AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE
10.1002/2016JA022721

Key Points:
- VLF data showed precursory signature in terminator time (TT) shift and nighttime fluctuations (NF) 1 day prior to EQ of M7.8 and M7.3
- The TT analysis yields significant shifts of 45 and 26 min in evening TT in the NWC VLF amplitude signal 1 day before both EQs
- The nighttime fluctuation analysis also showed consistent statistically significant increase in three parameters 1 day before both EQs

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Citation:
Maurya, A. K., K. Venkatesham, P. Tiwari, K. Vijaykumar, R. Singh, A. K. Singh, and D. S. Ramesh (2016), The 25 April 2015 Nepal Earthquake: Investigation of precursor in VLF subionospheric signal, *J. Geophys. Res. Space Physics*, *121*, doi:10.1002/2016JA022721.

Received 30 MAR 2016
Accepted 27 SEP 2016
Accepted article online 29 SEP 2016

The 25 April 2015 Nepal Earthquake: Investigation of precursor in VLF subionospheric signal

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Abstract We present a critical analysis of the observations and interpretation of VLF subionospheric measurements related to the main Nepal Gorkha earthquake which occurred on 25 April 2015 (M_w7.8) and its major aftershock on 12 May 2015 (M_w7.3). The VLF narrowband signal used is from North West Cape (NWC) (19.8 kHz) VLF transmitter located in Australia and recorded at Allahabad (latitude 25.41°N, longitude 81.93°E). Allahabad is located very close (~360 km) to these earthquake epicenters. Two widely used analysis, viz., (1) terminator time and (2) nighttime fluctuation techniques, are applied to extract seismic related effects in the NWC narrowband VLF data. The terminator time analysis yields statistically significant shifts of ~45 and ~26 min, respectively, in evening terminator time in the NWC VLF amplitude signal, 1 day before both the earthquakes. The nighttime fluctuation method shows a consistent, statistically significant, increase in three parameters 1 day before the earthquake. The observed terminator time and nighttime fluctuation shifts were associated with these earthquakes only after scrutinizing possible contributions from other potential sources such as solar activity; other earthquakes on the signal path; and meteorological disturbances such as lightning activity, wind speed, and temperature along the transmitter-receiver great circle path. The VLF subionospheric signal analysis results unambiguously point toward the presence of seismically excited atmospheric gravity waves during these major earthquakes and their important role in providing the coupling between the seismic source region and overlying ionosphere.

1. Introduction

Earthquakes (EQs) are one of the most devastating forms of natural disasters. Short-term prediction of their occurrence seems the possible way of their mitigation [*Hayakawa,* 2007]. During the past three decades, utilizing ground, and satellite data, several studies related to pre- and post-earthquake anomalies in the *D*, *E*, and *F* regions of the ionosphere together with the coseismic signatures were carried out in the direction of short time EQ forecast/precursor research [e.g., *Hayakawa et al*., 1996; *Maurya et al*., 2013; *Ondoh and Hayakawa*, 1999; *Sunil et al*., 2015]. All these wide varieties of observations are seldom consistent and often yield conflicting results even for the same earthquake. Hence, the reliability of the electromagnetic (EM) signals and radio sounding methods in the identification of preseismic and coseismic signatures still remains a subject of intense debate among the researchers.

The example of 11 March 2011, M_w 9.0 Tohoku-Oki mega earthquake is a classic case in the context of the study of preseismic, coseismic, and postseismic signatures. Though similar measurements are utilized, different studies yield diverse results. Using Global Positing System (GPS) data, *Ouzounov et al.* [2011] obtained global ionosphere maps over the Japanese region which indicates an increase in electron density, reaching a maximum value on 08 March 2011, i.e., 3 days before the earthquake. *Heki* [2011] reported enhancement in the GPS total electron content (TEC) data ~40 min before the Tohoku EQ using data from the Japanese network of GPS stations. *Heki and Enomoto* [2013, 2014] provided further evidence in support of the precursor observations reported by *Heki* [2011]. While *Kamogawa and Kakinami* [2013], *Utada and Shimizu* [2014], and *Masci et al.* [2015] contested the claims made by *Heki* [2011] and argued them as artifacts induced by the data fitting procedure adopted in that study.

Maruyama et al. [2011] with four ionosonde stations over Japan (Kokubunji, Wakkanai, Yamagawa, and Okinawa) in the distance range 440–2000 km from Tohoku epicenter reported the detection of strong ionospheric disturbances ~15 min after the earthquake. *Carter et al.* [2013] reexamined the ionosonde data from three of these stations: viz., Kokubunji, Wakkanai, and Yamagawa and reported a simultaneous increase in the critical frequency of F_2 region (f_oF_2) and *Es* layer peak plasma frequency (f_oEs) relative to a 30 day median within 1 h before the earthquake. Further, to validate these results they performed statistical analysis using 6 years of data and concluded that such anomalies are also observed on several other occasions without any reference to the occurrence of a seismic event.

Mullayarov et al. [2012] analyzed the amplitude of lightning electromagnetic signals (radio atmospherics) in extremely low frequency (ELF: 300 Hz–3000 Hz)—very low frequency (VLF: 3–30 kHz) band received at Yakutsk, Russia, passing over the Tohoku epicenter region and found a typical significant increase in atmospherics amplitude 12–14 days prior to the earthquake. Whereas *Cohen and Marshall* [2012] analyzed ELF/VLF broadband and narrow band data recorded at Onagawa, Japan, located very close to the epicenter (~102 km) of Tohoku EQ and observed no radio emissions preceding or coincident with the onset of the earthquake.

Despite reservations stemming from contradictory reports on use of electromagnetic methods in detection of pre-, co-, and post-EQ signatures, several researchers have presented case studies on EQ occurrence and their effects on the lower region (*D* region) of the ionosphere utilizing radio sounding techniques [e.g., *Shvets et al.,* 2004; *Hayakawa et al*., 2010]. The VLF signals from navigational transmitters propagate through a waveguide formed by the Earth's surface (ocean or ground) and the *D* region ionosphere, which is called the Earth-ionosphere waveguide (EIWG). Changes in the boundaries of this waveguide can be caused by various geophysical phenomena including EQs [e.g., *Gokhberg et al*., 1989; *Hayakawa et al*., 1996; *Hayakawa*, 2007; *Molchanov and Hayakawa*, 1998; *Maurya et al*., 2013]. Two methods, terminator time (TT) and nighttime fluctuations (NF), have been widely used in the past to detect preseismic and postseismic effects on the VLF navigational transmitter signals [*Gokhberg et al.*, 1989; *Hayakawa*, 2007, and references therein]. Based on the various analyses, the coupling of the lithosphere-atmosphere-ionosphere through atmospheric gravity waves (AGWs) generated on or near the ground surface during EQ preparation is proposed by researchers [e.g., *Shvets et al*., 2004; *Hayakawa et al*., 2010]. These together form the basis for EQ related studies using VLF signals.

In this study, we present the response of the lower ionosphere for pre- and post-earthquake scenarios as inferred from the ionospheric measurements of VLF signal amplitudes from North West Cape (NWC) (19.8 kHz) (geographic latitude 21.81°S, longitude 114.16°E) navigational transmitter located in Australia and recorded at Allahabad, India (geographic latitude 25.41°N, longitude 81.93°E). The receiving station Allahabad is located ~360 km away from the epicenter of the major earthquakes of Nepal which occurred on 25 April 2015 and 12 May 2015. The Nepal EQ sequence, as reported (http://www.usgs.gov/), is the result of thrust faulting on or near the main thrust interface between the subducting Indian plate and the overriding Eurasian plate to the north. A huge amount of energy released by the main EQ was followed by more than ~260 aftershocks, and tremors were felt over a large region of Nepal and India. *Yagi and Okuwaki* [2015] provided an integrated seismic source model of the 2015 Nepal earthquake. In the present investigation, modifications induced in the EIWG boundaries reflected as changes in the corresponding VLF signal amplitudes are detected utilizing the terminator time and nighttime fluctuation analysis techniques. Later, these observed terminator time and nighttime fluctuation shifts are attributed to the Nepal EQs occurrence only after ruling out the influence of competing geophysical phenomena such as solar activity, lightning discharge, and possible occurrence of some other EQs along the transmitter-receiver great circle path (TRGCP) of NWC signal from Australia to India which can also modify the EIWG.

2. Data Set and Analysis

The magnitude of Lamjung, Nepal (Gorkha), earthquake which occurred at 06:11:26 UT (11:41:26 LT) on 25 April 2015 was of M_w 7.8. The Indian local time (LT) is UT + 5 h and 30 min. The epicenter of the earthquake was located ~77 km northwest of Kathmandu (28.14°N, 84.70°E) with a shallow depth of ~15 km. Earthquake tremors were felt in a very large area of ~2000 km from the epicenter. The tectonic setting of these Gorkha EQs has been presented by various researchers [e.g., *Yagi and Okuwaki*, 2015; *Avouac et al*., 2015]. After the main shock on the 25 April 2015, more than ~260 aftershocks (http://earthquake.usgs.gov/earthquakes/) occurred in the region. An aftershock with $M_w > 5$ locations is depicted in Figure 1. On 12 May 2015, the largest aftershock occurred with a M_w 7.3 at 07:05:19 UT (12:35:19 LT). The

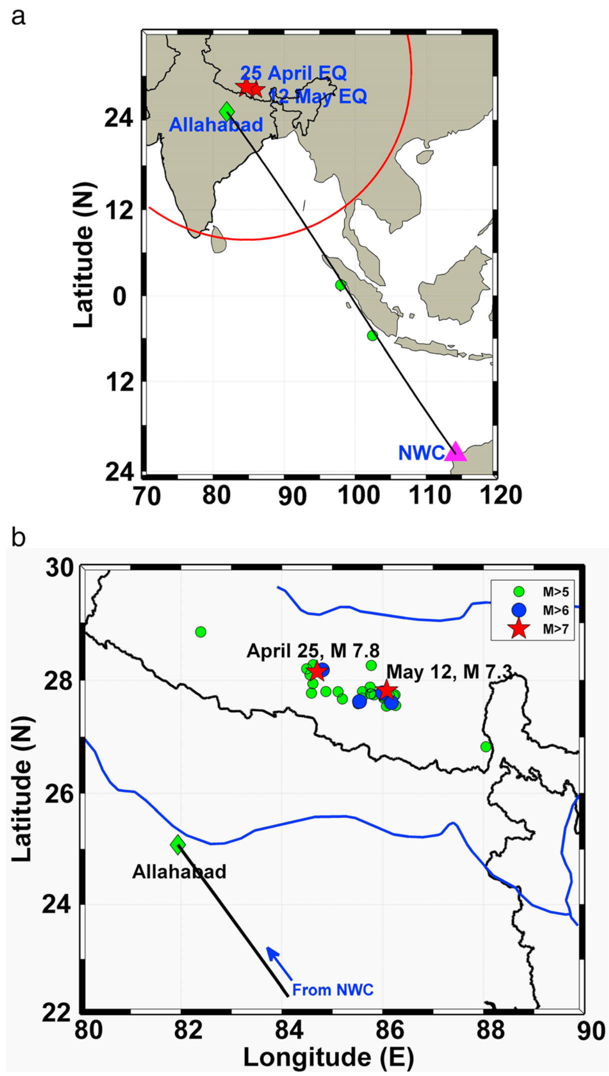

Figure 1. (a) Map depicting the location of two Nepal earthquakes on 25 April and 12 May 2015 (indicated by red stars), VLF NWC transmitter and VLF receiving station Allahabad, and TRGCP path along with the circle of EQ preparation zone. (b) Zoom in of the region to show details of both EQs and $M_w > 5$ aftershock locations.

epicenter of this aftershock was located ~75 km east of Kathmandu near Kodari (27.81°N, 86.08°E) and with shallow depth of ~15 km (Figure 1).

The VLF narrow band signals analyzed for these two 2015 Nepal earthquakes are from NWC (19.8 kHz) VLF transmitter located in Australia (21.6°S, 114.15°E) which are continuously recorded at Allahabad, using Atmospheric Weather Electromagnetic System for Observation Modeling and Education (AWESOME) VLF receiver [*Singh et al.*, 2010]. The NWC transmitter is located south-south-east of Allahabad. The transmitter-receiver great circle path (TRGCP) length of NWC and Allahabad is ~6300 km which comes under medium path length as classified by *Clilverd et al.* [2001]. The locations of Nepal EQs, VLF NWC transmitter and VLF receiving station Allahabad, and TRGCP path along with the circle of EQ preparation zone are shown in Figure 1a. The close-up locations of both EQs along with aftershocks are presented in Figure 1b. One minute averaged amplitude NWC VLF data are used in the present analysis.

Two well-documented techniques are used to extract the seismic related effects from the VLF data: (1) terminator time (TT) method [*Hayakawa et al.*, 1996; *Molchanov and Hayakawa*, 1998] and (2) nighttime fluctuation (NF) analysis [*Gokhberg et al.*, 1989; *Gufeld et al.*, 1992; *Shvets et al.*, 2004]. In the TT method, attention is paid to the time of morning and evening terminator (the characteristic minima around the sunrise and sunset of local time generated due to the modal interference between different modes) and time shifts are analyzed near the TT before and after the earthquakes. It is often suggested that the nighttime fluctuation method is best suited for medium and long TRGCP, while the terminator time method is more suitable when transmitter and receiver are located close by (~1000 km) [*Hayakawa*, 2007, and reference therein]. Nevertheless, both these techniques are applied to the NWC narrowband VLF data with a view to distilling earthquake-related signatures, if any. In order to avoid day to day variability and path effects arising from the variable propagation of the VLF signal and to further convince ourselves about the authenticity of possible pre- and post-EQ signatures, we also used additional statistical methods as discussed by several other workers [e.g., *Hayakawa*, 2007; *Maurya et al.*, 2013]. The nighttime fluctuation method concentrates on data collected during the local nighttime and the mean nighttime amplitude (fluctuation) is estimated one value for each day. The anomalous day is defined if fluctuations on a particular day crossed the 2σ criteria (σ: standard deviation over a whole period of data taken in the analysis).

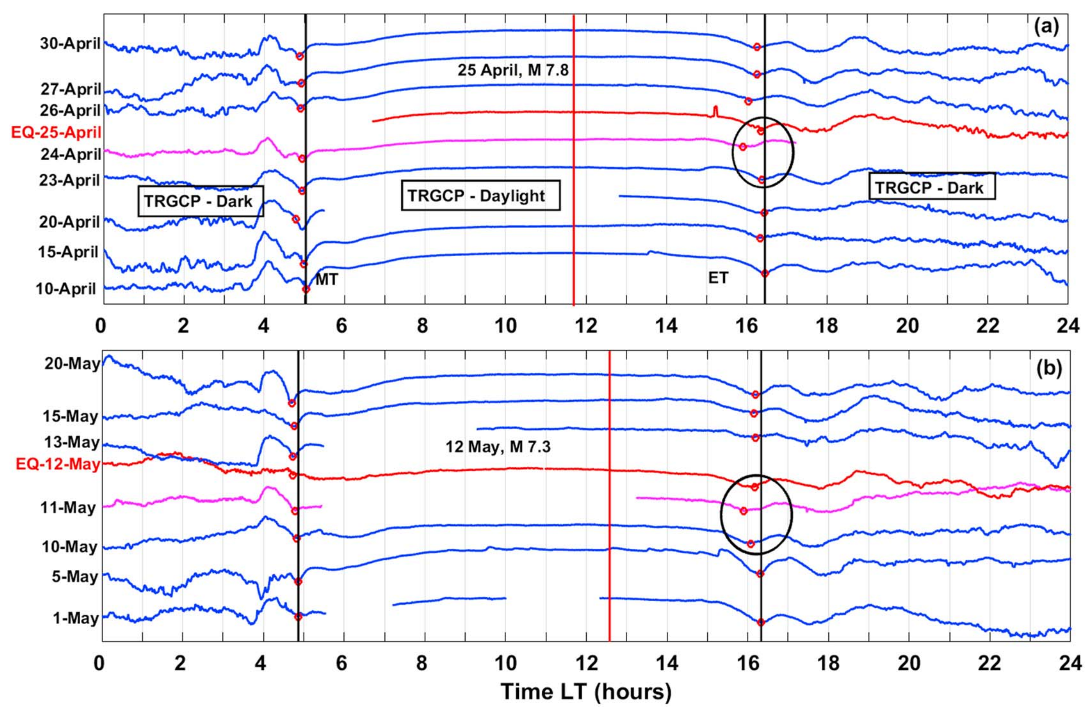

Figure 2. (a) Sequential plot of NWC (19.8 kHz) signal amplitude variation at Allahabad station for 24 h local time (LT = UT + 5:30 h) for April months. The black vertical line MT and ET marks the morning and evening terminator time. The abnormal shift in evening terminator time (ET) on 24 April is shown within the black circle with pink line. (b) The EQ time is marked with red vertical line represents the similar observation for 12 May 2015 EQ during month of May 2015.

3. Observations

3.1. Terminator Time (TT) Observations

Figure 2a shows daily sequential amplitude variations of NWC (19.8 kHz) signal recorded over Allahabad from 10 to 30 April 2015 for selected days (in order to avoid overlapping of daily sequential plots) with respect to local time (LT = UT + 5 h and 30 min) at Allahabad. In Figure 2a, the two vertical lines marked MT and ET are the morning terminator (MT) time and evening terminator (ET) time which occurred diurnally around ~05 h LT and ~16:20 h LT, respectively. Taking 01 April 2015 as a reference date, both MT and ET are marked by vertical lines. The diurnal shifts in terminators are marked by small red circles corresponding to MT and ET daily variations. It can be noticed that the evening terminator time (ET) shows fluctuations but remains very close to the reference line until 23 April 2015. On 24 April 2015, i.e., 1 day before the earthquake, a very significant shift in evening terminator time (ET) toward early hours (day side) is observed. Further, Figure 2b is daily sequential variations of NWC amplitude from 01 May 2015 to 20 May 2015, similar to Figure 2a. On 11 May 2015, 1 day before the M_w7.3 aftershock earthquake of 12 May 2015, a significant shift of ~ 26 min was observed. It should be noted that we do have data gaps on few days (20, 24, and 25 April and 1, 11, and 13 May) as seen in Figure 2. The data gaps are due to instrument recording problems and cannot account for the observed shifts in ET, as the significant shift is only visible on 24 April and 11 May despite other days of a data gap.

Next, we utilized a statistical method to remove day to day variability in TT due to local shift in sunrise and sunset. We have taken two months (60 days) data from 1 April to 30 May 2015. We have presented in Figure 3a a time series of evening terminator time (this time is corresponding to the minimum VLF signal amplitude in the evening time as marked by the red circle in Figure 2) for the two months from 1 April to 30 May 2015. In order to avoid day to day variability in TT (as can be seen in Figure 3a, ET decreases from April to May), we estimated running mean of evening terminator (ET) by taking window length of 3 days and then estimated the average for 58 days represented as $<t_e>$. As we have taken 3 days window length, we left initial 2 days (1 and 2 April) from analysis and total 58 days analysis (from 3 April to 30 May 2015) are presented. For each day we estimated the difference of evening terminator "dt_e" for a particular day as

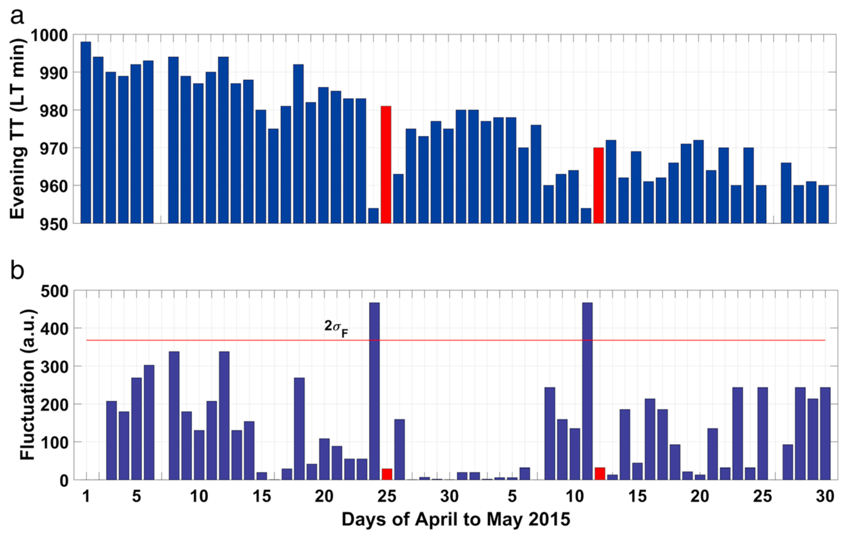

Figure 3. (a) The daily variations of evening terminator time during the month of April–May 2015 estimated corresponding to the minimum VLF signal amplitude in the evening time as marked by the red circle in Figure 2. The decreasing trend in ET time from April to May is the seasonal variations corresponding to increase in day length. (b) Anomalous fluctuation on 24 April and 11 May 2015. Fluctuations cross the $2\sigma_F$ criterion on these 2 days, i.e., 1 day prior to the respective EQs. The horizontal line shows 2σ criteria to define the anomalous day. The red bar in Figures 3a and 3b represents 25 April and 12 May EQ days, respectively.

$dt_e = (t_e - \langle t_e \rangle)$, where t_e is the observed evening terminator on a particular day and $\langle t_e \rangle$ is the average of running mean of evening terminator for 58 days. We estimated the $(dt_e)^2$ for each day and called it terminator time (TT) fluctuations. The final results based on total 58 days of analysis are presented in Figure 3b. The data are not available on 7 April and 26 May during this time. To determine the statistical importance of the anomalous day, standard deviation (σ) for 58 days is estimated and plotted in Figure 3b as $2\sigma_F$ line called $2\sigma_F$ anomalous criteria. Figure 3b, shows anomalous fluctuation on 24 April and 11 May 2015, as fluctuations crossing the $2\sigma_F$ criterion on these 2 days, i.e., 1 day prior to the respective EQs.

3.2. Nighttime Fluctuations (NF) Observations

The nighttime fluctuations (NF) analysis method is well explained by many researchers [e.g., *Shvets et al.*, 2004; *Hayakawa et al.*, 2010; *Maurya et al.*, 2013]. For the NF analysis, we have taken 8 h (08) nighttime NWC VLF amplitude data during 14:30 UT–22:30 UT (20:00 LT–04:00 LT) for 58 days period from 03 April 2015 to 30 May 2015. It is important to mention here that we do not have VLF data on 14 April, 24 April (1 day before the 25 April EQ), and 19 May 2015 during nighttime period to consider in the analysis. As explained and used by *Maurya et al.* [2013] for the 12 May 2008 China EQ (Wenchuan EQ), we estimated a total of three statistical parameters for NF analysis. First, we have taken the running mean of data for 3 days (window length 3 days) and then calculated the difference $dA(t)$ for a particular day as $dA(t) = (A(t) - \langle A(t) \rangle)$, where $A(t)$ is the VLF amplitude at time t on that particular day and $\langle A(t) \rangle$ is the average value at the same time t for 58 days from 03 April to 30 May 2015. The three parameters are estimated using difference $dA(t)$ and are defined as (1) trend (T): it is the average of nighttime amplitude difference $dA(t)$ for each day; (2) dispersion (D): it is the standard deviation of nighttime amplitude difference $dA(t)$ for each day; and (3) nighttime fluctuation (F): it is the $(dA(t))^2$ over relevant night hours which gives one data for each day.

Figure 4 presents nighttime fluctuation analysis for the Nepal EQs on 25 April 2015 and 12 May 2015. Figures 4a–4c show trend (T), fluctuation (F), and dispersion (D). The horizontal line in each panel depicts the 2 standard (2σ) deviation criterion to define the anomalous day. The parameters T (Figure 4a) exhibit a significant increase exceeding the $2\sigma_T$ criterion line, respectively, and correspond to a day before the 12 May 2015 aftershock EQ. The remaining four parameters F and D (Figures 4b and 4c) also exhibit similar significant increase exceeding $2\sigma_F$ and $2\sigma_D$ criterion, respectively, 1 day before the 12 May 2015 EQ. As we do not have nighttime data on 24 April 2015 (1 day before the main EQ on 25 April 2015), we are unable

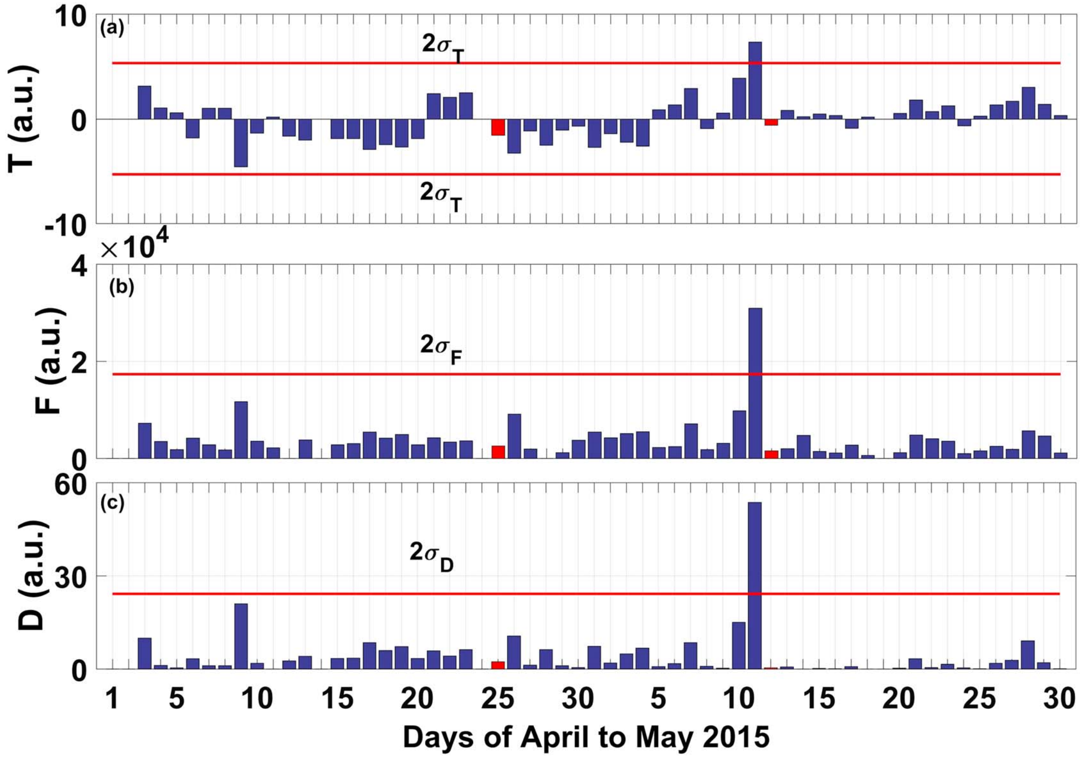

Figure 4. Nighttime Fluctuations analysis for April–May 2015 for the Nepal EQs on 25 April 2015 and 12 May 2015. (a) Trend (*T*), (b) fluctuation (*F*), and dispersion (*D*). The horizontal line in each panel depicts the 2σ deviation criterion to define the anomalous day.

to comment on the presence of anomalous day effect for the main earthquake. In Figure 4, on 9 April, a peak in all three parameters can be observed, but this remains much below the 2σ criterion. In some previous reports, VLF anomalies are reported to have appeared few hours to months before an impending EQ [*Hayakawa et al*., 2010]. However, in our case, such an anomaly is unambiguously observed just 1 day before the EQ as a possible precursor signal.

4. Discussion

Based on the classification of earthquakes by *Pulinets et al.* [2009], the 25 April 2015 Nepal earthquake qualifies as a major earthquake. In this report, we attempted to document precursor signatures of earthquake occurrence employing established electromagnetic observation methods utilizing subionospherically propagating VLF signals recorded at Allahabad, India in close proximity to the EQ epicenter (~360 km) region. We used two most widely applied analysis techniques, the terminator time (TT), and nighttime fluctuation (NF) and applied to narrowband VLF data. Internally consistent and statistically significant results by way of the presence of anomalies a day before both the EQs, as precursors, are obtained from TT and NF analysis.

Prior to attributing the observed anomaly precisely to EQ preparation period, it is important to explore and rule out alternate sources which may cause such effects in the VLF signal propagating through the EIWG. It is also important to mention that NWC VLF transmitter signal from Australia and received in Allahabad India crosses the equator and passes above both the ocean and dry land. Further, the signal also passes through the most seismically active regions of the world—the circum-Pacific seismic belt. Further, this region is also one of three most lightning-active regions in the world [*Christian et al*., 2003]. Also, the variation of other meteorological parameters like temperature, wind, humidity, and pressure affect the *D* region and hence the VLF signal [*Rozhnoi et al*., 2014]. All these could drastically affect the characteristics of boundaries of the EIWG and may cause the observed anomalies in the VLF signal obtained from the analysis presented above. Another crucial causative of similar anomaly is of solar origin, mainly due to geomagnetic storms or more precisely solar flares in the *D* region ionosphere which is the upper boundary of EIWG at which the

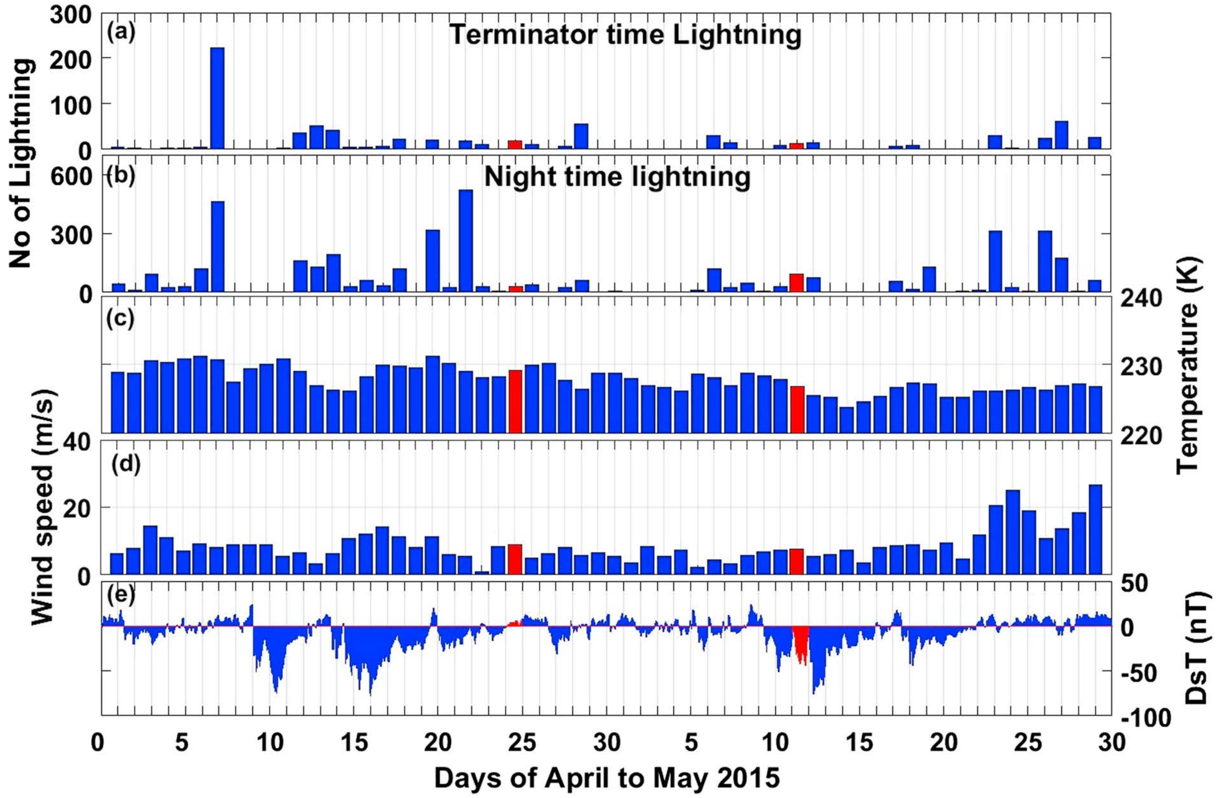

Figure 5. Depicts of (a) total number of lightning during evening terminator (ET) time (15 UT–17 UT) along the NWC-Allahabad TRGCP, (b) total number of lightning during nighttime (14 UT–22 UT) along the NWC-Allahabad TRGCP, (c) average temperature variation at ~63 km altitude, (d) average wind velocity variation at ~63 km altitude, and (e) disturbance time index (*Dst*) from 01 April to 30 May 2015. The red bar is showing EQ days.

narrowband VLF signals get reflected [*Zigman et al*., 2007; *Peter et al*., 2006; *Kumar and Kumar*, 2014; *Kumar et al*., 2015; *Selvakumaran et al*., 2015].

First, along the NWC VLF propagation path, we looked into the earthquake activity other than the Nepal earthquakes which may affect the VLF signal amplitudes. A rectangular region bounded by latitude 26°S–26°N and longitude 70°E–120°E along the NWC-Allahabad TRGCP is selected. Using the EQ archives of the United States Geological Survey (USGS) (http://earthquake.usgs.gov/earthquakes/) a total 102 EQs between 01 April and 30 May 2015 were identified. Results from earlier studies [*Rozhnoi et al.,* 2004; *Maekawa et al*., 2006], clearly suggested that EQs with magnitude $M < 5.5$ and depth $>$40 km do not affect the VLF signal. Application of the above magnitude and depth criteria as a filter to the 102 EQs which fall within the 2 month time window of Nepal EQ, resulted in only two EQs with *M* 5.7 and depths 27 km and 30 km. Locations of two *M*5.7 EQs were along the TRGCP with coordinates 1.54°N, 97.9°E and 5.68°S, 102.47°E (Figure 1a). These EQs occurred on 20 April and 08 May 2015. However, in another study, *Hayakawa et al.* [2010] found that earthquakes with a magnitude of 5.7 falls just below the desired threshold to obtain any significant correlation with the stated 2σ criterion. Therefore, it is very unlikely that these two EQs with *M*5.7 have a significant effect to manifest as the observed VLF signal anomalies registered at Allahabad on 24 April 2015 and 11 May 2105.

The Southeast Asian region through which most of the NWC-Allahabad VLF signal passes is a region of very significant lightning activity [*Christian et al*., 2003]. Lightning produces direct heating of the ionosphere above the region of an active thunderstorm and alters the propagation conditions for VLF signals passing over such regions [*Inan et al.,* 1996]. As shown in Figures 5a and 5b, we compared the total number of Global Lightning Detection 360 (GLD360) lightning network [*Said et al*., 2010] observed lightning flashes along the NWC-Allahabad TRGCP and the VLF signal anomaly presented in Figures 3 and 4 for the evening terminator time and nighttime fluctuations (NWC amplitude data during 14:30 UT–22:30 UT), respectively. The absence of significant correlation between number of lightning and EQs anomalies is noticeable. For example, very low lightning activity is observed on 24 April and 11 May 2015, while TT and NF anomalies in VLF signal amplitudes are significantly registered. Furthermore, another effect of lightning/thunderstorm on VLF signal is the direct penetration of thunderstorm/lightning electric field to the lower ionosphere which manifests itself very clearly as early/fast events in the VLF signal and are easily distinguishable in VLF data [*Inan et al*., 1988, 1991]. The absence of such early/fast events in VLF data during the time period of consideration clearly precludes the involvement of lightning/thunderstorm activity to give rise to the observed VLF anomalies. Further, meteorological parameters like temperature and wind velocity may also affect the *D* region. *Rozhnoi et al.* [2006] established a correlation between pressure, humidity, and low frequency (LF: 30–300 kHz) signal recorded over Russian and Japan region. They find that meteorological parameters during extreme weather activity prominently affect LF signals. Further, *Rozhnoi et al.* [2014] studied the effect of temperature, wind velocity, atmospheric pressure, and humidity on the lower ionosphere. They consider eight cases of cyclones of various intensity and found negative nighttime anomalies in the VLF/LF signal amplitude. They attributed anomalous effect due to cyclone-generated atmospheric gravity waves propagating up to the *D* region height and further concluded that characteristics of correlation of VLF/LF signal anomaly with weather depend on the relative position of receiver and transmitter, frequency of a signal, and specifics of weather conditions in the place of receiving station. It appears that extreme weather cases such as cyclones have a definite effect on the VLF signal, but we did not find any firm correlation between day to day meteorological parameter variations with VLF signal anomalies. Hence, for Nepal EQ we checked the cases of extreme weather events along the region of the NWC-Allahabad path during the period under consideration, but no such event found during the month of April–May 2015 (http://www.rsmcnewdelhi.imd.gov.in/index.php?lang=en; http://www.bom.gov.au/cyclone/history/index.shtml). To further confirm our results, we have also analyzed European Centre for Medium-Range Forecasts (ECMWF) wind and temperature fields data from 1 April to 30 May 2015 at 06:00 UT. The ECMWF fields are computed at T_L511 spectral resolution and with 60 sigma-pressure hybrid coordinate levels in the vertical between the surface and 0.1 hPa. The wind and temperature data were taken at level 1 (0.1 hPa) which correspond to ~63 km altitude. The average value for each day is presented in Figures 5c and 5d. From the Figures 5c and 5d, one can clearly observe the absence of significant correlation between a number of daily average temperature and average wind velocity and EQs anomalies on the 24 April and 11 May 2016 is noticeable. As this is a very crude way of correlation study, we cannot exclude such effect explicitly and left it as a separate study for future work.

The geomagnetic storms and solar flares in particular constitute the solar source [*Zigman et al*., 2007; *Peter et al*., 2006; *Kumar and Kumar*, 2014; *Selvakumaran et al*., 2015] that affect the subionospheric VLF data in a discernable manner. The time period considered in the present study was incidentally associated with many solar flare events of C and M class. The effect of solar flares can be clearly seen in the daytime *D* region ionosphere and last from few minutes to hours depending on the intensity of the flares [*Zigman et al*., 2007; *Selvakumaran et al*., 2015]. On 24 April and 11 May, there were C2.1 and C2.5 class flares (http://www.spaceweather.com/). But these are well before the TT time window considered in the present analysis. Also, such low-intensity flares do not have a significant effect on the VLF signal [*Selvakumaran et al*., 2015]. The period under study was geomagnetically active as shown in the Figure 5c. The disturbance storm time index (*Dst*) (http://wdc.kugi.kyoto-u.ac.jp/), which is a measure of the ring current, is the most widely used storm index to classify geomagnetic storms in low latitudes. A $Dst < -50$ nT is considered significant to affect the ionosphere. Three moderate geomagnetic storm days ($-100\ \text{nT} < Dst < -50\ \text{nT}$) occurred during the period related to the analysis of VLF data. The first storm occurred during 10–12 April 2015 with the *Dst* attaining its minimum level on 11 April, while the second storm that occurred between 15 and 17 April is associated with *Dst* reaching a minimum of −70 nT on 16 April. During the third storm, between 11 and 13 May 2015, the *Dst* index attained a minimum value of −76 nT on 13 May 2015. Such moderate storms, even with $Dst > \sim -80$ nT, are very unlikely to affect the *D* region of the ionosphere, particularly in the low latitude and equatorial ionosphere over which NWC-Allahabad TRGCP passes. Hence, a solar origin to explain the observed VLF anomaly during the analyzed period remains a distant possibility.

Interestingly, recent study by *Kumar and Kumar* [2014] on geomagnetic storm effects on the NWC VLF signal recorded at a low-latitude station Suva (Fiji) (latitude 18.14 S, longitude 178.44 E), which is on pure low-latitude path, demonstrated that a storm with $Dst < -140$ nT has no effect on the VLF signal. The other six storms, with *Dst* from −52 nT to −72 nT presented in this report do not show any effect. The geomagnetic storm effects generally last many days after onset of the storm, and yet no such prolonged effects are observed in the VLF signal amplitude. Furthermore, on 24 April and 11 May 2015, minimum *Dst* was ~ −16 nT and −51 nT, respectively, which is very low to affect the VLF signal and cause the observed anomalies.

Based on above critical analysis of the recorded VLF data and scrutiny of several possible candidate phenomena that can affect the VLF signal suggest that the observed VLF anomalies at Allahabad are most likely of seismo-ionospheric origin and evidently associated with the 2015 Nepal EQs preparatory phase. The two well-established techniques applied here, TT and NF methods, reveal a significant shift in the evening terminator 1 day before the occurrence of both the EQs. It is also important to note that in the present case, no significant shift was observed in the morning terminator while the shift in evening terminator was toward the dayside. These observations are opposed to that reported by *Hayakawa et al.* [1996] for Kobe EQ. *Hayakawa et al.* [1996] for the Kobe earthquake of 17 January 1995 ($M_w = 7.2$ and depth ~20 km) reported that evening terminators shifted toward the nightside (late hours) whereas morning terminator shifted toward morning side (early hours) few days before the earthquake and became normal few days after. They observed that evening terminator is more indicative of seismic effect and reported a maximum shift of ~45 min in the evening terminator for Kobe earthquake. The predominant shift in terminators is attributed to an increase in *D* region electron density which lowers the boundary of the ionosphere by ~1.5–2 km [*Yoshida et al.*, 2008]. The lowering of *D* region boundary changes the condition for modal interference to result in a shift in the VLF signal minima.

In the present case, while there is no significant effect on morning terminator, the evening terminator shows a shift toward "dayside," a behavior opposite to that registered for Kobe EQ. The morning terminator appears to be less responsive in showing EQ effects, as is also clear from Kobe EQ. In the following, we attempt to address this discrepancy in the TT results between the earlier reports and the present study. The difference between these two results could arise from the varied conditions for modal interference in the Earth-ionosphere waveguide (EIWG), which depends on several factors such as signal attenuation, TRGCP path length, direction with respect to sunrise transition line which controls the VLF propagation modes reaching the receiver, the conductivity along the path, differences in transmitter operating power and frequency, and ionospheric region perturbed by the earthquake [*Yokoyama and Tanimura*, 1933; *Joshi and Iyer*, 1988; *Clilverd et al.*, 2001; *Yoshida et al.*, 2008; *Lynn*, 2010, and references therein].

For example, signal attenuation in the EIWG is much higher during the day compared to nighttime and varies with diurnal variation in solar zenith angle [*Wait and Spies*, 1964]. Attenuation depends on the wave-mode number, wave frequency, TRGCP path length, reflection height of upper boundary (*D* region) of the waveguide. The higher-order modes suffer larger spatial attenuation while traveling great distances (>5000 km) [*Lynn*, 2010, and references therein]. During daytime, EIWG allows first-order mode to reach the receiver, whereas the nighttime supports propagation of higher-order modes too to reach the receiver. The number of modes reaching the receiver also depends on the width of EIWG, which ultimately depends on the state of *D* region of the ionosphere [*Lynn*, 2010]. Any perturbation in the *D* region results in changes in the number of modes reaching the receiver which in turn alters the condition for modal interference to cause a shift in the terminator time. It should be noted that this is the first report of the use of TT method for a long TRGCP (>2000 km), whereas earlier studies were conducted only for short TRGCP (<2000 km). As per the empirical relation of *Dobrovolsky et al.* [1979], the radius of EQ preparation zone is given by $\rho^{0.43Mw}$ km, where M_w is the wave magnitude of the EQ. For the Nepal EQ, with a M_w 7.8, the radius of preparation zone is ~2300 km. This implies that only a partial portion of the ~ 6400 km long NWC TRGCP toward the receiver (Allahabad) side may be considered as disturbed during EQ preparation time. This could have resulted in an increase of *D* region electron density [*Molchanov and Hayakawa*, 1998] which in turn decreased the width of the EIWG closer to receiver region while the EIWG width toward the transmitter (NWC) side remained same. Further, it is to be noted that because of very long TRGCP (~6400 km), during morning terminator time the entire TRGCP is in the daytime whereas during evening terminator time the transmitter side region is in dark (high solar zenith angle). This scenario of variable EIWG could have affected in terms of a number of wave modes reaching the receiver to significantly alter the interference and hence the evening terminator time. *Kikuchi* [1986] reported that mode conversion also depends on the angle between sunrise transition line and TRGCP and the geomagnetic field which is certainly at variance in the Nepal and Kobe EQ regions. This further explains the difference between the present observations and that of Kobe EQ. The validity of such a hypothesis needs to be tested utilizing more case histories of major EQs before reaching definite conclusions.

Previous reports of nighttime fluctuation analysis during some major EQs [*Gufeld et al*., 1992; *Shvets et al*., 2004; *Rozhnoi et al*., 2004; *Horie et al*., 2007; *Hayakawa et al*., 2010; *Maurya et al*., 2013, and reference therein] could be compared with the Nepal 2015 EQ. *Gufeld et al.* [1992] reported a significant propagation anomaly on the VLF/LF data over the two long-distance paths from Reunion to Moscow (TRGCP ~4124 km) and also to Omsk (TRGCP ~4049 km) a few days before the famous 07 December 1988 Spitak earthquake. An anomalous enhancement in fluctuation ~4 days before the occurrence of the 26 December 2004 Sumatra EQ ($M_w = 9.0$ and depth 30 km) was observed for the NWC-Japan VLF propagation path [*Horie et al.,* 2007]. Similarly, *Hayakawa et al.* [2006] reported significance enhancement in signal fluctuation, related to the 2004 mid-Niigata prefecture earthquake (*M*6.8 and depth 10 km), in the JJY (Fukushima Prefecture) to Kochi (KCH) signal about a week before this seismic event. *Maurya et al.* [2013] for long TRGCP (~5000 km) applied NF method for the great Wenchuan EQ of 12 May 2008 and estimated nighttime fluctuations parameters using JJI-Allahabad path and observed significant anomalies crossing 2σ criterions 02 and 19 days before the EQ. *Hayakawa et al.* [2012] studied the effect of 11 March 2011 Tohoku-Oki mega earthquake ($M = 9.0$) using VLF signal of NLK, the transmitter in USA (long TRGCP varies from ~7824 km to 8368 km) and measured at Japanese receiving stations. The EQ epicenter was located close to receivers as in the present case and by applying similar nighttime fluctuation method reported significant propagation anomaly ~5–6 days before the earthquake. In the statistical analysis report presented by *Maekawa et al.* [2006], for JJY-KCH propagation path (TRGCP ~700 km) in Japan using 6 years of VLF data, the trend, and NF exhibits an anomalous change 2–6 days before the occurrence of the shallow EQs. In another statistical study, using 7 years of VLF/LF data on different transmitter/receiver path pairs, *Hayakawa et al.* [2010] estimated the significant decrease in the trend and increase in normalized fluctuation and dispersion for EQs with magnitude > 6 and depth < 40 km. *Tojiev et al.* [2014] analyzed eight (08) EQ cases with magnitude $M > 5.0$, for various VLF transmitter signals recorded at Tashkent VLF station. All the TRGCP came under long path ($>$5000 km). They reported a significant increase in the changes in amplitude parameters (*D*, *F*, and *T*) few days before the EQ. One of the interesting case similar to the present case they reported is for the Japan EQ which occurred on 09 August 2009 with $M = 7.1$. This EQ occurred close to JJI transmitter (Japan) and showed a significant shift in trend (*T*) and fluctuation (*F*), almost 2 and 11 days before the EQ, respectively. From the reports, it appears that there is no uniform pattern, and different studies (case study as well as statistical study) report a variable range of precursory signatures from few days to 1 month from the day of EQ.

Among the results for the two Nepal EQs under analysis, while the TT results seem clear precursors in both cases 1 day before the EQs, NF analysis yields consistent increase in all the three parameters a day prior to the 12 May 2015 earthquake to qualify as a precursor to this seismic event. The results are consistent with the previous report on ionospheric precursors. We, however, refrain from commenting on the main EQ of 25 April 2015 due to nonavailability of data during the night of 24 April 2015. It should be noted that the discrepancy between the present event and many previous reports could be understood invoking variations in the daily and seasonal state of the ionosphere, status of the region of TRGCP, a distance of EQ epicenters from TRGCP, EQ under consideration, and level of geomagnetic disturbances [*Afraimovich et al*., 2001].

Our result are further supported by the recent report on Nepal EQ by *Ouzounov et al.* [2015] and *Christina et al.* [2016] further confirms that the ionosphere was disturbed a day to few days before the EQ. *Ouzounov et al.* [2015] have analyzed three different parameters of atmosphere outgoing Earth radiation (Outgoing Longwave Radiation), GPS TEC variation, and thermodynamic properties and found a strong connection with the earthquake preparation processes. The reported anomalies vary from 1 day to 09 days before both Nepal EQs. *Christina et al.* [2016] studied two major EQs: Nepal ($M = 7.8$) and Chile ($M = 8.3$) occurred in 2015. They have analyzed GPS TEC data from International GNSS Services (IGS) stations lying within and out of EQ preparation zone defined by the empirical relations of *Dobrovolsky et al.* [1979]. For the Nepal EQ, they have reported a high TEC fluctuations slightly exceeding the upper bound at LCK4 (Lucknow, India) and LHAZ (Lhasa, China) stations (up to 7%), and close to the bound at KIT3 (Kitab, Uzbekistan) station were registered 1 day prior to the earthquake. Similar TEC enhancement (crossing upper bound up to 7%) at HYDE (Hyderabad, India) 3 days before the EQ located south of the epicenter. They did not find any significant TEC variations at the stations located outside of preparation zone. The further analysis revealed pronounced periodic TEC oscillations with period ~20 min, which they linked with the impending Nepal EQ of 25 April 2015. The observed period is in the range of internal gravity waves period. By comparing results from previous report of *Klimenko et al.* [2011] who suggested that large TEC enhancements prior to the earthquake can be explained by the combined action of seismo-ionospheric vertical electric field and internal gravity waves generated by the solar terminator, they concluded that the observed wave-like TEC fluctuations prior the earthquake could be related either to the imminent earthquake or to the sunrise and sunset solar terminator transition, respectively, or to the joint action of both phenomena. This further validates the presence of seismic related disturbance in the ionosphere concomitant with EQ occurrence and also possibly during the earthquake preparation period over Allahabad and surrounding region which is just ~360 km away from the epicenter of Nepal earthquake.

Based on the present Nepal EQ observations and comparing the results from several previous reports on EQs precursor signatures in VLF signal using TT and NF methods [*Molchanov et al*., 2001; *Shvets et al*., 2004; *Hayakawa et al*., 2010; *Maurya et al*., 2013], it is worth to comment on how the ionospheric disturbance evolve due to seismicity or in other words the role of lithosphere-atmosphere-ionosphere (LAI) coupling mechanism, though this is not the main aim of this paper, and we are not concluding anything, rather we are trying to explain observed results on Nepal EQ on the basis of most suitable mechanism. As proposed by the many workers [e.g., *Molchanov et al*., 2001; *Miyaki et al*., 2002; *Shvets et al*., 2004; *Pulinets and Boyarchuk*, 2004, and reference therein] there are three different mechanism of Lithospheric-Atmospheric-Ionosphere coupling: (1) chemical channel: by the geochemical quantities, e.g., surface temperature, pressure, and radon emanation, produces change in the vertical electric field of the atmosphere which modify lower ionospheric properties; (2) acoustic and gravity wave channel: during EQ preparation period, change in various parameters excites the atmospheric oscillations traveling up to the ionosphere; and (3) electromagnetic channel: generation of radio emission from lithosphere which modifies ionospheric properties. As per present observation on Nepal EQ is concerned, we do not have direct observation of vertical electric field, atmospheric gravity waves, or radio emissions, but based on the past comparable results we may comment on the possible mechanism. Most of the report on the earthquake precursors signatures using subionospheric VLF/LF signals shown direct or indirect evidence of the presence of atmospheric gravity waves with periods of few minutes to few hours [*Molchanov et al*., 2001; *Shvets et al*., 2004; *Horie et al*., 2007; *Hayakawa*, 2007]. *Molchanov et al.* [2001] have presented some evidence of AGW related to seismic activity on VLF/LF signals. *Molchanov and Hayakawa* [1998] for the Kobe EQ, found significant variation in TT and suggested both mechanisms of (a) increase of the regular electric field due to radon exhalation before the earthquake and (b) intensification of planetary waves by seismically influenced atmospheric turbulence as the cause of observed TT anomalies. *Shvets et al.* [2004] in their statistical study of 6 months of VLF signal on Omega, Tsushima-Chofu (Tokyo), and NWC, Australia-Chofu long propagation paths reported the observation of wave-like signature 1–3 days before the strong EQs. They have suggested AGW from the seismic region as the principle mechanism of observed effect. *Hayakawa* [2007] reported the presence of wave-like signatures of the period of 20–100 min, through the wavelet analysis of nighttime fluctuations of NWC VLF signal recorded in Japan and considered AGWs as the promising candidates for LAI coupling. *Maurya et al.* [2013] for the 12 May 2008 Wenchuan EQ for the long TRGCP suggested a role of both 1 and 2 LAI mechanisms for the observed JJI VLF signal anomalies, whereas *Hayakawa et al.* [2010] supported AGWs as the most prominent mechanism for the observed anomalies in the VLF signals due to EQs. For the Nepal EQ of 25 April 2015, both *Ouzounov et al.* [2015] and *Christina et al.* [2016] reported significant TEC enhancement 1 day before the EQ. *Christina et al.* [2016] found pronounced wave-like signature in GPS TEC with period ~20 min, which they suggested could be due to seismic generated vertical electric field. The third mechanism of the electromagnetic channel is now discarded by many workers due to weak intensity of lithospheric radio emissions [*Hayakawa et al*., 2010]. Hence, in the present case, with above discussion and comparing results from previous reports/evidence it suggested that either seismically generated vertical electric field (channel 1) or acoustic and gravity waves generated during EQ preparation (channel 2) or a combination of both might be the better explanation of LAI coupling mechanism. But we further emphasize to carry out more study theoretically as well as observations to reach any conclusion on the LAI coupling process. This is because the ionosphere is highly variable and affected by various parameters (e.g., meteorological and solar). As VLF waves propagate by the multiple reflections between both boundaries of waveguides, most of the study considers variability only for the upper boundary and the Earth's surface which is lower boundary is considered nonvariable. But the Earth's surface can also influence the characteristics of VLF signal, especially during EQ preparation; the properties of Earth's surface (e.g., resistivity, conductivity) may change and can affect the waveguide excitation character and the VLF mode composition. It means that the lithosphere itself can be the source of VLF precursors. All these factors should be considered before reaching to any conclusion.

5. Summary

The seismo-ionospheric plasma perturbations are considered to be possibly linked to the preparatory phase of the upcoming earthquake. The most difficult part about earthquake precursor studies on short time scales (hours, days, or weeks before the earthquake) is to identify reliable and unambiguous precursors. Despite several new techniques and advances in statistical analysis, the reliability of ionospheric precursors remains debatable and is one of the challenging science questions under investigation. We presented here observations and analysis of subionospherically propagating VLF signal amplitudes from NWC (19.8 kHz) VLF transmitter located in Australia and recorded at Allahabad located just ~360 km from the Nepal earthquake epicenters. The terminator time (TT) analysis statistically shows a significant shift of ~45 and 26 min in evening terminator time 1 day before both the earthquakes (M_w 7.8 25 April 2015 and M_w 7.3 12 May 2015). The nighttime fluctuation (NF) method shows a consistent and statistically significant increase in three parameters 1 day before the EQ of 12 May 2015. By comparing results from previous studies, we suggest that combinations of both channel 1 (chemical) and channel 2 (acoustic and gravity wave) explain the observed VLF signal anomalies during major earthquakes like the Nepal earthquake. Finally, we emphasized on rigorous study of the correlation between various parameters (e.g., meteorological, solar, and lithospheric) and radio signal anomalies that will enable to discriminate between seismically induced radio signal anomalies and those of different extraterrestrial origin.

Acknowledgments
Authors from Indian Institute of Geomagnetism (IIG) are grateful to Department of Science and Technology, N. Delhi, for support to carry out the project and work. The data set used in the present study is from Indian Institute of Geomagnetism (http://iigm.res.in/) operated VLF recording instrument located at Allahabad, India. A.K.M. thanks USIEF, N. Delhi, India, for financial support under Fulbright-Nehru postdoctoral fellowship grant 9/1123(0001)/2 K14-485EMR-I. The details of earthquakes are taken from United States Geological Survey (USGS) (http://earthquake.usgs.gov/earthquakes/). The source of geomagnetic conditions used is from http://www.spaceweather.com/ and http://wdc.kugi.kyoto-u.ac.jp/ The ECMWF data used is from http://www.ecmwf.int/en/research/climate-reanalysis/era-interim Authors also thank M.B. Cohen, Georgia Tech., USA, for providing the GLD360 network lightning data. This work forms part of the IIG's earthquake precursor studies research program LAIM (lithosphere-atmosphere-ionosphere-magnetosphere) at the IIG's Shillong Geophysical Research Centre (SGRC).

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