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Formation of an Electric Charge in a Melting Layer of a Nimbostratus Cloud

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ABSTRACT: The paper presents a model of electric charge generation in precipitating clouds due to breaking of large particles in low melting layer. The Earth's electric field polarizes the droplets and they break into small negatively charged and large positively charged fragments. A negatively charged cloud region is formed below melting layer. The charged region induces a field, which increases both polarization of the breaking droplets and rate of charge generation. An equation is derived to describe spatial and temporal variability of the electric field, which depends on size spectrum of hydrometeors and vertical draft velocity.

The model yields an exponential growth of the electric field strength to 10^5 - 10^6 V/m after 15 min of raining at a rate of more than 10 mm/h. The major condition for that is a downdraft with a velocity of 0.5 - 1 m/s within the melting layer. The maximum field strength in clouds is found at $+2^0$C level where lightning strokes to aircraft are observed most frequently.

INTRODUCTION

The majority of theoretical models describe processes in cumulonimbus clouds. Models dealing with nimbostratus clouds are few and (like, for example, a model by Imyanitov and Chubarina, 1965) more of a qualitative nature. They do not offer any reliable quantitative estimates of the observed effects.

However, the electric charges are being generated not only in Cb but also in Ns clouds (Brylev et al., 1989). Moreover, about 80% of the electric discharges to the aircraft occur in Ns clouds. This is not an indication of a large electric activity of Ns clouds but, rather is a result of the fact that any flying in vicinity of the cumulonimbus clouds is prohibited because of strong vertical drafts inside them.

A PHENOMENOLOGICAL DESCRIPTION OF THE PROPOSED MODEL

Precipitation particles form from the water vapour mainly in the cold part of the cloud. Then, the ice particles (snow flakes, snow aggregates, graupel pellet) fall down into warm area and turn into droplets thus forming a so called melting layer. Its vertical extension is several hundred metres.

A distance covered by a falling ice particle before its total melting is approximately proportional to a cubic root of the particle mass (Kochin, 1994). In the low melting layer the largest ice particles will be transformed into largest droplets. Drops which diameter exceeds 4 mm are unstable and tend to break into a large number of smaller droplets. The process is as follows. A droplet with an initial diameter of 4-5 mm grows to 40-50 mm, transforming its shape to that of parachute. Then the parachute top breaks into a large number of small droplets, while its bottom yields a few large ones (Mason, 1971). If the ice particle spectrum contains crystals, which produce drops exceeding 4 mm in diameter, these drops will break. The

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radar observations have proved droplet breaking in the low melting layer in Ns and Cb (Kochin, 1994).

A rain droplet in the electric field behaves as a conducting sphere and polarises in response to electric field strength. This is why breaking of a large droplet in the electric field produces electrically charged fragments (Mason, 1971). The upper part of the break droplet transforms into small droplets with electric charges, which sign corresponds to that of the vertical component of electric field. The lower part of the droplet transforms into large droplets with charges of the opposite sign.

Usually the vertical component of the Earth's electric field is negative, so the small and large drops will be charged negatively and positively, respectively. The values of the forming charges are proportional to the field strength (Mason, 1971).

The partitioning of the charges occurs due to different falling velocities of the carriers of charges of different signs. Since the velocities of small droplets are smaller, their concentration in the vicinity of the melting layer will be much greater than concentration of the large droplets. Thus, a negatively charged region forms there.

As the distance from the melting layer increases, the concentration of small droplets declines. This results in a relative growth of large droplet concentration and inception of a positively charged region at some distance below the melting layer.

Initial large droplets break in the Earth's electric field (~150 V/m) and then the drop fragments (small and large droplets) leave the layer where the drops are breaking. After that, the electric field in this layer is controlled by interaction of negatively charged small droplets and positively charged large droplets. The small droplets induce a field which sign coincides with that of the Earth's field; a contribution of small droplets into the resulting field will be greater since they are closer to the droplet breaking layer. Hence, the electric field strength in that layer grows up. The value of the breaking charge is proportional to the field strength. Thus, a positive feedback arises which will lead to a continuos growth of the field strength because each subsequent portion of droplets breaks in a stronger electric field and produces a larger charge than the previous one.

QUANTITATIVE ESTIMATES OF ELECTRIC FIELD STRENGTH GROWTH

The above description of a charge generation mechanism presents only the basics of the proposed model. In order to give quantitative estimates one needs to derive an equation describing the charge generation process with an account of the affecting factors, i.e. vertical and horizontal extension of the droplet breaking layer, ice particle size distribution, vertical draft velocity within the melting layer, etc.

The amount of charge on a hemisphere resulting from polarization of the conducting sphere in the electric field equals to

$$q = 3\pi\varepsilon_0 r^2 E \tag{1}$$

where ε_0 - is the dielectric constant of vacuum, r is the sphere radius, E is the field strength. As the sphere disintegrates, its fragments are being charged. The total charge of fragments is determined by (1). The experimental studies of breaking of large unstable droplets in the electric field have shown (Muchnik, 1974) that (1) is applicable to the rain drops. This is because a charge emerging from the drop breaking does not depend on the droplet conductivity and is in a good agreement with (1), providing r is 0.025 m.

Let us assume that: a) a shape of the droplet breaking region is a vertical cylinder with number of breaking droplets N(h,t) in each horizontal intersection being independent of the distance from the cylinder axis, and b) the electric field strength, E(h,t), is constant within the horizontal intersection. The top of the cylinder will be taken as zero elevation with the positive axis directed downward. The Earth surface in this co-ordinate system corresponds to height H_E.

A charge dq is generated within a layer dh at a height h during time interval dt

$$dq = 3\pi^2 \varepsilon_0 r^2 R^2 N(h,t)E(h,t)dhdt \qquad (2)$$

where r is the drop radius just before breaking, see (1), R is the cylinder radius, N(h,t) is a number of breaking droplets in a unit volume per second, E(h,t) is the strength of electric field. In accordance with the assumptions a) and b), two disks are formed which move at different velocities, namely V_s (velocity of gravitational sedimentation of negatively charged small droplets plus vertical draft velocity) and V_l (velocity of gravitational sedimentation of positively charged large droplets plus vertical draft velocity), and carry charges of different signs. The charge surface density in the disk equals the charge value (see (2)) divided to the disk square.

Arrived at height h at a curtain time T will be the charged disks which have formed t time early than T ($T-h/V_{s,l} < t < T$) at the height $h - V_{s,l}$ (T-t) (subscripts s and l points to different deposition velocities of small and large droplets, respectively). Thus

$$\sigma(h,T) = 3\pi\ r^2 \varepsilon_0 dh \left\{ \int_{T-h/V_s}^{T} N\left[h - V_S(T-t), T-t\right] E\left[h - V_S(T-t), T-t\right] dt - \right.$$
$$\left. - \int_{T-h/V_l}^{T} N\left[h - V_l(T-t), T-t\right] E\left[h - V_l(T-t), T-t\right] dt \right\} \qquad (3)$$

where σ(h,T) is the surface charge density at height h at time T. The first and second integrals in (3) describe contributions of charged disks with small and large droplets, respectively.

The strength of field induced by a disk at its axis

$$E(h) = \frac{\sigma}{2\varepsilon_0}\left[1 - \frac{h}{(h^2 + R^2)^{0.5}}\right] \qquad (4)$$

where σ is the electric charge surface density, h is a distance from the disk to a point at the axis where the electric field is being determined. Electric field strength induced by the disk at the same distance h within a disk, equal in square and parallel to it, differs from (4) by several percent. This is why one may accept assumption b), and the electric field strength E(h,t) can be presented as a superposition of fields of all charged disks and the Earth's field.

The relations (3) and (4) yield an expression for the field strength E(H,T) at any height H ($0 < H < H_E$) at a given time T

$$-\frac{3\pi\ r^2}{2}\int_0^H dh\left[1-\frac{h}{\left(h^2+R^2\right)^{0.5}}\right]\times$$

$$\times\left\{\int_{T-h/V_S}^{T} N\left[h-V_S(T-t),T-t\right]E\left[h-V_S(T-t),T-t\right]dt-\right. \qquad (5)$$

$$\left.-\int_{T-h/V_l}^{T} N\left[h-V_l(T-t),T-t\right]E\left[h-V_l(T-t),T-t\right]dt\right\}+E_0$$

The first term in the right-hand side of (5) determines a contribution of the charged disks, located between level H and the level of Earth's surface H_E, while the second term describes effect of the upper disks; E_0 is the Earth's field strength.

The relation (5) has been investigated with numerical simulation methods which requires description of function N(h,t), i.e. number of breaking droplets at height h at a moment t.

The dN ice particles with diameters ranging from d to d + dd pass through area S on the top of cylinder during dt time period

$$dN = N(d)\ \ V_{sn}(d)S\ \ dt\ \ dd \qquad (6)$$

where d is an equivalent diameter of ice particle (diameter of a droplet of equal mass), N(d) is a differential size distribution of ice particles at zero isotherm level, $V_{sn}(d)$ is ice particle deposition velocity. The dN(h) droplets break at height h within interval dh during time dt

$$dN(h)dh = N\left[f^{-1}(h),t\right]\ V_{sn}\left[f^{-1}(h)\right]\frac{d}{dh}\left[f^{-1}(h)\right]\ Sdtdh \qquad (7)$$

where f(d) is a path of an ice particle until it melts entirely, while f(h) is a function inverse to f(d). Ice particle distribution was given in accordance with Rogers (1976) in the form

$$N(d) = 2500I^{-0.94}\exp\left(-2.29I^{-0.45}d\right) \qquad (8)$$

where N(d) is a differential size distribution of ice particles, $mm^{-1}\cdot m^{-3}$, I is precipitation intensity, mm/h, d is an equivalent diameter of the ice particles, mm. Dependence of N(h,t) upon t manifests itself in the fact that there has been no precipitation (I=0) before zero time (T=0). The precipitation intensity used as a parameter in (8) definitely determines dependence of ice particle sedimentation velocity V_{sn} (d) upon size in the form

$$V_{sn}(d) = 0.84d^{0.31} \tag{9}$$

where d and V_{sn} (d) are given in mm and m/s, respectively.

The length of the path of a particle before melting (f(d) in relation (7)) is expressed as a linear function in accordance with Kochin (1994)

$$L(d) = 100d \tag{10}$$

where d and L(d) are given in mm and m, respectively.

Mean velocities of vertical motion of charges of different signs are defined as

$$V_s = V_z + V_{gs} \tag{11}$$

where V_s is mean velocity of small droplets, produced from breaking droplets, V_z is velocity of the vertical draft, V_{gs} is velocity of gravitational sedimentation of small droplets,

$$V_L = V_z + V_{gl} \tag{12}$$

where V_L mean velocity of large droplets, produced from breaking droplets, V_z is velocity of the vertical draft, V_{g1} is velocity of gravitational sedimentation of large droplets.

The values V_{gs} and V_{g1} in relations (11) and (12) are estimated at 0.5 m/s and 7 m/s, respectively. The basis is, that according to experimental data, the upper part of droplet breaks into 400-500 small droplets while the bottom yields 4-6 large drops (Muchnik, 1974). If a droplet is assumed to break into two halves and the fragments are approximately similar in size, the above mentioned figures for the mean velocity of gravitational sedimentation are inferred.

Problems arise in determining the value of R, which is a radius of a region of breaking droplets. This parameter can not be evaluated from airborne measurements of hydrometeor size spectra because one needs a sample scale of several kilometers to obtain statistically significant values of large cloud drop concentration. So, we employed data from Doppler radar observations of the melting layer.

The methodology of observations was as follows. A Doppler radar, operating at a small beam elevation angle, measured the horizontal wind component at the 0°C level. Then the radar beam changed its direction to vertical. The effect of breaking droplets manifested itself in a sharp peak in the vertical profile of the Doppler velocity. The time of peak persistence in the Doppler velocity profile was derived and size of droplet breaking region estimated using the measured horizontal velocity.

The size of these regions fell within a range of 100 to 500 m, so the model value of R was put at 150 m.

A numerical model for solving equations (5) with an account of (6)-(12) was derived, based on precipitation rate I and vertical draft velocity (see (11), (12)) as parameters.

The constants assumed the following values.

The Earth's electric field strength E_0 and r were taken to be 150 V/m and 0.025 m, respectively, as mean values inferred from the experiment (Mason, 1971). The vertical grid interval was chosen 0.5 m and the time resolution adopted to be 1 sec.

RESULTS OF NUMERICAL SIMULATIONS

The numerical simulations based on equation (5) show that in the course of time the vertical profile of the field strength assumes a complicated shape of varying sign, caused by the vertical extension of the droplet breaking layer. In general, the maximum field strength grows up as precipitation enhances. Depending on the vertical draft velocity the maximum field strength in the melting layer can either be a monotonous function of time or have an oscillating nature, with the charge generation rate reaching maximum in the downdrafts with velocities of 0.5 - 1 m/s.

Temporal variation of the maximum electric field strength E_{max} in a downdraft with a velocity of 0.5 - 1 m/s is perfectly described by (for I>5mm/h, t>60s)

$$E_{max} = 250\exp\left[0.01\frac{I^2-20}{I^2}t\right] \qquad (13)$$

where E_{max} is expressed in V/m, I is precipitation rate, mm/h, t is time, sec.

The results of numerical simulations have also shown that

i) within updrafts or weak (less than 0.3 m/s) downdrafts the electric field strength is about 300 - 3000 V/m, with the maximum values only slightly depending on precipitation rate and having a spatial and temporal variability of charge sign;

ii) maximum electric field strength is attained in a layer with temperature +2°C;

iii) when the downdraft velocity is 0.5 - 1 m/s the charge generation rate is the largest and electric field strength growth rate increases as precipitation enhances. In this case the electric field strength reaches values of 10^5- 10^6 V/m after 15 min of raining at a rate of 10-15 mm/h.

ON FEASIBILITY OF PROPOSED MECHANISM IN CB CLOUDS

Apart from others, the proposed mechanism is likely to contribute to electrification of Cb clouds as well. This belief is supported by the fact that the model also agrees with the experimental data on the electrical activity of the Cb clouds.

According to the model results, under a near zero updraft velocity the electric field strength attains a value of 300 - 3000 V/m with no further build-up of the electric field strength. In strong updrafts the electric field strength varies within a range -300 - +300 V/m. This corresponds to the observed values in the non-lightening convective clouds.

In order that the field strength, typical of the thunderstorm, is achieved, it is essential that the precipitation area coincides with the downdrafts.

Usually, an updraft concentrates in the centre of the thunderstorm while downdrafts occupy the cloud periphery. The lower part of the cloud converges the horizontal air currents as the upper part is a region of divergence. In accordance with the proposed model, the charges are to generate on the cloud's periphery. The area of charge generation, comprising individual cells, forms a narrow ring or a sickle. This phenomenon has been already discovered from the experiments (Williams, 1989) but failed to be explained theoretically.

Besides that, the following phenomena should be observed near the melting layer:

- a fast change of value and sign of the hydrometeor's charge;
- maximum values of charges on hydrometeors .

Both effects have been found during aircraft spiral descents on the periphery of thunderstorm (McCready and Proudfit, 1965).

Two-charge clouds are most frequent to occur, with positively charged upper parts and negatively charged middles (Mason, 1971). So, one may believe that positive charges are descending, captured by updraft and carried to the cloud top. A similar process is observed in Cb clouds during the hailstone growth, namely, the large rain droplets are carried to the cloud top. Studies of the hail clouds have shown (Muchnik, 1974) that the hailstone growth is accompanied by a strong radio emission, typical of the thunderstorm inception and development stages, a fact that supports this belief.

In 10-15 min from start of precipitation, the positive charges, captured by updraft, will reach the cloud top. By that time the field strength will build-up to 10^5 - 10^6 V/m, resulting in lightening activity development.

In case of a sharp enhancement of downdrafts in a precipitating cloud the change of electric field sign within the melting layer is possible. The reason is that at the early stage of development the field sign is oscillating, so an increase in charge generation rate can "fix" the sign of field, which existed at the moment of the downdraft enhancement. As a result, an opposite (as compared to described above) distribution of cloud charges emerges, something which has been proved by observation (Mason, 1971).

Naturally, the given qualitative speculations are more a hypothesis. An application of the proposed model to Cb requires further investigations.

OUTLOOK FOR FURTHER STUDIES

The described model, however, fails to account for several factors, which strongly affect the charge generation rate.

There is a process, similar to droplet breaking, taking place in the melting layer and capable of generating charges. The thing is that the peripheral branches of melting snow crystals subject to breaking off. If this process is taking place in the electric field, the charged fragments emerge, similar to charge partitioning during droplet breaking. However, this process has not been studied in detail and there are only preliminary theoretical estimates of its effectiveness. Based on these results, a quantitative estimation of electric field growth rate has been made from the model equation (5). It has been found that under exponential ice particle size distribution the crystal destruction provides a fast growth of the electric field up to 10^3 V/m and its further oscillations.

If the ice particle size spectrum is transformed to a monodispersal one, the described process can lead to field strength values of 10^5 - 10^6 V/m even in a light precipitation (about 1-3 mm/h). Another possibility is charge generation in precipitating winter-time warm frontal clouds. This situation can provoke formation of a thin layer with positive temperatures, resulting in the same effect as produced by a transformation of the particle size spectrum to a monodispersal one.

Besides, as soon as the electric field strength reaches 10^4 - 10^5 V/m, the smaller droplets become unstable and begin breaking, thus giving birth to additional charge carriers.

As the electric field strength exceeds 10^5 V/m, another factor comes into play, i.e. the electrostatic interaction becomes comparable with the aerodynamical drag effect. This can alter the falling velocity of charged droplets.

A detail analysis of these processes is the next stage in the proposed model improvement.

CONCLUSIONS

In conclusion, one has to mention that despite a satisfactory agreement between obtained theoretical results and the experimental data, special experiments are needed for model verification. The experiment should include registration of starting moment and rate of the droplet breaking (e.g., with radar methods) and measurements of electric field strength. Such an experiment will allow to conclude whether physical bases for the proposed model are correct.

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