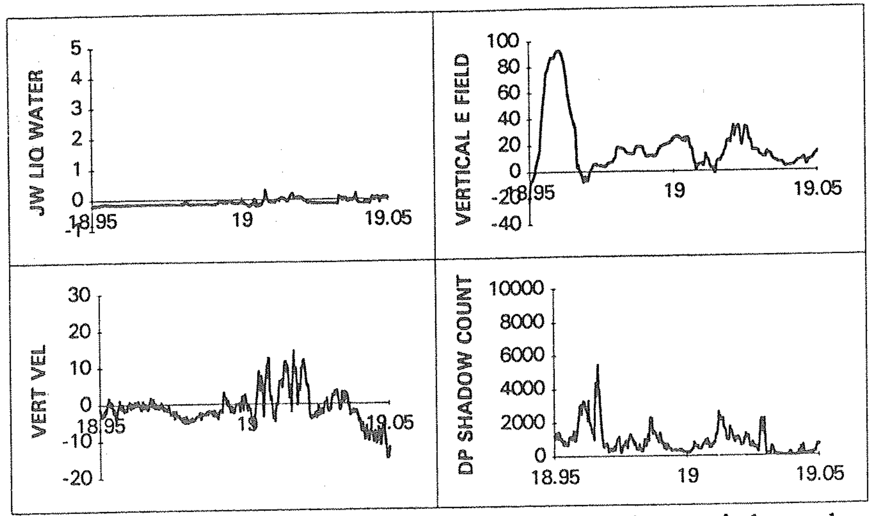

Figure 6. As in Figure 4, but for a later time. The x axis has values of time plotted in decimal hours.

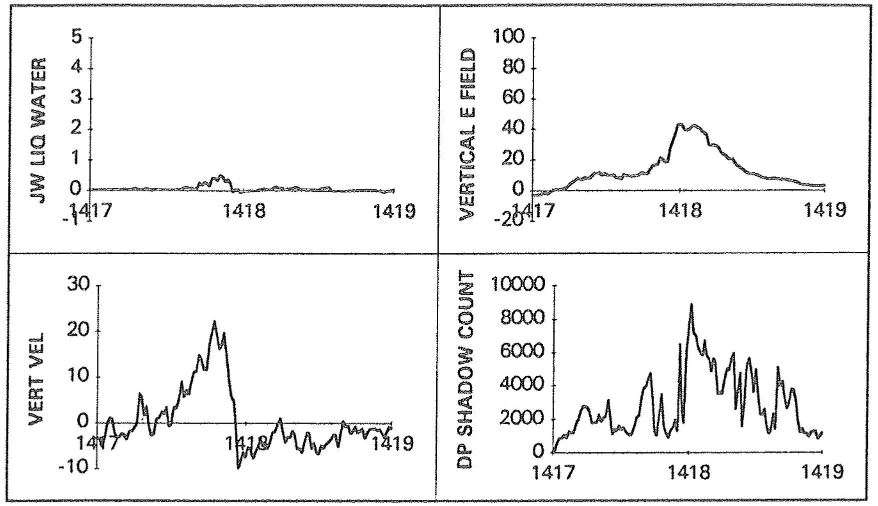

Figure 7. As in Figure 3, but for a 31 July 1991 case.

Figure 6, from 13 August 1991, is from a different storm system. It depicts a penetration of a cell at a mature stage having characteristic downdrafts and updrafts. The temperature measured by T-28 during this penetration was around -4°C. Again it is evident that cloud water content lies in the regions of updrafts. This updraft region is less organized with cloud liquid water content small compared to previous examples (the negative values for cloud liquid water content are due to zero-offset in the JW liquid water probe). This seems to indicate possible entrainment or dilution of outside air into the updraft. This region starting from 19:00 to 19:02 has low positive vertical electric field values. However, during the time period 18:95 to 18:97, we find higher precipitation content and a coinciding higher positive vertical electric field.

Figure 7 is from the 31 July 1991 research flight. This time period contains the third penetration through a target storm. The temperature measured during this penetration was around -6°C. Between time period 14:17:50 and 14:18:00, we find peak values of JW liquid water content (≈0.5 gm/m3) within updrafts with maximum speed of ≈22 m/s. The peak cloud liquid water content is relatively low and precipitation count high. As in the other cases, this period has low values of positive vertical electric field. Vertical electric field has higher values, again coinciding with regions of higher precipitation concentration at time period ≈14:18:00 to 14:18:30.

CONCLUSIONS

The origin of thundercloud electrification still remains an open question as studies have shown that no one hypothesis answers all the aspects of electrification correctly. It is clearly evident from the cases we have shown that high values of positive vertical electric field are found in regions having a high precipitation concentration and strong downdrafts. The first two figures both depict a highly vigorous updraft with high cloud water concentration but little precipitation. If we follow the reasoning of convective theory, we might have observed high vertical electric field values in those regions as charges would be on cloud droplets. However, that was not observed. In general, our data has shown that the initial electrification occurs following the growth of the precipitation in an updraft. This seems to indicate that the precipitation based theories appear to be the more probable of the two types of theories to account for the electrification of a thunderstorm.

We have not considered the cloud age while analyzing these examples. Cloud age would be an important factor in assessing convective theory. This is because time is required for transport of screening charge down from cloud top and its movement into the updraft. Also, low values of electric field do not necessarily indicate low charge values. Electric field can be zero at the center of any charge distribution regardless of the magnitudes of charges.

The relative contributions of precipitation and convection to electrification still require further study before we can validate one hypothesis or rule out the other. We intend to combine microphysical retrieval techniques using multiparameter radar in combination with the in-situ microphysical and electrical measurements presented here to further study precipitation formation and cloud electrification.

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