Anomalies observed in TEC and foF₂ data related to large magnitude earthquakes occurred in the year 2007

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Abstract. In this paper, we have studied the effect of earthquakes on Total Electron Content (TEC) data of the year 2007 at Agra (Geographic Lat. 27.2°N, Long. 78°E), India. The measurements of TEC are made by using a dual frequency GPS receiver system. We found 39 cases of earthquakes ($M \geq 5.0$) in the range of 2000 km from the observing station at Agra. It is observed that the TEC shows anomalous behavior in the form of enhancement and depletion 0-9 days prior to the occurrence of these earthquakes. We also study the simultaneous variation of foF₂ and TEC for the months of May and June, 2007. The foF₂ data exhibit enhanced anomaly on the same day of a large magnitude earthquake ($M=6.0$) in May, 2007 while for the same case of earthquake TEC shows anomaly before 02 days in the form of enhancement. The atmospheric oscillations and electric field generation during the earthquake preparation process may be the significant contributors of these anomalies in TEC and foF₂ data.

Key words: GPS, TEC, Earthquakes, Statistical analysis

1. Introduction

It is known for long that earthquakes could be a major cause of the ionospheric perturbations. For the first time, ionospheric anomaly before the earthquake was reported in 1964 when the great Alaskan earthquake was occurred on 28 March, 1964 (Davies and Baker, 1965). Since then ionospheric anomalies associated with earthquakes have been studied widely (Hayakawa et al., 1996; Liu et al., 2000; Singh et al., 2004). Particularly, during the event of earthquakes an extensive research has been carried out on two main ionospheric parameters, i.e., critical frequency of the ionospheric F2 region (foF₂), and total electron content (TEC). Ionosonde and satellite radio beacons were used mostly for their study (Dabas et al., 1980; see reviews by Davies 1980; Singh et al., 2004; Devi et al., 2004). However, in the last decade, TEC measurements have been carried out widely using Global Positioning System (GPS) (Calais and Minster, 1995; Liu et al., 2001, 2004). The TEC derived from GPS is defined as the sum (or integration) of ionospheric electron density along line-of-sight from a ground based receiver to the associated GPS satellite at an orbital altitude of about 20,200 km. Many workers have presented very interesting results of foF₂ and TEC during large magnitude ($M \geq 5.0$) earthquakes. For example Liu et al. (2000) examined the ionospheric plasma frequency (or electron density) recorded by a local ionosonde and found that the foF₂ significantly decreased 1-6 days prior to most of the 14 $M \geq 6.0$ earthquakes in the Taiwan area during 1994-1999. Liu et al., (2004) have examined variation of foF₂ recorded by an ionosonde, and the TEC derived from a network of 5-ground based GPS receivers in respect of 144 earthquakes ($M \geq 5.0$) in Taiwan during 1997-1999. They have found that the foF₂ and TEC yielded similar tendencies 4 days before the earthquakes. Hobara and Parrot (2005) observed foF₂ anomalies a couple of days before and after the main shock of the powerful Hachinohe earthquake ($M=8.3$) near Japan.

They found meaningful decrease in foF₂ at several stations located near the epicenter of the earthquake.

Das Gupta et al. (2006) reported a significant perturbation of strong 2004 Sumatra-Andaman earthquake (Mw=9.15) corresponding to Tsunami of 26 December, 2004. In this paper, we present the results of analysis of TEC data for a period of 12 months from 01 January- 31 December, 2007 and also study the simultaneous variation of foF₂ and TEC data for the months of May and June, 2007.

2. Experimental Setup

The experimental setup for TEC measurements at Agra is similar to that used by Chauhan et al. (2009). Briefly, a dual frequency GPS receiver has been employed for TEC measurements at Agra station and it is in operation since 24 June, 2006. The equipments used for TEC measurements are imported from USA which include L1/L2 GPS antenna (Novatel's Model GPS-702), a GPS receiver (Novatel's Euro Pak-3m), and relevant softwares. The TEC data have been recorded by GPS receiver at a sampling rate of 1-min.

3. Data and method of analysis

The output data from GPS receiver provide slant TEC values which are converted into vertical TEC (VTEC) using a mapping function at different IPP (Ionospheric Pierce Point) locations. The mapping function used for this purpose is defined as (Mannucci et al., 1993; Langley et al., 2002)

$$S(E) = \frac{1}{\cos(z)} = \left\{ 1 - \left(\frac{R_E \times \cos(E)}{R_E + h_s} \right)^2 \right\}^{-0.5}$$

where R_E is the mean radius of the earth in km, h_s is the ionosphere (effective) height above the earth's surface, z is the zenith angle and E is the elevation angle in degrees. The effective ionospheric height of 350 km is used for determination of IPP locations which is found to be valid for elevation angles $> 50^\circ$ in a low latitude sector (Rama Rao et al., 2006a). The IPPs obtained by the GPS receiver at Agra cover the ionospheric region about $+12^\circ$ geographic latitudes and $+2^\circ$ geographic longitudes from the geographic coordinates of the observing station Agra. The values of TEC are taken at higher elevation angles ($> 50^\circ$) to remove the effects of multipath, troposcatter and water vapor (Rama Rao et al., 2006b). Anomalous variations in TEC are identified by calculating differential TEC (dTEC) and its fix mean and standard deviation around mean ($m \pm 2\sigma$). The dTEC is obtained by subtracting 15 days backward running mean of VTEC from the values of observed VTEC at each epoch (hourly). A value of dTEC crossing $m+2\sigma$ or $m-2\sigma$ lines is said to be abnormal. The 2σ approach is adopted here to achieve a high degree of confidence. This consideration has been adopted by other workers also (Biagi and Hayakawa, 2002; Kushwah et al., 2007; Singh et al., 2009). To see the anomalies in foF₂ data, percent deviation from its monthly mean has been calculated.

The ionospheric data of foF₂ have been received from VSSC, Thiruvananthapuram. A digital ionosonde has been in operation at this station for a long time and distribution mechanism of data has been exemplary. However, for our study of year, 2007 we have obtained the foF₂ data corresponding to two months of May and June only.

To see the effect of seismic activity on TEC the earthquake data are taken from the website of USGS (<http://neic.usgs.gov>). In order to separate the influence of earthquakes on TEC from that of the effect of magnetic storms, we examine the changes in TEC in the

light of magnetic storms. For this purpose, we consider the Kp index data, which have been obtained from World Data Centre, Kyoto, Japan through website: (<http://swdcd.db.kugi.kyoto-u.ac.jp>).

4. Results and discussion

Here we analyze the data for a period of 12 months from 01 January, 2007 to 31 December, 2007. We also carried out a simultaneous study of TEC and foF₂ data for two months of May and June, 2007. The results are as follows;

4.1 TEC observations

A thorough analysis of the data shows anomalous variations in TEC in the form of depletions and enhancements. We examined the abnormal variations in the light of magnetic storms and earthquakes. We consider here both the depletions and enhancements and find that most of them have occurred during quiet magnetic conditions ($\Sigma K_p < 30$). There are few cases of the data influenced by both the magnetic storms and earthquakes. However, we consider only those data which are influenced by earthquakes clearly. We study TEC anomalies in the light of earthquakes ($M \geq 5.0$, depth ≤ 100 km) that occurred within 2000 km from the observing station during the period of observation. However, the depths of all the earthquakes are below 60 km except one case in which it is 93 km. The locations of all the earthquakes are shown in Fig.1 with solid circles. The observing station Agra is also indicated by a star in the figure. Two sample cases of isolated earthquakes which have been considered in this paper are shown by triangles.

Fig.1: Map of India and surrounding countries showing the locations of epicenters through solid circles and triangles. Location of observing station Agra is shown by a star.

These earthquakes occurred mostly in and around India in seismically active zones. From an analysis of data we find that anomalies occurred throughout the period under consideration and hence for the sake of brevity in the paper, we considered some sample cases only, i.e., an isolated case of large magnitude earthquake ($M=6.0$) occurred on 08 January, 2007 and an another isolated case of earthquake of magnitude $M=5.1$ occurred on 25 November, 2007. The locations of the epicenters of these earthquakes are shown in the

map of Fig.1 with a large and small triangle respectively. These earthquakes are chosen only due to the fact that they are isolated cases. The area of earthquake preparation zone and relative position of the observing station is not considered here. However, the GPS satellites which locked with the receiver cover a wide area in the ionosphere as mentioned in section 3. In Fig.2 we show the variation of TEC between 27 December, 2006 and 20 January, 2007, ± 12 days before and after the occurrence of earthquake on 08 January, 2007. Other than this event, not any large magnitude ($M \geq 6.0$) earthquake occurred during this period of 25 days. However, an earthquake of low magnitude ($M = 5.0$) occurred on 15 January. Therefore the event of 08 January, 2007 is an isolated case of large magnitude earthquake. In Fig.2 the upper panel shows the variation of raw data (VTEC) and middle panel shows the dTEC variations. The ΣK_p data are shown in the lower panel of the figure. In the figure, some minor depletions and enhancement in TEC data before the event of earthquake can be seen between 02 and 04 January while a major enhancement appeared on 10 January, two days after the occurrence of earthquake and a minor enhancement on 19 January. The major enhancement may be the result of combined effect of the earthquake on 08 January and precursory effect of earthquake on 15 January. It is well known that the major earthquakes ($M > 5.0$) may have either precursors or post shock anomalies or both due to the microfracturing phenomena. In the present case the large peak in VTEC after the main shock may possibly be due to aftereffect of earthquake occurred on 08 January and precursory effect of the earthquake occurred on 15 January. In a similar way, the minor enhancement on 19 January may possibly be the aftereffect of the earthquake occurred on 15 January. These anomalous variations cross $m \pm 2\sigma$ lines considerably. However, on the same day and one day after the event of earthquake the nighttime values of TEC do not cross the $m \pm 2\sigma$ lines but their values are high enough in comparison to other days. These anomalies can not be attributed to magnetic storms because, as seen from the lower panel of the figure, no severe magnetic storm ($\Sigma K_p > 30$) occurred during the period of observation. Hence, these unusual variations of TEC may be correlated with the earthquakes.

The TEC data corresponding to the earthquake occurred on 25 November, 2007 is presented in Fig.3. Similar to the previous case, here we plotted the TEC data between 13 November and 07 December, 2007. This is the single event of earthquake in the duration of 25 days. Two minor depletions in VTEC data can be seen on 18 and 19 November while a pronounced peak can be seen on 21 November, 2007, seven to four days prior to the occurrence of earthquake. The dTEC plot presented in the middle panel also represents the same features and confirms the effect of the earthquakes on the data. The ΣK_p variation is low in this case also and hence this anomalous feature in TEC data is very well correlating to the earthquake of 25 November, 2007. In a similar manner we have analysed the dTEC data for all the twelve months from 01 January to 31 December, 2007 and calculated the number of enhancements, depletions and precursory period corresponding to earthquakes occurring in each month. From the analysis of the earthquake data we find that a total of 39 earthquakes of moderate and high magnitudes ($5.0 \leq M \leq 6.0$) occurred during the period of observation. The locations of these earthquakes are already shown in Fig.1. We find that there are dTEC anomalies similar to those occurred in the cases of 08 January and 25 November, 2007 (Fig.2 and Fig.3) in almost all the cases of earthquakes. Out of 39 cases of earthquakes, both enhancements and depletions are observed in 20 cases, while in 15 cases either enhancements or depletions occurred. There was no data available for three cases and one case does not show any anomaly in the data. In all these cases of earthquakes the precursory period ranges between 0 and 9 days.

Fig.2: Variation of raw data (VTEC) for a period of 15 days from 27 December, 2006 to 20 January, 2007 (Top), variation of dTEC for the same period with horizontal lines representing $m\pm 2\sigma$ (middle) and variation of ΣKp for the same duration (bottom). Downward vertical arrows in the upper and middle panel show the day of occurrence of the earthquake on 08 January, 2007.

Fig.3: Same as Fig.2 but the variation for the earthquake occurred on 25 November, 2007.

4.2 Simultaneous study of TEC and foF₂ data

As mentioned above, we have obtained two months data of foF₂ corresponding to May and June, 2007. However, no significant variations are found in foF₂ data in the month of June, therefore we are presenting here the data of TEC and foF₂ for the month of May, 2007 only. The raw VTEC and foF₂ data for the month of May, 2007 are shown in Fig.4 and Fig.5 respectively. In these figures one month VTEC and foF₂ data have been divided in three panels and the days of earthquake events are shown by vertical downward arrows. In this month a large magnitude earthquakes (M=6.0) occurred on 05 May and three other earthquakes (M=5.0, 5.6 and 5.0) occurred on 06, 07 and 20 May respectively. As seen from the VTEC data (Fig.4), there are unusual enhancements between 01 and 04 May which may be correlated with the occurrence of these earthquakes. Unfortunately, the data are scarce before the earthquake of 20 May, 2007 due to power failure. The foF₂ data presented in Fig.5 also show enhanced values on 05 May at 2300 hrs LT (LT=UT+5.5 hrs) on the same day of the large magnitude earthquake (M=6.0) which occurred on 05 May. The enhanced value of foF₂ is shown by a dotted circle in the figure. The simultaneous variations of TEC and foF₂ alongwith the ΣK_p data for the same month are shown in Fig.6.

Fig.4: Variation of raw data (VTEC) for a period of one month of May, 2007. The downward vertical arrows representing the events of earthquakes occurred on 05, 06, 07 and 20 May, 2007 respectively.

Fig.5: Variation of raw data (foF₂) for a period of one month of May, 2007. The downward vertical arrows representing the events of earthquakes occurred on 05, 06, 07 and 20 May, 2007 respectively.

In this figure the percentage deviation of VTEC from its monthly mean values is shown in the upper panel and the middle panel represents the percentage change in foF₂ data. In both panels the straight lines represent $m \pm 2\sigma$ around the mean values of percentage deviation. The dTEC approach which was considered in the previous section has not been adopted here due to the non-availability of long term foF₂ data. We do not have the foF₂ data before May, 2007 therefore percentage change from mean values is calculated and standard deviation around the mean of percentage deviation is obtained. The variation of ΣK_p data is shown in lower panel of the figure. It can be seen from the figure that the VTEC enhanced upto 80% on 03 May, two days before the occurrence of earthquake on 05 May while similar enhancement in foF₂ data is found on same day of the event. This enhancement in foF₂ data is found during nighttime hours. These anomalous variations cross $m \pm 2\sigma$ lines considerably. Since ΣK_p variation is low during these earthquakes, these abnormal enhancements may correspond to the seismic events of 05, 06 and 07 May. No significant variation is observed in foF₂ data prior to the event of 20 May while there is lack of data in VTEC before this event.

Our results presented above are consistent with the observations made by other workers also. For example, Zakhrenkova et al. (2007) observed enhancements in GPS TEC data 05 days before the Hokkaido earthquake (M=8.3) occurred on 25 September, 2003.

Jusoh et al. (2007) have shown that two types of precursors (enhancement and depletion) occurred 05 days before the North Sumatra earthquake (associated with Tsunami) of 26 December, 2004 with magnitude of 9.3.

Fig.6: Percentage change in VTEC for a period of one month of May, 2007 with horizontal lines representing $m \pm 2\sigma$ (Top), variation of percentage change in foF₂ for the same duration with horizontal lines representing $m \pm 2\sigma$ (middle) and ΣK_p for the same duration (bottom). Downward vertical arrows in the upper and middle panels show the day of occurrence of the earthquake on 05, 06, 07 and 20 May, 2007 respectively.

The mechanism of coupling between the lithosphere activity and ionosphere has been proposed elaborately by Hayakawa et al. (2004a, b). They proposed three coupling channels, i.e. (1) chemical channel, (2) acoustic channel, (3) electromagnetic channel. Out of which the electromagnetic channel is found to be insufficient because of weak intensity of lithospheric radio emissions (Molchanov et al., 1993). The explanation of physical model of chemical channel is given in Pulinets and Boyarchuk (2004), Pulinets and Liu (2004) and Sorokin et al. (2007). Pulinets (2004) 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 data (Hayakawa,

2009; Molchanov, 2009). 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. (Molchanov et al., 2001; Miyaki et al., 2002; Shvets et al., 2004; Hayakawa, 2009).

5. Conclusions

The data resulting from TEC measurements using a dual frequency GPS receiver at Agra station in India are analysed for a period of twelve months between 01 January and 31 December, 2007. Since solar and geomagnetic activities are low during the duration of earthquakes these anomalies may be due to the large magnitude seismic events.

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