Comparative study of the possible anomalies in D-region electron density profile as computed from unusual terminator shifts in sub-ionospheric Very Low Frequency (VLF) signal during Honshu, 2011 and Nepal, 2015 earthquakes

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ARTICLE HISTORY
Compiled November 9, 2017

ABSTRACT
We present the perturbations in the propagation characteristics of Very Low Frequency (VLF) signals received at Ionospheric & Earthquake Research Centre (IERC) (Lat. 22.50°N, Long. 87.48°E) during and prior to the two devastating earthquakes in Honshu on 11th March 2011 at 11:16:24 a.m. local time (05:46:24 UTC) with magnitude of M=9 and depth 29 km at the Pacific coast of Honsu, Japan and another in Nepal on 12 May 2015 at 12:35:19 pm local time (07:05:19 UTC) with magnitude of M=7.3 and depth 18 km at south-east of Kodari. The VLF signal emitted from JJI/22.2KHz in Japan (Lat. 32.05°N, Long. 131.51°E) shows strong shift in VLF-sunrise terminator times towards nighttime starting from a few days prior to the earthquake. These two earthquakes have taken place near the VLF transmitter-end (JJI) and near the VLF receiver-end (IERC) respectively. In this work, we have utilized the situation and simulated the VLF sunrise terminator shifts using the RANGE model and EXPONENTIAL sub-program of Long Wavelength Propagation Capability (LWPC) code. To effectively represent the D-region ionospheric variabilities, we assumed a mean dynamic perturbation over the path and presented them with a set of effective Wait's parameters (β_{eff}, h'_{eff}). We have reproduced the temporal trend of the normalized VLF signal amplitude at VLF sunrise terminators for a few days around both the earthquakes. Then, we used Wait's two-component exponential ionospheric model for estimating the altitude profile of D-region electron density ($N_e(h)$) at VLF sunrise terminator times on all those days around both the earthquakes. Hence, we have studied quantitative changes of those $N_e(h)$-profiles during and prior to the seismic events.

KEYWORDS
Earthquake, VLF, Terminator Shift, Modelling, LWPC.

1. Introduction

The existence of pre-seismic anomalies in sub-ionospheric Very Low Frequency (VLF) signal has long been established through numerous works (Baba and Hayakawa 1996; Chakrabarti et al 2005, 2007, 2010; Clilverd et al 1999; Gokhberg et al. 1989; Hayakawa and Fujinawa 1994; Hayakawa and Sato 1994; Hayakawa et al. 1996a,b;

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Hayakawa 1999; Hayakawa and Molchanov 2002; Hayakawa et al. 2005, 2010; Horie et al. 2007a,b; Molchanov and Hayakawa 1998; Molchanov et al. 1998; Nemec et al. 2009; Ray et al. 2010, 2011, 2012; Ray and Chakrabarti 2013; Rodger et al. 1996; Rodger et al. 1999; Rozhnoi et al. 2007; Sasmal and Chakrabarti 2010; Sasmal et al. 2014; Shvets et al. 2004). Several theories have been suggested for possible Lithosphere-Atmosphere-Ionosphere Coupling (LAIC) mechanism which is responsible for such anomalies (Molchanov O.A. 2009; Pulinets and Boyarchuk 2004; Pulinets and Ouzonov 2011). There are various channels through which such coupling mechanism can happen as electromagnetic channel, chemical channel, thermal channel, gravity wave channel, etc. (Pulinets and Ouzonov 2011). It has been found that irrespective of the channel through which such coupling processes happen, the anomalies become evident from the received VLF signal amplitude/phase almost $0-4$ days prior to the main event (Chakrabarti et al 2005, 2007, 2010; Ray et al. 2010, 2011, 2012; Ray and Chakrabarti 2013; Sasmal and Chakrabarti 2009, 2010; Sasmal et al. 2014; Pal et al. 2017). Such anomalies in VLF signal include shift of Sunrise/Sunset Terminator Time(s) (SRT/SST) towards nighttime thereby increasing overall daylength (Hayakawa et al. 1996a,b), unusual enhancements of D-Layer Preparation Time (DLPT) and D-Layer Disappearance Time (DLDT) (Chakrabarti et al 2007, 2010; Sasmal and Chakrabarti 2010), unusual nighttime fluctuations (both positive and negative) before the earthquake (Ray et al. 2011, 2012), etc.

In previous literatures, the effects of a particular earthquake event on different VLF propagation paths (transmitter-receiver) have been presented (Ray and Chakrabarti 2013; Sasmal et al. 2014). Ray and Chakrabarti (2013) studied the effect of the devastating 2011 Pakistan earthquake ($M = 7.2$) on four different propagation paths: DHO-IERC (Sitapur), VTX-Pune, VTX-ICSP (Indian Centre for Space Physics, Kolkata) and NWC-IERC. They mainly concentrated on shifts in SRT and found its significant shifts towards nighttime for the paths DHO-IERC (2 days before EQ day), VTX-Pune (1 day before EQ day) and VTX-Kolkata (4 days before EQ day). For NWC propagation path, no such significant shift in SRT was observed which may be due to the fact that the path was far away from the earthquake epicenter. Sasmal et al. (2014) studied the effect of the 2011 Honshu, Japan earthquake ($M = 9.0$) on two propagation paths: JJI-IERC and NWC-IERC. For JJI-IERC propagation path, significant shifts in SRT was seen 2 days prior to the EQ day and the shift was beyond 3σ level. In addition, unusual enhancements in DLDT was also observed. For NWC-IERC path, the signal was affected by several solar flares and so such observation could not be achieved.

In the present study, contrary to previous works, we tried to find the effects of two different earthquakes on a single propagation path. Our primary focus is to reproduce the trend of VLF signal variation during the earthquake days: both before and after the main event. For this, we chose the JJI-IERC propagation path and the two earthquakes are 2011 Honshu earthquake ($M = 9.0$) and 2015 Nepal earthquake ($M = 7.3$). Hereafter, we will use the abbreviations $\mathbf{H-Eq}$ for Honshu earthquake case and $\mathbf{N-Eq}$ for Nepal earthquake case for simplicity. The H-Eq is located at the transmitter (JJI) end while the N-Eq is at the receiver (IERC) end. For these two earthquakes the receiving location is within the earthquake preparation zones as prescribed by Dobrovolsky (Dobrovolsky 1979). This choice of locations of these two epicenters facilitated us in monitoring the VLF signal modulations owing to two different scenarios: once when the signal is highly perturbed initially (transmitting end) and went through a continuous seismically perturbed earth-ionosphere waveguide towards the receiver; and secondly when the signal initially travels through an unperturbed region and then suffers strong seismo-ionospheric perturbation near the receiving end. This propagation path has a special characteristics that the solar illumination over the entire path is not homogeneous, rather variable due to its high longitudinal extent. So to replicate the true variation of solar illumination over the entire path at a particular time instant, we considered an *'effective'* ionospheric condition defined by the parameters h'_{eff} (effective ionospheric reflection height) and β_{eff} (effective steepness parameter). These parameter values were then fed into the RANGE subprogram of the well known Long Wavelength Propagation Capability (LWPC) code (Ferguson, 1998) to obtain the VLF signal amplitude at that instant. The same process was repeated over a definite time interval around SRT to obtain the desired signal variation for a single day. Finally, the whole method was repeated to reproduce the trend of signal for few days both before and after the Eq days. We also calculated the electron density profile from the well known Wait's formula (Wait 1962; Wait and Spies 1964).

The plan of the paper is as follows: In §2 we present our observations, in §3 we present the methods of numerical simulation, in §4 we present the results and finally, in §5 we make concluding remarks.

2. Observation

The unusual behavior of Very Low Frequency signal amplitude variation is observed during two major earthquakes in JJI/22.2 KHz at a power of 200 W (32°05′N; 131°51′E) received at IERC (22°30′N; 87°48′E), Sitapur. The two devastating earthquakes occurred one at Tohoku, Honshu, Japan on 11 March, 2011 at 11:16:24 local time (05:46:24 UTC) with Richter scale magnitude M=9.0 and depth 24 km and the second one at southeast of Kodari, Nepal on 12 may, 2015 at 12:35:19 pm local time (07:05:19 UTC) with a $M = 7.3$ and depth 18 km. As mentioned in the introduction, the two earthquakes are so chosen that one (H-Eq) is located near the transmitter end and the other (N-Eq) is located near the receiver end. Figure 1 shows the position of JJI (blue triangle), IERC (black circle), the wave paths, and the location of the two earthquake epicenters (red circle). The distance between JJI and IERC is 4355 km. The detail information of the earthquakes are given in Table I.

In this study we have used the VLF data recorded by the SoftPAL (Software Phase and Amplitude Logger) VLF antenna/receiver system. We use electric field antenna coupled with preamplifier and service unit. The service unit provides the electrical power to the pre-amplifier and the Global Positioning System (GPS) unit. The data are being stored by a USB dongle and Lab-chart software with a time stamped by the GPS unit.

In Figure 2a and 2b, we present a typical diurnal variation of JJI-IERC signal amplitude as a function of time in hours as recorded on 5th March, 2011, 6 days prior to H-Eq and 8th May, 2015, 4 days prior to N-Eq as the receiver is out of order from 22nd April, 2015 to 7th May, 2015 due to technical problems . Our prime focus is the movements of the Sunrise Terminator Time (SRT) during the two seismic events. In Figure 2a and 2b, the minimum after the actual sunrise is noted as SRT. The second VLF terminator (Sunset Terminator Time or SST) is also indicated in the Figures. The signal shows clear day and nighttime usual variation with true sunrise and sunset phenomena.

To understand the gradual or sudden movements of the SRTs during and prior to earthquakes, we present the variation of SRT during both earthquakes in Figure 3 and Figure 4. In Figure 3, the SRT variation for H-Eq is presented from 8th March to 15th March, 2011. After the earthquake occurred, the JJI transmitter was turned off during 12th May to 14th May, 2011. The signals are stacked with an amplitude shift of 10 dB for a better understanding of the SRT shifts (Figure 3). The red color plot represents the earthquake day. The value of SRT has been taken as normal or unperturbed for 8th May. On the next day (9th May) there is a shift of SRT towards daytime and after that small gradual shift occurred towards nighttime from 10th May. On 11th May, the SRT shift is maximum. After that it again started to come to normal or unperturbed condition on 15th. This can be due to the effects of aftershocks which followed by the main shock and continued upto 16th of March. The effect is most prominent on 11th which is itself the day of the quake.

In a similar way, we present the SRT variation for N-Eq in Figure 4 for the duration from 9th to 13th May, 2015. The signal are similarly stacked and the red color data is for the earthquake day. On the contrary of H-Eq, for N-Eq the SRT shifts are quite gradual and unidirectional towards nighttime. The shift started on 10th May and it became maximum on 11th May which is one day before the earthquake. It started returning to the normal position on 12th but did not reach it which may due to the similar reasons of aftershocks. For both the cases, the SRT shift is highly prominent. The difference due to seismic perturbation for N-Eq is that the change is more gradual than H-Eq. Also the major effects are preseismic for N-Eq where for H-Eq it is co-sesismic, in the same day with the earthquake.

3. Numerical Simulation

To reproduce the observed VLF signal variation during both earthquakes, we have coupled our observational data of VLF signal amplitude with the LWPC code (Ferguson 1998). The LWPC code is based on waveguide mode theory of radio wave propagation. It is a collection of programmes which is used to estimate the VLF signal profile corresponding to the given D-region conditions for which one has to provide the suitable boundary conditions for the lower and upper waveguide boundaries. The lower boundary parameters related to the waveguide propagation, i.e., the grid based global map of permittivity and conductivity (σ) of the earth are embedded in the code itself. It is chosen according to the characteristics of a baseline. The upper waveguide boundary, i.e., the D-region ionosphere is specified by the two component-exponential Wait's model having its major components, such as, electron density $N_e(h)$ and the electron-neutral collision frequency (σ_h) (Wait and Spies 1964; Pal and Chakrabarti 2010). In the Wait's exponential lower ionosphere model, the electron density is related to the steepness parameter (β) and reference height (h') as given by the equation,

$$Ne(h, h', \beta) \sim e^{(0.15h)} e^{(\beta - 0.15)(h - h')}. \qquad (1)$$

In this paper, we use RANGE model of LWPM program (which is incorporated in LWPC) and the subprogram EXPONENTIAL. Firstly, we supply the transmitter, receiver and propagation path information to RANGE as input. The JJI-IERC propagation path is a typical example of mid-latitude path (22.5°N to 32°N), where it is justified to neglect the latitude variation of D-region ionospheric characteristics. On the other hand, this path is significantly spreaded over longitude (87°E to 130°E). Hence, a notable contrast of solar irradiation induced net D-region ionization and electron content are present over the entire path, especially during sunrise and sunset terminator movements across it. To accommodate all these dynamic path variations of ionosphere using the Wait's exponential ionospheric model, we replace it with a dynamic mean D-region ionospheric variation and accordingly it is represented by a set of "h'_{eff} and β_{eff}". We normalized the observed VLF amplitude to the values corresponding to the unperturbed ionospheric condition as defined by LWPC. Secondly, we run the RANGE to reproduce the temporal trend of the observed VLF amplitude for a single day by supplying suitable values of these β_{eff} and h'_{eff} values in the EXPONENTIAL. Thirdly, we repeat this simulation procedure to reproduce the temporal trend of the normalized VLF amplitude for a few days around both the earthquake days, especially around the VLF-SRT and estimate the effective parameters. Fourthly, we calculate the altitude profile of D-region electron density ($N_e(h)$) from those effective parameters using Wait's model (see eqn.1) particularly at the respective VLF-SRTs of those days. According to LWPC, the $h'_{eff} = 74$km and $\beta_{eff} = 0.3\text{km}^{-1}$ represents the total ionospheric-day condition and $h'_{eff} = 87$km and $\beta_{eff} = 0.6km^{-1}$ represents a complete night. During this simulation, the β_{eff} and h'_{eff} varies within 0.4 to 0.55 km^{-1} and 78 to 82.5 km for N-Eq. For the case of H-Eq, the same varies within 0.35 to 0.6 km^{-1} and 76 to 80 km. Practically, β_{eff} and h'_{eff} values in these range effectively represent the mixed day-night conditions over the path.

4. Results and Interpretation

We present the observed and simulated temporal variation of VLF-SRTs during both the earthquakes. In Figure 5(a-b), we present the observational VLF signal amplitude as a function of time starting from 04:00:00 to 06:00:00 IST and the corresponding simulated amplitude (lower panel) for the same time period for H-Eq. In both figures, the black curves and the red curve indicates the signal on the normal days and the earthquake day respectively. The VLF signal amplitudes are stacked in a similar manner as presented in §2. The arrows indicate corresponding VLF-SRTs. From figures 5(a-b), we can clearly see that the SRTs are shifted towards nighttime and reaches the maxima on 11th March 2011, i.e., the H-Eq day which satisfies our observation. The net shift of VLF-SRT observed on 11th March compared to 8th March (normal day) is $\sim$ 18.4 minutes, where the same obtained from simulation is $\sim$ 20.2 minutes.

Figure 6(a-b) presents the similar works as for N-Eq. Here, we present the observational VLF signal amplitude for the duration from 03:09:57 to 03:40:60 IST. We choose the time span in such a way that the position of the VLF-SRT is in the middle and the temporal variation is clearly understandable. We also present the simulated counterpart of it for the same time period in Figure 6(b). We can clearly see that the shift of VLF-SRT towards nighttime is more gradual than H-Eq. Here, it reaches the maxima on 11th May 2015, i.e., a day before the N-Eq which is also evident from our observation. The net shift of VLF-SRT observed on 11th May compared to 9th May is $\sim$ 19.1 minutes, where the same computed from simulation is $\sim$ 20.4 minutes. The net shift on the earthquake day, i.e. 12th May in VLF-SRT observed compared to 9th May is 16.2 minutes, where the same obtained from simulation is 16.6 minutes. It is clearly noticed that the shift is decreased by (19.1 - 16.2)= 2.9 minutes which indicates that the D-region ionospheric recovery processes is already initiated and the VLF-SRT is started returning to its original value right from the earthquake day. This phenomenon is in contrary with H-Eq case, where the same recovery mechanism has started 2-3 days after the day of earthquake (Fig.5(a-b)). The possible reason behind this contradiction may be associated with the locations of the epicenters in reference to the receiving location, IERC.

In Figure 7 and 8, we present the altitude profile of electron densities ($N_e(h)$) in m^{-3} in logarithmic scale obtained from Wait's ionospheric model at VLF-SRTs on the days on and around H-Eq and N-Eq respectively. In Figure 7, the $N_e(h)$s are calculated at VLF-SRT of 8th March 2011, which is treated as a quiet day for H-Eq. For altitudes above 78 km, the $N_e(h)$ decreases as one approaches to the day of H-Eq. The $N_e(h)$ change is sudden from 9th March to 10th March by an amount of $\sim$40% at a height of 82 km and interestingly the VLF-SRT change then is comparatively higher ($\sim$20.4 minutes). The $N_e(h)$ does not change much from 11th March 2011 to 15th March 2011 possibly of a series of aftershocks took place at that time and it did not allow the ionosphere to return to the so called quiet or unperturbed state.

For Figure 8, the electron density profile $N_e(h)$ as a function of reflection height is presented at the time of VLF-SRT of 9th May 2015, which is treated as normal day for N-Eq. In a similar manner, for altitude above 80 km, the electron density decreases gradually as one approaches to the earthquake day. The value of $N_e(h)$ became minimum on 11th May. After that it started increasing and on 13th May and reaches almost the same level from where it started initially. The maximum change of $N_e(h)$ from 9th May to 11th May in around 76%.

To highlight the solar geomagnetic effects in our results, we checked the solar geomagnetic k_p index during our observation. For H-Eq, the k_p values are moderate (k_p

<5). For N-Eq, it was found geomagnetically quiet for almost the entire duration of our study ($k_p < 3$) except on 13th May when it was moderate with $k_p < 5$.

5. Conclusion and Discussion

In this paper, our prime focus was to study the VLF signal anomalies related to possible ionospheric perturbations due to two earthquakes whose epicenters are far away and situated on the same VLF propagation path in such a way that one is closer to the transmitter and the other to the receiver. These two earthquakes in Honshu, 11th March, 2011 and in Nepal, 12th May, 2015 were in the vicinity of transmitter JJI and receiver IERC respectively. We observed significant shift in VLF-SRTs towards nighttime for both the quakes. We numerically reproduced the temporal profile of signal amplitude which includes the shifts in SRT by using LWPC model. We computed the normal and seismically perturbed electron density profiles during these events using Wait's formula. We found significant differences in the behavior of VLF signals for these two earthquakes. For H-Eq, which is closer to the transmitter, the study shows sudden change in the SRT shift and the effect is co-seismic in nature i.e., the maximum shift occurred on the day of the earthquake. On the other hand, for N-Eq, the shifts are quite gradual and pre-seismic i.e., the maximum effects in the signal is one day prior to the earthquake. This is also reflected in the simulation and we found the expected sudden and gradual trend in the $N_e(h)$ profile for H-Eq and N-Eq respectively. There are notable quantitative differences present in the change of $N_e(h)$ profile at 82 km and the change is larger for the N-Eq (76%) than H-Eq (40%). For the two earthquakes, the JJI signal propagated through two distinct conditions. For, H-Eq, it traveled from a higher seismically perturbed region to a lower one but for N-Eq just the opposite situation happened where it went from an unperturbed zone to a highly pertrubed one. These differences in signal anomalies can be connected with these relative locations of the epicenters of the two earthquakes and the characteristics of the propagation path.

To understand the physical interpretation of the observed pre-seismic phenomenon several models are studied and their results can be used as supportive evidence. According to acoustic gravity models, the atmospheric acoustic gravity waves (AGWs) are generated several days before earthquakes near the Earth's surface in earthquake preparation zones and propagate upward through the atmosphere at an angle with respect to the horizontal and reach ionospheric altitudes. An AGW propagation angle depends on a wave period. Subsequently, disturbances of the ionospheric plasma neutral component can cause disturbances of a charged particle density in the ionosphere owing to ionneutral collisions. In a seismically active zone, AGW generation can be caused by several factors. Movements of the Earth's crust (which has a block structure), unstable thermal anomalies (caused by emission of hotbed gases into the atmosphere in fault zones of the Earth's crust), and unstable release of lithospheric gases into the atmosphere (Gokhberg et al., 1996) can be among these factors. It is known that the spectrum of seismo-gravitational vibrations of the Earth with periods of 30 minutes to 4 hours is stably registered during seismological measurements (Lin'kov et al. 1990), and seismo-gravitational vibrations with periods from 1 to 5 hr are usually intensified several days before strong earthquakes with M 6.0 (Garmash et al. 1989). During seismo-gravitational vibrations, the Earth's surface can affect the atmosphere as a piston and can cause variations in temperature, conductivity, and pressure resulting in AGW generation in the atmosphere. In addition, these vibrations can lead to emission of radon and other gases into the atmosphere. Anomalous variations in the atmospheric pressure, relative humidity, air temperature, and wind velocity (Mil'kis 1986) were observed in Central Asia several hoursseveral days before a number of strong earthquakes. Disturbances propagate into the ionospheric F region in many stages (Ghosh et al. 2017); AGWs create only initial plasma disturbance, and the Rayleigh-Taylor instability subsequently develops. This instability can result in the origination of ionospheric plasma bulbs, which manifest themselves as plasma density variations with characteristic horizontal dimensions of 1100 km during a satellite pass.

Electric field modulation is based on an increased radon emission in earthquake preparation regions seven-ten days before earthquakes. Radioactive elements come into the atmosphere together with the soil air. Before earthquakes, an ion production rate increases. Radon is carried upward to an altitude of several kilometers by air flows. The observational data indicate that the level of atmospheric radioactivity increases during earthquake preparation. The model of origination of quasi constant local electric field modifications in the atmosphere above earthquake preparation regions was developed in (Sorokin and Yashchenko 1999; Sorokin and Chmyrev 2002). The idea of the works is based on the facts that radon is often emitted into the atmosphere in an earthquake preparation region and the radon concentration can increase several times, leading to an increase in the level of radioactivity and consequently, ionization in the atmosphere (Chakraborty et al 2017). Conductivity of the near Earth atmosphere increases in this case.

The models of the lithosphere-atmosphere-ionosphere coupling (an electrostatic model) also considers the effect of radon emission in the near Earth atmosphere above fault zones before earthquakes (Pulinets 1998; Pulinets et al. 2000; Pulinets et al. 2006; Pulinets and Boyarchuk 2004; Pulinets and Liu 2004). These works were based on the observations of disturbances in the Earth's vertical electrostatic field in the near Earth atmospheric layer with a thickness of several meters a few days before an earthquake. The model takes into account that radon causes ionization and results in the production of positive and negative ions and more complex hydrated ions (ion clusters) near the Earths surface. It is also assumed that ions are captured by aerosols, and the stationary system of oppositely charged aerosols is formed.

The nonstationary effect at high atmospheric altitudes was considered in (Liperovsky et al. 2007). The nonstationary electric fields with the characteristic times about an hour before earthquakes were observed and analyzed in the cycle of works (Mikhailov et al. 2004, 2005)

For better understanding of this effect, multiple paths with similar type of earthquake locations has to be studied in detail. This will be done in future.

Acknowledgement(s)

The authors acknowledge Ministry of Earth Sciences (MoES) for financial supports.

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