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Sustained heating of the ionosphere above thunderstorms as evidenced in "early/fast" VLF events

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Abstract. Quasi-electrostatic (QE) thundercloud fields are proposed to maintain the ionospheric electrons at a persistently heated level well above their ambient thermal energy. Changes in the thundercloud charge (e.g., in lightning discharges) lead to heating/cooling above/below this quiescent level, and are registered as sudden (i.e., 'fast' < 20 ms) subionospheric VLF signal changes, occurring simultaneously (i.e., 'early', <20 ms) with lightning discharges, and referred to as early/fast VLF events [*Inan et al.*, 1993].

Introduction

'Early/Fast' VLF events [*Armstrong*, 1983; *Inan et al.*, 1988], typically exhibit 10 to 100 s recoveries to pre-event levels [*Inan et al.*, 1993], although short-duration early/fast events, exhibiting rapid (few secs) decays, have also been observed [*Dowden et al.*, 1994; *Inan et al.*, 1996a]. Many early/fast events also exhibit 'postonset peaks' [*Inan et al.*, 1996a; *Rodriguez et al.*, 1992], lasting $\sim$ 1 s (Figure 1). The 10-100 s recoveries were interpreted as the relaxation of electron density enhancements in the lower ionosphere. We suggest that most early/fast VLF events may not involve ionization changes and that the recoveries represent the decay or build-up of the thundercloud charges after a lightning discharge. However, ionization changes may be involved in VLF events observed in association with more intense lightning discharges and sprites [*Inan et al.*, 1995].

The proposed new mechanism is illustrated in Figure 1. Immediately after lightning discharges intense transient QE fields exist at high altitudes above thunderstorms [*Pasko et al.*, 1995] and produce heating and conductivity changes ($\Delta\sigma_T$) over large (a few hundred km) regions. In cases of particularly intense discharges these transient QE fields may lead to the production of luminous glows observed as sprites [e.g., *Sentman et al.*, 1995; *Pasko et al.*, 1995]. Once the QE transients are over, the ionospheric electric fields (E) settle down to quiescent values, supported by the thundercloud charge distributions. These tens of mV/m quiescent QE fields nevertheless heat the electrons, leading to conductivity changes of $\Delta\sigma_Q$ in smaller regions of $\sim$ 100 km lateral extent. The signal amplitude change ΔA observed in an early/fast event corresponds to the difference between the pre-discharge ($\Delta\sigma_Q^-$) and post-discharge $\Delta\sigma_Q^+$ quiescent heating levels, which in turn may correspond respectively to states of separated dipole charge and a single isolated charge (which remains after a discharge) in the thundercloud. The 'recovery' occurs as the thundercloud recharges to the pre-discharge configuration. E field recoveries above thunderstorms take place over many tens of seconds [*Deaver and Krider*, 1991], similar to the recovery signatures of early/fast VLF events (Figure 2).

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Scientific Background

Characteristics of Early/Fast VLF Events. The properties of early/fast events documented with lightning data and identified on the basis of simultaneity (<20 ms) of event onsets with a radio atmospheric and/or CG lightning are:
1) Amplitude changes are typically 0.2 to 0.8 dB, with a few rare cases of > 1 dB [*Inan et al.*, 1993; 1996a].
2) Estimated peak currents of the associated CG lightning ranged from 20 to 180 kA and the CG flashes were found to be located within ±50 km of the perturbed VLF path, indicating $\sim$ 100 to 150 km lateral extent for the disturbances [*Inan et al.*, 1993, 1995; 1996a].
3) The VLF events exhibited complex recovery signatures, ranging from exponential-like recovery to pre-event levels in ~30-120 s to step-like changes lasting for up to 200 s.
4) Unusual early/fast VLF events included (i) a 0.8 dB change produced by a 100 kA CG flash with recovery time > 200 s [*Inan et al.*, 1988], (ii) $\sim$ 2 dB change produced by a 180 kA CG flash which recovered to pre-event level in ~10 minutes, and occurred in the midst of many smaller

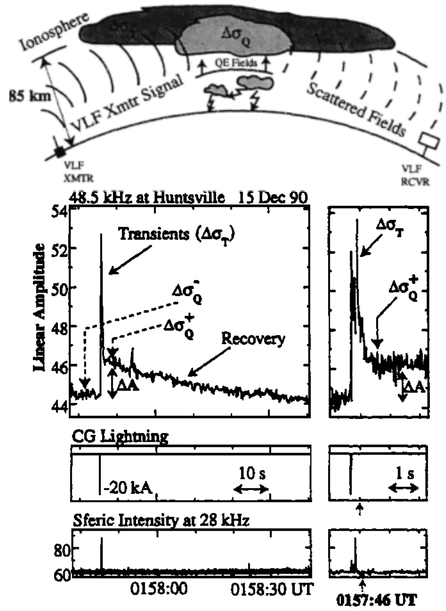

Figure 1. An early/fast VLF event, showing the simultaneity with a radio atmospheric and a negative CG discharge. The initial peak, lasting for < 2 s, is referred to as a postonset peak [*Inan et al.*, 1996a], and is believed to be due to the intense heating ($\Delta\sigma_t$) by the transient QE fields which exist immediately after the discharge. We concentrate here on the period after these transients, where the amplitude is different from the pre-event level by ΔA and recovers to the pre-event level over $\sim$ 50 s.

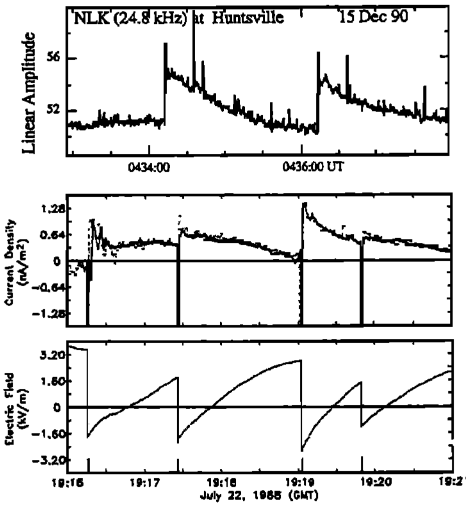

Figure 2. Bottom two panels: total current density and electric field measured near (within < 10 km) a small Florida thunderstorm [*Deaver and Krider*, 1991], showing the four discharges and subsequent field recoveries. Top panel: two early/fast VLF events from *Inan et al.*[1996a].

early/fast events [*Inan et al.*, 1996a], and (iii) an isolated ~ 5 dB change which occurred in assocaition with an unusually intense sferic (no CG lightning data were available) and recovered to pre-event level in 20 minutes [*Inan*, 1993].

Previously Suggested Mechanisms. Ionospheric heating and ionization by intense lightning electromagnetic fields (EMP) can account for slower recoveries [*Inan et al.*, 1991; *Taranenko et al.*, 1993] and the large (~100 to 200 km) lateral extent [*Inan et al.*, 1996b] but primarily occur above the nighttime VLF reflection height of ~ 85 km. Also, EMPs with peak discharge currents >100 kA are needed for ionization [*Inan et al.*, 1995], while some early/fast VLF events are associated with ~20 kA CG flashes [*Inan et al.*, 1993].

QE fields can also heat the electrons and may lead to ionization changes in the altitude range of 60-85 km, and in regions with 20-50 km lateral extent [*Pasko et al.*, 1995]. However, the causative discharges have to be particularly intense (typically requiring the removal of ~100 C in ~1 ms, or peak currents of > 100 kA [e.g., *Inan et al.*, 1996a]). Also, the < 50km lateral extent of the resultant ionization regions are inconsistent with the ~ 100 to 150 km implied by the VLF diffraction pattern [*Inan et al.*, 1996a].

Burke [1991] attributed early/fast VLF events to secondary ionization produced by precipitation of high energy electrons pitch angle scattered near their geomagnetic mirror points by lightning E fields. However, only an upward directed (i.e., -CG flash) ionospheric E field would lower the mirror points of electrons, although early/fast events are associated with both +CG and -CG flashes [*Inan et al.*, 1993; 1996a].

Dowden et al. [1994] suggested that the rapid-onset,rapid-decay events may be due to scattering of VLF waves from ionization columns of few km lateral extent. However, such scattering would be nearly isotropic, inconsistent with the experimental data indicating that the source lightning is typically within ±50 km of the path.

VLF Events as Heating Level Changes

QE fields which exist for <1 s after lightning discharges can alter the ionospheric conductivity (σ) in large regions, causing intense heating of electrons (i.e., $\Delta\nu_{\rm eff}/\nu_{\rm eff} \simeq$ 50-500, where $\nu_{\rm eff}$ is the effective electron collision frequency) and may lead to luminous high altitude glows referred to as sprites [*Pasko et al.*, 1995]. The associated large σ changes would cause VLF perturbations, whose measurement may be hindered by the radio atmospheric energy radiated by the discharge which intrudes into the narrowband VLF channels [*Rodriguez et al.*, 1992]. When QE fields do persist for up to ~ 200 ms (beyond the sferic), their heating may be registered as postonset peaks, such as the 'transient' marked in Figure 1. However, these transient QE fields can not account for the 10-200 s recovery of early/fast events.

On the other hand, recent observations of ionospheric heating by VLF transmitters [*Inan*, 1990; *Rodriguez et al.*, 1994] indicate that relativelly smaller heating levels of $\Delta\nu_{\rm eff}/\nu_{\rm eff}$ ~0.1-1 of can be detected as subionospheric VLF perturbations. For example, *Rodriguez et al.* [1994] found that the NAA transmitter, radiating ~ 1000 kW (projecting few to tens of μV/m to ionospheric altitudes), produces up to $\Delta\nu_{\rm eff}/\nu_{\rm eff}$ ~1 over a region of ~150 km lateral extent and causes easily detectable VLF perturbations.

Thus, early/fast VLF events may represent slight changes in the heating level (i.e., $\Delta\nu_{\rm eff}/\nu_{\rm eff}$ of tens of percent) of the lower ionospheric electrons, corresponding to the difference between the ionospheric E fields driven by the pre- and post-discharge thundercloud charge configurations. The quasi-steady ionospheric E fields before/after lightning discharges are supported by the thundercloud charges and, assuming an exponential σ profile, vary with altitude z as $\sim e^{-z/(2H)}$, where H is scale height of σ [*Holzer and Saxon*, 1952]. Self-consistent calculations indicate that E fields of order 10 mV/m still exist, for example, at ~70 km altitude, even ~10 s after the discharge [*Pasko et al.*, 1995]. This residual field would persist as long as the thundercloud remains charged. However, the charge left in the thundercloud after a discharge would either relax or redistribute, or, new charge separation would occur, leading to the formation of a dipole. If a new thundercloud dipole is thus established, the ionospheric E field would vary with time in a similar manner, and the heating level of the electrons would 'recover' back to approximately the pre-discharge conditions.

That such a scenario may account for the observed 10-100 s recovery times of early/fast VLF events is consistent with E field and current density measurements above thunderstorms [e.g., *Deaver and Krider*, 1991; *Blakeslee et al.*, 1989], which indicate field recoveries taking place over a few to many tens of seconds, with temporal signatures remarkably similar to those of early/fast VLF events (Figure 2).

Model Results

We use a three-dimensional cylindrically symmetric model of the interaction with the lower ionosphere of QE thundercloud fields [*Pasko et al.*, 1995] to determine whether $\Delta\nu_{\rm eff}/\nu_{\rm eff}$ of tens of percent can occur over regions of ~ 100 to 150 km in extent for tens of seconds after lightning discharges. The $\nu_{\rm eff} = e/(m_e\mu_e)$ is calculated using analytical fits to experimental data on electron mobility μ_e as a function of E field and neutral density [*Pasko et al.*, 1995, and references therein]. We consider a 40 s episode consisting of charge accumulation (20 s), discharge (10 ms), and recovery of charge to the pre-discharge value (20 s). We self consistently determine the temporal and spatial structure of the QE field and the resultant heating of the ambient electrons (i.e., $\Delta\nu_{\rm eff}(r,z,t)$) in a three-dimensional cylindrically symmetric region 80 km high ($0 < z < 80$ km) and 300-km wide ($0 < r < 150$ km).

The thundercloud charge distribution is modeled as a dipole, with negative and positive charges at 10 km and 20 km altitudes, respectively, and having a Gaussian spherically symmetric distribution with scale 10 km. The charge values are exponentially increased from zero to ±10 C over $0 < t < 20$ s; one of the charges (+10 C or -10 C depending on the polarity of the discharge) is then removed within 10

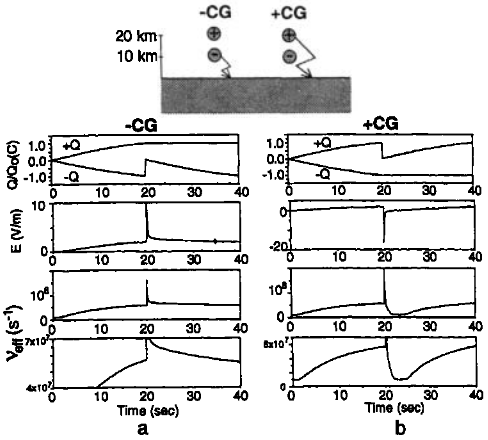

Figure 3. Thundercloud charge, electric field and ν_{eff} at 70-km and at $r = 0$, (a) -CG, (b) +CG. The lowest panel shows an expanded record of ν_{eff}.

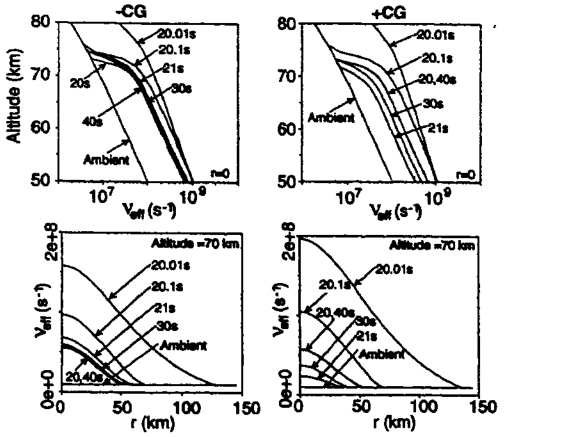

Figure 4. Altitude and radial profiles of ν_{eff} at different times. (a) -CG, (b) +CG.

ms, and subsequently recharged to a value of ±10 C over $20 < t < 40$ s. A tenuous electron density profile [*Pasko et al.*, 1995] and an ambient ion σ similar to that measured over thunderstorms [*Holzworth et al.*, 1985] are assumed. The altitudes of the thundercloud charges (20 km), the duration of charge accumulation and recovery (20 sec), and the 80-km top altitude are chosen to make the simulation feasible within available resources. The physical effects we consider do not critically depend on these parameters.

Figure 3a,b respectively show the time evolution of positive and negative thundercloud charges, as well as the E field and ν_{eff} at 70 km altitude, for -CG and +CG discharges. The -CG discharge (Figure 3a) leads to an increase in E field and heating with $\nu_{eff}(t)$ similar to the early/fast VLF event signature in Figure 1. The 'recovery' of ν_{eff} is due to the interplay between the assumed recharging of the thundercloud and the relaxation time of the E field at different altitudes [*Pasko et al.*, 1995]. For +CG (Figure 3b), the removal of the charge at the higher altitude leads to large heating transients but an eventual reduction in the E field and thus 'cooling' of the electrons ($\Delta\nu_{eff} < 0$). The build-up of the negative charge causes ν_{eff} to recover. The altitude of the removed charge (rather than its polarity) is the controlling factor; if the negative charge was on top (i.e., at 20 km altitude), then the $\nu_{eff}(t)$ shown in Figure 3a would occur when the lower altitude positive charge were removed, i.e., for a +CG discharge.

The top two panels of Figure 4 show the altitude profiles of ν_{eff} at $r = 0$ at different times and separately for the -CG and +CG cases. The curves for $t = 20$ s represent the pre-discharge heating level, which is substantially above the 'ambient' level and corresponds to the persistent presence of the thundercloud charge somewhere within the storm center. Following the discharge, large transient QE fields lead to large transient ν_{eff} for both the +CG and -CG cases at all altitudes. By $t = 21$ s, ν_{eff} for the -CG case is reduced to an altitude profile similar to that prior to discharge; however, ν_{eff} is nevertheless larger by a factor of ~ 3 at 73 km altitude from the pre-discharge level. For the +CG case ν_{eff} first increases and than rapidly (few hundred ms) decreases to a level substantially below the pre-discharge level; by $t = 21$ s, the electrons have 'cooled' below their pre-discharge level with ν_{eff} reduced by a factor of ~ 5 at 70 km altitude. The radial profiles of ν_{eff} corresponding to the same cases and times are shown in the bottom panels of Figure 4. The lateral extent of the region over which the ambient electrons are heated by the pre-discharge thundercloud fields (i.e., at t=20 s) is $\sim$ 50 to 100 km. For a brief (<1s) period immediately after the discharge, a much larger region (> 100 km) is heated, as indicated in Figure 1.

The net change in the amplitude of the VLF signal in an early/fast VLF event occurs in response to the difference in the heating level of electrons between the pre-discharge (i.e., $t = 20$ s) and post-discharge (i.e., $t > 21$ s) levels. Accordingly, we plot in Figure 5 the altitude and radial profiles of $\overline{\nu}_{eff} \equiv \Delta\nu_{eff}/\nu_{eff}$ for the same parameters as in Figure 4 and at $t = 21$ and 30 s. Values of $|\overline{\nu}_{eff}|$ of tens of percent remain in effect well after the initial transients (i.e., for $t > 21$ s). The ~100 km transverse extent of these heating/cooling disturbance regions are consistent with experimental data on VLF diffraction patterns. The magnitudes of $|\overline{\nu}_{eff}|$ are comparable to those produced by VLF transmitters, the ON/OFF effects of which are clearly detectable as VLF signal changes [*Rodriguez et al.*, 1994].

Our numerical modeling in this paper was limited to altitudes below 80 km, primarily for reasons of numerical efficiency (The difficulty here lies primarily in the vast differences between relaxation times of the medium at cloud tops versus ionospheric heights). For the ambient σ profile used [*Holzworth et al.*, 1984], the electron component of σ is dominant above ~65 km altitude. Since the main physical effect is the heating/cooling of the electrons, the altitude range over which the quantity $|\Delta\sigma_Q| = (\Delta\sigma_Q^- - \Delta\sigma_Q^+)$ is significant lies between ~65 km and ~75 km. At higher altitude the scale height of the electron component of σ causes the QE field to rapidly relax. For example, a factor of ~10 larger ion σ at altitude~40 to ~65 km [e.g., *Hale et al.*, 1981], extends the altitude range of significant $|\Delta\sigma_Q|$ to 70 to 80 km. In terms of the resultant effects on the subionospheric VLF signal, disturbances at altitudes closer to the nighttime reflection height would cause larger signal changes (i.e., larger ΔA). Thus, it is likely that early/fast VLF events are better detectable under ionospheric conditions of higher ambient ion σ. Preliminary calculations using three dimensional VLF propagation and scattering models [*Poulsen et al.*, 1993] for the propagation path from the NLK transmitter (24.8 kHz, Jim Creek, Washington) to Huntsville, Alabama and for a range of ν_{eff} profiles shown in Figures 3 through 5 and similar ones corresponding to a factor of ten higher ion σ at altitudes below ~65 km give ΔA values of 0.01 to 0.1 dB.

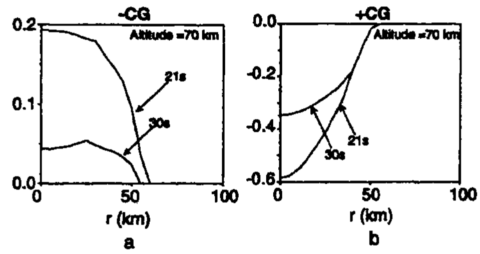

Figure 5. Altitude and radial profiles of $\overline{\nu}_{eff} = \Delta\nu_{eff}/\nu_{eff}$ at $t = 21$ and 30 s. (a) -CG, (b) +CG.

The relatively low values (compared to measured values of 0.2-0.8 dB) are due to the fact that the disturbances considered here are located largely below the nighttime VLF reflection height of ~85 km, since we have limited our self-consistent QE heating model to altitudes below 80 km, for purposes of numerical efficiency, as mentioned above.

Overall, the model results are consistent with early/fast VLF events being due to relatively small heating/cooling of ionospheric electrons above/below a quiescent heated level maintained by QE thundercloud fields.

Summary and Discussion

For the results in Figures 3 through 5, we have considered relatively weak lightning discharges (involving the removal of 10 C of charge in 1 ms) the transient QE fields of which are not intense enough to heat the electrons beyond the thresholds of attachment or ionization, so that the ionospheric σ changes are only due to the heating (or cooling) of electrons, but are nevertheless consistent with the observed characteristics of at least some early/fast VLF events. However, VLF events associated with intense lightning discharges and sprites [*Inan et al.*, 1995] may well be caused by a combination of heating and ionization changes.

Our results indicate that the lower ionospheric electrons above an active thunderstorm are persistently heated to a quiescent level well above the ambient. This heating is maintained by the relatively small lower ionospheric E fields which exist during the thundercloud charge accumulation phase, in a manner physically similar to fair weather E fields. The difference in the heating levels before and after the discharge transients account for the observed VLF signal changes, with the observed 10-100 s recoveries being due to the dissipation of charge or re-charging of the thundercloud. In rare cases, this re-charging may occur over many minutes, which accounts for the few observed cases of events with unusually long recovery times.

If thunderstorms maintain the overlying ionospheric electrons at a persistently heated quiescent level, significant changes in ionospheric chemistry might occur, given that ~2000 thunderstorms may be active around the globe at any given time [*Volland*, 1984]. For example, *Rodriguez and Inan* [1994] showed that similar heating produced by VLF transmitters might substantially reduce the three-body electron attachment rate and lead to depletions of electron density. Early/fast VLF events may thus be evidence for thermal and aeronomic coupling between the troposphere and the mesosphere/ionosphere, with potentially more important implications than the spectacular optical displays (i.e., sprites) observed during the brief transients immediately after lightning discharges.

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