The initiation of lightning by runaway air breakdown

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[1] A mechanism for lightning initiation by the sustained runaway breakdown of air is presented. Unlike earlier models that rely upon large cosmic-ray air showers, this mechanism uses the runaway electrons produced by the steady background of atmospheric cosmic-rays to amplify non-uniformities in the electric field. The ionization of air from the runaway electrons creates a region of discharge that propagates in the opposite direction of the electrons, enhancing the electric field in front of it to the point where a conventional breakdown can occur. As the discharged region grows, positron feedback can become important, dramatically increasing the flux of runaway electrons and increasing the propagation speed of the discharged region up to 10^6 m/s. The ambient electric field strength needed for this mechanism is within the range of values observed in thunderclouds and is substantially lower than that required by most other mechanisms. **Citation:** Dwyer, J. R. (2005), The initiation of lightning by runaway air breakdown, *Geophys. Res. Lett.*, *32*, L20808, doi:10.1029/2005GL023975.

1. Introduction

[2] How lightning is initiated inside thunderclouds is one of the great unsolved problems in the atmospheric sciences [*Rakov and Uman*, 2003]. In order to form a lightning leader, at some place in the thundercloud, the electric field must reach a large enough value for conventional breakdown to occur. In dry air at sea-level the conventional breakdown threshold, E_b, is about 2.6×10^6 V/m [*Raether*, 1964]. When precipitation is present, this threshold is reduced to $1.0–1.4 \times 10^6$ V/m, depending upon the size and shape of the precipitants [*Solomon et al.*, 2001]. Decades of *in situ* electric field measurements have failed to find electric field strengths anywhere near the conventional breakdown threshold, even when the effects of precipitation are included [*MacGorman and Rust*, 1998]. Indeed, the maximum electric field strength, scaled to the equivalent field at sea level, appears to rarely exceed about 4.0×10^5 V/m, one third the required value with precipitation. In this paper, unless otherwise specified, the electric fields will be presented as their sea-level equivalent values. To obtain the actual electric field at a given altitude, the sea-level equivalent field should be multiplied by the ratio of the density of air at that altitude to the value at STP, n/n_o.

[3] A recent idea that has shown promise is that runaway air breakdown is involved in some way in the lightning initiation process [*Gurevich et al.*, 1992, 1997]. During runaway breakdown, the electric force experienced by fast electrons is greater than the effective frictional force produced by the motion of the electrons through air, allowing the electrons to run away and gain large amounts of energy [*Gurevich and Zybin*, 2001]. The runaway breakdown idea has gained some support from the fact the maximum electric field observed inside thunderclouds [*Marshall et al.*, 2005] is sometimes near or slightly above the runaway breakdown threshold ($E_{th} \approx 2.84 \times 10^5$ V/m) [*Dwyer*, 2003]. Furthermore, x-ray emission has been reported to be associated with lightning channels near the ground [*Moore et al.*, 2001; *Dwyer et al.*, 2003, 2004]. Because runaway breakdown is the only viable mechanism for producing such x-ray emission, these observations have given some support to the runaway breakdown initiation hypothesis.

[4] Unfortunately, exactly how runaway breakdown manages to initiate lightning has remained elusive. A model proposed by *Gurevich et al.* [1999] postulated that when an extensive cosmic-ray air shower passes through a region with a large enough electric field to produce runaway breakdown, the resulting secondary ionization might locally enhance the electric field to the point where a conventional discharge could occur. Unfortunately, this interesting idea has some difficulties: The runaway avalanche develops a considerable lateral extent due to the initial transverse velocities and scattering of the runaway electrons. For example, for a 4.0×10^5 V/m field, Monte Carlo simulations show that, even when the initial size of the air shower is ignored, the avalanche will be more than 250 m across at the end of a typical avalanche region at 8 km altitude. It is not at all clear how such a large but diffuse runaway avalanche could result in a hot leader channel. Also, the amount of avalanche multiplication required by this model is very large. Because positrons and x-rays, produced as byproducts of runaway breakdown, can propagate to the start of the avalanche region and produce more energetic seed electrons [*Dwyer*, 2003; *Babich et al.*, 2005], this positive feedback mechanism can greatly enhance the number of runaway electrons to the point where the electric field collapses. The feedback mechanism may prevent the electric field from becoming large enough for the cosmic-ray air shower model to become plausible. However, in this paper, it will be shown that this collapse of the electric field due to the ambient cosmic-ray flux, augmented by positron feedback, may itself be the key to understanding the initiation of lightning.

2. The Lightning Initiation Model

[5] As the electric field slowly increases past E_{th} in some region of the thundercloud, due to thunderstorm electrification, runaway breakdown will produce secondary ionization in that region. The free low-energy electrons quickly attach to oxygen, resulting in a large number of positive and negative ions. In most cases the recombination rate of the

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ions is not significant and the ions drift in the electric field. In clouds, the ions drift until they attach to cloud droplets (and to a smaller degree precipitation). The absorption length of such ions is a function of the liquid water content and number density of cloud droplets, the convective velocity of the droplets, the ambient electric field strength and the charge per droplet [*Chiu*, 1978]. For typical thundercloud values, the absorption length is found to be in the range 3–20 m.

[6] As the ions drift, the electric polarization (electric dipole moment per unit volume) due to these ions increases until they become attached to droplets, at which point the electric polarization from these particular ions is frozen in. Note: for the short time periods considered here, the motion of the droplets is not important. This electric polarization will reduce the electric field in some regions and enhance it in others. Runaway breakdown is extremely sensitive to the electric field strength, E, especially near the threshold field, E_{th}. Because the characteristic length-scale (e-folding length) of the runaway avalanche decreases rapidly with increasing E, a small enhancement in E, produced by the electric polarization, will greatly increase the production of runaway electrons and hence secondary ionization in that region, which in turn can further increase the electric polarization and so on. This is analogous to the mechanism involved in a positive streamer discharge. For a positive streamer, the ionization is caused by avalanches of low-energy electrons originating in front of the streamer head, and, in this case, the ionization is caused by avalanches of runaway electrons originating in front of a much larger discharged region.

[7] In order to investigate the development of runaway breakdown in the thunderstorm environment, the runaway electrons were modeled using the steady state equation

$$\vec{\nabla} \cdot (\vec{v}N) - \vec{\nabla} \cdot \left[D\left(\vec{\nabla}N - \vec{v}\left(\vec{v} \cdot \vec{\nabla}N\right)/v^2\right)\right] = \frac{vN}{\lambda} + S, \qquad (1)$$

where N and $\vec{v}$ are the number density and velocity of the runaway electrons. The speed of the runaway electrons, v, was chosen to correspond to the average energy of 7.2 MeV, and the velocity was calculated using $\vec{v} = -v\vec{E}/E$. Because the timescale needed for runaway breakdown to reach the steady state is much shorter than that required for the electric field to change appreciably, the steady state condition is justified. The variable, λ, which was determined by detailed Monte Carlo simulations [*Dwyer*, 2003, 2004], is the avalanche length for $E > E_{th}$ and is the length-scale over which runaway electrons are lost for $E < E_{th}$. In equation (1), S is the rate that new runaway electrons are injected per unit volume into the avalanche region, either from atmospheric cosmic-rays or from positron feedback. The contribution from atmospheric cosmic-rays was calculated assuming a constant, uniform flux of F_{cr} = 1000 s^{-1} m^{-2}. When $E > E_{th}$, this flux produces seed runaway electrons via hard scattering with air atoms at the rate F_{cr}/λ. The effects of positron feedback on S were included using the feedback rates calculated by *Dwyer* [2003] and *Babich et al.* [2005]. The second term on the left hand side describes lateral diffusion of the avalanche due to the emission angle of energetic "knock-off" electrons and due to scattering of the runaway electrons. The diffusion coefficient, which depends upon the electric field strength and the density of air, was found from Monte Carlo simulations to decrease from 8×10^8 (n_o/n) m^2/s to 5×10^7 (n_o/n) m^2/s as E increases from 3×10^5 V/m to 1.2×10^6 V/m.

[8] For each time step, the trajectories of the runaway electrons in the electric field were calculated, starting with the upstream boundary condition that no runaway electrons are produced for $E < E_{th}$. A 2-D finite difference code with cylindrical symmetry was then used to solve equation (1) along these trajectories. The method was determined to be stable and to give results in good agreement with Monte Carlo calculations. The electric polarization was calculated from the runaway electron density, N, using the average ionization rate per runaway electron of $9000(n/n_o)$ per m, the drift velocities of the positive and negative ions in the electric field ($\vec{v}_\pm = \pm\mu_\pm\vec{E}$, where $\mu_+ = 1.4 \times 10^{-4}$ m^2/V s, $\mu_- = 1.9 \times 10^{-4}$ m^2/V s and $\vec{E}$ is the sea-level equivalent field vector), the recombination rate of positive and negative ions, and the absorption of the ions by cloud droplets. The time steps were chosen so that the maximum change in the electric field during each step remained small. After each time step, the new electric polarization, both from drifting ions and charged cloud droplets, was found, and the electric field change produced by the electric polarization was calculated. Note: the electric field change caused by the charge transfer of the runaway electrons themselves is completely negligible compared with the contribution from the secondary ionization. The runaway breakdown calculation was then repeated with the new electric field.

[9] Figure 1 shows the electric field strength and average runaway electron trajectories as calculated by the simulation for a discharge at an altitude of about 8 km. The black curves, which are just a small sample of the calculated trajectories, were plotted only for values of $E > E_{th}$. However, the runaway electrons in reality (and in the model) travel about 100 m or so into the low field region before stopping. Because the number of runaway electrons increases exponentially along the trajectories shown in Figure 1, the number of runaway electrons at the end of the avalanche can be very large, producing large amounts of ionization there.

[10] The ambient electric field within the cylindrical simulation volume was the sum of a large-scale electric field and smaller electric field perturbations, simulating non-uniformities in the field. Because the upper positive charge region tends to be more diffuse than the main negative region, the large-scale electric field was chosen to be uniform in the sea-level equivalent field and pointed downward. The electric field perturbations were produced by Gaussian charge density distributions with the negative and positive charge regions centered at 5.9 km and 10 km, respectively. The 1σ widths for the charge distributions were chosen to give the same maximum sea-level equivalent fields near the top and bottom of the simulation volume and were 680 m and 805 m for the bottom and top charge distributions, respectively. The maximum contribution of the perturbations to the total electric field was adjustable, but was set to 20% for the simulation shown in Figure 1. At the beginning of the simulation, the ambient electric field

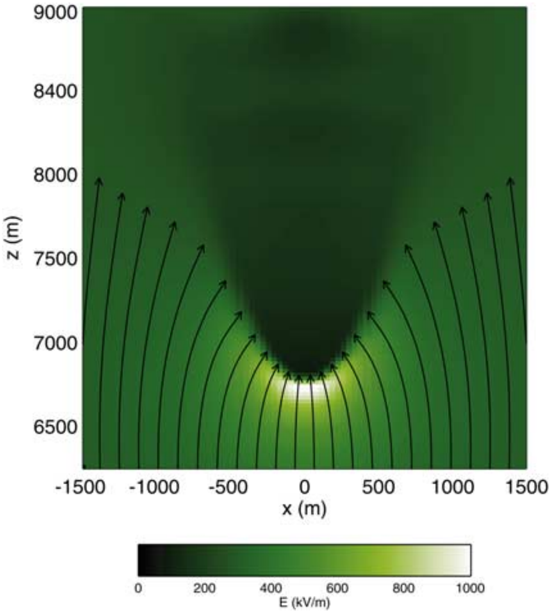

Figure 1. Example of the runaway breakdown mechanism. The vertical axis is height above sea-level. The color scale gives the sea-level equivalent electric field strength with black corresponding to no electric field and white the maximum electric field. The black curves with arrows are samples of the average trajectories of the runaway electrons for $E > E_{th}$. The positive and negative charge regions are located at the top and bottom of the figure, respectively. The maximum electric field produced at the head of the discharge at this point in the simulation was 430 kV/m, which corresponds to a field of 1000 kV/m at sea-level. The field at the discharge head is already 2.86 times the maximum ambient field and continues rising as the discharge propagates towards the bottom of the figure.

was slowly increased over a time period of many seconds, simulating the gradual electrification of the storm. In the absence of runaway breakdown, the maximum value that the ambient field would have reached was 350 kV/m (sea-level equivalent), a value measured inside thunderclouds. As can be seen, a large discharged region developed with a reduced electric field inside and an enhanced electric field at its front. The region propagates downward in Figure 1.

[11] Figure 2 shows the electric field along the cylindrical axis as a function of altitude as the region discharged by the runaway electrons shown in Figure 1 continues to propagate. In Figure 2, for clarity, black corresponds to early times, red to middle times and orange to later times. As can be seen, the electric field in front of the discharged region ramps up to extremely large values. Energetically this is allowed, since the discharged region causes the total electric field energy to steadily decrease with time once the ambient field reaches its maximum value.

[12] The simulation was stopped once the field of 1300 kV/m was reached, since conventional breakdown is likely to occur for electric fields above about 1200 kV/m when hydrometeors are present. Such fields, which are easily reached by the mechanism presented in this paper, are likely to be sufficient to initiate lightning. However, at the point that the simulation was stopped the field was continuing to rise and so could potentially reach larger values.

3. Discussion

[13] The rapid amplification of the electric field due to perturbations in the uniform field was found to occur over a wide range of conditions. For example, the mechanism was found to work when the 1σ width of the charge distributions was in the range 400–1600 m, when only perturbations from the positive charge region were included, when only perturbations from the negative charge region were included, and when the maximum size of the perturbation was varied from 10% of the total field to 100% of the total field. The latter case shows that a uniform background field is not a necessary ingredient.

[14] The speed that the discharged region propagates depends upon the flux of the runaway electrons, which depends upon the length of the avalanche region, the electric field strength, and the resulting feedback rate. As the discharged region grows, the positive feedback effect from positrons propagating to the beginning of the avalanche region and initiating new runaway electron avalanches can become large. Simulations show that as the discharged region propagates, the electric field can adjust itself to maintain the positron feedback, greatly increasing the speed that the discharged region advances to about 10^6 m/s. The time needed to increase the field from 284 kV/m, the runaway breakdown threshold, to 350 kV/m was 6 s, at which point the field collapsed at the end of the avalanche region and feedback became important. The time for the field to then shoot up to 1200 kV/m was only 3.3 msec. If feedback effects are not included, or if the avalanche multiplication is lower due to smaller electric fields, the propagation speed is reduced and a longer time is required for the field to increase.

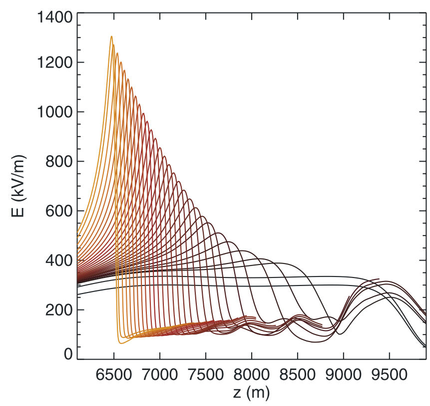

Figure 2. Sea-level equivalent electric field strength versus height during the propagation of the runaway breakdown shown in Figure 1. For clarity, the curves go from black to red to orange as time progresses. Due to the ionization of the air from the runaway breakdown, the electric field is reduced at the end of the avalanche region and is enhanced in front of the discharged region. As the discharged region propagates from right to left, the electric field increases, reaching values at which conventional breakdown is very likely to occur.

[15] The ambient electric field required by this mechanism is found to be within the range of measured values. For example, using balloon soundings, *Marshall et al.* [2005] measured several cases in which the electric field strength inside thunderstorms was well in excess of the runaway breakdown threshold, reaching 370 kV/m in one case. The maximum ambient electric field used in the simulation was 350 kV/m and occurred at 6.6 km, corresponding to 150 kV/m at that altitude, which is below the values believed necessary to initiate lightning by coronal discharge from hydrometeors [*Crabb and Latham*, 1974]. This runaway breakdown mechanism also works at lower electric field values as long as $E > E_{th}$, but the length of the avalanche region in such cases becomes rather long.

[16] The size of the electric field (magnitude and length scale) needed for this mechanism is also well below that needed for extensive cosmic-ray air showers to have an impact. Indeed, for the electric field used in the simulation for Figures 1 and 2, the maximum density of positive and negative ions produced by an extensive air shower with an energy of 10^{16} eV was about 3 orders of magnitude smaller than the charge density produced by the sustained runaway breakdown shown in Figures 1 and 2. As a result, if a large air shower happened to pass through the high field region, the effects would not be significant.

[17] The runaway breakdown model presented here requires that the electric field exceed the runaway breakdown threshold over a long enough length to produce substantial avalanche multiplication. For example, in order for the runaway breakdown to ramp up the electric field to very large values, the potential difference across the high field region needs to be about 200 MV if the maximum ambient electric field is 600 kV/m and 450 MV if the maximum ambient electric field is 350 kV/m. Accurately measuring the electric potential difference within thunderclouds is extremely difficult, because of the large time variability and the need to make spatially separated, simultaneous measurements within the highest field regions of the storm. As a result, it is not clear how common such potential differences are. On the other hand, if only modest enhancements in the ambient field are needed, e.g. a 50% increase, then this mechanism can work with much lower values for the electric potential and the electric field strength.

[18] X-ray emission from thunderclouds has already been observed [*Parks et al.*, 1981; *Eack et al.*, 1996]. This emission, which typically lasts on the order of seconds, is frequently seen to terminate once lightning begins. Such emission is a natural consequence of the mechanism proposed in this paper. Furthermore, x-rays have been reported in association with the propagation of lightning stepped leaders [*Dwyer et al.*, 2005], suggesting that runaway breakdown continues to play a role after a conventional discharge begins.

[19] In this paper, a mechanism for initiating lightning has been presented that involves the runaway breakdown of air. The results are found to be robust and not particularly sensitive to the cloud parameters chosen. The mechanism uses well understood physics of runaway air breakdown and uses reasonable assumptions that are largely in agreement with nominal values measured inside thunderclouds. The maximum value of the ambient electric field needed for this mechanism is about 350 kV/m, which corresponds to 130 kV/m at an altitude of 8 km, a value well within the range measured inside thunderstorms and a lower value than required by most other models.

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