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Broadband very low frequency measurement of *D* region ionospheric perturbations caused by lightning electromagnetic pulses

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[1] Prompt early/fast perturbations on narrowband sub-ionospherically propagating very low frequency (VLF) signals are the primary evidence for the direct coupling of energy released by lightning discharge to the lower ionosphere. Different mechanisms have been advanced to explain the fast ionospheric perturbations, such as heating and ionization from the lightning electromagnetic pulse (EMP) associated with elves or from quasielectrostatic fields associated with sprites and halos. By comparing the broadband VLF spectra (3–25 kHz) of lightning discharges that shortly followed high peak current lightning discharges with the spectra of lightning discharges that did not, we detect *D* region perturbations caused by these intense lightning strokes over the U.S. East Coast and the U.S. High Plains. The electron density changes are measured by analyzing the broadband VLF propagation changes, and the perturbed electron density profiles from both regions are found to be consistent with those theoretically predicted for strong lightning EMP. In one case, a *D* region perturbation was detected following a lightning stroke that produced an isolated elve recorded by the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) instrument on the FORMOSAT-2 satellite, confirming the EMP origins of these ionospheric perturbations. For this case, we measure electron density enhancements of 460 cm^{-3} averaged over a 220-km radius and 10-km-high perturbation region, in good agreement with the 210 cm^{-3} measured optically by Mende et al. (2005) for a different elve event. The characteristics of the lightning responsible for these ionospheric perturbations are investigated by comparing high peak current lighting strokes that do and do not generate detectable ionospheric perturbations.

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1. Introduction

[2] Strong lightning discharges can directly heat and ionize the lower ionosphere. The first experimental evidence of the impulsive direct coupling of energy released by lightning discharge to the lower ionosphere was reported by *Armstrong* [1983] in the form of early/fast perturbations of narrowband sub-ionospherically propagating very low frequency (VLF) signals. Observed events exhibit rapid changes that begin within 20 ms of the causative lightning [*Inan et al.*, 1988], followed by a relatively slow recovery (typically 10–100 s) [*Inan et al.*, 1993]. The physical mechanism underlying these events is still not quantitatively understood and remains somewhat controversial.

[3] *Inan et al.* [1993] suggested that fast narrowband VLF perturbations are produced by ionization changes in the *D* region over the thunderstorm because of the heating of ionospheric electrons by the electromagnetic pulse (EMP) from lightning (in a manner similar to that which produce fast optical emissions called elves [*Fukunishi et al.*, 1996]) with the ionospheric disturbances expanding to radial distances of up to 150 km [*Inan et al.*, 1996a]. *Taranenko et al.* [1993] demonstrated that lightning EMP could cause significant ionization, especially above 85 km, using a fully kinetic one-dimensional formulation of the EMP-ionosphere interaction. However, ionospheric perturbations detected through narrowband VLF measurements have rarely been observed in association with elves. *Hobara et al.* [2001] reported that small narrowband VLF perturbations could be produced by scattering from ionospheric perturbations produced by lightning EMP, but *Rodger and McCormick* [2004] suggested that they might actually be due to transient quasi-electrostatic (QE) fields instead of lightning EMP. *Mika et al.* [2003] reported one clear early/fast VLF event associated with an elve.

[4] Fast narrowband VLF perturbations could also be caused by sustained QE fields that quiescently heat the *D* region and modify the ambient conductivity over a large region [*Inan et al.*, 1996b]. Similar narrowband VLF measurements have indicated that VLF perturbations may be produced by narrow plasma columns associated with sprites [*Dowden et al.*, 1996; *Hardman et al.*, 1998], which

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are produced by intense transient QE fields [*Pasko et al.*, 1997]. Recently, *Haldoupis et al.* [2004] and *Mika et al.* [2003] reported early VLF perturbations in a nearly one-to-one relationship with imaged sprites.

[5] *Barrington-Leigh et al.* [2001] suggested that fast narrowband VLF perturbations might be associated with sprite halos that also result from intense transient QE fields above thunderstorms and produce substantial ionization changes from 70 to 85 km altitude. Later, *Moore et al.* [2003] found that at least some of fast narrowband VLF perturbations are related to sprite halos by measuring the electron density changes using the two-dimensional long-wave propagation capability electromagnetic propagation model together with geographically distributed narrowband measurements. *Moore et al.* [2003] indicated that the scattering pattern of the sprite halo disturbance agrees with that of the narrowband VLF perturbations reported by *Inan et al.* [1996c] and *Johnson et al.* [1999].

[6] Regardless of the mechanism of these fast VLF perturbations, their sensitive dependence on the *D* region conductivity profile produces characteristic perturbation signatures on sub-ionospherically propagating VLF signals that are reliably identifiable by wideband as well as narrowband measurements. *Cheng and Cummer* [2004] reported the detection and measured altitude profiles of electron density perturbations caused by lightning EMP using a broadband (3–7 kHz) VLF measurement technique. In the present study, this previous work is expanded by comparing the broadband (3–25 kHz) VLF spectra of lightning discharges that occurred closely after (<15 s) an intense lightning discharge (>60 kA peak current) with the spectra of lightning discharges that were not preceded by an intense lightning discharge by at least 60 s. Although 60 s is shorter than some perturbation recovery times, our broadband VLF technique is not generally able to detect the small changes present this long after the initial perturbation. In most of the cases reported here (>60%), a probe lightning stroke more than 100 s after the initial perturbation was used to sense the ambient electron density profile. The measurements reported here thus reasonably reflect the ionospheric change from before to after the perturbation. Extremely large perturbations ought to be detectable for longer duration, but we have yet to have such a perturbation occur along with a probe signal at the right time to be able to detect it.

[7] We apply this broadband approach in three scenarios. In the first case, we show an ionospheric perturbation produced by a large negative lightning stroke that created an elve according to records by the Imager of Sprites and Upper Atmospheric Lightning (ISUAL) instrument on the FORMOSAT-2 satellite. In the second case, we analyze the average of 27 individual broadband VLF perturbation events over the U.S. East Coast at night on 13 July 2004 to better quantify the ionization profiles and their link to lightning parameters. In the third case, we show that similar broadband VLF perturbation events occur in other geographic regions by reporting one broadband VLF perturbation event in the U.S. High Plains on 18 July 2005. In all cases, the detailed electron density change profiles are extracted with the broadband VLF measurement technique and are compared to the theoretical predictions of different mechanisms. We find consistency with the EMP mechanism and inconsistency with others. Our average ionization measurement inferred from the VLF spectral perturbations is also in good agreement with that reported by *Mende et al.* [2005] for an elve based solely on optical measurements. This confirms that detectable electron density perturbations are created through the EMP mechanism of direct lightning-ionosphere interaction.

2. Description of the Experiment

[8] Broadband extremely low frequency (ELF)/VLF (50 Hz–25 kHz) magnetic field waveforms from lightning were continuously recorded at Duke University during the summers of 2004 and 2005 and at Fort Collins, CO, during July and August of 2005. Signals from both locations sampled at 100 kHz with 6-pole (Colorado) and 8-pole (Duke) 25-kHz antialiasing low-pass filters that produce a roll-off that becomes significant above about 22 kHz. Additionally, the Duke system response includes a single-pole 13-kHz low-pass filter that reduces the signal by an additional 20–50% between 10 and 20 kHz. The spectra presented below have not had this response removed. The signal between 2 and 10 kHz that forms the basis for the reported measurements falls in the flat part of the frequency response of both systems, and the presented spectra in this range are correctly calibrated.

[9] U.S. National Lightning Detection Network (NLDN) data are used to determine the precise time (greater than 1-ms accuracy), location (an accuracy of a few kilometers) [*Cummins et al.*, 1998], and peak current of the source lightning discharge, and also to provide distance and bearing from the source to receiver, which are needed to model the propagation effects accurately. It should be noted that NLDN may underestimate the peak currents by about 18% for lightning with peak current smaller than 50 kA [*Jerauld et al.*, 2005]. The accuracy of estimates for larger peak currents is not determined yet because of the unavailability of ground truth data with peak current exceeding 60 kA [*Cummins et al.*, 1998].

[10] The Earth-ionosphere waveguide is bounded by a highly conducting ground and the conducting ionosphere at VLF and lower frequencies, and electromagnetic pulses from lightning may propagate long distances in modes analogous to the modes of an ideal parallel-plate waveguide [e.g., *Inan and Inan*, 1999, p. 739]. Because the ionosphere (and thus waveguide) is anisotropic, azimuthal (B_ϕ) and radial (B_r) components of the horizontal magnetic field are nonzero. However, the azimuthal component is much larger at most frequencies, and the information we seek is most readily quantified in the spectral amplitude of B_ϕ [*Cummer et al.*, 1998]. Thus the spectrum of B_ϕ is reported and analyzed in this work.

[11] *Cheng and Cummer* [2004] showed that, in order to apply the broadband VLF measurement to search for small (~300 km in extent for EMP and ~100 km for QE) and short-lived (tens of seconds duration) ionospheric perturbations, a number of specific conditions must be met. The lightning that causes the ionospheric disturbance must occur close to the propagation path between the sensor and the probe lightning strokes. Also, the propagation distance range should be 300–500 km in order to reliably measure the ionospheric perturbations. In the three measurement cases which are discussed below, the causative lightning occurred approximately at the same locations of the probe

lightning, and the propagation paths are around 380, 415, and 310 km, respectively. Additionally, the timing of the probe lightning strokes must meet specific constraints [*Cheng and Cummer*, 2004]. We use lightning that did not follow an intense lightning stroke (>60 kA) by more than 60 s to probe the ambient electron density profile [*Cummer et al.*, 1998], and we use lightning that occurred right after (20 ms–15 s) an intense lightning stroke to detect the disturbance. When possible, we also use lightning that occurred approximately 10–50 s after the intense lightning to detect the decay of the perturbation.

3. Ionospheric Perturbation Detection

[12] Below we present the three experimental cases analyzed in this work. The first is a single broadband VLF perturbation associated with a satellite-observed elve. The second is a statistical analysis of 27 individual broadband VLF perturbations detected on a single night over the U.S. East Coast. The third is a single broadband VLF perturbation detected over the U.S. High Plains.

3.1. Elve-Associated Ionospheric Perturbation on 1 September 2004 Over the U.S. East Coast

[13] The EMP from an intense lightning discharge has been found to produce short-lived luminous events in the lower ionosphere, termed elves [*Fukunishi et al.*, 1996]. Elves last less than 1 ms, occur at approximately 75- to 105-km altitude, and have a horizontal diameter of up to 700 km [*Barrington-Leigh and Inan*, 1999]. Although it was originally reported that elves are always accompanied by "large amplitude VLF perturbations," examples of these perturbations are rare. Here we present a broadband VLF perturbation detected on 1 September 2004 over the U.S. East Coast that was associated with an elve recorded by the ISUAL instrument on the FORMOSAT-2 satellite [*Chern et al.*, 2003]. For unknown reasons, the ISUAL-event-triggered time (04:32:51 UT) and the time for this event to be moved from a temporary storage buffer into the data processing module (06:11:18 UT) were not consistent. After considering the altitude of the FORMOSAT-2 satellite, the field of view of the ISUAL imager, and the intensity of the causative lightning stroke, it was determined that 04:32:51 UT was most likely the event time for the elve recorded by ISUAL. Our analysis below is additional evidence that the correct elve time was 04:32:51 UT.

[14] The elve-producing lightning was 383 km away from the Duke sensors (35.975°N, 79.100°E) with an arrival azimuth of approximately 194° (almost due south of the sensors). The pre-event probe lightning stroke was a −57-kA stroke 33 s before the perturbation. The elve and ionospheric perturbation were produced by a −106-kA stroke. The second probe lightning stroke (−18 kA) occurred approximately 132 ms after this high peak current stroke and is used to detect the ionospheric disturbance (and infer the disturbed profile below in section 4). The third probe lightning stroke (−56 kA) occurred 24 s after the perturbation and is used to measure the recovery of the perturbation.

[15] Figure 1 shows the normalized sferic (B_ϕ) spectra of the three probe lightning strokes. Between 3 and 25 kHz, the sferic spectrum characteristics, which are produced by interference between distinct propagation modes within the Earth-ionosphere waveguide, show a significant amplitude change and frequency shift of the modal interference variations immediately following the perturbation-producing stroke. The waveguide mode interference in the VLF spectrum depends on *D* region reflection height and sharpness [*Cummer et al.*, 1998], and the change in the modal interference reflects the changing of the *D* region ionosphere due to the intense lightning stroke. In this case, we detected an ionosphere perturbation that was present 132 ms after the intense causative lightning that produced the elve. However, 24 s after the large lightning stroke, the sferic spectrum is nearly indistinguishable from that 33 s before the elve, which indicates that the disturbed ionosphere recovered significantly in this period.

[16] Narrowband VLF perturbations show that the *D* region ionization changes decay over timescales on the order of many tens of seconds and can be as long as 100 s [*Inan et al.*, 1993]. However, because we can use the signal from only one lightning stroke to probe a single perturbation (in contrast to the average of many lightning strokes used to measure the ambient profile, as in *Cummer et al.* [1998]), the broadband VLF method is less sensitive to small ionospheric perturbations, and it is not surprising that we cannot detect any perturbation 24 s after the causative stroke. The smallest perturbation detectable with a single probe signal is discussed in more detail in section 4.

[17] Because the ISUAL records show that there is an elve (and no sprite and no halo) associated with this perturbation-producing lightning stroke, this example confirms that detectable ionospheric perturbations of this type are produced by the same nonlinear lightning EMP process that produces elves.

3.2. Statistical Ionospheric Disturbances Over the U.S. East Coast

[18] We now examine the average characteristics of many ionospheric disturbances detected on a single night. On 13 July 2004, a high concentration of high NLDN peak current lightning strokes occurred in a relatively small geographic window centered at latitude 37.85°E and longitude 74.90°W with a 415-km range and 58° arrival azimuth to the Duke sensors. A total of 70 negative lightning strokes with peak current magnitude greater than 60 kA occurred during the 0411 to 0455 UT period. We chose −60 kA as the cutoff peak current because *Taranenko et al.* [1993] indicated that a single lightning stroke with peak current equal to 60 kA can produce 25% increase in electron density at around 88-km altitude. We found that 27 (39%) of these lightning strokes produced detectable broadband VLF perturbations. This subset had an average peak current of −79 kA.

[19] The VLF spectra of the probe lightning strokes surrounding these strong strokes in time are classified into three different groups. The first group contains 28 lightning strokes that occurred less than 15 s after the intense causative lightning (>60 kA) with average delay time of 4.3 s. The average VLF spectrum of this group (with −29-kA average peak current) is used to measure the average disturbed electron density profile. The second group contains 18 lightning strokes that occurred from 10 to 55 s after the causative lightning with average delay time of 30.5 s. The average VLF spectrum of this group (with −38-kA average peak current) is used to measure the decay of the ionospheric

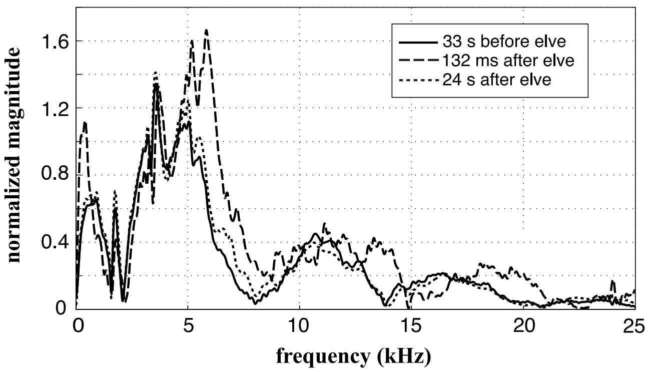

Figure 1. VLF spectra of the three probe lightning strokes on 1 September 2004.

disturbance. The third group contains 68 lightning strokes that did not follow an intense lightning stroke by less than 60 s. The average VLF spectrum of this group (with −50-kA average peak current) is used to measure the ambient electron density profile. The average spectra of each group are shown in Figure 2.

[20] The clear changes in the normalized VLF sferic spectra of different groups reflect the changing of the *D* region ionosphere due to the intense lightning strokes. The differences between the averaged spectra indicate that the ionospheric perturbations produced by the intense lightning strokes are significant and clearly detectable 4.3 s after the big causative lightning and are diminished but still detectable 30.5 s later. If the perturbations exhibited an exponential decay during the first 30.5 s, then comparison with propagation simulations shows that the decay time constant is approximately 26 s, which is consistent with the recovery signature of narrowband VLF perturbations [*Sampath et al.*, 2000].

[21] The possibility that repeated large lightning strokes could produce significant and long-lived ionization enhancement above ~85-km altitude where the recovery times are fairly slow was first suggested by *Barrington-Leigh et al.* [1999] and was analyzed in detail by *Rodger et al.* [2001]. The conditions under which such long-lived change could be produced were met by this experimental scenario in which 70 high peak current lightning strokes occurred at a rate of more than one per minute in a small geographic region. Each individual perturbation decayed back to an ionospheric state that, with our method, was indistinguishable from the pre-perturbation condition. We also examined VLF spectra from strokes from the beginning and end of the period and found that the spectra were consistent with no net change in the *D* region profile. It should be noted, however, that small perturbations are not easily detectable in single VLF spectra, and the predicted long-term perturbations are largest at altitudes above 90 km which is above the altitude of maximum sensitivity for VLF propagation [*Cummer et al.*, 1998]. These data thus cannot reliably say whether there was or was not a longer-term ionospheric change from these lightning strokes.

3.3. Ionospheric Disturbances Over the U.S. High Plains

[22] In contrast to the U.S. East Coast, U.S. High Plains thunderstorms contain more large peak current positive lightning strokes that produce sprites and halos [*Lyons et al.*, 1998]. We applied the same broadband technique to 11 nights of VLF data recorded during 0400–0900 UT between 28 June 2005 and 13 August 2005 to detect ionospheric perturbations associated with both negative and positive lightning strokes in this region. A search for lightning strokes having >60-kA peak current that satisfy the geometry and timing constrains indicated by *Cheng and Cummer* [2004] revealed 54 positive lightning strokes and 10 negative lightning strokes. However, out of all of these strokes, only one detectable broadband VLF perturbation was found, and it was associated with a negative stroke. The challenge in detecting broadband perturbations was partly a function of the higher background VLF noise at the Yucca Ridge site. There were also far fewer high peak current strokes in the needed locations compared to the Duke site. A repeat of this experiment would benefit from a sensor location farther to the east so that it is surrounded by High Plains storms rather than on the periphery and therefore the optimal several hundred kilometers from many more lightning strokes.

[23] The one detected broadband VLF perturbation occurred on 18 July 2005. The two probe lightning strokes occurred approximately at the same location as the intense causative lightning stroke (39.7°N, 101.6°E), 310 km from the receiver at Fort Collins (40.702°N, 105.031°E). A −143.3-kA CG perturbed the ionosphere over the propagation path, and the probe lightning stroke (−22 kA) used to detect the perturbation occurred 183 ms later. The second probe lightning stroke (−55 kA) occurred 5.5 min later and is used to measure the recovered ambient (undisturbed) ionosphere. Figure 3 shows the normalized sferic spectra of the two probe strokes and that which produced the perturbation. The modal interference variations of the broadband VLF sferic spectra change significantly immediately after the large stroke, unambiguously indicating a change in the *D* region ionosphere.

[24] We had hoped to find ionospheric perturbations consistent with transient QE heating (an entirely different mechanism) in this geographic region, as have been found previously using single frequency VLF probe waves [e.g., *Mika et al.*, 2003]. However, an ongoing search for transient QE-type perturbations in this data set has not yet yielded any such events. We attribute this in part to the smaller size of this class of ionospheric disturbance [*Barrington-Leigh et al.*, 2001], which places stronger geographic constraints

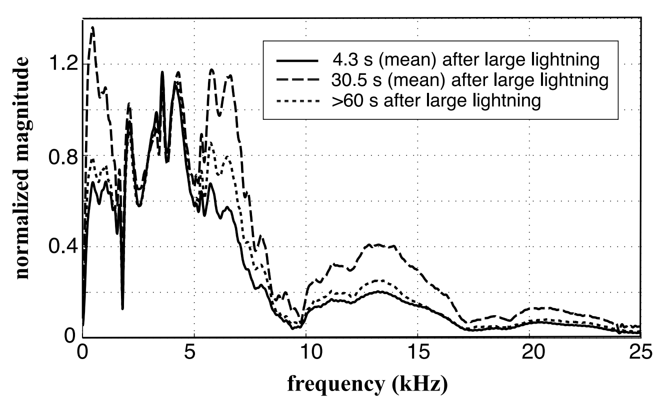

Figure 2. Average VLF spectra of three different groups of probe lightning strokes on 13 July 2004.

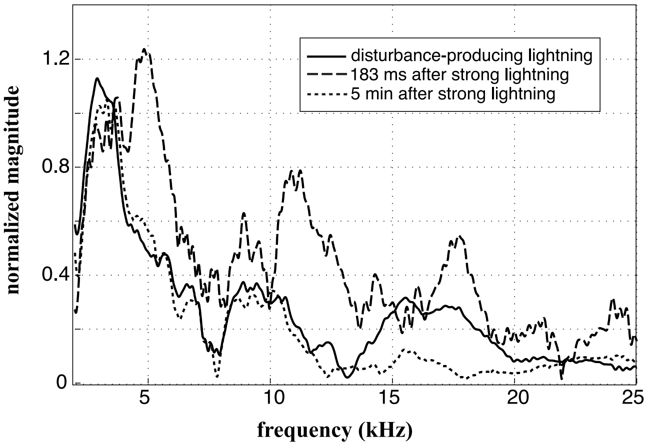

Figure 3. VLF spectra of two probe strokes and the intense causative lightning stroke on 18 July 2005 at the same source location.

on the arrangement of probe lightning strokes to detect it. A sensor location farther east than Colorado that would be closer to the center of High Plains lightning activity would also improve the chances of detection.

4. Measured Electron Density Changes

[25] We now quantitatively infer the *D* region electron density perturbations described in the previous sections using the method described in detail by *Cheng and Cummer* [2004]. The disturbed electron density profile is first extracted as an independent two-parameter exponential profile that could be different in any way from the ambient profile. Then the altitude range of this change is reduced iteratively to determine the narrowest altitude range over which the perturbation needs to be present to be consistent with the data. The end result is the smallest, in both amplitude and altitude range, electron density perturbation that is consistent with the measured broadband VLF spectral change.

[26] The *D* region ionosphere electron density profiles during all three cases described above (the elve, the statistical perturbation, and the U.S. High Plains event) are shown in Figure 4. In all cases, the high peak current lightning sharpened the electron density profile, with electron density decreasing from approximately 75 to 85 km and increasing from approximately 85 to 95 km. From a careful examination of the noise levels in the VLF spectrum from a single sferic, the smallest ionospheric perturbation reliably detectable with a single sferic is essentially the larger perturbation in the second panel of Figure 4. We note that a statistical analysis of many lightning strokes can detect a smaller (but averaged across many events) perturbation. This is because a broadband VLF spectrum from the average of many lightning strokes has lower noise.

[27] The middle panel of Figure 4 does not indicate the expected altitude-dependent decay rate of ionization [*Rodger*, 2003]. We attribute this to the manner in which our method is designed to extract the perturbation with the narrowest altitude range and smallest magnitude that is consistent with the perturbed VLF spectrum. This method is progressively less sensitive to perturbations as altitude increases because of the nature of VLF propagation [*Cheng and Cummer*, 2004]. Consequently, there may be significant and longer-lived ionization changes above 95 km that are not detectable by our technique.

[28] Figure 5 compares the measured electron density perturbation profiles (defined as the absolute change in electron density) for the above measurements along with a theoretically predicted perturbation profile from *Taranenko et al.* [1993] for a single lightning stroke with 60-kA peak current. The measured perturbations in the second and third cases from both the U.S. East Coast and High Plains are in close agreement with the theoretical prediction from the EMP mechanism. The first is around three times bigger than the theoretical prediction but with an altitude range that is still consistent with the EMP mechanism. *Rodger et al.* [2001] found that the greatest density changes in electron density produced by lightning EMP occur at 90- to 92-km altitude, about the same altitude as the maximum elve luminosity [*Barrington-Leigh and Inan*, 1999]. *Cheng and Cummer* [2004] showed that electron perturbations in this altitude range are not consistent with other mechanisms that can cause ionospheric perturbations, namely, QE heating and ionization and lightning-induced electron precipitation from the magnetosphere.

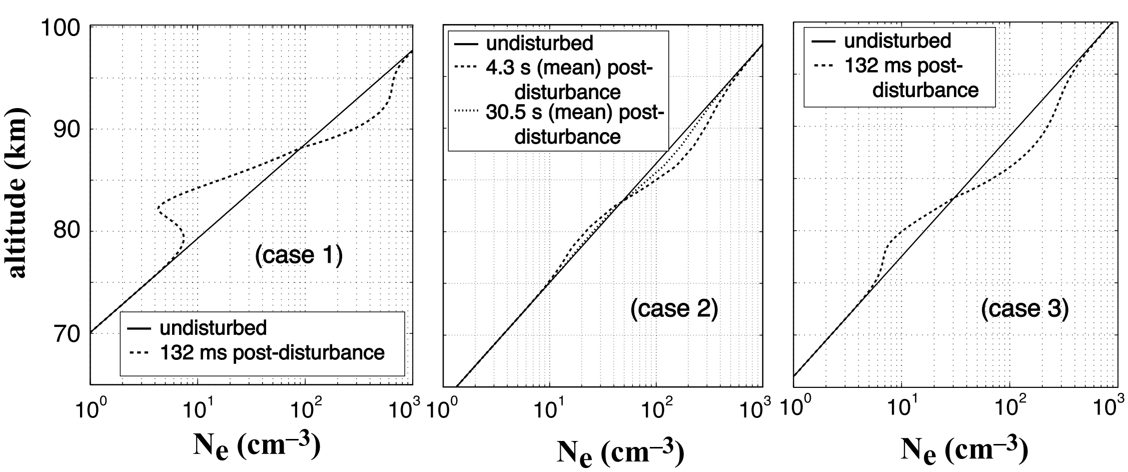

Figure 4. Measured *D* region electron density profiles during the ionospheric perturbations of all three cases.

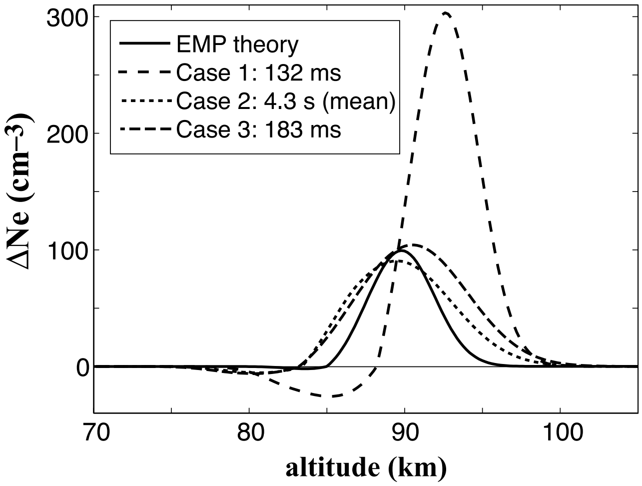

Figure 5. Resulting electron density changes (ΔN_e) caused by the intense lightning strokes in our three measurement cases and compared to the qualitative shape of ΔN_e produced by EMP-related model.

[29] To further confirm the EMP mechanism as the source of the detected broadband VLF perturbations, recent measurements from *Mende et al.* [2005] enable a direct comparison to the ionization enhancements in elves, which are produced by the EMP mechanism. First, we note that the electron density profiles inferred above are the average electron density profiles across the entire propagation paths between the probe lightning strokes and the receiver, which assumes that the ionospheric disturbance is uniformly distributed along the paths. If only a fraction of the total propagation path is disturbed, then the perturbation over that part of the path is even greater than those presented. For the 1 September 2004 event described above, which was independently confirmed by ISUAL to have been associated with an elve, we estimate the perturbation size and strength by using a horizontally inhomogeneous finite difference time domain (FDTD) VLF propagation model [*Hu and Cummer*, 2006]. We first assume that the ionospheric perturbation varies radially in proportion to the peak electric field as described by *Rowland* [1998]. The result is a donut-shaped perturbation of approximately 200-km radius. Propagation simulations in this radially inhomogeneous scenario show that the radially inhomogeneous electron density perturbation in the left panel of Figure 6 combined with the measured altitude variation from Figure 4 produces the same broadband VLF perturbation.

[30] When we average this inhomogeneous perturbation from 88- to 98-km altitude, the range of the significant ionization enhancement, and over 0- to 220-km radius, we find an average electron density enhancement of 460 cm^{-3} in the perturbation region. This is within a factor of about 2 of the 210 cm^{-3} measured by *Mende et al.* [2005] for a different elve. Figure 6 compares these different elve-associated electron density enhancements. Given that we are comparing different events measured by completely different methods, the two average electron density measurements are remarkably consistent. A direct comparison of the electron density changes measured using our broadband VLF method and that derived from ISUAL observations for the same elve event would be more valuable. Unfortunately, the ISUAL event where an elve was simultaneously seen when we detected a clear broadband VLF perturbation (as described in section 3.1) could not be analyzed because of lightning contamination. Comparison of different events is the best possible at present.

[31] We also simulated the broadband VLF spectrum (not shown) after propagation under a region containing a QE-produced ionospheric perturbation to further confirm the inconsistency of these observations with that mechanism. A QE-disturbed profile was estimated [*Moore et al.*, 2003] for a lightning stroke with a peak current of 100 kA and placed with a 50-km radius on a 383-km propagation path covered by the ambient profile of case 1 shown in Figure 4. The same FDTD VLF propagation model mentioned above was used to compute the ambient and disturbed spectra. Such a disturbance should be detectable when it occurs directly over a path of this length, and the VLF spectral perturbation is noticeably different from EMP-produced perturbations reported above, especially above 10 kHz. Broadband VLF detection and analysis of QE-driven ionospheric perturbation would be valuable confirmation that both mechanisms can create significant *D* region perturbations.

5. Characteristics of Perturbation-Producing Lightning

[32] We now analyze in detail the charge moment changes, NLDN peak currents, and measured VLF characteristics of the lightning responsible for producing the detected perturbations. This will provide further information about the mechanisms responsible for the ionization and improve methods for predicting perturbation occurrence based on indirect measurements such as lightning peak current.

[33] The charge moment changes of the perturbation-producing lightning strokes provide additional evidence of an EMP-associated mechanism. According to *Pasko et al.* [1997], the transient QE mechanism requires several hundreds of coulomb kilometers of charge moment changes

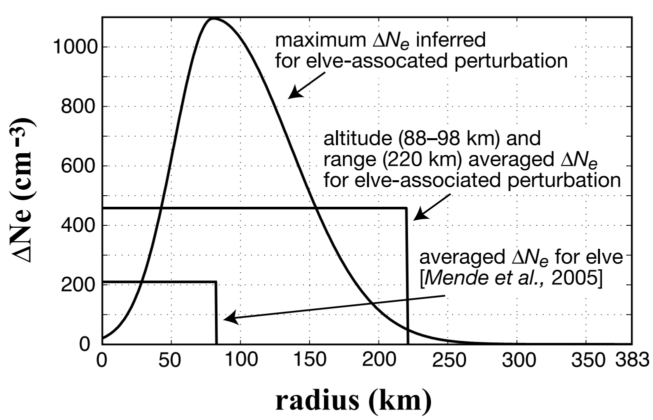

Figure 6. Radial profile of the maximum ΔN_e consistent with the VLF measurements, the resulting altitude-averaged total electron density change throughout the elve (assumed radius = 220 km), and a comparison to the same altitude-averaged total electron density change measured optically by *Mende et al.* [2005] for a different elve.

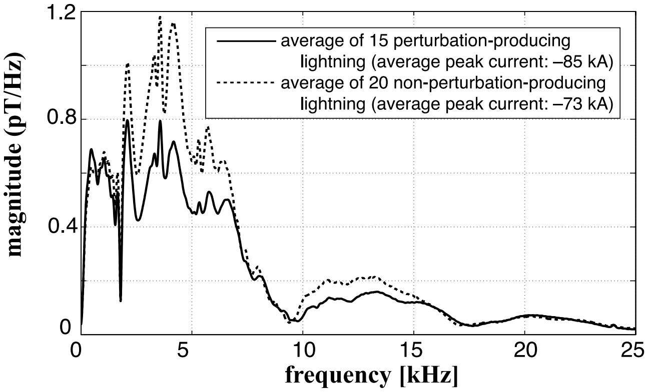

Figure 7. Absolute magnitude comparison of average sferic spectra from 15 perturbation-producing lightning strokes and 20 non-perturbation-producing lightning strokes.

to produce significant ionization around 70-km altitudes. Using the method described by *Cummer and Inan* [2000], we computed the charge moment changes of the average and individual causative lightning strokes of all three cases reported above. The measured charge moment changes are 86 C km for the confirmed elve, 60 C km for the average perturbation-producing stroke, and 17 C km for the single Midwestern event. On the basis of ongoing comparisons with other measurements, the absolute uncertainties in these numbers are at most in error +50/33%. The relatively small values are further evidence that the detected ionospheric perturbations reported here are associated with the EMP mechanism and not with sprites or halos.

[34] In an effort to understand why only some of the intense lightning strokes with large peak currents (>60 kA) produce detectable VLF perturbations in our measurements, we compare the characteristics of the high peak current lightning strokes that do and do not produce detectable VLF perturbations. On 13 July 2004, there were 70 strokes with peak current >60 kA between 0411 and 0455 UT from the source location, and we found that 15 lightning strokes (with average peak current of −85 kA) produced detectable VLF perturbations and had a high signal-to-noise ratio (SNR). Twenty of these strokes (with average peak current of −73 kA) had a high SNR and did not produce detectable perturbations. Figure 7 compares the absolute average sferic spectral amplitudes of these two groups. The spectral magnitudes of the two groups are approximately equal below 1 kHz, which indicates that the charge moment changes for both types of the average lightning strokes are close (around 60 C km in this case). However, the perturbation-producing population has an almost 50% higher spectral amplitude between 3 and 15 kHz despite having only 16% higher average peak current. This suggests that the magnitude of the VLF sferic spectrum is a better indicator of perturbation production than either peak current or charge moment change. This is not surprising since the EMP mechanism is directly related to peak VLF field.

[35] For these data, we find that the best statistical indicator of perturbation production is the spectral amplitude average from 10 to 13 kHz, which corresponds to a local spectral maximum for these sferics. Of the eight strokes whose average spectral amplitude in this band exceeded 0.17 pT/Hz, all of them produced detectable perturbations. This threshold captures more than 50% of the strokes that produced perturbations and admits none that did not. Below this threshold, only 7 out of 27 strokes (26%) produced detectable perturbations. In contrast, eight of the perturbation-producing strokes exceeded −81 kA in peak current, but so did four of the strokes that did not produce perturbations.

[36] This 10- to 13-kHz spectral band is within the flat passband of the sensors, as described above, and thus this 0.17 pT/Hz threshold is close to the true magnitude of the lightning signal. We note, however, that the specific band coincides with a local spectral maximum for strokes approximately 450 km from the source on this night, and for different ranges on different nights, a different spectral band will probably be the best perturbation indicator. But the EMP mechanism suggests that, in any case, the best indicator should be upper VLF (10 kHz) spectral amplitude, as was found in this case.

6. Summary and Conclusions

[37] We used VLF radio emissions radiated from lightning discharges as a broadband (3–25 kHz) probe to search for and quantify disturbances in the lower ionosphere caused by intense lightning in the U.S. High Plains and the U.S. East Coast. A clear broadband VLF perturbation produced by a lightning stroke that also produced an elve simultaneously detected by the ISUAL instrument on the FORMOSAT-2 satellite was measured on 1 September 2004 over the U.S. East Coast, confirming that this class of ionospheric disturbance is associated with the lightning EMP mechanism. A detailed study of many strokes in a 45-min time period on 13 July 2004 showed that 27 out of 70 (39%) lightning strokes with peak currents greater than 60 kA produced detectable ionospheric perturbations. We also found a similar broadband VLF perturbation event from the U.S. High Plains on 18 July 2005, showing that this class of ionospheric disturbance is detectable in different geographic regions.

[38] We quantitatively analyzed the *D* region electron density perturbations caused by these intense lightning strokes and found that the electron density changes from both the U.S. East Coast and High Plains are consistent with a sharpening of the electron density profile near the main VLF reflection altitude (85–90 km). The observed ionization enhancements between 85- and 95-km altitude are in close agreement with the theoretically expected ionization changes produced by the EMP mechanism. Our VLF-based estimate of the average ionization enhancement (460 cm^{-3}) is within a factor of 2.2 of that reported by *Mende et al.* [2005] based on an analysis of optical measurements of a different elve.

[39] We examined in detail the characteristics of the lightning strokes that produced detectable perturbations. For signals from the specific range observed, an average VLF spectral magnitude in the 10- to 13-kHz band that exceeded 0.17 pT/Hz was a more reliable perturbation predictor than peak current for lightning strokes from this range. These results further confirm that detectable VLF propagation perturbations are produced by ionospheric

interactions with the lightning electromagnetic pulse, and that these perturbations can be reliably detected and measured from broadband VLF measurement.

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