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A morphological study of low latitude ionosphere and its implication in identifying earthquake precursors

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ABSTRACT

The low latitude ionosphere is highly variable because of the existence of equatorial ionization anomaly (EIA) and irregularities like spread-F and sporadic E. The GPS-TEC data have been analyzed from 01 January to 31 December 2007 (Period-I) and then from 01 January to 31 December, 2011 (Period-II) during low and high solar activity periods respectively. The results are validated with the recent ionospheric model IRI-2012 and we found a very good agreement in trend. However, IRI model indicated larger values of diurnal variations for both the periods. We have found a strong correlation ($\approx$ 0.98) between IRI and TEC data during each of the three seasons (winter, summer, and equinox) for both periods except for winter season ($\approx$ 0.85) of period-I. The TEC values are larger during equinox and smaller during winter season which may be attributed to solar activity. The peak GPS-TEC values are found in the range of 15-25 TECU and 25-30 TECU during the first and second periods respectively. To examine the effect of magnetic storms on TEC data, monthly correlation coefficients have been calculated between $\sum$Kp and TEC for period-II but it was very poor. A few specific cases of magnetic storms have shown their delayed effect on the TEC data at low latitude Agra station, 1-4 days after the occurrence of event. Therefore, TEC anomalies attributed to earthquakes have to be examined in the light of anomalies caused by the above factors.

Key words: GPS-TEC, morphological study, low latitude, IRI-2012 model, Earthquakes.

INTRODUCTION

The low latitude ionosphere is also influenced by the geophysical phenomena like solar flares, magnetic storms and various anthropogenic sources like nuclear explosions, volcanic activities, dust storms, and seismic activities (Pulinets and Davidenko, 2014) in addition to the EIA spread-F and sporadic E. These factors bring out substantial variation in the structure and dynamics of the low latitude ionosphere. In view of the occasional existence of the ionization anomalies produced by these factors, it is sometimes difficult to identify the anomalies produced by the seismic events. Hence, a morphological study of the low latitude ionosphere is essential so that anomalies produced by earthquakes may be clearly identified and separated from those produced by other sources.

Globally, a number of researchers have studied the morphological features of the ionosphere using GPS based TEC measurements and found very interesting and valuable results (Warnant, 2000; Wu et al., 2008, 2012; Natali and Meza, 2011; Akala et al., 2013; Huy et al., 2014). In India, due to existence of the EIA, researchers have studied the low latitude ionosphere extensively using GPS based TEC measurements and also compared their results with ionospheric IRI models (Gupta and Singh, 2000; Bhuyan and Borah, 2007; Bagiya et al., 2009; Chauhan and Singh, 2010; Mukherjee et al., 2010; Kumar et al., 2012; Prasad et al., 2012; Sharma et al., 2012; Chakraborty et al., 2014; Karia et al., 2015; Rathore et al., 2015). Recently, the GPS-TEC studies have achieved a great success in predicting the behavior of the ionosphere and also proved to be very useful to detect the effects of solar events (Lastovicka, 2002; Dashora et al., 2009; Trivedi et al., 2011, 2013; Xu et al., 2012; Adebiyi et al., 2014). The morphological studies by Rama Rao et al., (2006a) investigated the temporal and spatial variations of TEC data taken from the Indian GPS network during the period of low solar activity of 2004-2005. The diurnal variation in TEC in the equatorial ionization anomaly (EIA) region shows its maximum value between 13:00 and 16:00 LT and the day minimum between 05:00 and 06:00 LT at all the observing stations from the equator to the EIA crest region. The seasonal variations of TEC have shown maximum during the equinox months and minimum during the summer. Prasad et al., (2012) have also studied the variations of TEC at four Indian GPS stations during the year 2004. The higher and lower TEC values are found during equinoctial and summer months respectively and a significant day-to-day variability was also observed. The variations are higher at the anomaly crest locations and lesser at the equatorial stations which are supported well by IRI-2007 model over the four Indian GPS stations. The variations with solar activity indices (SSN, F10.7 and EUV) have shown a good correlation during equinoctial months and a poor correlation during summer months. In spite of many reports available in literature on the morphological study of GPS-TEC over low latitudes during low and high solar activity periods, no attempts have been made to examine the influence of seismic activities and segregate them from general morphological features. The purpose of the present work is to identify earthquake precursors from the complex morphological variation in the low latitude ionosphere, a new attempt made in this area.

Experimental setup

The experimental setup of TEC measurements has been installed at Seismo-electromagnetics and Space Research Laboratory (SESRL) of R.B.S. Engineering Technical Campus, Bichpuri, Agra (Formerly R.B.S. College Agra) by our earlier group (Chauhan et al., 2012). Bichpuri is located 12 km west of Agra city in a rural area where electrical and electromagnetic noises are very low and round the clock observations have been taken since 2006. The related equipment from Silicon Valley, U.S.A. includes GPS antenna (Novatel's Model GPS702), receiver (Novatel's Euro Pak 3-M), connecting cables and relevant software (novatel.com). GPS receiver can be operated at two ultra-high frequencies L1 = 1575.42 MHz and L2 = 1227.6 MHz and we can receive 11 GPS satellite signals at these frequencies. It measures phase and amplitude at 50-Hz rate and code/carrier divergence at 1 Hz rate for each satellite being tracked and computes TEC from combined frequencies by pseudo range and carrier phase measurements. The primary purpose of the GPS receiver is to collect ionospheric scintillation and TEC data for all visible satellites.

Method of Analysis

The analysis procedure is to convert slant-TEC (STEC) into vertical-TEC (VTEC) by multiplying with a suitable mapping function as given by (Mannucci et al., 1993);

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

where R_E is the mean radius of the earth in km, h_s, the ionosphere (effective) height above the earth's surface, z, the zenith angle and E, the elevation angle in degrees. The effective ionospheric height of 350 km is used for determination of IPP locations (Rama Rao et al., 2006b). Since TEC variation may be affected by multipath, troposcatter and water vapor at low elevation angles (Rama Rao et al., 2006b), values of TEC are taken at higher elevation angles (50^o).

In this paper, the results of analysis of TEC data for two years from 01 January-31 December, 2007 (period-I) and 01 January-31 December, 2011 (period-II) recorded at the low latitude GPS station Agra, India during low and high solar activity periods are presented. The study of diurnal and seasonal variations of TEC data indicated significant variations from low to high solar activity periods. The results are also compared with recent ionospheric model IRI-2012 and we find a very good agreement in trends (strong correlation) but IRI model overestimates during each of the three seasons (winter, summer and equinox) for both the periods. The effects of magnetic storms have also been examined on TEC data which are found to cause a significant change. The data of ∑Kp, solar flux (F10.7 cm) indices and IRI-2012 model are taken from the NASA website of http://omniweb.gsfc.nasa.gov/form/dx1.html and http://omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html respectively. This paper suggested that morphological study of GPS-TEC data must be taken into account while examining the earthquake induced TEC anomalies.

The correlation coefficient has also been calculated between GPS-TEC and IRI-TEC and then GPS-TEC and ∑Kp respectively by using following equation;

$$\text{Correlation Coefficient} = \frac{N\sum xy - (\sum x)(\sum y)}{\sqrt{[N(\sum x^2) - (\sum x)^2][N\sum y^2 - (\sum y)^2]}} \quad \text{.....2}$$

where x and y are two samples, and N is the number of pairs. ∑Kp index quantifies the disturbances in the horizontal component of the earth's magnetic field recorded at magnetic observatories located around the globe. It has been widely used in ionospheric and atmospheric studies for the examination of magnetic storm. It records in three hours interval over magnetic observatories and the final data are found by averaging the data recorded over all the observatories. This data is available on the websites of Kyoto, Japan and NASA, USA for public access.

RESULTS

Diurnal variations

The four contour diagrams shown in Figure 1 depict the average monthly variations of TEC data for each period from 01 January-31 December, 2007 and 01 January-31 December, 2011 at our Agra station and the same variations with IRI-2012 model. Here, one TEC unit (1TECU) is ≈ 10^{16} electrons per meter^2. The diurnal pattern of VTEC increases during sunrise to an afternoon maximum and then decreases to a minimum just before sunset.

The usual features of low latitude ionosphere as appeared in diurnal variation of TEC data like VTEC values show a minimum during morning hours and gradually increase with the time of the day attaining a maximum in the afternoon and again decrease steadily

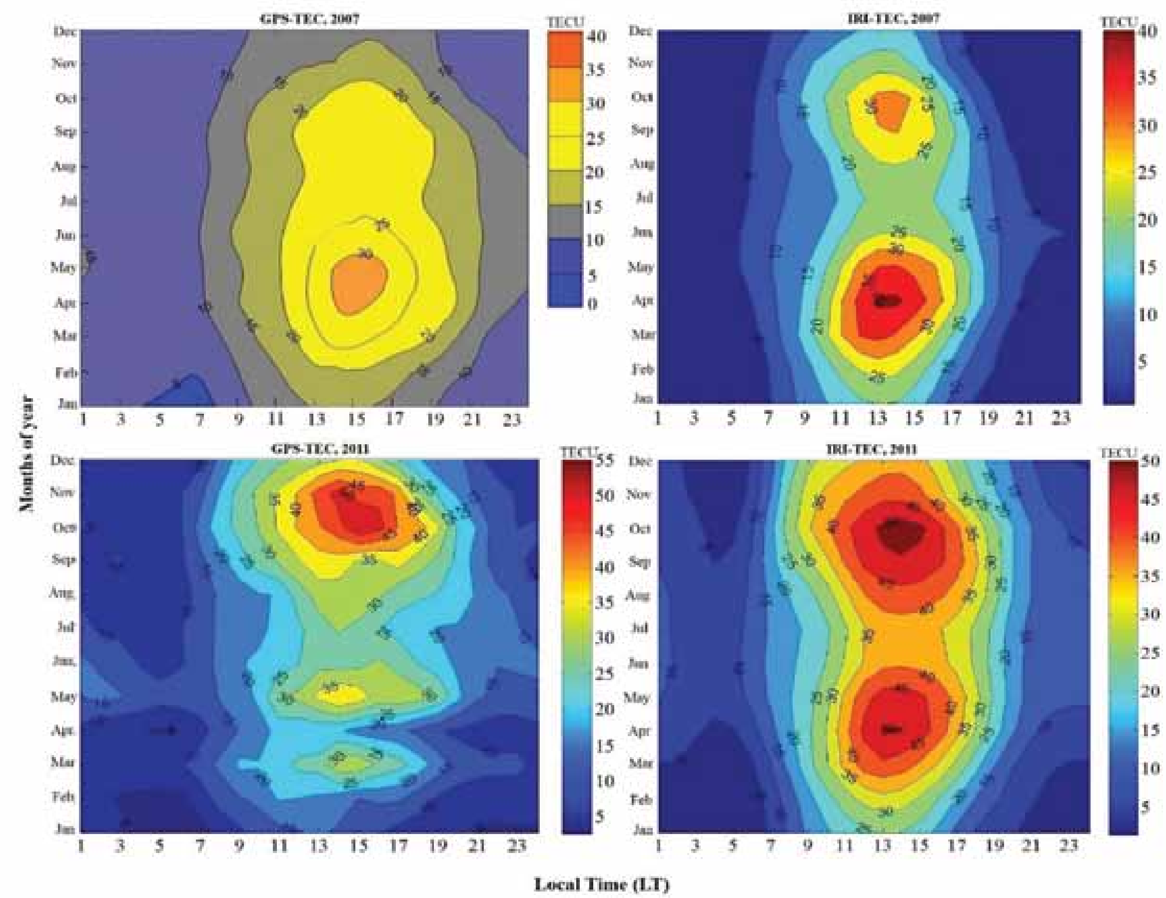

Figure 1. Upper panel (left) shows the contour plot of average monthly GPS-TEC variations during period-I (2007) over a low latitude station, Agra, India and the upper panel (right) presents the IRI-2012 model TEC data variations over the same station and for the same period. The lower panel shows the same variations as above but for the period-II (2011).

after sunset. These features are similar to those obtained by earlier workers (Mukherjee et al., 2010; Kumar et al., 2012; Sharma et al., 2012). The peak value of the VTEC lies between 14:00 and 16:00 hrs. These plots show the monthly variations of VTEC, mostly during the mid-day to morning hours which are helpful in forecasting and navigation (Bagiya et al., 2009; Rama Rao et al., 2006a). The monthly variations of VTEC at Agra may be attributed to the changes in the intensity of the arriving solar radiations (Natali and Meza, 2011; Akala et al., 2013). The highest GPS-TEC values are found in equinoctial month of April (≈ 30 TECU) for period-I also supported by corresponding IRI-TEC variation. The highest GPS-TEC values for period-II are also found in equinoctial months of November and October (≈ 45-50 TECU). Here, it can be noticed that IRI-TEC variations are almost similar to our results during both the periods except that IRI model shows ≈ 5 TECU higher values of TEC as compared to our data for equinoctial months for period-I. So it may be concluded here that TEC values are enhanced in equinox than in winter and summer season.

Seasonal Variations

The seasonal variations of TEC and their comparison with IRI model are shown in Figures 2 and 3. Here, the three seasons are considered i.e. summer, equinox, and winter. The months of April, May, June, and July are taken in summer solstice. The average of TEC data is taken for the months of March, April, and September, October corresponding to two equinoxes. Another combination of months of November, December, January, and February, corresponds to winter solstice. In these figures, the upper panels show the variation of TEC data in each of three seasons (winter, summer, and equinox) and the same variations with seasonal IRI-TEC shown by solid and dotted lines respectively and the lower panels present the correlation plot between GPS-TEC and IRI-TEC for the two periods. The peak GPS-TEC values are found in the range of 15-25 TECU for all the seasons. Here, the IRI model overestimates during peak hours and underestimates during morning and afternoon hours in case of winter and equinox season. It underestimates during morning

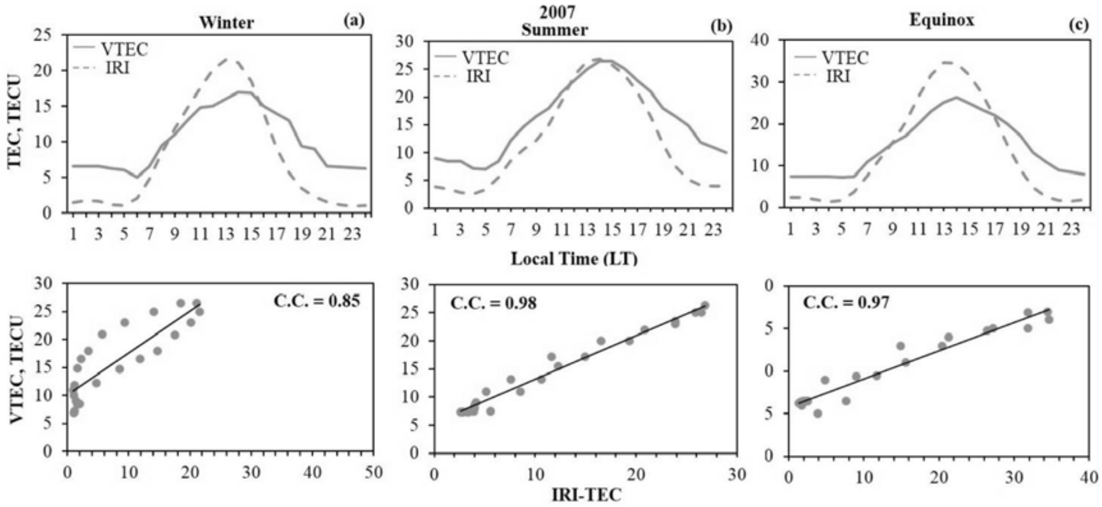

Figure 2. Upper panel presents the variation of GPS-TEC and IRI-TEC by solid and dotted lines during each of the three seasons (winter, summer and equinox) respectively for the period-I (2007). The lower panel shows the correlation plots between VTEC and IRI-TEC for the same as above.

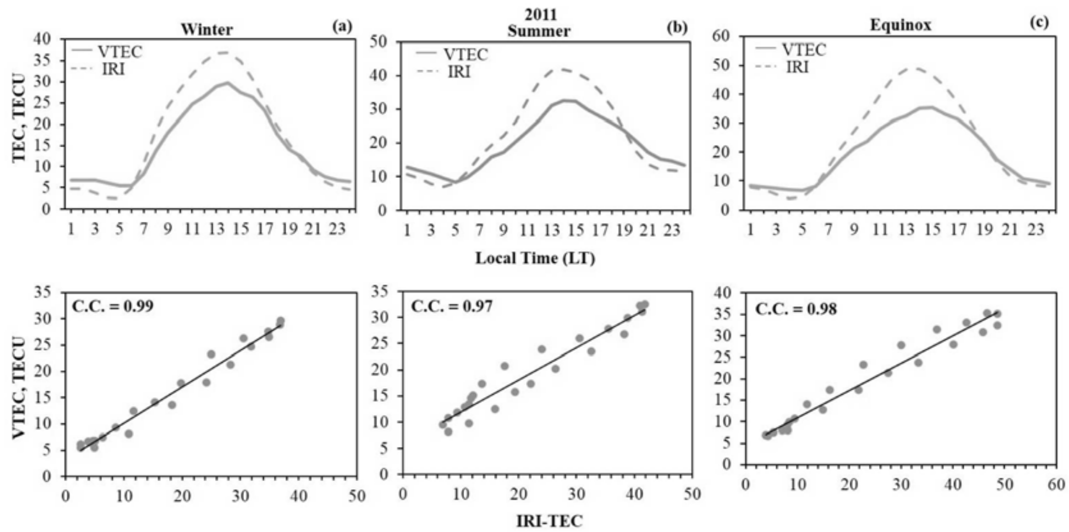

Figure 3. Shows the same as Figure 2 but for the period-II (2011).

and afternoon hours in summer season. To validate our results, the correlation coefficients are calculated between GPS-TEC and ionospheric IRI-2012 model TEC data for each of the three seasons which shows a strong correlation (≈ 0.98) between them except for winter where it is 0.85 during period-I.

In Figure 3, one can see that the TEC values are higher in period-II as compared to that in period-I. It may be because of the direct effect of solar activity. The peak TEC values lie in the interval of 25-30 TECU. From this figure, it can be seen that IRI model overestimates in this period also but shows a strong correlation ≈ 0.98 for all the seasons. One more interesting point is a change in TEC values from period-I to period-II. So these changes may be interpreted in the light of solar activity (discussed in solar activity dependence and geomagnetic storm effect). The GPS-TEC and IRI-TEC show higher values during equinoxes and lower values in winter relative to those in summer for both the periods. These results are similar to the findings of earlier workers (Kumar et al., 2012; Sharma et al., 2012). The mechanisms which are related to these variations are described later. This study is consistent with the studies of other low latitude stations in the vicinity of our station. For example, Sharma et al., (2012) have investigated the TEC variations over Delhi (beyond the EIA region and closer to Agra) in addition to Trivandrum equatorial station during low and high solar activity and found similar variations.

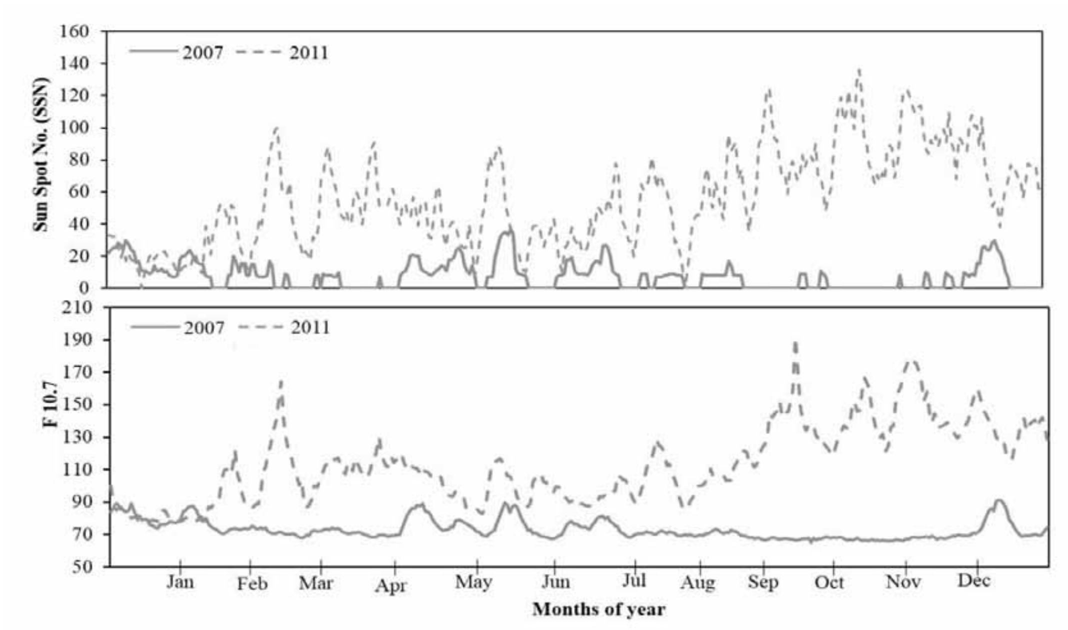

Figure 4. Upper panel shows the variations of Sun Spot Numbers (SSNs) for the period-I (2007) and period-II (2011) by solid and dotted lines respectively. The lower panel shows the variations of F10.7 flux for the same periods.

Solar activity dependence and geomagnetic storm effect

To see the effect of solar activity on TEC data during the period under consideration, sun spot numbers (SSNs) and solar flux F10.7 indices are plotted for period-I and period-II by solid and dotted lines respectively (Figure 4). The upper panel of this figure shows the variation of SSN which is almost quiet for period-I but shows large variations for period-II in equinoctial months. As it may be seen here, the maximum values of SSN are ≈ 30 and ≈ 140 during period-I and period-II respectively. The lower panel of this figure shows the variation of solar flux F10.7 during both the periods. We can clearly see that the maximum values of solar flux F10.7 are ≈ 90 for period-I and ≈ 190 for period-II. Here, a large change in maximum values of solar activity parameters can be seen between the two periods. It confirms that the solar activity affects the TEC data largely during period-II in comparison to period-I.

To see the effect of geomagnetic storms on the TEC data at our Agra station, we examined the correlation between the monthly TEC variations and geomagnetic activities for which the correlation coefficient between TEC data and ∑Kp index is calculated for each month of year 2011. The results are shown in Figure 5. Here, it is noted that values of correlation coefficients are very poor for the period under consideration, so we can say that geomagnetic activity does not affect the TEC data largely.

While the monthly correlation does not produce a satisfactory result, four cases of magnetic storms are selected to see the effect of magnetic storm on TEC data such as those occurred on 06 August, 27 September, 25 October and on 01 November, 2011. On these days, ∑Kp index values are high compared to the values on normal days. For the first case, the VTEC variations (upper panel) and corresponding ∑Kp index (lower panel) are plotted for the period of 03 August to 16 August 2011 in Figure 6a. It can be seen that the enhancement in VTEC data occurs on 07 August, one day after the occurrence of a magnetic storm. In the second case, the period of 25 September to 08 October 2011 is considered and plotted in the same way corresponding to this period. One can notice in Figure 6b that ∑Kp index values (lower panel) are > 30 between 26-29 September, whereas the major enhancements occur in TEC data during 2-3 October (5-6 days after). Similarly, two other cases of VTEC variations in relation to magnetic storms during 23 October-05 November are shown in Figure 6c. In the lower panel of this figure, it can be seen that ∑Kp values are high (≥ 30) on 25 October and 01 November. The enhancements occur in the data corresponding to these two moderate magnetic storms during 1-4 days after the occurrence of these storms. However, it is well known that geomagnetic storm can produce large perturbations in the ionospheric F-region in the form of enhancements and depletions in the electron density during periods of positive and negative phases of a magnetic storm, respectively.

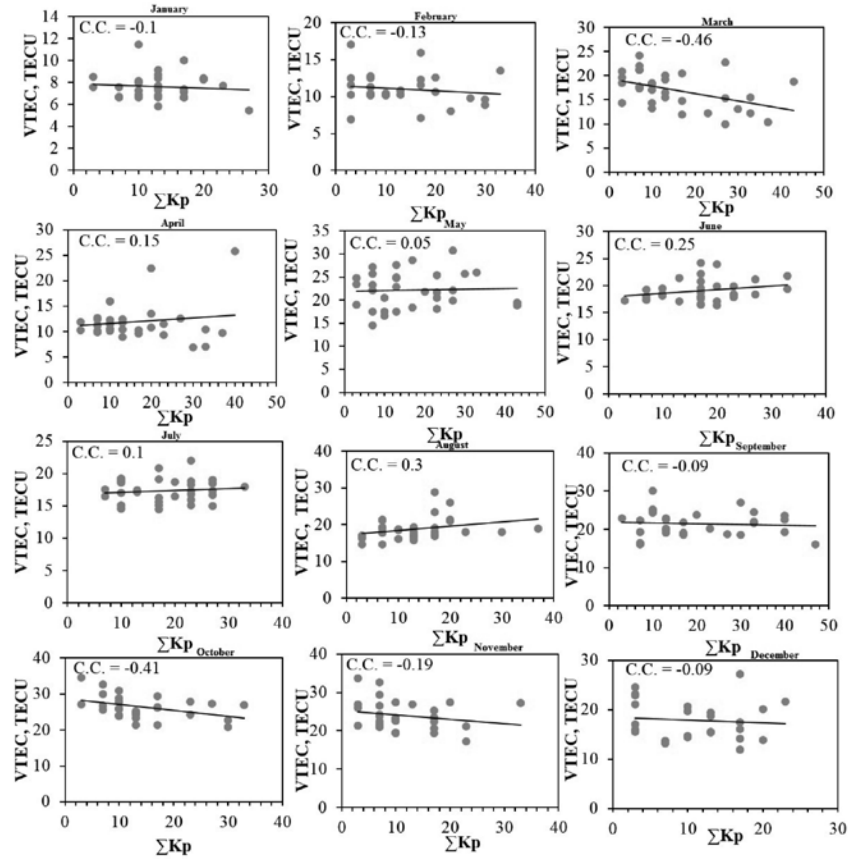

Figure 5. The correlation plots between VTEC and geomagnetic activity factor (∑ Kp index) during the period-II (2011).

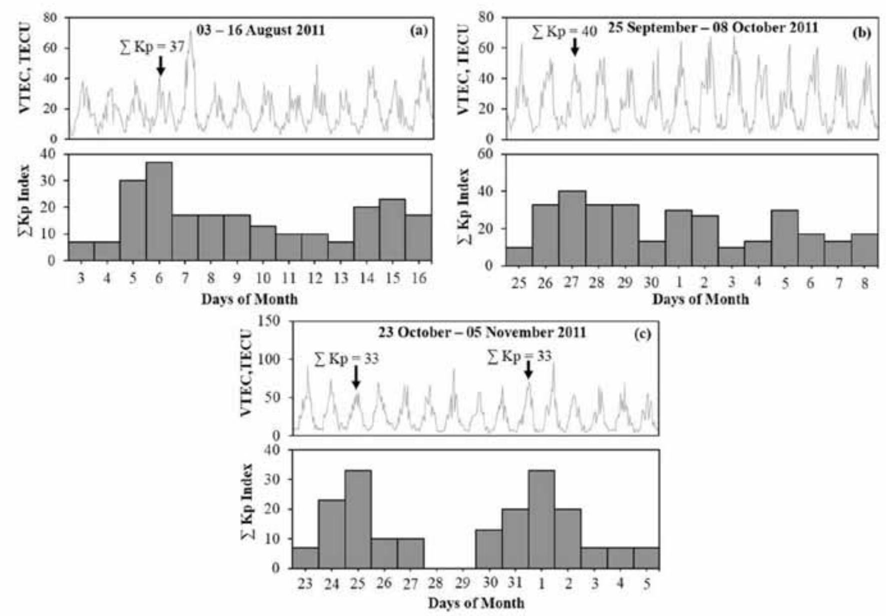

Figure 6. (a) Upper panel shows the diurnal variations of GPS-TEC between 3 and 16 August, 2011. The downward arrow indicates the day of occurrence of magnetic storm, the lower panel shows the variations of ∑ Kp index for the same period. (b) the same variations as Figure 6a but for the period of 25 September-08 October, 2011. (c) same variations as Figure 6a but for the period of 23 October-05 November, 2011.

Table 1. Main points of the interpretation of results.

S. N.	Type of variation	Quiet Period (2007)	High Solar Activity period (2011)
1.	General variation	In summer, the TEC values are high (≈ 30 TECU).	In both summer and equinox TEC values are high (≈ 40 and 50 TECU respectively).
2.	Solar activity variation (a) Sunspot Numbers	In summer TEC (≈ 35 TECU) is relatively higher than other months of seasons.	TEC is much higher (≈45-50 TECU) during equinoctial months.
	(b) F10.7 cm	Similar to the above	Similar to the above
3.	Magnetic storms (moderate)	-----	TEC enhanced 1-4 days after the occurrence of event.

Summary of the results

The results obtained from the analysis of the GPS-TEC data over Agra during low and high solar activity periods are summarized in the Table 1.

Analysis of the results for interpreting earthquake induced TEC anomalies

From the summary of the results presented above, it is clear that TEC values vary significantly with seasons and solar activity i.e. during quiet periods TEC shows enhancement in summer, while during disturbed periods it shows enhancements in equinoxes also. A particular point to be noted is that TEC shows anomalously enhanced values after a few days of occurrence of magnetic storms. Several workers have reported rise in TEC a few days before the occurrence of earthquakes (Dabas et al., 2007; Chauhan et al., 2012; Singh et al., 2012). In order to authenticate such results, it is necessary to examine the variation in TEC with respect to season and solar activity so that it will not lead to wrong conclusion.

Now, it is necessary to justify the GPS-TEC variations using possible mechanisms. The rise in TEC data can be attributed to solar extreme UV ionization coupled with the upward vertical E × B drift. Our station is located in the equatorial ionization anomaly region in which two crests in the ionospheric electron density often show a minimum nearby magnetic dips 15^0 north and south respectively (Appleton, 1946). In this study, we find that the GPS-TEC and IRI-TEC show higher values during equinoxes and lower values in winter relative to those in summer for both the study periods. Here, it may be noticed that the large difference in magnitude of VTEC exists between period-I and period-II because of the low to high solar activity period. Generally, during the daytime, the equator is hotter than the North and South poles which causes meridional wind flow towards the poles from the equator. The flow of meridional wind changes the neutral composition and O/N_2 decreases at equatorial stations. This decrease in O/N_2 ratio, which is maximum during the equinox months, will result in higher electron density. Hence equinox VTEC will be highest (Bagiya et al., 2009; Kumar et al., 2012).

Solar activity affects the magnetospheric dynamics, and influences the plasma density distribution within the ionosphere. The variations of ionospheric VTEC with solar activity can be studied, using solar flux F10.7 cm and SSN which are the useful indicators of solar activity relevant for ionospheric effects. The F10.7 cm flux may be defined as the radio power of sun at a frequency of 2800 MHz commonly measured in solar flux unit (1 sfu = 10^{-22} Wm^{-2} Hz^{-1}). Generally, the ionization level varies to higher values during a high solar activity period and lower values during a low solar activity period. SSN is a temporary phenomenon but it is very important to define the solar activity effect. The changes in the TEC data variations at our station are attributed to the changes in the solar activity period which is confirmed by the variations of solar activity factors (F10.7 and SSN) which matches well with the earlier studies.

The rise in TEC data during the periods of magnetic storms may be attributed to the delayed effects of the induced electric field penetrating the low latitude ionosphere and magnetosphere (Jain and Singh, 1977; Rastogi and Klobuchar 1990; Lakshmi et al., 1983, 1997; Jain et al., 2010). Basically, two main factors may affect the ionosphere during a magnetic storm: First is thermospheric heating mainly caused by storm-induced thermospheric winds (Danilov and Lastovicka 2001), which results at low latitudes, ionization level increase short of any noteworthy changes in the ratio of atom to molecule (Fuller-Rowell et al., 1994). Second is the penetration of an eastward electric field to low latitudes which results in the enhancements of the fountain effect and the EIA poleward. The enhanced fountain effect is responsible for the enhancements in TEC data measured at low latitudes.

There are numerous reports showing TEC anomalies a few days prior to the occurrence of earthquakes. It has been suggested that earthquake induced electric fields penetrate the ionosphere and cause such anomalies. However, the TEC anomalies occur with season and magnetic storms also. It is very useful to examine TEC variations carefully.

CONCLUSIONS

The GPS-TEC data have been analyzed at a low latitude station Agra, India for two periods i.e. from 01 January-31 December, 2007 and 01 January-31 December, 2011 corresponding to low and high solar activity periods respectively. The diurnal and seasonal TEC variations have been studied for both the periods of observation. The effect of solar activity has been examined in terms of sun spot numbers and F10.7 flux variation whose maximum values are 30 and 90 for period-I and 140 and 190 for period-II respectively. The maximum values of GPS-TEC have been found during equinox (30 and 50 TECU) and minimum in winter (5 and 15 TECU) during period-I and period-II. A strong correlation (≈ 0.98) between GPS-TEC and IRI-2012 model have been found for each season except winter season (≈ 0.85) of period-I. Hence, it may be concluded that the TEC value will be maximum during equinox season which may be attributed to solar activity for each period. The monthly correlation between $\sum$Kp and GPS-TEC was not found to be so good but in four specific cases of magnetic storms, TEC increases, 1-4 days after the occurrence of the events. Finally, it is concluded that TEC anomalies attributed to earthquakes must be examined in the light of anomalies caused by the factors which have considered in this paper.

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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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"By the time we see that climate change is really bad, your ability to fix it is extremely limited... The carbon gets up there, but the heating effect is delayed. And then the effect of that heat on the species and ecosystem is delayed. That means that even when you turn virtuous, things are actually going to get worse for quite a while".

Bill Gates

(**Source:** https://www.brainyquote.com/quotes/keywords/climate_change.html)