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RESEARCH ARTICLE

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VLF and Ionospheric *D*-Region Perturbations Associated With WWLLN-Detected Lightning in the South Pacific Region

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Key Points:

- The relationship between the energy of the lightning strokes and the level of very low frequency (VLF) perturbation has been studied for the first time
- Low-energy lightning stroke can produce a comparable level of perturbation to that of strong lightning
- The modeling results of scattered amplitude (*M*) and echo phase (ϕ_E) of a long recovery early fast VLF event exhibit a better exponential fit ($r \sim 0.9$)

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The subionospheric early very low frequency (VLF) perturbations observed on NWC (19.8 kHz) navigational transmitter signal monitored at a low-latitude station, Suva (18.1°S, 178.5°E), Fiji, during campaign periods of November 2011, 2012, and 2014 and December 2014, are presented. Early VLF events are associated with *D*-region conductivity changes mainly produced by lightning-generated transient luminous events (TLEs). Early VLF events occurred both during daytime and nighttime, with a considerably higher occurrence at nighttime. VLF perturbations caused by lightning strokes located up to 100 km off the transmitter-receiver great circle path (TRGCP) are attributed to narrow-angle scattering, while lightning strokes 100–500 km off the TRGCP are considered to cause early VLF events by wide-angle scattering. Using the World Wide Lightning Location Network data, for the first time, we have studied the relationship between the energy of lightning strokes and the level of VLF perturbations. Greater is the energy of lightning, greater would be the strength of the VLF perturbation. However, the low-energy lightning stroke can also produce a comparable level of perturbation to that of strong lightning. The modeling results of scattered amplitude (*M*) and echo phase (ϕ_E) of the unusually long recovery early/fast VLF event showed a better exponential fit ($r \sim 0.9$) than the logarithmic fit. Long-wavelength propagation capability (LWPC) code modeling of nighttime early VLF events considering causative TLE width of 50 km column indicated a decrease in the *D*-region reference height (H') by up to 30 km and an increase in the sharpness factor (β) by 0.25 km^{-1}.

1. Introduction

Lightning strokes usually trigger an extra-ionization of the *D*-region of the ionosphere, which leads to the scattering of very low frequency (VLF, 3–30 kHz) transmitter signals that manifest as VLF perturbations at the receiver. The *D*-region is the lowest part of the ionosphere, which exists from ∼60 to 75 km in the daytime and ∼75 to 95 km in the nighttime (Hargreaves, 1992). The fast and short-duration changes that occur in the subionospheric VLF signal because of direct impulsive coupling between lightning and the lower ionosphere (*D*-region) are known as early VLF perturbations or early VLF events (Inan et al., 1988, 1995; Salut et al., 2013).

The term "early" denotes the nature of these abrupt perturbations, meaning that they occur immediately (<20 ms) after the causative lightning discharge with an onset duration ranging from <20 ms up to 2 s (Haldoupis et al., 2006; Inan et al., 1988). Typically, the recovery time of early VLF events lasts many tens of seconds, whereas in rare cases, as shown in previous studies (Cotts & Inan, 2007; Haldoupis et al., 2012, 2013; Kotovsky & Moore, 2017; S. Kumar & Kumar, 2013; NaitAmor et al., 2013, 2017; Salut et al., 2012, 2013), recovery time can go up to many minutes. Early VLF events can be classified as early/fast, early/slow, rapid onset raid decay, long recovery early (LORE) events, and early step-like events based on the onset duration and the recovery time. Onset duration is the time interval between the start of the early VLF perturbation and the occurrence of the maximal amplitude/phase perturbation (Kotovsky & Moore, 2015). In this study, our focus is mainly on early/fast, early/slow, and LORE VLF events. Early/slow VLF events have an onset duration of ∼0.5–2.5 s (Haldoupis et al., 2004, 2006; S. Kumar & Kumar, 2013), whereas early/fast VLF events have an onset duration of <50 ms (Inan et al., 1988). The recovery time of these events typically ranges to many tens of seconds (10–180 s; Sampath et al., 2000). Early/fast events with unusual recovery times (5–20 min) are referred to as LORE (Cotts & Inan, 2007; Haldoupis et al., 2013; S. Kumar & Kumar, 2013).

Previous studies have reported that sprite-producing lightning is very often, if not always, associated with early VLF events (e.g., Haldoupis et al., 2004, 2010; Salut et al., 2013). Inan et al. (1995) first reported the correlation

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between early VLF events and sprite-producing lightning that occurred within ±50 km off the transmitter-receiver great circle path (TRGCP), exhibiting narrow-angle forward scattering. However, this relation was found only for a small subset of sprites. However, Dowden et al. (1994, 1996) showed that narrow ionization columns in sprite-producing lightning can also produce early VLF events due to wide-angle scattering (>100 km) and even in the backward direction. Haldoupis et al. (2004), Neubert et al. (2005), and Mika et al. (2005) reported convincing observations in favor of a close relationship between sprites-producing lightning and early VLF perturbations, suggesting a nearly one-to-one association. Marshall et al. (2006) analyzed a data set of concurrent sprite-producing lightning and early VLF perturbations. They found that backscattering from sprite-related early VLF perturbations occurred only for a very small subset of sprites. NaitAmor et al. (2010, 2013) proposed experimentally that the transmitter frequency, the distance from perturbation to the receiver, the distance from the transmitter to the perturbation, modal structure of various TRGCPs at the location of the ionospheric disturbance, and the scattering process are all important characteristics in the observations of early VLF perturbations. NaitAmor et al. (2013) also proposed that VLF signal perturbation properties depend strongly on the distance to the receiver locations: the closer the sprite to the receiver, the larger the amplitude of perturbation and longer the recovery time of the VLF signal perturbation events.

The purpose of this paper is to find the correlation between the short-duration VLF perturbation and the intensity of the lightning strokes producing these perturbations. The other characteristics of the VLF perturbations have also been studied, including the decay form of unusually long recovery events, scattering characteristics of VLF perturbations, and selected VLF perturbation events have been modeled using the long-wavelength propagation capability (LWPC) code to investigate the changes in the *D*-region Wait parameters. We have used the NWC (19.8 kHz) transmitter signal to examine the characteristics of early VLF events at our low-latitude station, Suva, during the campaign periods of November 2011, 2012, and 2014, and December 2014, which is the active lightning period in the South Pacific Region. We will present the relationship between the occurrence of early VLF events and the energy of lightning strokes detected by the World Wide Lightning Location Network (WWLLN). The nighttime *D*-region Wait parameters: reference height (H') in km and sharpness factor (β) in km^{-1} (Wait & Spies, 1964) for the sprites produced early VLF events have been estimated using Long Wave Propagation Code V2.1 code. The decay form of LORE events has been modeled for the exponential and logarithmic fits.

2. Experimental Data

Software-based VLF phase and amplitude logger, "SoftPAL," was used to record the amplitude and phase of the NWC transmitter signal. NWC is powerful (1,000 kW) VLF (19.8 kHz) transmitter, which is located in the North West Cape, Australia (21.82°S, 114.17°E). The NWC transmitter signal was recorded continuously with a time resolution of 10–100 ms, using a global position system based timing. The continuous recording of phase and amplitude is chosen to monitor the diurnal and short-time scale changes of ionization properties in the lower ionosphere along the VLF signal paths. The VLF data for a total of 4 months recorded during November (2011, 2012, and 2014) and December (2014) have been analyzed. The months of November and December were selected since they fall in the wet season with comparatively high occurrences of lightnings and thunderstorms in the South Pacific Region. The SoftPAL data for about 15 days in November (2011) at 10 ms sampling rates and for about 20 days in November (2012) at 20 ms sampling rates were recorded to study the onset and recovery time of early VLF events associated with the causative lightning more accurately. For other times, the data were recorded at 100 ms resolution. For each day during these 4 months, all early VLF events were visually inspected, and a count of early VLF events (≥0.2 dB) along with their time of occurrence, onset time, recovery time, amplitude change (ΔA) in dB, and phase change ($\Delta \phi$) in degrees were recorded. ΔA and $\Delta \phi$ are the difference between the preevent signal level and the signal level at the peak of perturbation in the amplitude and phase of the signal, respectively. Early VLF events associated with the whistler-induced precipitations into the lower ionosphere are unlikely to occur at our receiving station, Suva, which is a low-latitude (18.2°S, 178.3°E) station, and the TRGCP is within a low-latitude belt. The NWC-Suva TRGCP is about 6.696 Mm consisting of a mixture of land and sea paths. Based on the signal-to-noise ratio of the received VLF signal, a minimum detectable amplitude perturbation of 0.2 dB has been taken to confirm early VLF events. We have also analyzed WWLLN data to detect the causative lightning which occurred within 500 km off the TRGCPs and within 100 ms of the occurrence of early VLF events. After selecting all of the early VLF events observed on NWC signal, WWLLN data were examined to locate the causative lightnings. WWLLN (see http://wwlln.net for more information) consists of over 80 VLF radio receivers around the globe that detect VLF radiation in the band from 100 Hz to 24 kHz sampled at 48,000

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samples per second (Holzworth et al., 2019). Using the time-of-group-arrival technique, it provides the real-time lightning location of global lightning by measuring VLF radiation emanating from lightning discharges. Stroke locations and occurrence times are accurate within about 5 km and 10 μs, respectively (Abarca et al., 2010; Hutchins et al., 2012; Rodger et al., 2009), and the detection efficiency of WWLLN for strokes above 50 kA peak current is now up to about 80% (Holzworth et al., 2019). WWLLN also provides the far-field energy of the lightning strokes along with the uncertainty in the measured values. The estimated lightning stroke energy is the root-mean-square electric field of the detected stroke from 1.3 ms waveform sampling between 6 and 18 kHz band (Hutchins et al., 2012). The WWLLN data including lightning energy used in this study were provided by Prof. Robert Holzworth, Director of WWLLN (http://wwlln.net). LWPC version 2.1 code has been used to estimate the changes in the VLF reference height (H') in km and sharpness factor (β) in km^{-1} associated with VLF perturbations. LWPC was developed by the Space and Naval Warfare Systems Center (Ferguson, 1998). This program has been extensively validated (NaitAmor et al., 2017) and is quite successful in modeling the long-range propagation of VLF signals.

3. Results

3.1. Occurrence of Early VLF Events

We have analyzed 4 months of VLF data during November (2011, 2012, and 2014) and December (2014) to study the characteristics of early VLF events at our low-latitude station, Suva. We have examined the amplitude and phase of the NWC transmitter signal and found that 305 events appeared to have early VLF signatures. Forty of those events, and their main characteristics, are listed in Table S1.

VLF perturbations showing early VLF characteristics were found in both the amplitude and phase of the signal. Our results showed that about 34.8% of early VLF events (106 cases out of 305) exhibited simultaneous amplitude and phase perturbations, and about 65.2% (199 cases) exhibited either amplitude or phase perturbation. Of these 305 events, 226 (74.1%) were classified as early/fast VLF events, and 79 (25.9%) as early/slow VLF events having onset durations between 0.5 and 2.5 s. Out of the 305 early VLF events, 242 (79.3%) occurred when the TRGCP was in the complete nighttime, and 53 (17.4%) cases were observed for the daytime TRGCP. The remaining 10 (3.3%) events were observed during the transition period of the day–night terminator between the transmitter and the receiver.

The early/fast VLF events are characterized by an abrupt onset of less than 20 ms (i.e., fast; Inan et al., 1988) followed by relatively slower relaxation times of several tens of seconds (typically 10–100 s) and occur due to their immediate detection (∼20 ms) after the causative lightning stroke (Inan et al., 1993). These events show the combination of different types of perturbations possible in terms of the direction of the phase and amplitude (−, ++, −+, and +−) and are mainly observed when the TRGCPs of the VLF signals are entirely or partially in the dark. Some early/fast VLF events were also observed in the daytime. Out of 226 early/fast VLF events, about 81.9% (185 events) occurred at nighttime and about 15.5% (35 events) during the daytime. The remaining 2.7% (six events) of early/fast VLF events occurred during partial sunlit or dark conditions. We also observed that about 36.3% (82 events) of early/fast VLF events exhibited both amplitude and phase perturbations, and about 63.7% (144 events) exhibited either amplitude or phase perturbations.

Figure 1 presents an example of a series of early/fast VLF events detected on the NWC signal at nighttime on 22 November 2012. The six early/fast VLF events labeled as 1–6 occurred within about 17 min, producing perturbations both in the amplitude and phase. The magnitude of the amplitude perturbations ranged between 1.0 and 2.5 dB, while the phase perturbations were between 2° and 15°, indicating that some of these events were quite strong. The WWLLN-detected causative lightning for each of these six early/fast VLF events, and their geographical locations are plotted in Figure 1b. The lightning locations 2, 3, and 6 were within 5–20 km off the NWC to Suva TRGCP, while locations 1, 4, and 5 were within 30–50 km off the TRGCP, indicating that all the perturbations were produced by narrow-angle scattering of the VLF signals.

In contrast to early/fast VLF events, early/slow VLF events have "slow" onset durations ranging from about ∼0.5 to 2.5 s. With a sampling rate of 10, 20, and 100 ms, we were able to observe and classify early/slow VLF events clearly, displaying the onset durations comparable to that reported by Haldoupis et al. (2004, 2006). The occurrence rate of early/slow VLF events is low compared to early/fast VLF events: 226 early/fast VLF events were observed, while 79 early/slow VLF events were observed. Out of 79 early/slow VLF events, about 57 (72.2%)

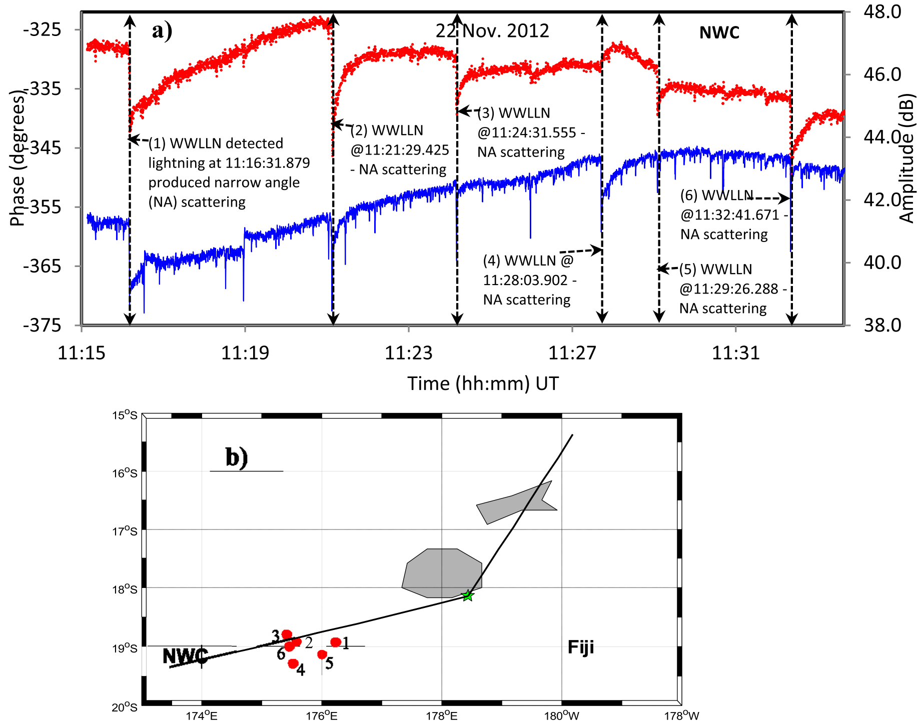

Figure 1. (a) A series of early/fast events observed on the NWC signal at nighttime on 22 November 2012 both on amplitude (blue curve) and phase (red curve). World Wide Lightning Location Network (WWLLN)-detected lightning locations are labeled as 1–6 using arrows. (b) The positions of the six lightning are plotted as red spots along the NWC-Suva transmitter-receiver great circle path (TRGCP).

occurred when TRGCP was entirely in the dark (nighttime), and 18 (22.8%) events occurred when TRGCP was completely in light (daytime). The remaining four (5.06%) events occurred when TRGCP was partially in the sunlit or dark condition. From our observations, we also noted that about 30.4% of early/slow VLF events (24 cases) had both amplitude and phase perturbation, while about 69.6% (55 cases) had either amplitude or phase perturbation.

During the campaign period, we observed 305 early VLF events, out of which only 110 (36.1%) causative lightnings were detected by WWLLN. These events were associated with strong causative lightning occurring within the millisecond of onset of perturbation and showing the signatures of early VLF events considered in this analysis. Early VLF events associated with causative lightning discharges located ±50–100 km off the TRGCPs have been attributed to narrow-angle forward scattering (Inan et al., 1995), while those that are located ±100–500 km off the TRGCP (or even behind the transmitter/receiver) have been attributed to wide-angle scattering (Dowden et al., 1996). Under the above criteria, out of 110 early VLF events, we found that 67 (60.9%) events were associated with narrow-angle scattering, and 43 (39.1%) events were produced by wide-angle scattering from *D*-region conductivity perturbations associated with WWLLN-detected causative lightning discharges. The geographical locations of the causative lightnings associated with early VLF events due to narrow- (solid red circle) and wide-angle (solid blue circle) scatterings from the NWC transmitter to the receiving station, Suva, are shown in Figure 2. Figure 3 shows the distribution of the lateral distance (in km) of the causative WWLLN-detected lightnings associated with early VLF events from the TRGCP. We measured the lateral distance of the causative lightning of all early VLF events from the TRGCP to approximate the size of the region affected by intense lightning discharges. The causative lightning discharge associated with 67 early

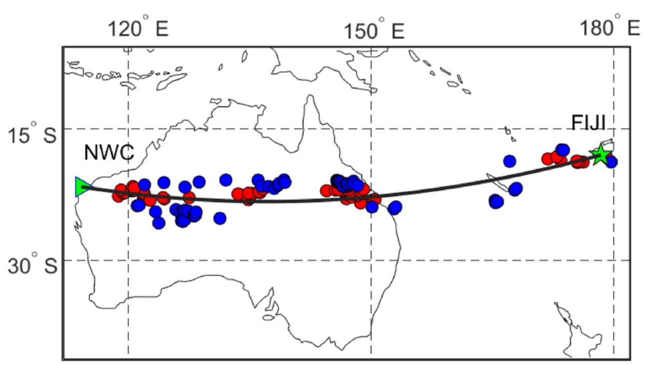

Figure 2. Map showing the location of World Wide Lightning Location Network (WWLLN)-detected causative lightning locations associated with early very low frequency (VLF) events observed during November (2011, 2012, and 2014) and December (2014) due to narrow-angle (solid red circle) and wide-angle (solid blue circle) scatterings. Solid black line represents the transmitter-receiver great circle path (TRGCP) from the NWC transmitter (green triangle) to the receiving station, Suva (green star).

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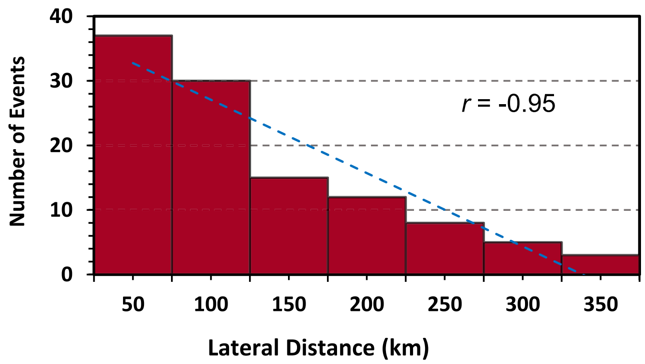

Figure 3. Lateral distance of the causative lightning associated with early very low frequency (VLF) events on NWC signal with a linear regression correlation coefficient (r). The blue dashed line is the linear regression line.

VLF events (about 60.9%) occurred within 100 km off the TRGCP and thus exhibiting narrow-angle scattering. Other 43 events showed wide-angle scattering where the causative lightning discharges were located between 100 and 350 km from the TRGCP. The linear correlation coefficient (r) between the number of VLF perturbation events and lateral distance of the lightning stroke location from the VLF signal path is $r = -0.95$, which suggests a strong negative correlation indicating that more is the lightning occurrence distance off the TRGCP less is the number of VLF events. The majority of the lightning strokes producing VLF perturbations occurred in the 100 km range.

3.2. Modeling Decay of Unusually Long Recovery Events

Dowden and Adams (1988), using phasor formalism, designed a model to construct the amplitude and phase of the scattered wave from the measured signal. This model from early/fast VLF events was used by Dowden and Rodger (1997) to examine the logarithmic or exponential decay of scattered waves associated with early/fast events observed on the NWC signal. The scattering amplitude (M) and echo phase (ϕ_E) of early/fast events on NWC signal was modeled using the model suggested by Dowden and Rodger (1997), which is given by $M = \sqrt{R^2 + 1 - 2R\cos\Delta\phi}$ and $\tan\phi = (R\sin\Delta\phi)/(R\cos\Delta\phi - 1)$, respectively, where R is the ratio (A/A_0) of the amplitude of the perturbed wave (A) to the unperturbed wave (A_0) in dB and $\Delta\phi$ ($\Delta\phi = \phi - \phi_0$) is the phase of perturbed wave (ϕ) minus phase of unperturbed wave (ϕ_0) in degrees. The recovery times of scattered amplitude and phase were fitted into logarithmic and exponential forms. A. Kumar (2015) analyzed 15 early/fast events and found that the correlation coefficient (r) of the logarithmic fit ($r = 0.91$) of the recovery times of scattered amplitude was higher when compared to the exponential fit ($r = 0.83$). Those 15 early/fast events had a mean duration of the nose (τ_n) as 12.4 s. The τ_n is determined as a time when the amplitude recovers to 50% of the initial maximum perturbation level. Out of all the early events, a small subset of the events is found to have a longer recovery time. These were termed as unusually long recovery early/fast events having a recovery time of 5–20 min, which is much longer than typical early/fast events. LORE events were first reported by Cotts and Inan (2007). For example, an unusual LORE on the NWC signal recorded at the Suva station is presented in Figure 4. The recovery time (~5 min) calculated from amplitude perturbation is indicated in the panel. The phase builds with time, not returning to the preevent level; therefore, in the case of long recovery events, the amplitude perturbations give a better measure of the recovery times. The vertical line in Figure 4 shows the occurrence time lightning detected by WWLLN. The location of this lightning discharge associated with the perturbation was geog. lat., −19.20°S, geog. long., 175.02°W, which was within 100 km off the TRGCP, indicating that this event was produced by narrow-angle scattering.

To study the recovery/decay patterns of the scattered wave amplitude and phase for long recovery events, the phasor formalism suggested by Dowden and Adams (1988) has been used. The scattered (echo) amplitude (M) and echo phase (ϕ_E) were obtained using the formulas above. Using this model, M and ϕ_E were calculated for the long recovery early/fast event of 6 January 2007 at 10:23:43.6 UT on the NWC signal of Figure 4, which are shown in Figure 5. The M and ϕ_E were plotted for 150 s from the onset point. The recovery times of echo M and ϕ_E were fitted into logarithmic and exponential forms and the correlation coefficient (r) of the scattered (echo) amplitude (r_M) and echo phase ($r_{\phi E}$) were also calculated. The correlation coefficient of the exponential fit ($r_M = 0.9334$) was found to be higher than the logarithmic fit ($r_M = 0.8125$) for M, while for ϕ_E, the exponential fit ($r_{\phi E} = 0.7392$) was only possible. When compared to the modeling results of the conventional short recovery (10–100 s) early/fast events of A. Kumar (2015) and Dowden and Rodger (1997), which displayed better fit curves for the logarithmic decay, the unusually long recovery event reported here exhibited better fit for exponential decays of M and ϕ_E.

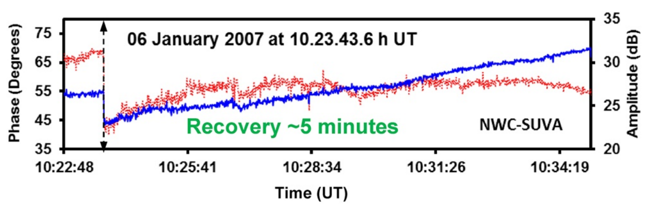

Figure 4. Typical example of nighttime unusually long recovery early/fast event observed on NWC signal on 6 January 2007. The blue graph is for amplitude while the red is for phase.

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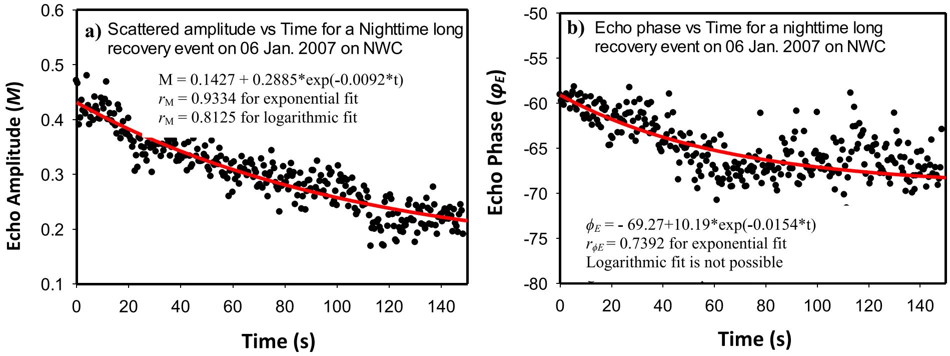

Figure 5. The plots showing the (a) decay of the scattered (echo) amplitude and (b) echo phase with respect to time from the point of onset of the long recovery of early/fast very low frequency (VLF) event on NWC on 6 January 2007. r_M and $r_{\phi E}$ denote the correlation coefficient of the scattered (echo) amplitude and echo phase, respectively.

3.3. Relationship Between Early VLF Events and Lightning Stroke Energy

WWLLN lightning energy data have been used to find the relationship between early VLF events and the energy of the causative lightning stroke. Figure 6 shows the energy distribution of lightning strokes producing amplitude perturbations associated with narrow and wide-angle scatterings. It was found that most of the lightning strokes (31 out of 43) producing VLF perturbations due to wide-angle scattering had lower energy (0.3–4 kJ), and the lightning strokes producing VLF perturbations due to narrow-angle scattering had higher energy (>4 kJ). However, a significant amount of lightning strokes associated with narrow-angle scattering also have lower energy (0.3–4 kJ) which suggests that weak lightning can also cause narrow-angle scattering. Figure 7 shows the relationship between the strength of amplitude perturbation and the lateral distance of causative lightning strokes associated with early VLF events having narrow-angle scattering for the energy ranging from 0 to 5 kJ in which most of the VLF perturbation events occurred. In total, 67% of VLF perturbation events had energy ranging from 0 to 5 kJ. The linear correlation coefficient (r) between the amplitude perturbations (dB) and the energy of the lightning stroke for narrow-angle scattering is $r_A = -0.54$, which suggests a moderate negative relationship between amplitude perturbations and lateral distance of early VLF events associated with causative lightning. From this observation, we suggest that the causative lightning associated with early VLF events which occur closer (0–40 km) to the TRGCP path cause stronger amplitude perturbations as compared to the causative lightning further away (40–100 km) from the TRGCP. Figure 8 shows the distribution of energy of the lightning stroke producing amplitude perturbations in early VLF events due to narrow (a) and wide (b) angle scatterings. From Figure 8a, we note that lightning strokes with large energy (>4 kJ) more often produce large amplitude (>0.5 dB) perturbation events. The correlation between the amplitude perturbations and the energy of the lightning for narrow-angle scattering (Figure 8a) shows $r_A = 0.43$, which suggests a weak positive correlation. This agrees with our general intuition, the larger energy of the lightning stroke is more likely to cause greater ionospheric disturbance and, subsequently, a larger amplitude perturbation. From this observation, we can say that as the energy of the lightning stroke increases, the degree of amplitude perturbation associated with narrow-angle scattering also increases. For the VLF events associated with wide-angle scattering, as shown in Figure 8b $r_A = 0.50$, which shows a moderate positive relationship. This also agrees with our general intuition and suggests that a stronger lightning stroke is more likely to produce a larger amplitude perturbation and a weak lightning stroke is more likely to have a smaller amplitude perturbation. Figure 9 shows the relationship between the energy of the lightning strokes and the recovery time (90% decay) of amplitude perturbations of early VLF events due to narrow-angle (a) and wide-angle (b) scatterings. There is a poor correlation ($r_A < 0.4$) between the energy of the lightning stroke and the recovery period of the associated early VLF events for both narrow- and wide-angle scatterings. This suggests that lightning strokes with lower energy can also cause a comparable level of perturbations and can have a large recovery time to that of high-energy lightning strokes. Also, the

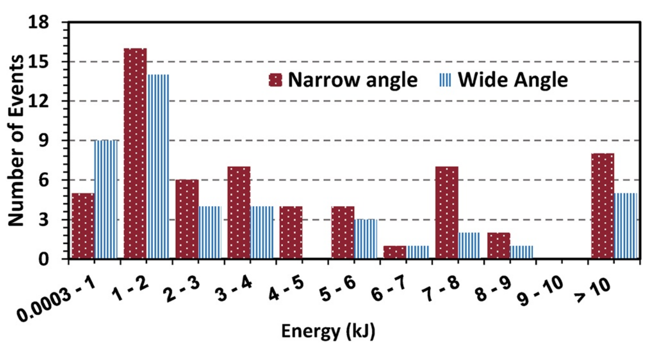

Figure 6. Stroke energy distribution of the early very low frequency (VLF) events associated with narrow- and wide-angle scatterings of the NWC VLF signal, observed during the study period (November 2011, 2012, and 2014, and December 2014).

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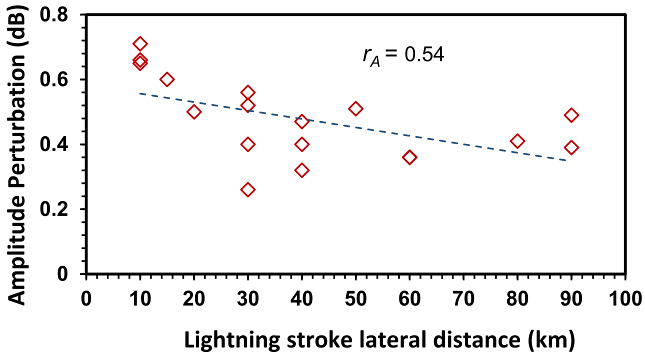

Figure 7. The scatterplot of amplitude perturbation as a function of the lateral distance of causative lightning associated with early very low frequency (VLF) events having narrow-angle scattering together with a linear regression correlation coefficient (*r*).

spread of the recovery times for a narrow range of lightning stroke energy is very high, for example, the recovery time for 1–2 kJ energy lightning varied from about 2 to 30 s (Figure 9b).

3.4. *D*-Region Ionospheric Parameters Using LWPC Modeling

The early VLF signal perturbations observed on the NWC signal were modeled using LWPC Version 2.1 code to estimate changes in the *D*-region ionospheric parameters: the reference height (H') in km and the exponential sharpness factor (β) in km^{-1}. A total of nine nighttime early VLF events having both amplitude and phase perturbation exhibiting narrow-angle scattering were modeled to estimate H' and β. This was done by first identifying the approximate location of the lightning-associated transient luminous event (TLE) along the TRGCP and then adjusting the H' and β only for that perturbed region to match the observed amplitude and phase perturbations while keeping these parameters the same for the other unperturbed regions of the TRGCP. The lightning location is assumed to be in the center of the horizontal sprite column along the TRGCP path. Here, we assumed that the ionosphere is horizontally homogenous, and under unperturbed conditions, H' and β are constant along the TRGCP (Marshall & Inan, 2010; NaitAmor et al., 2017). The extra-ionization produced by the sprite is uniform throughout the sprite column, therefore, the basic nature of *D*-region ionization which is exponential with height still remains the same in the sprite column with modified H' and β parameters. We have used single value of the perturbed parameters going from the center of the sprite to either side up to 25 km. The resulting agreement between modeled and observed amplitude and phase perturbation at the peak of the perturbation provides a likely set of values for the perturbed H' and β within the sprite body.

In this study, we have considered the width of the sprite column for the nighttime *D*-region ionosphere to be 50 km for all the cases studied in this paper. By varying the H' and β in the LWPC code only in the sprite disturbed region to match the amplitude and phase outputs with their observed values, we estimated the perturbed values of H' and β for nine lightning events.

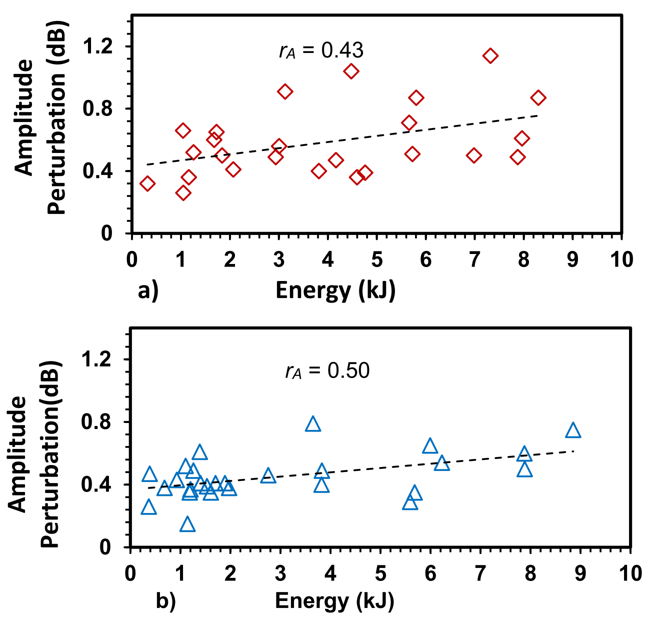

Figure 8. The scatterplot of amplitude perturbation as a function of the energy of strokes producing early very low frequency (VLF) events associated with (a) narrow- and (b) wide-angle scatterings of NWC VLF signal, together with a linear regression correlation coefficient (*r*).

First, we run the LWPC code on the day and times of the early VLF event to get the LWPC amplitude (A) and phase (ϕ). Second, we find the change in amplitude (ΔA) and phase ($\Delta\phi$) from the SoftPAL data for the early VLF events to preevent levels. These values were then added to the LWPC amplitude and phase to get the observed amplitude ($A' = A + \Delta A$) and phase ($\phi' = \phi + \Delta\phi$) of early VLF events. We varied the values of H' and β only in the sprite disturbed region, and the combination of H' and β, which gave the best matching between the LWPC amplitude and phase outputs with their observed values, were considered as the perturbed H' and β (called H_p' and β_p). The mean values of H_p' and β_p obtained from the LWPC modeling of nine lightning nighttime events are $H_p' = 75.2$ km, $\beta_p = 0.59$ km^{-1}. The perturbed H_p' and β_p values varied in the range 57.0–82.5 km and 0.45–0.75 km^{-1}, respectively. The unperturbed nighttime values of H' and β obtained from LWPC modeling are $H' = 87$ km and $\beta = 0.4$ km^{-1}. Table 1 shows the perturbed H_p' and β_p estimated from LWPC modeling for three lightning events.

4. Discussion

To address the aim of the paper, we have presented results on the characteristics of early VLF events, which occur due to the scattering of VLF transmitter signals from regions of modified conductivity in the lower ionosphere (*D*-region). These conductivity changes in the *D*-region of the ionosphere can result from extra-ionization, enhancing the electron density, or

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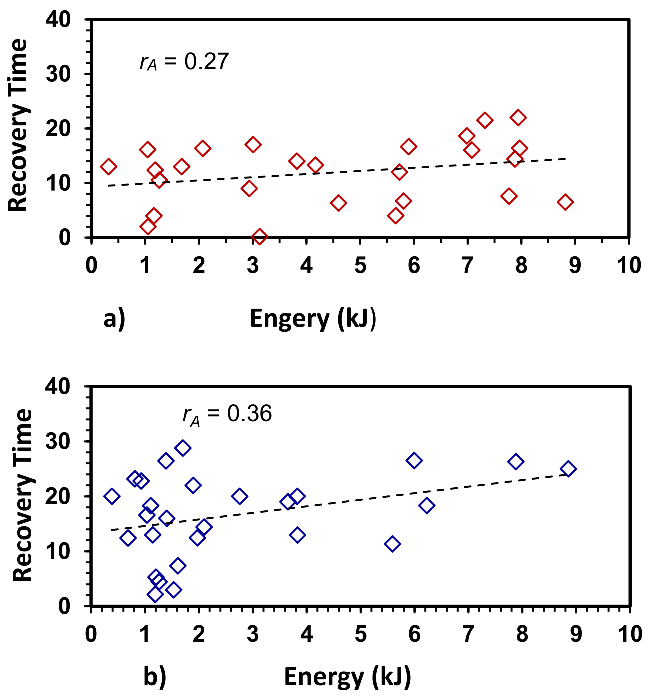

Figure 9. The scatterplot of recovery time (90% decay) of amplitude perturbations of early/fast very low frequency (VLF) events as a function of the energy of the lightning strokes producing early VLF events associated with (a) narrow- and (b) wide-angle scatterings, along with together with a linear regression correlation coefficient (*r*).

through electron heating, modifying the electron-neutral collision frequency (Kabirzadeh et al., 2017). Most early VLF events are characterized by abrupt increases or decreases (early/fast) in the received signal amplitude and or phase with onset durations of less than ∼20 ms and slow onset (early/slow) durations of about ∼0.5–2.5 s (Haldoupis et al., 2006). The early/fast events are the most common types of early VLF perturbations observed on subionospheric VLF transmission from NWC VLF transmitter received at Suva and are believed to be the effect of extra-ionization in the lower ionosphere caused by the intense lightning discharges. We observed that most of the early VLF events (about 79.3%) occurred during the nighttime, between 10:00 and 17:00 UT (22:00 and 05:00 LT), which is consistent with previous studies (Inan et al., 1988, 1993; Kabirzadeh et al., 2017; S. Kumar & Kumar, 2013; Pandey et al., 2016). The occurrence rate of early VLF events in the daytime is much lower than at the nighttime, resulting from the lower reference height due to the larger *D*-region electron density during the daytime and the enhancement of lightning with a larger charge moment change to produce extra-ionization at the lower altitudes. Much emphasis has not been paid to daytime events (S. Kumar & Kumar, 2013; S. Kumar et al., 2008). During the daytime, solar radiation is the primary source of ionization that controls VLF signal variability, decreasing the ionospheric sensitivity to other external sources such as strong geomagnetic storms, whereas, during nighttime, direct solar radiation is absent; hence, ionospheric sensitivity is high to external sources, such as X-ray bursts from a remote cosmic source (Raulin et al., 2014), allowing a wider range of physical and chemical processes to influence VLF propagation conditions. Inan et al. (1988, 1993) found that early/fast VLF events are caused mostly by forward scattering from localized regions of ionization enhancements above an active thunderstorm close to the TRGCP. Kabirzadeh et al. (2017) reported that a combination of quiescent heating mechanisms and the electron density changes in the lower ionosphere during strong cloud-to-ground lightning may account for the observation of early/fast VLF events. However, most of the early/fast VLF events are likely to be produced by the electron density changes due to lightning discharge associated quasi-electrostatic fields.

The occurrence frequency of early/fast VLF events reported in our study is high (about 74.1%) compared to early/slow VLF events (25.9%). Kotovsky and Moore (2015) reported that early/fast and early/slow VLF events in most cases may be produced by the same physical process but may also reflect different onset times in received VLF signals due to the different interpretations of amplitude and phase data. Haldoupis et al. (2004, 2006) found that the gradual onset growth of early/slow VLF events is due to the complex nature of lightning discharges comprising a few cloud-to-ground return strokes and clusters of intracloud discharges which cause primary and secondary ionizations, respectively. The long onset duration (>0.5 s, slow) of early/slow VLF events is also suggested here due to secondary ionization build-up in the lower region of the ionosphere below the nighttime VLF reference heights produced by electromagnetic pulse fields of successive horizontal intracloud discharges.

Table 1
D-Region Parameters Obtained From LWPC Modeling of Three Nighttime Lightning-Associated Early VLF Events

Event no.	Event day and time (UT)	ΔA (dB)	$\Delta\phi$ (°)	Unperturbed Wait parameters H'	β	Perturbed Wait parameters H_p'	β_p
1	17/11/2011 14:02:50:48	−0.37	−2.44	87	0.4	57.3	0.65
2	09/11/2014 15:45:41:2	−0.48	−3.00	87	0.4	57.5	0.60
3	09/11/2014 15.04.56.7	+0.24	+1.07	87	0.4	79.6	0.57

Early/slow VLF events have been reported to occur usually at nighttime conditions along the TRGCP (Haldoupis et al., 2004, 2006; Inan et al., 1988; Kotovsky & Moore, 2015; S. Kumar & Kumar, 2013; S. Kumar et al., 2008). However, very few researchers have observed early/slow events during the daytime of the TRGCPs (A. Kumar, 2015; S. Kumar & Kumar, 2013; Pandey et al., 2016), as the occurrence frequency of early/slow VLF events in the daytime is rare and many past analyses were carried out for nighttime VLF data only. S. Kumar and Kumar (2013) presented the first observation of daytime early/slow VLF events. In our study, we have reported that about 22.8% of early/slow VLF events occurred during the daytime and about

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72.2% occurred during nighttime, and the remaining 5% occurred during the transition period of the day–night terminator between the transmitter and the receiver. Pandey et al. (2016) reported that the occurrence frequency of early/slow VLF events during the daytime is much less than at nighttime and has a faster recovery time, which indicates a shorter relaxation time for electron density enhancement at the VLF reference heights triggered by the daytime TLEs.

To identify the causative lightning for early VLF events, the nature of the associated scattering, and their origin, we analyzed the WWLLN lightning data for locations within 500 km off the TRGCPs. Previous studies (Dowden & Rodger, 1997; Dowden et al., 1996; Hardman et al., 1998; Inan et al., 1996; Johnson et al., 1999; Marshall et al., 2006; Mika et al., 2005; S. Kumar & Kumar, 2013) have demonstrated that most of the early VLF events are correlated with narrow-angle scatterings which are also observed in our studies. We reported that 60.9% of early VLF events were associated with narrow-angle scatterings, and about 39.1% were produced by wide-angle scattering. Inan et al. (1995) reported that the vast majority of the causative lightning discharges responsible for sprite-associated early VLF events occur within ±50 km off the TRGCP, exhibiting narrow-angle scattering and in the forward direction. On the other hand, Dowden et al. (1994, 1996) proposed that wide-angle scattering was possible, and sprites can also produce early VLF events at wide-angle scattering even in the backward direction. Early/fast VLF events associated with wide-angle scatterings have also been reported under the EuroSprite-2007 observations (NaitAmor et al., 2010).

Salut et al. (2013) reported that the peak current magnitude of the causative lightning strongly affects the recovery duration, scattering process, and occurrence frequency of early VLF events. Their results suggest that higher peak current (>+200 and < −250 kA) lightning strokes can also produce early VLF events associated with narrow-angle scattering when the causative lightning discharge occurs at larger distances of up to ∼400 km off the TRGCP. Therefore, detailed and long-term research is needed in this field to better understand the correlation between the TLEs and early VLF events.

The decay of M and ϕ_E could be explained in terms of scattering from bundles of conducting columns of sprite plasma. Dowden et al. (1997) suggested that such conducting columns formed by lighting discharges associated with TLEs probably sprites would decay several hundred times faster at the bottom end (around 40 km altitude) than at the top (∼90 km). Since the plasma at any altitude decays exponentially in time with the time constants increasing exponentially with altitudes, the altitude of the effective bottom of the columns would decrease logarithmically with time. The VLF waves will see an exponential decrease in the plasma density of conducting column and a logarithmic reduction in column length. Both may affect the scattered amplitude and phase; as a result, both types of fittings are possible. However, the better exponential fit curve for the scattered quantities of the long recovery event in our study (Figure 6) indicates that the conducting columns of the plasma may last for a longer duration and the length of the conducting column decreases slowly, which causes the slow/long recovery of the early/fast events.

Salut et al. (2013) found that the observed amplitude perturbation is not significantly dependent on the peak current intensity, which may be the reason why there is a weak-moderate correlation between the energy of the lightning stroke and amplitude perturbation as seen from our results in Figure 8. This could also be due to the scattering geometry, such as scattering pattern, TRGCP distance to the perturbation, transmitter frequency, and geographic location, which could have affected the amplitude perturbation (NaitAmor et al., 2010, 2013). A weak positive correlation ($r_A < 0.4$) is reported in our study between the energy of the lightning stroke and the recovery time of the amplitude perturbation of early VLF events associated with narrow and wide-angle scatterings. This suggests that lightning strokes with lower energy can also cause a comparable level of perturbations and recovery time to that of high-energy lightning strokes. Haldoupis et al. (2013) and Salut et al. (2013) reported that the occurrence rate of long recovery early VLF events increases with peak current intensity, which is not so evident in our study, as shown in Figure 9. In this study, a weak correlation has been observed, which suggests that recovery time is largely not a function of lightning stroke energy. Using a machine learning classifier, Pailoor and Cohen (2022) conducted a mass statistical analysis of early VLF events and reported that their result did not provide a direct relationship between the recovery time and the peak current of early VLF events. Our results suggest that lightning strokes with lower energy can also cause a comparable level of perturbations and can have a large recovery time to that of high-energy lightning strokes, thus supporting the model results of Pailoor and Cohen (2022).

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Researchers in the past have used LWPC code to estimate the perturbation to the *D*-region ionosphere both in the daytime and nighttime, for instance, associated with solar eclipses (Clilverd et al., 2001), solar flares (Thomson et al., 2005), lightning-induced electron precipitation (Poulsen, Bell, et al., 1993; Poulsen, Inan, et al., 1993), early VLF perturbation (NaitAmor et al., 2017), geomagnetic storms (A. Kumar, 2015), and tropical cyclone (S. Kumar et al., 2017). Using LWPC code, NaitAmor et al. (2017) modeled early VLF perturbations associated with a gigantic jet and a sprite halo observed on 12 December 2009 for the NRK-Tunis VLF path and estimated the nighttime perturbed H_p' as 66.4 km ($\Delta H' = 20.6$ km). Their nighttime perturbed H_p' value is lower by 8.8 km than our mean value of perturbed H_p' (75.2 km). The difference in the two perturbed H_p' values is due to the characteristics of early VLF events, which are heavily linked to the geometry of the TRGCP, including the location of the transmitter, disturbed region, and receiver (NaitAmor et al., 2010, 2013, 2017).

5. Summary and Conclusions

The subionospheric VLF perturbations referred to as early VLF events recorded during a total of 4 months, November (2011, 2012, and 2014) and December (2014), have been analyzed on the NWC-Suva VLF propagation path. We have studied the characteristics of the early VLF events, their scattering pattern and occurrence rate associated with the causative lightning, their correlations with the energy of lightning stroke, and the level of VLF perturbations along with the lateral displacement of the lightning off the TRGCP. Our results showed a weak correlation between the level of VLF perturbations and the energy of the lightning strokes. About 60.9% of early VLF events were associated with narrow-angle scattering due to lightning that occurred within 100 km off the TRGCP, and about 39.1% of VLF events were associated with wide-angle scattering due to lightning that occurred more than 100 km off the TRGCP which is consistent with some past studies while not with others which reported VLF events dominantly (~95%) associated with narrow-angle scattering. The causative lightning associated with early VLF events near (0–40 km) the TRGCP path generally causes stronger amplitude perturbations than those located further away (40–60 km). Lightning strokes with large energy (>4 kJ) mostly produce large amplitude (>0.5 dB) perturbation events with longer recovery times. However, it is also seen from our results that lightning with lower stroke current can also cause a comparable level of perturbation and recovery time to those of stronger stroke current, although both are located at similar distances away from TRGCP. The unusually long recovery early/fast VLF event observed on the NWC signal was modeled. Our result shows better fit curves for exponential decays of M and ϕ_E for long recovery early events, in contrast to sprite-associated normal recovery early VLF events that showed better logarithmic fit to their decay. This could be explained in terms of scattering from bundles of conducting columns of sprite plasma. The *D*-region conductivity changes associated with early VLF events have also been modeled using the LWPC version 2.1 code. The mean value of perturbed H_p' and β_p are $H_p' = 75.2$ km, $\beta_p = 0.59$ km^{-1} over the unperturbed nighttime values of $H_p' = 87$ km and $\beta_p = 0.4$ km^{-1}. Detailed study and long-term observations of early VLF events associated with causative lightning may reveal a better relationship between the level of VLF perturbation and the energy of the lightning stroke.

Data Availability Statement

The VLF data used to study and characterized early VLF events are available at the Centre for Research Data repository and can be obtained from https://doi.org/10.4121/20730058.v1. WWLLN data used to identify the causative lightning associated with early VLF events can be accessed at http://wwlln.net/. The LWPC version 2.1 code used in this study to conduct modeling of early VLF events is available at the GitHub repository (https://github.com/mlhutchins/LWPC).

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