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VLF SIGNATURES OF LIGHTNING-INDUCED HEATING AND IONIZATION OF THE NIGHTTIME D-REGION

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Abstract. 48.5 kHz signals from a transmitter in Silver Creek, Nebraska, propagating to Huntsville (HU), Alabama over a ~1200 km Great Circle Path (GCP) exhibit characteristic amplitude changes which appear within 20 ms of cloud-to-ground (CG) flashes located within 50 km of the path. Data are consistent with the heating of ionospheric electrons by the electromagnetic (EM) pulse from lightning producing ionization changes in the D-region over the thunderstorm.

1. Introduction

The first experimental evidence for the heating and ionization of the nighttime lower ionosphere by intense EM pulses radiated by lightning discharges (Figure 1) as suggested by *Inan et al.* [1991] was in the form of unusually 'early' subionospheric VLF perturbations which occur within 50 ms of associated lightning, radio atmospherics and/or whistlers [*Inan et al.*, 1988]. Self-consistent solution of the electrodynamic coupling to the lower ionosphere of an intense EM pulse indicates that significant ionization only occurs at night, with up to 30% ionization enhancements at altitudes > 85 km and as much as 20% decreases in density at lower altitudes, due to dissociative attachment of O_2 [*Taranenko et al.*, 1993]. In this paper, we present a case study of a sequence of 'early' VLF perturbation events causatively related to CG lightning recorded by the National Lightning Detection Network (NLDN). Our results indicate that CG flashes correlated with observed heating events are generally within 50 km of the perturbed GCP and may have first return stroke peak E-field intensities normalized to 100-km distance (E_{100}) of as low as 6 V/m. In contrast, CG flashes correlated with lightning-induced electron precipitation (LEP) events tend to be more intense, and can be located up to 500 km from the GCP, consistent with previous findings [*Yip et al.*, 1991].

2. Description of the Experimental Data

The VLF data were acquired at HU and at Arecibo (AR), Puerto Rico, where the signals from the 48.5 kHz transmitter, the 24.8 kHz NLK transmitter in Jim Creek, Washington, and the 28.5 kHz NAU transmitter in Aguadilla, Puerto Rico were monitored as shown in Figure 2, typically during 0000-1200 UT. Abbreviated reference of, for example, 48.5-HU, indicates the signal from the 48.5 kHz transmitter observed at HU. Starting 23 Jan 1990, VLF data was collected in HU and AR nearly continuously each night. The case presented here was selected on the basis of a cursory examination of VLF perturbation activity during 23 January-30 March 1990. 25 Jan 1990 was one of 5 days during which >10 active event hours (i.e., at least one VLF event (LEP or heating type; see Figure 4) per hour) were observed. Its use for this case study is not based on a thorough examination of the bulk of the data but rather on the observation of clear examples of heating (i.e., 'early') VLF events.

The NLDN uses a nationwide network of magnetic direction finders to locate individual CG flashes and to record the first stroke peak current (from which E_{100} can be derived), polarity and number of strokes [*Orville*, 1991]. NLDN data for 0200-0300 UT on 25 January 1990 are superposed on the VLF paths in Figure 2 (+'s represent CG locations regardless of polarity), and show two thunderstorm centers, one in Missouri and another in Louisiana. During 0100-0500 UT the thunderstorm intensified and moved northward (Figure 3). The active storm centers were well within the region of coverage of NLDN where the estimated detection efficiency is 70-80% [*Orville et al.*,1987]. However, weaker peak currents are less likely to be detected. Recent studies have shown that strokes with E_{100} <3 V/m are not likely to be detected with good efficiency [*Orville*, 1991; *Idone et al.*, in press].

Figure 3 shows VLF events simultaneously registered on 48.5-HU, NLK-HU and 48.5-AR (top panels); that the NAU-HU signal is not perturbed is consistent with a disturbance location between the 48.5 kHz transmitter and HU. The varying degree of simultaneity of events on 48.5-HU, NLK-HU and 48.5-AR is expected since these paths do not precisely overlap and respond differently to a given disturbance [*Wolf and Inan*, 1990].

The CG flashes shown in the lower panels of Figure 3 are displayed with 20 ms resolution. Many CG flashes do not lead to detectable VLF events on 48.5-HU, and many VLF events occur with no associated CG lightning. The latter is likely due to NLDN recording only CG flashes (intra-cloud flashes are not detected); indeed *all* VLF events are accompanied by impulsive radio atmospherics observed in Stanford VLF data. The temporal alignment of the VLF event onsets and CG lightning in the few associated cases (see below) indicates that the two phenomena are causatively related.

The temporal signature of an 'early' VLF event is illustrated in Figure 4, in comparison with an LEP event observed ~2 minutes earlier. Both perturbations involve rapid (< 1 s) changes in amplitude and slower (10-100 s) recoveries.

LEP events are equally likely to be positive or negative amplitude (or phase) changes [*Wolf and Inan*, 1990], consistent with the multiple-mode nature of VLF propagation in the earth-ionosphere waveguide [*Poulsen et al.*, 1993]. LEP event onsets exhibit delays (Δt) (with respect to the causative lightning) of 0.3-1.0 s and onset durations (t_d) of 0.5-1.5 s, as expected for an equatorial gyroresonant interaction with lightning-generated whistlers [e.g., *Inan et al.*, 1990].

'Early' VLF event signatures have Δt < 20 ms, as expected for direct heating and ionization by the EM pulse from lightning, and often have rapid onset durations (i.e., t_d), consistent with the typically < 100μs duration of the EM pulse [*Inan et al.*,1991]. Note that t_d can appear to be longer for successive flashes or flashes with multiple strokes.

The recovery time of 'early' VLF events are somewhat longer than that of LEP events, as seen from Figure 4 and as was found in another case [*Inan et al.*, 1988], possibly due to the generally higher altitudes (~85-95 km) at which ionization in produced in heating compared to LEP events (~70-85 km) [*Inan et al.*, 1991; *Taranenko et al.*, 1993].

3. Association of VLF Events and Lightning

Figure 5 shows a succession of well defined VLF perturbations marked A,B,C, and D observed on 48.5-HU together with radio atmospheric intensities in a 23.40±0.25 kHz channel, and CG lightning. All four of the CG flashes shown occurred within 50 km of the 48.5-HU path. Expanded records of events A,B,C, and D (Figure 7) show that the first two events (A,B) are not accompanied by recorded CG lightning but are clearly associated with nearly simultaneous radio atmospherics. Events C and D are respectively associated with

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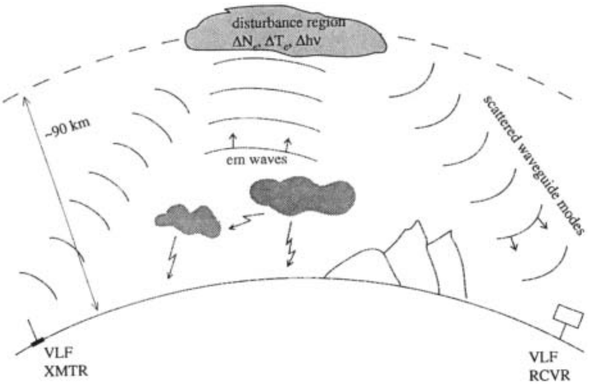

Figure 1. EM radiation from lightning propagates upward, interacting with the lower ionosphere, heating the electrons and producing ionization changes. A subionospheric VLF signal propagating between a transmitter and a receiver on the earth's surface is used to measure the disturbance.

-6.3 V/m and 6.8 V/m CG flashes. A weaker event (< 0.2 dB) D′ is also time-correlated with a radio atmospheric. The -10.5 V/m flash at 0230:25 UT is correlated with a ~0.4 dB reduction in 48.5-HU intensity, marked B′, which is interpreted as an LEP event and included in the event statistics (Table 1), although many LEP events were better defined.

Table 1 shows results of visual analysis of high time resolution data for the period 0100-0500 UT to document VLF perturbation events, defined as positive or negative changes in amplitude of ≥ 0.2 dB occurring within 1 s of a radio atmospheric, followed by recovery to pre-event levels in $\geq$10 s. Events for which the spheric preceded the onset by $\Delta t > 200$ ms were identified as LEP events, whereas those for which $\Delta t < 20$ ms were categorized as heating events. The absolute amplitudes of the heating events ranged from 0.2 dB to 1.7 dB, with most events being 0.2-0.8 dB. All except one of the LEP events were negative amplitude changes, and all but one (a very weak event) of the heating events were amplitude increases. The statistics of heating and LEP events observed on 48.5-AR were similar, although heating events were better defined and more numerous on 48.5-HU, whereas LEP events were better defined and more numerous on 48.5-AR.

As the CG flash rate intensified, a higher rate of LEP events was observed, whereas the occurrence of heating events peaked during the 0200-0300 UT period, when the Missouri storm was centered on 48.5-HU. The fewest heating events were observed during the 0400 UT hour, when the storm center (Figure 3) had moved well north of the path, even though the CG lightning rate is higher. More CG flashes within 50 km of 48.5-HU occured during 0300 UT than 0200 UT; however, many of these were relatively less intense (Figure 7).

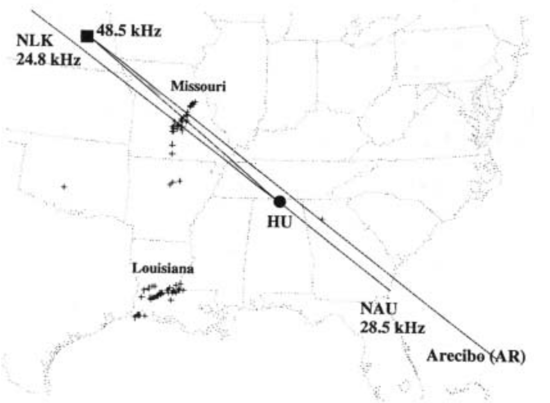

Figure 2. Distribution of VLF great circle propagation paths from the NLK, 48.5 and NAU transmitters to HU and AR. CG lightning discharges observed by the NLDN during 0200-0300 UT are superposed as +'s.

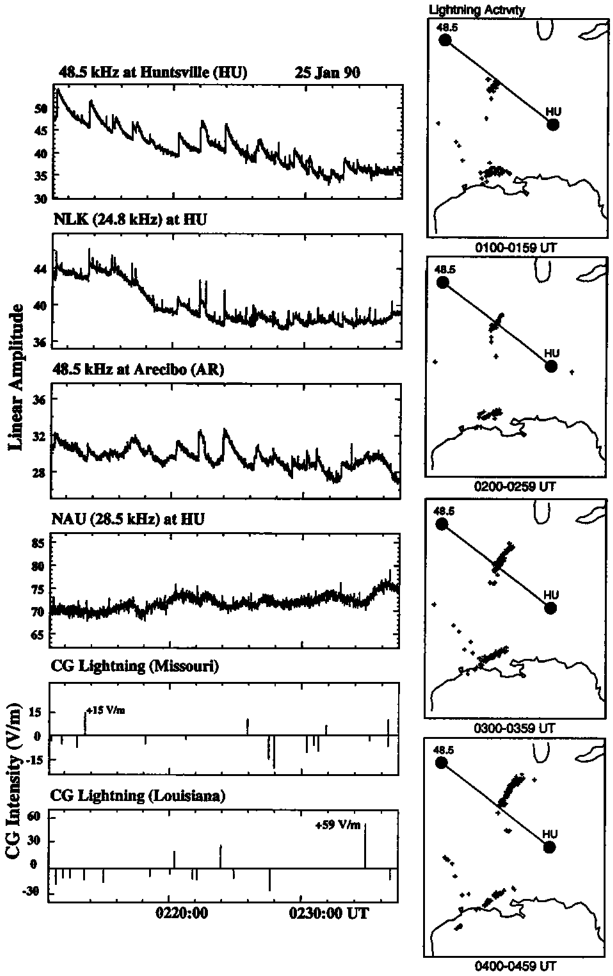

Figure 3. Top panels on the left show VLF events observed during 0211-0237 UT on three collinear paths, 48.5-HU, NLK-HU and 48.5-AR. The vertical axes show linear amplitude A, with $A = 0$ representing the absence of signal. The two panels on the lower left show CG lightning occurrence time and intensity, separately for the two storm centers. The right hand panels show the recorded CG lightning activity during 0100-0500 UT.

Figure 7 shows the dependence of the VLF event-CG lightning association on the intensity of CG flashes expressed as the normalized electric field in V/m (E_{100}) and the shortest great circle distance from the recorded CG location to the 48.5-HU path, with positive (negative) values corresponding to north-east (south-west) of the path. CG flashes time-correlated with LEP or heating events are separately marked.

CG flashes with E_{100} as low as ~6 V/m can apparently lead to detectable ionization changes, providing an important basis for calibration of theoretical models of the highly nonlinear electrodynamic coupling of the EM pulse to the ionosphere [*Taranenko et al.*, 1993]. During 0200 and 0300 UT, *all* CG flashes correlated with heating events are within 50 km of the 48.5-HU path, and the more intense of these appear to be more likely to lead to heating events. The single CG-correlated heating event observed during 0400 UT is associated with the CG flash closest to 48.5-HU. Similarly, the only two correlated CG flashes during 0100 UT are at the northern tip of the storm center, closest to the VLF path. Other characteristics of lightning, not recorded by NLDN, may well be important since some flashes which are similarly intense and close to the path do not lead to heating events. Also, many VLF heating events with no associated CG lightning were observed (Table 1), presumably triggered by intracloud flashes or CG flashes not recorded by the network. The distribution of the

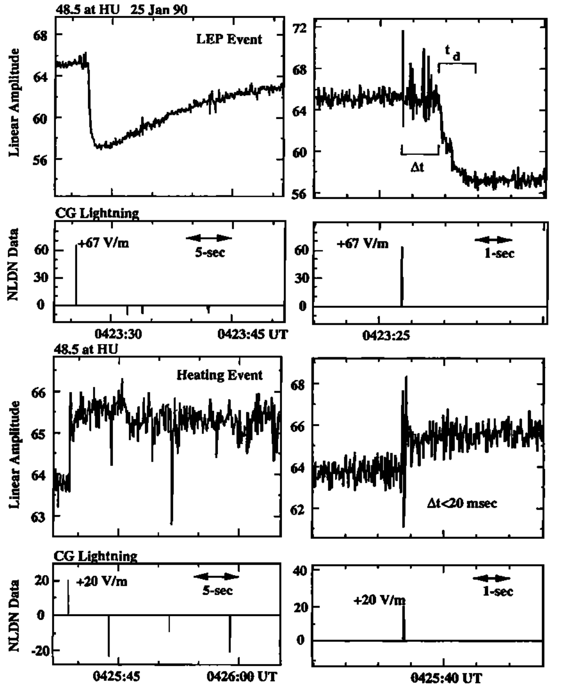

Figure 4. Comparison of high-time-resolution signatures of LEP and heating events. Right hand panels show 20 ms data samples with no averaging, whereas left hand panels show the same data time averaged over 80 ms. The vertical axes show linear amplitude as in Figure 3.

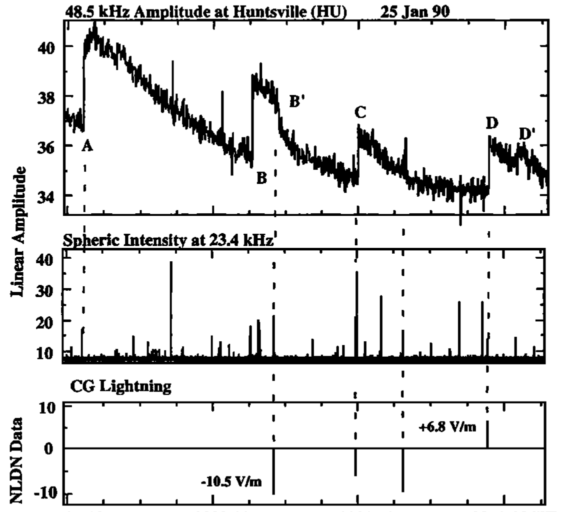

Figure 5. A sequence of well-defined events (A, B, C, and D) VLF perturbation events, associated radio atmospherics and CG lightning. The format of the data displays is the same as that of Figure 3. The spheric intensity is measured in the 23.4±0.25 kHz band. The data in the top panel represent 100-ms time averages, whereas the middle panel shows individual 20 ms data samples. All four of the CG flashes recorded during this period were from the Missouri storm, and were located within ±50 km of the 48.5-HU path.

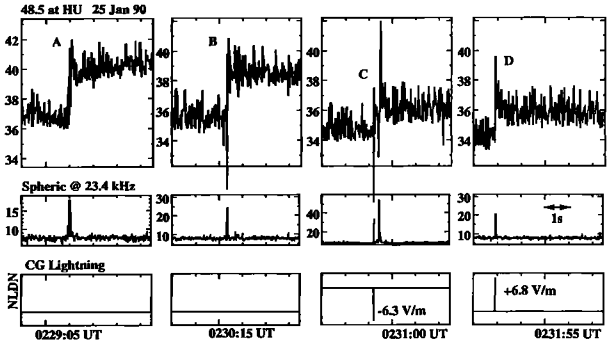

Figure 6. Expanded records of events A, B, C, and D from Figure 5.

associated CG lightning both in intensity and distance from the 48.5-AR path was similar to that for 48.5-HU, although fewer heating events were observed on 48.5-AR.

In contrast, the association of CG flashes with LEP events does not depend on flash proximity to the VLF path, consistent with earlier findings [*Yip et al.*, 1991]. The peak current magnitude appears to be a stronger factor for initiation of LEP events. CG flashes in the Louisiana storm are significantly more intense than those in Missouri and LEP events more intense than those in Missouri and LEP events are associated with some of the most intense flashes from the former. Most LEP event correlated flashes are positive, except for a very intense ($E_{100} = -50$ V/m) flash during 0400-0500 UT. Note that some equally intense flashes do not lead to LEP events and some LEP events are not associated with recorded CG flashes, as in other studies of LEP event and CG lightning associations [*Inan et al.*, 1988; *Yip et al.*, 1991].

We note from Table 1 that, depending on the hour, 45-100% of the LEP events are associated with CG lightning, while only 12-44% of the heating events are, consistent with even relatively weak flashes causing heating events, while LEP events are associated with stronger flashes.

4. Discussion

Our data reveal little information on the actual location of the ionospheric disturbances produced by LEP events. The lack of events on NAU-HU indicates that the disturbed region is probably not over HU and previous data [*Inan et al.*, 1990] and theoretical modeling [*Poulsen et al.*, 1993] suggest it to be within 100-200 km of the perturbed paths. No LEP events were observed during 0100-0200 UT (Table 1), before the storm overlapped 48.5-HU and other paths, reminiscent of an earlier case [*Inan et al.*, 1988], where heating type VLF perturbations were observed as thunderstorm activity located under the VLF GCP built up, followed by a succession of LEP events. This phenomenology is consistent with the lightning activity possibly leading to the formation of whistler-mode ducts. Geomagnetically, the Missouri storm is located at $L \simeq 2.5$, where LEP events are most commonly observed.

Significantly more heating events are observed on 48.5-HU, with only a subset of them registered on 48.5-AR. Since the CG flash activity equally overlaps both paths (Figures 2 and 3), the 48.5-HU path, substantially shorter than the 48.5-AR path (i.e., the signal is constituted by a large number of waveguide modes), appears to be a more sensitive indicator of the heating type ionospheric disturbances. On the contrary, many more LEP events and a larger range of amplitude changes (up to -7.8 dB) are observed during 0400-0500 UT on 48.5-AR, with only a subset observed on 48.5-HU, indicating that 48.5-AR is more sensitive for ionospheric disturbances produced in LEP events. Path dependence of the range of amplitude changes was previously noted [*Wolf and Inan*, 1990].

TABLE 1: VLF Event and CG Lightning Statistics on 25 Jan 1990

Period (UT)	0100-0200		0200-0300		0300-0400		0400-0500	
# of CG Flashes	143		114		265		474	
48.5-	AR	HU	AR	HU	AR	HU	AR	HU
# of Heating Events	0	12	17	36	4	9	0	3
# Correlated with CG	0	2	2	6	1	4	0	1
# of LEP Events	0	0	2	5	9	4	> 20	9
# Correlated with CG	0	0	2	4	9	4	9	6

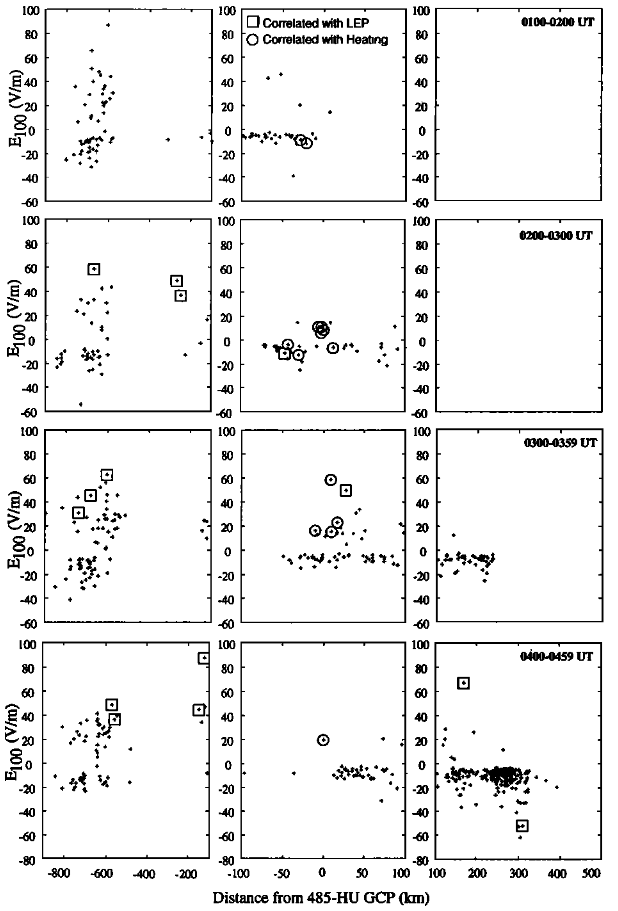

Figure 7. Distribution of CG lightning in terms of flash intensity E_{100} with $E_{100} < 0$ indicating a negative CG flash, and distance from the 48.5-HU path. Note the scale change on the horizontal axes between panels.

Most heretofore reported observations of 'early' or heating type VLF events [*Inan et al.*, 1988; *Inan*, 1990] including the case here, as well as other clear examples of such events observed but as yet unreported in Stanford data, are *positive* amplitude changes, consistent with the 'sharpening' of the D-region density profile by increased attachment (density decrease) below 85 km and enhanced ionization above 85 km [*Taranenko et al.*, 1993]. A sharper profile provides better reflection for all waveguide modes, and reduction of density at lower altitudes reduces absorption for the signal along its path, thus leading to amplitude increases. In contrast, LEP event signatures are equally likely to be positive or negative [*Wolf and Inan*, 1990; *Poulsen et al.*, 1993].

In principle, some lightning flashes should lead to both heating and LEP events; however, no such case was found in the 25 Jan 1990 data.

5. Summary

Perturbations of subionospheric VLF signal amplitudes, occuring within < 20 ms of associated lightning discharges or radio atmospherics but recovering in 10-100 s, provide clear evidence of direct coupling of electromagnetic energy from lightning to the lower ionosphere, consistent in all of its manifestations with the proposed mechanism of heating and ionization of the lower ionosphere by the intense EM pulses from lightning [*Inan et al.*, 1991; *Taranenko et al.*, 1993]. The data indicates that CG flashes of intensities as low as $\sim$6 V/m can produce detectable ionization changes. In the case studied here, CG flashes associated with heating events are found to be exclusively within < 50 km of the perturbed VLF paths.

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