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On the physics of high altitude lightning

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Abstract. Past and recent observations indicate the presence of lightning at altitudes in excess of 30 km. The phenomenon is manifested as a high altitude optical flash, correlated with the presence of giant thunderstorms in the atmosphere below. This letter presents the first physical model of the process. The model is based on low frequency RF breakdown of the upper atmosphere, ignited by the upward propagating electromagnetic pulses due to conventional low altitude lightning. Horizontal intercloud lightning strokes form the optimal configuration. Horizontal lightning discharges with cloud-to-cloud moment charge ~ 6,000 — 8,000 C-km account for the observed level of optical emissions.

Introduction

A number of authors [*Boek et al.*, 1992; *Franz et al.*, 1990; *Winckler et al.*, 1993; *Vaugham and Vonnegut*, 1989; *Vaugham et al.*, 1992; *Lyons*, 1994] reported the presence of optical flashes at high altitudes above thunderstorm clouds. *Sentman and Wescott* [1993] describe the phenomenon, often called high altitude lightning (HAL), as a luminous column stretched between 30 and 80 km, with peak luminosity in the vicinity of 60 km. HAL correlates with massive thunderstorms, and occurs with a frequency between 0.5 and 5% compared to the total number of lightning strokes. It is the objective of this letter to produce the first quantitative model of the HAL process.

The model is based on upper atmospheric electron energization or breakdown caused by an electromagnetic pulse induced by low altitude lightning. It is analogous to the recently studied ionospheric and atmospheric breakdown by ground based RF transmitters [*Borisov et al.*, 1986; *Tsang et al.*, 1991; *Papadopoulos et al.*, 1993]. Emphasis is placed on intercloud lightning strokes since, as shown below, they produce optimal configuration for upper atmospheric breakdown.

Spatial Distribution of the Electric Field and Energy Deposition

We study first upper atmospheric breakdown by an electromagnetic pulse due to a horizontal lightning stroke. A simple model of lightning, as a line current connecting two discharging clouds located at altitude z_o and separated by distance L above a perfectly conducting ground is assumed (Figure 1). The current density $\vec{J}(\vec{x},t)$ is modeled as

$$\vec{J}(\vec{x},t) = I_o(e^{-\alpha t} - e^{-\beta t})H_1[H_2 - H_3]\delta(y)\delta(z-z_o)\hat{x} \quad (1)$$

where $H_{1,2,3}$ are the Heaviside unit functions with arguments t, x + L/2, x — L/2 correspondingly, $\delta(x)$ is the delta function, and $\hat{x}$ is the unit vector in x direction. Ground reflection is treated as an image charge and current induced below a perfectly conducting ground. Using the charge density, derived from the charge conservation equation, and the current density given by eq. (1) as a source, the electric field induced by the lightning discharge at a point z on the z-axis is $E_y = E_z = 0$ and

$$E_x = E_1 e^{-\eta\tau}\{H(\tau)H(\gamma)F(\eta,\tau^2-1)$$

$$-H(\gamma)\{\frac{\xi e^{\eta\sqrt{1+\xi^2}}}{\eta^2}\left[\frac{1}{(1+\xi^2)^{3/2}} - \frac{\eta}{1+\xi^2}\right] + F(\eta,\xi)\}\} \quad (2)$$

Here $F(\eta,y) = \int_0^y e^{\eta\sqrt{1+x^2}}/\sqrt{1+x^2}\,dx$, $\gamma = \sqrt{1+\xi^2} - \tau$, and the following dimensionless parameters were used

$$\eta = \frac{\beta}{c}(z-z_o),\ \tau = \frac{\beta t}{\eta},\ \xi = \frac{L}{2\,(z-z_o)},\ E_1 = I_o\,\frac{2\,\beta}{c^2} \quad (3)$$

In eq. (2) $F(\eta,y)$ represents the transient field, while the rest is the quasi-static field due to the point charges. For times $\tau < \sqrt{1+\xi^2}$ the field at the point z is determined only by the transient field.

The total electric field on the axes is given by

$$E_{tot}(z,I_o,\tau) = E_x(z-z_o,I_o,\tau) - E_x(z+z_o,-I_o,\tau) \quad (4)$$

The second term on the right hand side represents the contribution of the electric field due to the ground reflection.

From eqs. (2)-(4) we find that, in practical units, the electric field induced by a lightning stroke with peak current I_o, and pulse duration t_p in the upper atmosphere is

$$E\left(\frac{V}{m}\right) = 0.2\,I_o(kA)\left(\frac{ms}{t_p}\right)\tilde{E}_{tot}(\eta(t_p),\ \xi,\ \tau) \quad (5)$$

where $\tilde{E}_{tot} = |E_{tot}|/E_1$ is the absolute value of the dimen-

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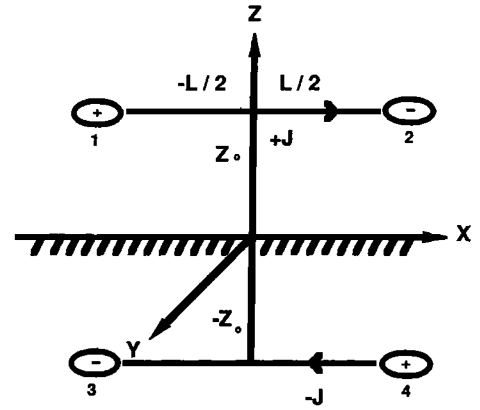

Figure 1. Schematic of the proposed model.

sionless electric field. Finally, the horizontal distribution of the electric field due to a long pulse, $\eta << 1$, is given by

$$\frac{E(x,z)}{E(0,z)} \simeq \frac{1}{\left[1+\left(\frac{x}{z-z_o}\right)^2\right]^{3/2}} \quad (6)$$

We comment briefly on the key dependences of eqs. (2)-(5), which give the distribution of the maximum field value induced by low altitude lightning at an altitude z, as a function of the peak current I_o, pulse width $t_p=1/\beta$, discharge length L, and lightning altitude z_o. The electric field scales linearly with I_o. Figure 2 illustrates the temporal evolution of $\tilde{E}(\tau) = E_x(\tau)/E_1$ for values of the parameter $\eta = 1$ and $\eta = 0.25$. A nonlinear, threshold like behavior of the field on η is apparent. Of particular importance is the nonlinear dependance on the pulse width t_p. In addition, Figure 2 shows that increasing the parameter $\xi = 0.5\,L/(z-z_o)$ leads to larger transient electric fields. As a result stronger fields are produced by lightning strokes with long path lengths.

Figure 3 shows the temporal evolution of the total electric field amplitude $\tilde{E}_{tot}$ for two values of $\chi \equiv (z-z_o)/(z+z_o)$. The parameter χ determines the delay time between the signals arriving at z from the discharge current and from its ground reflection. For short delays (solid curve) the signal due to the reflected field significantly reduces the total field. For longer delays (broken curve) the reflected field appears as a second peak in $\tilde{E}_{tot}$, following the decay of the field due to the discharge current.

The critical parameter [*Papadopoulos et al.*, 1993] that controls energy deposition and the subsequent observables is the value of the generalized electron quiver energy $\tilde{\epsilon}$ which, for pulses with duration $t_p >> 1/\nu$, $1/\Omega$, where ν is the frequency of electron-neutral collision *Gurevich* [1978] and Ω the electron cyclotron frequency, is given by

$$\tilde{\epsilon} = \frac{1}{2}\frac{e^2E^2}{m(\nu^2+\Omega^2)} \quad (7)$$

For values of $\tilde{\epsilon} < 0.02$ eV most of the energy absorbed by the electrons excites the low lying vibrational levels of nitrogen, and emissions in the visible range cannot be excited. For $0.02\,\text{eV} < \tilde{\epsilon} < 0.1\,\text{eV}$ the electron energy results in excitation of optical emissions and molecular dissociation. For $\tilde{\epsilon} > 0.1\,\text{eV}$ breakdown is initiated.

From the dependance of $\tilde{\epsilon}$ on altitude (Figure 4) we expect emissions in the visible at altitudes z>50 km in the presence of ambient electrons. Their intensity depends on the density profile. When $\tilde{\epsilon}$ exceeds the ionization threshold strong emissions will result even for low ambient electron density. The $\tilde{\epsilon}$ dependence is universal and indicates that the value of $\tilde{\epsilon}$ maximizes at altitudes of about 70 km. This is due to the fact that $\nu \sim e^{-z/L}$ while $E \sim 1/z^3$. For altitudes in excess of 70 km, where $\nu < \Omega$, the quiver energy drops sharply. When $\tilde{\epsilon} \geq 0.2$ eV self absorption becomes important. In the present paper we concentrate on HAL at lower altitudes, $z \leq 70$ km, where self absorption is negligible.

Optical Emissions and Ionization

The calculation of optical emissions follows the well established procedure of ionospheric breakdown [*Borisov et al.*, 1986; *Tsang et al.*, 1991; *Papadopoulos et al.*, 1993]. First, the local kinetic equation that describes the evolution of the electron distribution f(v,t) in the presence of an ambient electric field and inelastic collisions, is solved and the stationary state is found. This equation is given by

$$\frac{\partial f(v,t)}{\partial t} = \frac{eE}{3mv^2}\frac{\partial}{\partial v}\left(\frac{1}{\nu^2+\Omega^2}\frac{\partial f(v,t)}{\partial v}\right) - L(f(v)) \quad (8)$$

where L(f(v)) is an operator that describes the effects of the inelastic collisions. The form of L(f(v)) for air can be found in the above references. For a given altitude and value of E(z), a steady state is quickly established so that f(v) becomes independent of time and is only a function of z, and E(z). Second, the excitation rate ν_{ex}^{js} of the j electronic level of specie s by electron impact, defined by

$$\nu_{ex}^{js} = 4\pi N_s \int f(v,E)\,v^3\sigma_{ex}^{js}(v)dv, \quad (9)$$

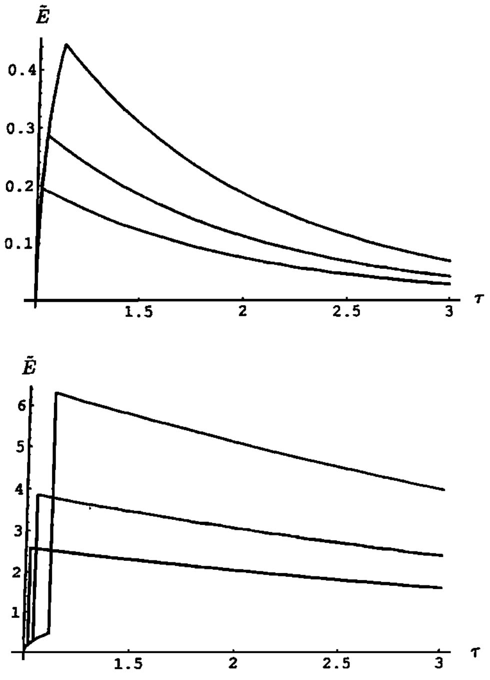

Figure 2. The field $\tilde{E}$ as a function of τ for (a) η = 1, (b) η = 0.25. From top to bottom ξ = 0.5, 0.3 and 0.2.

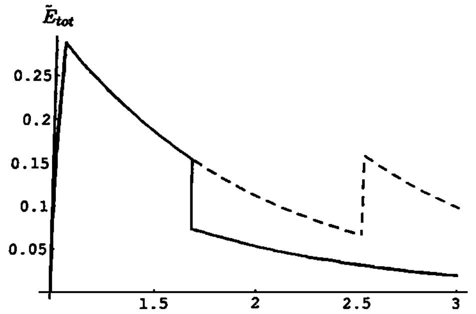

Figure 3. The total field $\tilde{E}_{tot}$ as a function of time τ for $\eta = 1$, $\xi = 0.3$, and $\chi = 0.6$ (solid line), $\chi = 0.4$ (broken line).

where N_s is the density of specie s, and $\sigma_{ex}^{js}(v)$ the excitation cross-section, is computed. Third, the equations which describe the densities of the excited molecules N_{js}^* and electrons N_e

$$\frac{dN_{js}^*}{dt} = \nu_{ex}^{js} N_e - \frac{N_{js}^*}{\tau_{js}} - \nu_q^{js} N_s^* \qquad (10)$$
$$\frac{dN_e}{dt} = \nu_i^{ef} N_e,$$

where τ_{js} is the lifetime of the excited molecules, ν_q^{js} the quenching rate, and ν_i^{ef} the effective ionization rate defined as the difference between the ionization and attachment rates, are solved under the following initial conditions

$$N_e(t=0,z) = N_o(z) \qquad (11)$$
$$N_{js}^*(t=0,z) = 0,$$

where $N_o(z)$ is the density of the ambient electrons.

We proceed next to calculate the expected HAL optical emissions under giant thunderstorm conditions. In such a case clouds extend up to 15-20 km [*Uman*, 1984]. In addition, the HAL seems to be correlated with lightning pulses with duration ~ 20 ms, called "long events" [*Winckler et al.*, 1993]. We consider the particular case of horizontal intercloud lightning at z_o=10 km, with t_p=10 and 20 ms, and L = 10 km. We consider the optical emissions due to three nitrogen bands, 1st positive ($B^3\Pi_g \rightarrow A^3\Sigma_u^+$), 2nd positive ($C^3\Pi_u \rightarrow B^3\Pi_g$), and 1st negative band ($B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$), with lifetimes of 8 μs, 38 ns and 63 ns correspondingly. To compute the optical emissions, we first calculate the peak electric field per unit current as a function of altitude. This electric field is used in the Fokker-Planck code, which solves numerically eq. (8), to compute the ionization and excitation rates for the three nitrogen bands of interest. The intensity of the optical emissions as a function of altitude is computed by using the ionization and excitation rates in eq. (10). The quenching rates of the excited electronic levels are taken from *Jones* [1974]. The analysis was performed assuming a middle latitude model of the neutral atmosphere [*Brasseur and Solomon*, 1984] and two profiles of the electron density representing "tenuous" and "dense" nighttime D regions [*Taranenko et al.*, 1993]. Figure 5 presents the altitude distribution of the total intensity of the artificial optical emissions as a function of the peak electric current of the intercloud lightning stroke. It indicates that optical emissions with intensity of tens of kR can be induced by lightning pulses with duration 20 ms and peak current 30–40 kA at 60–70 km for dense ionosphere, or at 65–70 km for tenuous ionosphere. These values are consistent with the observations by *Sentman and Wescott* [1993] of 10–50 kR brightness of upper atmospheric optical flashes. The value of the threshold electric field required at 60–70 km can be found from Figure 2 and eq. (5). For the values quoted above it corresponds to 130–250 V/m.

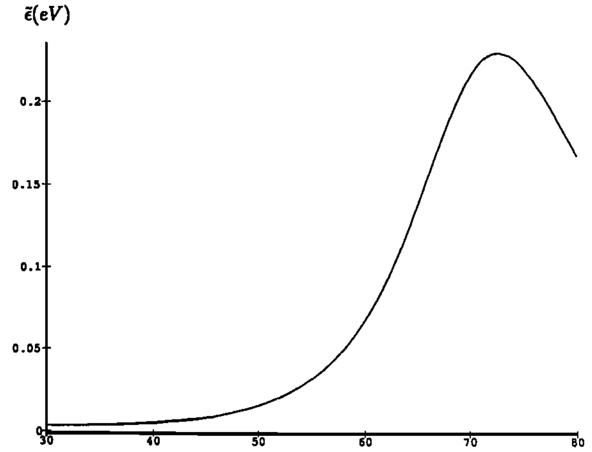

Figure 4. Altitude dependance of $\tilde{\epsilon}$ for z_o=10 km, L=10 km, Ω=8.5×10^6 1/s, I_o=30 kA, and t_p=20 ms.

The most important parameter in the model is the value of cloud-to-cloud (CC) moment charge M. To produce 10–50 kR brightness M≈6–8×10^3 C-km is required. This should be compared to average values of M~200–400 C-km [*Wang*, 1963; *Hatakeyama*, 1958]. It is difficult to determine the probability of occurrence of HAL, although some data are becoming available [*Lyons*, 1994]. We can speculate that if the value of M scales as a self similar fractal [*Bak et al.*, 1987] M^{α} with α=-1, then HAL will occur in a few percent of CC discharges over giant thunderstorms. There are, however, a number of measurements indicating that few hundreds of C are frequently discharged in CC events. For example, *Workman et al.* [1942] noted that CC charge transfer reached, on occasion, 100 C. *Smith* [1957] observed that in almost horizontal discharges charge between 130–250 C was transferred, and *Takeuti* [1965] noted that charge

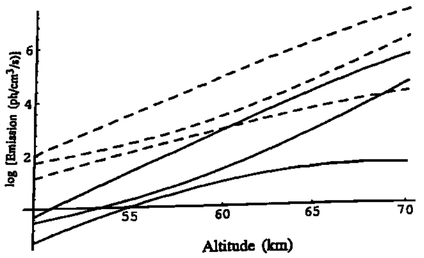

Figure 5. Altitude dependance of the total intensity of the optical emissions due to a lightning stroke located at z_o = 10 km, pulse width t_p = 20 ms, and path length L = 10 km, for different values of the peak electric current. Numbers 1, 2 and 3 correspond to I_o = 20, 30 and 40 kA. Solid and broken lines show emissions for tenuous and dense electron density models.

transfer in CC discharges often exceeds 100 C. Such values with L≈10 km are consistent with the requirements of the model.

The intensity of the optical emissions changes drastically with small variations ($\leq 10 - 15\%$) in the local electric field. This allows us to estimate the horizontal extend of the optical flashes by using eq. (6). In fact, at z = 60 km the electric field amplitude drops 10–15% when moving 14–16 km away from the peak point located above the middle point of the lightning, reducing the optical emissions below the observational threshold. This spatial scale is consistent with the observations of *Sentman and Wescott* [1993] who reported optical flashes with horizontal extent of 10–50 km.

We finally note that the flashes often appear in pairs [*Franz et al.*, 1990]. The present theory naturally accounts for this relying on ignition by the reflected pulse. A slope in the ground surface or deviation of the lightning path from the horizontal direction, leads to lateral displacement of the flash induced by the ground reflection.

Conclusions

A model of HAL based on electron energization induced by horizontal long lightning pulses has been presented. The model naturally accounts for the observed correlation of HAL with giant thunderstorms, implying horizontal scales in excess of 10 km, pulse duration in excess of 20 ms and for the appearance of correlated pairs of flashes. The intensity of the observed emissions requires discharge currents of the order of 30–40 kA, or a cloud-to-cloud moment charge in excess of $6\text{–}8\times10^3$ C-km. Detailed analysis of the phenomenon and its environmental implications will be published elsewhere.

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