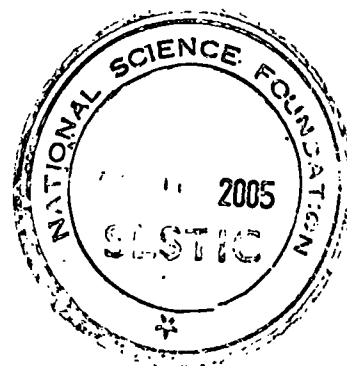




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What directs a lightning flash towards ground?

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Abstract

In this paper we attempt to show that the necessary condition to create a lightning ground flash is the generation of a vertical conducting channel below the main negative charge centre. The probability of such an event increases if frequent breakdown takes place between the negative charge centre and the lower positive charge centre (LPCC). Analysis of electromagnetic field signatures produced by ground flashes in Sweden show pronounced radiation during the preliminary breakdown process. Such strong pulses are rarely found in tropical thunderstorms in Sri Lanka. We attribute these signatures to preliminary breakdown between the main negative charge centre and the LPCC and argue that meteorological conditions which favour the production of strong LPCC's are more likely to be found at mid and high latitudes than in the tropics, thus explaining why there is a greater probability of lightning flashes striking the ground in these regions.

1. INTRODUCTION

It is the general consensus that the fraction of lightning flashes that strike the ground in the tropics is much less than the corresponding figure in temperate regions (Prentice and Mackeras¹; Price and Rind²). The common explanation given for this observation is that the higher freezing levels associated with the lower latitudes lead to a lower probability of flashes to ground since the ground is more distant from the charge centres.

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However, a simple calculation is sufficient to show that the ground cannot significantly influence the magnitude of electrostatic fields within the cloud, regardless of whether they are located at a height of 7 km, as in the tropics, or when they are at a height of 4 km, as in temperate regions. If this is the case, what is the reason for having a larger percentage of ground flashes in temperate regions than in the tropics? We believe (and a comparison of electric fields from lightning in tropical Sri Lanka and temperate Sweden seems to suggest) that the amount of charge in the lower positive charge centre may play an important role in determining the probability of lightning striking the ground.

2. THE INITIATION MECHANISM OF GROUND FLASHES

Electric field measurements at ground level and within thunderclouds indicate that there are three main charge centres in the cloud - an upper positive charge centre, a negative charge centre located in the middle and a small positive charge pocket close to the 0° C isotherm, generally associated with precipitation (Simpson and Scrase³, Williams⁴) at the base of the cloud. To initiate a lightning flash, electrical breakdown should occur in the cloud (unless, of course, the lightning is initiated by a grounded structure). The space averaged maximum field values measured in the clouds are in the range of 2×10^5 V/m. Though these fields are not strong enough to cause breakdown in air at the heights at which clouds form, the presence of water drops and ice does seem to decrease the breakdown strength in the cloud environment to an extent sufficient for these fields to initiate electrical breakdown. It is reasonable to assume that these maximum fields occur at the outer boundaries of the charge centres, and especially in regions facing the opposite charge centres.

When electrical breakdown takes place in the cloud it leads to the formation of a conducting channel. When this is exposed to an electric field, the resulting accumulation of opposite charge at the ends of the channel causes the channel tips to propagate in opposite directions. This is known in the literature as bi-directional propagation. The necessary charge accumulation at the tips of the channel for this propagation to occur is created in the channel itself under the influence of the electric field. In the absence of conducting electrodes, bi-directional propagation is the most probable mechanism for the generation of a propagating discharge. In the case of lightning initiation, one end of the conducting channel grows toward the opposite charge centre and the other end grows either into or around the mother charge centre. This is the preliminary stage of a lightning discharge. Whether the final outcome will be a ground flash, a cloud flash or a premature end of a

discharge process will be decided by the location of the preliminary breakdown channel and the amount of charge available in the charge centres.

When the electric field between the main negative charge centre and the positive charge pocket leads to electrical breakdown, one end of the discharge channel grows into the negative charge centre and the other grows towards the positive charge pocket. The orientation of this channel will be determined by the relative location of the two charged regions. If the positive charge pocket is located below the negative charge centre, the channel will grow more or less in a vertical direction. When this channel reaches the positive charge pocket, neutralisation of the charges takes place. Once this neutralisation is complete, a vertical conductive channel is left behind in the air.

Our calculations show that the field enhancement caused by a conductor of length 100 m and of 1 cm diameter (hemispherical capped cylinder) is a factor of 32. If the length is 1 km instead, the field enhancement factor goes up to 36. At 5.5km, the air pressure is half the value at ground level thus essentially the breakdown strength of air also reduces by half. Consequently, a 1-km long conductor needs a background field of about 50 kV/m to initiate electrical breakdown at its ends. The presence of water drops may decrease the value of this critical field even further. Now, fields of the above magnitude are not uncommon in a thundercloud environment. Thus, after neutralisation of the positive charge pocket, the conducting channel may continue to grow along the direction of the ambient electric field. If the positive charge was originally located below the negative charge centre, the channel grows downwards toward the ground. This leads to a ground flash. However, if the preliminary breakdown takes place between the upper part of the negative charge centre and the positive charge at the cloud top, an intra-cloud flash could be the final outcome. Thus, a necessary condition for the initiation of ground flashes is the creation of a vertical conducting channel in air below the negative charge centre.

The probability of this process occurring increases with the presence of a lower positive charge pocket directly below the negative charge centre. In such situations electrical breakdown between the two charge centres leads to an approximately vertical conducting channel. The higher the concentration and the amount of charge in the positive charge pocket, the larger is the probability of breakdown between it and the negative charge centre. This leads to a larger percentage of ground flashes. Thus, the lower positive charge pocket may play a major role in the development of a ground flash.

We hypothesize that the low percentage of ground flashes in the tropics compared to middle and high latitudes is due to the LPCC in tropical clouds being too weak (in comparison to those in temperate clouds) to play a dominant role in initiating ground flashes. There are other indirect observations which may be used to make a case for the hypothesis we have presented here. Whenever a thundercloud is mature enough to produce electrical activity, the first few lightning flashes it creates are confined inside the cloud. It

seems that, at these times, the triggering mechanism necessary for ground flashes is absent. The reason could be the absence of a sufficiently strong LPCC. With the build up of a LPCC the probability of ground flashes increases.

The pioneering work conducted by Malan and Shonland⁵ and Clarenece and Malan⁶ showed that radiation fields of the first return strokes are preceded by about 10 to 100 ms by a pulse burst. They called this pulse burst 'preliminary breakdown'. Furthermore, they assumed that this pulse burst is generated by the electrical breakdown between the negative charge centre and the LPCC just before a ground flash. If this reasoning is correct the strength of this pulse burst should depend on the magnitude and the concentration of the LPCC. Thus we decided to analyse and compare the radiation fields preliminary breakdown processes in tropical Sri Lanka and in temperate Sweden.

3. COMPARISON OF PRELIMINARY BREAKDOWN PROCESSES IN SRI LANKA AND SWEDEN

During the last twenty years we have been engaged in the analysis of electromagnetic field signatures produced by Swedish ground flashes. One remarkable fact we have noticed is the presence of strong radiation during the preliminary breakdown process. Not only is this pronounced in Swedish lightning flashes, but it is also a very common feature in them. Rarely do we see ground flashes without appreciable preliminary breakdown processes. On the other hand, our observations in Sri Lanka show that the preliminary breakdown process, as judged from the electric radiation field, is not as active as it is in Sweden. For example, Gomes et al.⁷ analysed the preliminary breakdown processes in 47 flashes observed in Sri Lanka and 41 flashes recorded in Sweden. In the data obtained in Sri Lanka, breakdown pulses could be detected only in nine of the flashes and for these the ratio of the maximum amplitude of the breakdown pulses to the return stroke amplitude (BP/RS ratio) was 0.16. All the flashes recorded in Sweden showed very clear preliminary breakdown pulses and for these BP/RS ratio was 1. These results clearly show that the preliminary breakdown process is very common in Swedish lightning flashes and the intensity of the breakdown is much higher compared to that in Sri Lanka.

Examples of the electric fields associated with preliminary breakdown processes and the resulting HF radiation at 3 MHz measured in Sweden and in Sri Lanka are shown in Figures 1 to 5. First note that in both countries the onset of HF radiation coincides with the commencement of the preliminary breakdown. Second, note that in tropical lightning

flashes the electric field pulses associated with the preliminary breakdown are weak (compared to the electric field generated by the return stroke). These results, together with those presented earlier indicate that the preliminary breakdown process in tropical clouds is less energetic and we speculate that the reason for this is the inability of the LPCC to strongly influence the preliminary breakdown process in the tropics. Of course, depending on the meteorological conditions, LPCC's similar to those in the tropics may also occasionally occur in temperate thunderstorms. In such cases we would expect a less active preliminary breakdown process. Thus it would be of value to test for a correlation between the meteorological conditions and the strength of the electric field pulses associated with the preliminary breakdown processes in ground flashes.

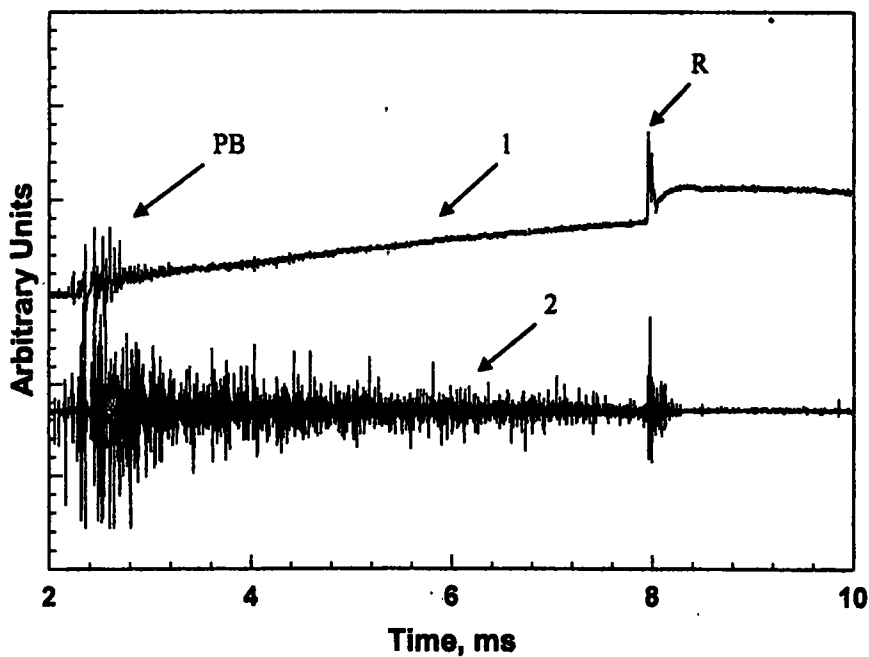


Fig. 1: Vertical electric field (curve 1) and HF radiation (curve 2) generated by a negative ground flash in temperate Sweden. The pulse burst generated by the preliminary breakdown process is marked 'PB' and the return stroke is marked 'R'.

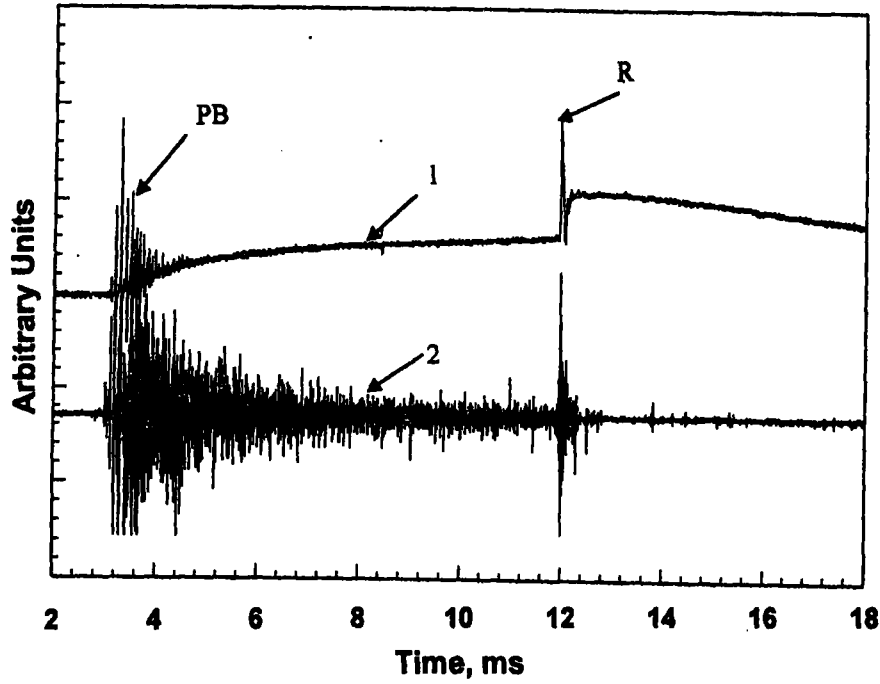


Fig. 2: Vertical electric field (curve 1) and HF radiation (curve 2) generated by a negative ground flash in temperate Sweden. The pulse burst generated by the preliminary breakdown process is marked 'PB' and the return stroke is marked 'R'.

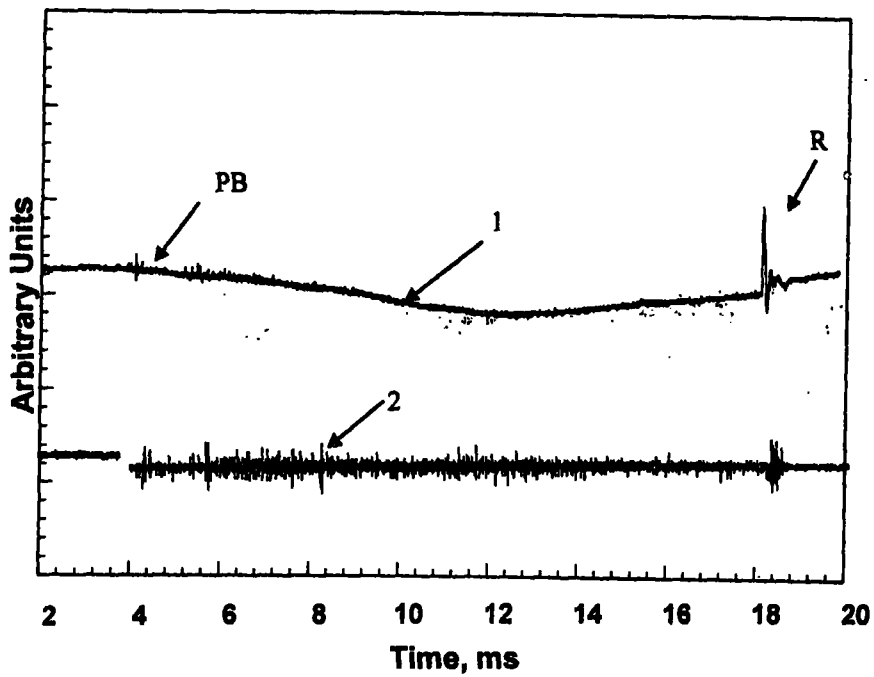


Fig. 3: Vertical electric field (curve 1) and HF radiation (curve 2) generated by a negative ground flash in tropical Sri Lanka. The pulse burst generated by the preliminary breakdown process is marked 'PB' and the return stroke is marked 'R'.

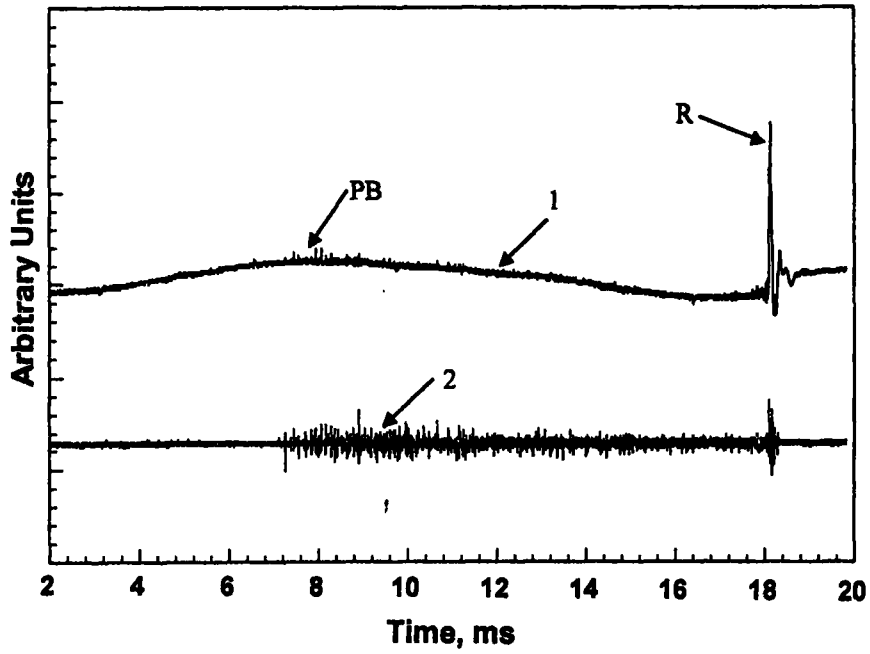


Fig. 4: Vertical electric field (curve 1) and HF radiation (curve 2) generated by a negative ground flash in tropical Sri Lanka. The pulse burst generated by the preliminary breakdown process is marked 'PB' and the return stroke is marked 'R'.

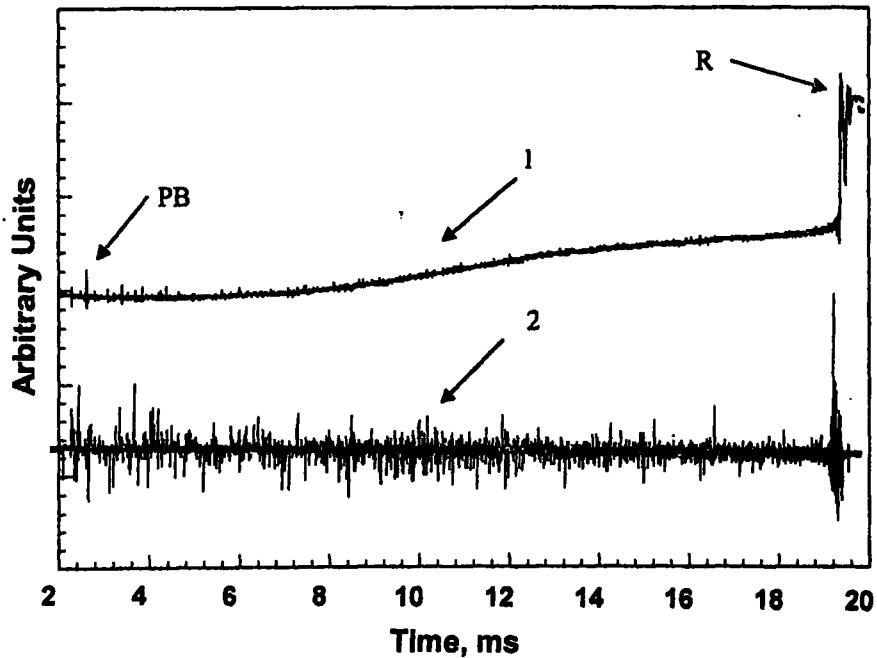


Fig. 5: Vertical electric field (curve 1) and HF radiation (curve 2) generated by a negative ground flash in tropical Sri Lanka. The pulse burst generated by the preliminary breakdown process is marked 'PB' and the return stroke is marked 'R'.

4. POSSIBLE REASONS FOR THE LOW CONCENTRATION OF LPCC OF TROPICAL CLOUDS

There are two ways to account for the generation of an LPCC in thunderclouds. The first possibility is the accumulation of positive charge at the cloud base due to corona. The other possibility is the complex interaction between cloud particles leading to the generation of positive charge. Let us consider the ground corona first. It is a well documented fact that small objects, plants and trees situated on the ground goes into corona when the ambient field increases above about 1kV/m. Since thunderclouds can produce fields much higher than these critical fields at ground level there will be a stream of positive charges, created by the updrafts and electric fields, drifting from ground towards the base of the thundercloud. Indeed, the experimental observations do indicate that ground corona can transport an appreciable amount of charge toward the cloud base (Chauzy; personal communication). Therefore, the corona discharges at ground level may significantly influence the magnitude of the charge in the LPCC. Now, as one moves from temperate to tropical regions, the height to the negative charge centre increases. As a consequence, the electric field at ground level generated by a given amount of charge in the cloud decreases as one moves from temperate to tropical regions. Thus fewer positive ions are produced by ground corona in the tropics during the active lifetime of a thunder cell. With decreasing production of ground corona, the positive charge transported to the cloud base decreases, thereby weakening the role of the LPCC in the creation of ground flashes. If this is the case then it will provide a connection between the surface properties of the ground and the ground flash density. For example, a ground surface covered with thick vegetation contains a large number of corona points, which increase the production of corona and hence enhance the production of the LPCC. One may expect, therefore, a higher ground flash density in regions with thick vegetation, such as forests. However, it should be investigated further to obtain the quantitative information on the enhancement factors of corona over the land.

Next we consider the second possibility. Laboratory studies of thunderstorm electrification have shown that significant amounts of charge are separated when vapour-grown ice crystals make rebounding collisions with riming graupel or soft hail particles (Takahashi⁸, Jayaratne et al.⁹). Jayaratne et al. showed that the sign of charge acquired by the graupel was generally positive at temperatures higher than -20° C and negative below. According to Takahashi the reversal temperature is around -10° C. They were, thus, able to offer an explanation for the commonly observed tri-polar charge structure in thunderstorms. Jayaratne and Saunders¹⁰ pointed out that negatively charged graupel falling from the upper reaches of an electrified thundercloud must first be neutralised by further ice crystal collisions below the charge sign reversal temperature before they are able to acquire a net positive charge. Thus, the creation of an LPCC was conditional on the existence of a

sufficiently high concentration of graupel and ice crystals within the lower regions of a thundercloud.

Thunderstorms are formed due to conditional instability in the atmosphere, a mechanism closely controlled by the convective available potential energy (CAPE). On a thermodynamic diagram, CAPE is represented by the positive area bounded by the temperature sounding and the wet adiabatic. Larger CAPE is associated with deeper clouds and high updraft speeds, and give rise to large ice particles in the mixed phase region (Williams et al.¹¹). These conditions result in more vigorous separation of charge by ice particle collisions, leading to enhanced lightning activity (Williams⁴). Williams showed that large ice particles are most strongly stimulated by the presence of substantial CAPE below and within the lower portion of the mixed phase region. Thus, the vertical distribution of CAPE, as evidenced by its 'shape' on a thermodynamic diagram, is as important as CAPE itself in determining the vertical structure of the precipitation, which in turn controls the intensity of electrification and lightning. The electrical activity in tropical monsoon and along the inter-tropical convergence zone (ITCZ) is less intense than mid-latitude summer thunderstorms.

Tropical storms are effectively stirred in the vertical by moist convection and consequently contain low CAPE whose shape appears as a long and thin area in a thermodynamic diagram. On the other hand, severe mid-latitude thunderstorms are less well-mixed and have very high CAPE with their corresponding shape being short and wide. Williams argued that the latter are electrically more active than the monsoon storms because more CAPE is available within the lower regions of the mixed-phase growth region. This is precisely the region where laboratory experiments predict positive charging of graupel. Thus we would expect LPCC's to be more commonly found in mid latitude storms than in tropical storms. Extending this argument a step further, if most of the CAPE is restricted to lower altitudes, we would expect strong updrafts and high concentration of large graupel at temperatures below the -20 C height - conditions that may lead to an inverted charge structure, with the positive charge below the negative. Anomalous electrical characteristics with unusually large numbers of positive ground flashes have been reported in severe storms in the mid-western United States (Seimon¹² ; Stolzenburg¹³). As far as we know, no such anomalous behaviour has been observed in the tropics.

5. CONCLUSIONS

We hypothesize that a lightning ground flash is an event that is caused by the creation of a vertical conducting channel below the negative charge centre. The probability of such an event increases with an increase in the charge and concentration of an LPCC. Thus, in

situations where the meteorological conditions do not favour the generation of a LPCC, we can expect a relatively small number of ground flashes. We suggest that this is the reason for the lower percentage of ground flashes in the tropics. Arguments based on ground corona and the application of laboratory results of thunderstorm electrification to thunderstorm dynamics appear to support this hypothesis.

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