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A statistical study of TEC anomalies induced by major earthquakes occurred around Indian Subcontinent

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ABSTRACT

The GPS based TEC measurements have been in progress at Bichpuri, Agra station (27.2º N, 78º E) in India since 1 April 2006 using a dual frequency GPS-receiver. In the present paper, we analyze the TEC data for the period of April-September 2013 to examine the anomalous variations as precursors corresponding to some major earthquakes (M > 6) that occurred during this period in the Indian subcontinent. We processed the data using well known mean (m) and standard deviation around the mean (σ) criterion to see the anomalous variations as precursors in the form of enhancements above the upper limit (m + σ). Then we found the correlation coefficients between magnitude of earthquakes and precursory days and average TEC enhancement, respectively. We found significant correlation coefficients in the two cases. Finally, we tested the null hypothesis for pairs, which have the maximum and minimum values of correlation coefficients. In this way, the precursory days and corresponding TEC anomalies are fixed for the earthquakes. The concepts of E × B drift mechanism and Global Electric Circuit (GEC) are invoked to explain the ionospheric precursors of earthquakes.

Key words: Multiple earthquakes; GPS-TEC; correlation coefficients; null hypothesis; E × B drift; Global Electric Circuit (GEC) .

INTRODUCTION

In the recent past, several researchers have studied GPS-TEC anomalies related to earthquakes and their results have shown unusual precursors as enhancements or depletions in TEC prior to the earthquakes (Calais and Minster, 1995; Liu et al., 2000, 2001, 2002, 2004a, b, 2008, 2009; Pulinets et al., 2007; Dautermann et al., 2007, Zhao et al., 2008). Reviews on early studies have been presented by Pulinets (2004) and Pulinets and Boyarchuk (2004) and on recent studies by Pulinets and Davidenko (2014). Generally, it has been found that such ionospheric precursors show a temporal variation by occurring not only on a single day but on few different days prior to the main shock. For example Liu et al., (2001) analyzed the GPS based TEC data prior to occurrence of Chi-Chi earthquake and found significant precursors on 1, 3 and 4 days prior to the occurrence of earthquake (M = 7.7). Similarly, Liu et al., (2004a) examined pre-earthquake ionospheric data of GPS-TEC and identified the precursors on different days in the interval of 1-5 days prior to the earthquakes. Recently, Kon et al., (2011) analyzed global ionospheric maps (GIMs) data for 12 years to see the effect of earthquakes. They found that the ionospheric anomalies occurred on different days in the interval of 1-5 days before the occurrence of all earthquakes. More recently, Pundhir et al., (2014) have examined the effect of a major earthquake on GPS-TEC observed at Agra station (27.2º N, 78º E) and found the precursory period of 1-9 days prior to the main shock.

While intermittent appearance of anomalies before the major shock is normally interpreted in terms of processes in the earthquake preparation zone and resulting electric field penetration in the ionosphere (Pulinets, 2004), there is a possibility that some of the anomalies might be caused by other factors as well. For example, there are evidences that magnetic storm induced electric field may penetrate the ionosphere and magnetosphere at low latitudes a few days late and play useful role in ionospheric dynamics (Jain et al., 1977; Lakshmi et al., 1983, 1997). It is also known that day to day variability in foF_2, which is not related to any solar geophysical phenomenon is also very large at low latitudes. Other factors influencing the ionospheric precursors may include volcanic activities, nuclear explosions, and dust storms ,which may cause drop of atmospheric conductivity (what is equivalent to the column resistance increase) leading to increase in earth-ionosphere potential and appearance of local positive TEC anomalies (Pulinets and Davidenko, 2014). In order to reach a definite conclusion of whether the ionospheric anomalies are produced by earthquakes or by other factors, it is worthwhile to examine them by carrying out extensive correlation studies and significant statistical tests.

In the present paper, we consider five major earthquakes (M > 6) which occurred in Indian subcontinent between

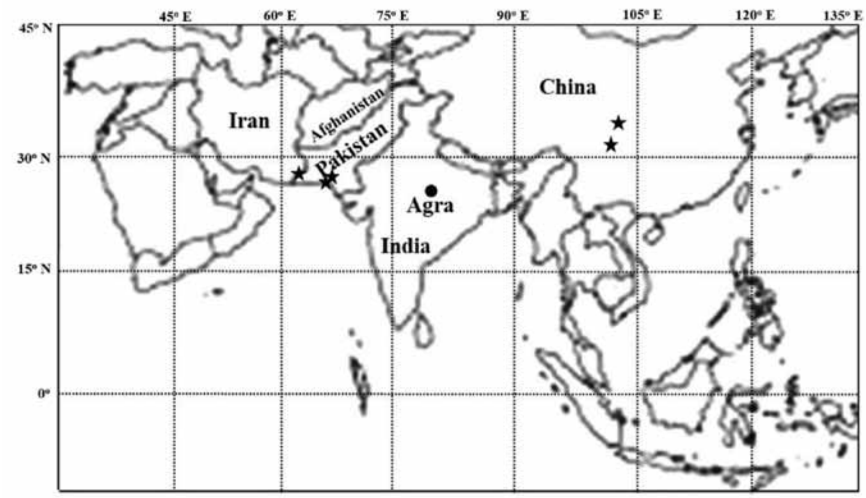

Figure 1. The map of India and its surrounding countries indicating the epicenters of earthquakes (by star). The solid circle shows the location of TEC observing station Agra in India.

Table 1. Details of Major Earthquakes during the period of April to September 2013 in neighbouring countries around India.

Sl. No.	Date of Earthquake	Time (UT)	Lat. (deg.)	Long. (deg.)	Depth (km)	Magnitude	Region	Radius of Influence Zone (km)
1	16/04/2013	10:44:11	28.0°N	62.1°E	46	7.8	Pakistan-Iran Border	2259.4
2	20/04/2013	00:02:48	30.2°N	103.0°E	29	6.6	Sichuan, China	688.7
3	21/07/2013	23:45:56	34.5°N	104.2°E	10	6.2	Gansu, China	463.4
4	24/09/2013	11:29:48	27.0°N	65.7°E	10	7.4	Pakistan	1520.5
5	28/09/2013	07:34:10	27.2°N	65.9°E	20	6.8	Pakistan	839.5

April and September 2013, and examine the effect of these earthquakes on TEC data observed at Agra station. Initially, we ascertain their character as precursors by applying mean and standard deviation criterion and then calculate the correlation coefficients between magnitude of earthquakes, precursory days, and average TEC enhancements to confirm ionospheric precursors of earthquakes. Finally, we test our results by applying null hypothesis.

Experimental setup and method of analysis

The experimental setup used for TEC measurements at Agra station is similar to that used by our group earlier (Singh et al., 2009). The GPS receiver and antenna are placed in the seismo-electromagnetic and space research laboratory in the Faculty of Engineering building at Bichpuri Campus of our college and round the clock observations are taken. Bichpuri is located in rural area about 12 km west of Agra city where local electrical and electromagnetic disturbances are extremely low. We have used the well-developed statistical σ criterion to analyze the TEC data for the months of April, July and September 2013 (in which the major earthquakes occurred) to find the anomalous variation in data and also calculate the corresponding mean and standard deviation for each month separately. Further, we have calculated the sum $(m + \sigma)$ and difference $(m - \sigma)$ of mean and standard deviation, respectively. Then, we have found the correlation coefficients between magnitude of earthquakes and precursory days, and between magnitude of earthquakes and average enhancement of TEC data, respectively. Finally, we have tested the null hypothesis using 't' test for the pairs, which have shown the maximum positive and maximum negative correlation coefficients.

RESULTS AND DISCUSSION

Figure 1 shows the map of Indian subcontinent in which the stars indicate the location of earthquakes and solid circle indicates the location of observing station Agra (27.2° N, 78° E). The details of these earthquakes are mentioned in Table 1. Details include the days of occurrence, magnitudes, depths (km), locations (Latitude and Longitude in degrees), radius of influence zone (km) and distances from the Agra station (km). The details of the earthquake data have been taken from United States Geological Survey (USGS) website www.earthquake.usgs.gov.in. The radius of influence zone is calculated by using the expression $R = 10^{0.43M}$, where M is the magnitude of the earthquake (Dobrovolsky et al., 1979). Although these earthquakes have occurred far away from the observing station Agra, at least two of them cover the observing station very well through large radii of influence zone (> 1000 km). However, the effect of smaller earthquakes (7 > M > 6) on the ionosphere considered here cannot be ruled out because there are several satellite based observations showing large ionospheric perturbation zones ranging between ± 5° to ± 30° longitudes around the epicenters of the earthquakes (Galperin et al., 1992; Molchanov et al., 1993; Sorokin and Chmyrev, 1999). In the light of these results the consideration of all the earthquakes including those of M = 6.2, 6.6, and 6.8 in this paper is highly justified. To support our selection of earthquakes, it may be mentioned that many researchers have investigated the earthquakes of even moderate and low magnitudes that are far away from the observing stations (> 1000 km). For example, Dabas et al., (2007) have presented the variations of foF_2 and TEC data observed at Delhi station in relation to earthquakes, which occurred in the North-East countries around India. In a similar way, Singh et al., (2012) have also investigated foF_2 variations using the multi-instruments at Varanasi and Delhi stations to see the effect of earthquakes varying in magnitude between 5 and 7.5 on Richter scale. Most of the earthquakes have occurred in China, Myanmar, Indonesia and Japan. Zhao et al., (2008) and Liu et al., (2010) have also found that the ionospheric anomalies may extend to adjacent region around the epicenter. By adjacent region, they possibly mean the large perturbation zones, as stated above. We have also seen the variations of geomagnetic parameters such as Dst index and ∑Kp for each case separately for which data have been taken from the website http://omniweb.gsfc.nasa.gov/form/dx1.html. We can see from Table 1 that all the earthquakes have shallow focal depths except one of them. The earthquake with 46 km focal depth has not been ignored as this earthquake is of relatively large magnitude (M = 7.8). Two of the earthquakes occurred in the month of April, one in July, and rest of the two in September, 2013.

The top two panels of Figure 2 show the day to day variation of GPS-TEC for the month of April 2013, as observed at Agra station. Here, the vertical-TEC is shown in blue colour and the corresponding sum (m + σ) and difference (m – σ) are shown in red and green colours respectively. The days of occurrence of the two earthquakes are shown by solid black stars. The variation of Dst and ∑Kp Indices are shown in bottom two panels respectively, for the period under consideration. The major enhancements in the data can be seen clearly on 9, 16 and 29 April. Since Agra station lies between the epicenters of the two earthquakes under consideration the influence of both the earthquakes on TEC enhancements on 9 and 16 April cannot be ruled out, although the effect of larger earthquake of magnitude M = 7.8 is expected to be more than that of the smaller magnitude earthquake because of varying influence zone. Here, we consider two separate cases for each of the two earthquakes causing the enhancements in TEC over Agra station and hence, as shown in table 2, the precursory periods for the earthquake of magnitude M = 7.8 will be 0 and 7 days, whereas those for the earthquake of magnitude M = 6.6 will be 4 and 11 days. It may be seen from bottom two panels of Figure 2 that these periods are magnetically quiet and hence the ionospheric perturbations may be caused solely due to earthquakes. The enhancement on 29 April may be due to isolated geomagnetic storm on 24 April (∑Kp > 30). The minor depletions and enhancements have also been seen throughout the month but they are insignificant.

Figure 3 (top two panels) shows the variations of GPS-TEC for the month of July 2013 and the bottom two panels show the variation of Dst and ∑Kp data. The other descriptions are same as mentioned in preceding Figure. From table 1 and Figure 3 it may be seen that an earthquake of magnitude M = 6.2 occurred on 21 July 2013 in China and the enhancements in the TEC data crossing the upper bound (m + σ) occurred on 6, 7, 13 and 19 July. Further, it may be seen from the bottom panels that sporadic magnetic storms (∑Kp ≥ 40) occurred on 6, 10 and 14 July also. Now, we need to explain these enhancements in the light of magnetic storms and earthquakes. The possibility of enhancements on 6 and 7 July may be due to relatively large geomagnetic storm on 6 July (Dst ≈ -60nT and ∑Kp ≥ 40). This needs to be explained as follows; Usually, over the equatorial and low latitudes, the main phase (MP) of the magnetic storm is characterized by negative storm (depletion in TEC) and recovery phase (RP) is characterized by the positive storm i.e. large enhancement in TEC. The TEC enhancements observed on 6 and 7 July correspond to recovery phase of the magnetic storm on 6 July as found from the examination of hourly Dst data, where recovery phase starts in the evening of 6 July itself. The enhancements of 13 July may also be influenced by the magnetic storm of 10 July (Dst ≈ -40nT and ∑Kp ≥ 40) as effect of magnetic storms may take few days to one week to reach the low latitude ionosphere (Jain et al., 1977; Lakshmi et al., 1997). So, we neglect these enhancements from our analysis. The enhancement of 19 July may possibly be due to combined effect of magnetic storm of 14 July (Dst ≈ -40nT and ∑Kp ≥ 37) and precursory effect of the earthquake on 21 July, as it is difficult to attribute the cause of this anomaly to a single source. However, the possibility of this anomaly due to earthquake is larger because of its large magnitude and shallow depth. The effect of magnetic storm may not be as large as that of the earthquake because it is not so severe and also occurred 5 days before the ionospheric anomaly. In contrast to this, the other magnetic storms of 6 July and 10 July considered in this paper are relatively stronger and they occurred less than 3 days before the anomalies. Although, the earthquake is also of relatively smaller

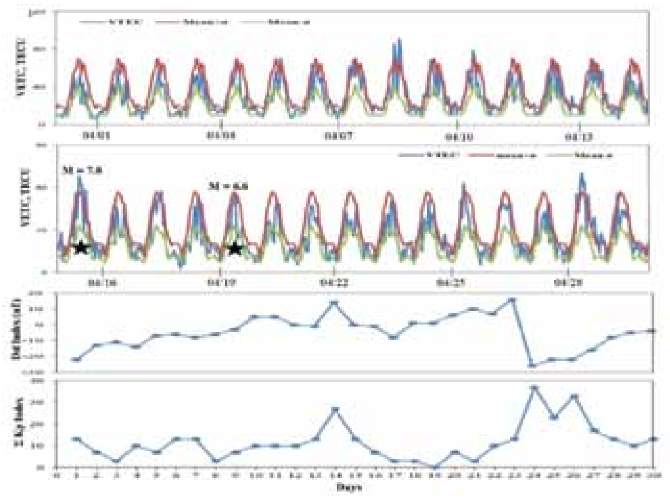

Figure 2. Two top panels show the variation of GPS-TEC for the period of April 2013, in blue colour. The corresponding deviations m + σ, and m – σ are shown in red, and green colours, respectively. The black stars show the days of earthquakes. The variation of Dst and Σ Kp Indices are shown in the lower two panels.

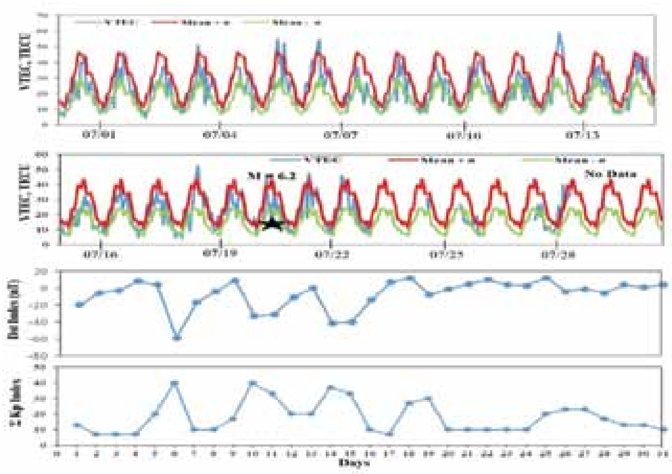

Figure 3. Similar as Figure 2 but for the month of July 2013 in which an earthquake of magnitude M = 6.2 occurred.

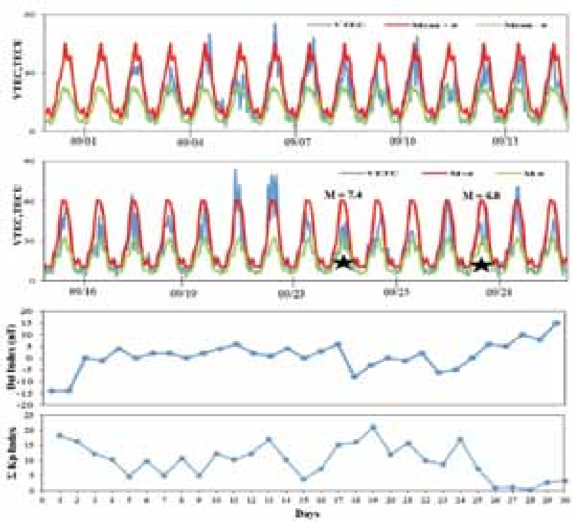

Figure 4. Similar to Figure 2 but for the month of September 2013 in which earthquakes of magnitudes M = 7.4 and 6.8 occurred.

magnitude, as it is greater than 6 its effect may extend to large ionospheric perturbations zones as stated earlier. The minor enhancements and depletions have also occurred on other days in this month but they are insignificant as compared to these enhancements.

The top two panels of Figure 4 show the variation of GPS-TEC at observing station Agra. They correspond to the earthquakes that occurred in the month of September 2013. The bottom two panels show the variations of Dst and ∑Kp index as usual to examine the effect of geomagnetic storm. From Table 1 and Figure 4 it may be seen that a large earthquake of magnitude M = 7.4 occurred on 24 September, followed by another large magnitude earthquake (M = 6.8) on 28 September. From Figure 4 it may be seen that unusually large TEC enhancements crossing (m + σ) limit occurred on 7, 21 and 22 September. We also see some minor enhancements and depletions in the data in this month but they are insignificant. This month was magnetically quiet as ∑Kp remained less than 20 throughout. This case is simpler to interpret in terms of the precursory effect of earthquakes on 24 and 28 September because no magnetic storm occurred in this month. The effects of these earthquakes are pronounced as compared to those occurred in April because these are shallower (depth < 20 km) earthquakes. As shown in table 2 the precursory periods of the larger earthquake (M = 7.4) are 17, 3, and 2 days. The earthquake of magnitude M = 6.8 seems to be an aftershock of the earlier one because of its close location and short period of occurrence from the main shock of M = 7.4. Hence, its effect on the ionosphere over Agra may possibly be a combined effect of both the earthquakes (as considered for the April earthquake). In the light of this, precursory period of 4 days is added to the earlier one for this earthquake.

The three panels of Figure 5 show the days of occurrence and magnitude of earthquakes (by histograms) and days of precursors in TEC enhancements (by arrows) so that we may have clear information about the magnitude of earthquakes and corresponding precursory days for the three months of data under study. These data are presented column-wise in table 2 also. Now, we make pairs between columns of earthquakes and columns containing different enhancements in TEC data and different precursory days as shown in table 2 and calculate correlation coefficients. Here, it may be noted that for those columns in which there is no data, we have taken the data of previous columns one after the other to calculate the correlation coefficients. This has been done simply to fill up the gaps with the observed data corresponding to the same earthquake for the purpose of mathematical convenience. Then from the results of calculated correlation coefficients (C.C.) we select two columns, one for enhancements giving largest positive correlation coefficient and the other for precursory days giving most negative correlation coefficient. The selection of these two columns is based on the assumption that the enhancements in TEC increase and precursory days decrease with the increasing magnitude of the earthquakes. The results of this exercise are shown in table 3 in which the columns of average TEC enhancements giving a correlation coefficient of 0.98 and the same of precursory days giving a correlation coefficient of -0.52 are shown.

The results are also shown graphically in Figure 6 where solid triangles show the increasing TEC enhancements and solid squares show the decreasing relation between precursory days with increasing magnitude of earthquakes. In other words, the enhancements in TEC increase with the increase in the magnitude of the earthquake, whereas the precursory days decrease with increase of the magnitude of the earthquake. Finally, we find the probability (p) for these pairs to test the null hypothesis using 't' test. The results of probability are also shown on the bottom of table 3. The value of probability for the average TEC enhancements is less than 0.05 or 5%. It shows that our results are significant and null hypothesis is satisfied. On the other hand, the probability of 0.37 for precursory days is large but it may be considered as significant especially for geophysical measurements like this.

We have also calculated the correlation coefficient between one case of magnetic storm of Figure 2 and three cases of Figure 3 (total four cases) and corresponding average TEC enhancements and found a positive correlation of 0.86. This result supports our argument that the enhancements in TEC on the days after the earthquakes in April and prior to the earthquake in July are caused by magnetic storms. Such an exercise cannot be done for effective days of the storm because of uncertainty of penetration characteristics of the electric field in the low latitude ionosphere (Jain et al., 1977; Lakshmi et al., 1983).

Now, the question arises how these earthquake-induced anomalous enhancements have occurred in the TEC data at low latitudes. Several mechanisms have been suggested by the researchers but none of them has received proper approval from the global scientific community. However, there is a growing consensus that it is due to E × B drift mechanism, where the electric field (E) triggered by an earthquake preparatory process penetrates the ionosphere and, in the presence of local magnetic field (B), causes upward or downward movement of the ionization depending upon the direction of the electric field (Depueva and Ruzhin, 1993). Then, the question remains about the mechanism of the electric field generation from the earthquake region. Pulinets (2004) has suggested that radon emissions come out from earthquake epicentral region, and ionize the near earth atmosphere over the seismic zones that lead to formation of quasi-neutral ion clusters, which are destroyed by the air motion caused by acoustic gravity waves generated by accumulation of greenhouse gases over the seismic region. The breaking of ion clusters

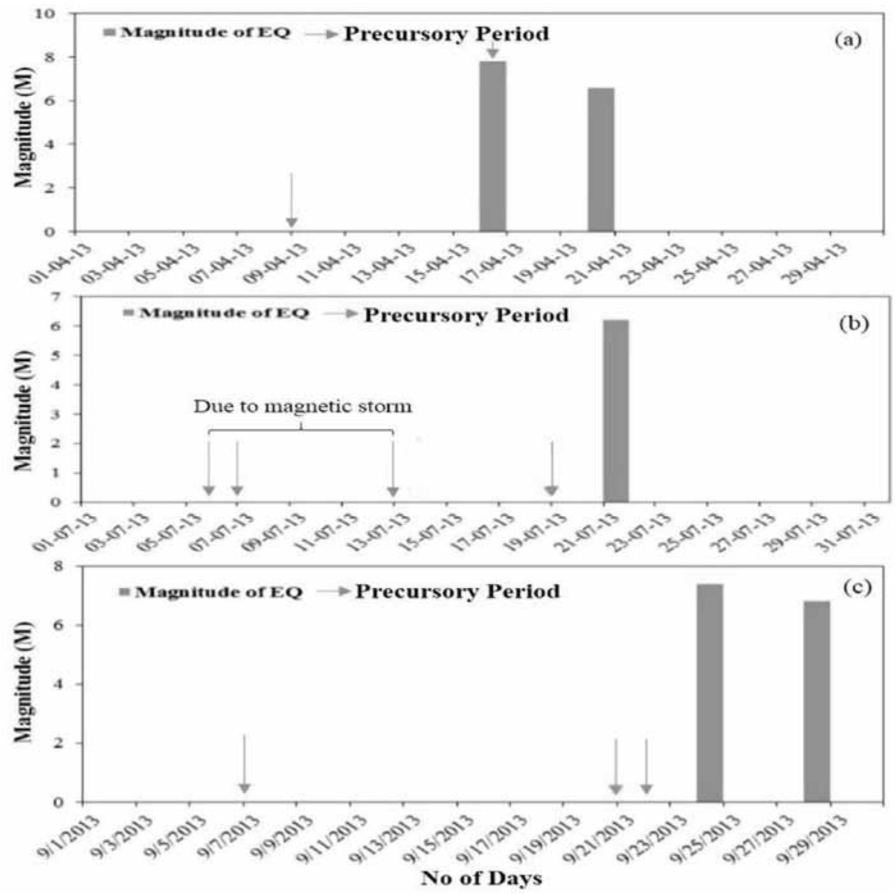

Figure 5. The three panels show the histograms of magnitude of earthquakes and corresponding days of anomalies (shown by downward arrows) for the three months of April, July, and September, 2013.

Table 2. Details of average TEC enhancements and precursory days corresponding to earthquakes occurred.

Sl. No.	Magnitude	Average TEC Enhancements (TECU)			Precursory days		
1	7.8	10.5	4.8	---	0	7	---
2	6.6	10.5	4.8	---	4	11	---
3	6.2	3	---	---	2	---	---
4	7.4	7.18	9.31	11.9	17	3	2
5	6.8	7.18	9.31	11.9	21	7	6

Table 3. Results of correlation coefficients and probability showing most significant data on TEC enhancements and precursory days.

Sl. No.	Earthquake magnitude	Average TEC enhancements (TECU) giving most positive C. C.	Precursory days giving most negative C. C.
1	7.8	10.5	0
2	6.6	4.8	4
3	6.2	3	2
4	7.4	9.31	2
5	6.8	7.18	6
C.C.		0.98	-0.52
Probability (p)		0.003	0.37

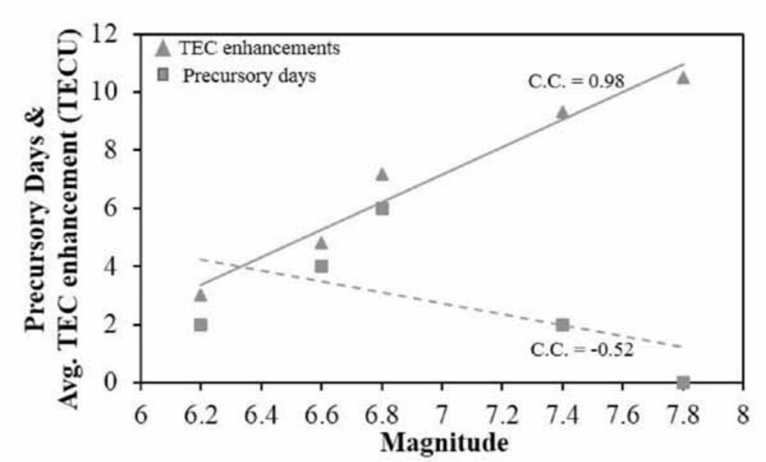

Figure 6. Variation of anomalous TEC enhancements (shown by solid triangles) and precursory days (shown by solid stars), with increasing magnitude of earthquakes. The continuous and dashed lines correspond to the positive and negative values of the correlation coefficients.

makes the near ground layer of the atmosphere rich in ion (concentration $\approx 10^5 - 10^6$ cm^{-3}). The charge separation process leads to generation of anomalously strong vertical electric field ($\approx$1KVm^{-1}) in comparison with the fair weather electric field ($\approx$ 100 Vm^{-1}). Pulinets (2009) provides the explanation of the existence of a vertical atmospheric electric field and coupling between the ground and ionosphere using the concept of Global Electric Circuit (GEC). In brief, Global Electric Circuit (GEC) is the system of quasi-stationary electric current between ground and ionosphere driven by global thunderstorm activity and works in transmitting the information from ground surface up to the ionosphere through the changing of its electric properties due to natural ionization and ion induced nucleation changing the conductivity of atmosphere.

In addition to the electric field generation mechanism mentioned as above, more convincing mechanism has been proposed by some researchers recently. For example Oyama et al., (2011), while interpreting the anomalous trough (precursor ionization anomaly, PIA) in the variations of atomic oxygen ion (O^+) and molecular ion observed by DE-2 satellite over the epicenter of a large magnitude earthquake (M = 7.5) suggested that the PIA trough was caused by lifting the plasma upward by eastward electric field, which was possibly generated as a result of disturbing the dynamo wind by internal gravity waves in the E-region of the ionosphere. This trough was in addition to the usual trough at the magnetic equator due to equatorial ionization anomaly (EIA). Sun et al., (2011) also supported a similar mechanism and, in order to support it, they studied the relationship between the height profile of neutral temperature (Tn) and critical frequency of F-layer (foF_2) for two large earthquakes, the Wenchuan (M = 7.9) and Pungtung Doublet (M = 6.9) occurred on 12 May, 2008 and 26 December, 2006 ,respectively. They found a clear relation between the foF_2 and the intensity of the amplitude with a vertical wavelength of 22-30 km in Tn height profiles suggesting that the electric field is generated in the E-region of the ionosphere under the influence of internal gravity waves.

Since there were no other factors like nuclear explosions, volcanic activities, and dust storms during this period of observations in the region of the earthquakes, the anomalous variations in TEC cannot be attributed to these factors. The only reason for anomalies has been caused by the occurrence of earthquakes. This fact is supported by statistical analysis also.

In our results presented above, we have found the enhancements in TEC as the precursors of major earthquakes in Indian subcontinent but these results are in contrast with the results of other researchers ,who have found the depletions also (Liu et al., 2004a, b, and 2009). This contrast in results may be due to latitude dependence and the enhancements in TEC data caused by the upward electric field that penetrated the ionosphere eastward, according to the mechanism mentioned above.

CONCLUSIONS

In this paper, we have analyzed six months of GPS-TEC data observed at Agra station between April-September, 2013 in order to examine the effect of the earthquakes on the diurnal variation of TEC data. We have found that during months of April, July, and September five major earthquakes (M > 6) have occurred around India.Hence, detailed analysis of TEC data corresponding to these months have been undertaken. We have found significant enhancements in TEC 1-21 days prior to the earthquakes. The enhancements are examined in the light of magnetic storm data (Dst and $\sum$Kp) also and those affected by such storms are ignored. Then we have calculated correlation coefficients between magnitude of the earthquake and enhancements in TEC and also between magnitude of the earthquakes and precursory period. Finally, we have tested the null hypothesis. The overall results of the exercise show that there clearly exists a positive correlation between magnitude of the earthquakes and enhancements in TEC.

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Compliance with Ethical Standards

The authors declare that they have no conflict of interest and adhere to copyright norms.

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