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Study of Ionospheric TEC from GPS observations and comparisons with IRI and SPIM model predictions in the low latitude anomaly Indian subcontinental region

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Abstract

The present study investigates variation of the ionospheric total electron content (TEC) in the low latitude Indian sub-continental region from the GPS observations and its comparison with the global ionosphere maps (GIMs), standard international reference ionosphere (IRI 2012), and the standard plasmasphere–ionosphere model (SPIM) for the period from November 2011 to October 2012 that corresponds to the progressive phase towards the midst of the solar cycle-24. Observations during quiet period show diurnal maximum of TEC occurring around 14:00–16:00 IST, with relatively broader and longer duration of local maximum at Bangalore and behave reversely towards Delhi. The secondary maximum of TEC was markedly noticeable at Bangalore during the months of March and September, and only in the month of September at Hyderabad and Mumbai. However, the relatively higher TEC during December month than the June is ascribed to the winter anomaly which is more prevalent during the high solar activity periods. The prevailing instability in latitudes of anomaly crest during January 2012 is possibly due to the seasonal variation of lunar tidal effects, modulating the EEJ strength at the equator. The studies covered the period of a strong geomagnetic storm during 6–11 March 2012 (SYM-H: −149 nT) which resulted in positive deviation of GPS-TEC at Bangalore (↑ 20%), Hyderabad (↑ 22%), and Lucknow (↑ 94%) compared to the mean quiet days level. The relatively large deviation of TEC at Lucknow could be attributed to the poleward shifting of the anomaly crest, manifested by enhanced fountain effect at the equator. Studies confirm excellent agreement (80–85%) of GPS-TEC with IGS-GIM at Bangalore and Hyderabad with the exception of the night-time hours (Deviations >50%). However relatively larger deviation of GPS-TEC from GIM-TEC at Delhi could be due to the unavailability of IGS stations in the proximity of the position. Predictions of the SPIM model (extension of IRI up to GPS altitude) exhibit much higher deviation from the in situ GPS observations as well as GIM and IRI outputs during quiet periods. Correspondingly, either of the models (IRI and SPIM) did not respond well to the arrival of the sudden storm commencements (SSCs) during the storm period (6–11 March 2012). When SPIM is used instead of IRI, the overestimation from GPS-TECs are further exaggerated by 13–18% (December solstice), 27–37% (March equinox), 15–31% (June solstice), and 20–32% (September equinox) during peak hours of the period. We attribute the relatively more deviation of the SPIM than the IRI model possibly due to its plasmaspheric extension to the IRI model by adding the Russian SMI model of high latitude characteristics. Hence, we emphasize the further improvement in the model with due consideration of the driving forces at play in the region, for reliable predictions of the low latitude ionosphere.

Keywords: Ionosphere; GPS; TEC; EIA region; IRI; SPIM

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1. Introduction

The ionosphere is a layer of the Earth's upper atmosphere comprising high concentration of electrons and ions, mostly caused by solar radiation producing free electrons from the existing atoms of Earth's atmospheric gases (Klobuchar, 1991). It extends from 50 km to more than 1000 km altitude; at the higher altitudes although solar radiation is stronger but there are fewer gaseous atoms to interact with, hence ionization is sparse. The ionospheric properties such as electron density, ion and electron temperatures, ionospheric composition as well as dynamics varies with altitude, latitude, longitude, local time, season, solar cycle and magnetic activity etc. (Hong, 2008). These variations in ionization at the equatorial and polar regions are known to be high compared to relatively moderate changes in the mid-latitude region (Davies and Hartmann, 1997). The variability in the equatorial ionosphere is due to large-scale electrodynamic phenomena associated with the equatorial electrojet (EEJ) current, plasma fountain, equatorial ionization anomaly (EIA) etc. The EEJ refers to an enhanced eastward electric current in the E region due to a strong vertical polarization electric field developed in a latitude band of $\pm 3^{\circ}$ about the dip equator (Chapman, 1951). This eastward electric field is mapped onto F region at the geomagnetic equator and the $E \times B$ drift lifts the plasma to higher altitudes. This plasma diffuses down along magnetic field lines into both hemispheres creating two crests of plasma, one in each hemisphere (EIA generation). The overall process is known as the "fountain effect" (Appleton, 1946; Mitra, 1946; Martyn, 1947). The EIA is characterized by a minimum in the ionization densities (or trough) at the geomagnetic equator and maxima (crests) around $\pm 15^{\circ}$ magnetic latitude on both the hemispheres.

The quiet day variation of F-region electron density in the low latitude is dependent on the strength of EEJ and thereby intensity of fountain effect over the region. However, the irregular disturbances occur randomly, the major source of which are the solar flares resulting in sudden ionospheric disturbance (SID), polar cap absorption (PCA), ionospheric scintillations as well as geomagnetic and ionospheric storms. Also solid Earth-related phenomena like volcanoes and earthquakes may cause perturbations in the ionosphere triggered by the seismic surface waves, but usually less in comparison to solar and magnetospheric activities (Davies and Hartmann, 1997). The level of ionospheric activity is described in terms of electron density quantified by counting the number of electrons in a vertical column with a cross sectional area of 1 m^2 (one square meter), called as total electron content (TEC) of the medium (Klobuchar, 1991). The TEC is measured in a unit called TECU, where $1 TECU = 1 \times 10^{16}$ electrons/m^2. Broad features in the temporal and spatial behavior of ionospheric TEC is known to a great extent in global as well as regional perspective, however the daily variation has the greatest effect on present days (Kane, 1980; Oyeyemi, 2005). The ever-increasing exploitation of trans-ionospheric communications in satellite, aircraft, and surface transportation system navigations require more precise estimation of the ionospheric delay error in the navigation signal due to the free electrons and ions in the ionosphere (Cai, 2007; Rao et al., 2009, 2010). Prior to establishment of the global navigation satellite system (GNSS), there was less extent of the spatial and temporal imaging of ionosphere and related phenomena with existing ground and space-based measuring techniques, such as ionosondes, topside sounders, backscatter radars, satellite measurements based on principles like back scattering, Doppler effect, Faraday rotations and dual frequency microwave tracking systems etc. Nevertheless, all these methods have limitations in terms of complete profiling of ionosphere, wide spread operational availability and expenses. In recent years, GPS and GLONASS navigational satellite signals are emphasized in exploring ionospheric electron density (TEC) on regional as well as global basis, due to availability of signals in all-time and all-weather condition around the globe (Calais and Minster, 1995; Liu et al., 2004; Komjathy, 1997).

Previously the satellite based GPS system was mainly used for navigation, relative positioning and time transfer. However, the GPS signals traverse the dispersed ionosphere carrying its signature, hence offer exceptional opportunities for ionospheric research. Ionospheric TEC from ground-based GPS observations have been investigated widely in the past few decades (Mannucci et al., 1998; Liu et al., 2005; McKinnell et al., 2007; Moeketsi et al., 2007; Opperman et al., 2007; Venkatesh et al., 2011). The GPS satellites orbit at about 20,200 km altitude in 6 orbital planes covering almost whole part of the globe. The signals from the GPS satellites experience phase advance and group delays mostly due to the free electrons (TEC) in the ionosphere. The importance of ionosphere studies over the Indian region is due to its large span of coverage across the equatorial ionization anomaly zone (EIA). The magnetic equator passes beneath the southern tip of the country through the Indian ocean, and the northern hemisphere EIA crest contour ties over central India straddling the line joining Kolkata and Ahmedabad (DasGupta et al., 1997). It must be noted that earlier the magnetic equator was passing through the peninsular mainland of India via Trivandrum, but is now migrating into the Indian ocean at an approximate rate of 0.14 degrees a year.

Here, an experiment has been carried out to investigate diurnal, monthly, seasonal as well as latitudinal variation of TEC over the low latitudes. For clear understanding of ionospheric variations, a thorough review of solar and geomagnetic field indices has been done during the period November 2011–October 2012. The estimated TEC from in situ GPS observations is validated with interpolated TEC from international GNSS service global ionosphere map (hereafter written as IGS-GIM). The consistency of TEC estimations from International reference ionosphere

(IRI) and standard plasmasphere–ionosphere model (SPIM) is also verified in this study. The IRI is an empirical standard model sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI) (Bilitza et al., 1990). Several papers have been published on the simultaneous measurement of foF2/TEC, its noontime bite-out and secondary peak during evening, winter anomaly, solar activity dependance, and corresponding model predictions in the equatorial and low latitudes (Sethia et al., 1979; Dabas et al., 1984; McNamara, 1985; Rastogi and Klobuchar, 1990; Batista et al., 1994; Abdu et al., 1996; Ezquer et al., 1999; Sethi et al., 2001, 2011; Rao et al., 2006; Bhuyan and Borah, 2007; Bagiya et al., 2009; Chauhan and Singh, 2010; Aggarwal, 2011; Adewale et al., 2012; Prasad et al., 2012; Olwendo et al., 2012; Bhuyan and Hazarika, 2013; Sur and Paul, 2013; Hazarika and Bhuyan, 2014; Kumar et al., 2014a). Efforts are also being made to update and improve the model since its development in 1969, with newer data and better modeling techniques. The recently established SPIM model is an extension to the IRI model, developed under international standardization organization (ISO) project by merging (1) IRI below 1000 km, and (2) the plasmasphere region of the Russian standard model of ionosphere (SMI) up to 20,000 km, thereby improving the accuracy of the ionosphere plasmasphere TEC forecasting by 2–3 times as compared with CCIR prediction (Gulyaeva, 2003; Gulyaeva and Bilitza, 2012). The subroutines for the SPIM model are available at ftp://ftp.izmiran.rssi.ru/pub/izmiran/SPIM/. As per our knowledge, only a few papers have been published till the date on comparative study and credibility of SPIM model predictions with in situ ground measurements (Troitsky et al., 2007; Liu et al., 2012, 2013; Zakharenkova et al., 2013, 2015; Sezen et al., 2013; Maltseva et al., 2013). The review of literature confirms that although studies have been done on the suitability of the IRI at low latitude EIA region over Indian subcontinent, the suitability of SPIM is yet to be tested over the region. Hence, an attempt has been made in this study to highlight the suitability of SPIM predictions in the low latitude anomaly Indian subcontinental region.

2. Measurement of TEC

The present study has been carried out with GPS observation data of three International GNSS Service (IGS) stations at Bangalore, Hyderabad and Lucknow and five permanent GPS stations at Mumbai, Kolkata, Guwahati, and Delhi across the Indian subcontinental region. The IGS GPS observation data are accessed from Crustal Dynamics Data Information System (CDDIS) server (ftp://cddis.gsfc.nasa.gov/) and data of other permanent GPS stations are obtained from Indian Meteorological Department. The GPS observation data are processed in the GPS-TEC analysis application software, developed by Gopi Seemala at Institute for Scientific Research, Boston College, USA (Seemala and Valladares, 2011). The software algorithm calculates slant TEC (STEC) along the ray path using differential phase advance and group delay measurements of the L1 and L2 frequencies, broadcast ephemeris (BRDC) and differential code biases (DCBs). The TEC derived from group delays have large uncertainties, hence are smoothed by carrier phase leveling techniques. The GPS BRDC files are downloaded from CDDIS server, whereas the satellite DCBs ($P1C1$ and $P1P2$) are obtained from the Center for Orbit Determination in Europe (CODE), Astronomical Institute, University of Bern. The receiver differential code biases are estimated from diurnal minimum TEC at each station and then by subjecting 2-sigma iterated average of all satellites passing over the stations. The STEC is converted to its vertical equivalent (VTEC), using single layer model (SLM) mapping function associated with an ionospheric pierce point (IPP) latitude and longitude (Schaer, 1999). Here, we have processed the GPS observation data for the period of November 2011–October 2012 following the above methods. The geographic as well as geomagnetic co-ordinates of the GPS stations and their geographical distribution across Indian region are shown in Table 1 and Fig. 1 respectively. During data processing, an elevation angle of 40° is chosen to neglect the multipath error, change in satellite geometry and other atmospheric effects.

3. Solar and geophysical indices

Fig. 2 shows variations of the daily averages of solar extreme ultraviolet (EUV) flux in 26–34 nm wave-band and geomagnetic indices (daily ΣKp, Ap, and hourly Dst) during November 2011 to October 2012. The solar EUV flux continuously monitored by the Solar EUV Monitor (SEM) onboard Solar Heliospheric Observatory (SOHO) satellite is available at http://www.usc.edu/dept/space_science/semdatafolder/long. Majority of ionization in the ionosphere is induced by the solar EUV irradiance which changes by factors of 2 to 10 from solar minimum to solar maximum (Mahajan and Dwivedi, 2005). Hence, it has a great importance in studying/modeling the ionospheric variations. It has been well established that the sunspots and geomagnetic cycles are statistically interrelated, the geomagnetic Kp, Ap, and Dst indices follow similar trend with solar activity. The Dst index has significant role in estimating intensity of the geomagnetic storms.

Table 1
Geographic and geomagnetic co-ordinates of permanent GPS stations across Indian region.

GPS station	Geog. lat. (N)	Geog. lon. (E)	Geomag. lat. (N)
Delhi (IMDD)	28.59	77.22	20.0
Lucknow (LCK2)*	26.91	80.96	18.0
Guwahati (GUWA)	26.10	91.59	16.6
Kolkata (KOLK)	22.54	88.33	13.2
Mumbai (MUMB)	18.89	72.81	10.7
Hyderabad (HYDE)*	17.42	78.55	8.7
Bangalore (IISC)*	13.02	77.57	4.4

The stations with asteric mark (*) are IGS stations.

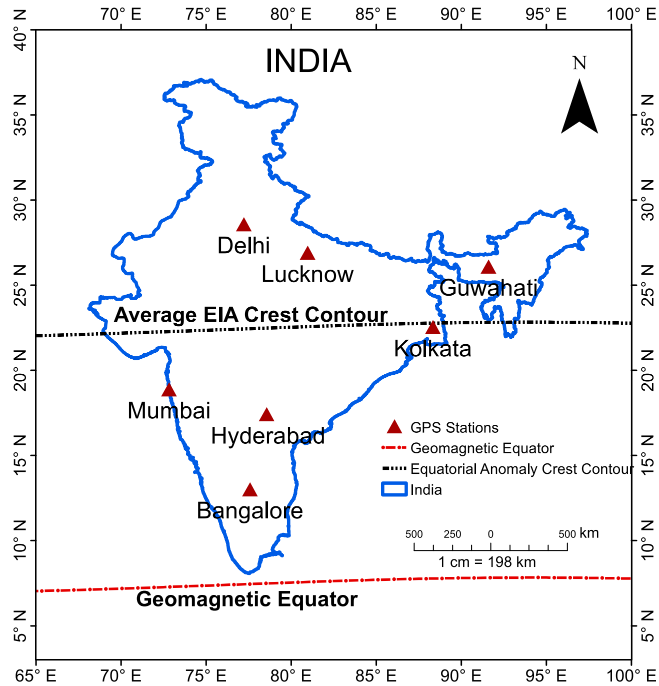

Fig. 1. Permanent GPS stations including 3 IGS stations, i.e., Bangalore, Hyderabad, and Lucknow across Indian region, geomagnetic equator, and average equatorial ionization anomaly (EIA) crest contour during 2011 to 2012.

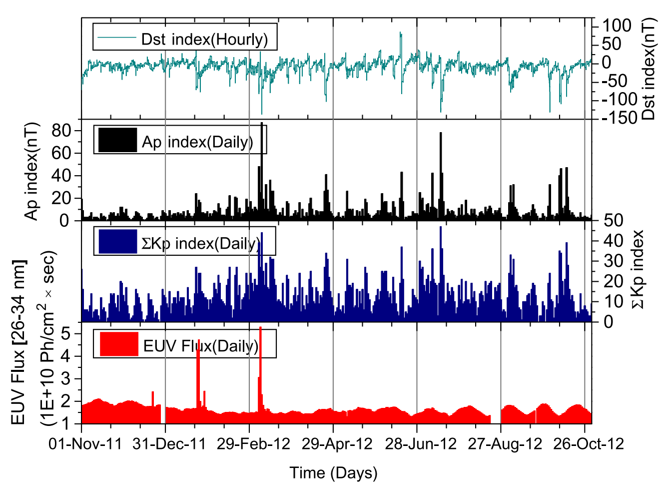

Fig. 2. Variations of daily averages of Solar EUV flux (26–34 nm waveband), daily geomagnetic ΣKp, Ap, and hourly Dst indices during the period from November 2011 to October 2012.

Variations of TEC in response to geomagnetic storms have been studied by many researchers over Indian region (Dashora et al., 2009; Rao et al., 2009; Sharma et al., 2011; Sreeja et al., 2009; Panda and Gedam, 2012). It is noticed from the Fig. 2 that the overall EUV flux level was high during November–December 2011. However abrupt peaks are clearly seen during January and March of 2012 that corresponds to high solar activity period. Though the geomagnetic signatures follow similar trend with EUV flux during high solar activity period, unlike the latter markedly enhancements are also observed during July and October months of 2012. To avoid the effect of geomagnetic storms due to Earth and solar events, only five international quietest days (Q-Days) are considered in this study. The list of 10 Q-Days, most disturbed days (D-days) are periodically uploaded in the World Data Center for Geomagnetism, Kyoto website; http://wdc.kugi.kyoto-u.ac.jp/.

4. Results and discussion

Here, we examine the diurnal, monthly, seasonal and latitudinal variations of ionospheric TEC estimated from GPS observations. The results are compared with global ionosphere maps and standard model outputs in the analysis. Also the spatio-temporal variation of GPS-TEC and model predictions are examined during geomagnetic storm to analyze its effects on ionospheric TEC.

4.1. Diurnal variation

The diurnal variation in TEC is due to the daily rotation of the Earth about its own axis following the apparent movement of the Sun. However, the net diurnal change in the quiet day low latitude ionosphere mostly depend on the photo-ionization production and recombination losses associated with local solar radiation and the field-aligned diffusion of the transported electrons from the equator. Fig. 3 shows diurnal variation of TEC at different stations on a typical quiet day (19 October 2012, Σ Kp = 5). It is clear from the figure that TEC gradually increases with sunrise, attains a peak at around 14:00–16:00 IST (IST = UT + 5:30) and later declines to attain the minimum value after midnight. There is a comparatively broader and longer duration of day maximum value of TEC at Bangalore, the station towards the equator (Mag. Lat = 4.4°N) than the station beyond the anomaly crest region i.e., at

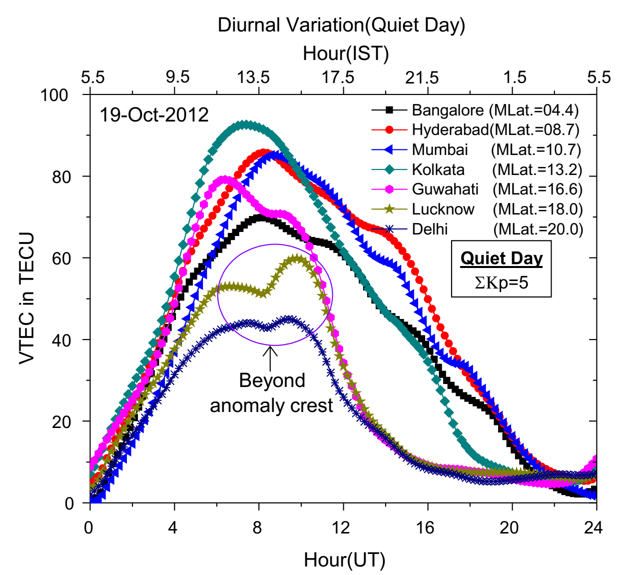

Fig. 3. Diurnal variations of GPS-TEC at different latitudes across Indian region on a typical quiet day (19 October 2012; Σ Kp = 5).

Delhi (Mag. Lat = 20°N). Conversely, opposite effects are observed during night time at Delhi with day minimum value lasting for longer duration. It is well-known that diurnal peak value is more during equinox and less during solstice seasons, but the pattern of TEC curve is more or less similar in all months during the period. However, frequent fluctuation of diurnal TEC is noticed at Lucknow (Mag. Lat = 18°N) and Delhi (Mag. Lat = 20°N). The nighttime variability is maximum towards Bangalore and minimum towards stations away from anomaly crest region, i.e., Delhi. This is consistent with observations of Bhuyan and Borah (2007) over Indian region during 2003–2004. The time of diurnal peak is found to vary from day to day and month to month. The averaged diurnal contour plot of TEC derived from GPS observations during January (December solstice), April (March equinox), June (June solstice) and October (September equinox) of 2012 are shown in Fig. 4. It is clear from the figure that during the month of January, the latitudinal range of crest development varies a lot, this is possibly due to fluctuation of EEJ strength during this period owing to the seasonal variation of geomagnetic lunar tides attributing exceptional global enhancement around this month (Mayaud, 1977; Schlapp and Malin, 1979; Bhargava et al., 1983).

4.2. Monthly variation

The monthly mean TEC with its standard deviations at four different stations; Bangalore, Hyderabad, Mumbai, and Lucknow, are shown in Figs. 5–8 respectively. The monthly plots of TEC during months of May–June 2012 at Hyderabad (Fig. 6) is left blank due to unavailability of observation data. The maximum value of monthly mean diurnal peak TEC is ~75 TECU at Bangalore, ~87 TECU at Hyderabad, ~82 TECU at Mumbai, and ~57 TECU at Lucknow are witnessed during November 2011 (a solstice month) possibly due to high solar activity period. However, during December 2011, the mean diurnal peak observed at Bangalore is ~50 TECU, whereas the average values at Hyderabad, Mumbai and Lucknow are ~60 TECU, ~55 TECU, ~35 TECU respectively. The higher TEC value during the winter solstice month than the summer solstice months could be due to the winter anomaly (or seasonal anomaly) which is more prevalent at the northern hemisphere and during the high solar activity periods (Bhuyan and Hazarika, 2013). Although the winter anomaly at the mid- to high-latitude regions mostly depend on changes in the $[O/N_2]$ ratio, the scenario at the low latitude region is the outcome of the additional equatorial electrodynamic effects over the region (Lee et al., 2011; Xu et al., 2012; Kumar et al., 2014a). During the year 2012, the September month witnessed high TEC value at all stations, followed by March and October. The lowest value of peak TEC are obtained at Hyderabad and Lucknow during January and February. But Bangalore and Mumbai stations depict lowest value during June and July solstice months. The daily primery peak of TEC is seen to occur at about 10:00 UT at all stations. Moreover, the secondary peak in the evening hours is markedly noticed at Bangalore during March and September months, but only noticed in September at Hyderabad and to very small extent at Mumbai.

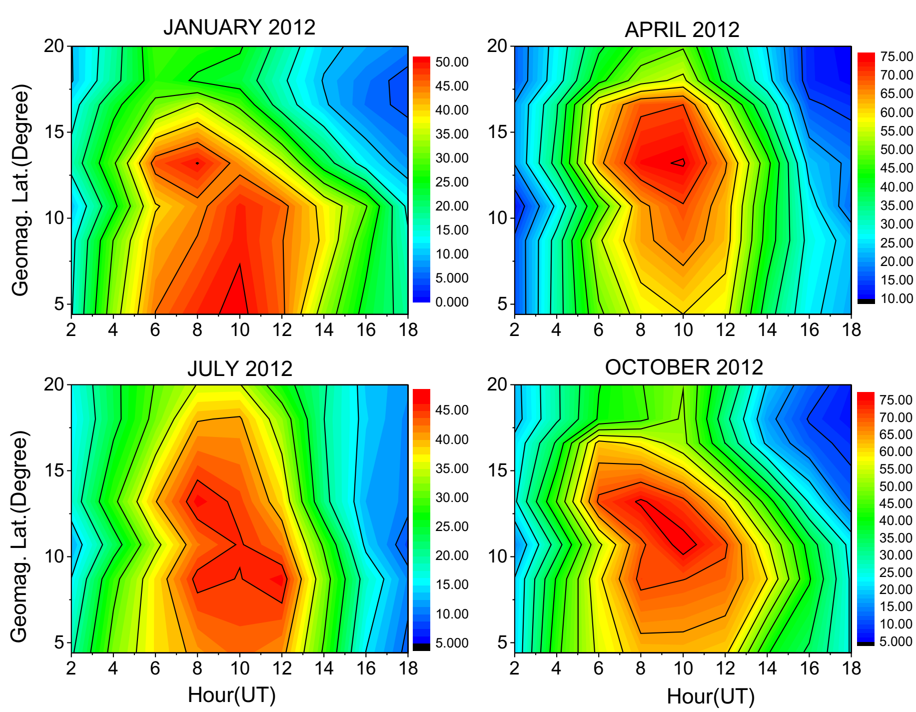

Fig. 4. Averaged diurnal color contour plots of TEC over Indian region during (1) January (December solstice), (2) April (March equinox), (3) June (June solstice) and (4) October (September equinox) of year 2012.

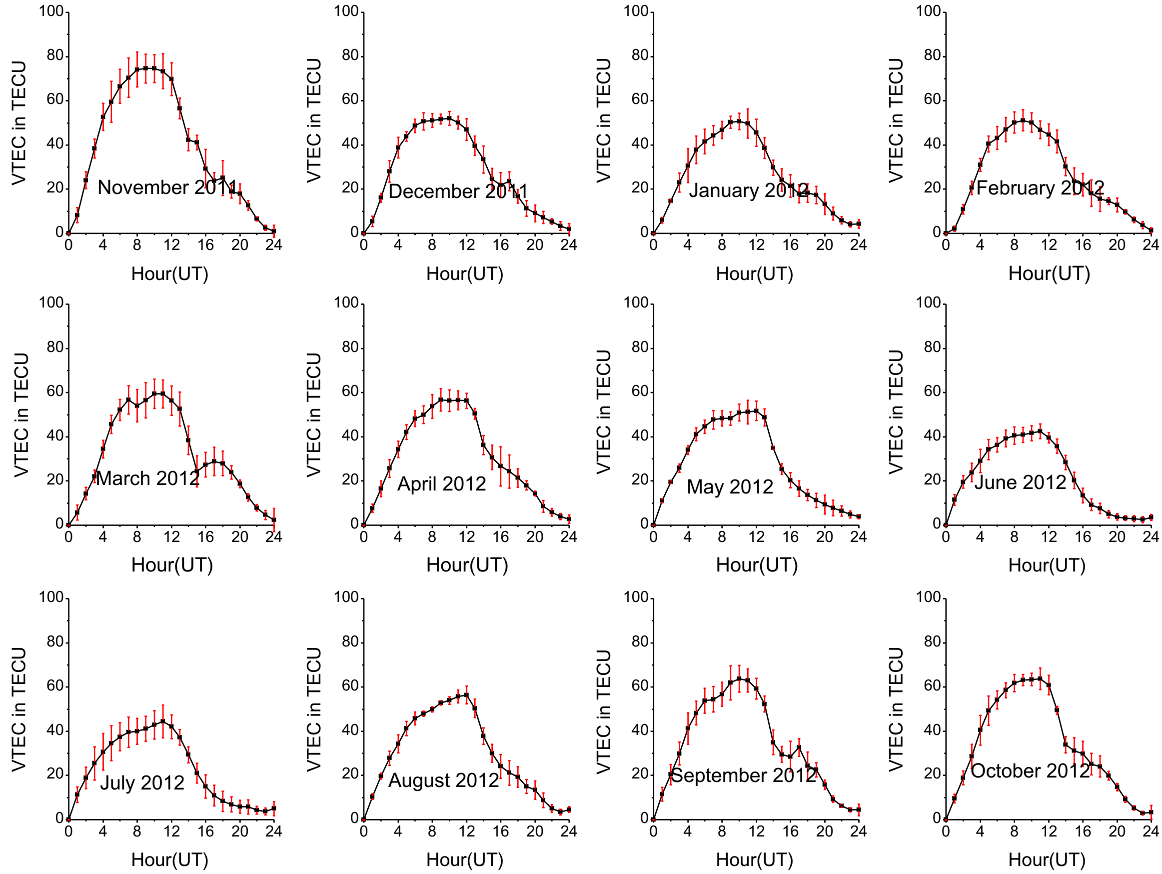

Fig. 5. Monthly averaged variation of GPS-TEC with standard deviation (SD) error bars at Bangalore during November 2011 to October 2012.

4.3. Latitudinal variation

As latitude increases from equator towards north and south direction, the solar radiation strikes the atmosphere more obliquely. Hence, the intensity of radiation and production of free electrons decrease with increasing latitude. Near the geomagnetic equator, the geomagnetic field is horizontal and electric field is eastward during day and westward at night due to dynamic effect by atmospheric motion. This allows the region to be prone to the equatorial electro-dynamic phenomena. The E-region electric field is mapped into F-layer and thereby lifting the plasma upward through $(E \times B)$ drift and diffusing along the slope of magnetic field lines at approximately $\pm 15^{\circ}$ geomagnetic latitudes on both the hemisphere (equatorial ionospheric anomaly region). Hence, the TEC is believed to be increased gradually towards the anomaly crest regions, beyond it the value further decreases to attain lower value at mid-latitude regions. Also, the TEC above mid latitude region varies less during a day than low and high latitude regions as these latitudes are sensitive to solar–terrestrial conditions. As we have considered the stations within a narrow range of longitudes in the Indian sector, it is assumed that the diurnal variations of TEC at different stations are dependent almostmostly on varying distances from the geomagnetic equator. The latitudinal variation of TEC during October 2012 is shown in Fig. 9. It can be observed that during daytime the TEC increases from Bangalore towards Kolkata (close to anomaly crest region) beyond which it drops down to minimum value at Delhi, a station above EIA crest and towards mid-latitudes. However, the latitude of crest development vary with strength of EEJ and the season of the year. As the station at Lucknow is just above the EIA crest, the abnormal variation of TEC is observed and the day maximum also occurs slightly later than near equator stations, i.e., Bangalore and Hyderabad. This is possibly due to the time lag between peak of EEJ strength and maximum intensity of fountain effect. Similar studies have been done at all stations to observe monthly ionospheric changes and latitudinal variation during November 2011–October 2012. We observed higher value of daily maximum TEC during March followed by April, May, September, October and November while the months of January, June and July show lower values of TEC at all stations. The diurnal variability of TEC at Bangalore is less as the latitude falls in the tropical region in between geomagnetic equator and EIA crest.

4.4. Seasonal variation

The whole year is categorized into four seasons, i.e., December solstice (November, December and January),

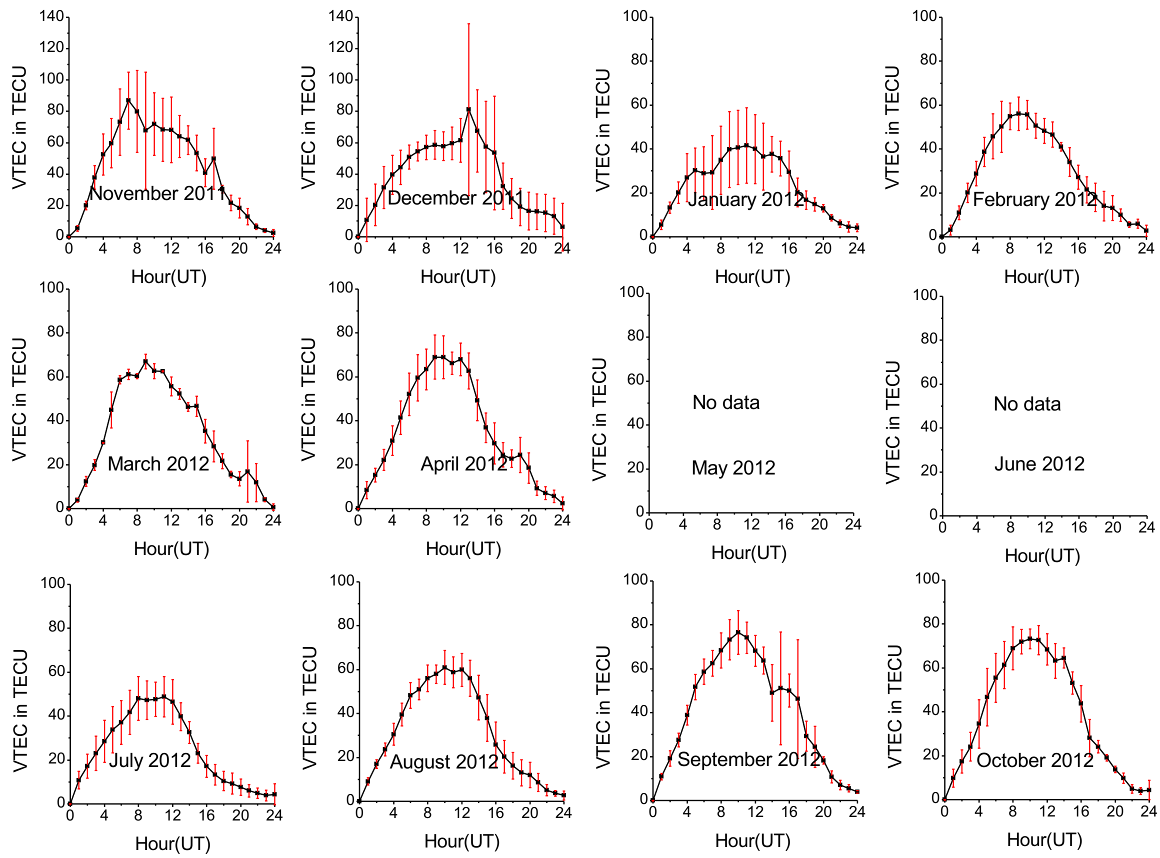

Fig. 6. Monthly averaged variation of GPS-TEC with standard deviation (SD) error bars at Hyderabad during November 2011 to October 2012.

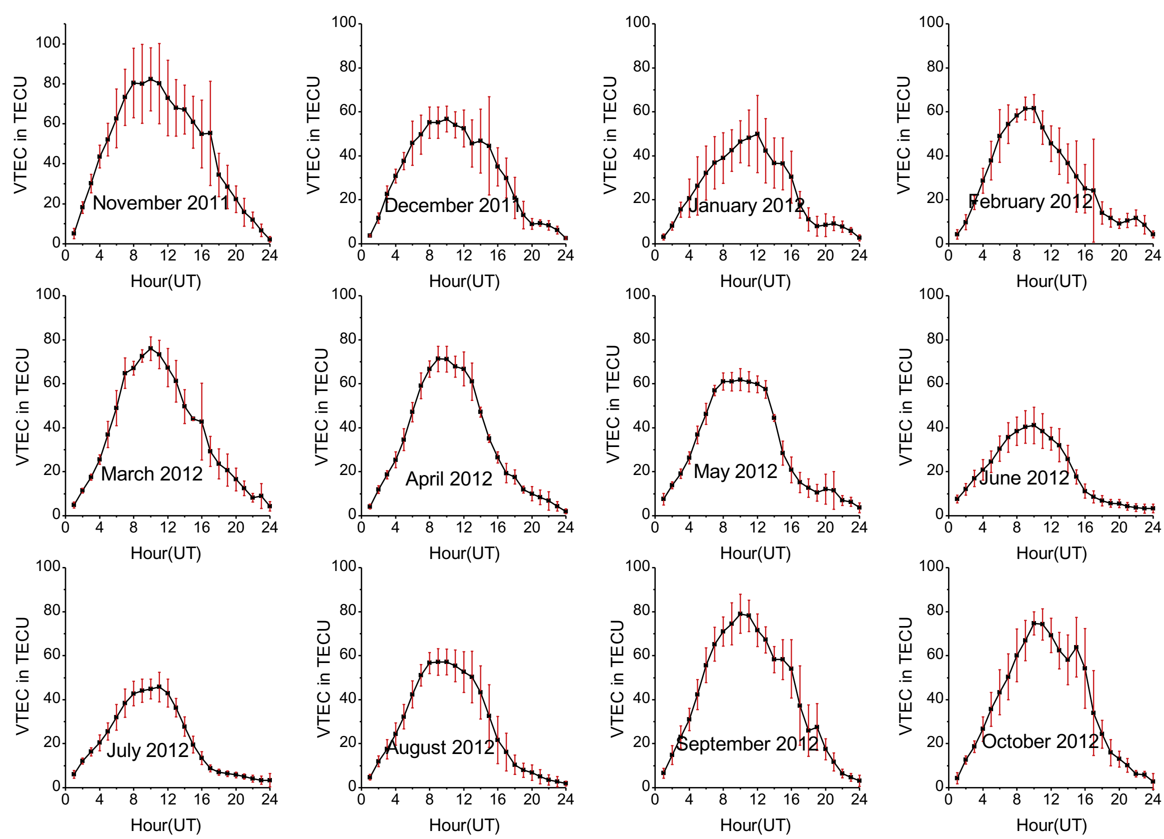

Fig. 7. Monthly averaged variation of GPS-TEC with standard deviation (SD) error bars at Mumbai during November 2011 to October 2012.

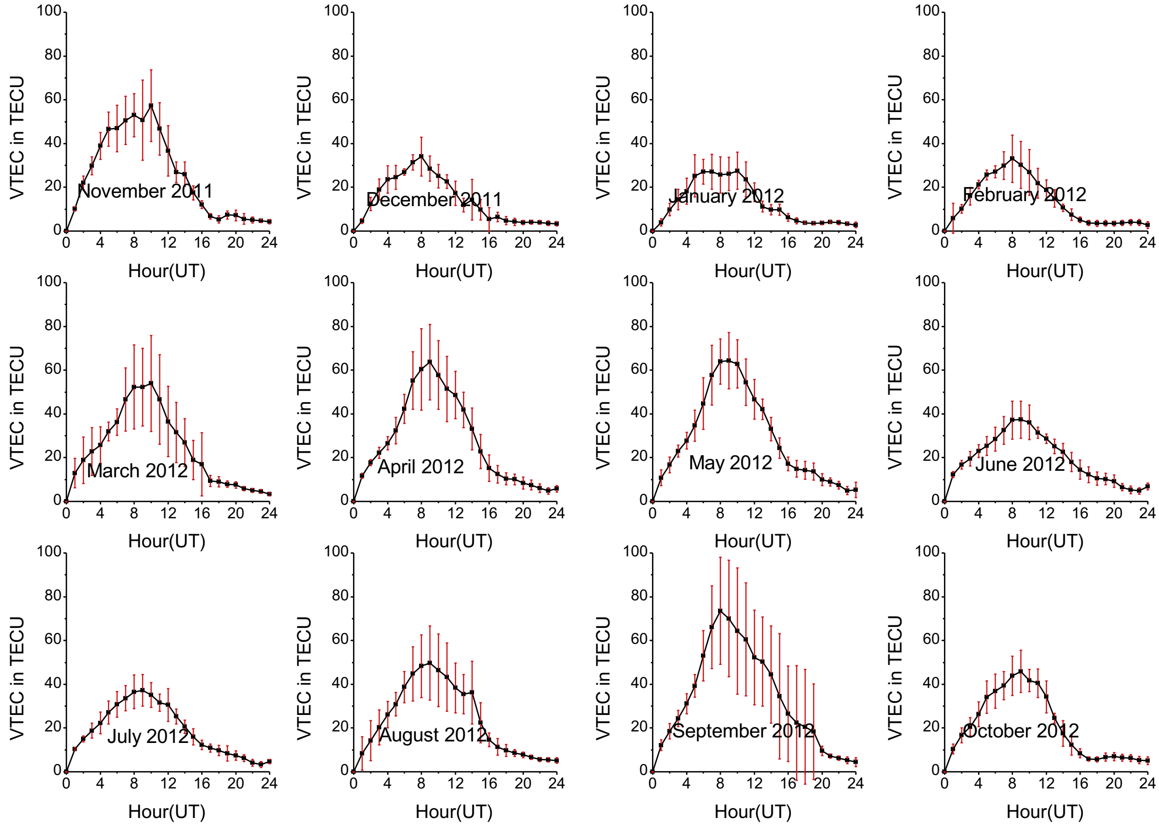

Fig. 8. Monthly averaged variation of GPS-TEC with standard deviation (SD) error bars at Lucknow during November 2011 to October 2012.

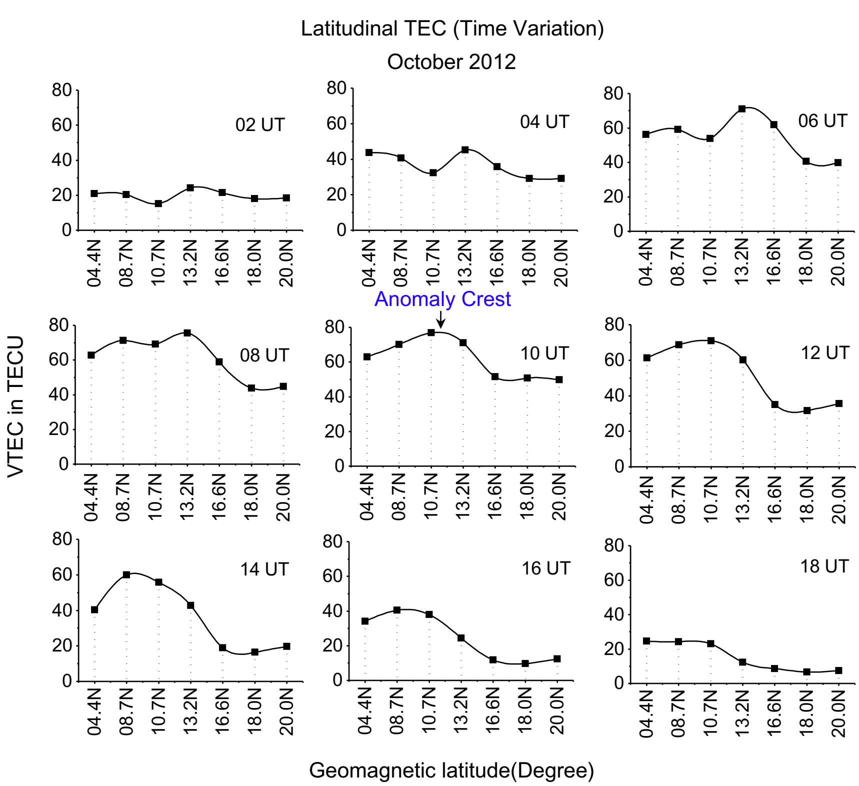

Fig. 9. Monthly mean latitudinal plots (2 hourly) of GPS-TEC over Indian region during October 2012.

March equinox (February, March, and April), June solstice (May, June, and July) and September equinox (August, September, and October). During equinoctial seasons, the sub-solar point remains around the equator resulting high photo-ionizations. But during December (sub-solar point is in the northern hemisphere) and June solstice (when the sub-solar point is in the southern hemisphere), low ionization is expected above equatorial stations. Fig. 10 depicts seasonal variation of TEC at (a) Bangalore, (b) Hyderabad, (c) Mumbai, and (d) Lucknow. The plots show a semi-annual mode, maxima in equinoxes and minima in summer as well as in winter solstices. The maximum value of TEC is observed during the equinoxes of which the September equinox shows slightly higher value, i.e., ∼61 TECU (Bangalore), ∼70 TECU (Hyderabad), ∼69 TECU (Mumbai), and ∼55 TECU (Lucknow), than the March equinox. The results are similar to the reports of Galav et al. (2010) studied during the period 2005–2008. But, Bagiya et al. (2011) have reported that during descending period of solar cycle-23 (2005–2007), March equinox shows larger value than the September equinox. In our study, the minimum value is observed at Bangalore, Hyderabad and Mumbai during June solstice, while the station at Lucknow shows minimum value during December solstice. In practice, the December solstice should show higher TEC than June solstice. This is due to transport of neutral constituents from the summer to the winter hemisphere, thereby increasing the production of electrons in winter hemisphere due to increased O/N_2 ratio. Also the meridional neutral wind component blowing from summer to winter obstructs the anomaly crest development in the Summer hemisphere and enhances in the Winter hemisphere (Bramley and Young, 1968; Torr and Torr, 1973; Rishbeth et al., 1995; Tsai et al., 2001). The increased value of December solstice than June solstice has been explained earlier by Zhao et al. (2009), Bhuyan et al. (2003), and Liu et al. (2012), but

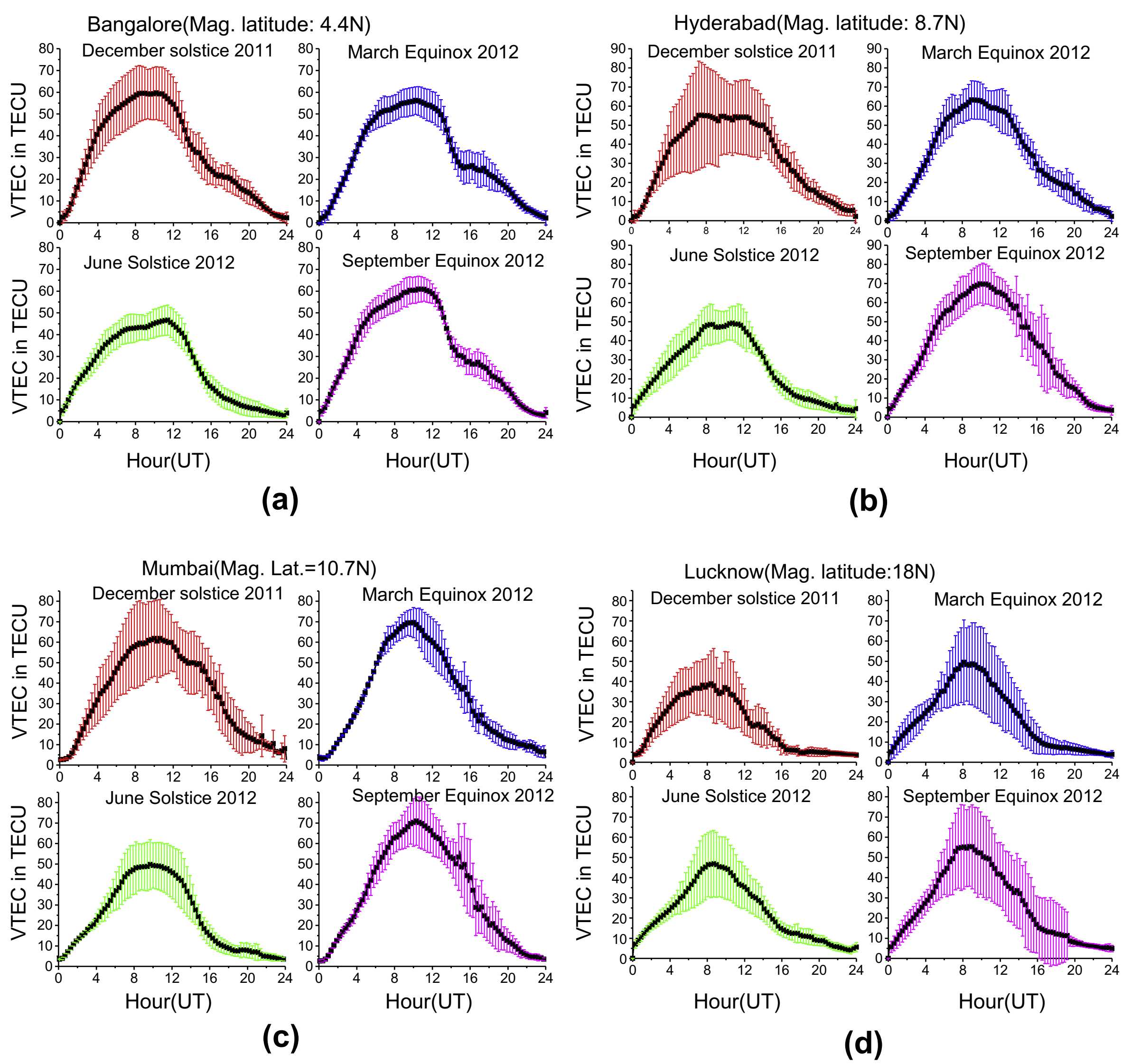

Fig. 10. Seasonal variations of GPS-TEC at (a) Bangalore, (b) Hyderabad, (c) Mumbai, and (d) Lucknow during the period November 2011 to October 2012.

studies of Chauhan and Singh (2010), Galav et al. (2010) and Bagiya et al. (2011) report reversely during low solar activity period which is concurrent with results at Lucknow station only. However, the high solar activity towards the end of year-2011 enhanced the overall TEC at the northern anomaly region. Frequent fluctuations in diurnal TEC is also observed at all stations during the December solstice due to high solar activity. Nevertheless, in the September equinox the Lucknow station shows highly varied diurnal value after the noon.

4.5. Storm time variation

Geomagnetic storms are caused by coronal mass ejections (CMEs) or solar flares from the Sun, and are responsible for ionospheric storms. A geomagnetic storm usually starts with increased intensity of Earth 's magnetic field called the initial phase, followed by a large decrease termed as the main phase, and the subsequent period of recovery phase. Effects of the geomagnetic storms on the ionosphere are more severe over the auroral zone, but the consequences are more complex in the equatorial anomaly region by prompt penetration of interplanetary electric field (IEF) and the disturbance dynamo. Study of the storms with different intensity levels provides excellent opportunity for verifying the reliability of empirical models. This study investigates anomalous variation of ionospheric TEC during the storm event (March 6–11, 2012) at Bangalore, Hyderabad, and Lucknow, situated at varying latitudes in the equatorial anomaly Indian region. This storm period consists of two successive events, (1) moderate (7 March 2012) and (2) strong (9 March 2012) storms associated with a massive solar flare (X5.4; 00:28 UT) on March 7, 2012. Fig. 11 represents geomagnetic Kp and SYM-H (equivalent to Dst) in the bottom panel, cosmic ray variation at five different latitudes (second from bottom), proton flux (third from bottom), plasma speed (middle), interplanetary electric field (Ey; third from top) and Z-component of interplanetary magnetic field (IMF-Bz; second from top), and TEC variation at Bangalore, Hyderabad and Lucknow (upper panel). It is clear from the figure that the SYM-H attains its minimum value in a series of two steps, (1) about −98 nT on 7 March (09:15 UT) and (2) about −149 nT on 9 March (08:00 UT) following two consecutive SSCs on 7 March (04:20 UT) and 8 March (11:03 UT) respectively. The penetration of electric fields from high latitude to lower latitudes is satisfied owing to southward turning of IMF-Bz. However, notable to say that fluctuations in the IMF-Bz intensity is marked within a range of ±18 nT before it turned northward. Similarly, significant depression in electric field (Ey; −14 nT) is noticed on 9 March with remarkable enhancement in the

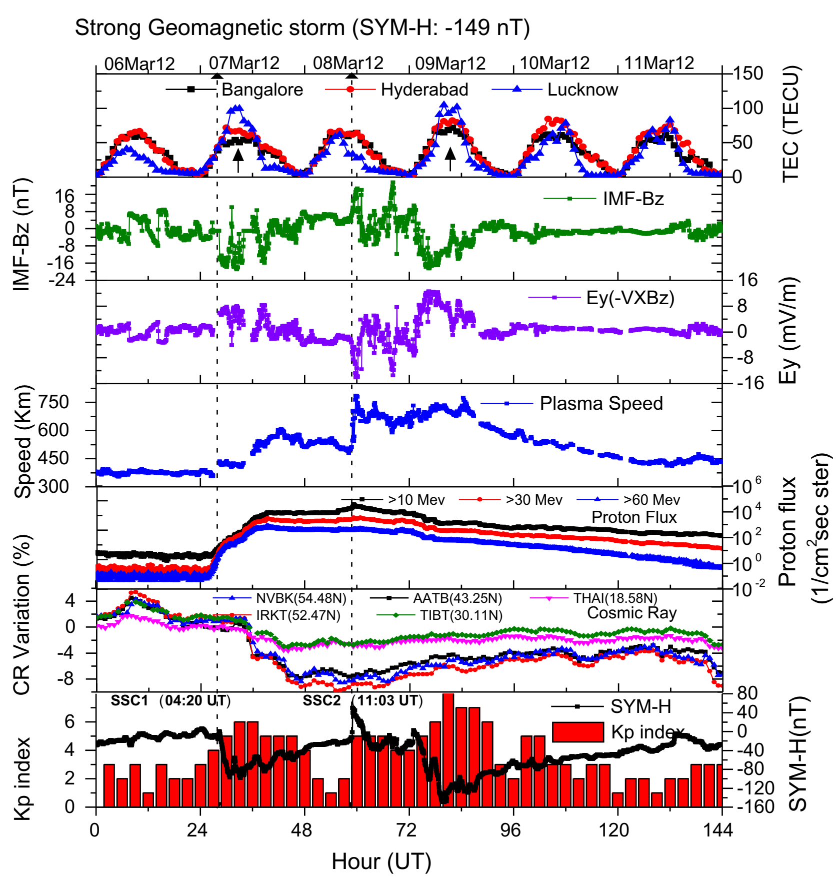

Fig. 11. Variations of geomagnetic Kp and SYM-H indices, cosmic rays, proton flux, Plasma speed, electric field (Ey), IMF-Bz, and GPS-TEC at Bangalore, Hyderabad, and Lucknow during geomagnetic storm of March 06–11, 2012.

plasma speed (>700 km/s). There is sharp increase in proton flux (measured by Geostationary Operational Environmental Satellite) and abrupt decrease (>8% at mid-latitude and ~3% at low latitude stations) in the galactic cosmic rays (Forbush decrease; FD) at different latitudes as measured by neutron monitors following the CMEs. In general the FDs are typically in a range of 3–20% and remain for a period of several hours to a few days. The diurnal peak of GPS-TEC is greatly enhanced at Lucknow (towards mid-latitude) than other two stations during the storm period. However, the level of increment on 7 March (moderate storm) is not prominent at Bangalore and Hyderabad. The enhanced value of TEC at Bangalore, Hyderabad, and Lucknow on the storm day (9 March) are observed to be ~71 (↑ 20%), ~82 (↑ 22%), and ~105 (↑ 94%) respectively around 09:00 UT, with maximum positive deviation than the averaged quiet days level being witnessed at Lucknow. The upward arrow (↑) indicates the % increase in the TEC at respective stations. The relatively larger deviation of the storm time TEC at Lucknow is possibly due to the poleward forcing of the fountain effect following the daytime prompt penetration of electric field (magnetospheric origin) at the equator.

4.6. Model comparisons

The VTEC extracted from global ionosphere maps (IGS-GIMs) are used as reference during analysis of the model estimations in this study. The ionosphere maps accessed from ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex are with spatial resolution of 5° longitude, and 2.5° latitude and temporal interval of 2 h. The IGS-GIM VTEC maps have become a reliable source of ionospheric information since 1998 due to global distribution of continuous-tracking sites (Feltens, 2003; Hernández-Pajares et al., 2009). In the present study, the VTEC at different latitudes are extracted from the final IGS-GIM by using bilinear spatial interpolation of VTEC values from four nearest grid points (Schaer et al., 1998). The GPS derived TEC is compared with the standard IRI and SPIM model predictions to examine reliability of the models over the low latitude Indian region. Past studies of Abdu et al. (1996), Bhuyan and Chamua (2002), Iyer et al. (1996), Bittencourt and Chryssafidis (1994) and Kumar et al. (2014b) report IRI overestimates electron density/TEC during solar minimum and underestimates during solar maximum, and shows comparatively good agreement during intermediate solar activity in the Indian and Brazilian sectors. The deviation is maximum in equinox and minimum in summer (Mukherjee et al., 2010). Also, Shastri et al. (1996) and Ezquer et al. (2004) have shown that the prediction accuracy varies with local time and location, over low latitudes the model overestimates during hours of minimum TEC and underestimates during peak hours. From the experiments over 600 km above South American anomaly crest region, Ezquer et al. (1999) conformed that IRI underestimates the observed electron density by 50% and 60% during equinox and winter, and overestimates by as much as 150% in summer. Also Bhuyan et al. (2003) reported that IRI failsfailure of the IRI model to produce the secondary peak of electron density during the low solar activity period (1994–1997).

The model comparison of TEC with in situ GPS observations is important for nowcasting and forecasting of near future ionosphere instability that would help in trans-ionospheric services. It is well known that there is shortcomings in the standard IRI model predictions over equatorial low latitude sector which estimates up to a height of 2000 km above Earth, whereas the GPS derived outputs are estimates of ionospheric TEC up to the GPS satellite flying height (i.e., about 20,200 km). Hence, anticipating that the extension of IRI model to the plasmasphere or up to the altitude of the GPS satellite orbits might justify the comparison with GPS derived TEC, the SPIM model is considered for this study. After development of SPIM model, its predicted outputs at a location and its comparative study with ground-based GPS derived TEC, eventually its reliability at four different locations, with varying latitudes in the low latitude anomaly Indian region, is attempted in this study with a year of datasets.

Fig. 12 depicts diurnal distribution of GPS-TEC, IGS-GIM TEC, and IRI as well as SPIM model TEC estimations at Bangalore, Hyderabad, and Delhi during the quiet period 19–21 October 2012. During this period, we observed relatively lower deviation of GPS-TEC from the IGS-GIM TEC at Bangalore (about 20%) and Hyderabad

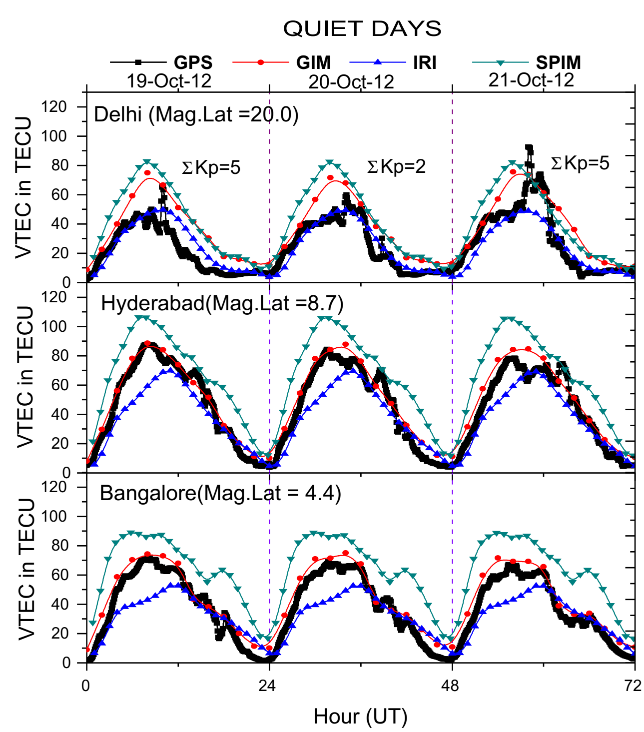

Fig. 12. Comparison of GPS-TEC with IGS-GIM, IRI, and SPIM model estimations at Bangalore, Hyderabad, and Delhi during quiet period (19–21 October 2012).

(about 15%) during daytime but the deviations exceed 50% during nighttime at both the stations. However, the deviation of GPS-TEC from the IGS-GIM TEC is seen to be relatively more at Delhi (exceeding 70% during nighttime) except for few hours in the morning. The disparity between both the values at Delhi (not an IGS station) is possibly due to its spatial distance from the IGS stations whose data are used for the GIMs. Here it must be noted that the accuracy of ionospheric TEC grid in IGS-GIM varies between 2–8 TECU (Jakowski et al., 2011), and our GPS derived results are consistently lowered by about 5 TECU than the IGS-GIM interpolated value. As the major source of IGS-GIM TEC is world-wide network of IGS stations, the grids having IGS stations inside would give better accuracy than the grids without any IGS stations. Reports of Ho et al. (1997) suggests the vertical TEC error level of the IGS-GIM diurnal maximum TEC remaining within a range of 10–20% (between 3–10 TECU) of the actual diurnal peak value, the largest error being occurred near the equator during the storm period. They also report relatively better performance of the GIM in the middle latitude ionosphere within 1000 km of the source station which corresponds to 14° elevation angle cutoff. However, the IRI-2012 model predictions (blue curves) underestimated the measured value towards equatorial stations but are approximately similar to GPS-TEC towards mid-latitude station. The SPIM model predictions (dark cyan curves) show much higher values than the GPS derived TEC and IRI outputs at all stations, though the second maximum is prominent at station towards the equator, i.e., Bangalore. Similarly, during storm period of 6–11 March 2012 (Fig. 14), although the IGS-GIM interpolations agree with in situ GPS derived TEC, the storm models of IRI and SPIM do not respond well to the commencement of storm.

We computed the correlation of GPS-TEC with IGS-GIM, IRI and SPIM outputs during selective quiet and storm periods as shown in Figs. 13 and 15 respectively. The best correlation between GPS-TEC and GIM-TEC during quiet period (19–21 October 2012) is observed at Bangalore, followed by Hyderabad and Delhi. However, during storm period (6–11 March 2012) we found relatively low correlation between the two at Bangalore ($R^2 = 0.793$). On the whole, during the selected quiet period the correlation between GPS versus GIM, IRI, and SPIM TEC are seen to be relatively lowered at Delhi. However, the correlation coefficient of GPS versus SPIM is comparatively lowered than the GPS versus IRI values at all stations. This suggests that the assumption of SPIM prediction superiority from the IRI model might not be remarkable across the low latitude and equatorial region. Fig. 16 shows the comparative study of seasonal variations in GPS-derived TEC with global map (IGS-GIM TEC) and the standard models (IRI and SPIM) at Bangalore, Hyderabad, Mumbai, and Lucknow during the period November 2011 to October 2012. Both the IRI and SPIM models overestimated than the in situ measurements in all seasons, however the difference is less during the December solstice in our study. This is due to fact that the December solstice chosen in this study fall under high solar active period. The double-hump structure with second maximum during equinoctial season

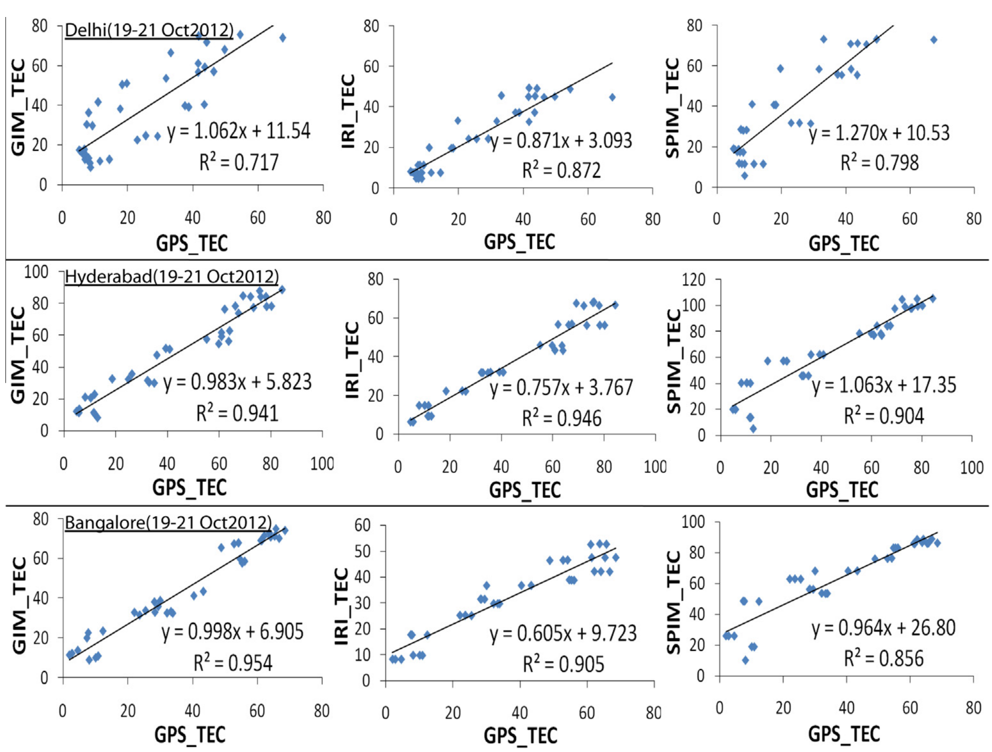

Fig. 13. Correlations between GPS-TEC versus IGS-GIM, IRI-2012, and SPIM Model predictions during quiet period (19–21 October 2012).

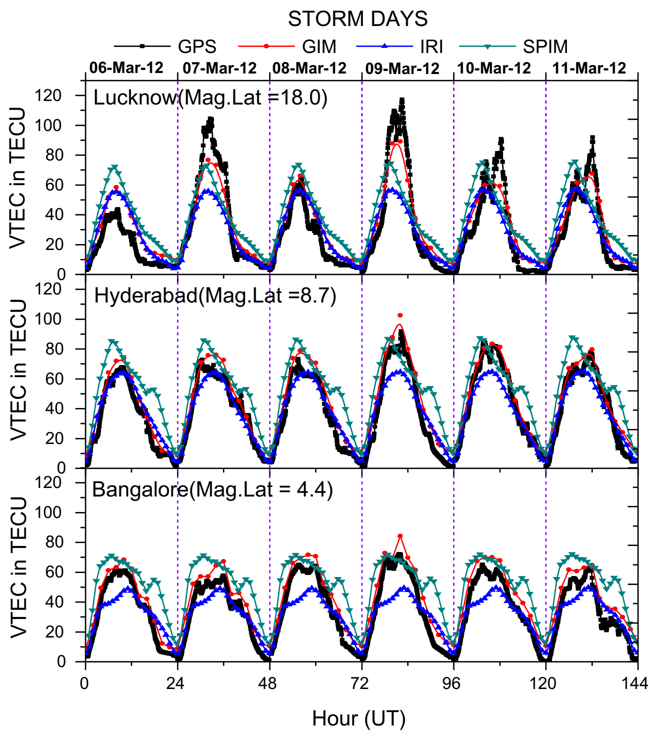

Fig. 14. Comparison of GPS-TEC with IGS-GIM, IRI, and SPIM model estimations at Bangalore, Hyderabad, and Lucknow during storm period (06–11 March 2012).

is prominently visible at the near-equatorial station Bangalore, and less prominently at Hyderabad, but the seasonal average TEC at Mumbai and Lucknow do not show any secondary peak. However, the secondary maximum of IGS-GIM TEC and GPS measured TEC is sparsely seen only at Bangalore and not distinguishable at other stations. It may be noticed that estimations from IRI and SPIM concur well with each other in most of the time except during peak hours of the day. The % increase of SPIM predictions from the IRI during the peak hours at Bangalore (18%, 27%, 15%, and 20%), Hyderabad (13%, 36%, 17%, and 26%), Mumbai (17%, 37%, 31%, and 32%), and Lucknow (13%, 28%, 18%, and 28%) during December solstice, March equinox, June solstice, and September equinox respectively. The overestimation of both the models and particularly in the SPIM is due to the fact that most of the experimental data for the IRI model are collected from mid-latitudes and the upper half of SPIM model, i.e., the SMI model itself is based on most of the data from high-latitudes. Also the literatures of previous studies describe that IRI over estimates in general over low latitudes during low and moderate solar activity periods, the SPIM is a merged product of IRI and SMI, hence it is believed that the combined product might overestimate at the low latitudes. Recent studies of Zakharenkova et al. (2015) also reports over estimation of SPIM observations than the GPS-TEC at European mid-latitude station especially during low and moderate solar activity condition. They suspect it could be either due to the plasmasphere addition to the IRI or the (top side + plasmasphere) estimates This suggests that the present model lacks reliability at the low latitude Indian region, hence further improvements are necessary for relatively better predictions in the low latitudes.

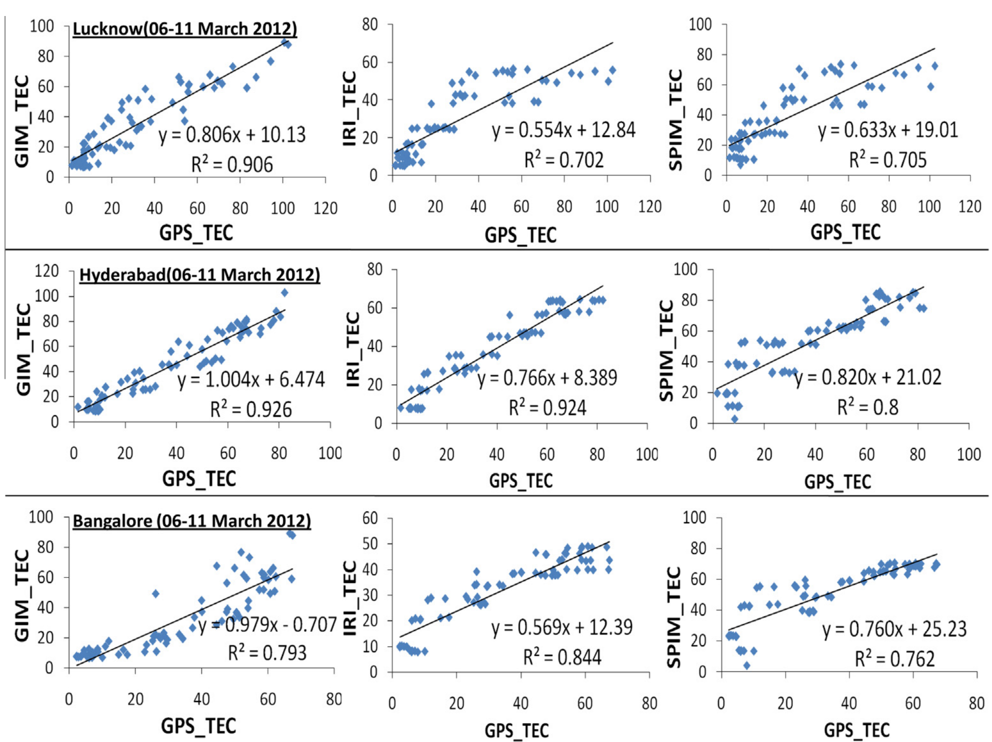

Fig. 15. Correlations between GPS-TEC versus IGS-GIM, IRI-2012, and SPIM Model predictions during disturbed period (06–11 March 2012).

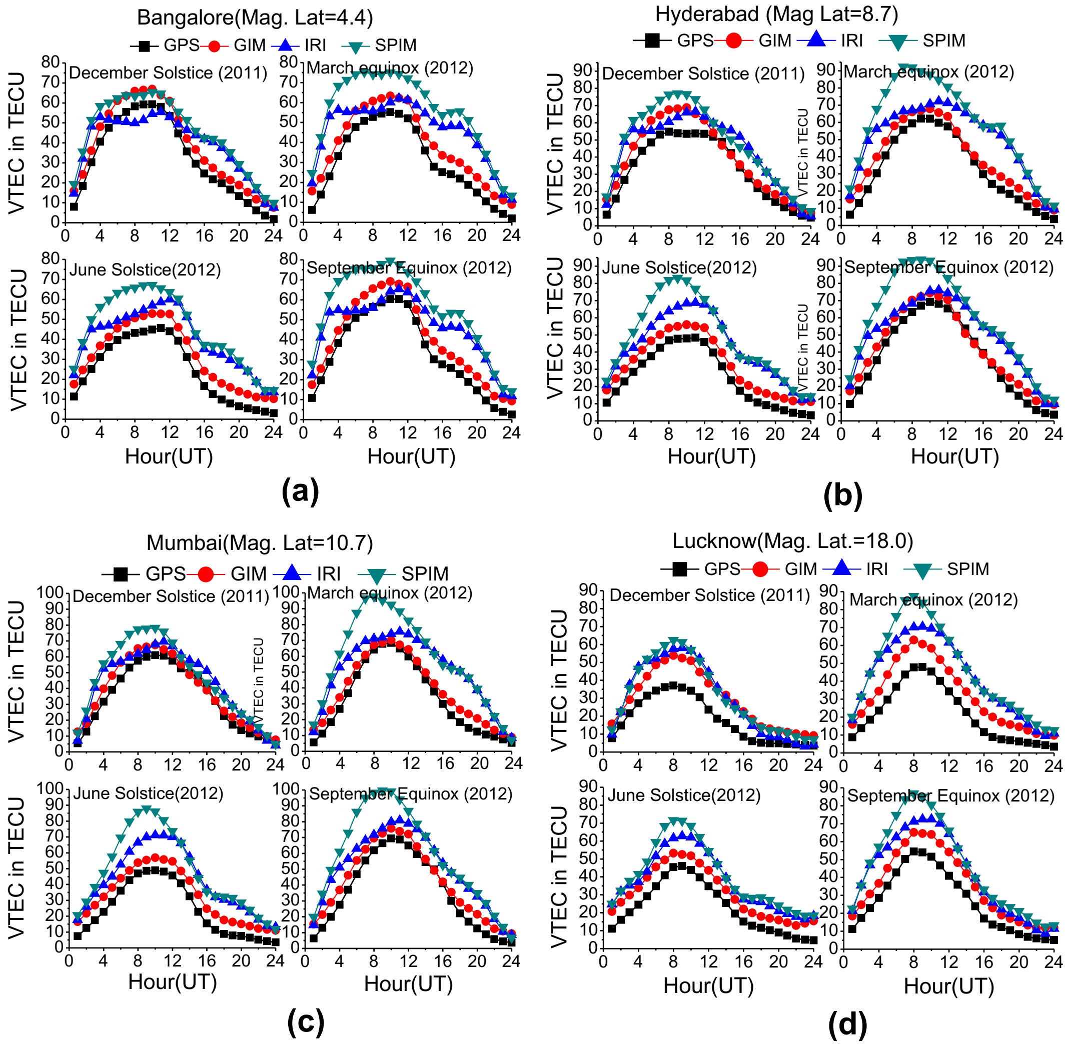

Fig. 16. Comparison of seasonal variations of GPS-TEC with IGS-GIM, IRI, and SPIM model estimated TEC at (a) Bangalore, (b) Hyderabad, (c) Mumbai, and (d) Lucknow during November 2011 to October 2012.

5. Conclusion and discussions

In this study ionospheric TEC is investigated at seven ground-based permanent GPS stations with varying latitudes across Indian region during November 2011 to October 2012. The major findings of the study are as follows;

(i) The typical quiet day variation of TEC demonstrates a gradual increase of electron content with sunrise, peaking around local afternoon between 14:00–16:00 IST (IST = UT + 5:30), and reaching minimum value after midnight. However, the overall amplitude of TEC curve varies by days, months and seasons with apparent positions of Sun over a location and moreover the strength of electrojet at the equator.

(ii) Towards the end of year 2011, the solar activity was quiet high portraying significant changes in TEC due to increased eruptions from the Sun. Hence, the seasonal variation statistics over the region elucidates high electron content during autumnal equinox followed by spring equinox. Among the solstice seasons, the December solstice has markedly increased value than the June solstice. This could be due to the winter anomaly attributable to the changes in the $[O/N_2]$ ratio which is more frequent during the high solar activity periods in the northern hemisphere.

(iii) Remarkable enhancement in diurnal peak TEC due to the strong geomagnetic storm on 9 March 2012 is markedly noticed around 9:00 UT at Lucknow (∼105 TECU), followed by Hyderabad (∼82 TECU), and Bangalore (∼71 TECU).

(iv) Model estimations of recent version of the IRI model (i.e., IRI-2012) during quiet periods show very good agreements during night time at all stations, but during daytime, it underestimates relatively towards the equatorial stations. Nevertheless, the SPIM outputs much higher value of TEC than the GPS observations at all stations, the difference being less towards the mid-latitude stations.

(v) During disturbed period, the storm sudden commencements (SSCs) and the abrupt transition in TEC are not clearly noticed in either of the two standard ionosphere models (IRI and SPIM).
(vi) Similarly, the results of seasonal variations demonstrate overestimation of IRI as well as SPIM through out the period in this study.
(vii) It is inferred from the IRI and SPIM outputs that both the values are somehow concurring well with each other except during the peak hours of the day, whilst the SPIM estimations are markedly higher than the IRI estimations.

The present study put across lacking of the reliable predictions of TEC from IRI as well as SPIM models, in the low latitude EIA region. Although the second maxima, a feature of diurnal plots over low latitude stations, is distinctly visible in the IRI and SPIM, the overall prediction is very high in SPIM. This is probably due to two main reasons, firstly the upper sub-part of the model, i.e., Russian SMI model is typically a high latitude model, most of the data belongs to high latitude. Secondly, the lower part of SPIM is the IRI model, which itself overestimates during low solar activity and underestimates during high solar activity condition. From most of the previous literatures in context of IRI predictions at low latitudes and also our results it is known that the IRI is lacking reliable results over the region due to the fact that most of the data used in this empirical model are collected from mid-latitudes. Hence the combined product of IRI and SMI, i.e., the SPIM is obvious to result overvalue unless necessary care is not taken on model running over low latitudes. The EEJ is a characteristic phenomena over geomagnetic equator controlling the anomaly strength, hence spatial and temporal distribution of F-region electron density, i.e., TEC at low latitude region. Conversely, the reversal of EEJ strength, i.e., the counter equatorial electrojet (CEJ) occurring mostly in the early morning or afternoon time may tremendously effect the pumping of electrons towards the anomaly crest region. Hence, further improvements in the existing models are desirable for relatively better predictions of the ionospheric electron density/TEC over the anomaly zone in the low latitude Indian subcontinental region.

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