Some inferences on the role of lower positive charge region in facilitating different types of lightning

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[1] It is generally thought that the lower positive charge region 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 and thus "converting" the potential cloud-to-ground flash to an intracloud (or cloud-to-air) one. 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, we qualitatively examine the inferred dependence of lightning type on the magnitude of this charge region. Citation: Nag, A., and V. A. Rakov (2009), Some inferences on the role of lower positive charge region in facilitating different types of lightning, Geophys. Res. Lett., 36, L05815, doi:10.1029/2008GL036783.

1. Introduction

[2] The gross charge structure of a "normal" thundercloud can be viewed as a vertical tripole consisting of three charge centers (regions), main positive at the top, main negative in the middle, and an additional positive below the main negative [Williams, 1989]. The magnitudes of the main positive and negative charges are typically some tens of coulombs, while the lower positive charge is probably 10 C or less. The negative charge region is apparently related to the −10 to −25°C (0 to −15°C in earlier studies) temperature range, while the lower positive charge is typically found just below the freezing level. Four different hypotheses regarding the origin of the lower positive charge region (LPCR) are reviewed by Rakov and Uman [2003, p. 88]. The LPCR can be associated with (a) graupel, which, according to the graupel-ice cloud electrification mechanism, charges positively at temperatures warmer than the reversal temperature, (b) positive charge deposited in the cloud by lightning, (c) corona at ground surface, and (d) positive screening layer at the lower cloud boundary. In this paper, we assume that the charge that is produced by corona at ground under thunderclouds and subsequently carried by updraft into the cloud is a significant contributor to the LPCR. Chauzy and Soula [1999] have provided a quantitative evidence (the other three hypothetical scenarios remain largely qualitative) for the corona origin. They estimated, from measurements and modeling, that a significant portion (some tens to few hundred coulombs) of positive charge produced by corona at ground level could be transferred to an altitude of 1000 m (the upper limit of their computational domain) over an area of 10 × 10 km² for the entire thunderstorm lifetime. Chauzy and Soula noted that some positive charge will be carried by updrafts from 1000 m to higher altitudes. They concluded that the corona-produced charge can account for the formation of the LPCR, as earlier suggested by Malan [1952].

[3] Whatever the source of the LPCR, it is generally thought that the LPCR serves to enhance the electric field at the bottom of the negative charge region and thereby facilitate the launching of a negatively-charged leader toward ground [e.g., Clarence and Malan, 1957; Ogawa, 1993; Tessendorf et al., 2007]. On the other hand, the presence of "excessive" lower positive charge in thunderclouds over the Tibetan Plateau has been reported to prevent the occurrence of negative cloud-to-ground discharges and facilitate intracloud discharges between the main negative and lower positive charge regions [Qie et al., 2005]. Thus, electric breakdown between the main negative and lower positive charge regions may result in either a cloud-to-ground (CG) or an intracloud (IC) flash.

[4] Bipolar pulse trains in wideband electric field records typically occurring a few tens of milliseconds (sometimes considerably less) prior to the first return-stroke pulse and having overall duration of a few milliseconds are often attributed to preliminary breakdown (PB) process [e.g., Brook, 1992; Heavner et al., 2002]. The amplitude of largest pulses in PB pulse trains can be comparable to or even exceed that of the first return-stroke pulse [Gomes et al., 1998; Schulz and Diendorfer, 2006; Nag and Rakov, 2009]. These pulse trains were studied by a number of researchers, including Clarence and Malan [1957], Beasley et al. [1982], Gomes et al. [1998], and Nag and Rakov [2009]. However, in many cases (at least in some locations, as discussed below) the first return-stroke pulse is not preceded by a detectable PB pulse train.

[5] Nag and Rakov [2008] have identified and examined electric field pulse trains that are characteristic of preliminary breakdown in negative CG discharges but are not followed by return-stroke waveforms. They attributed these trains to attempted cloud-to-ground leaders. Some of their attempted leaders could also be classified as "inverted intracloud flashes", occurring between the main negative and lower positive charge regions. In that case, the lower positive charge can be viewed as "blocking" the progression of descending negative leader from reaching ground and thus "converting" the potential CG flash to an intracloud (or cloud-to-air) one. The relationship between type of lightning discharge and cloud charge structure, with emphasis on blue and gigantic jets, was recently studied.

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Figure 1. (left) A schematic illustration (not to scale) of electric field enhancement and reduction effects of the lower positive charge region (+Q_{LP}) below the main negative charge region (−Q_{N}). The main positive charge region is not shown. Arrows indicate the direction of vertical components of electric field vectors. The total electric field is enhanced, (E_{N} + E_{LP}), between the negative and positive charge regions and reduced, (E_{N} − E_{LP}), below the positive charge region. (right, top) Schematic representation of preliminary breakdown stepping process in negative ground flashes. Negatively-sloped arrow indicates the overall downward extension of negatively charged channel through the LPCR. Three steps giving rise to current (and light) pulses are shown. Each current pulse originates at the tip of downward-extending channel and propagates upward (positively-sloped arrows). (right, bottom) A sketch of expected electric field record of resultant wideband PB pulse train.

by Kreibiel et al. [2008] (see also commentary by E. R. Williams on pp. 216–217).

PB pulse trains were observed to occur at the beginning of electrostatic field changes produced by stepped leaders [e.g., Beasley et al., 1982], which implies that, when they do occur, they have something to do with initiation of appreciable charge transfer. Beasley et al. [1982, Figure 26] reported that PB pulses in Florida were radiated between altitudes of 4 to 6 km and their VHF sources appeared to propagate downward, apparently from the lower boundary of main negative charge region toward and into the LPCR. Similar downward progression was also reported by Heavner et al. [2002]. Further, Schönland [1956], working in South Africa, attributed the initial (faster, brighter, and heavily branched) stage of the β leader, this initial stage being the same as the PB discussed here, to accumulations of positive space charge near the cloud base. Thus, it is likely that the PB pulse train is a manifestation of interaction of a downward-extending negative leader channel with the LPCR.

In this study, we examine variations in occurrence of PB pulse trains in CG flashes. Assuming that the PB pulse train is a manifestation of interaction of a downward-extending negative leader channel with the LPCR, we qualitatively examine the inferred dependence of lightning flash type on the magnitude of this charge region. The result is a set of conceptual scenarios that can be tested by future observations.

2. Analysis and Discussion

2.1. Generation of Preliminary Breakdown Pulse Train

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2.1. Generation of Preliminary Breakdown Pulse Train

Figure 1 (left) shows the vertical components of electric field vectors, E_{N} and E_{LP}, due to the main negative and lower positive cloud charge regions, respectively. Between the negative and positive charge regions, E_{N} and E_{LP} are in the same direction and hence electric field is enhanced due to the presence of the LPCR. On the other hand, in the region below the LPCR E_{N} and E_{LP} are in opposite directions and hence the field is reduced. It follows that a descending leader originating at the lower boundary of main negative charge region would be initially accelerated and then (after traversing the LPCR) decelerated due to the presence of the LPCR. This scenario appears to be consistent with description of β-type leader [Schonland, 1956], which exhibits a higher speed near the cloud base and a lower speed at lower altitudes (although it does accelerate near ground). The initial part of the β-type leader is associated with pronounced electric field pulses, which are the same as the PB pulses considered in this paper.

In the following, we assume that the PB pulse train occurs when a descending negative leader encounters a significant LPCR and continues to propagate through it in a primarily downward direction. The negative leader is stepped, and the presence of positive space charge along its path is expected to intensify the steps, compared to the case of stepping in the absence of ambient space charge. When the LPCR is small or absent, the initiation of negative leader is essentially not assisted by the LPCR (such initiation would generally require a stronger negative-charge source) and no appreciable pulse train is produced. In this view, the occurrence of pronounced PB pulse train can be used as a proxy of existence of significant LPCR.

The initial polarity of PB pulses in negative ground discharges is the same as that of the following return-stroke pulse. In effect, both types of pulses (negative return-stroke pulse and PB pulses) are due to a “recoil” process occurring when the negative leader channel comes in contact with ground (return-stroke pulse) or with progressively lower layers of the LPCR (PB pulses). Conceptually, the “recoil” process in the case of PB should be similar to the step-formation process optically observed in rocket-triggered lightning by Wang et al. [1999]. Based on this analogy, we schematically show in Figure 1 (right) the PB stepping process in the cloud and resultant electric field pulse train.

2.2. Variations in Occurrence of Preliminary Breakdown Pulse Train

Nag and Rakov [2008], who used an 8-bit measuring system in Gainesville, Florida, noted that PB pulse trains are...
Figure 2. (a) Percentage of flashes with detectable PB pulse train and (b) altitudes of the upper cloud boundary (UCB), the main negative charge region (assumed to be between the 0°C and −15°C isotherms), and the lower cloud boundary (LCB) [Rakov and Dulzon, 1984], each as a function of latitude. The altitudes are averages for the Northern Hemisphere in July, but assumed to be applicable, as a first approximation, to the Southern Hemisphere as well. Note that the lower percentage of flashes with detectable PB pulse train appears to be associated with higher altitude of main negative charge region above ground and vice versa.

detected prior to the first return-stroke pulse in only about 18% of CG flashes. On the other hand, Schulz and Diendorfer [2006], who used a 12-bit measuring system set up at an electromagnetically quiet site in Austria, reported considerably larger percentage of ground flashes showing PB pulse trains. In their data set, 89% of 92 negative multiple-stroke flashes and 71% of 94 negative single-stroke flashes (that is, 80% of 186 negative CG flashes) had detectable PB pulse trains. Further, Gomes et al. [1998] reported that essentially all electric field records of 41 negative CG flashes acquired in Sweden, contained detectable PB pulse trains, while the corresponding percentage for Sri Lanka was only 19%. It is important to note that the same instrumentation and methodology were used in both Sweden and Sri Lanka. Ogawa [1993] reported that 32 out of 89 (36%) CG flashes in Kyoto, Japan had electric field signatures indicative of PB pulse trains. Clarence and Malan [1957] found that out of their total 407 first-stroke electric field waveforms recorded at Johannesburg, South Africa, 16% were preceded by so-called “fast β-type leaders” (exhibiting pronounced PB pulses). They also observed “slow β-type leaders” that were characterized by small PB pulses and constituted 21% of their data set. If we combine both fast and slow β-type leaders, the percentage of flashes with detectable PB pulses in South Africa will be 37%. Recently, Makela et al. [2008] reported that at least 90% of CG flashes in southwest Finland exhibited PB pulse trains.

[12] Percentage of flashes with detectable PB pulse trains as a function of latitude is shown in Figure 2a and discussed next. If the PB pulse train were indeed an indication of the presence of a significant LPCR in the thundercloud, the detection of PB pulse trains in the majority of negative ground discharges in Sweden, Finland, and Austria compared to just about 20% of negative ground discharges in Florida and Sri Lanka, 16 to 37% in South Africa, and 36% in Japan could be interpreted as being due to the more frequent presence of a significant LPCR at higher latitudes than at relatively low ones. This could be due to more intense corona at ground (which we assume to be a significant, if not dominant, source of the LPCR) at higher latitudes. This hypothesis is consistent with the work of Chauzy and Soula [1999], who used measured electric fields and numerical modeling to estimate the amount of charge produced by corona during thunderstorms in Florida (lower latitude) and in southwestern France (higher latitude). The corona-produced positive charge at ground level over a 10 × 10 km² area varied from 63 to 124 C (94 C on average) in Florida and from 106 to 362 C (214 C on average) in southwestern France; that is, the average positive charge at the higher-latitude location was found to be more than twice larger than at the lower-latitude one (although the higher terrain is France could have also been a factor). Further, it is known that the height of the main negative charge region, shown to be between the 0°C and −15°C isotherms in Figure 2, above ground tends to be smaller at higher latitudes [e.g., Rakov and Dulzon, 1984], as seen in Figure 2b. This can increase electric field at ground and make positive corona production at ground more efficient (due to the cubic dependence of corona current on surface electric field) at higher latitudes.

2.3. Type of Discharge Versus Magnitude of Lower Positive Charge Region

[13] We now discuss four conceptual scenarios (shown in Figure 3, left) that may arise depending upon the magnitude of the LPCR when a negative leader channel extends downward from the negative charge region. Examples of expected electric field signatures for these scenarios are shown in Figure 3 (right). The field signatures were recorded in Gainesville, Florida, and interpreted as resulting from proposed scenarios, although no information on cloud charge structure was available.

[14] When the magnitude of LPCR is abnormally large, say, comparable in magnitude to that of main negative charge, as shown in Figure 3a (left), inverted IC discharges are expected to occur. This type of discharge bridging the main negative and abnormally large lower positive charge regions have been reported by Qie et al. [2005]. In this scenario, a descending negative leader would likely change its direction of propagation to predominantly horizontal [Coleman et al., 2008], interact with the LPCR, and be unable to forge its way to ground. The result is an inverted IC flash. VHF imaging presented by Tessendorf et al. [2007] indicates that the LPCR appears to be vertically deeper and to have a larger horizontal extent when such IC flashes occur. An example of expected electric field signature of such a discharge is shown in Figure 3a (right), which exhibits a PB pulse train followed by static field change some tens of milliseconds in duration, indicative of an inverted IC flash (attempted cloud-to-ground leader [Nag and Rakov, 2008]). If the lightning channel emerges from
the cloud, it can be viewed as an “air discharge” or even as a “spider” lightning, if it develops over a large distance near the cloud base.

[15] Figure 3b (left) shows the scenario where the magnitude of the LPCR is somewhat smaller than in scenario A. Similar to scenario A, a negatively-charged leader channel extending vertically from the main negative charge region would become predominantly horizontal, but would eventually make termination on ground. In this case, the discharge can be viewed as a hybrid flash (an IC followed by a CG). Such flashes (with IC durations ranging from a few tens to over 100 ms) were examined by Coleman et al. [2008]. The electric field signature expected for this type of discharge is shown in Figure 3b (right), which shows a PB pulse train followed by a field change characteristic of a cloud discharge lasting for about 50 ms, followed by the first return stroke waveform of a CG flash.

[16] If the magnitude of the lower positive charge relative to the main negative charge is even smaller, as shown in Figure 3c (left), the descending negative leader would traverse the positive charge region and continue to propagate in a predominantly vertical direction to ground. The electric field signature expected to be produced in this case is shown in Figure 3c (right). It exhibits a PB pulse train and stepped-leader waveform followed by the first return stroke (RS) waveform. Leader duration, found as the time interval between PB and RS, is about 20 ms. Negative stepped leaders that are characterized by very short (a few milliseconds) durations and, by inference, very high speeds ($\sim$10$^5$ m/s versus typical $\sim$10$^2$ m/s) also belong to this category. In this latter case, the lower positive charge is either entirely consumed by the negative leader or whatever remains of it is incapable of decelerating this leader. Very fast stepped leaders, which are probably associated with very strong negative-charge sources, were observed in different geographical locations, in different seasons, and both over water and over land [e.g., Clarence and Malan, 1957; Heavner et al., 2002; Frey et al., 2005]. In Florida, only about 5% of stepped leaders are shorter than 5 ms, suggesting that such very fast stepped leaders are relatively rare.

[17] Figure 3d (left) shows the scenario when the LPCR is insignificant. This scenario is similar to scenario C, except for the LPCR playing essentially no role in negative leader initiation. The electric field signature produced in this case is expected to be that of a stepped leader/return stroke sequence not preceded by a detectable PB pulse train, as shown in Figure 3d (right).

3. Summary

[18] We interpret the PB pulse train as being generated when a negatively-charged channel extends downward from the main negative charge region and encounters an appreciable LPCR. When the LPCR is small no PB pulse train may be produced. In this view, the fact that in some negative CG flashes no PB pulse train is detectable could be due to insignificant LPCR. It appears that at higher latitudes a larger percentage of CG discharges exhibit detectable PB pulse trains than at lower latitudes. This implies that a significant LPCR (or its portion originating from corona at ground) is present in thunderclouds more

Figure 3. (left) Schematic representation of four types of lightning, A–D, that may arise depending upon the magnitude of the LPCR. The charge configuration in each of the scenarios represents only its vertical profile (no lateral boundaries are shown). Arrows indicate the direction of propagation of negative leader. (right) The corresponding examples of expected electric field signatures. The field waveforms are from four different thunderstorms recorded at some tens of kilometers in Gainesville, Florida, using the same instrumentation with a decay time constant of 10 ms. PB = preliminary breakdown pulse train; RS = return-stroke waveform.
often at higher latitudes than at relatively low latitudes. While the LPCR may serve to enhance the electric field at the bottom of the negative charge region and thereby facilitate the launching of a negatively-charged leader toward ground, presence of excessive LPCR may prevent the occurrence of negative CG flashes by “blocking” the progression of descending negative leader from reaching ground. We infer four conceptual lightning scenarios that may arise depending upon the magnitude of the LPCR.

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References


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