

A search for precursors of earthquakes from multi-station ULF observations and TEC measurements in India

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Ground based observations have been carried out for ultra low frequency (ULF) precursors of earthquakes at four different stations in India, namely Agra (geographic lat 27°N, long 78°E), Guttu (lat 31.53°N, long 78.75°E), Shillong (lat 25.92°N, long 91.88°E) and Kolhapur (lat 16.40°N, long 74.15°E) using identical 3-component search coil magnetometers ($f = 0.01-30$ Hz) obtained from Lviv Centre of Space Research, Ukraine. An offline analysis of the combined data has been carried out in relation to a major earthquake of magnitude $M=7.9$ occurred in the neighbouring country China (lat 31°N, long 103.32°E, depth=19 km) under the National Program of Earthquakes Precursors (NPEP) launched in India since May 2009. The results of the analysis show occurrence of amplitude anomalies as precursors whose amplitudes decrease with distance. The precursor periods range between 2 and 5 days and are large for the stations nearer to epicenter. A graphical determination of location of the epicenter has been found to be satisfactory with errors within 20.5%. Further, the total electron content (TEC) data obtained from a dual frequency GPS receiver at Agra station and global ionospheric maps (GIMs) of TEC corresponding to the Wenchuan earthquake have also been analysed. The GIM TEC data have been analysed for five different locations which lie between Agra and the epicenter of the earthquake. The anomalies in TEC data are investigated by using quartile based statistical process. It has been found that GPS and GIM TEC data show anomalous depletions of 02 - 13 days before and anomalous enhancements of 03 - 10 days prior to the occurrence of earthquake.

Keywords: Earthquake, ULF anomalies, Total electron content (TEC), Ionospheric precursors

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1 Introduction

The electromagnetic emissions associated with earthquakes consist of wide range of frequencies from DC to high frequency (HF). However, the ultra low frequency (ULF) band (0.01-10.0 Hz), which is characterized by large skin depth, low attenuation and less contamination from other sources, can penetrate the crust and propagate in the atmosphere, ionosphere and magnetosphere providing convincing precursors of earthquakes on the ground and satellite¹⁻¹¹.

While identifying the precursory behaviour of ULF emissions, some researchers have attempted to determine the direction of emissions and location of epicenters of the earthquakes. For example, Du *et al.*¹² have conducted observations of ULF emissions associated with Hetian earthquake ($M=7.1$) at three different stations in China and determined

polarisation angles at these three stations. The polarisation angle is the angle between the east direction of the geomagnetic field and major axis of the polarisation ellipse, which is obtained from the filtered data of two horizontal components. The source of ULF emissions before earthquake was expected in a direction perpendicular to the polarisation major axis. By applying this technique, they located the source as the cross of two source directions one day before the earthquakes which was found to be consistent with the epicenter of the earthquake. Ismagulov *et al.*¹³ have studied the anomalous behaviour of amplitude, gradient of amplitude and phase velocity of ULF electromagnetic disturbances ($f = 0.002-0.5$ Hz) before and during a seismo-active period by carrying out measurements at two magnetic stations separated by about 140 km and

a reference station (>200 km) at Tzu and Chiba peninsula in Japan. It was found that the gradient vectors related to a strong seismic shock ($M=7.6$) were directed to the regions with increased conductivity. Schekotov *et al.*¹⁴ have attempted to determine the source azimuth using a technique which is based on the analysis of total field and its polarised pulsed component. For this purpose, they have used the pre-seismic ULF/ELF magnetic data measured at Kamchatka, Russia along with data on local seismic activity during eight years of observation. The technique shows a better accuracy in the source azimuth direction. The errors of the method are associated with non-seismic sources and due to one point observations. Multi-point observations are suggested to eliminate the errors.

Zhang *et al.*¹⁵ have made a ground and satellite based study of DC-ULF electric field anomalies observed at three different stations within 500 km around Wenchuan earthquake. Their short-term study shows amplitude anomalies of 3-100 mV km⁻¹ range with different shapes and amplitudes at different stations which were attributed largely due to individual underground layer conductivity, water level, etc. The analysis of long time series illustrates that the abnormal geo-electric field started two months before. A comparison of ground and space anomalies (measured onboard DEMETER satellite) showed consistent results.

For the first time ionospheric anomalies prior to the occurrence of Alaskan earthquakes of 28 March 1964 were reported by Moore¹⁶ and Davis & Baker¹⁷. Later, a lot of work appeared which showed the seismic signatures in the ionosphere. Different ionospheric parameters, like critical frequencies of the ionospheric F₂ region (f_0f_2) and E-region (f_0E_s), and total electron content (TEC) are used by many researchers to study seismic responses in the ionosphere¹⁸⁻²². A detailed study in this direction can be found in research papers by Hayakawa & Fujinawa²³, Hayakawa & Molchanov²⁴, Singh²⁵, Hayakawa²⁶, Molchanov²⁷ and references therein. During the last decade Global Positioning System (GPS) based TEC anomalies have been widely used for investigating ionospheric precursors of earthquakes²⁸⁻²⁹. GPS based TEC provides an overall description of the ionisation and is measured in TEC units where one TEC unit is equal to 1×10^{16} el m⁻². From various studies, it has been found that earthquakes of magnitude $M \geq 5.0$ show significant ionospheric signatures prior to and

after their occurrence. Many researchers have reported apparent reduction and enhancement in GPS-TEC a few days before the earthquake²⁹⁻³³. Recently, alongwith the experimental results of TEC data obtained from individual GPS receivers, the global ionospheric maps (GIMs) are also being studied extensively for TEC variations across the globe³⁴⁻³⁶. The International GNSS Service (IGS) provides to the public the global vertical TEC (VTEC) maps, namely the GIMs of TEC on the basis of observation from hundreds of ground-based GPS receivers distributed globally. In these maps, the height of the sub-ionospheric point is taken as 450 km. These global TEC maps are generated routinely by the IGS community with the temporal resolution of 2 h and the spatial resolution of 50 and 2.50 in longitude and latitude, respectively³⁷.

The north-east to north-west parts of India including Himalayan regions are major seismic belts where more than six major earthquakes have occurred during the last fifteen years and caused heavy losses of lives and properties. Keeping the importance of ULF studies in view, the Ministry of Earth Sciences (MoES), Government of India, has established a network of stations in the country for such studies which include Guttu (geographic lat 31.53°N, long 78.75°E), Agra (lat 27°N, long 78°E), Shillong (lat 25.92°N, long 91.88°E), and Kolhapur (lat 16.40°N, long 74.15°E). In this paper, an offline analysis of the ULF data has been carried out in relation to a major earthquake of magnitude $M=7.9$ that occurred in the neighbouring country, China on 12 May 2008 (well known as Wenchuan earthquake). The precursory period and amplitude of the anomalies from the ULF data, and their variation with distance from the epicenter of the earthquake have been determined. Also, the location of epicenter has been determined manually from polarisation angles at which directions from two stations cross each other. The calculated distance is found to be consistent with the observations within an error of about 20.5%. In addition, the variations in TEC data obtained at Agra station and the GIM TEC data analysed for five different locations which lie between Agra and the epicenter of the earthquake of 12 May 2008 mentioned above have also been presented here.

2 Experimental setup and Method of analysis

Three component search coil magnetometers (LEMI-30) that have been imported from Lviv Center of Institute of Space Research, Ukraine have been

used. Identical experimental set up has been used at all the four stations. The three sensors of the magnetometers are buried underground in orthogonal directions (the X-component along the north-south, Y-component along east-west, and Z-component along vertical directions). The amplified signals from the magnetometers were carried to the communication unit through shielded cables. A GPS antenna was used at each station for time synchronization. The magnetometers work for the frequency band 0.01-30 Hz over which the noise level varies from 20 to 0.04 pT Hz^{-1/2}. The data from each sensor is digitized at a sampling frequency of 60 Hz and recorded on hard disc. The raw data consisting of amplitude variation with time can be further analysed for frequency-time spectrograms or power spectrum study using FFT available in the MATLAB software with 1024 words of data length at a time. The observations were taken in noise free areas at all the centers where the chances of data contamination were less.

A dual frequency (1575.42 and 1227.6 MHz) GPS receiver system (GSV4004B) has been employed at Agra station for the measurements of TEC. The continuous measurements of TEC data using above mentioned GPS receiver are in progress at Agra station since 24 June 2006. The equipments for this purpose have been imported from USA and include an L₁/L₂ GPS antenna (Novatel's Model GPS 702), a GPS receiver (Novatel's Euro Pak 3-M) and relevant softwares. The TEC measurements are being carried out through combined frequencies pseudo range and carrier phase measurements. The instrumental biases such as receiver and satellite biases are taken care prior to final TEC calculations.

In order to determine IPP locations, the effective ionospheric height equal to 350 km is taken into consideration which is found to be valid for higher elevation angles in a low latitude sector³⁸. TEC values obtained at higher elevation angles (>50°) are taken into consideration to remove the effects due to multipath, tropo-scatter and water vapour on TEC at low elevation angles. Data are recorded at a sampling rate of 60 seconds.

The global TEC maps in the IONEX format are accessible at the site <ftp://cddis.gsfc.nasa.gov/gps/products/ionex>. The combined International GNSS Service (IGS) TEC maps denoted by the prefix "igsg" in the IONEX filename are used in this study. The estimation accuracy for the TEC maps provided by IGS is about 10-20% (Ref. 37). The TEC data from GIMs of TEC is written as GIM TEC in this paper.

To investigate the anomalous variations in TEC-Agra and GIM TEC data, a quartile-based statistical method is adopted similar to that used by Liu *et al.*³⁴ At first a median (M) of every successive 15 days of TEC is computed to find the deviation on 16th day. Two quartiles, first (or lower) and third (or upper) are calculated which are denoted by LQ and UQ, respectively. It has been shown by earlier researchers that under the assumption of a normal distribution with mean (m) and standard deviation (σ) for GPS TEC, the expected values of M and LQ or UQ are m and 1.34σ, respectively^{34,39}. Finally, the lower bound (LB) and upper bound (UB) are calculated as: LB = M - 1.5 (M - LQ); UB = M + 1.5 (UQ-M). The values of TEC crossing these LB and UB are detected as abnormal variation in TEC data.

3 Earthquake, Lightning and Magnetic storm data

The earthquake data for the case under study have been taken from United States Geological Survey website (<http://neic.usgs.gov>). The details of the data are listed as:

- Date of earthquake : 12 May 2008
- Time of earthquake : 06:28:01.57 hrs UT
- Location : Lat 31.0°N, Long 103.32°E
- Depth : 19 km
- Magnitude : 7.9

The location of the earthquake and ULF observing stations are shown in Fig. 1 by star and solid circles, respectively. The effect of magnetic storms are examined in terms of ΣKp and Dst index variation, for which the data have been taken from geophysical data bulletin provided by World Data Center, Kyoto, Japan website (<http://swdedb.kugi.kyoto-u.ac.jp>).

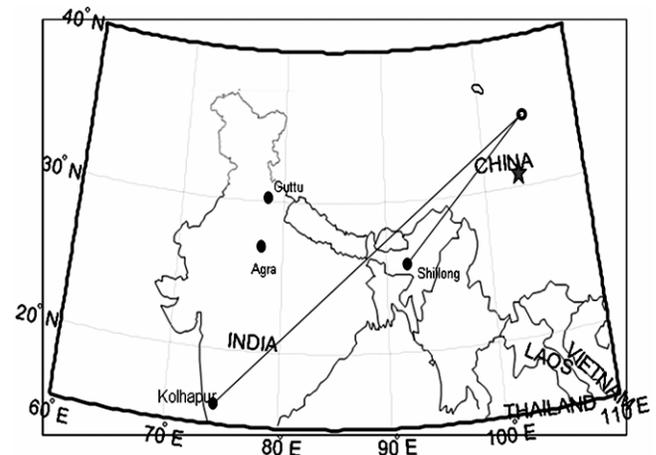


Fig. 1 — Map of India and around showing the epicenter of the earthquake (star) and locations of observing stations (solid circles)

The lightning activity around an observing station may also contaminate the ULF data. This has been examined by considering the lightning activity data around the observing stations. The lightning data are taken from website <http://www.wunderground.com/>.

4 Results and Discussion

4.1 Analysis of ULF data

The ULF studies related to seismic activities have been in progress at Agra station for a long time^{10,11,40-41}. Such studies have been started at other stations, viz. Guttu, Shillong and Kolhapur, recently under the National Programme of Earthquake Precursors (NPEP) launched by Ministry of Earth Sciences (MoES), Government of India, New Delhi in May 2009. The Agra station has been assigned the responsibility of processing joint analysis of ULF data related to some seismic events and examine the precursory characteristics of ULF emissions. With this in view, a major seismic event of Wenchuan earthquake that occurred in China on 12 May 2008 has been considered and then ULF data (amplitude-time) has been collected for a period of ± 7 days from the respective date of seismic event

from other stations: Guttu, Shillong and Kolhapur and anomalous variations have been observed in the X, Y and Z components of the data such as amplitude bursts. The studied time scale chosen to study the short-term precursors of earthquakes is 15 days only. The data for this possibly correspond solely to Wenchuan earthquake and not to other which may possibly occur if long data set is considered. It is necessary to mention here that during this period of 15 days, no major earthquakes occurred within 2000 km from Agra station except two: one at 949 km ($M=4.9$) and other at 1992 km ($M=4.8$) between 01 and 25 May 2008. The effects of such earthquakes are unlikely to influence the present data as compared to Wenchuan earthquake. Further, it is worthwhile to mention here that Zhang *et al.*¹⁵ also made a similar short-term study for 15 days observing ULF electric field anomalies related to Wenchuan earthquake at three stations within 500 km of the epicenter. Kushwah *et al.*⁴¹ have described the occurrence features of such ULF bursts recorded at Agra station which are similar to those recorded by other researchers^{2,42-44}. An example of such bursts recorded on 10 May 2008 at Guttu station is shown in Fig. 2.

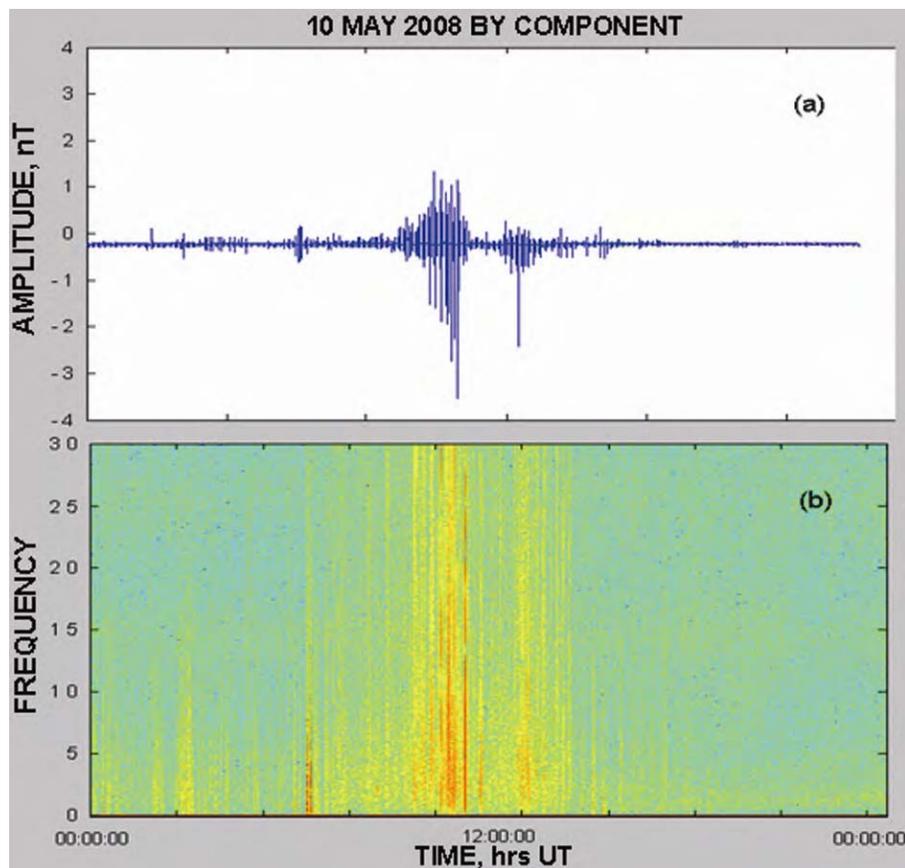


Fig. 2 — Example of amplitude burst: (a) and frequency-time spectrogram; (b) recorded at Guttu on 10 May 2008 showing amplitude anomaly

Similar ULF bursts have occurred in the data available from other stations also. A preliminary examination of ULF data from all the stations shows that in about 80% cases, the X and Y components have similar amplitude bursts. The ULF amplitude burst shown in the upper portion of Fig. 2 shows two amplitude anomalies occurring one after the other with varying amplitudes. Such anomalies occurred in the data recorded at all the three stations. The period of the amplitude bursts varied between 1-3 hours largely except one which existed for 5 hours with large amplitude fluctuation almost co-seismic at Shillong. The average of maximum amplitude

deviation has been taken in each of the burst. The amplitude enhancements less than 0.2 nT (nano Tesla) are not considered. The lower portion of the figure shows the frequency-time spectrogram of the upper part determined from MATLAB. Further, since the X component data are scantily available due to malfunctioning of sensors at some of the stations, amplitude anomalies, reflected in Y component for which sufficient data are available, have been considered.

In Fig. 3, the details of ULF bursts corresponding to the case of earthquake under consideration has been shown. The figure is divided in four panels to

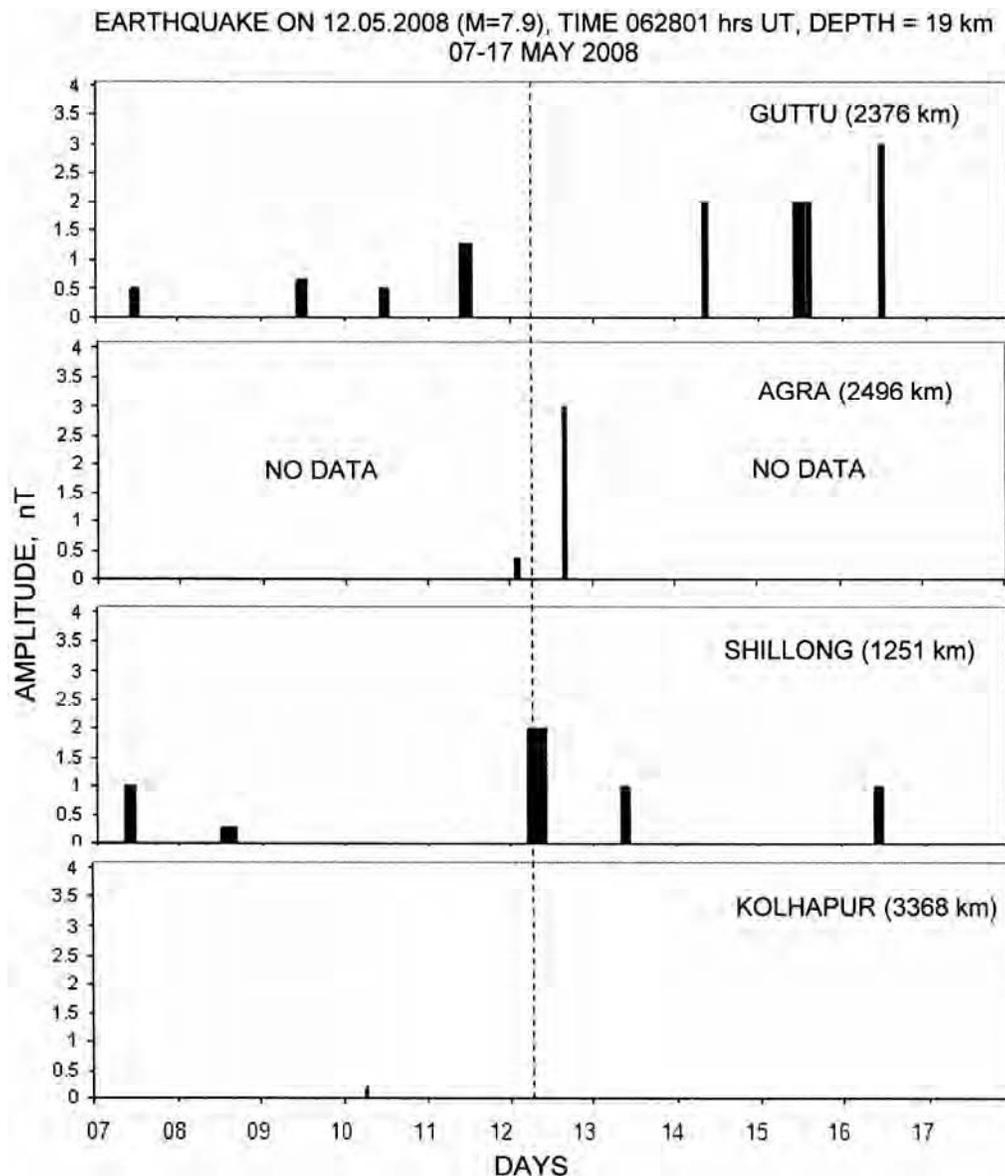


Fig. 3 — Occurrence pattern of amplitude bursts at the observing stations of Guttu, Agra, Shillong, and Kolhapur related to Wenchuan earthquake (M=7.9) [distances of the epicenters from observing stations are shown in the brackets; vertical dotted line shows the day and time of the main shock]

indicate the diurnal pattern of occurrence of ULF bursts at each station, i.e. Guttu, Agra, Shillong and Kolhapur. The distances of the observing stations from the epicenter of earthquake are indicated in brackets along with the name of each station. The date, time, depth of occurrence of earthquake, and duration of data considered are indicated on the top of the figure. The histograms show the day and time (hrs UT) of ULF burst, their heights show the amplitude in nano Tesla (nT), and the width show the duration. The data are shown for a period of 10 days (± 5 days from the main shock). A dashed vertical line shows the day and time of occurrence of the main shock of earthquake. This figure shows the complete occurrence pattern of the burst from which one can determine amplitude, duration, date, time of each burst occurred during the analysis period.

From Fig. 3, it may be seen that the amplitude bursts occurred at Guttu on four different days of 7, 9, 10 and 11 May as precursors and on 14, 15, 16 and 18 May as post-shock events. While the data for other days are not available, two amplitude bursts occurred at Agra station on the same day, one at 0115 hrs UT about 5 h before the main shock as precursor, and the other about 9 h after the shock. At Shillong station, which is nearest to the epicenter, anomalies occurred on 7, 8 and 12 May as precursors and on 13 and 16 as post-shock effects. On 12 May, the anomaly is found to be strongest (2 nT) with duration from 0500 to 1000 hrs UT. There is a small 3 min anomaly of magnitude 0.2 nT at Kolhapur which occurred at 0603 hrs UT on 10 May, about 2 days before the shock. It may be seen that all the amplitude anomalies shown by histograms in Fig. 3 at different stations are not synchronous except few at any two of the four stations under consideration. For example, the anomalies are synchronous at Guttu and Shillong on 7 May and at Guttu and Kolhapur on 10 May with significant variation in amplitude and duration. However, the result obtained in Fig. 3 show that amplitude anomalies occurred at Guttu and Shillong stations 5 days before the main shock and at Kolhapur two days before the main shock. The anomalies occurred at Shillong with relatively large amplitude enhancement possibly due to the reason that it was located nearest to the epicenter and very small amplitude at Kolhapur due to being at very large distance. A temporal shift in the occurrence of burst with epicentral distance is not seen between the data set at Guttu and Shillong stations, but a

difference in magnitude of the anomaly with distance does exist. A systematic temporal shift with epicentral distance cannot be expected because of varying electrical conductivity in the directions of the observing stations. Perhaps due to this reason, Zhang *et al.*¹⁵ also observed randomly distributed anomalies at the three stations considered by them. They interpreted their results in the light of the work of Sorokin & Pokhotelov⁴⁵ who suggested that the ULF geomagnetic pulsations before earthquake were connected with migration of fluid and gases and the variation of electrical conductivity in the layer induced the impulsive electric current. Hence, the difference in underground layer conductivity and water level in different regions may lead to anomalous signals with different amplitude and shapes.

The variation of amplitude with distance of precursory ULF bursts corresponding to the Wenchuan earthquake is presented in Fig. 4(a). In this figure, the maximum amplitude of the burst recorded at a station and its corresponding distance from the epicenter has been plotted. For example, the maximum precursory amplitudes of the bursts shown by histograms at Shillong, Guttu, Agra and Kolhapur stations are 2, 1.25, 0.35, and 0.2 nT which are shown in the figure with the corresponding distances from the epicenter. It is clear from this figure that the amplitudes of the precursory signals fall gradually with increasing distance. This result is consistent with Tsarev & Sasaki⁴⁶ and Singh *et al.*⁴⁷ who have calculated the attenuation of ULF signals by using suitable conductivity models and shown that because of low attenuation, such signals can propagate to long distances in the crustal region and emerge in the atmosphere through some special geological formation. From Fig. 4(a), one can also make an assessment of the distance for ULF wave propagation from earthquake region. Since a low amplitude and small duration precursor is obtained at Kolhapur which is 3368 km away from the epicenter, this may be considered as maximum distance to which the ULF wave could travel. This is higher than that calculated from empirical relation $R=10^{0.43M}$ given by Dobrovolsky *et al.*⁴⁸ and used by Pulinets⁴⁹ which is 2494 km, though there is just 26% error for the earthquake of magnitude $M=7.9$. From Fig. 3, it can be seen that precursory periods for this earthquake at the present network of ground stations range between 2 and 5 days. The large precursory period for earthquake of large magnitude may be understood

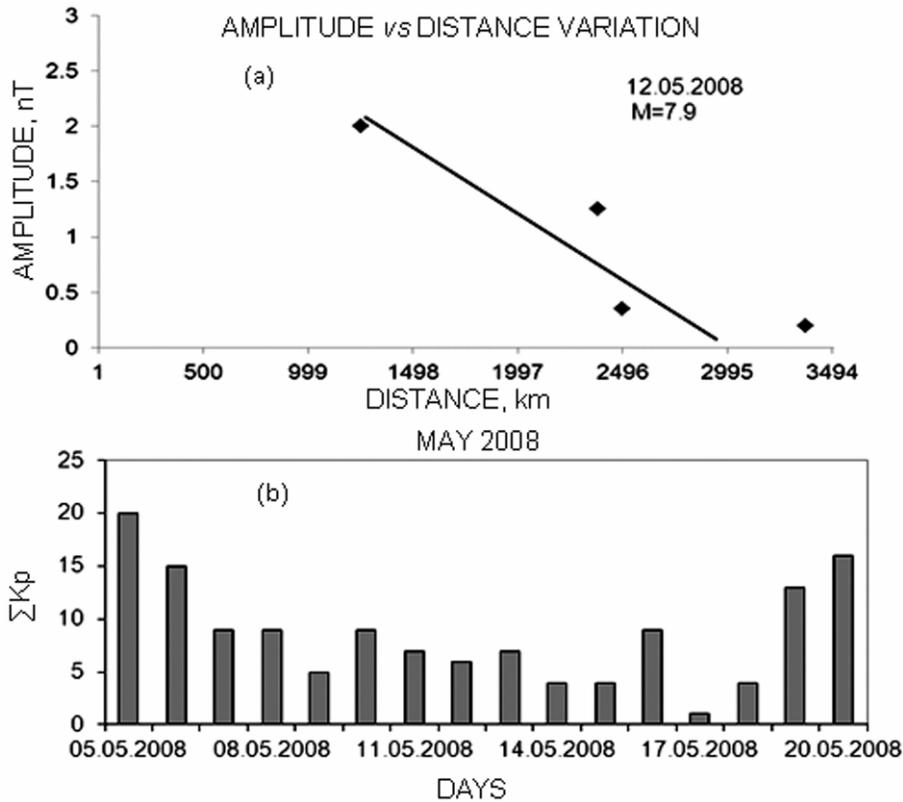


Fig. 4 — (a) Variation of amplitude with distance as observed from the ULF data related to the earthquakes under consideration; and (b) variation of $\sum Kp$ during ± 7 days around the earthquake in each month, showing magnetically quiet periods over all

well in the light of energy generated during the earthquake processes for which an empirical relation has been given by Gutenberg & Richter⁵⁰ as:

$$\text{Log } E = 11.8 + 1.5 M$$

where, E , is the seismic wave energy; and M , the magnitude of earthquake. The strain energy accumulated in the focal region is much higher and even if a fraction of this is converted into electrical energy, it will be sufficient enough to propagate to long distances. For large earthquake of magnitude $M=7.9$, the ULF bursts reach Shillong and Guttu much earlier between 5 and 5.6 days from the day of main shock possibly because they are nearer to the epicenter as compared to Agra and Kolhapur.

From the analysis of lightning activity data, it is found that lightning activities occurred at Delhi and Jaipur between 8 and 12 May 2008. These places are 200 to 250 km away from Agra and Guttu observing stations and hence the ULF electric and magnetic fields associated with the emissions are unlikely to influence the data presented in Fig. 3. This is due to the reason that the influence of electrostatic fields at such frequencies is confined mostly to the distances

less than 10 km around the location of the thunderstorms⁵¹. Further, the radiation energy of a single lightning discharge, which may travel to long distances, peaks at very low frequency (VLF) between 1-10 kHz and the energy of ULF is about 4 orders of magnitude lower than VLF if measured in the vicinity of the lightning center⁵². In view of this, the ULF part cannot travel to 200-250 km to influence the data at Agra and Guttu. No data are available to examine the lightning activities around Shillong and Kolhapur.

The $\sum Kp$ variation for a period of 15 days (± 7 days from the day of main shock) has been shown in Fig. 4(b) to examine the effect of magnetospheric ULF emissions (micro pulsation) on the data under study. The figure shows $\sum Kp < 30$ on all days in the month of May 2008 which indicate quiet magnetic conditions. Further, such ULF emissions should appear in the form of bursts on all stations simultaneously which is not found from Fig. 3. Hence, the possibility of micro pulsations affecting the data does not exist. It may be mentioned here that the criteria of polarisation analysis ($Z/X < 1$ or > 1 for the ULF signals

of magnetospheric origin or lithospheric origin) does not apply in the present case because the epicenters of the earthquakes are far away from the observing stations. In such case, even the criteria $Z/X < 1$ may show the origin of the signals in the lithospheric (Nickolencov A P, University of Electro Communication, Chofu, Tokyo, Personal communication, 04 March 2008).

An attempt has been made to locate the epicenter of the earthquake graphically by calculating the directions of the signals from the data at any two stations. The directions of the signals crossing each other at a point would determine the location of the earthquake. This attempt is on the line similar to Du *et al.*¹² and Dudkin & Korepanov⁵³. However, the present attempt is little different and simple as compared to Du *et al.*¹². Since X component data are not available at Guttu and Agra stations corresponding to this earthquake, this analysis has been shown for the data obtained at Shillong and Kolhapur only. The present method is based on finding the direction of emission using the relation

$\theta = \arctan(Y/X)$ from the two stations where X and Y data are available and then determine the point of intersection (Fig. 1). Then, the calculated distances between the epicenters and observing stations have been measured and compared with the actual distances. The results are given in Table 1. The angle

in Fig. 1 are calculated from X and Y component data available at Shillong and Kolhapur only. In this calculation, the co-seismic burst at Shillong showed 01 h precursor (on 12 May 2008) and the only one precursor at Kolhapur occurred 2 days before (on 10 May 2008) are considered. In Table 1, two types of distances are shown: one actual distance between the observing station and the epicenter, and the other measured from the graph.

It may be seen from this table that distances between epicenters and observing stations agree reasonably with errors within about 20.5%. It may be mentioned here clearly that the graphical

Table 1 — Manual calculation of epicentral distances

Earthquake Locations	Actual distance, km	Calculated distance, km	Error, %
M=7.9 Shillong - epicenter	1251	1570	20.38
Kolhapur - epicenter	3368	3653	7.8
Guttu - epicenter	2376	2596	8.47
Agra - epicenter	2496	2704	7.6

Distance between actual and calculated epicenters = 448 km

determination of the position of epicenter as presented above is indeed an approximate one and needs certainly a better and modified approach.

4.2 Analysis of TEC data

It has already been mentioned above that the TEC measurements using a dual frequency GPS receiver have been in progress at Agra station since 24 June 2006. Here, the TEC data corresponding to the Wenchuan earthquake (M=7.9) of 12 May 2008 occurred in China has been analysed. It is to be noted that numerous results have been published on the precursory effects on ionospheric parameters related to this devastating earthquake^{34-35,54-55}. Results of variations in TEC data and ionospheric electron density associated with this earthquake were also published significantly. The locations of the epicenter of the earthquake and observing station Agra are shown in Fig. 5 by a large and a small star, respectively. The small solid circles numbering 1 to 5 shown in the figure represent the GIM TEC locations. The TEC data obtained at these locations are denoted by TEC1, TEC2, TEC3, TEC4 and TEC5 and their geographic coordinates are (27.5°E, 80°N), (30°E, 85°N), (25°E, 90°N), (25°E, 100°N) and (30°E, 105°N), respectively. These GIM TEC locations are extending from Agra station to very near the epicenter of the earthquake and are chosen so that the TEC variations in between could be examined.

The variation of TEC-Agra from 27 April to 27 May 2008, ±15 days from the occurrence of the earthquake, have been shown in Fig. 6. The median, lower bound (LB) and upper bound (UB) of the data

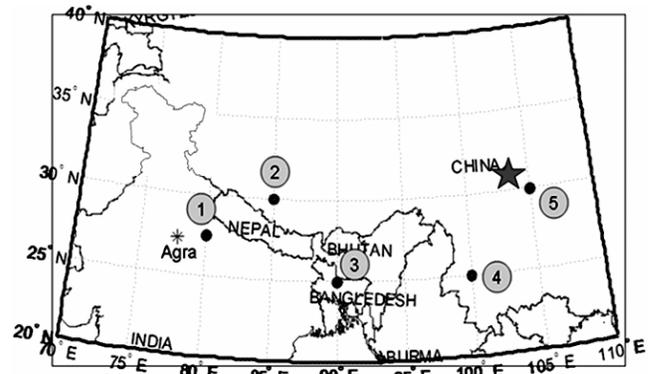


Fig. 5 — Map of India and China region depicting the locations of epicenter of the earthquake (M=7.9) occurred in Wenchuan, China on 12 May 2008 and observing station Agra by a large and a small star respectively [five small dark solid circles numbered from 01 to 05 represent the locations of GIM TEC data considered in this study]

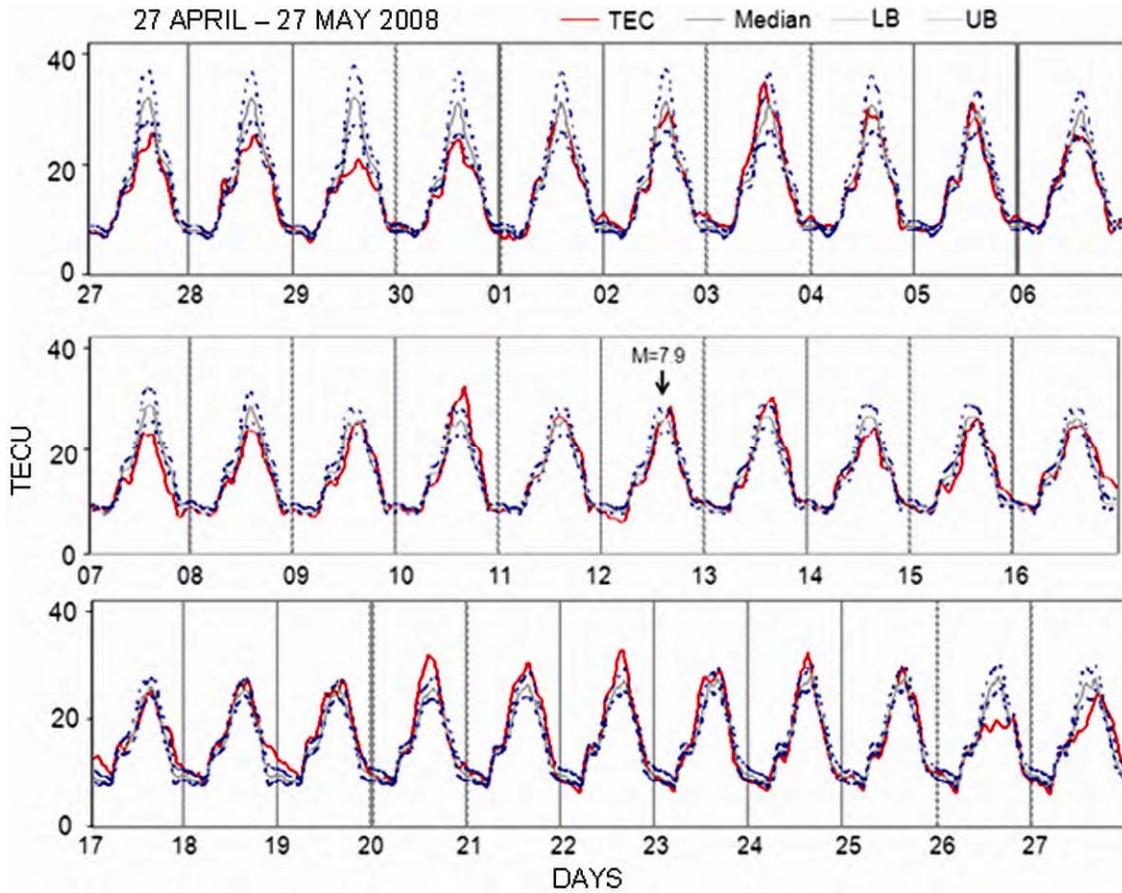


Fig. 6 — Variation of TEC data (dark continuous solid curves) obtained at Agra station between the upper bound (UB) and lower bound (LB) which are shown by dashed curves [median is shown by light continuous solid curves between UB, LB and TEC data; these variations are shown for the period 27 April - 27 May 2008]

are plotted in this figure by using statistical quartile based method as mentioned earlier. The TEC-Agra is plotted in between the UB and LB. It can be seen from the figure that a major reduction appeared in TEC-Agra below LB on 29 April, 13 days before the occurrence of earthquake. Further, a major enhancement crossing the UB is seen on 10 May, 2 days prior to the day of earthquake and a minor one on 3 May, 9 days before the earthquake. There are also some minor depletions appeared in this period prior to the occurrence of earthquake. However, some major enhancements are seen after the occurrence of earthquake between 16 and 22 May 2008.

To see the variation of geomagnetic activity during this period, the Dst index data has been analysed and plotted in Fig. 7 for the same period from 27 April to 27 May 2008. It can be seen clearly that the whole period under consideration is magnetically quiet since Dst is less than -30 nT throughout the period of observation. Similar to that of Fig. 6, the analysis process has been applied on all the above mentioned

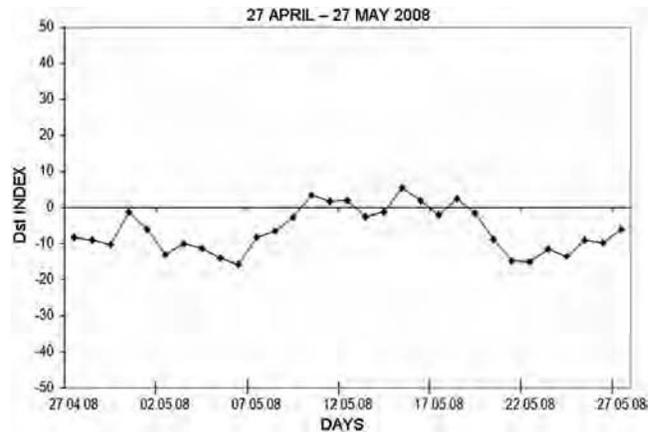


Fig. 7 — Variation of Dst index for the period 27 April - 27 May 2008

five locations of GIM TEC and the values crossing LB (depletions) and UB (enhancements) are presented separately for the same period in Figs (8 and 9), respectively alongwith TEC-Agra. Figure 8 shows the depletions in TEC crossing the LB in six panels at Agra (top) and five locations of GIM TEC

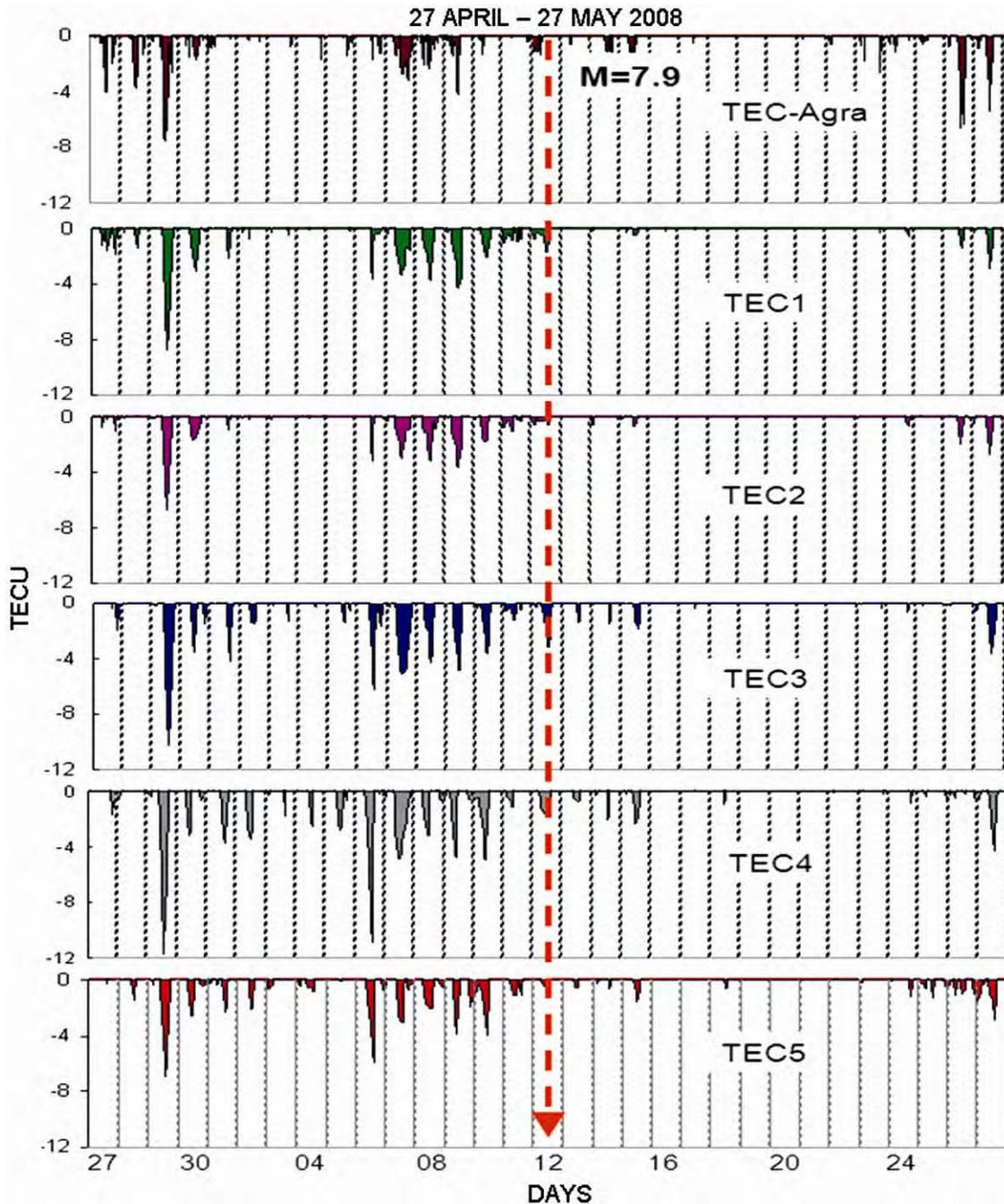


Fig. 8 — Six panels demonstrating separately the TEC depletions crossing the lower bound (LB) [first panel shows the TEC data from Agra station (TEC-Agra) and rest of the five panels representing the similar GIM TEC depletions below LB; the day of the earthquake is shown by a dashed vertical line passing through all panels; magnitude of the earthquake is shown in the top panel]

(2nd to bottom) for the period from 27 April to 27 May 2008. The day of the earthquake (12 May 2008) is shown by a dashed vertical line crossing all panels. From Fig. 8, one can see that a major depletion appeared on 29 April 2008, 13 days before the occurrence of earthquake. The level of depletion is found to be highly pronounced in TEC3 and TEC4

(below -8 TECU) which correspond to the locations towards the epicenter. Surprisingly, TEC5 shows some less depletion although it is very close to the epicenter of the earthquake. Further, significant depletions are also seen on other days between 6 and 10 May 2008 in TEC3, TEC4 and TEC5. These depletions are smallest in TEC-Agra and

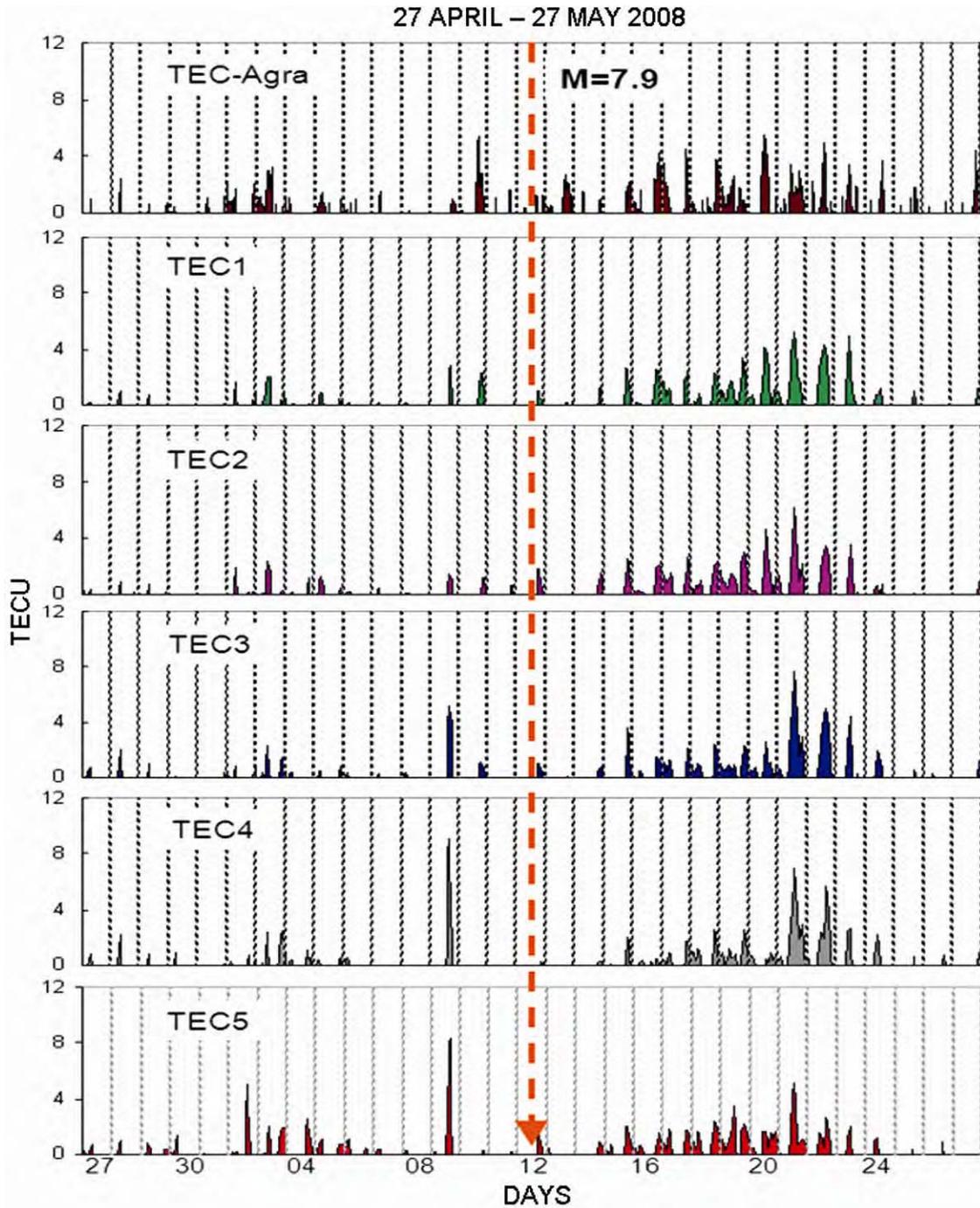


Fig. 9 — Six panels demonstrating separately the TEC depletions crossing the upper bound (UB) [first panel shows the TEC data from Agra station (TEC-Agra) and rest of the five panels representing the similar GIM TEC depletions above UB; the day of the earthquake is shown by a dashed vertical line passing through all panels; magnitude of the earthquake is shown in the top panel]

relatively small in TEC1 and TEC2. Post-seismic depletions are very minor at all locations and almost absent in TEC1 and TEC2. Similar to Fig. 8, Fig. 9 shows the enhancements in TEC crossing the UB. In this figure, TEC-Agra shows a major enhancement before the earthquake on 10 May 2008 and a minor

one on 3 May 2008, while GIM TEC data show a major enhancement on 9 May in TEC3, TEC4 and TEC5 which are the locations near to the epicenter of the earthquake. A minor enhancement is also appearing on 2 May in TEC5, 10 days before the occurrence of the earthquake. This is to be noted here

that the enhancement in GIM TEC near the epicenter appear one day before the enhancement observed in TEC-Agra. Post-seismic major enhancements are also appearing in all the panels between 16 and 22 May 2008. These major enhancements may be attributed to the effect of large aftershocks ($M \leq 6.1$) which occurred after the Wenchuan earthquake. This study clearly shows that the major depletions and enhancements appeared near the location of epicenter of the earthquake but similar types of anomalies are also registered at Agra station with less intensity.

The mechanism of coupling between the lithosphere activity and ionosphere has been proposed elaborately by Hayakawa *et al.*⁵⁶⁻⁵⁷ They proposed three coupling channels, i.e. (i) chemical channel, (ii) acoustic channel, and (iii) electromagnetic channel. Out of these, the electromagnetic channel is found to be insufficient because of weak intensity of lithospheric radio emissions⁵⁸. The explanation of physical model of chemical channel is given in Pulinets & Boyarchuk⁵⁹, Pulinets & Liu⁶⁰ and Sorokin *et al.*⁶¹, Pulinets⁴⁹ has proposed that the radon emission ionizes the near earth atmosphere over the seismic zone. He suggested formation of quasi-neutral ion-clusters as a first state of seismo-ionospheric coupling and then the generation of electric field in the next stage. However, there is lack of evidences on the direct correlation of the radon emanation with the ionospheric perturbation. On the other hand the acoustic channel has a lot of evidences in the VLF/LF subionospheric data²⁶⁻²⁷. This acoustic channel is based on the key role of atmospheric oscillations in the lithosphere-atmosphere-ionosphere coupling, and the perturbation in the Earth's surface (such as temperature, pressure) in a seismo-active region excites the atmospheric oscillations traveling up to the ionosphere and including the ionospheric density perturbations^{26,62-64}.

5 Conclusions

The ULF data obtained from four different Indian stations of Agra, Guttu, Shillong, and Kolhapur are analysed in relation to Wenchuan earthquake ($M=7.9$) occurred in neighboring country China on 12 May 2008. The results show precursors of periods between 2 and 5 days, the largest precursory periods corresponding to stations nearer to the epicenter. The amplitudes fall gradually with increasing distance. The occurrences of precursors at large distances, and large precursory periods at specific stations are interpreted in terms of propagation in

middle layer crust with low conductivity and emerging in the atmosphere through some special geological formation in the crustal region. The position of epicenter is determined graphically and a reasonable agreement is found between the actual and calculated distances between the epicenters and observing stations with errors within 20.5%. Simultaneously, daily variation of vertical TEC data recorded at Bichpuri Agra station employing a GPS receiver and GIM TEC data at five different locations have been studied in relation to the same earthquake. It has been found that TEC data obtained at Agra and other locations show anomalous depletions 2 to 13 days before and anomalous enhancements 3 to 10 days prior to the occurrence of earthquake. It has also been found that the level of anomalies are more distinct near the epicenter than at the Agra station and they appeared earlier at the location near the epicenter than other locations. The atmospheric oscillations and electric field generation during the earthquake preparation process may be the significant contributors of these anomalies in TEC data.

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