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Model study of electric field growth in thunderstorm

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The electric field growth inside Montana cumulonimbus cloud is tested using a parallel plate capacitor model. It is found that the results of laboratory charge transfer experiments of ice crystal-hailstone non-inductive mechanism can explain the observed electric field growth.

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1 Introduction

Thunderstorms are generally found to have a pocket of net positive charge at the top and negative charge at the bottom. A subsidiary small positive charge may also exist at the base of the cloud. The negative charge centres are found to be co-located with precipitation particles in well-defined temperature regions between − 10 and − 17°C regardless of the geographical location of the storm, whilst those of the main positive charge are several kilometres higher. A number of charging mechanisms have been proposed to explain the thundercloud charging[1-3].

The efficiency of convective mechanism is limited by the weak downdrafts around the cloud boundaries and longer time (> 10s) that is required to transport the ions to the cloud heights. The efficiency of inductive mechanism is limited by the fact that the rebounding probability in water-water collisions falls to zero above the electric field of 25 kV/m. The charge buildup in the ice phase due to this mechanism is limited by the higher relaxation time (of about 100 μs) of surface against the contact time (< 1 μs). Significant charge transfer is found to occur in the non-inductive collisions between rimmed targets and unrimmed ice crystals. The other mechanisms are shown to have severe limitations and, therefore, not significant to thunderstorm electrification.

In this paper, laboratory results from the experiments of ice crystals-hailstone interactions[4-6] have been used in the model calculations and compared with the observed electrification of a small isolated Montana cumulonimbus clouds[7].

2 Field observations

Four instrumented aircrafts were used to probe the microphysical and electrical properties of the thunderstorm that occurred on 19 July 1981. While three aircrafts, i.e. King Air, Aerocommander and Sailplane probed inside the thunderstorm, the fourth aircraft Queen Air flew below the cloud base. The important microphysical and electrical observations of this storm[7] are summarized in Tables 1 and 2. The King Air was equipped for making only microphysical measurements, but during the same time and at the same isotherm of − 10°C the Sailplane was observing the electrical evolution of the storm. Between 1631 and 1632 hrs LT, the Sailplane observed an electric field of 800 V/m and between 1637 and 1638 hrs LT it observed that the electric field has increased to 8 kV/m. Measurements of electric field made by Aerocommander (Table 2) from its three penetrations at − 6°C isotherm show an electric field of 500 V/m at 1632 hrs LT, a rapid increase to about 15 kV/m at about 1636 hrs LT and a decrease to 4 kV/m at about 1640 hrs LT. Thus both the aircrafts observed the same general history for the electrical development, i.e. 500-1000 V/m at around 1630 hrs LT with a rapid increase to 8-15 kV/m by 1637 hrs LT.

The observations in the − 10°C isotherm when the electric field was about 800 V/m showed that the liquid water content (LWC) was 1.77 g m^{-3} and the vertical velocity of wind in the cloud wa 9 ms^{-1}. The distribution of ice particles during this period (1629-1630 hrs LT) was found to be[7]

$$N(d) = 10^4 e^{-2d} \text{ in m}^{-3}\text{mm}^{-1} \qquad \ldots(1)$$

Table 1—Properties of thunderstorms as observed by King Air penetrations[7]

Time hrs LT	Altitude km	Temp. °C	LWC g m^{-3}	Vertical wind ms^{-1}	Ice concentration per litre	Largest graupel size mm
1617-1618	6.0	−15	1.37	5	0.2	0.6
1620-1621	6.0	−15	1.01	3	0.6	0.8
1622-1623	6.0	−15	1.75	10	0.6	1.6
1625-1626	6.0	−15	2.19	10	4.7	2.2
1629-1630	5.4	−10	1.77	9	2.0	5.0
1632-1633	5.2	−10	0.71	6	0.7	7.2
1640-1641	5.3	−10	0.34	3	29.3	7.2
1642-1643	5.6	−11	0.04	0.3		4.5
1647-1648	6.0	−15	0.06	1	63.8	5.0
1650-1651	6.1	−15	0.04	−2	45.3	4.5

Table 2—Properties of thunderstorms as observed by Aerocommander penetrations[7]

Time hrs LT	Altitude km	Temp. °C	LWC g m^{-3}	Vertical wind ms^{-1}	Ice concentration per litre	Largest graupel size mm	Electric field kV/m
1631-1633	4.3	−5	0.31	9	0.3	3.9	0.5
1635-1637	4.5	−6	0.36	3	20.4	3.2	15
1639-1641	4.6	−6	0.04	2	21.7	4.4	4

where d is the particle size in mm. By the end of the electrical life of the storm (1640-1641 hrs LT) the LWC in this region was 0.34 g m^{-3} and the vertical velocity of wind in the cloud was 3 ms^{-1}. The ice particle distribution during this period (1640-1641 hrs LT) was found to be

$$N(d) = 10^5 e^{-2.76d} \text{ in m}^{-3}\text{mm}^{-1} \qquad \ldots(2)$$

The two distributions indicate an increase in the concentration of ice particles during 1629-1640 hrs LT. The presence of large and small ice particles co-existing with supercooled water in the fringes of updraft may be playing an important role in the electrification of the cloud.

3 Laboratory observations

In the laboratory experiments[4-6,8] significant charge transfer was found to occur during collision between unrimmed ice crystal and rimmed ice target in the presence of supercooled water droplets.

At the temperatures below −10°C and LWC of 1 g m^{-3}, a charge transfer of about -16.5×10^{-15} C was found[4] when a 100-μm size crystal collided with rimmed target at an impact velocity of 9 ms^{-1}; and a charge transfer of -12×10^{-15}C was reported[5] when a 100-μm ice sphere collided with a hailstone at an impact velocity of 8 ms^{-1}, the LWC in the chamber being 0.8 g m^{-3}.

Similar experiments were performed[8] at an impact velocity of 3 ms^{-1} and it was found that the charging of rimmer per collision is proportional to the fourth power of the size of the ice crystal. These experiments were further extended[6] and it was found that at temperature of −15°C with LWC of 1 g m^{-3} and an impact velocity of 3 ms^{-1} a 800-μm size crystal separated a charge of -220×10^{-15}C, a 450-μm crystal separated -160×10^{-15}C and a 200-μm size ice crystal separated a charge of -40×10^{-15}C.

4 Model calculations

Assuming a d^4-dependent charge transfer (q) per collision based on the data[8] for small ice crystals (< 125 μm), the charge density inside the Montana storm was assessed and the observed features were reproduced reasonably well[9]. However, some later experiments[6,10] indicated that q is limited by the onset of corona among the interacting particles when the large ice crystals (> 450 μm) are involved in the collision with rimmer. It was found that the dependence of q on crystal size falls to $d^{0.5}$ at larger crystal sizes. As it is difficult to deduce the charge and size relationship from the field observations inside Montana storm[11], we have taken the approach of calculating the growth of electric field. The electric field growth is examined for different leakage currents utilizing the laboratory charge transfer values as closely as possible.

The parallel plate capacitor model for electric field growth rate due to non-inductive process[12] is used for the present calculations. The time variation of electric field inside a thundercloud can be obtained from current density equation as follows.

$$\varepsilon \frac{dE}{dt} = -[NQ(V-v) - \lambda E] \qquad \ldots(3)$$

$$\frac{dQ}{dt} = \pi R^2 (V-v) nqa \qquad \ldots(4)$$

$$\varepsilon \frac{d^2E}{dt^2} + \lambda \frac{dE}{dt} = -Nn\pi R^2 (V-v)^2 qa \qquad \ldots(5)$$

$$E(t) = E_0 + \frac{Bt}{A} + \left(E_0 - \frac{B}{A^2}\right)(1 - e^{-At}) \qquad \ldots(6)$$

where

$$A = \lambda / \varepsilon$$

$$B = \frac{\pi N n}{\varepsilon} R^2 qa (V-v)^2$$

N	Number density of hail pellets of radius R
n	Number density of ice crystals
V	Terminal velocity of hail pellet
v	Terminal velocity of ice crystal
q	Charge transferred per collision
a	Event probability and the values have been taken from the observations reported by Keith[13]
E_0	Initial electric field
ε	Permittivity of free space which is $8.89 \times 10^{-12} N^{-1} C^2 m^{-2}$
λ	Conductivity inside the cloud

Eq. (4) gives the rate of graupel electrification due to non-inductive process. The model assumes the radius of the graupel to be constant throughout its fall in the cloud. Therefore, the model provides the rate of electric field growth only due to charging of a particular size of the graupel.

In this paper we have calculated the field growth for particle concentrations N and n observed in the Montana thundercloud described by Eq. (2) for assumed conductivities $\lambda = 2.22 \times 10^{-14}$ Sm^{-1} (normal), $\lambda = 2.22 \times 10^{-13}$ Sm^{-1} (one order higher) and $\lambda = 2.22 \times 10^{-15}$ Sm^{-1} (one order lower) of air within the cloud domain.

5 Discussion

Figures 1-3 show the growth of electric field with time for different conductivities for the variables that have been given in Table 3. If the interactions between the various crystal sizes with graupel are integrated then the charge transfer rates observed in the earlier laboratory experiments[6,8] and used in this crude model are sufficient to generate the observed electric field of Montana thunderstorm in 7 min. This is true even if a normal fair weather conductivity value is assumed to be present inside the cloud (Fig. 1).

The experiments performed earlier[4,5] at high impact velocities of 9 ms^{-1} seem to be unrealistic as is evident from the electric field growth shown in Figs 1-3 for the variables of sets 4 and 5 of Table 3. In actual situations, as seen from Tables 1 and 2, although such values of vertical wind are present, the ice crystals and hail pellets would be colliding with a velocity which is the difference of their terminal velocities and, therefore, will be of the same order of impact velocities as used in the later laboratory experiments[6,8].

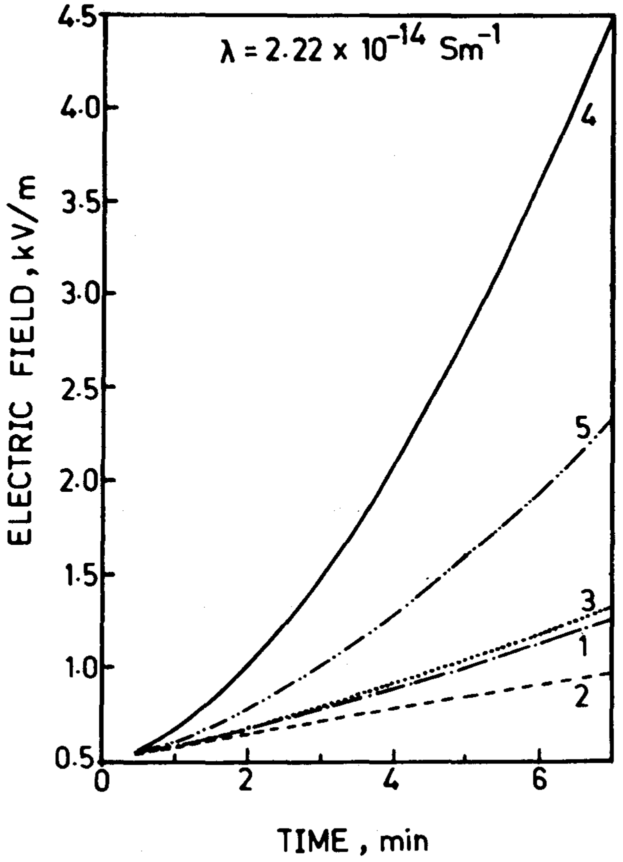

Fig. 1—Electric field growth with time for normal conductivity $\lambda = 2.22 \times 10^{-14}$ Sm^{-1} (the curve nos. correspond to the set nos. of Table 3)

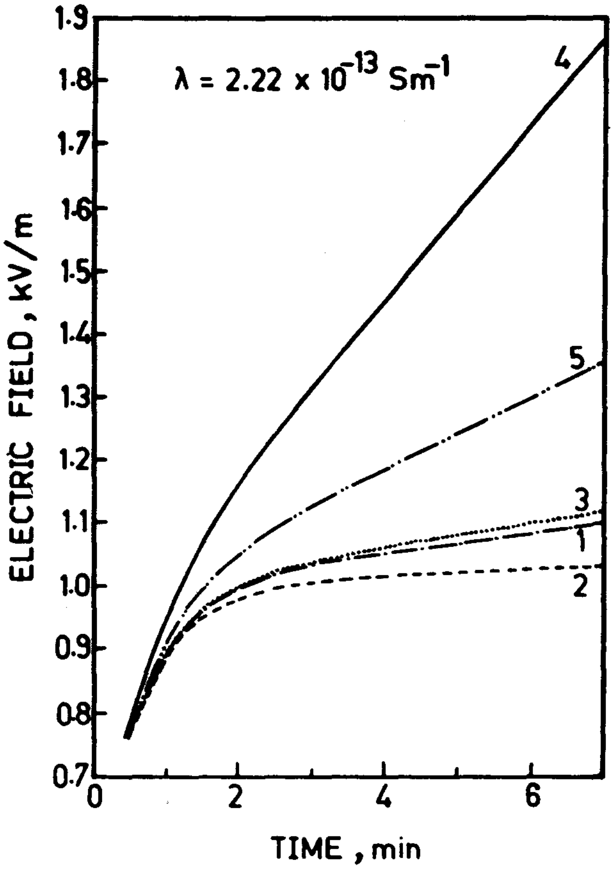

Fig. 2—Same as Fig. 1 but for $\lambda = 2.22 \times 10^{-13}$ Sm^{-1}

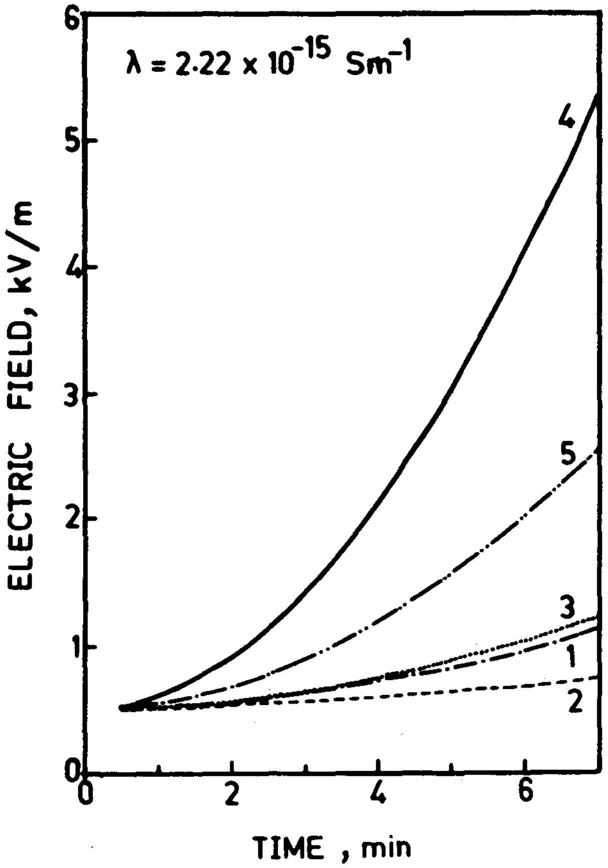

Fig. 3—Same as Fig. 1 but for $\lambda = 2.22 \times 10^{-15}$ Sm^{-1}

Table 3—Variables used for electric field growth calculations

Set of calculation	q f.c.	n m^{-3}	d μm	$V-v$ ms^{-1}	a	Ref. No.
1	220	219	800	3	0.58	6
2	40	1151	200	3	0.20	6
3	160	578	450	3	0.35	6
4	40	1517	100	9	0.43	5
5	16.5	1517	100	9	0.43	4

Note : $E_0 = 500$ V/m, $t = 7$ min, $N = 34$ m^{-3}, $R = 1.5$ mm, 1 f.c. = 10^{-15}C.

From the above model calculations it can be seen that charge transfer during ice crystal-hailstone interactions in the presence of supercooled droplets can explain the observed thunderstorm electric field growth. As seen from Tables 1 and 2 the presence of large and small ice particles co-existing with supercooled water in the fringes of updraft is playing an important role in the electrification of the cloud. Also it is seen from Table 2 that even though the maximum ice diameter and concentration of ice have increased during 1635-1639 hrs LT, the electric field in the vicinity has dropped from 15 to 4 kV/m which is associated with the decrease of LWC from 0.36 to 0.04 g m^{-3}. In the laboratory experiments[6,8] also a decrease in charge transfer with decrease in LWC has been observed. However, more measurements from inside the thunderstorm and more laboratory experiments, using uniform sizes of rimmed hail observed in different stages of cloud growth with realistic impact velocities, are necessary for better assessment.

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