International Journal of Advance Research in Science and Engineering
Volume No.07, Special Issue No.02, April 2018
www.ijarse.com
IJARSE
ISSN: 2319-8354

Ionospheric Effect Of Earthquake As Determined From Narrowband VLF Transmitter Signals

Dushyant Singh, Dhananjali Singh and Birbal Singh

Department of Electronics and Communication Engineering, Raja Balwant Singh Engineering Technical Campus, Bichpuri, Agra 283105, India

ABSTRACT

Employing SoftPAL receiver, amplitude variations of very low frequency (VLF) NWC (19.8 kHz) transmitter signals are analyzed at Agra station in India (Geograph. lat. 27.2˚N, long. 78˚E) ±15 days from one major earthquake of magnitude M = 6.9 occurred in Nepal-India (Sikkim) border region on 18 September, 2011. We apply nighttime fluctuation (NF) method and show that the trend decreases and dispersion and NF increase on the same day 15 days prior to the main shock. Assuming that the ionospheric perturbations are caused by atmospheric gravity waves (AGW), we also calculate AGW modulation index and find its values increased on the day amplitude fluctuations take place.

Keywords:VLF; Nighttime fluctuation; Earthquake precursors

I. INTRODUCTION

VLF signals transmitted from fixed frequency ground transmitters are propagated to long distances through the space between earth and ionosphere. Since the earth has large conductivity, the changes in the amplitude and phase of VLF signals are caused mostly by structural and dynamical changes in the lower ionosphere (Cromie, 1965). Solar flares, magnetic storms, galactic cosmic rays, lightning, etc. are some of the well-known factors which are responsible for causing such changes (Inan et al., 1996; Peter et al., 2006; Zigman et al., 2007). Recently, it has been found that such changes in the lower ionosphere are caused by earthquakes also and to ascertain this phenomenon two methods have been proposed, one of which is known as Termination Time (TT) method (Hayakawa et al., 1996) and the other is known as Nighttime Fluctuation (NF) method (Gokhberg et al., 1989; Gufeld et al., 1992). The TT method is based on the study of characteristic times of minima in the amplitude and phase of diurnal variations during sunrise and sunset times. However, this method has not found large adaptability because it is useful for short distance propagation paths (~1000 km) and East–West direction of propagation only (Maekawa and Hayakawa, 2006; Hayakawa, 2007).

The nighttime fluctuation (NF) method is based on the analysis of nighttime amplitude anomalies of VLF signals and examining the variations of three parameters, trend, dispersion, and nighttime fluctuation (NF) and, in contrast to limitations in TT method it has received wider adaptability. This method is examined and developed by Shvets et al. (2002, 2004a, b) and Rozhnoi et al. (2004). It has been found that prior to the occurrence of earthquake the trend decreases with simultaneous increase in the dispersion and nighttime fluctuations. (Kasahara et al., 2010; Hayakawa et al., 2010a; Maurya et al., 2013). One more factor was proposed by Muto et al. (2009), atmospheric gravity waves modulation index (AGW M) i.e. the fluctuation spectra in the frequency range of atmospheric gravity waves (period 10 min-100 min). They found that the study of this factor would increase the confirmation of the seismoionospheric perturbations. We analyzed the VLF signals received from the NWC transmitter by employing the NF technique to study the precursory characteristics of a major earthquake. In order to study the ionospheric perturbations due to earthquake we analyzed the AGW modulation index.

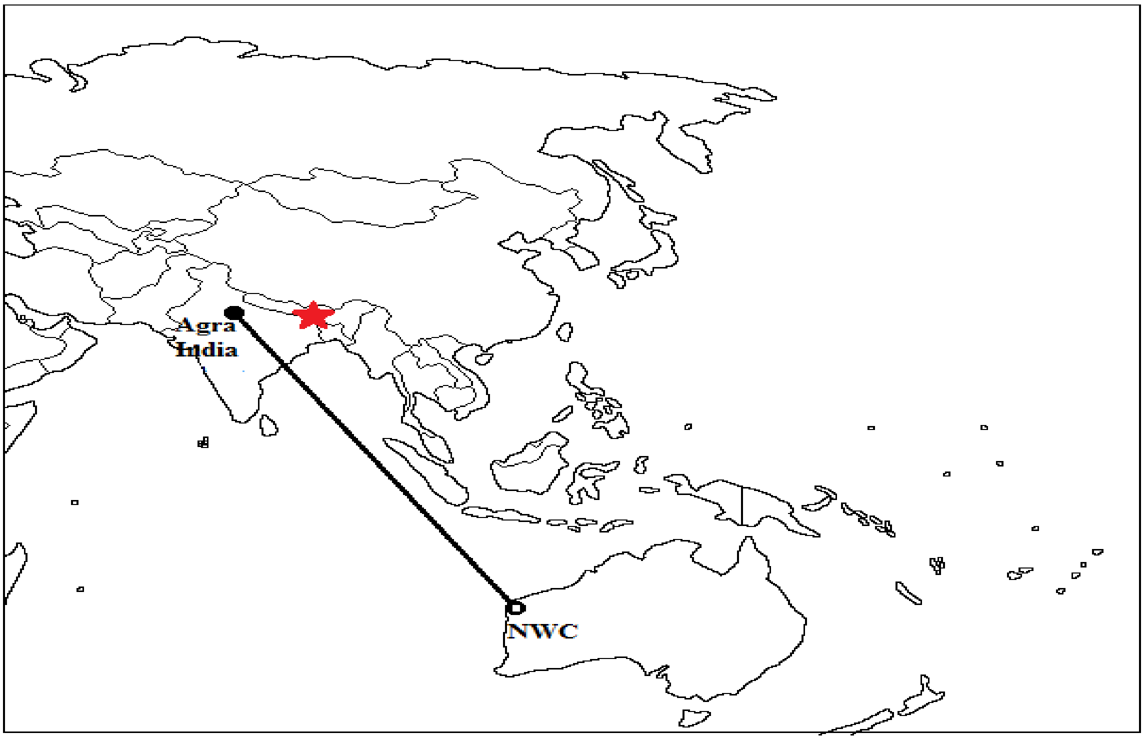

Fig. 1: Great circle path for NWC signals. Location of earthquake and receiver are shown by star and solid circle respectively.

2. Experimental setup

Our experimental setup for VLF measurements is similar to that employed by our group earlier (Pundhir et al., 2016; Singh and Singh, 2017). We have employed Software based Phase and Amplitude Logger (SoftPAL) receiver for monitoring the phase and amplitude of fixed frequency VLF transmitter signals. We monitor the phase and amplitude of the signals of frequencies 19.8 KHz (NWC, Australia), 21.4 kHz (NPM, Hawaii), and 24 kHz (NAA, Cutler, Maine). The propagation path of first signal is shown in the map of Fig. 1. The equipments which are used are electric and GPS antennas, VLF amplifier, a service unit, DSP card, and necessary software.

The sampling rate used is 60 s. The regular monitoring of phase and amplitude variations of the signals has been started since 1 April, 2010 in the Seismo-Electromagnetic and Space Research Laboratory of R.B.S. Engineering Technical Campus, Bichpuri, Agra. It is a rural area which is located at about 12 km west of Agra city and the local electric and electromagnetics disturbances are low here.

3. Earthquake data

In the present study the details of the earthquake data are taken from United States Geological Survey (USGS) website http://earthquake.usgs.gov/earthquakes/ . The details of the earthquake such as date, time, and location of their occurrence are given in Table 1. The location of this earthquake is shown in Fig.1 by star and the location of Agra station is shown by solid circle. As it can be seen here that the earthquake is of large magnitudes (M = 6.9) and occurred near the propagation path of VLF signals from NWC to Agra.

Date of Earthquake	**Time (UT)**	**Lat. (deg.)**	**Long. (deg.)**	**Depth (km)**	**Magnitude**	**Region**
18/09/2011	12:40:47	27.8°N	88.1°E	46	6.9	Nepal-India (Sikkim) Border Region

Table 1: Details of earthquake considered in the present study.

4. Method of data analysis

We have employed NF method in the present study and we carry out amplitude analysis of one VLF transmitter signals, NWC (19.8 KHz) which are originated from NWC, Australia (Geograph. lat. 21.8˚S, long. 114˚E). The analysis technique used by us is similar to that used by earlier workers (Kasahara et al., 2010; Hayakawa et al., 2010a, 2011). The nighttime data for the period between 14:30 and 22:30 UT is chosen which is equivalent to Local time 20:00 and 04:00 hrs (LT = UT + 5.5 hrs). We analyze ±15 days of VLF data corresponding to each earthquake under consideration. We study three parameters that are trend, dispersion, nighttime fluctuations derived from amplitude analysis. We also determine atmospheric gravity waves (AGW) modulation index so as to examine if AGWs are responsible for perturbation (Muto et al., 2009) and determine their values from the expression used by earlier workers (Maekawa et al., 2006;Muto et al., 2009;Kasahara et al., 2010;Hayakawa et al., 2010a, 2011) given by $dA(t) = A(t) – \langle A(t) \rangle$, where A(t) is the amplitude at the time t on a particular day which describes the diurnal variations of the signal amplitude and $\langle A(t) \rangle$ is defined as the average value at the same time t over ± 15 days of the current day. The trend is the mean value of dA(t) for each day, whereas dispersion is statistical quantity of dispersion of dA(t) for each day. The third parameter, nighttime fluctuation (NF) is defined by the area of $dA(t)<0$ integrated over the whole nighttime. Details on these parameters are given by Kasahara et al. (2010), and Hayakawa et al. (2010a). The fourth parameter AGW modulation index is estimated as explained by Muto et al. (2009) for which we perform the FFT analysis on dA(t) and obtain the fluctuation spectrum dS(f) in a wide frequency range of AGW. Then we estimate dS(f) = S(f) − <S(f)> for each day, where S(f) is the FFT spectrum on the current day and <S(f)> is the mean spectrum over ± 15 days of the earthquake day. Here, we take only positive dS(f) (dS(f)>0). The AGW modulation (M) is defined as follows.

$$\text{AGW } M = \frac{\int dS(f)df}{\text{Range (in frequency) of AGW}} \qquad (1)$$

Further, we use statistical analysis as explained by Muto et al. (2009) and Hayakawa et al. (2010a) where normalized values of these four parameters are calculated with respect to their corresponding standard deviations to remove the long term (e.g. seasonal) effect.

5. Results

From the details of earthquake presented in Table 1 and its location shown in Fig. 1, it may be seen that the earthquake occurred in North-East region of Nepal-India Border. Hence this earthquake might influence the propagation path of NWC signals (f = 19.8 kHz). It is for this reason that we analyze the amplitude data of NWC signal corresponding to this earthquake. As mentioned in section 4, we have taken nighttime amplitude data for the period of eight hours between 14:30 and 22:30 UT (20:00 to 04:00 LT). The amplitude data A(t) are measured at every minute between this interval and averaged, which provides <A(t)>. From these two values dA(t) is calculated for each day from the expression given in section 4, and then the average of dA(t) is calculated for each day, which is trend. The standard deviation of dA(t) gives the dispersion. The nighttime fluctuation (NF) is calculated by using the procedure of Hayakawa et al. (2010a) which is mentioned in section 4. Further we have calculated the normalized values of these parameters also by following the procedure of Hayakawa et al. (2010a). The values of these parameters so calculated for a period of ± 15 days from the earthquake occurred on 18 September, 2011 are shown in first three panels of Fig. 2 (a)-(c). In these figures, 0 on the x-axis shows the day of the earthquake and the two horizontal lines in each panel show ±2σ standard deviations. The last fourth panel, Fig. 2 (d) shows the variation of normalized values of AGW modulation index which will be discussed later. The two panels Fig. 3 (a), (b) show the variation of magnetic storm index (Dst) and ∑Kp index for the period indicated in the respective two panels. These parameters indicate the strength of magnetic storm and their values are taken from the website: http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html.From this figure it may be seen that the normalized trend decreases along with simultaneous increase in normalized values of dispersion, nighttime fluctuations (NF), and AGW M on 3 September, 2011 i.e. 15 days before earthquake. The dispersion and nighttime fluctuations (NF) are significant enough as they crossed 2σ line. For clarity in this figure these values are enclosed in a vertical rectangular block. Further the two panels of Fig. 3 show that there was a magnetic quiet condition during this period.

6. Discussion

From the results presented in Fig. 2 it is seen that the anomaly parameter trend decreases along with simultaneous increase in dispersion, and nighttime fluctuations (NF). These results are significant enough as they satisfy 2σ criterion. In all the cases of earthquakes our results are consistent with those obtained by earlier workers (Kasahara et al., 2010; Hayakawa et al., 2010a, b, 2011; Maurya et al., 2013). The anomalies occur 15 days before the earthquake which is derived from the amplitude analysis of NWC signals. It may be noted here that precursory periods of 2-15 days have been reported earlier by many workers. (Maekawa et al., 2006; Hayakawa et al., 2010a, b, 2011, 2013; Rozhnoi et al., 2009; Maurya et al. 2013)

The variations of atmospheric gravity waves modulation index (AGW M) are presented in Fig. 2 (d) which show increased value of the index in this case of earthquake. The increase in the modulation index indicates the concentration of atmospheric gravity waves in the ionosphere. A theoretical explanation as to how the AGW can perturb the ionosphere is given byRozhnoi et al. (2012). The variation of the magnetic storm parameters (Dst and ∑Kp) as shown in the two panels of the Fig. 3 (a), (b) show that all these anomalies occurred during magnetically quiet days. Hence the question of magnetic storms influencing the anomalies (Peter et al., 2006) does not arise. A possibility of lightning activity affecting the lower ionosphere and causing VLF perturbations (Inanet al., 1996), does not arise also because as seen from the website https://www.wunderground.com/ no lightning activities occurred on the days when the VLF anomalies were observed.

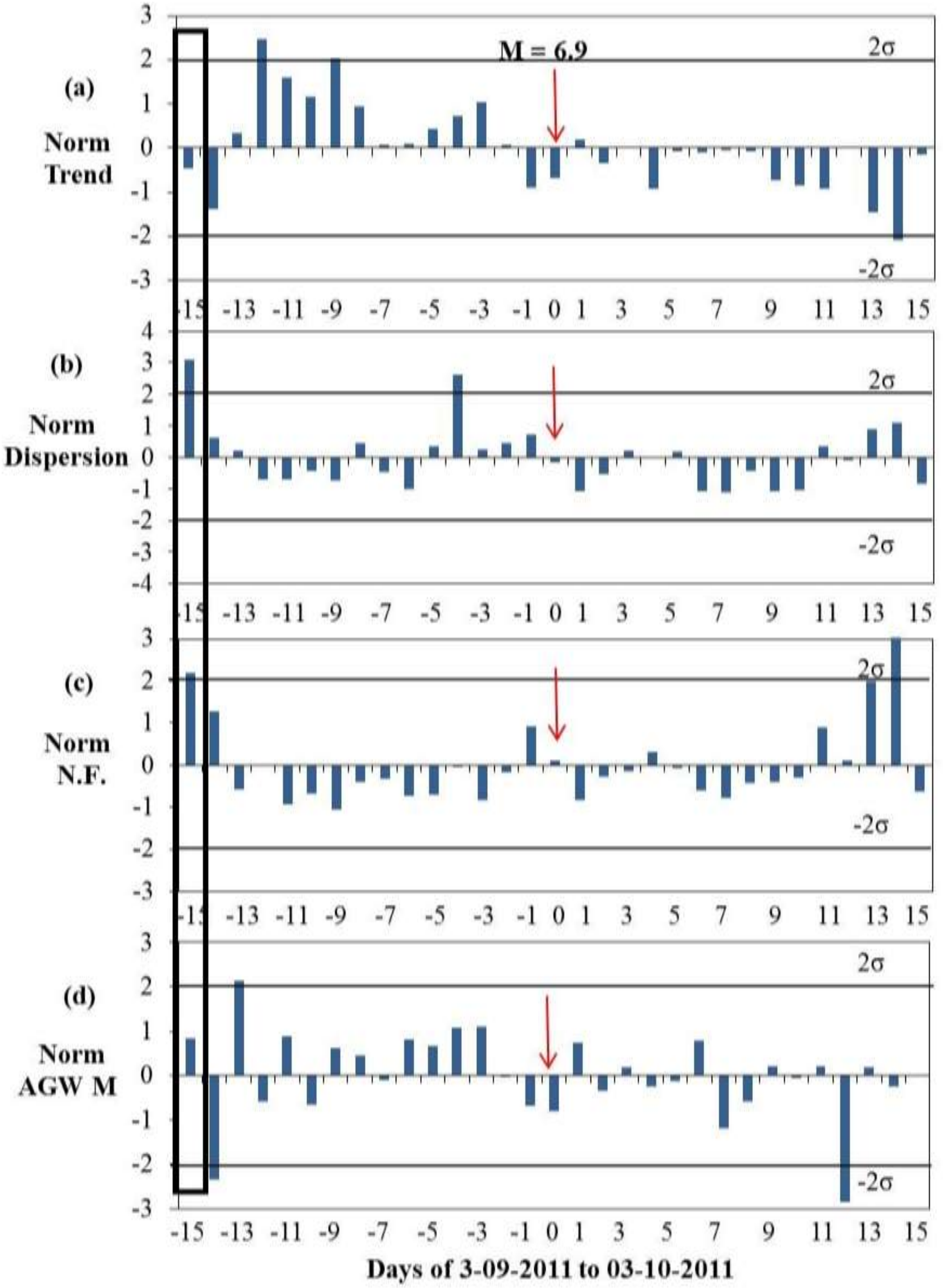

Fig. 2: Temporal evolutions of four normalized physical parameters (a) Trend, (b) Dispersion, (c) Nighttime Fluctuations (NF), and (d) Atmospheric gravity waves modulation index (AGW M) during 3 September, 2011 to 3 October, 2011 deduced form NWC signals. The x-axis shows ± 15 days from the day of occurrence of the

earthquake on 18 September, 2011 shown by 0. The vertical rectangular block indicates the anomalous day and horizontal lines in each panel show ±2σ criterion.

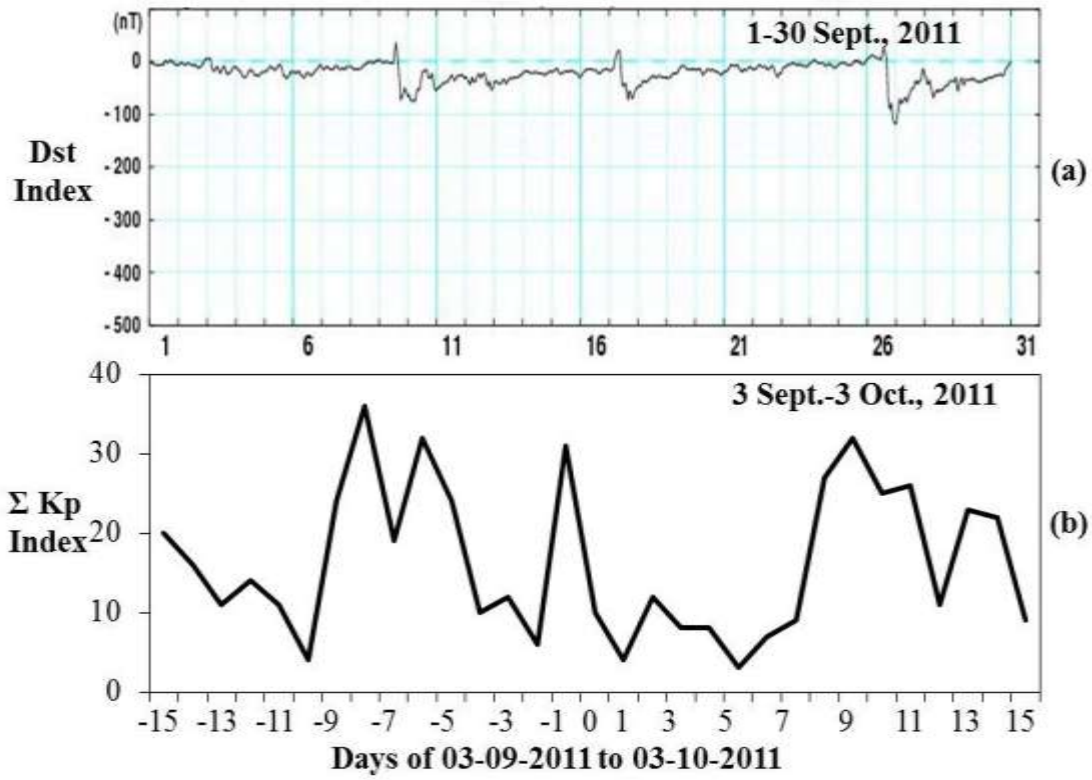

Fig. 3: The two panels show the variation of magnetic storm indices Dst (a) and Σ Kp (b).The x-axis in (b) shows ± 15 days from the day of occurrence of the earthquake on 18 September, 2011 shown by 0.

The question of solar flares causing the anomalies (Zigmanet al., 2007) may not arise also because we have analyzed the nighttime data. Here it may be mentioned that while studying the perturbations due to earthquakes in the lower ionosphere by VLF method, solar flares and lightning are not given attention because their effect is short lived and can be easily identified. The lightning induced electric field does penetrate the upper ionosphere provided it is generated from the thunderstorm region. However, the effect of magnetic storm must be taken into account (Hayakawa et al., 2010c).

The ionosphere is known to be under forcing from below by a number of factors in two channels which include (1) electrical and electromagnetic channel and (2) upward propagating waves in the neutral atmosphere. The second category is more important from the point of view of energy deposition and atmospheric modification than the phenomena under first category. It includes variety of up propagating waves which are planetary waves (PW), tidal waves, gravity waves and infrasonic waves (Lastovicka, 2006). During the period of earthquakes, the gravity waves (atmospheric gravity waves and acoustic waves), planetary and infrasonic waves are intensified. Atmospheric gravity waves and planetary waves are generated prior to the occurrence of the earthquake also whereas acoustic and infrasonic waves are generated after the earthquakes and rarely occur before. These waves perturb the ionosphere significantly (Molchanov, 1993;Lizunov and Hayakawa, 2004;Hao et al., 2012) and may cause regular fluctuations in the amplitude of the VLF signals. In Fig. 2 (d) we have interpreted the nighttime fluctuation in VLF signals in terms of intensification of gravity waves at the ionospheric heights. In order to explain this it may be mentioned that various physical mechanisms exist to explain the ionospheric perturbations associated with earthquakes prominent among them being atmospheric gravity waves (AGW). Molchanov and Hayakawa (1998) have found the effect of AGW turbulence being the agent of ionospheric perturbations based on the observations of VLF subionospheric signals. These gravity waves are considered to be generated by gas release from the crust above earthquake preparation process (Pulinets et al., 1994) along with variations in other atmospheric parameters like pressure, temperature, etc. So it is clear from the analysis of AGW modulation index that the atmospheric waves have been prominent in creating the ionospheric perturbations.

7. Conclusion

We have analyzed VLF amplitude data obtained from monitoring of NWC (19.8 kHz) transmitter signals to examine the influence of earthquake of large magnitude (M = 6.9) which occurred in the North-East region of Nepal-India border. We have employed Nighttime fluctuation method in which we calculated three VLF anomaly parameters i.e. trend, dispersion and nighttime fluctuation (NF). We find that trend decreases along with simultaneous increase in dispersion and nighttime fluctuation, a result consistent with those obtained by earlier workers. We have also calculated atmospheric gravity waves modulation index (AGW M) for all the earthquakes and found its increased values suggesting atmospheric gravity waves concentration responsible for VLF anomalies observed. The VLF anomalies occur 15 days prior to the occurrence of all the earthquakes which are consistent with precursory periods reported by earlier workers.

Acknowledgements

The Authors are grateful to Dr. DevbratPundhir and Mr. Ajay Singh for their help in carrying out this research work. We are also thankful to Ministry of Earth Sciences (MoES), New Delhi for financial support in the form of a major research project.

References

Cromie, D. D., 1965.On the use of VLF measurements for obtaining information on the lower ionosphere (Especially during Solar Flares). Proc. IEEE 53 (12), 2027–2034.

Gokhberg, M. B., Gufeld, I. L., Rozhnoy, A. A., Marenko, V. F., Yampolsky, V. S., Ponomarev, E. A., 1989. Study of seismic influence on the ionosphere by super long wave probing of the Earth-ionosphere waveguide.Phys. Earth Planet. Inter. 57, 64–67.

Gufeld, I. L., Rozhnoy, A. A., Tyumentsev, S. N., Sherstyuk, S. V., Yampolsky, V. S., 1992. Radio wave field disturbances prior to Rudbar and Rachinsk earthquakes.Izvestiya, Phys. Solid Earth 28, 267–270.

Hao, Y. Q., Xiao, Z., Zhang, D. H., 2012.Multi-instrument observation on co-seismic ionospheric effects after great Tohoku earthquake.J. Geophys. Res. 117 (A02305), 1–8.

Hayakawa, M., Molchanov, O. A., Ondoh, T., Kawai, E., 1996. The precursory signature effect of the Kobe earthquake on VLF subionospheric signals. J. Comm. Res. Lab., Tokyo 43, 169–180.

Hayakawa, M., 2007. VLF/LF radio sounding of ionospheric perturbations associated with earthquakes. Sensors 7, 1141–1158.

Hayakawa, M., Kasahara, Y., Nakamura, T., Muto, F., Horie, T., Maekawa, S., Hobara, Y., Rozhnoi, A. A., Solovieva, M., Molchanov, O. A., 2010a.A statistical study on the correlation between lower ionospheric perturbations as seen by subionospheric VLF/LF propagation and earthquakes.J. Geophys. Res. 115 (A09305), 1–9.

Hayakawa, M., Kasahara, Y., Nakamura, T., Hobara, Y., Rozhnoi, A., Solovieva, M., Molchanov, O. A., 2010b.On the correlation between ionospheric perturbations as detected by subionospheric VLF/LF signals and earthquakes as characterized by seismic intensity.J. Atmos. Sol.-Terr. Phys. 72, 982–987.

Hayakawa, M., Horie, T., Muto, F., Kasahara, Y., Ohta, K., Liu, J. Y., Hobara, Y., 2010c. Subionospheric VLF/LF probing of ionospheric perturbations associated with earthquakes: A possibility of earthquake prediction. SICE J. Cont. Measur. Sys.Integ.3, 10–14.

Hayakawa, M., Raulin, J. P., Kasahara, Y., Bertoni, F. C. P., Hobara, Y., Guevara-Day, W., 2011.Ionospheric perturbations in possible association with the 2010 Haiti earthquake, as based on medium-distance subionospheric VLF propagation data.Nat. Hazards Earth Syst. Sci. 11, 513–518.

Hayakawa, M., Hobara, Y., Rozhnoi, A., Solovieva, M., Ohta, K., Izutsu, J., Nakamura, T., Kasahara, Y., 2013.The Ionospheric Precursor to the 2011 March 11 Earthquake Based upon Observations Obtained from the Japan-Pacific Subionospheric VLF/LF Network. Terr. Atmos. Ocean. Sci. 24 (3), 393–408.

Inan, U. S., Pasko, V. P., Bell, T. F., 1996. Sustained heating of the ionosphere above thunderstorms as evidenced in “early/fast” events. Geophys. Res. Lett. 23 (10), 1067–1070.

Kasahara, Y., Muto, F., Hobara, Y., Hayakawa, M., 2010. The ionospheric perturbations associated with Asian earthquakes as seen from the subionospheric propagation from NWC to Japanese stations. Nat. Hazards Earth Syst. Sci. 10, 581–588.

Lastovicka, J., 2006. Forcing of the ionosphere by waves from below.J. Atmos. Sol.-Terr. Phys. 68, 479–497.

Lizunov, G., Hayakawa, M., 2004.Atmospheric gravity waves and their role in the Lithosphere-Troposphere-Ionosphere interactions. IEEJ Trans. FM. 124 (12), 1109–1120.

Maekawa, S., Hayakawa, M., 2006. A statistical study on the dependence of characteristics of VLF/LF terminator times on the propagation direction. Trans. Inst. Electr.Engrs. Japan, Fundamentals and Materials, Special Issue on Recent Progress in Seismo-Electromagnetics 126 (4), 220–226.

Maekawa, S., Horie, T., Yamauchi, T., Sawaya, T., Ishikawa, M., Hayakawa, M., Sasaki, H., 2006. A statistical study on the effect of earthquakes on the ionosphere, based on the subionospheric LF propagation data in Japan. Ann. Geophys. 24, 2219–2225.

Maurya, A. K., Singh, R., Veenadhari, B., Kumar, S., Singh, A. K., 2013.Subionospheric very low frequency perturbations associated with the 12 May 2008 M = 7.9 Wenchuan earthquake. Nat. Hazards Earth Syst. Sci. 13 (9), 2331–2336.

Molchanov, O. A., 1993. Wave and plasma phenomena inside the ionosphere and magnetosphere associated with earthquakes. Int. Union Rad. Sci. 28, 591–599.

Molchanov, O. A., Hayakawa, M., 1998.Subionospheric VLF signal perturbations possibly related to earthquakes. J. Geophys. Res. 103 (A8), 17489–17504.

Muto, F., Kasahara, Y., Hobara, Y., Hayakawa, M., Rozhnoi, A., Solovieva, M., Molchanov, O. A., 2009.Further study on the role of atmospheric gravity waves on the seismo-ionospheric perturbations as detected by subionospheric VLF/LF propagation.Nat. Hazards Earth Syst. Sci. 9, 1111–1118.

Peter, W. B., Chevalier, M. W., Inan, U. S., 2006. Perturbations of mid latitude subionospheric VLF signals associated with lower ionospheric disturbances during major geomagnetic storms. J. Geophys. Res. 111 (A03301), 1–14.

Pulinets, S. A., Legenka, A. D., Alekseev, V. A., 1994. Pre-earthquake ionospheric effects and their possible mechanisms, In Dust and Dirty Plasmas, Noise and Chaos in Space and in the Laboratory, (Ed.) H. Kikuchi, Plenum Press, New York, 545–556.

Pundhir, D., Singh, B., Singh, O. P., Gupta, S. K., 2016. Anomalous variations of ionosphere associated with strong earthquake at Pakistan-Iran border at a low latitude station Agra, India. ActaGeophysica 64 (3), 796–809.

Rozhnoi, A., Solovieva, M. S., Molchanov, O. A., Hayakawa, M., 2004. Middle latitude LF (40 kHz) phase variations associated with earthquakes for quiet and disturbed geomagnetic conditions. Phys. Chem. Earth 29, 589–598.

Rozhnoi, A., Solovieva, M., Molchanov, O., Schwingenschuh, K., Boudjada, M., Biagi, P. F., Maggipinto, T., Castellana, L., Ermini, A., Hayakawa, M., 2009. Anomalies in VLF radio signals prior the Abruzzo earthquake (M = 6.3) on 6 April 2009. Nat. Hazards Earth Syst. Sci. 9, 1727–1732.

Rozhnoi, A., Shalimov, S., Solovieva, M., Levin, B., Hayakawa, M., Walker, S., 2012. Tsunami-induced phase and amplitude perturbations of subionospheric VLF signals. J. Geophys. Res. 117 (A09313), 1–8.

Shvets, A. V., Hayakawa, M., Molchanov, O. A., 2002.Subionospheric VLF monitoring for earthquake-related ionospheric perturbations. J. Atmos. Electr. 22, 87–99.

Shvets, A. V., Hayakawa, M., Molchanov, O. A., Ando, Y., 2004a.A study of ionospheric response to regional seismic activity by VLF radio sounding. Phys. Chem. Earth 29, 627–637.

Shvets, A. V., Hayakawa, M., Maekawa, S., 2004b. Results of subionospheric radio LF monitoring prior to the Tokachi (M = 8, Hokkaido, 25 September 2003) earthquake. Nat. Hazards Earth Syst. Sci. 4, 647–653.

Singh, D., Singh, B., 2017. Termination Time anomalies associated with some regional earthquakes. Int. J. of Adv. Res. in Electrical, Electronics &Instrum.Engg. 6 (5), 3451–3457.

Zigman, V., Grubor, D., Sulic, D., 2007. D-region electron density evaluated from VLF amplitude time delay during X-ray solar flares. J. Atmos. Sol.-Terr. Phys. 69 (7), 775–792.