Lower ionospheric perturbations associated with lightning activity

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Abstract

The lower Ionospheric region is probed through very low frequencies (VLF) caused by lightning strokes. The lightning strokes increase the extra-ionization of the D-region, which ranges from 55 to 75 km during the day and 75 to 95 km at night. The physical mechanism and scattering pattern of early VLF perturbing events have been debated. The purpose of this paper is to analyze the correlation between early/slow VLF perturbations and lateral distance of causative lightning. The study analyzes 2 months of NWC transmitter, recorded at low altitude in Dehradun, India. The study also examines the World Wide Lightning Location Network (WWLLN) to detect lightning within +/-1000 km of the TRGCP for two months. The study has used the LWPC version 2.1 code to model variation in lower Ionospheric region parameters, reference height H-prime (H′) and sharpness factor beta (β) in km^{-1}. The LWPC code was used to estimate the change in amplitude of early/slow VLF events, with the mean values of Hp′ and βp varying between 83-85.8 km and 0.66-0.82 km^{-1}. The study also observed the characteristics of early/slow VLF events, their occurrence rate, and their correlations with causative lightning distance from the TRGCP path. Results showed a negative correlation between early/slow VLF perturbations and the distance of causative lightning.

1. Introduction

The lower Ionospheric region is probed and investigated by very low frequencies (VLF, 3 to 30 kHz) signals from navigational transmitters. The amplitude and phase of the VLF signal abruptly change due to variations in the lower ionospheric region caused by causative lightning discharges. The most common perturbation of the VLF signals induced by lightning discharges is known as early events [5]. The term "early" refers to an abrupt perturbation that occurs right after a lightning discharge. These perturbations can have an onset time that ranges from < 20 milliseconds to up to 2 seconds [5].
Lightning stroke impact on the lower ionospheric region is still not completely understood by researchers. Early VLF events are categorized into different types based on their change in amplitude and recovery time. These types include early/fast, early/slow, rapid onset and short recovery time, long recovery early (LORE) events, and early step-like events[4][7]. The onset duration is the time interval between the start of the early VLF perturbation and the occurrence of the maximal amplitude/phase perturbation [8]. This duration is an important parameter in classifying these events. Previous research provides insight into this classification. The early events are further classified into two subcategories of early VLF perturbations based on their onset duration: "early/fast" and "early/slow" events[8].
The purpose of this paper is to analyze 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 that have been modelled using the long-wavelength propagation capability (LWPC) code to investigate the changes in the D-region Wait parameters. The night-time D-region Wait parameters: reference height (H′) in km and sharpness factor (β) in km^{-1} using Long Wave Propagation Code V2.1 code [12].

2. Experimental data

We have analyzed 2 months of narrowband NWC (19.8kHz) VLF data from March 2021 to April 2021. The NWC VLF transmitter is located in the North West Cape, Australia and is being recorded at low latitude recording station Dehradun. The transmitter receiver's great circle path (TRGCP) is shown in Figure 1. The recorded data NWC includes amplitude (ΔA) in db and phase (Δϕ) in degree.

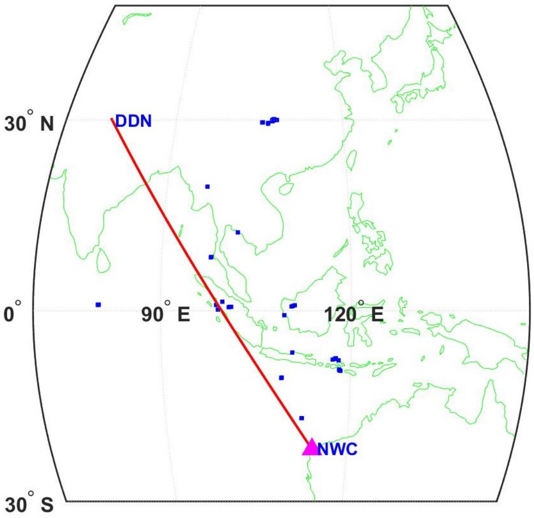

Fig 1. Geographical location of NWC transmitter and receiver which shows a great circle path of VLF transmitter with lightning location of WWLLN

We also examined World Wide Lightning Location Network (WWLLN), to detect lightning that occurred within 1000 km of the TRGCPs. WWLLN provides real-time lightning discharges, with stroke locations and far-field energy of the lightning stroke occurrence rate accurate within about 5 km 10 µs, respectively [1][2]. The detection efficiency of WWLLN for strokes above 50 kA peak current is now up to about 80% (Holzworth et al., 2009). The WWLLN data including lightning energy used in the study, were provided by Prof. Robert Holzworth, Director of WWLLN. The LWPC version 2.1 code has been employed to estimate the changes in VLF reference height (H′) in km and sharpness factor (β) in associated with VLF perturbation, it was developed by the Space and Naval Warfare Systems Centre and has been extensively validated[3].

3. Results

We have examined 2 months of NWC VLF data for March 2021 to April 2021 to observe the characteristics of early/slow VLF events at a low-latitude station, in Dehradun, India. We have analyzed the amplitude of the NWC transmitter signals and recorded a total of 76 VLF events which include 58 early/slow, 11 LOREs and 7 step-like LOREs perturbing events that show an early VLF signature. The early/slow events are characterized by an abrupt onset duration of 0.5 to 2 s and a slower recovery time of 10 to 280 s. We observed all VLF events during night-time and correlated them with lightning energy (joule) with early/slow VLF events. Fig 2 shows an example of early/slow VLF events which are recorded on the NWC transmitter signal.

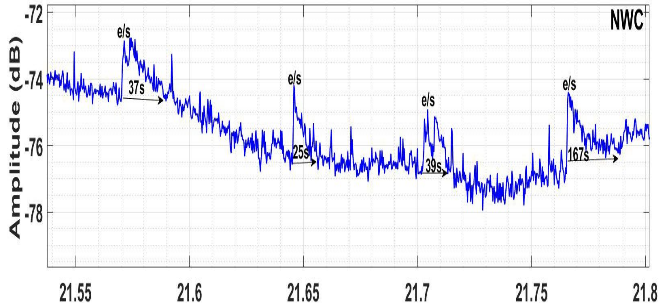

Fig 2. Examples of early/slow events that have 37 s, 25 s, 39 s and 167 s recovery times were recorded on 30 April 2021

We used WWLLN data to analyze the relationship between the lateral distance of causative lightning distance and early/slow VLF events. VLF events associated with lightning discharges 50–100km off the TRGCP have been attributed to narrow-angle scattering [6]. On the other hand, events found approximately 100-500 km off the TRGCP have been associated with wide-angle scattering [2][6]. From the above criteria, most events are related to wide-angle scattering with a correlation coefficient of -0.72.

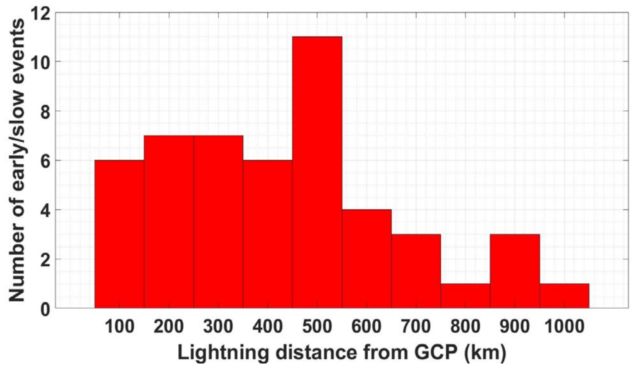

Fig 3. The histogram shows how lateral distance is associated with early/slow VLF events

4. LWPC modeling

The perturbing events modelled in our study observed on the NWC signal using the LWPC version 2.1 code to estimate changes in the lower Ionospheric (D-region) parameters, specifically the reference height H-prime (H′) in kilometres and the exponential sharpness beta (β) in km^{-1}. First, we run the LWPC code on the day and times of the early VLF event to get the LWPC amplitude. Second, we find the change in amplitude (ΔA) from the Minimum shift key (MSK) data for the early/slow VLF events to prevent levels. These values were then added to the LWPC amplitude to get the observed amplitude (A′ = A + ΔA) and of early/slow VLF events. The combination of H′ and β, which gave the best matching between the LWPC amplitude outputs with their observed values, were considered as the perturbed H′ and β (called Hp′ and βp). The mean values of Hp′ and βp obtained from the LWPC modelling of 5 lightning night-time events are Hp′ = 84.14 km, βp = 0.76 km⁻¹. The perturbed Hp′ and βp values varied between 83–85.8 km and 0.66–0.82 km⁻¹, respectively. The unperturbed night-time values of H′ and β obtained from LWPC modelling are H′ = 87 km and β = 0.4 km⁻¹. Table 1 shows the perturbed Hp′ and βp estimated from LWPC modelling for five lightning events.

Table 1. D-Region parameters obtained from LWPC Modeling of five night-times Lightning-associated early/slow

Events	Date	Time(UTC)	ΔA(dB)	H′	β	Hp′	βp
1	14-03-2021	18:22:45	+0.53	87	0.4	85.3	0.78
2	15-03-2021	21:29:22	-1.09	87	0.4	82.8	0.79
3	14-04-2021	20:35:27	-1.57	87	0.4	83	0.78
4	28-04-2021	18:02:53	-0.6	87	0.4	85.8	0.79
5	30-04-2021	21:34:36	+1.84	87	0.4	83.8	0.66

5. Discussion

This paper aims to understand the characteristics of early/slow VLF events, which have been observed during night-time. Researchers observed that Early/slow VLF events usually occurred at the time of the TRGCPs[4][10] while some of them reported early/slow VLF events occurred at day- time along with the TRGCPs [9][10]. We have also analyzed WWLLN lightning data for early/slow VLF events to detect the nature of associated scattering, and their trigger point for locations within 100 km of the TRGCPs. Earlier studies reported that most early events are correlated with narrow-angle scattering, however, our study showed most of the early/slow events correlate with wide-angle scattering which is similar to the results of NaitAmorte. [9][5][11]

7. Conclusion

The lower ionospheric VLF perturbations referred to as early VLF events recorded during a total of two months March and April 2021 have been analyzed on the NWC-Suva VLF propagation path. We have studied the characteristics, scattering pattern and occurrence rate of the early/slow VLF events associated with the causative lightning discharges along the TRGCP. Results showed an anti-correlation (-0.72) between the level of VLF perturbations and the lateral distance of causative lightning from TRGCP. About 6 out of 44 early/slow VLF events were associated with narrow-angle scattering (~13.6%) due to lightning that occurred within 100 km of the TRGCP and about 38 out of 44 VLF events were associated with wide-angle scattering (86%) due to lightning that occurred more than 100 km off the TRGCP.

The D-region variability associated with early/slow VLF events has been modelled using the LWPC version 2.1 code. The quit nighttime reference height (h') and sharpness factor (β) were found to be 87 km and 0.4 respectively. The perturbed values of the reference height and sharpness factor corresponding to the events are shown in Table 1. The ambient electron density during the event days was 65.1 el/cc. During the event period electron density increased for all the events. The electron density increased from its ambient value to 766.5 el/cc, 5789 el/cc, 4609 el/cc, 541 el/cc, and 1735 el/cc on 14, 15 March and 14, 28, 30 April 2021 respectively at an altitude of 90 km.

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7. References

[1] Abarca, S. F., Corbosiero, K. L., & Galarneau, T. J., Jr. (2010). An evaluation of the Worldwide Lightning Location Network (WWLLN) using the National Lightning Detection Network (NLDN) as ground truth. Journal of Geophysical Research, 115, D18206. https://doi.org/10.1029/2009JD013411

[2] Dowden, R. L., Brundell, J. B., & Rodger, C. J. (1997). Temporal evolution of very strong Trimpis observed at Darwin, Australia. Geophysical Research Letters, 24(19), 2419–2422. https://doi.org/10.1029/97GL02357

[3] Ferguson, J. A. (1998). Computer programs for assessment of long wavelength radio communications, version 2.0. Space and Naval Warfare Systems Center (56 pp.).

[4] Haldoupis, C., Neubert, T., Inan, U. S., Mika, A., Allin, T. H., & Marshall, R. A. (2004). Subionospheric early VLF signal perturbations observed in one-to-one association with sprites. Journal of Geophysical Research, 109, A10303. https://doi.org/10.1029/2004JA010651

[5] Haldoupis, C., Steiner, R. J., Mika, A., Shalimov, S., Marshall, R. A., Inan, U. S., et al. (2006). "Early/slow" events: A new category of VLF perturbations observed in relation to sprites. Journal of Geophysical Research, 111, A11321. https://doi.org/10.1029/2006JA011960

[6] Inan, U. S., Bell, T. F., Pasko, V. P., Sentman, D. D., Wescott, E. M., & Lyons, W. A. (1995). VLF signatures of ionospheric disturbances associated with sprites. Geophysical Research Letters, 22(24), 3461–3464. https://doi.org/10.1029/95GL03507

[7] Inan, U. S., Shafer, D. C., Yip, W. Y., & Orville, R. E. (1988). Subionospheric VLF signatures of nighttime D region perturbations in the vicinity of lightning discharges. Journal of Geophysical Research, 93(A10), 11455–11472. https://doi.org/10.1029/JA093iA10p11455

[8] Kotovsky, D. A., & Moore, R. C. (2015). Classifying onset durations of early VLF events: Scattered field analysis and new insights. Journal of Geophysical Research: Space Physics, 120, 6661–6668. https://doi.org/10.1002/2015JA021370

[9] Kumar, S., & Kumar, A. (2013). Lightning-associated VLF perturbations observed at low latitude: Occurrence and scattering characteristics. Earth Planets and Space, 65(1), 25–37. https://doi.org/10.5047/eps.2012.05.019

[10] Kumar, A. (2015). Ionospheric D-region investigation using ELF-VLF radio wave techniques (Ph.D. thesis). The University of the South Pacific.

[11] NaitAmor, S., AlAbdoadaim, M. A., Cohen, M. B., Cotts, B. R. T., Soula, S., Chanrion, O., et al. (2010). VLF observations of ionospheric disturbances in association with TLEs from the EuroSprite-2007 campaign. Journal of Geophysical Research, 115, A00E47. https://doi.org/10.1029/2009JA015026

[12] Wait, J. R., & Spies, K. P. (1964). Characteristics of the earth-ionosphere waveguide for VLF radio waves. U.S. Government Printing Office.