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Anomalous behaviour of very low frequency signals during the earthquake events

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The seismo-ionospheric coupling has been extensively studied in the recent years adopting various ionospheric parameters, like the critical frequency of F_2 and E_s layers and total electron content (TEC). There have been reports of seismic signatures in the amplitude and phase of the very low frequency (VLF) waves when an intense earthquake occurs near the propagation path. In the present paper, the amplitude of VLF waves transmitted from GQD (UK), GBZ (UK) and TBB (Turkey) received in South France during the period 2010-2013 has been studied for the precursory effect of earthquakes on the morning and evening terminator timings (TT). Six earthquake events of magnitude greater than 5 have been considered. The results of the present study show that the evening terminator undergoes many fluctuations during the pre-earthquake period of 5-15 days. But the pre-earthquake fluctuations in the morning terminator are predominant for three events, namely 8 March 2010, 11 April 2010 and 22 May 2012. The VLF day (time between morning terminator and evening terminator) is observed to be longer in the pre-earthquake period for three events.

Keywords: Earth-ionosphere wave guide, VLF radio wave, Terminator time, Earthquake

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1 Introduction

The D-region of the ionosphere, which is mainly solar controlled, undergoes changes regularly resulting in its complex behaviour. The solar flare, magnetic storms, microwave bursts, which are of solar origin give rise to sudden ionospheric disturbances at D-region altitudes. This region, lying at the base of the ionosphere with its complex chemical processes, has a profound influence on the propagation of radio waves especially in VLF and LF bands. The ground based experiments are considered to be still reliable in the study of D-region even after the advent of satellites in recent years. Among these, the study of phase and amplitude of VLF (3-30 kHz) waves has long been used to probe the ionospheric D-region since their propagation path completely lies in this region both during day and night. The propagation of VLF waves to long distances is generally explained using the wave-guide mode theory[1]. According to this theory, the earth is considered to be perfectly conducting and the D-region act as the two walls of the wave-guide. The phase velocity and height of reflection of these waves propagating obliquely in the earth-ionosphere wave-guide depend on its width, which is dependent on the D-region conductivity. The relative phase and amplitude of the VLF waves show signatures of the solar flares during which the D-region ionization changes due to sudden enhancement of X-ray flux.

From recent studies[2-5], it is established that the ionosphere gets disturbed before the occurrence of an earthquake. From GPS and satellite data, it is observed that TEC and ionosperic electron densities are enhanced before and after the occurrence of earthquakes of moderate intensity[5]. Singh & Singh[6] reported anomalous variations of E_s and F-layer critical frequencies in the pre-earthquake period of 2-20 days. Pulinets *et al.*[7] argued that the metallic aerosols and Radon gas emanated from the earth's interior are responsible for the change of ionospheric conductivity during the pre-earthquake period resulting in anomalous variations of ionospheric parameters, like f_oF_2, f_oE_s and TEC. There are reports of abnormal fluctuations in the night time VLF amplitude during the strong earthquakes occurring near the propagation path[8,9]. During the day time, these waves get reflected from a lower altitude around 70 km and during night, the reflection height goes up to 90 km. This change in day to night reflection height is due to absence of photo ionization process during the nighttime. Normal day VLF signal variation is shown in Fig. 1. The first minimum in the morning is designated as morning terminator and the minimum in the evening, the evening terminator. Molchanov *et al.*[10] reported that the evening terminator deviated significantly from the monthly average during earthquake period. Rodger *et al.*[11] have studied the length of the day between the morning and evening terminators known as VLF day and found that the VLF day is longer in the pre-earthquake time. They suggested that this change in the VLF day is not just due to change in reflection height of these waves. There are reports that when an earthquake occurs, the evening terminator was observed to be shifting towards night[12]. But from a statistical analysis of 5 years of VLF observations on long path of 12 Mm, Clilverd *et al.*[13] found that the earthquake predictions using the terminator timings (TT) method cannot be distinguished from that of a chance.

In this context, the authors have made an attempt to look into the variation of the morning and evening terminator timings during the earthquake periods adopting the VLF amplitude data from 2010 to 2013 available on internet.

2 Data

The signal strength of VLF waves, transmitted from Anthorn, UK (GBZ) (54°54'N, 3°16'W) at 19.5 kHz; Skelton, UK (GQD) (54°43'N, 2°52'W) at 22.1 kHz and Bafa, Turkey (TBB) (37°24'N, 27°19'E) at 26.7 kHz frequency, recorded at the receiving station (46°N, 2°E) in South France during the period 2010 – 2013, available on website http://sidstation.loudet.org/ data-en.xhtml has been considered for this study. The transmitters and the receiver are located in the latitude ranging 38°N - 55°N and longitude ranging 3°W - 28°E. The earthquake event data were taken from the United States Geological Survey site (http://earthquake.usgs.gov/earthquakes/eqinthenews). This study was carried out using the VLF signal strength data during the period 2010 - 2013. The seismic events are so selected that epicenter of the earthquake lies near the propagation paths and the details of the earthquake events considered are listed in the Table 1. The coordinates of the transmitters (TBB, GQD and GBZ) and the receiving station along with those of the seismic events are shown in the Fig. 2. The great circle path between the transmitters and the receiver is also shown in the figure.

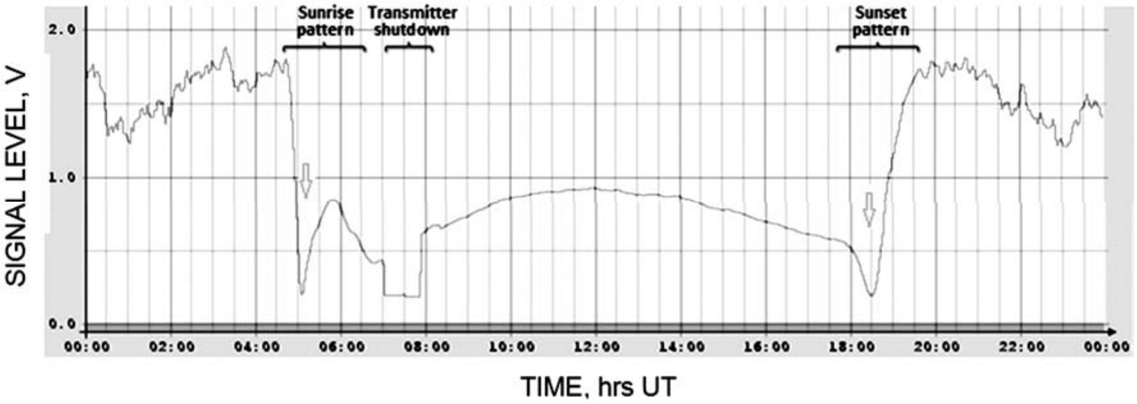

Fig. 1 — Diurnal variation of VLF amplitude

Table 1 — Details of earthquake events considered

S No	Name of transmitter	Distance from midpoint of Great Circle Path, km	Seismic event day	Magnitude	Coordinates of the place where seismic event occurred
1	TBB	2092	8 March 2010	6.1	38.8°N, 39.9°E
2	GBZ	1518	11 April 2010	6.3	37°N, 3.5°W
3	GQD	1415	11 May 2011	5.1	37.7°N, 1.6°W
4	TBB	1253	19 May 2011	5.8	39.1°N, 29.7°E
5	TBB	620	22 May 2012	5.6	42.6°N, 23°E
6	TBB	1009	12 Oct 2013	6.6	35.5°N, 23.2°E

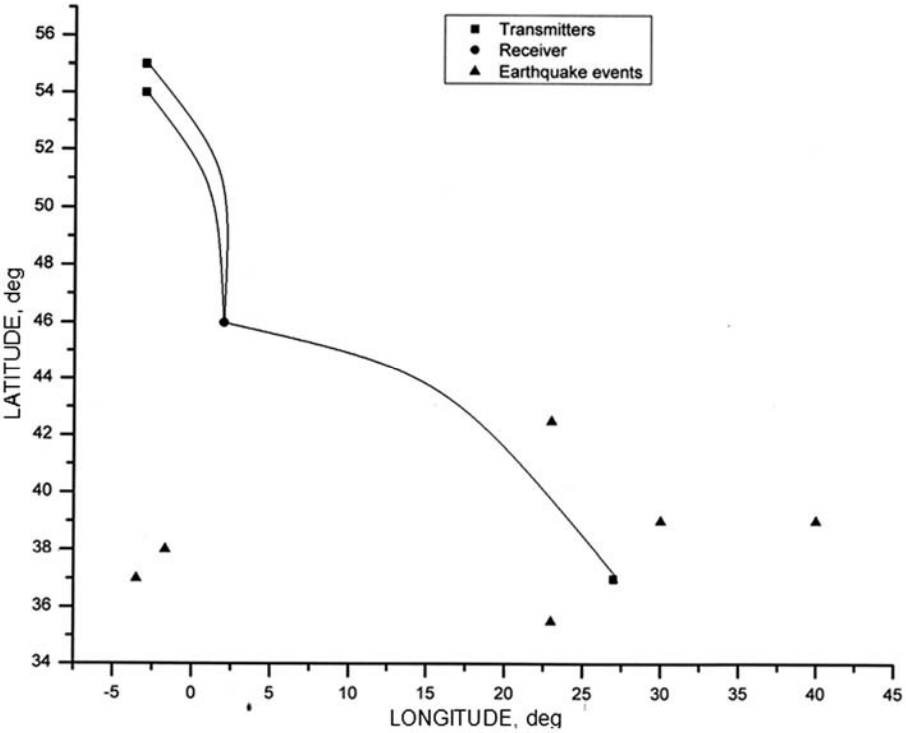

Fig. 2 — Locations of transmitter, receiver and earthquake events

There have been reports of the precursory effect of ionospheric perturbations revealed from night time fluctuations in VLF amplitude[9] and VLF terminator method[10,12]. Maekawa & Hayakawa[14] observed that the terminator method is effective for East-West propagation direction. In the present study, as the VLF propagation path between TBB and the receiving station in South France mainly extends in the East-West direction, the authors have looked into the seismic effects in the terminator timings of the received VLF signal. The daily morning and evening terminator timings (T_m and T_e, respectively) during the respective months are plotted in Fig. 3(a-l) along with the days of occurrence of seismic events shown with arrows.

3 Results and Discussion

From Fig. 3, it can be observed that the T_e shows fluctuations in the pre-earthquake period. But T_m shows remarkable fluctuations in the pre-earthquake period for three events, i.e. 22 May 2012, 11 April 2010 and 8 March 2010. These events occurred at 620, 1518 and 2092 km from the midpoint of their respective great circle paths. Apart from the fluctuations in the daily TTs, the evening terminator shows movement towards night in the pre-earthquake period of 5-6 days for all the events except the 12 October 2013 event and this is in agreement with the previous investigations[12]. But the morning terminator shows a large deviation of 40-50 minutes in the pre-earthquake period for the three events mentioned earlier. The length of VLF day for all the events is shown in Fig. 4. From this figure, it can be observed that for 22 May 2012, 19 May 2011 and 11 April 2010, the VLF day is longer in pre-earthquake period of 5 days. This observation is in agreement with the results of Rodger *et al.*[11]. But for the other three events, this feature is not evident. To understand the effect of earthquake on the T_m and T_e timings clearly, the standard deviation parameter (σ) has been evaluated using the formula[10]:

$$\sigma = <(T_{e,m} - <T_{e,m}>)^2>^{1/2}$$

where, $T_{e,m}$, are evening terminator and morning terminator, respectively, and < > is the monthly average value.

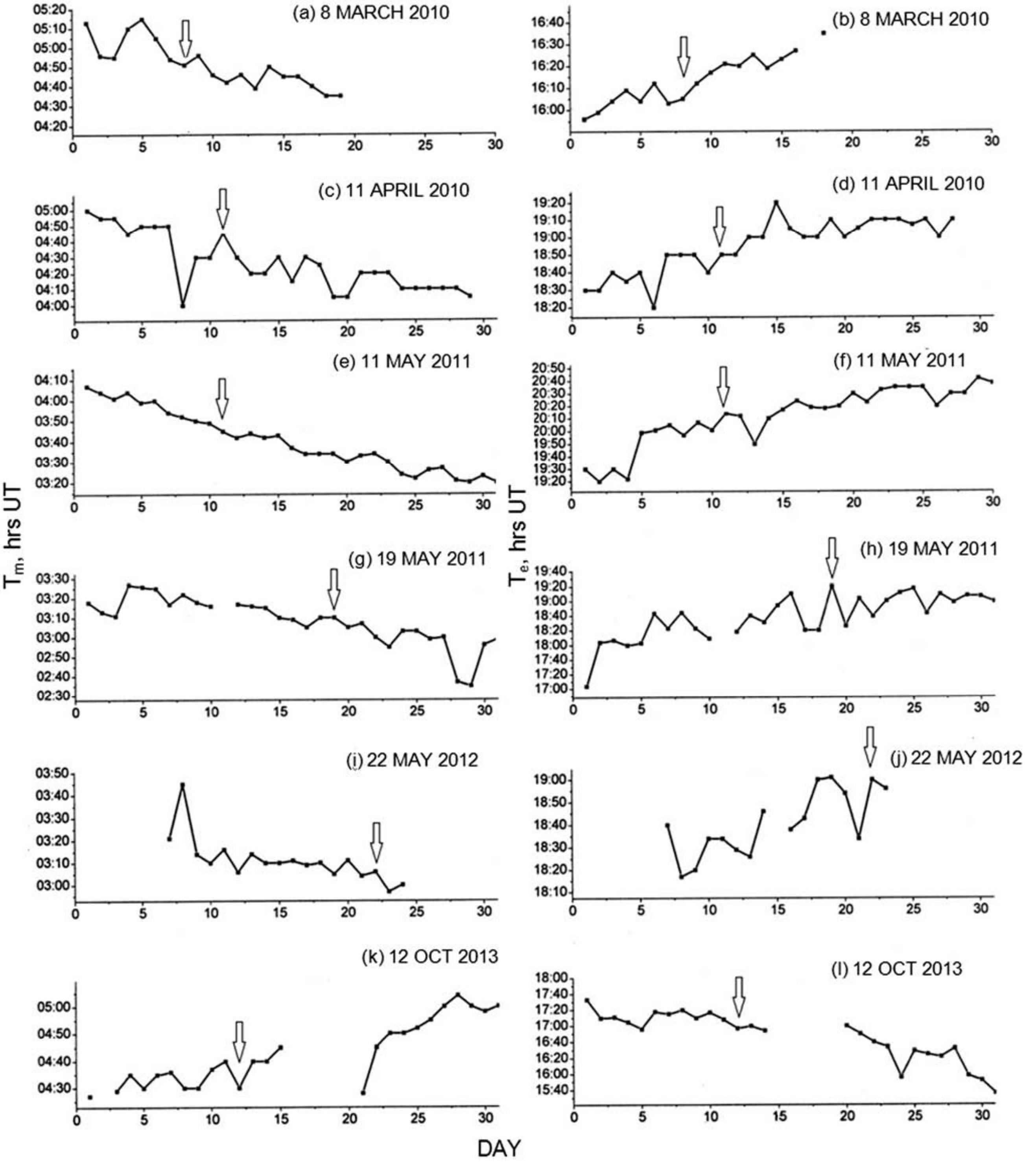

Fig. 3 — (a-l) Variation of morning and evening terminators (T_m and T_e, respectively) during the respective months for the six earthquake events (arrows indicate day of the earthquake)

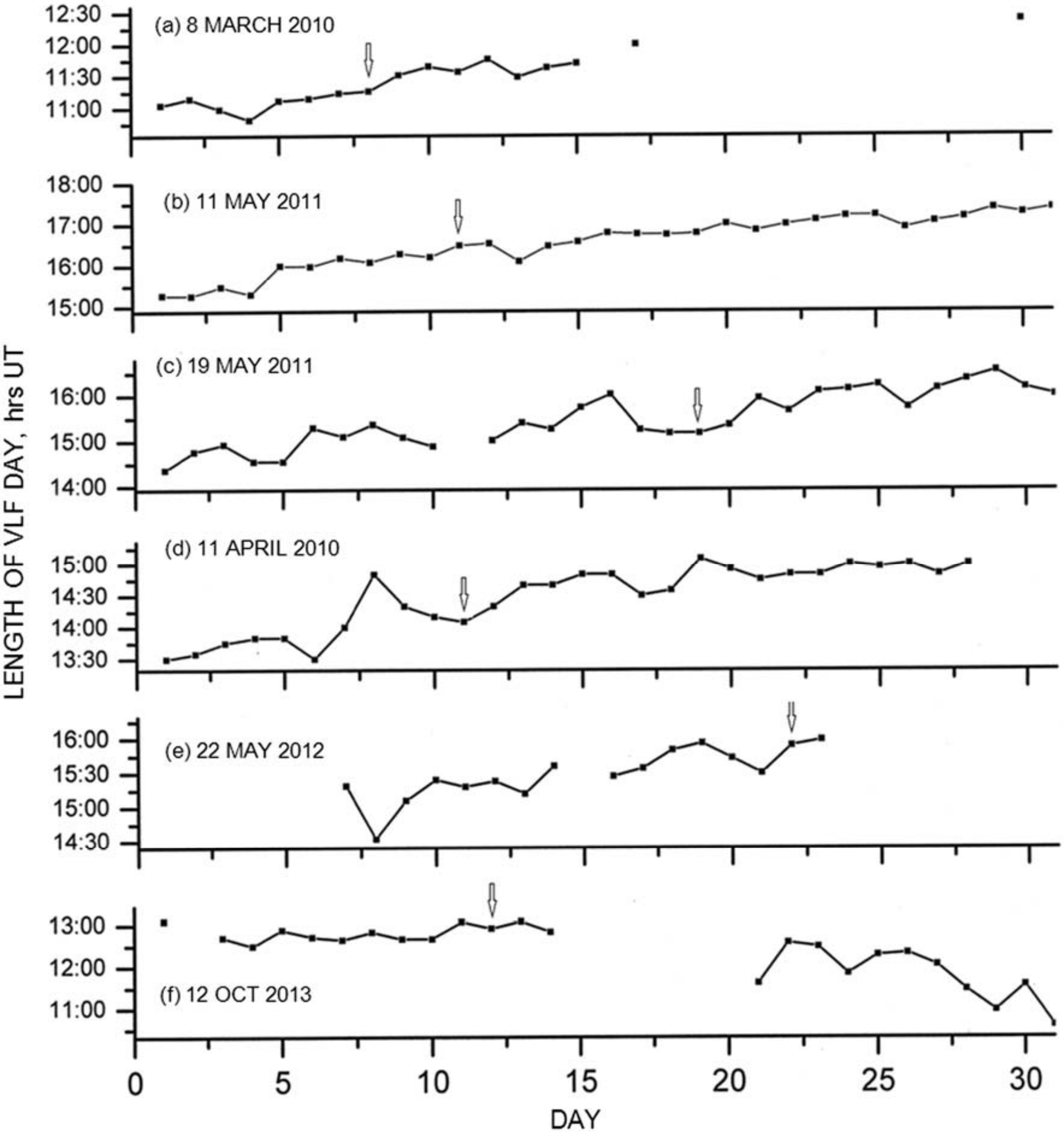

Fig. 4 — (a-f) Length of VLF day for the six earthquake events (arrows indicate day of the earthquake)

The shifts of terminator timings from monthly mean values are presented in Fig. 5(a-l). It can be observed in this figure for 8 March 2010 and 22 May 2012 events that the shifts of morning terminator from the monthly mean crossed 2σ level in the pre-earthquake period of 3-14 days. The 22 May 2012 event occurred 620 km from the midpoint of the GCP, and is 692 km from transmitter (TBB) and is of 5.6 intensity. Though, the earthquake is of moderate intensity less than 6, it occurred near the transmitter and the shift crossed 3σ level on 8 May 2012. The 8 March 2010 event occurred 2092 km from the midpoint and is of 6.1 intensity. The evening terminator crossed 2σ level for 11 May 2011 and 22 May 2012 during 7-14 days before occurrence of earthquakes though the 11 May 2011 event is of less intensity (5.1) and is 1415 km from the midpoint of the GCP. The shift of both TTs crossed the 2σ level for 22 May 2012 event on 8 May 2012 resulting in shorter VLF day, which is evident in Fig. 4(e).

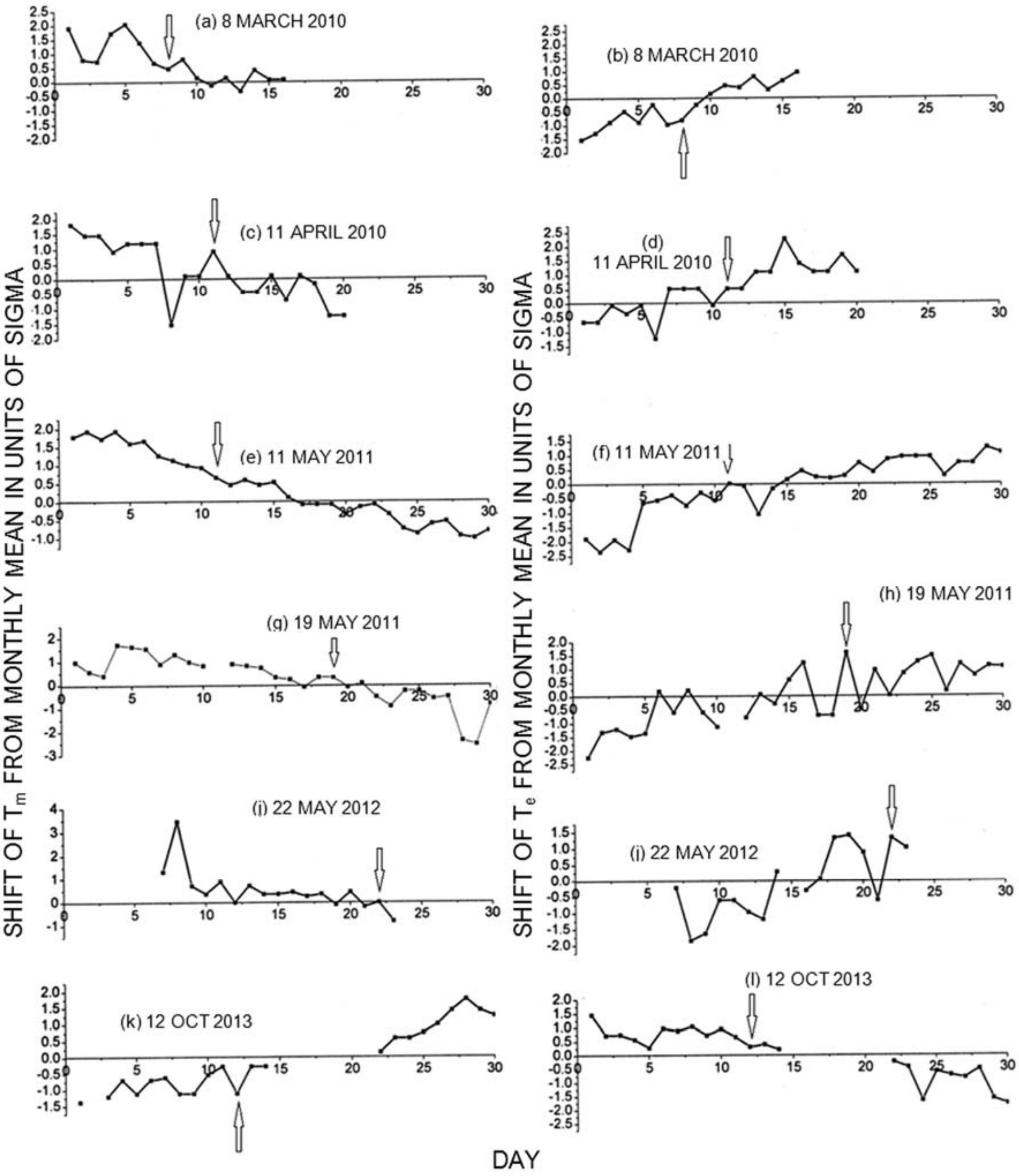

Fig. 5 — (a-l) Shift of T_m and T_e from monthly mean in units of σ (arrows indicate day of the earthquake)

Previous investigations on VLF perturbations associated with earthquakes show that the terminator timings deviate significantly from their monthly averages during the pre-earthquake period[10,11]. From their model, Molchanov *et al.*[10] have shown that the deviation in TT is due to decrease of reflection height by nearly 2 km, which may be due to increase in electric field or intensification of planetary waves. Rodger *et al.*[11] felt that this drop in reflection height is to be larger than 2 km to cause the observed TT changes. Abhikesh Kumar *et al.*[15] reported anomalous deviations in sunrise terminator timings of VLF waves propagating to long distances during earthquake of 18 December 2006. The results of present study show that there is considerable deviation in timings of both T_e and T_m in the pre-earthquake period. There are reports of enhanced radioactive gas concentrations observed before strong earthquakes[16]. These gases change the electrical parameters, which contribute much to the D-region electrical conductivity. The observed deviations in terminator timings must be due to depletion of the reflection height of the VLF waves. The enhancement in the D-region electrical conductivity due to the emanations of the radioactive gases in the pre-earthquake period may be responsible for the depletion of reflection height. Simple analysis carried out in the present study confirms that the VLF propagation gets affected during the pre-earthquake period.

4 Conclusions

The results of the present study using the VLF amplitude data for three propagation paths analyzed for deviations in terminator timings show that there are fluctuations in morning and evening TTs in the pre-earthquake period. The evening terminator is moving towards night during the pre-earthquake period of 5-6 days except for 12 October 2013 event. The VLF day is found to be longer in the pre-earthquake period of 3-5 days. The possible mechanism behind the observed precursory effects in TTs may be the lowering of reflection height of VLF waves.

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