Influence of Lower Positive Charge Region on Occurrence of Different Types of Lightning

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ABSTRACT: There is a controversy in lightning community regarding the origin and the role of the lower positive charge region in the cloud. Whatever the source of the lower positive charge, it is generally thought that it serves to enhance the electric field at the bottom of the main negative charge region and thereby facilitate the launching of a negatively-charged leader toward ground. On the other hand, the presence of excessive lower positive charge region may prevent the occurrence of negative cloud-to-ground discharges by ”blocking” the progression of descending negative leader from reaching ground. Based on the graph theory and percolation theory, we develop a fractal simulation code to take into account the detailed space and temporal dynamics of the cloud discharge, and the fine structure of the electric field and charge in a cloud. The results will be compared with observations to address some problems of lightning initiation physics. We quantitatively and qualitatively examine the dependence of lightning type statistics on the magnitude and lateral structure of the lower positive charge region.

INTRODUCTION

Processes in a TC are very diverse and complicated. A classical cloud to ground (CG) lightning discharge includes three stages: Preliminary breakdown, leader formation and return stroke [*Proctor et al.*, 1988; *Rakov and Uman*, 2003]. The existing theoretical models of lightning discharges are based on its similarity with a laboratory long spark. It actually relates to the leader formation and return stroke. But there is a very important difference, which concerns a preliminary stage of the discharge. In the case of a laboratory spark electrical charge is accumulated on a conducting wall(s) of a discharge space and flows down easily into the spark channel. It is not clear what mechanism could provide the electric charge gathering over all cloud volume (or over its considerable part) to the leader channel. Apparently a certain important process which supplies this gathering, takes place during the preliminary breakdown stage. In its most developed phase, preliminary breakdown stage lasts approximately one tenth of a second, and consists of numerous (up to 10,000) relatively weak discharges [*Proctor et al.*, 1988]. The experimental investigations have demonstrated several peculiarities at the preliminary stage, proving it to be a very complex and puzzling phenomenon. Assuming that the preliminary breakdown pulse train is a manifestation of interaction of a downward-extending negative leader channel with the lower positive charge region (LPCR), Nag and Rakov recently qualitatively examine the inferred dependence of lightning type on the magnitude of this charge region [*Nag and Rakov*, 2009]. We skip here the discussion of different hypotheses regarding the origin of the LPCR that were particularly reviewed by [*Rakov and Uman*, 2003].

INTRACLOUD ELECTRIC FIELD FINE STRUCTURE

It is common knowledge that the intracloud electrification process is extremely complex and intricate. Since charges of intracloud particles are the balanced sum of many unobserved random events, the central limit theorem (in its common form) provides a partial explanation for the prevalence of normal probability

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distribution. Therefore one may consider an ensemble of intra-cloud particles as a gas of point charges q with the following Gaussian charge distribution function

$$P(q) = \frac{1}{Q\sqrt{2\pi}} \exp\Big(-\frac{1}{2}\Big(\frac{q}{Q}\Big)^2\Big), \tag{1}$$

where $\langle q \rangle = f(z)$ changes with altitude z and $Q = \langle q^2 \rangle^{1/2}$ is the charge distribution mean square displacement[†]. We assume that the particles are uniformly distributed in space and the space charge density $\rho(\mathbf{r})$ corresponds to the spatial white noise that satisfies the following conditions:

$$\langle \rho(\mathbf{r}) \rangle = f(z); \; \langle \rho(\mathbf{r}_1)\rho(\mathbf{r}_2) \rangle = Q^2 n \delta(\mathbf{r}_1 - \mathbf{r}_2), \tag{2}$$

where n is the cloud particles concentration and $\delta(\mathbf{r})$ is Dirac delta function (the product $Q^2 n$ is the spatial white noise source intensity).

To reproduce the gross charge structure $f(z)$ of a "normal" thundercloud we consider a vertical tripole consisting of three charge layers, main positive at the top, main negative in the middle, and an additional positive below the main negative (see Figure 1). The magnitudes of the main positive and negative charges are typically some tens of coulombs, while the lower positive charge varies from zero up to $10C$.

CELLULAR AUTOMATON MODEL

Lightning modelling tradition approach [e.g., *Petrov and Petrova*, 1996; *Mansell et al.*, 2002] is based on the well-known consideration [e.g., *Niemeyer et al.*, 1984; *Wiesmann and Zeller*, 1986] where the self-similar structure of the discharge pattern is caused by features of an algorithm of Laplace fractal growth. The pattern grows stepwise. At each modeling time step only one bond is added to the pattern, linking a point of the pattern with a new point. That point is chosen randomly, given the following distribution of probability:

$$P(r_i) = \begin{cases} \frac{1}{Z}|E(r_i) - E^{\pm}_{cr}|^m, & \text{if } E(r_i) \geq E_{cr} \\ 0, & \text{if } E(r_i) < E_{cr} \end{cases} \tag{3}$$

where $E^{\pm}_{cr}$ are positive and negative streamer critical field, r_i $(i = 1, \dots N)$ represents the discrete lattice coordinates of the pattern peripheral points, electric field amplitude $E(r_i)$ is determined by the solution of discrete Poisson equation and

$$Z = \sum_{E(r_i) \geq E_{cr}}^{N} |E(r_i) - E^{\pm}_{cr}|^m. \tag{4}$$

Moreover, the geometry of space between the electrodes or the geometry of area with $E(r) > E_{cr}$ completely determine the typical size and configuration of a discharge pattern even in a weak super criticality case, $0 < (E - E_{cr})/E_{cr} \ll 1$.

We consider an electrical breakdown model which is principally different from the model outlined above [*Trakhtengerts et al.*, 2002; *Iudin*, 2003; *Trakhtengerts et al.*, 2003]. We are going to bring the idea that we can expect more adequate pictures on the development of discharge pattern if we change the above model in the two points. The first suggestion is that streamers could develop simultaneously in different pattern peripheral points. Secondly, we suggest that the probability of streamer development has

[†]One obtains the same result using either a homogeneous distribution $P(q) = \frac{1}{2\sqrt{3}Q}$ $-\sqrt{3}Q < q < \sqrt{3}Q$ or a binary one $P(q) = \frac{1}{2}\delta(q+Q) + \frac{1}{2}\delta(q-Q)$ instead of Gaussian charge distribution

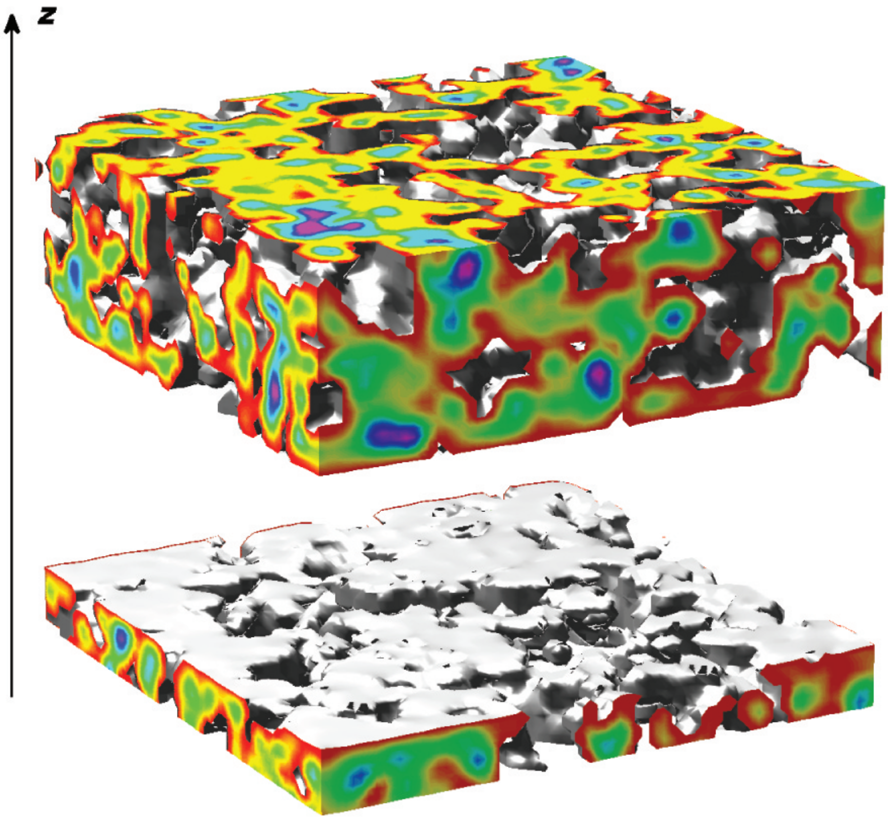

Figure 1: 3D model representation of the thundercloud gross charge structure $f(z)$ with spatial perturbations. Only positive charge is displaied: main positive at the top and an additional positive below the main negative (LPCR)

an essential anisotropy caused by the presence of a large-scale thunderstorm electric field. The first change is easily achieved by the use of the probability in the following Weibull form:

$$P(r_i) = \begin{cases} 1 - \exp\left\{ - \left| \dfrac{E(r_i) - E^{\pm}_{cr}}{E^{\pm}_{cr}} \right|^m \right\}, & \text{if } E(r_i) \geq E_{cr} \\ 0, & \text{if } E(r_i) < E_{cr}, \end{cases} \tag{5}$$

where m is Weibull's index. Note that for small overvoltages when

$$\left| \frac{E(r_i) - E^{\pm}_{cr}}{E^{\pm}_{cr}} \right| \ll 1, \tag{6}$$

this Weibullized form is transformed into the following simple form

$$P(r_i) \sim |E(r_i) - E^{\pm}_{cr}|^m, \tag{7}$$

which is similar to Eq.(3) and is extensively used in electric breakdown problems. The second change is closely connected to the first. The matter is that independent growth of various points of the pattern periphery pulls our problem together with percolation one [*Iudin*, 2003; *Hayakawa*, 2008].

RESULT AND CONCLUSION

The model discussed allows us to reproduce the lightning discharge patterns that may arise depending upon the magnitude of the LPCR. If the magnitude of the lower positive charge relative to the main negative charge is smaller than a quarter, the descending negative leader would traverse the positive charge region and continue to propagate in a predominantly vertical direction to ground. When the magnitude of LPCR is comparable in magnitude to that of main negative charge a descending negative part of discharge tree would likely change its direction of propagation to predominantly horizontal (see Fig. 2).

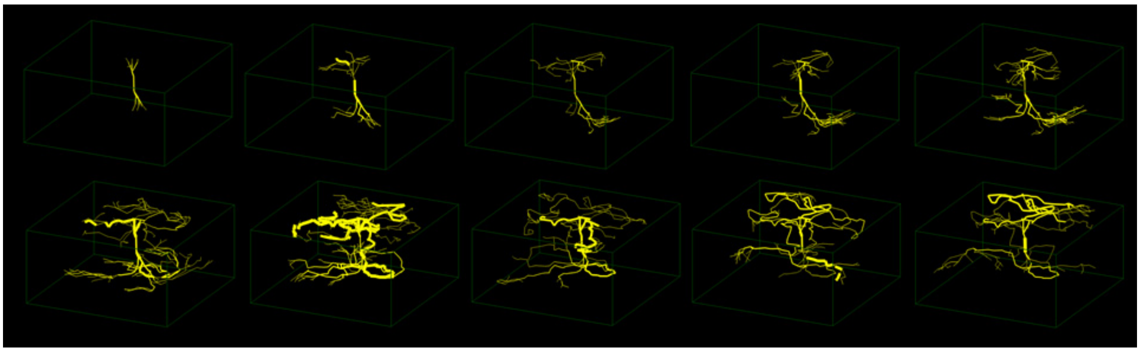

Figure 2: The model 3D lightning discharge pattern for the case when the magnitude of LPCR is comparable in magnitude to that of main negative charge

Our model reproduces four conceptual lightning scenarios that may arise depending upon the magnitude of the LPCR. These scenarios was recently suggested and qualitatively discussed in [*Nag and Rakov*, 2009].

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