

The Collection Efficiencies of Highly Charged Water Drops for Uncharged Cloud Droplets

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ABSTRACT

Experiments have been conducted to investigate the collection efficiencies of highly charged drops with radii from 60 to 120 μm for relatively uncharged droplets of about 20 μm radius. The measurements indicate that, for drop charges approaching the Rayleigh limit value, the collection efficiencies are increased by a factor of around 20–30 over those for uncharged drops. The high collection efficiencies imply that a highly charged drop is capable of collecting uncharged droplets initially situated at distances of several drop radii from the fall trajectory of the drop.

Calculations utilizing a simple numerical model for the interaction of a drop and droplet pair demonstrate that these high values of collection efficiency are due to the electrical forces of attraction arising between the drop charge and the dipole induced within the uncharged droplet.

The implications of this work for the modification and dissipation of warm clouds and fogs are briefly discussed.

1. Introduction

Considerable interest from two points of view centers around the question of whether electric forces are capable of significantly modifying the growth rate of precipitation within clouds. First, on the basis of their observations, using radar, of precipitation development in New Mexico thunderclouds, Moore and Vonnegut (1960) estimated that for precipitation to grow at the recorded rate, the values of the droplet collection efficiencies must have been 4–10 times greater than the accepted values pertaining to non-electrified clouds. While this claimed causal relationship between cloud electrification and rapid precipitation development has been challenged by Brazier-Smith *et al.* (1973), further discussion by Moore and Vonnegut (1973) has left a situation in which the possibility of rainfall development being influenced by electric forces in clouds may be regarded as neither proven nor disproven.

Vonnegut and Moore (1960) advanced the theory that a lightning discharge introduces a large quantity of charge into the cloud opposite in polarity to the droplet charges in that region. These ions may very rapidly charge the nearby droplets to close to their Rayleigh limit and these droplets would be driven outward by forces of mutual repulsion. Coalescence with several other oppositely, and much lesser, charged droplets may follow, leading to drops large enough to grow thereafter by collection and eventually precipitate out of the cloud.

Some “best estimates” of collision efficiencies including the influence of charges and fields from zero to those found in mature thunderstorms have been made by Sartor (1970) and incorporated into calculations of the instantaneous mass accretion rates of the full range of cloud drop and raindrop sizes, an embryonic hailstone, and two larger hailstones. These calculations imply that the instantaneous mass growth rate of the particles may be speeded up by more than an order of magnitude by electric forces when all the particles involved are less than about 100 μm in radius. Thus it seems that these electric forces may have a crucial role to play in accelerating the growth of cloud droplets if we are to account for the development of precipitation at the greatly enhanced levels observed in mature thunderstorms. One point concerning the generation of the intense electric fields found in developed thunderstorms is that the electrically enhanced coalescence of drops and droplets could set a limit on those cloud charging processes which require the interaction and subsequent separation of such particles.

Second, there is a great deal of interest in the possibility that the artificial introduction of electrically charged particles may provide a means of enhancing the dissipation of fogs—particularly at temperatures above the freezing level for which satisfactory techniques do not exist. Accordingly, laboratory experiments were planned to investigate the efficacy of electric forces in promoting drop coalescence and to delineate the conditions under which charged particles might be useful in stimulating the development of clouds and the dissipation of warm fogs. The studies

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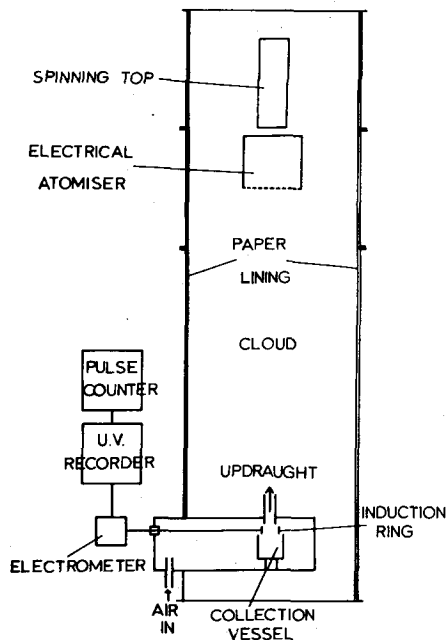


FIG. 1. Schematic diagram of the apparatus.

reported here were aimed at investigating the interactions of highly charged drops and neutral cloud droplets.

2. Experimental arrangement

The apparatus utilized for these studies is shown schematically in Fig. 1. In these experiments, a stream of highly charged pure water drops was introduced into a cloud of droplets produced by the atomization of a sodium chloride solution containing 0.25 kg of salt per kg of solution by means of an air-driven "spinning-top," similar to that devised by May (1966). This system was capable of generating almost monodisperse droplets in the size range 5 to 30 μm radius dispensing up to 1 g of solution per minute. It was very difficult to achieve 100% relative humidity throughout the entire experimental volume and therefore droplets of pure water would undergo considerable size changes in the course of an experiment. The use of saline solution droplets permitted humidities of around 80–90% within which range small changes in humidity did not appreciably influence the equilibrium droplet sizes. The drops and droplets were contained within a vertical column 2 m in length comprising a number of sections of aluminum tube 0.5 m diameter with welded flanges which were bolted together. In order to maintain the relative humidity within this column at the desired level, the walls of these tube sections were lined with moistened blotting paper.

The streams of charged drops were produced by means of a technique described by Vonnegut and Neubauer (1952) for generating monodisperse highly charged drops of pure water or salt solutions. The

equipment, which is shown schematically in Fig. 2, consisted basically of a fine capillary needle of size 29 s.w.g. having a bore of approximately 100 μm connected to a reservoir of water arranged so that the head of liquid was sufficient to give a very slow flow from the capillary tip. A wire connected to a high-voltage supply was inserted in the liquid so that potentials up to 30 kV could be applied. Above a critical voltage of about 12 kV, determined empirically for a given experimental system, a fine stream of drops all carrying positive charges approaching their limiting value was ejected from the needle tip. A Faraday cage system was employed so that, once the drops had passed through the mesh, neither the drops nor the droplets were influenced by the high potentials applied to the needle. The close proximity of the mesh to the needle also allowed lower voltages (~ 6 kV) to be applied than for the case of an "isolated" needle. Using this arrangement, it proved possible to generate steady streams of essentially monodisperse drops with radii from about 50 to 150 μm and carrying charges of between 70 and 80% of their Rayleigh limit values at rates of 100–200 per second.

In the initial series of experiments, a physicochemical method of collecting the drops and droplets, similar to that described by Farlow (1956), was utilized. This technique employed a clear 35 mm film base coated with polyvinylalcohol (PVA) which had been sensitized by means of a solution of silver nitrate and hydrogen peroxide and was capable of distinguishing between saline and pure water drops. Droplets as small as 5 μm radius were readily measurable by this

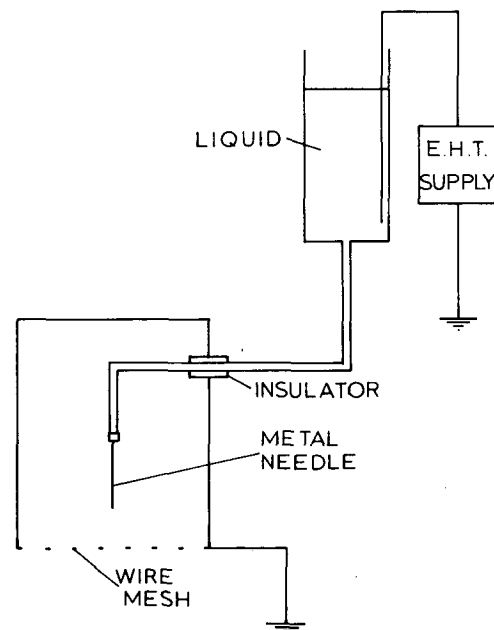


FIG. 2. Schematic diagram of the electrical atomizer for producing highly charged drops.

process, in which permanent crater-like impressions were produced by water drops landing on this material and distorting the water-soluble coating. The silver nitrate, buffered with hydrogen peroxide, was added to the plastic coating to promote a precipitation reaction between the chloride ions in the saline drops and the silver. The resultant silver chloride precipitated only within the bounds of the droplet spread on the film. By photochemically reducing the silver chloride to colloidal silver with a high-intensity sun lamp, strong color differences were produced between the distilled water and the saline drops. Trials of this technique demonstrated its ability to distinguish readily those drops which had collected droplets from those which had not. A device for transporting the coated film through the experiment sampling region was required and was constructed from a laboratory construction kit.

3. Experimental technique

A typical experiment began by setting up the electrical atomizer to give the desired drops by carefully adjusting the flow rate and the potential applied to the liquid from the high-voltage power supply. The air supply to the spinning-top was then turned on and the pressure regulator adjusted to give the required rotational speed. Initially, pure water was fed to the top from a pressurized bottle at a rate of about 5 g min^{-1} for about 20 min and served to saturate the tube with water vapor. Toward the end of this period, the film transport was mounted in the tube and set in motion at the appropriate speed. At this point, the change from pure water to saline solution was effected and the flow of liquid to the top was reduced to about 1 g min^{-1} to ensure a greater degree of droplet monodispersity than at the higher flow rate. The experiment was then continued under these conditions with all the systems operating undisturbed. The time at which the conditions became stable enough for meaningful measurements to be made was readily noted after the experiment by studying the distribution and sizes of droplets on the sensitive film.

In principle, the experiment could continue for an indefinite length of time but, unfortunately, there appeared to be a limitation to the production of droplets of saline solution by the spinning top. The spinning top atomizer, which is described in detail by May, consists of a rotating conical top, or rotor, mounted in a static section, or stator. The rotor is supported and driven at high speeds by means of air forced through angled holes in the stator. Liquid, fed to the upper surface of the top through a centrally positioned hypodermic needle, is flung from the edges forming a cloud of droplets. Since the rotor is of smaller diameter than the stator, the air, after leaving the top, clings to the stator surface and is vented from the system. By arranging a shielding plate

around the spinning rotor, a slight suction exists between the rotor edge and the plate which serves to extract the smaller satellite droplets generated during the atomization process. However, when saline solution was atomized, these satellite droplets evaporated extremely rapidly in the undersaturated air supplied to the top thus building up a crust of salt on the stator. This crust eventually interfered with the operation of the top and effectively limited the period of operation with saline solution to around 30 min.

At the end of the experiment, a change to pure water at a flow rate of about 5 g min^{-1} was made in order to partially clean the top. The experiment was then completely shut down and the spinning top was removed in order to clean away any remaining salt.

The drops and droplets settled at differing rates and were replicated upon the coated film. Thus the proportion of drops which captured droplets could be determined by examination of the replicas on the film. Also, the number concentration and sizes of the droplets could be obtained from the film and, knowing the relevant equipment parameters, be related to cloud liquid water content.

4. Preliminary results

Although the PVA film coating proved a very sensitive indicator of the presence or absence of salt within a drop, it provided only a qualitative indication of the quantity of salt and therefore gave a poor analysis of those situations where the drops had made multiple collections of droplets. In all the films analyzed, virtually all the drops had undergone multiple collections as a result of a combination of long fall-path length, high droplet concentrations, and high values of collection efficiency. Several remedies were tried without success.

The drop fall-path length was considerably reduced but the origin of the fall-path near the electrical atomizer was not clearly defined and therefore further reduction led to larger errors in this measurement.

The flow rate of solution to the spinning-top could not be reduced further since the needle which fed the solution to the surface of the top tended to become clogged at low flow rates.

In order to obtain a crude estimate of collection efficiency, a comparison film was made upon which drops produced from solutions of known salt concentrations were deposited. Drop replicas from these films were then compared with ones from experimental films to allow estimates to be made of the number of droplets captured. In this way, it was found that the drops generally collected between about 10 and 30 droplets in passing through clouds for which the drops might have been expected to collect not more than one drop each solely under the influence of hydrodynamic forces. Thus the indications were that these highly charged drops had collection efficiencies

TABLE 1. Results of the experimental measurements.

	Case 1	Case 2	Case 3	Case 4	Case 5
Initial drop radius R (μm)	116	66	72	85	85
Droplet radius r (μm)	22	20	22	18	23
Final drop radius (μm)	144	114	115	132	118
Number of drops	850	601	215	776	551
Conductivity of water (μS)	136	87	39	145	68
Number of droplets per drop	131.7	148.5	106.8	291.7	83.7
Number of droplets collected for $E = 1$	5.6	3.3	2.4	8.5	2.1
Corrected experimental collection efficiency	19.1	25.1	27.1	21.4	28.1
Calculated collection efficiency	17.2	28.6	28.0	20.2	24.8
r/R_{mean}	0.169	0.222	0.234	0.165	0.225

due to electric forces more than an order of magnitude greater than their normal values. It was decided that a revised experimental method was required to permit more accurate measurements to be made.

5. Revised experimental technique

The electrical conductivity of a salt solution is an extremely sensitive measure of the concentration of salt within that solution: a single grain of salt added to a beaker of distilled water changes its conductivity by a factor of 4 or 5. Thus an experimental technique based upon this relationship was utilized.

A number of drops were collected in a clean beaker after they had passed through the droplet cloud and the beaker was then carefully rinsed out with distilled water and the electrical conductivity, and mass, of these washings measured. The conductivity measurements were obtained by utilizing a standard commercially-available conductivity cell. The concentration of salt in the washings was found from the conductivity by means of a graph drawn from the results of a separate experiment in which the conductivities of solutions of known salt concentration were measured. The total number of droplets which had been collected by the drops could be calculated from the concentration of salt in, and mass of, the washings from the collection vessel once the droplet radii were known. The radii of both drops and droplets were established during the course of an experiment by replicating samples of them on short sections of PVA coated film.

The drops entering the collector were counted by means of an induction ring coupled to an electrometer. On passing through the induction ring, the high charges on the drops provided clear pulses which were amplified by the electrometer and recorded upon a U.V. recorder and a pulse counter.

The drops passed through a short tube prior to entering the collection vessel and an updraft was passed through this tube of sufficient velocity to prevent the droplets from reaching the collector solely under the influence of gravity. The efficacy of this system was established in separate experiments which

demonstrated that negligible numbers of droplets were collected in the absence of the stream of drops.

One disadvantage of this technique was that independent measurements of the liquid water content of the cloud had to be made. Separate experiments were therefore conducted in which the cloud liquid water content was measured by a filtration technique and related to the rate of feed of solution to the top and the size of the droplets produced. Values of cloud liquid water content were typically in the range $4\text{--}8\text{ g m}^{-3}$. These subsidiary experiments also indicated that only two-thirds of the solution fed to the atomizer appeared as cloud droplets, the remaining one-third being lost to the tube walls and the spinning top supporting structure.

6. Results and calculations

The results of the experiments carried out are shown in Table 1. The total number of droplets collected and hence the mean number of droplets collected per drop was established using the known relationship between conductivity and salt concentration. The final drop radius was calculated on the assumption that each drop collected the mean number of droplets, in order to give some estimation of the mean drop growth.

The number N of droplets of radius r which each drop of radius R might be expected to collect in falling a distance L assuming a collection efficiency E of unity was calculated from

$$N = \pi(R+r)^2 \left(\frac{V_R - V_r}{V_R} \right) nLE, \quad (1)$$

where n is the concentration of droplets per unit volume, with V_R and V_r being respectively the drop and droplet fall velocities. The experimental collection efficiency value is thus the mean number of droplets per drop divided by N . However, this value will only be true if the drop radius R has not increased significantly in passing through the cloud; actually, in each of the experiments, the mass of droplets collected exceeded the drop mass. A corrected collection efficiency was therefore calculated by using the mean

value of the collection kernel $(R+r)^2(V_R-V_r)/V_R$ in (1).

It may be noted that the collection efficiency tends to increase for increasing values of the ratio of droplet to drop radius, as might be expected; drops and droplets of more nearly equal sizes are more susceptible to the influence of electric forces since their lower relative velocities provide more time for these forces to operate.

It was apparent from the high values of collection efficiencies found in these experiments that the electric forces had little difficulty in ensuring the coalescence of closely approaching drops and droplets. In order to attain these values, the charged drops must be capable of collecting all droplets initially situated at distances of several drop radii from their fall trajectories. In an attempt to estimate the distances over which the trajectories of droplets might be influenced by highly charged drops, a simple model of the interaction of a drop and droplet was devised.

The droplet experiences forces due to its small but finite charge q and also due to the charges induced in the droplet by the presence of the much larger charge Q on the drop. The simple Coulomb force between drop and droplet, a distance l apart, is given by

$$F_c = \frac{Qq}{4\pi\epsilon_0 l^2} \tag{2}$$

It was assumed that the charges induced in the droplet by the drop could be approximated to a simple dipole consisting of an image charge Q' situated a distance a from the droplet center and a compensating charge Q'' at the center where

$$Q' = \frac{r}{l}Q, \quad a = \frac{r^2}{l}, \quad Q'' = -Q'$$

The attractive force between the drop and droplet due to this dipole is given by

$$F_D = \frac{Q^2 r}{4\pi\epsilon_0 l^3} \left[\frac{1}{(l-a)^2} - \frac{1}{l^2} \right] \tag{3}$$

At large separations ($l > 2r$) this equation agrees with more exact solutions, which take multiple images into account, such as that of Davis (1964). For separations $< r$, Eq. (3) increasingly underestimates the attractive force, for example, by about two orders of magnitude for a separation of $r/100$. The errors inherent in this and other approximations will be discussed subsequently. The net attractive force acting on the droplet is thus the sum of Eqs. (2) and (3).

Clearly, the charges upon the droplets could have an influence upon the observed collection efficiencies and, accordingly, subsidiary experiments were conducted in which the droplet charge distribution was measured by a technique involving the deflection of

the fall-paths of the droplets by a horizontal electrostatic field. It was found that the droplets were predominantly negatively charged with a mean charge of 0.17 fC and an upper quartile mean charge of 0.27 fC per droplet. A few charges as high as 0.5 fC were also recorded. Taking droplet charges within the observed range, it was calculated that the force of attraction due to the induced dipole exceeds that resulting from simple Coulomb attraction for all drop droplet separations less than about 1000 μm , the disparity increasing rapidly as the separation decreases.

The model assumes that the droplet velocity relative to the drop is simply the algebraic sum of the terminal velocities of the drop and droplet together with an additional velocity component arising from the electrical attraction. It was assumed that this velocity component v was related to the electrical force F by Stokes law and is therefore given by the equation

$$F = kv + m \frac{dv}{dt}$$

where k is a constant and m is equal to the droplet mass. For a small time increment Δt during which the droplet velocity changes from v to $v + \Delta v$, this expression may be rewritten as

$$F = 0.5k(2v + \Delta v) + m\Delta v/\Delta t \tag{5}$$

Utilizing (2), (3) and (5), trajectories of droplets approaching the drop may be calculated numerically for a variety of initial conditions.

The results of the computation of droplet trajectories for one drop and droplet combination are illustrated in Fig. 3. It may be seen from this diagram that there is a critical value X_c of the X coordinate, for a given set of initial conditions, within which a droplet must be situated if it is to be captured by

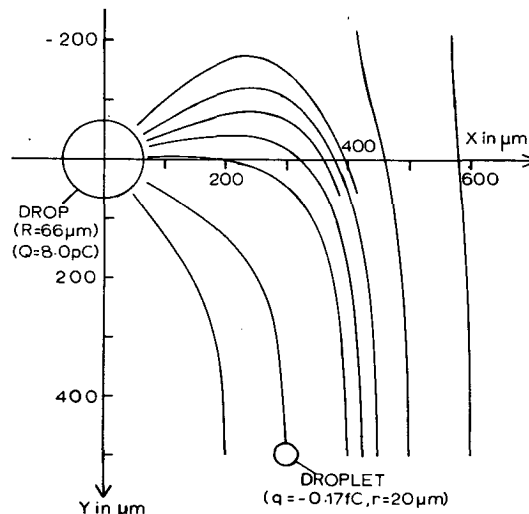


FIG. 3. Calculated droplet trajectories relative to a passing highly charged drop.

the passing highly charged drop. The mean value of the droplet charges was taken in the above case; using the maximum observed charge only increased the value of X_c by about 2%, with uncharged droplets giving a reduction of similar magnitude.

As the droplet approaches the drop, the electrical force of attraction becomes so large that the simple Stokesian expression increasingly overestimates the corresponding droplet velocity. This factor is of greatest significance for that region of the critical trajectory where the vertical component of the droplet velocity relative to the drop is equal to zero. However, subsidiary calculations indicate that the error in X_c arising from these non-Stokesian drag forces does not exceed a few percent for the situations investigated. As the droplet approaches beyond this region to within a few tens of micrometers of the drop, capture of the droplet is assured. Overestimation of the droplet approach velocity due to the use of Stokes law and due to the fact that no account is taken of the repulsive forces arising from the compression of the air film between the drop and droplet surfaces is, at least partially, offset by the underestimation of the electrical attraction by the dipole approximation mentioned previously and, in any case, serves only to precipitate the inevitable coalescence. Taking all sources of error into account, it is estimated that the model is capable of providing values of X_c for the experimental situations given in Table 1 with an error of less than about 10%. The calculated values of collection efficiency E included in the table are given by

$$E = \frac{X_c^2}{(R+r)^2}$$

Further calculations suggest that, for charges approaching the Rayleigh limit value, the collection efficiency for any given drop-droplet combination is approximately linearly proportional to the charge upon the drop.

7. Discussion

It has been demonstrated both experimentally and with a simple theoretical model that the presence of high charges on drops can have a profound influence upon the drop capture cross section for relatively uncharged cloud droplets. For drop charges approaching Rayleigh limit values, this influence extends to several drop radii giving collection efficiencies over 20 times greater than the values pertaining to uncharged drops. Furthermore, these electrical effects become more pronounced as both drop and droplet radii are reduced and their ratio approaches unity.

The applicability of this mechanism to the "rain-gush" hypothesis suggested by Vonnegut and Moore is, of necessity, speculative. However, we might rea-

sonably expect the maximum charges acquired by the drops in regions around the lightning channel to be given (in SI units) by

$$Q = 12\pi\epsilon_0 E r^2.$$

This expression, from Ladenburg (1930), has been verified experimentally by Abbas and Latham (1967) for drops in an electric field with ions of only one sign of charge present. The Rayleigh limit charge (in SI units) is given by

$$Q_R = (56\eta r^3)^{1/2} \times 10^{-5},$$

where η is the surface tension of the drop; we may, therefore, derive an expression giving the ratio of the two charge values for a given drop size:

$$\left(\frac{Q}{Q_R}\right)^2 \approx 2 \times 10^{-11} \frac{E^2 r}{\eta}.$$

If we take the maximum field strength in these regions to be of the order of 10^6 V m^{-1} , then the maximum charge which may be acquired by a drop of $50 \mu\text{m}$ radius is about 10% of its limiting value. While charges of this magnitude are not capable of providing the dramatic increase in collection efficiencies noted in the experiments, they may nevertheless lead to a significant enhancement of the drop growth process assisted appreciably by the fact that the droplets in the surrounding regions will generally carry opposite, though lesser, charges.

Clearly, more results are required before a definitive assessment of the applicability of electrically charged drops to fog modification can be undertaken. However, it is apparent that drops of around $100 \mu\text{m}$ radius, when carrying charges approaching their Rayleigh limit values, are capable of capturing all cloud droplets situated within a cylinder of several times the drop radius. If we assume that a drop of $66 \mu\text{m}$ radius, as shown in Fig. 3, would sweep out a column of $400 \mu\text{m}$ radius through a natural fog, then we may show that 250 liters of water distributed evenly in the form of highly charged drops would be capable of clearing a fog $1000 \text{ m long} \times 100 \text{ m wide} \times 100 \text{ m deep}$.

The distribution of charge in this manner would, however, give charge densities of some $2 \times 10^{-6} \text{ C m}^{-2}$, leading to electric field intensities within the fog of around $5 \times 10^5 \text{ V m}^{-1}$. If electric fields of this magnitude were attainable then they would doubtless have a profound influence upon the fog regardless of the effect of the individual charged drops. However, attempts to introduce unipolar charge densities of this order would meet with severe engineering difficulties since the high local fields generated around the dispensing system oppose the production processes, as suggested by Smith (1972) and observed in the experimental research program reported by Loveland

et al. (1972). Some of the problems associated with the dispensing of charged particles into the atmosphere have been discussed in detail by Vonnegut *et al.* (1967). Since the effect of electric charge upon drop collection efficiency is independent of the sign of the charge, these problems may be overcome by dispensing equal numbers of droplets carrying opposite signs of charge as would be necessary in any case when operating from an electrically isolated system such as an aircraft. It is perhaps worth emphasizing that the high values of collection efficiencies noted in this paper are a consequence solely of the high charges present upon the drops and do not require the presence of either an electric field or charges upon the captured droplets; clearly, however, the presence of an electric field or significant charges of opposite polarity upon the droplets would result in even higher values of collection efficiencies. Thus, in principle, the introduction of highly charged drops should be capable of significantly modifying the development of warm clouds and fogs.

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