Electric Field Enlarges Raindrops beneath Electrified Clouds: Observational Evidence

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Abstract: Simultaneous measurements of cloud electric field and raindrop size at the surface have been analysed to investigate an anticipated relation between the two cloud parameters. A significant positive correlation is observed between the magnitude of the surface electric field and raindrop size supported by a theoretical framework advanced here. It is shown that in the presence of an electric field, raindrops increase their sizes through electrically-induced collision and coalescence processes near the Earth's surface. This study also demonstrates that the presence of an electric field inside the cloud can enhance the rain intensity by influencing the growth rate of raindrops. This new insight may be useful for a proper understanding of the rain microphysics and for developing better numerical weather models for simulation and forecasting of heavy rainfall events associated with stronger in-cloud electrical environments.

Plain language summary: The rainfall observed at the Erath's surface is a manifestation of different cloud microphysical processes. The condensation of water vapor on cloud condensation nuclei (CCN) and subsequent collision/coalescence between cloud droplets are the two dominant processes of rain formation in the warm phase of cloud. Many laboratory investigations suggest that both the processes are quite sensitive to the electrification of cloud. But direct evidence of the influence of cloud electric field on the rain formation in the real atmospheric condition is lacking till now. With simultaneous observations of cloud electric field and raindrop size distribution below a few strongly electrified clouds, for the first time, it has been shown that higher cloud electric field remains associated with larger raindrops at the Earth's surface. A mathematical framework has also been developed to support the observations. It has also been shown that cloud electric field can modify the rain rate at the Earth's surface by enhancing the growth of raindrops.

Introduction:

Electrical modification of cloud microphysical properties and rain formation in the liquid phase of the cloud have been discussed for a long time (*Rayleigh*,1879; *Moore and Vonnegut* , 1959; *Lindblad*,1964; *Goyer et al.*, 1960; *Freier*, 1960; *Jayaratne et al.*, 1964*; Jennings*, 1975). Recently it has been shown that the rainfall at the Earth's surface can be enhanced by droplet charging, which is related to the global circuit current flowing through clouds (*Harrison et al*., 2020), although the precise mechanism for the same has not been addressed quantitatively. The process of *electro-coalescence*, an electrically induced coalescence of two liquid drops, has been investigated numerically as well as in the laboratory by numerous investigators over the years (*Goyer et al*., 1960; *Freier*, 1960; *Jayaratne et al*., 1964; *Jennings*, 1975). Many laboratory measurements reported a substantial influence of an electric field on the growth of raindrops (*Moore and Vonnegut*, 1959, *Goyer et al*., 1960; *Freier*, 1960; *Jayaratne et al*., 1964; *Jennings*, 1975,). A very rapid intensification of rain echo was observed by radar in New Mexico thunderstorms with the inference that electrification of the cloud may be a possible cause of such rapid growth of raindrops (*Moore and Vonnegut*, 1959). Even though many laboratory and numerical studies clearly suggest that an electric field may modify the microphysical properties of raindrops, no direct observational measurement connecting the cloud electric field and raindrop size in the Earth's atmosphere has been reported yet in the literature. Simultaneous measurements of cloud electric field and raindrop size at the Earth's surface provide a unique opportunity to analyse the much anticipated association between the two parameters for the very first time. Here, we have advanced an analysis connecting the two measurements carried out at the Atmospheric Electricity Observatory (AEO) in Pune, India. Even though the space charge generated by corona discharges can reduce the magnitude of the surface electric field during storms, it can be a good indicator of the magnitude of the electric field between the main negative charge center and the ground (*Standler et al*.,1979; *Soula and Chauzy*,1991).

In the Earth's atmosphere raindrops form by two distinct processes, namely (a) condensation of water vapor on cloud condensation nuclei, and (b) subsequent collision and coalescence of cloud droplets to form the millimeter-size raindrops. Two mathematical frameworks incorporating the electrical effect has been constructed using analytical equations for both these processes based on the literature (*Rogers and Yau*,1989, *Lapshin et al*., 2002; *Nielsen et al*, 2010; *Pruppacher and Klet*, 1996). Then keeping the analytical framework in the background, observational evidence has been advanced to support the hypothesis that the cloud electric field can indeed enhance the growth of raindrops and hence the rain rate.

Growth by Condensation:

Cloud droplets start to form on the cloud condensation nucleus (CCN) through deposition of water vapour on the CCN. The physical mechanism is the diffusion of water vapor which depends on the ambient temperature and pressure. The saturation vapor pressure over a liquid water drop governed by the Clausius Clapeyron equation determines the rate of growth of a cloud droplet by vapor diffusion. The growth rate of a droplet of radius r can be expressed as (*Rogers and Yau*,1989)

$$r\frac{dr}{dt} = \frac{S-1}{F_k+F_d} \qquad (1)$$

Where, $S(=\frac{e}{e_s(T)})$ is the ambient saturation ratio, e is ambient vapor pressure and $e_s(T)$ is saturation vapor pressure over the spherical drop of radius r at temperature T and F_k is associated with heat conduction and F_d is associated with vapor diffusion. Please see the supporting information for the expansion of the terms.

It has been shown that polar molecules such as water (dipole moment, $P = 1.86D$) can easily condense on charged particles because of the attractive force between the particle and the dipoles oriented along the electric field produced by the charged particle (*Lapshin et al.*, 2002). The charge–dipole interaction can creates a depression $[\frac{e}{e_s(T)} = \exp(-\frac{qP}{4\pi\varepsilon_0 k_B T_\propto r^2})]$ of the ambient saturation vapour pressure over a charged surface as a function of surface charge density protecting the particle from evaporation, thereby assisting the growth by diffusion of water vapor into the droplet. This process of charge-dipole interaction can be incorporated in equation (1) as (*Nielsen et al,* 2010)

$$r\frac{dr}{dt} = \frac{(1+U_d)S-1}{F_k+F_d} \qquad (2)$$

Where

$$U_d = \frac{qP}{4\pi\varepsilon_0 k_B T_\propto r^2} \qquad (3)$$

with q is the particle charge, P is the water dipole moment, k_B is Boltzmann constant, $T_\propto$ is ambient temperature, and ε_0 the permittivity of vacuum.

This dimensionless quantity in equation (3) can be written as

$$U_d = \frac{E_r P}{k_B T_\propto} \qquad (4)$$

where, E_r is the electric field at the droplet surface.

The maximum value of q depends on the external electric, E as $q = 0.5\, Er^2$ (*Pruppacher and Klett*, 1996) according to the Rayleigh limit for drop disruption, which expresses the condition of mechanical instability involving the equalization of surface electrostatic stress and surface tension stress (*Rayleigh*,1882). In a strongly electrified cloud, E may go up to 4×10^5 V m^{-1} (*Winn et al.*, 1974)$^{\cdot}$ Considering this value of electric field, the maximum charge on a cloud droplet of radius r may be expressed as $q = 7r^2$. Considering the droplet in a vertical external electric field $\vec{E}=E\hat{e_z}$, the radial electric field at the droplet surface can be expressed as (*Griffiths* ,1999)

$$E_r = 3E\cos\theta + \frac{q}{r^2} \qquad (5)$$

Clearly, the first term in equation (5) is the dipole field induced by the external electric field. Here θ is the polar angle measured from the direction of $\hat{e_z}$

Using this field in equation (5) and putting it back in the equation (2), we can express the time evolution of r as

$$r = \sqrt{r_0^2 + ct} \qquad (6)$$

Here, r_0 is the initial radius of a droplet and $c = \frac{(1+U_d)S-1}{F_k+F_d}$

Using the equation (6), the growth rate of a droplet with initial radius 1µm can be calculated assuming a water vapor saturation ratio 1.01 at a temperature 273K, and assuming a droplet charge 2.3×10^{-17}C in an external electric field 4×10^5 V m^{-1}.

Figure 1 depicts the diffusional growth rate of a 1µm droplet in the presence and absence of surface charge and external electric field. A substantially higher growth rate can be observed when the droplet is electrified compared to the neutral situation. The growth rate of the neutral drops is found to be comparable with calculations in *Mason*, (1971). This suggests that clouds in the presence of a vertical electric field will exhibit larger droplets than the neutral counterpart. This electrically induced condensation growth has been experimentally verified by *Dmitrii et al.* (2020) and *Reznikov* (2015).

Growth by Collision-Coalescence:

Before the cloud droplets start to grow by the collision-coalescence process to form the millimeter-size raindrops, they much reach a critical radius of 13 µm through diffusional growth (*Freud and Rosenfeld*, 2012). Figure 1 suggests that an electrified cloud will produce this size droplet faster than the neutral counterpart. The fundamental quantity which determines the raindrop spectrum is the rate at which drops collide with each other (*Rogers and Yau*, 1989). The rate at which large drops of diameter D_L collide with smaller droplets of diameter D_s inside a cloud volume with droplet size distribution $n(D_0)dD_0$ can be expressed as collision rate, C (sec^{-1}) (*Pruppacher and Klett*, 1996)

$$C = \frac{1}{4} \int_{D_s}^{D_L} n(D_0) E\pi [U_L - U(D_0)](D_L + D_0)^2 dD_0 \quad (7)$$

Here the quantity E is the dimensionless collision efficiency expressed as

$$E(D_L, D_s) = \frac{b^2}{(D_L + D_S)^2} \quad (8)$$

b is the impact parameter (Figure 2b) within which a collision is certain to occur. $n(D_0)$ is the number of droplets in the distribution $n(D_0)dD_0$. U_L is the terminal velocity of the large drop falling under gravity while $U(D_0)$ is the same quantity for the droplets. In the presence of an attractive force between the larger drops and smaller droplets, $U(D_0)$ will be reduced considerably, thereby allowing more time for interaction between the drop and droplets. Considering the collision between the drops as a classical two-body problem with charges Q_L and Q_S, it can be shown that $b \propto Q_L Q_s$ (*Upadhyaya*, 2010). It is quite conceivable that, because of the attractive force between the drops in the presence of an electric field the impact parameter b will increase. This clearly suggests that the droplet which would have just grazed the large drop in the neutral condition, will now come inside the collision cross-section of the colliding system, thereby guaranteeing a collision. A laboratory investigation suggests, if two electrified drops collide, inherently, they will coalesce (*Ochs and Czys*, 1987). The force law between two charged spherical conductors (the drops can be considered as spherical conductors) in a uniform external electric field can be found in (*Davis*, 1964) which shows that the external field always produces a force of attraction between the drops independent of the charge the drops carry. The equation of motion for the drops incorporating the external electric field can be found in earlier literature (*Schlamp et al*., 1976,1979). They reported that the collision efficiency of highly charged drops might be up to two order magnitude higher than the neutral drop pair of the same size. The force of attraction acts to increase the number of droplets in the volume swept out by the large collector drop per unit time, thereby increasing the collision efficiency. A numerical calculation of collision efficiency indicates 3 order magnitude higher collision efficiency for the charged drops than the neutral ones (*Khain et al*., 2004). It has been observed that colliding drops inherently coalesce upon collision if they are subjected to an electric field of 25 kV m^{-1} (*Jennings*, 1975). Electric fields of this magnitude are common in both electrified clouds and in thunderclouds. The experiment of *Lord Rayleigh* (1879) suggests that if the colliding drops are charged with same polarity, they will experience repulsion and suppress coalescence, particularly if they are of the same size. This is a viable scenario in weak electric field condition. But in a real situation of collision-coalescence inside the cloud, the collector drops are always larger than the collected droplets. The larger drops generally carry more charges (for example, the Rayleigh limit, *Rayleigh*, 1882) than the droplets in an external electric field. Hence the larger drops may induce charge of the opposite sign in the droplets when they are at the closest distance of approach, exceeding the effect of the initial charge on the droplets and thereby guaranteeing an attractive force favorable to coalescence.

Measurement of Surface Electric Field:

The presence of a fair weather downward directed electric field of approximate magnitude 130 V m^{-1} produced by the potential difference between the ionosphere and Earth surface is well known (*Chalmers*,1967; *Harrison*, 2011). This fair weather field gets disturbed when clouds form overhead because of the internal charging mechanism of the cloud. Among many earlier suggestions, the well-accepted charging mechanism is the non-inductive process, in which the collision between ice particles with larger size graupel particles in the temperature regime -10^{o}C to -25^{o}C, the supercooled regime, is considered as the primary mechanism (*Takahashi*,1978; *Saunders et al.,* 1991). This internal charging mechanism produces a tripole structure (*Williams*, 1989) inside a strongly electrified cloud as shown in the schematic diagram 2(a). A field of magnitude as large as 4×10^5 v m^{-1} (*Winn et al*., 1975) has been observed inside strongly electrified clouds. Numerous surface measurements of electric field below lightning-producing-clouds suggest the presence of a vertical electric field (upward or downward directed) (*Chauzy and Soula*, 1987; *Chauzy et al*. 1991; *Pawar et al*., 2002). The vertical electric field at the surface $E(z)$ below a strongly electrified cloud is a superposition of fields produced by the main negative charge center residing above the melting layer (Figure 2a) and the space charge in the sub-cloud layer (*Pawar and Kamra*, 2002). The polarity of the surface field changes according to the prevailing electrification processes inside the cloud depending upon its convective state. Although, the actual magnitude of the field produced by the charge centers inside the cloud may not be reflected at the surface as the ions produced by corona discharges at the ground can limit the actual magnitude of the field, It has been observed that the strength of the surface field remains coupled with the charging processes in and above the main negative charge center (*Standler et al*.,1979; *Soula and Chauzy*,1991). The present study is primarily focused on the effect of the cloud electric field on the raindrop size, rather than on the cause of the cloud electrification.

The AEO has been established in Pune, India, to study the electrical properties of clouds. In the year 2008, a few measurements of surface electric field have been carried out using a locally fabricated a. c. field mill which records the vertical component of the atmospheric electric field at the surface. More details about the electric field mill can be found in *Chalmers* (1967). Five traces of surface electric field have been selected for analysis from all the measurement for which simultaneous raindrop size distributions (RDSDs) were also available to check for an anticipated relationship between the two observables. All 5 electric field traces have been shown in Figure S2 in the supplementary materials. The observed discontinuities of the field are caused by lightning discharges. These discharges reduce the cloud electric field, and charging processes operating inside the cloud build the field to the breakdown threshold in a time determined by the prevailing cloud dynamical and microphysical state.

Measurement of Raindrop size and Rain rate:

With the measurement of cloud electric field at the surface, the simultaneous measurement of RDSD has been carried out with a collocated optical disdrometer. The disdrometer is a laser-based optical system for measurement of all types of precipitation particles. The instrument consists of a laser emitter at one end which produces a horizontal beam of light of wavelength 650 nm along with a receiver at the other end. The precipitation particles passing through the laser beam block off a portion of the beam which corresponds to their diameters. The resultant reduced voltage at the receiver is the measure of the particle size. By measuring the blocking off time of the laser beam by the precipitation particle, the particle’s fall speed can also be determined. Liquid precipitation is measured in the size range from 0.2-8 mm while solid precipitation is measured in the size range from 0.2-25 mm (*Löffler-Mang and Joss*, 2000). The validation studies for this disdrometer can be found in *Tokay et al.*,(2013). Also, see the supporting Figure S1. Among the 5 events, for some events the data were collected with a time resolution of 10 seconds while for the others, data were available in every 30 seconds.

The RDSD can be expressed as a three-parameter gamma distribution (*Ulbrich*, 1983)

$$N(D) = N_0 D^{\mu} e^{-\lambda D} \qquad (9)$$

where, $N(D)$ ($m^{-3}\,mm^{-1}$) is the number of drops per unit volume per unit size interval, $D(mm)$ is the diameter, N_0 is the intercept parameter ($mm^{-1-\mu}\,m^{-3}$), μ is the shape parameter and λ (mm^{-1}) is the slope of the distribution.

From the measured RDSD, the Mass-weighted Diameter (MWD) of raindrops can be derived as the ratio of the fourth to the third moment of the distribution.

$$\mathrm{MWD} = \frac{\int_{\mathbf{D_{min}}}^{\mathbf{D_{max}}} \mathbf{D^4 N(D) d(D)}}{\int_{\mathbf{D_{min}}}^{\mathbf{D_{max}}} \mathbf{D^3 N(D) d(D)}} \qquad (10)$$

Here, D_{max} and D_{min} are the maximum and minimum drop diameters for a given RDSD.

The derived values of MWD have been compared against the measured value of electric field for all the events individually to investigate their anticipated relationship.

The association between Electric Field and raindrops size:

In the strongly electrified cloud, cloud/raindrops can be visualised as particles moving and interacting with each other between two electrodes, a high voltage field in between (Figure 2a). Hence, an electrical influence on the interacting drops and smaller droplets has been anticipated. The analytical framework presented above predicts an increase in the size of the drops and droplets as the magnitude of the field increases. To investigate this matter, a scatter plot representation of MWD as a function of the surface electric field has been shown in Figure 3 (a-e). For all the 5 events considered here, the MWD and magnitude of the surface electric field have been averaged over two-minute time intervals. Some rain events lasted for 30-45 minute, while others are of relatively long duration of 3-4 hours. Both the observables are observed to be associated with a varying degree of correlation coefficient ranging from $r = 0.48 - 0.70$. These 'r' values are calculated with 'p' values < 0.05. The highly scattered nature of MWD is expected (as observed) as the MWD may also get affected by many other meteorological parameters like wind speed, liquid water content of cloud, updraft and downdraft along with the other prevailing microphysical processes. Considering so many sources of variability, this observed correlation between the two observables can be considered as significant. It should be also noted that melting of larger size graupel particles associated with the electrification of the cloud also can produce larger raindrops at the surface, but in that case, the observation of larger raindrops at the surface is expected to lag the rise in surface electric field as the raindrops will take around 7-10 minutes to reach the ground from the melting layer depending upon the prevailing updraft /downdraft and the vertical development of the storms. In the present observation, the increase in the electric field and drop size are observed to be concurrent for all the events. A lead/lag correlation analysis with a lag time of 10 minutes shows no correlation between electric field and the raindrop size. Although with 4-6 minutes lag time, we observe slightly better correlation for 3 events out of five. The concurrent and time-lag (4-6 minutes) correlation between the two observables suggests that an increase in cloud electric field could influence the growth of raindrops from the surface up to the melting layer.

The enhancement in rain intensity:

The numerical simulation study of *Khain et al*. (2004) suggests a faster conversion of cloud water to rainwater if the drops are electrified as compared with the uncharged cloud. Rain intensity can be derived from the disdrometer measured RDSD using the equation

$$\boldsymbol{R = 10^{-3}\frac{\pi}{6}\rho_w \int_{D_{min}}^{D_{max}} v(D) D^3 N(D) d(D)} \quad (11)$$

Where, R is the rain rate (mm hr^{-1}) and $v\ (D)$ is the fall velocity (m sec^{-1}) of a drop of diameter D.

As a vertical electric field is present below a cloud to make the raindrop sizes larger as evident from Figure 3, a valid assumption can be made that, the electric field present inside a strongly electrified cloud will also enhance the growth of raindrops through efficient conversion of cloud water to rain water. This size modification also should reflect on the rain intensity as suggested by the equation (11). To verify this expectation, we have superimposed the rain intensity on the time evolution plot of the surface electric field for an event observed on 1st Septembers, 2008 over the AEO in Figure 4(a). It has been observed that a rise in rainfall intensity is preceded by a peak in the magnitude of the surface electric field with time intervals of 2-5 minutes. This delay can be accounted for by considering that to increase the rainfall amount, a substantial number of raindrops should fall to the ground from inside the cloud where the raindrops grow in general. With a fall speed of 10-15m/sec, which may be considerably modified by the updraft/downdraft linked with cloud dynamics, from a height of

2-3 km, the raindrops will take 2-5 minutes to reach the ground. To quantify the microphysical changes caused by the electric field, two time intervals (T1 and T2) are selected as shown in Figure 4(a). T1 is preceded by a lower magnitude of the electric field while T2 is preceded by a higher magnitude of the surface electric field as can be seen from the Figure. From T1 to T2, the rain intensity is observed to increase by 156%. Figure 4(b) depicts the two RDSDs averaged over intervals T1 and T2, respectively. Clear evidence depicts the presence of a higher number concentration of larger drops (> 2mm) while the medium-size drops in the range 1-2 mm get reduced, suggesting an enhanced coalescence of raindrops. It is also observed that the 156% of enhancement in the rain intensity is a result of a 45% increase in raindrop size and 15% increase in raindrop total number concentration. So, the electric field induced rain enhancement can be treated as size-controlled.

Discussion:

After a long-standing speculation for almost 150 years, here we present the first observational evidence from the measurement at the Earth's surface that the natural cloud electric field can enlarge raindrops, supported by analytical evidence. The mechanism proposed is enhanced condensation and collision-coalescence growth facilitated by the cloud electric field. The electrification of cloud particles through artificial ionization has been observed to increase the daily rain amount by 24% (*Harrison et al.*, 2020). Here, it is observed that the vertical electric field below or inside a strongly electrified cloud can electrify the raindrops through polarization and enhance the rain intensity substantially by producing larger raindrops. We are aware of the fact that the electric field measured at the surface does not necessarily reflect the actual magnitude of the field inside the cloud overhead, but it is well known that measurements at the surface remain coupled with the prevailing charging processes overhead (*Standler and Winn*, 1979). The measurement advanced in this paper can be treated as a 'proof of concept' regarding the influence of electric field on the coalescence properties of raindrops, built on the backdrop of extensive laboratory investigation. A direct projection of these results to the cloud microphysical processes inside clouds may not be linear in general. But, this new insight may be useful for developing an accurate microphysical tendency equation in numerical weather/climate models for the simulation and the forecasting of heavy rainfall events.

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Figure Caption:

Figure 1: The theoretical growth rate of a 1 μ m cloud droplet by condensation growth in a saturation ratio 1.01 at a temperature 273K assuming a 2.3×10^{-17} C charge on the droplet in an external electric field 4×10^{5} V m^{-1}. The blue curve represents a neutral droplet while the red curve corresponds to a droplet in an external vertical electric field.

Figure 2: (a) Schematic representation of the charge structure of a strongly electrified cloud. The collision process of polarized raindrops in the presence of an external electric field $E(z)$ below the melting level is shown. 'CBH' indicate cloud base height. The electric field is shown vertically upward for representation purpose only. (b) The Collision geometry of two colliding drops of diameter D_L and D_S. 'b' is the impact parameter of collision.

Figure 3: Scatter plot representation of Mass-weighted diameter (MWD) of raindrops as a function of surface-measured electric field below the cloud at the Atmospheric Electricity Observatory, Pune (AEO). The labeling is the same as Table S1. The 'r' indicate the correlation coefficients with 'p' values <0.05. Both the observables have been averaged over two minutes interval during the rainy periods for all the events.

Figure 4: (a) Time evolution of rain rate during a storm on 1 September 2008 , superimposed on the surface measurement of electric field observed over the Atmospheric Electricity Observatory(AEO), Pune. (b) The raindrop size distribution (RDSD) averaged over the time intervals T1 and T2 as shown in (a). N(D) is the number of drops per unit volume per unit size bin.

Figure 1.

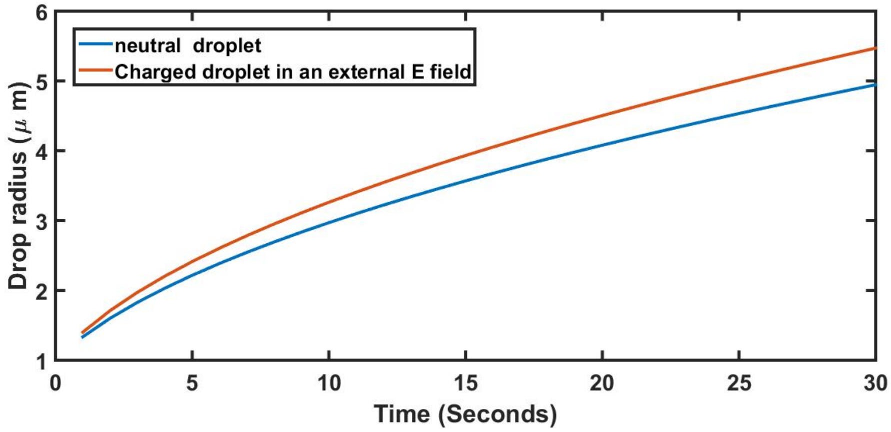

neutral droplet
Charged droplet in an external E field
Drop radius (μ m)
Time (Seconds)
0
5
10
15
20
25
30
1
2
3
4
5
6

Figure 2.

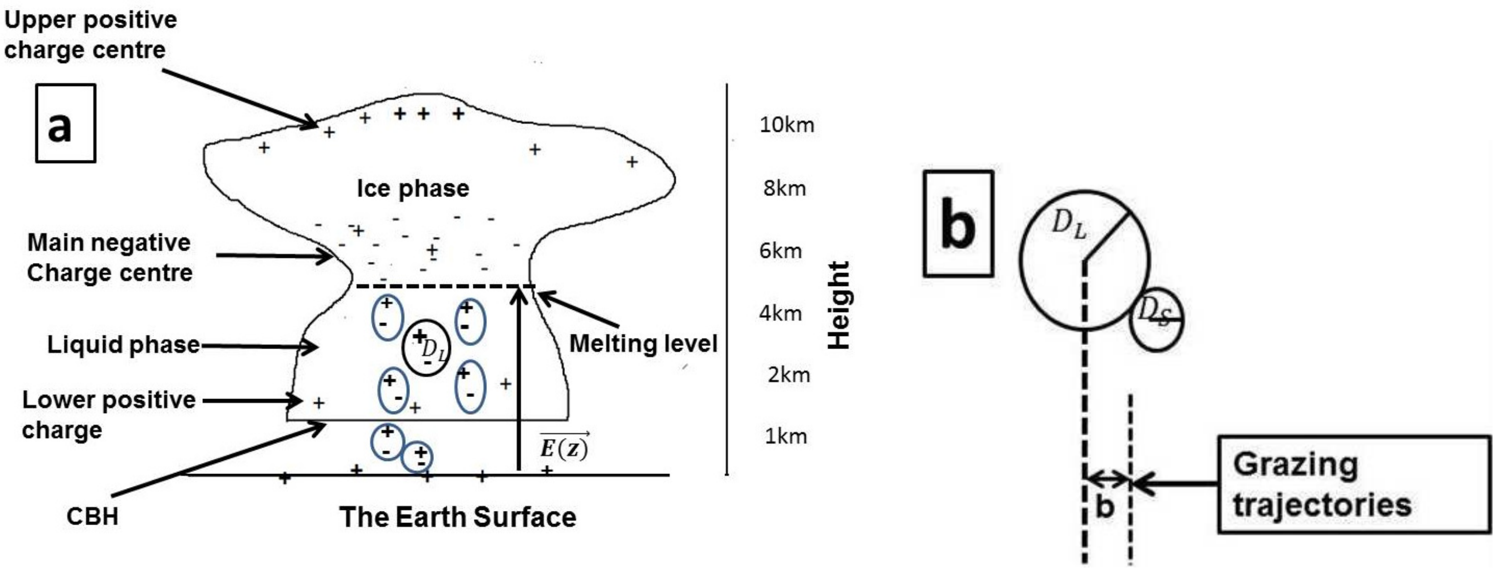

a
Upper positive charge centre
Ice phase
Main negative Charge centre
Liquid phase
Lower positive charge
CBH
The Earth Surface
Melting level
D_L
$\overrightarrow{E(z)}$
10km
8km
6km
4km
2km
1km
Height
b
D_L
D_S
b
Grazing trajectories

Figure 3.

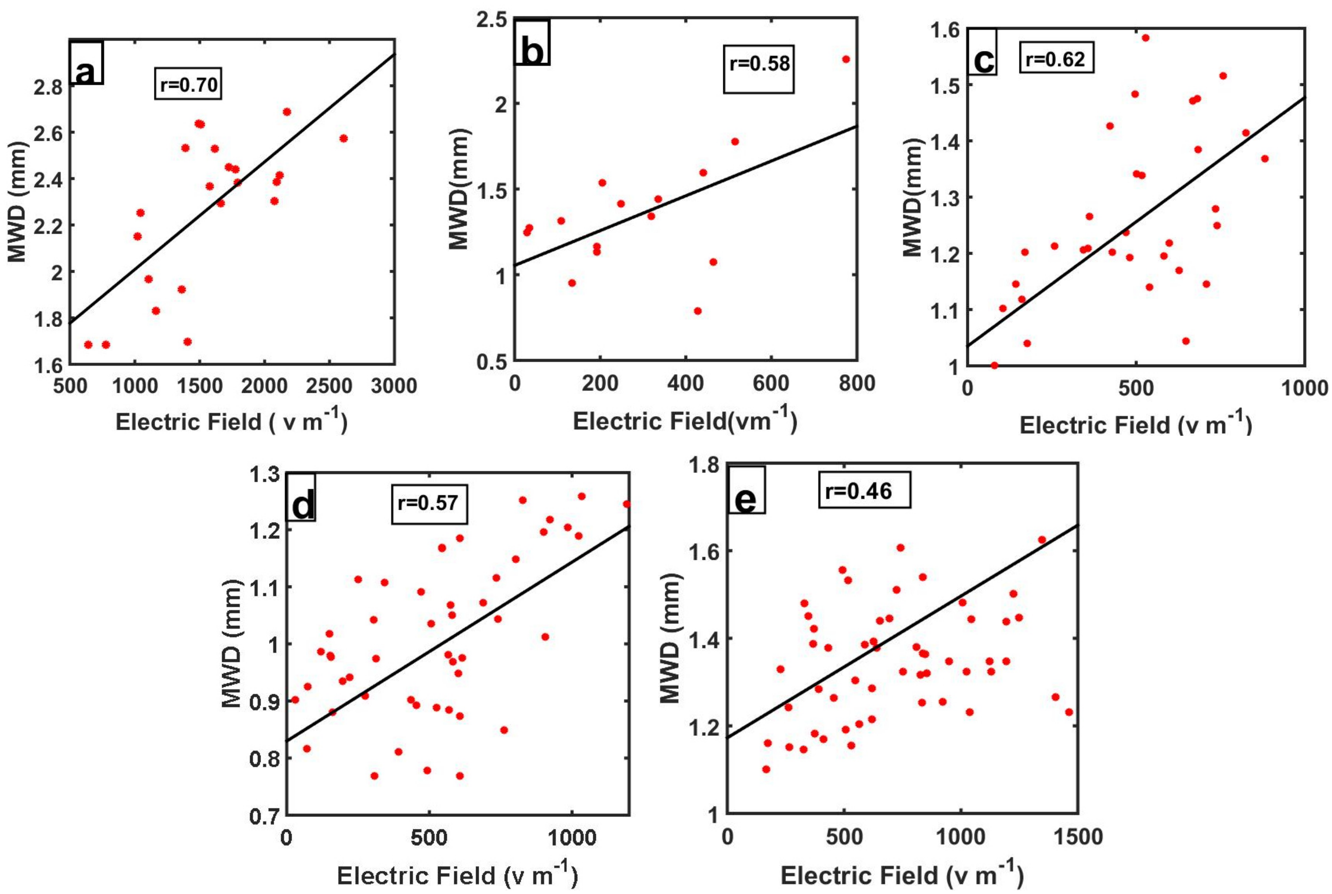
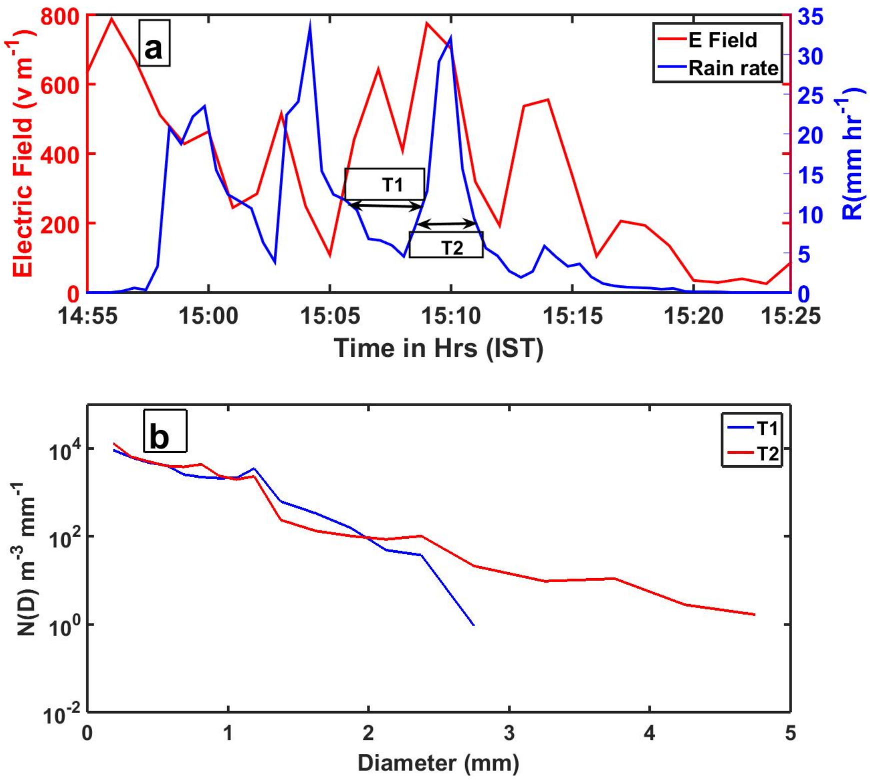

a
r=0.70
MWD (mm)
Electric Field (v m^{-1})
b
r=0.58
MWD(mm)
Electric Field(vm^{-1})
c
r=0.62
MWD(mm)
Electric Field (v m^{-1})
d
r=0.57
MWD (mm)
Electric Field (v m^{-1})
e
r=0.46
MWD (mm)
Electric Field (v m^{-1})

Figure 4.


a
E Field
Rain rate
Electric Field (v m^{-1})
R(mm hr^{-1})
T1
T2
Time in Hrs (IST)
b
T1
T2
N(D) m^{-3} mm^{-1}
Diameter (mm)