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Lightning-driven electric fields measured in the lower ionosphere: Implications for transient luminous events

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[1] Transient luminous events above thunderstorms such as sprites, halos, and elves require large electric fields in the lower ionosphere. Yet very few in situ measurements in this region have been successfully accomplished, since it is typically too low in altitude for rockets and satellites and too high for balloons. In this article, we present some rare examples of lightning-driven electric field changes obtained at 75–130 km altitude during a sounding rocket flight from Wallops Island, Virginia, in 1995. We summarize these electric field changes and present a few detailed case studies. Our measurements are compared directly to a 2D numerical model of lightning-driven electromagnetic fields in the middle and upper atmosphere. We find that the in situ electric field changes are smaller than predicted by the model, and the amplitudes of these fields are insufficient for elve production when extrapolated to a 100 kA peak current stroke. This disagreement could be due to lightning-induced ionospheric conductivity enhancement, or it might be evidence of flaws in the electromagnetic pulse mechanism for elves.

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1. Introduction

[2] Recent experimental and theoretical studies have suggested that the middle and upper atmosphere of the earth is affected by processes in the troposphere. Well-known examples of this are transient luminous events (TLEs), such as sprites, halos, and elves, that are driven by thunderstorms and lightning [*Franz et al.*, 1990; *Fuknunishi et al.*, 1996; *Rodger*, 1999; *Lyons et al.*, 2003]. These TLEs occur at altitudes of about 40–95 km [*Sentman et al.*, 1995], which is a difficult region to probe, since it is typically too low in altitude for rockets and satellites and too high for balloons. This article presents some of the only published observations of lightning-driven electric fields measured in the upper mesosphere and lower ionosphere (75–130 km altitude). To our knowledge, excluding the work by *Barnum* [1999] that initiated our analysis, only *Kelley et al.* [1985] and *Holzworth et al.* [1985] have reported measurements of lightning-driven electric fields in this region. They discuss one electric field change in the lower ionosphere, a 20 mV/m change at 88 km altitude without lightning location data (see Figure 2 in the study by *Kelley et al.* [1985]). We investigate 60 lightning-driven electric field changes measured at 75–130 km altitude during the descent of the Thunderstorm-III rocket. These measurements are compared with the electrical breakdown and excitation strengths needed for optical emissions, as well as a numerical electromagnetic model, to examine TLE production mechanisms.

[3] Research into the physical nature of these TLEs has been rapid, however, nearly all this research interest and activity is associated with remote sensing and modeling [*Cummer and Lyons*, 2004, 2005; *Pasko et al.*, 1997]. This research has lead to some prominent TLE mechanisms, namely, the quasi-electrostatic field (QSF) model for sprites and halos and the electromagnetic pulse (EMP) model for elves. In the QSF model, large charge moment change lightning, which are predominately positive in polarity [*Boccippio et al.*, 1995], generate a large quasi-static electric field (an electrostatic field that decays in time due to the non-zero atmospheric conductivity) above the thundercloud, which leads to breakdown seen as sprites [*Roussel-Dupre and Gurevich*, 1996; *Pasko et al.*, 1997; *Lehtinen et al.*, 1997; *Rowland*, 1998]. Sprites are initiated in the mesosphere at altitudes of about 70–80 km [*Stanley et al.*, 1999; *Wescott et al.*, 2001; *McHarg et al.*, 2007]. After this initial breakdown, sprite streamers can propagate down to about 40 km and up to about 80 km [*Stanley et al.*, 1999; *Pasko et al.*, 1998; *McHarg et al.*, 2007], and a diffuse glow, known as the sprite halo, forms at about 80–90 km [*Wescott et al.*, 2001; *Pasko et al.*, 1998].

[4] Unlike sprites and jets which are likely caused by quasi-electrostatic fields, models and remote observations suggest that elves are the result of electromagnetic pulses

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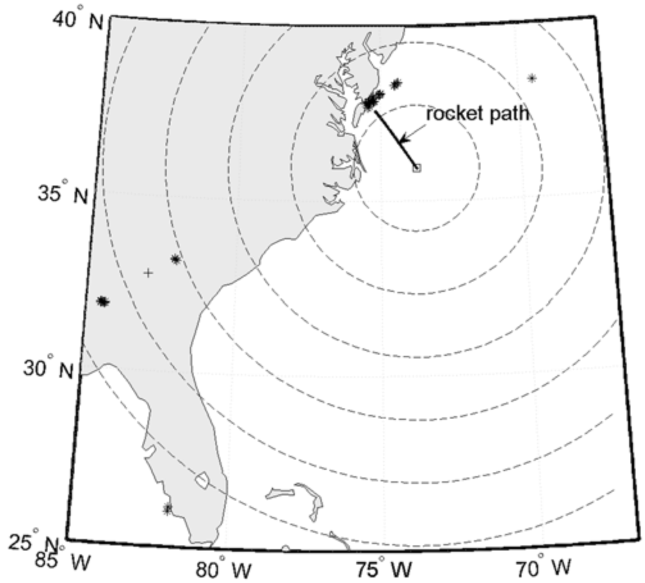

Figure 1. Cloud-to-ground lightning located by the National Lightning Detection Network while the Thunderstorm-III rocket was descending from 130 to 75 km in altitude and located near the square on the map. The solid line is the rocket path for the entire 10-minute flight. The dotted circles are spaced 200 km apart.

(EMPs) generated by large peak current lightning return strokes (both negative and positive polarity) exciting and ionizing the lower ionosphere at 90–100 km [*Fernsler and Rowland*, 1996; *Rowland*, 1998; *Barrington-Leigh and Inan*, 1999]. *Barrington-Leigh and Inan* [1999] studied 86 events detected by the National Lightning Detection Network (NLDN) with peak currents greater than 38 kA and found correlated elves for 52% of these, and for peak currents above 57 kA, all 34 NLDN flashes had correlated elves. They found that the lateral extent of the elves ranged from 200–700 km. A more recent study [*Cheng et al.*, 2007] generally agreed with these results, setting the threshold for EMP induced conductivity perturbations in the ionosphere at about 40–60 kA.

[5] However, these remote data and numerical models cannot directly address how these TLEs are generated. Only nearby in situ measurements can determine if the magnitudes and relaxation times of the nearby lightning-driven quasi-electrostatic fields (QSF) and electromagnetic pulses (EMPs) above thunderstorms are sufficient for TLE production and growth. Recent studies have reported lightning-driven QSFs and EMPs in the stratosphere at about 35 km altitude [*Holzworth et al.*, 2005; *Thomas et al.*, 2005a, 2005b]. We present, for the first time, in situ measurements in the upper mesosphere and lower ionosphere that have been analyzed to specifically address TLE production. Since our measurements are at horizontal distances of greater than about 250 km, we focus primarily on the weaker ionization TLEs, such as elves and sprite halos. Our work is guided by addressing the following questions:

[6] 1. Are the magnitudes and durations of lightning-driven electric field changes sufficient to generate transient luminous events, especially elves and sprite halos?

[7] 2. Do electromagnetic models and other experiments agree with these measurements?

[8] 3. Do lightning discharges change the conductivity in the lower ionosphere resulting in reduced or increased electric field changes?

2. Thunderstorm-III Sounding Rocket

[9] Thunderstorm-III (NASA sounding rocket 36.111) was launched from Wallops Island, VA, USA at local time 21:13 on 1 September 1 1995 (UT 01:13, 2 September) over an active thunderstorm. Electric fields (10 Hz–2 MHz), optical power, low-energy electrons, electron density, and dc to VLF magnetic fields were measured on-board the rocket at altitudes of 75–400 km. However, some of these parameters were only successfully measured for part of the flight. More than 700 electric field changes correlated in time with NLDN-located cloud-to-ground lightning were observed during the 10-minute flight.

[10] Previous studies using Thunderstorm-III data have focused mainly on measurements above 130 km in altitude [*Barnum*, 1999; *Kelley et al.*, 1997]. *Barnum* [1999] provided an overview of the Thunderstorm-III campaign with a detailed description of the dc to VLF electric field measurements, and they examined pulses aligned with the geomagnetic field occurring up to 230 km altitude in the lower F region that were first observed during previous rocket flights [*Kelley et al.*, 1985, 1990]. Additionally, *Barnum* [1999] presented a few examples of lightning-driven fields below 90 km altitude, which initiated our study. *Kelley et al.* [1997] described the LF to MF (20 kHz–2 MHz) lightning-driven electric fields in the F-region, including the first measurements of upward-going whistler waves with a nose-whistler wave shape.

[11] This study focuses on 60 ELF to VLF electric field changes correlated with cloud-to-ground (CG) lightning located by NLDN and measured at 75–130 km altitude during the descent of the rocket. Figure 1 is a map showing the location of the NLDN CG strokes along with the rocket path. A square has been placed at the location of the rocket when the measurements presented in this study occurred and dashed circles are placed at 200 km increments from this location. Most of the NLDN located lightning activity occurs near Wallops Island, at a horizontal distance of about 250–300 km, but there are other smaller storms producing lightning farther away. In addition to providing CG lightning location, NLDN estimates the return stroke peak current.

[12] The electric fields were measured using the double Langmuir probe technique with three opposing pairs of conducting spheres measuring the 3-axis (vector) electric field [*Holzworth and Bering*, 1998; *Thomas et al.*, 2004]. Each sphere measures the voltage difference between itself and the payload ground, and the electric field is then determined by taking the difference between the two opposing spheres and dividing by their separation distance [see *Barnum*, 1999]. The VLF electric field channels we present here were low-pass filtered using a 3-pole Butterworth with 3 dB roll-off at 18 kHz and sampled at 40 kHz. Electric fields above about 130 km altitude on the ascent and down to about 75 km altitude on the descent were accurately measured by the VLF channels. The rocket

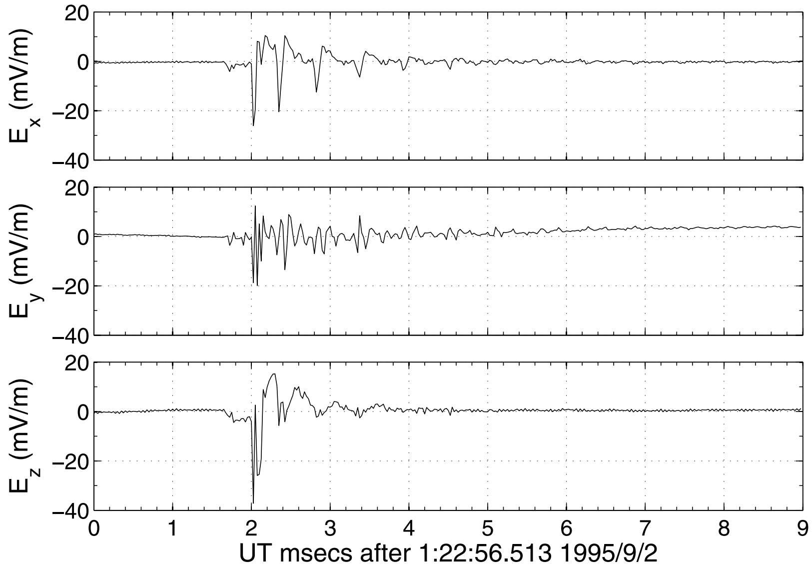

Figure 2. Example of a regime 1 electric field change at 81.4 km altitude, 257 km horizontal distance driven by a −31.7 kA CG.

payload was spin-aligned with the geomagnetic field to within 10–20 degrees.

3. In Situ Electric Field Measurements

[13] Figures 2 to 6 show examples of lightning-driven electric field changes measured in the upper mesosphere and lower ionosphere during Thunderstorm-III. For each case, the bottom panel shows the electric field (E_z) measured along the rocket payload axis, which is parallel to the geomagnetic field and has an inclination angle of about 67^0 with the earth's surface. A positive E_z indicates an electric field that is directed upward, away from the earth. The top and middle panels are electric field components (E_x and E_y) perpendicular to the rocket payload axis and each other. Unfortunately, for these low altitude measurements, the compass was no longer functioning and the orientation of E_x and E_y as the rocket rotated along its axis is not known. Hence it is not possible to change the coordinate system such that E_z is directed perpendicular to the earth's surface, which would be more convenient for studying TLEs.

[14] In analyzing the 60 lightning-driven electric field changes at 75–130 km altitude, five regimes could be identified by examining geomagnetic field aligned E_z waveforms. Using case studies, we describe these regimes below. We also summarize our findings in Table 1.

[15] Regime 1, altitude = 75–85 km, horizontal distance = 255–275 km: Large electromagnetic (EM) sferics that are initially downward (for -CG strokes) and no quasi-electrostatic fields (QSF). Figure 2 is an example of a regime 1 electric field change measured at 81.4 km altitude, 257 km horizontal distance driven by a −31.7 kA CG. The E_z component EM sferic is initially downward with a peak-to-peak magnitude of about 50 mV/m. There is no slow, QSF change in the E_z channel. The perpendicular field changes (E_x and E_y) are also EM sferics with magnitudes of about 30 mV/m, which are similar to the E_z magnitude. The apparent QSF change in E_y is likely due to payload noise, since similar changes are seen in E_y before and after this sferic when no lightning is occurring. In this study, we use the term sferic to describe lightning-driven radiation that has numerous oscillations in time.

[16] Regime 2, altitude = 85–100 km, horizontal distance = 255–275 km: Large electromagnetic sferics that are initially downward (for -CG strokes) and large QSFs. Figure 3 is an example of a regime 2 electric field change measured at 89.8 km altitude, 262 km horizontal distance driven by a −19.9 kA CG. The E_z component EM sferic is initially downward with a peak-to-peak magnitude of about 15 mV/m. This EM sferic is followed by a slow, positive QSF change of about 3 mV/m. E_x and E_y include only EM sferics (no QSFs) with magnitudes comparable to E_z of about 7–15 mV/m.

[17] Regime 3, altitude = 100–130 km, horizontal distance = 255–275 km: Weak unipolar electromagnetic pulses that are downward (for -CG strokes) and no QSF change. Figure 4 is an example of a regime 3 electric field change measured at 115.4 km altitude, 247 km horizontal distance driven by a −24.8 kA CG. The magnitude of the downward pulse is about 1.3 mV/m. These unipolar pulses are similar to those observed in the F-region during this flight [*Barnum*, 1999] and during a previous rocket flight above a thunderstorm [*Kelley et al.*, 1990]. E_x and E_y are sferics with lower frequencies than in regimes 1 and 2 and

Table 1. Five Regimes of Lightning-Driven E_z (Geomagnetic Field Aligned) Waveforms[a]

Regime	Altitude (km)	Range (km)	EM	QSF	Waveform	Initial Polarity
I	75–85	255–275	Y	N	Sferic	Down
II	85–100	255–275	Y	Y	Sferic	Down
III	100–130	255–275	Y	N	Unipolar	Down
IV	75–100	800–1400	Y	N	Bipolar	Down
V	100–130	800–1400	Y	N	Bipolar	Up

[a]In this study, we use the term sferic to describe lightning-driven radiation that has numerous oscillations in time.

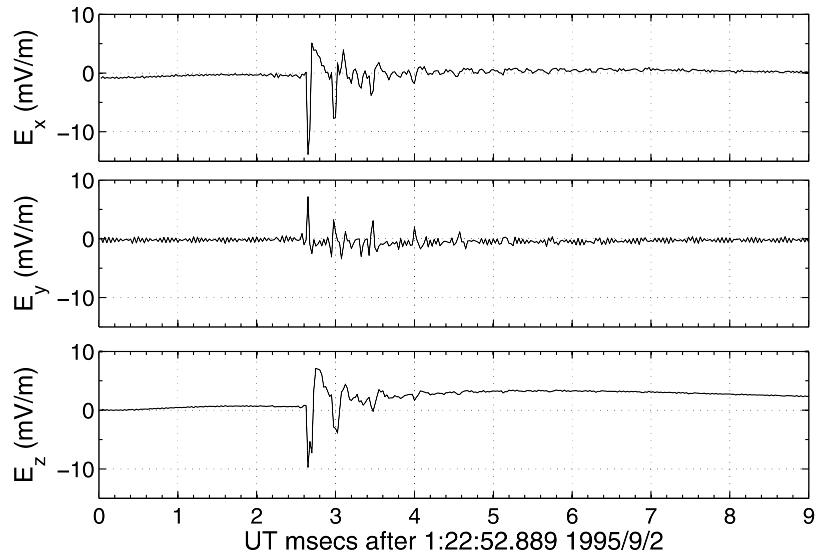

Figure 3. Example of a regime 2 electric field change at 89.8 km altitude, 262 km horizontal distance driven by a −19.9 kA CG.

magnitudes of about 8 mV/m, which is much larger than the E_z magnitude.

[18] Regime 4, altitude = 75–100 km, horizontal distance = 800–1400 km: Bipolar electromagnetic pulses that are initially downward (for -CG strokes) and no QSF change. Figure 5 is an example of a regime 4 electric field change measured at 81.0 km altitude, 821 km horizontal distance driven by a −22.7 kA CG. The peak-to-peak magnitude of the bipolar pulse is about 7 mV/m. E_x and E_y are sferics with lower frequencies than in regimes 1 and 2 and magnitudes of about 5–7 mV/m, which is similar to the E_z magnitude. Like in regime 1, the apparent QSF change in E_y is likely caused by payload noise, since similar changes are seen in E_y before and after this sferic when no lightning is occurring.

[19] Regime 5, altitude = 100–130 km, horizontal distance = 800–1400 km: Bipolar electromagnetic pulses that are initially upward (for -CG strokes) and no QSF change. Figure 6 is an example of a regime 5 electric field change measured at 101.2 km altitude, 1085 km horizontal distance driven by a −30.0 kA CG. The peak-to-peak magnitude of the bipolar pulse is about 1.1 mV/m. E_x and E_y are bipolar pulses with slow tails with magnitudes larger than E_z of about 3 mV/m.

4. Comparing In Situ Electric Field Measurements and a Numerical Model

[20] The five regimes outlined above show how lightning generated fields in the lower ionosphere depend critically on altitude and horizontal distance. Each regime is worthy of its own detailed study, but this is beyond the scope of this article. We now focus our attention on regimes 1 and 2 where TLEs occur and compare the vertical electric field waveforms in Figures 2 and 3 with a numerical model.

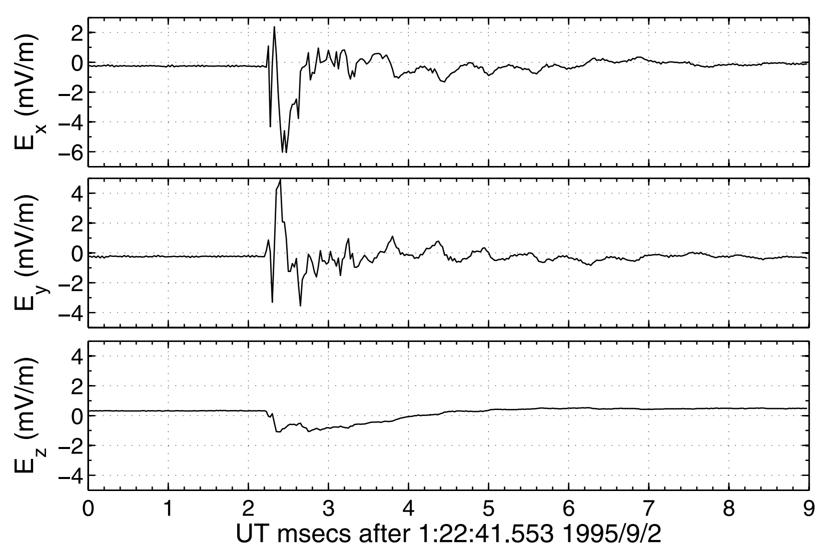

Figure 4. Example of regime 3 electric field change at 115.4 km altitude, 247 km horizontal distance driven by a −24.8 kA CG.

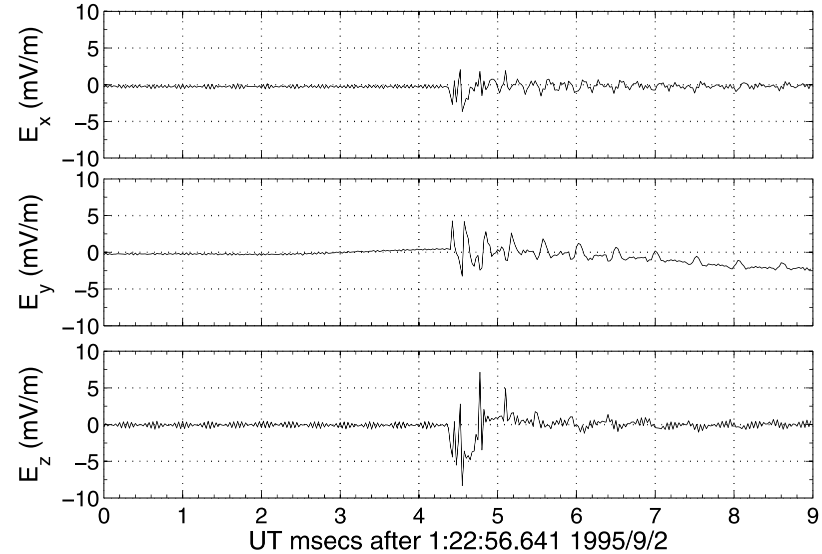

Figure 5. Example of a regime 4 electric field change at 81.0 km altitude, 821 km horizontal distance driven by a −22.7 kA CG.

[21] We employ the numerical electromagnetic simulation of *Cho and Rycroft* [1998] that solves Maxwell's equations using an axi-symmetric two-dimensional cylindrical coordinate system with grid-spacing of 1 km in both dimensions. The atmospheric conductivity is initialized according to Figure 1 in the study by *Cho and Rycroft* [1998] and evolves in time due to the lightning-driven electromagnetic field via heating, ionization, and attachment processes. The simulation of *Cho and Rycroft* [1998] does not include the nonlinear effects and spatial resolution to properly model streamer dynamics in sprites. More sophisticated models [e.g., *Liu and Pasko*, 2004] have been developed that can better describe these streamer processes. Nonetheless, the model of *Cho and Rycroft* [1998] is adequate for weak ionization cases, such as in elves and sprite halos, that are the primary focus of our work. In Figures 7 and 8, we compare the vertical electric field measured at 81.4 km and 89.8 km altitude (regime 1 and 2; Figures 2 and 3, respectively) with this model.

[22] According to the model of *Cho and Rycroft* [1998], the current waveform as a function of time ($I(t)$) of the lightning stroke has the form

$$I(t) = Q\frac{1}{12}\frac{1}{\tau}\left(\frac{t}{\tau}\right)\exp\left(-\left(\frac{t}{\tau}\right)^{1/2}\right) \qquad (1)$$

where Q is the charge removed and τ is a time constant. The maximum value of this current waveform, or peak current (I_p), is

$$I_p = I(t = 4\tau) = 0.0451 \times \frac{Q}{\tau}. \qquad (2)$$

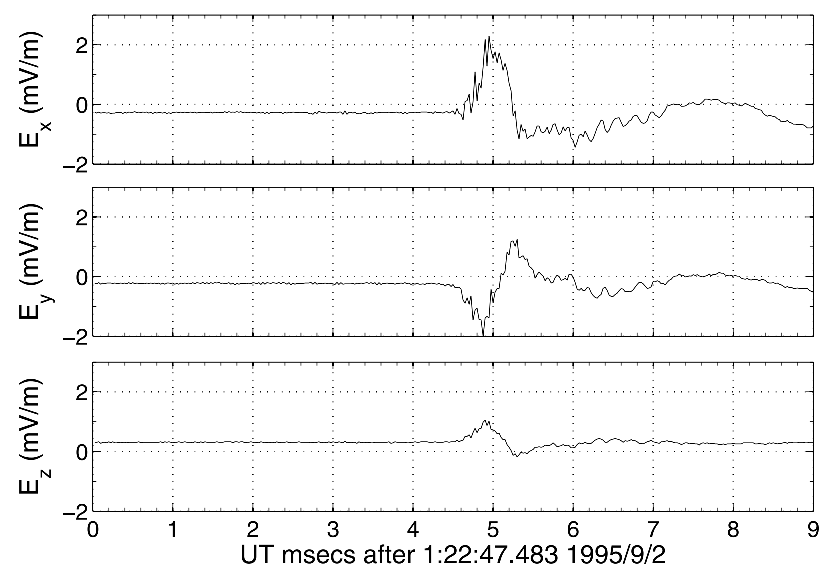

Figure 6. Example of a regime 5 electric field at 102.2 km altitude, 1085 km horizontal distance driven by a −30 kA CG.

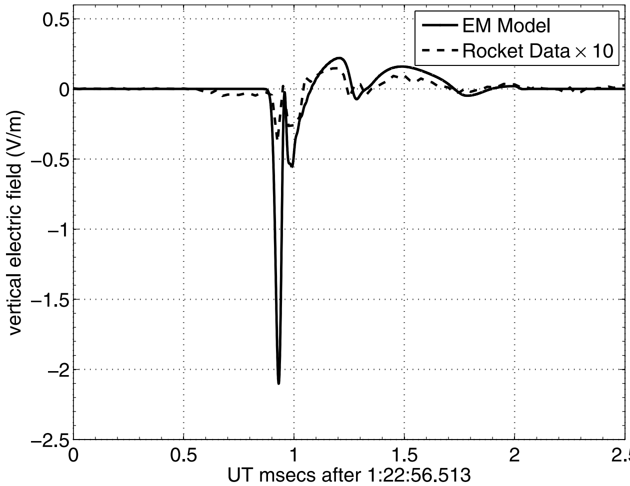

Figure 7. The vertical electric field driven by a −31.7 kA -CG stroke measured at Z = 81.4 km and R = 257 km (regime 1) compared directly with a numerical model of lightning driven electromagnetic fields [*Cho and Rycroft*, 1998] in the upper atmosphere.

Using τ = 15 microseconds, which would approximately give the current waveform for a typical -CG stroke, and the peak current values determined by NLDN (−31.7 and −19.9 kA) we calculate the charge removed Q to be 10.5 and 6.6 C for the events in Figures 7 and 8, respectively. These value of Q and τ are used as the input parameters for the numerical simulation.

[23] The rocket data are dc to 18 kHz. Therefore the model output have been low-pass filtered at 18 kHz for direct comparison. Note that the rocket data in Figures 7 and 8 are multiplied by a factor of 10. In both cases, the in situ electric fields and the modeled field have similar waveforms, but the in situ fields are more than 10 times smaller in amplitude for all T-III measurements at 75−90 km altitude. This disagreement between the rocket measurements and the numerical simulation could be due to the atmospheric conductivity being much higher than employed in the model.

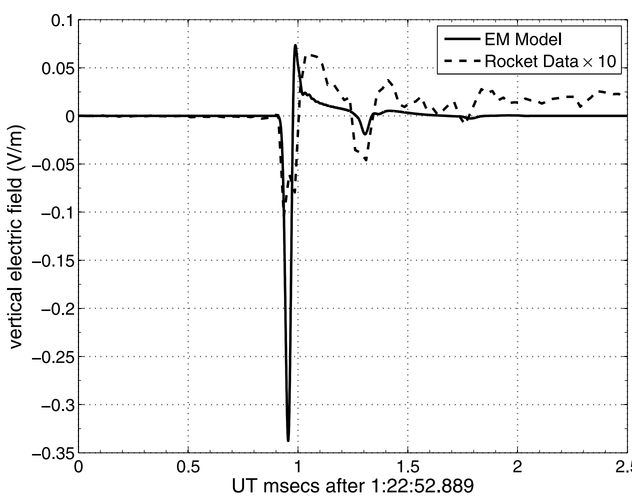

Figure 8. The vertical electric field driven by a −19.9 kA -CG stroke measured at Z = 89.8 km and R = 262 km (regime 2) compared directly with a numerical model of lightning driven electromagnetic fields [*Cho and Rycroft*, 1998] in the upper atmosphere.

[24] The waveforms in Figures 7 and 8 are well understood [*Schonland et al.*, 1940; *McDonald et al.*, 1979]. The initial downward spikes in Figures 7 and 8 are due to electromagnetic radiation directly from the lightning channel. These are followed by upward spikes that are due to the radiation reflecting off of the conductive earth before reaching the rocket altitude. The downward and upward pulses that follow are the result of further reflections off of the earth and the ionosphere at 90−100 km altitude.

5. Discussion

[25] Lightning strokes with peak currents greater than about 40 kA have been observed to trigger elves [*Barrington-Leigh and Inan*, 1999; *Barrington-Leigh et al.*, 2001; *Cheng et al.*, 2007]. All of the strokes examined in this study have peak currents below this threshold. Hence we must extrapolate our measurements. Using the maximum electric field measured by the rocket at 81, 84, and 90 km altitude and the numerical model of *Cho and Rycroft* [1998], we estimate the maximum total electric field for a −100 kA CG stroke. To accomplish this, we scale the rocket measurements of electric fields driven by lightning with peak currents of 15−30 kA to 100 kA via the numerical model using a horizontal distance of 260 km. More precisely, this can be expressed as

$$\widetilde{E}_{rocket} = E_{rocket} \times \left(\frac{E_{100}}{E_{model}}\right) \qquad (3)$$

where $\widetilde{E}_{rocket}$ is the rocket measurement scaled to 100 kA, E_{rocket} is the maximum field measured by the rocket, E_{100} is

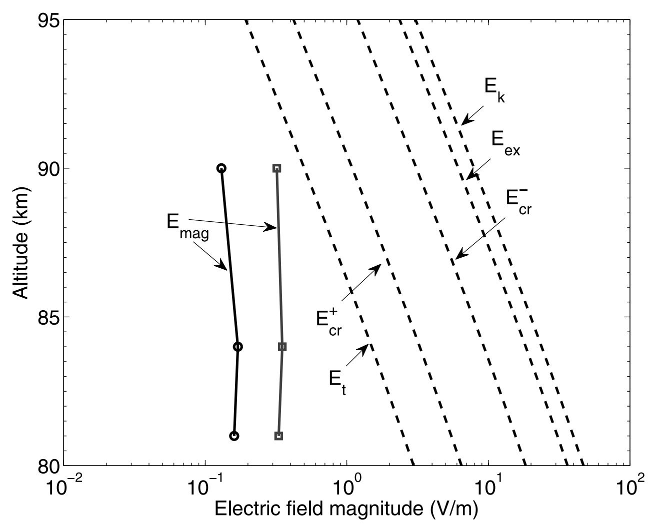

Figure 9. The maximum electric field for a −100 kA CG stroke is estimated using the maximum electric field measured by the rocket and the numerical EM model of *Cho and Rycroft* [1998] at 81, 84, and 90 km altitude and horizontal distances of 260 km (line with circles) and 100 km (line with squares).

the maximum field for a 100 kA stroke indicated by the model, and E_{model} is the maximum field indicated by the model for the peak current of the observed stroke. We also use the numerical model to extrapolate this estimate to a horizontal distance of 100 km.

[26] In Figure 9, the estimated electric field at a horizontal distance of 260 km (line with circles) and 100 km (line with squares) is compared to the conventional breakdown (ionization) threshold (E_k), the N^2 first positive excitation threshold (E_{ex}), the negative streamer threshold (E_{cr}^-), the positive streamer threshold (E_{cr}^+), and the relativistic runaway threshold (E_t) [*Pasko et al.*, 1997]. Hence the estimated electric field magnitude is 10 to 100 times smaller than needed for ionization (E_k) or excitation (E_{ex}) processes that would generate elves. This disagrees with the EMP model for elves at this altitude and horizontal distance imaged during other campaigns driven by CG lightning with peak currents greater than 40–60 kA [*Barrington-Leigh and Inan*, 1999; *Barrington-Leigh et al.*, 2001]. Additionally, these estimated electric fields, which range from about 0.1–0.4 V/m, are more than an order of magnitude lower than the electric field of 7.8 V/m that was estimated from photometric emissions of elves measured by the FORMOSAT-2 satellite [*Mende et al.*, 2005]. Although the magnitudes are too low, the time duration of the electric field pulses observed on the rocket are in good agreement with observations. The initial downward spike of the field lasts for a few hundred microseconds, which agrees with the model of *Cho and Rycroft* [1998] and imaging of elves [*Barrington-Leigh and Inan*, 1999; *Barrington-Leigh et al.*, 2001].

[27] These electric fields, which are smaller than predicted by the model of *Cho and Rycroft* [1998] and insufficient to generate elves, might be explained by elevated atmospheric conductivity. This higher conductivity might be the result of previous lightning strokes from the same storm ionizing the atmosphere and increasing the electron density, and in turn, the conductivity. Work by *Rodger et al.* [2001] showed that this is possible by modeling the effect of lightning on the middle atmosphere during an entire storm over the US High Plains. Another possibility is that the ambient conductivity, which can vary due to solar-terrestrial interactions [*Holzworth and Hu*, 1995], was much higher than employed in the model. Although, the level of geomagnetic activity was low during 00–03 UT on 2 September 1995 with K_p = 1. We tried increasing the atmospheric conductivity profile by various multiplicative constants for altitudes up to 100 km to test this hypothesis. However, this caused the waveforms of the rocket data and model output to disagree greatly. Thus, if an increased conductivity is occurring, it is more complicated than simply multiplying the profile by a constant. This is expected since the chemistry that governs the conductivity is anisotropic with altitude [*Rodger et al.*, 2001].

[28] An instrumentation problem might also explain these smaller than predicted electric fields. If the low-pass frequency response of the double Langmuir probe electric field sensor was below 18 kHz, then the lightning driven electromagnetic pulse would have been poorly resolved. However, it is extremely unlikely that this could explain the 1–2 order of magnitude disagreement with the numerical model since the frequency response of the probes was carefully tested as discussed by *Barnum* [1999].

[29] Electric fields changes measured at 85–100 km altitude and 255–275 km horizontal distance (regime 2, Figure 3) have surprisingly large QSF components. Indeed, they are almost as large as the EM fields, which is not predicted by the fully electromagnetic model of *Cho and Rycroft* [1998]. QSFs should increase with decreasing conductivity, and thus should be larger in regime 1 (<85 km altitude). The lack of large QSFs at these lower altitudes could be indicative of a conductivity profile inversion in the lower ionosphere possibly due to the thunderstorm effects described above. Although the strengths of the QSFs at these horizontal distances are many orders of magnitude lower than the conventional breakdown threshold, a naive extrapolation of our measurements to directly above the lightning locations would suggest larger than predicted fields where sprites occur. This would have implications for sprite and halo development. Of course, electric field measurements directly above lightning in the mesosphere/lower ionosphere are needed to test our simple extrapolation. Moreover, perhaps these large QSFs add to the EM fields to allow the total field magnitude to surpass the excitation threshold needed for elves.

[30] There have been previous comparisons of these rocket measurements with numerical simulations. *Barnum* [1999] compared measurements above about 100 km to a full-wave model of lightning-driven electromagnetic fields developed by *Miyamura et al.* [1996]. They found that the model and data generally agree above about 250 km, and from 100–250 km the modeled fields were two to ten times larger than the rocket measurements (see Tables 8.1 and 8.2 in the study by *Barnum* [1999]). Since no comparison was made for the 80 to 90 km altitude range, we cannot directly compare the *Miyamura et al.* [1996] and *Cho and Rycroft* [1998] model results.

6. Conclusion

[31] Electric field change characteristics in the upper mesosphere and lower ionosphere can be grouped into five different regimes based on altitude and distance from the causative lightning stroke (see section 3 for summary). Electric field changes measured at 75–100 km altitude and about 260 km horizontal distance have similar waveforms but much smaller amplitudes than predicted by the numerical model of *Cho and Rycroft* [1998]. The electric field changes measured by the rocket are extrapolated to a 100 kA peak current negative cloud-to-ground stroke using this model. These extrapolated electric fields are 1 to 2 orders of magnitude smaller than the breakdown thresholds needed for TLEs. Thus our results disagree with the electromagnetic pulse (EMP) mechanism for elves that have been observed at the same altitudes and horizontal distances as our in situ measurements [*Barrington-Leigh and Inan*, 1999]. This disagreement might suggest that the thunderstorm increased the atmospheric conductivity which, in turn, weakened the electric field magnitude, but it may be indicative of fundamental shortcomings in the EMP model. From the unexpectedly large quasi-electrostatic fields that we measured in regime 2, we hypothesize that QSFs can add to the EMP to allow the total field to surpass the

threshold needed for optical emissions. In totality, our results highlight the need for future in situ exploration of the lower ionosphere above thunderstorms.

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[33] Zuyin Pu thanks the reviewers for their assistance in evaluating this paper.

References

Barnum, B. H. (1999), Electromagnetic and optical characteristics of lightning measured in the earth's ionosphere, Ph.D. thesis, Univ. of Washington, Geophys. Program, Seattle, Wash.

Barrington-Leigh, C. P., and U. S. Inan (1999), Elves triggered by positive and negative lightning discharges, *Geophys. Res. Lett.*, *26*, 683–686.

Barrington-Leigh, C. P., U. S. Inan, and M. Stanley (2001), Identification of sprites and elves with intensified video and broadband array photometry, *J. Geophys. Res.*, *106*, 1741–1750.

Boccippio, D., E. Williams, S. Heckman, W. Lyons, I. Baker, and R. Boldi (1995), Sprites, ELF transients, and positive ground strokes, *Science*, *269*, 1088.

Cheng, Z., S. A. Cummer, H. T. Su, and R. R. Hsu (2007), Broadband VLF measurement of D region ionospheric perturbations caused by lightning electromagnetic pulses, *J. Geophys. Res.*, *112*, A06318, doi:10.1029/2006JA011840.

Cho, M., and M. Rycroft (1998), Computer simulation of the electric field structure and optical emission from cloud-top to the ionosphere, *J. Atmos. Sol. Terr.*, *60*, 871–888.

Cummer, S. A., and W. A. Lyons (2004), Lightning charge moment changes in U.S. High Plains thunderstorms, *Geophys. Res. Lett.*, *31*, L05114, doi:10.1029/2003GL019043.

Cummer, S. A., and W. A. Lyons (2005), Implications of lightning charge moment changes for sprite initiation, *J. Geophys. Res.*, *110*, A04304, doi:10.1029/2004JA010812.

Fernsler, R. F., and H. L. Rowland (1996), Models of lightning-produced sprites and elves, *J. Geophys. Res.*, *101*, 29,653–29,662.

Franz, R. C., R. J. Nemzek, and J. R. Winckler (1990), Television image of a large electrical discharge above a thunderstorm system, *Science*, *249*, 48–51.

Fuknunishi, H., Y. Takahashi, M. Kubota, K. Sakanoi, U. S. Inan, and W. A. Lyons (1996), Elves: Lightning-induced transient luminous events in the lower ionosphere, *Geophys. Res. Lett.*, *23*, 2157–2160.

Holzworth, R. H., and E. Bering (1998), Ionospheric electric fields from stratospheric balloon-borne probes, in *Measurement Techniques in Space Plasmas: Fields*, *Geophys. Monogr. Ser.*, vol. 103, pp. 79–84, AGU, Washington, D. C.

Holzworth, R. H., and H. Hu (1995), Global electrodynamics from superpressure balloons, *Adv. Space Res.*, *16*, 131–140.

Holzworth, R. H., M. C. Kelley, C. L. Siefring, L. C. Hale, and J. D. Mitchell (1985), Electrical measurements in the atmosphere and the ionosphere over an active thunderstorm. 2: Direct current electric fields and conductivity, *J. Geophys. Res.*, *90*, 9824–9830.

Holzworth, R. H., M. P. McCarthy, J. N. Thomas, J. Chin, T. M. Chinowsky, M. J. Taylor, and O. Pinto Jr. (2005), Strong electric fields from positive lightning strokes in the stratosphere, *Geophys. Res. Lett.*, *32*, L04809, doi:10.1029/2004GL021554.

Kelley, M. C., et al. (1985), Electrical measurements in the atmosphere and the ionosphere over an active thunderstorm. 1: Campaign overview and initial ionospheric results, *J. Geophys. Res.*, *90*, 9815–9823.

Kelley, M. C., J. G. Ding, and R. H. Holzworth (1990), Intense ionospheric electric and magnetic field pulses generated by lightning, *Geophys. Res. Lett.*, *17*, 2221–2224.

Kelley, M. C., S. D. Baker, R. H. Holzworth, P. Argo, and S. A. Cummer (1997), LF and MF observations of lightning electromagnetic pulse at ionospheric altitudes, *Geophys. Res. Lett.*, *24*, 1111–1114.

Lehtinen, N. G., T. F. Bell, V. P. Pasko, and U. S. Inan (1997), A two-dimensional model of runaway electron beams driven by quasi-electrostatic thundercloud fields, *Geophys. Res. Lett.*, *24*, 2639–2642.

Liu, N., and V. P. Pasko (2004), Effects of photoionization on propagation and branching of positive and negative streamers in sprites, *J. Geophys. Res.*, *109*, A04301, doi:10.1029/2003JA010064.

Lyons, W. A., T. E. Nelson, R. A. Armstrong, V. P. Pasko, and M. A. Stanley (2003), Upward electrical discharges from thunderstorm tops, *Bull. Am. Meteorol. Soc.*, *84*(4), 445–454.

McDonald, T. B., M. A. Uman, J. A. Tiller, and W. H. Beasley (1979), Lightning location and lower-ionosphere height determined from two-station magnetic field measurements, *J. Geophys. Res.*, *84*, 1727–1734.

McHarg, M. G., H. C. Stenbaek-Nielsen, and T. Kammae (2007), Observations of streamer formation in sprites, *Geophys. Res. Lett.*, *34*, L06804, doi:10.1029/2006GL027854.

Mende, S. B., H. U. Frey, R. R. Hsu, H. T. Su, A. B. Chen, L. C. Lee, D. D. Sentman, Y. Takahashi, and H. Fukunishi (2005), D region ionization by lightning-induced electromagnetic pulses, *J. Geophys. Res.*, *110*, A11312, doi:10.1029/2005JA011064.

Miyamura, K., I. Nagano, S. Yagitani, and Y. Murakami (1996), Full wave calculation of 3d vlf/lf wave fields radiated from a lightning discharge, in *Proceedings of ISAP*, pp. 701–704, Chiba, Japan.

Pasko, V. P., U. S. Inan, T. F. Bell, and Y. N. Taranenko (1997), Sprites produced by quasi-electrostratic heating and ionization in the lower ionosphere, *J. Geophys. Res.*, *102*, 4529–4562.

Pasko, V. P., U. S. Inan, and T. F. Bell (1998), Spatial structure of sprites, *Geophys. Res. Lett.*, *25*, 2123–2126.

Rodger, C. J. (1999), Red sprites, upward lightning, and VLF perturbations, *Rev. Geophys.*, *37*, 317–336.

Rodger, C. J., M. Cho, M. A. Clilverd, and M. J. Rycroft (2001), Lower ionospheric modification by lightning-EMP: Simulation of the night ionosphere over the United States, *Geophys. Res. Lett.*, *28*, 199–202.

Roussel-Dupre, R., and A. V. Gurevich (1996), On runaway breakdown and upward propagating discharges, *J. Geophys. Res.*, *101*, 2297–2311.

Rowland, H. L. (1998), Theories and simulations of elves, sprites and blue jets, *J. Atmos. Sol. Terr.*, *60*, 831–844.

Schonland, B. F. J., J. S. Elder, D. G. Hodges, W. E. Phillips, and J. W. van Wyk (1940), The waveform of atmospherics at night, *Proc. R. Soc., A*, *176*, 180–202.

Sentman, D. D., E. M. Wescott, D. L. Osborne, D. L. Hampton, and M. J. Heavner (1995), Preliminary results from the Sprites94 aircraft campaign, 1: Red sprites, *Geophys. Res. Lett.*, *22*, 1205–1208.

Stanley, M., P. Krehbiel, M. Brook, C. B. Moore, W. Rison, and B. Abrahams (1999), High speed video of initial sprite development, *Geophys. Res. Lett.*, *26*, 3201–3204.

Thomas, J. N., R. H. Holzworth, and J. Chin (2004), A new high-voltage electric field instrument for studying sprites, *IEEE Trans. Geosci. Remote Sens.*, *42*(7), 1399–1404.

Thomas, J. N., R. H. Holzworth, M. P. McCarthy, and O. Pinto Jr. (2005a), Predicting lightning-driven quasi-electrostatic fields at sprite altitudes using in situ measurements and a numerical model, *Geophys. Res. Lett.*, *32*, L10809, doi:10.1029/2005GL022693.

Thomas, J. N., R. H. Holzworth, M. P. McCarthy, and O. Pinto Jr. (2005b), Lightning sferics and stroke delayed pulses measured in the stratosphere: Implications for mesospheric currents, *Geophys. Res. Lett.*, *32*, L22807, doi:10.1029/2005GL024629.

Wescott, E. M., H. C. Stenbaek-Nielsen, D. D. Sentman, M. J. Heavner, D. R. Moudry, and F. T. S. Sabbas (2001), Triangulation of sprites, associated halos and their possible relation to causative lightning and micrometeors, *J. Geophys. Res.*, *106*, 10,467–10,477.

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