Ionospheric TEC Variations at low Latitude Indian Region

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Additional information is available at the end of the chapter

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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 the solar radiation producing free electrons from the existing atmospheric gases. It extends from 50 km to more than 1000 km altitude. Although solar radiation is stronger at higher altitude but there are very few gaseous atoms at this height; hence the ionization is sparse. The ionospheric properties such as electron density, ion and electron temperatures, ionospheric composition, and dynamics vary with altitude, latitude, longitude, local time, season, solar cycle, as well as magnetic activity. Ionization changes at the equatorial and polar regions are known to be high compared to relatively moderate changes in the mid-latitude region. The variability of the equatorial and low latitude ionosphere is due to the large-scale electrodynamics associated with the equatorial electrojet (EEJ), plasma fountain, equatorial ionization anomaly (EIA), equatorial wind, and temperature anomaly etc. The EEJ refers to an enhanced daytime eastward electric current in the E region due to a strong vertical polarization electric field developed in a latitude band of $\pm 3°$ about the dip equator. This eastward electric field at the dip equator gets mapped onto F region through the $(E \times B)$ drift, lifting the plasma to higher altitudes. The uplifted 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 called as the "fountain effect" [2]. The EIA can be described by a trough (minimum) in the ionization densities around the dip equator and a crest (maximum) around $\pm 15°$ magnetic latitude on each hemisphere. The EIA intensity on a day and its latitude of crest development explicitly depends on the EEJ strength at the equator. Hence, there is strong EIA on a day with strong EEJ, less prominent EIA on a day when CEJ develops, and even absence of EIA crest during certain severe geomagnetic disturbances [19]. All these unique features at the equatorial and low latitude ionosphere are due to the perfect horizontal alignment of the geomagnetic field

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lines at the dip equator and the shifting between the geographic and geomagnetic equator [10].

The quiet day variation of the low latitude F-region electron density depends on the strength of EEJ and thereby the intensity of fountain effect over the region. However, the irregular disturbances occur randomly, major source of which are the solar flares and coronal mass ejections, causing geomagnetic and ionospheric storms, sudden ionospheric disturbance (SID), polar cap absorption (PCA), as well as ionospheric scintillations. Solid Earth-related phenomena namely volcanoes and earthquakes may also cause perturbations in the ionosphere triggered by the seismic surface waves, though usually uncommon in comparison to solar and magnetospheric activities. The level of ionospheric activity is described in terms of electron density quantified by the number of electrons in a vertical column of cross-sectional area $1m^2$, called as total electron content (TEC) of the medium [34]. The TEC is measured in a unit called TECU, where $1\ TECU = 1 \times 10^{16} electrons/m^2$. It is well known that major part of the F-layer density refers to the TEC, but behavioral changes of both may be different in the low latitudes during certain geomagnetic conditions as the F-layer density is only restricted to the bottom side of the ionosphere. Broad features in the temporal and spatial behavior of 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. 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 free electrons and ions in the ionosphere. Fortunately, the electron density is retrievable from the refracted signals by modeling of the associated signal delays. Exploitation of the dual frequency global positioning system (GPS) signals for studying ionospheric characteristics is now of great interest due to the dispersive nature of the ionosphere at the frequency range of GPS signals. Previously the satellite-based GPS system was mainly used for positioning, navigation, and time-transfer. However, the GPS signals traverse the dispersed ionosphere carrying its signature, hence offer exceptional opportunities for ionospheric research. The ionospheric TEC from ground-based GPS observations has been investigated widely in the past few decades. The GPS satellites orbit twice a day at about 20,200 km altitude in 6 orbital planes covering almost whole part of the globe. The satellites continuously broadcast position and time information towards receivers on ground, aircraft, or other satellites in the form of one-way ranging spread spectrum pseudorandom noise codes, i.e., precision code (P), coarse-acquisition code (C/A), and navigation data stream modulated upon L-band carrier frequencies ($L1 = 1575.42MHz$ and $L2 = 1227.60MHz$). While passing through the intervening ionosphere, the GPS signals experience phase advance and group delays, mostly due to the free electrons along the signal path from the satellite to the receiver, i.e., the TEC. A standard TEC measuring technique involve ground or space-based receivers capable of processing signals from satellites effectively by the synchronized exploitation of carrier phase advance and group delay observations. For processing the dual frequency GPS data for retrieval of TEC, the International GNSS Service (IGS) Analysis Centers routinely provide the ephemerids and the differential code biases (DCBs). The DCBs are one of the major sources of error during measurement of precise TEC from the GNSS data which needs to be estimated carefully for the regional and local network of GPS receivers. A standard DCB estimation technique following the least squares principle and constraining through standard deviation minimization, has been provided in Jin et al. [28].

2. Importance of Ionospheric studies over Indian region

The importance of ionosphere studies over the Indian region is due to its large span of coverage across the northern equatorial ionization anomaly zone (EIA). The magnetic equator passes beneath the southern tip of the country through the Indian ocean, and the northern EIA crest contour lies over central India straddling the line joining Kolkata and Ahmedabad. Notable to mention 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. The notable feature controlling the spatio-temporal distribution of electron density in the equatorial and low latitudes over Indian region is the intense east⇆west electric current (EEJ) driven by flow of neutral wind over the dip equator as a consequence of the temperature gradients between the dawn and the dusk terminators. The EIA intensity on a quiet day depends on the overall drift of plasma through the fountain process and its subsequent diffusion towards higher latitudes. However, the regular EEJ development process gets corrupted during different seasons and certain solar-terrestrial events due to interference of meridional wind, gravitational tidal forces and external electric fields manifesting positive or negative effects. The strength of EEJ is manifested in the magnetometer H variation; hence it acts as a proxy EEJ index over the dip equator. In context to Indian region the magnetic data from two stations, an equatorial station Tirunelveli (in the vicinity of EEJ) and an off-equatorial station Alibag (outside EEJ effects) are used to estimate the EEJ strength. Earlier, the magnetometer station at Trivandrum and Alibag were used for calculating EEJ; however after 30 Oct 1999, the Trivandrum station was decommissioned in place of which the Tirunelveli magnetometer has been used for this purpose. A standard way of estimating EEJ strength is to first subtract the night time mean H value at each station and then finding the difference between two stations, i.e., $[\Delta H_{TIR} - \Delta H_{ABG}]$, ensuring removal of magnetospheric contributions. This method was suggested by Chandra et al. [12] and later used by several workers [11, 44, 52] and references therein.

3. Ionospheric TEC over Indian region

Prior to exploitations of global navigation satellite systems (GNSS), there was less extent of the spatial and temporal imaging of the ionospheric TEC and related phenomena over Indian subcontinental region, with the existing ground and space-based measuring techniques, such as ionosondes, topside sounders, backscatter radars, and satellites. All these measurements are based on various principles like backscattering, Doppler effect, Faraday rotations etc. Nevertheless, these methods have limitations of their own in terms of complete profiling, widespread operations, and usability expenses. Now a days, GPS and GLONASS observables are potentially used for imaging the global as well as regional ionosphere due to all-time all weather availability of their signals anywhere on or above the earth. Moreover the instigation of GAGAN (GPS Aided and GEO Augmented Navigation system) and IRNSS (Indian Regional Navigation Satellite System) has opened a new era of imaging the equatorial and low latitude ionosphere over Indian region.

3.1. Earlier TEC studies from Faraday rotation and differential Doppler measurements

The ionospheric TEC studies over Indian region started during early 1962 by the National Physical Laboratory (NPL), New Delhi from the radio signals of the Russian orbiting satellite

COSMOS-V. Subsequently, many other research groups in India began active participation in studying the ionosphere by using the polar orbiting satellites signals such as BE-B, BE-C and INTASAT, etc. The physical presence of EIA in the Indian sector was first reported by Ram Tyagi and Somayajulu [48] with a latitudinal network of stations spreading from equator to mid-latitudes, later supported by similar studies of many researchers. Signals from geostationary satellite Intelsat-2F2 in the Indian sector were first used by Basu et al. [5] and Bhar et al. [6] at Kolkata, near the anomaly crest latitude studying diurnal variations in TEC and its day-to-day variability, distinct features like pre-dawn minimum (short-lived), broad day maximum, and their apparent periodic variation. They also computed the equivalent vertical slab thickness using additional ionosonde parameter (NmF2) confirming an early morning peak (1200 km) followed by an average diurnal value of about 400 km, its periodic variation often referred to as Travelling Ionospheric Disturbances (TIDs). Nevertheless, the first coordinated campaign for TEC measurements was initiated during the year 1975-76 with the opportunity of signals from the geostationary satellite ATS-6 received at stations extending from equator to the anomaly crest latitude and beyond, which markedly supported the occurrence of maximum TEC values around the crest region through the effects of EEJ at the equator [19]. The characteristics of the TIDs were extensively studied by Deshpande et al. [20], reporting its peak occurrence around 14:00 hrs LT at all the stations with a wave period of about 20 min. Extensive radio beacon studies from the Japanese geostationary satellite ETS-II (130°E) were then done by many Indian groups signifying periodical variability of TEC with typical low latitude features such as nighttime minimum, sharp early morning increase, broad day maximum, and occasional post-sunset enhancements. Studies also reveal equinoctial and winter maxima in TEC with its minimum values during summer months and effects of solar activity on TEC. Besides the characteristic diurnal features of TEC, its latitudinal gradients were also discussed by Rama Rao et al. [50], from the measurements at Waltair and Kolkata during the period 1980-81. Using measured TEC at a chain of six stations in the Indian region from ATS-6 satellite during 1975-76, the electrojet control over the EIA region was reported, suggesting that the location of crest development depends strongly on the Integrated EEJ (IEEJ) strength. Studies confirm development of crest away from equator during the strong EEJ days, while anomaly might be absent an a day having no EEJ or an abnormal CEJ which indicates that the diurnal peak TEC is positively correlated with the daytime integrated EEJ strength ($\sum$ EEJ). The TEC data were also studied to observe the effects of geomagnetic storms indicating its increased/decreased value during daytime/nighttime storm and its dependence on the strength of the main phase of the storm.

3.2. Recent TEC studies from GPS observations

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 conditions around the globe. During the last decade, with the launch of the jointly coordinated GAGAN program in India, a network of dual frequency GPS stations were being established at 18 locations across the Indian subcontinent. In fact GAGAN is one among the SBAS systems initiated and managed by the Indian Space Research Organization (ISRO) and the Airport Authority of India (AAI) for reducing the ionospheric, satellite clock errors and the ephemeris errors from the GPS satellites by using differential correction technique. Currently, the system is under certification process and very soon it will be publicly available to ensure a good positional accuracy over the Indian region. The complementary opportunity of this program is to continuously monitor TEC and scintillations, and studying their temporal and spatial behaviour in a greater detail, eventually for increasing positioning and navigation accuracy across the Indian territory. The present chain of GPS receivers has provided an opportunity to attempt a comprehensive and long-term study of the Indian ionosphere and its extension to the plasmasphere. Besides the GAGAN program, the Indian Regional Navigation Satellite System (IRNSS) is a regional navigation satellite system under development by India to relatively improve the positional accuracy (better than 20 m) for the users in India as well as the surrounding region within its primary service area. In this system, the ionospheric corrections for single frequency users of L5 band are provided at $5° \times 5°$ grids at 350 km altitude for correcting the delays [65]. However the 1^{st} order ionospheric corrections could be achieved with the two frequencies L5 and S in the dual frequency receivers. The whole aim is to generate a GPS based regional ionosphere model for navigational and position applications with the analysis of the temporal and spatial distribution of ionospheric TEC over the equatorial and low latitude Indian region, as the contemporary global models can not sustain reliability in the highly varying environment of this region owing to their scarcity of adequate experimental data.

For computing TEC from GPS observables over the low latitude anomaly Indian region, the selection of valid ionospheric piercing point (IPP) altitude is an important aspect. From a number of trial and error methods, Rama Rao et al. [49] inferred that the commonly used IPP altitude of 350 km may be taken in the Indian sector, subject to the signals received from the satellites are with elevation angles above 50°. Nevertheless, there are still unsolved questions on the assumption of uniform thin shell, its altitude, and its validity over the low latitude Indian region. With the slant TEC (STEC) of all GPS satellite ray paths, the three dimensional (3D) ionospheric electron density profiles can be produced through a tomography reconstruction algorithm which would better represent the ionospheric variations over a region [30]. It can integrate the data from all available GPS receivers as well as visible GPS satellites at each of these receivers above a user-specified elevation cut-off angle. From a sufficient number of GPS data generating the 3D picture of the ionosphere above, the equivalent ionospheric slab thickness can be estimated which has great influence on representing the shape of the ionospheric electron density profile. Thus it helps in understanding the nature of variations and modeling of the upper atmosphere. The equivalent slab thickness can be defined as the ratio of the TEC to the maximum electron density of the F-region (NmF2). The equivalent slab thickness and its variations over low latitude Indian region has been studied in details by many researchers [8, 60] and references therein, with more or less success in the results as the ionosphere over the region is highly variable owing to resulting larger uncertainties. Moreover, the systematic study of diurnal and latitudinal TEC and slab thickness from GAGAN network of stations along with other individual GPS and ionosonde monitoring stations across the Indian region do strengthen the earlier reports of dependency of latitudinal variation of TEC on the IEEJ strength, and higher value of TEC during equinoctial season followed by the winter and the lowest during summer.

4. Regular TEC variations over Indian region

Investigations have been carried out dynamically in the last decade with the GAGAN set of TEC data along with other individual stations and satellite data resources by researchers at various organizations, institutions, and universities, to understand and model the quiet time diurnal, seasonal, latitudinal variations of TEC and effects of other solar-terrestrial events across the Indian low latitudes. The regular variations are due to the apparent movements of the Sun and Earth. However, the lunar and solar cycles do affect in a more or less regularized manner with maximum TEC during high solar activity period which gradually decreases towards the low solar activity periods. The ionospheric effects of geomagnetic lunar tidal movements in the lower atmosphere due to the lunal cycle changes over the month. In general, the net TEC on a regular day is the integrated effect of all these parameters. This section discusses the diurnal and seasonal changes in the low latitude Indian ionosphere, and their latitudinal disparities.

4.1. Diurnal variation

The diurnal variation in TEC is due to the regular 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 the local solar radiation and the field-aligned diffusion of the transported electrons from the equator. With excellent coverage of GAGAN network of GPS-TEC data at 18 stations Bhuyan et al. [10] during $2003 - 2004$ and Rama Rao et al. [49] during 2004-2005 demonstrated the diurnal variation in TEC in the EIA region as a minimum in the pre-sunrise hours, which sharply increases to maximum values between 13:00 to 16:00 LT, while the peak at the equator occurs around 16:00 LT. Beyond the anomaly crest, the diurnal maximum value decreases with increasing distance from the geomagnetic equator. The nighttime TEC is almost flat attaining lowest value during 22:00 to 06:00 LT, similar to that of mid-latitude region. The minimum and maximum variation of TEC during a day is about 5-50 TECU at the equator and about 5-90 TECU around the crest region. Also, significant day-to-day variations are seen at all the stations, predominantly during the daytime hours, with a higher value at the EIA crest regions corresponding to the equatorial electrojet (EEJ) strength. Subsequently, Bagiya et al. [3]($2005 - 2007$), Chauhan et al. [13]($2006 - 2009$), Galav et al. [23]($2005 - 2010$), Karia and Pathak [33]($2008 - 2009$) have studied the TEC variation at the respective near anomaly crest stations at Rajkot, Agra, Udaipur, and Surat, confirming similar behavior of TEC as studied by the previous researchers. Reports of Panda et al. [42, 43] from studies of a chain of stations over the Indian region during $2011 - 2012$, also suggests comparatively broader and longer duration of the day maximum TEC towards equator, while converse effect is observed beyond the anomaly crest station. The nighttime variability is maximum towards equator and minimum towards stations beyond the anomaly crest region. They also noticed that during the month of Jan 2012, the latitudinal range of crest development varies a lot, which is possibly due to fluctuation of EEJ strength owing to the seasonal variation of geomagnetic lunar tides manifesting exceptional global enhancement around this month.

Fig. 1 shows diurnal variation of TEC at different stations on a typical quiet day (19 Oct 2012, $\Sigma Kp = 5$). It is clear from the figure that the crest has been developed around Kolkata (highest TEC), while the stations at Lucknow and Delhi perceived least values being situated beyond the anomaly crest latitude. Now 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.

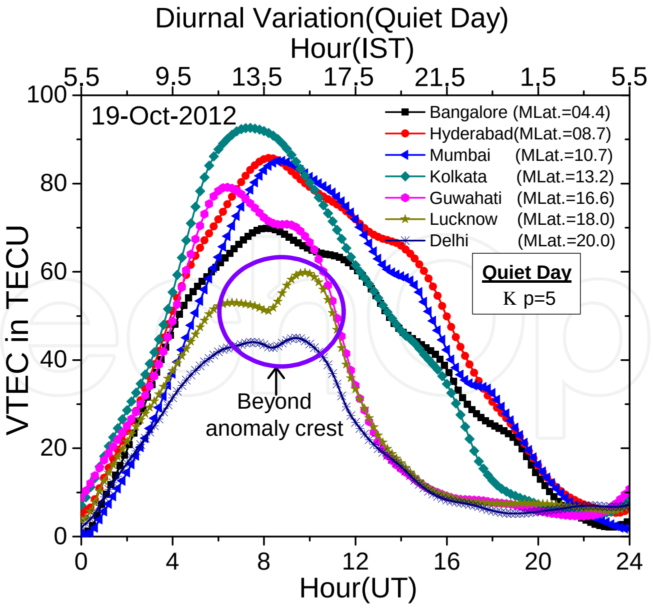


Figure 1. Diurnal variations of GPS-TEC at different latitudes across Indian region on a typical quiet day (19 October 2012; Σ Kp=5)[43].

4.2. Seasonal variations

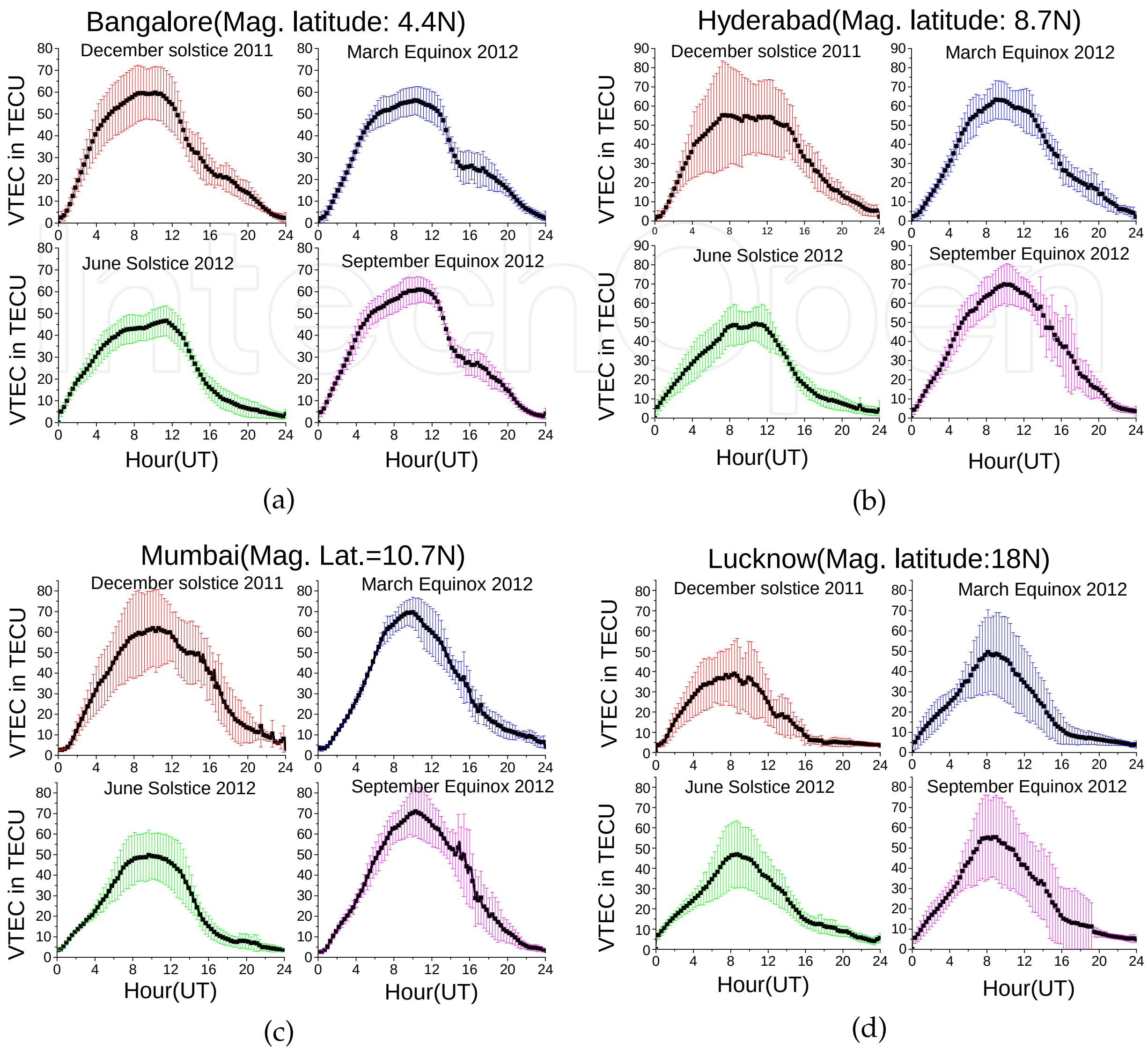
The seasonal variations in TEC is due to the tilt and rotation of the earth around the Sun; the relative position of the Sun moves from one hemisphere to the other with seasonal variation of solar zenith angle and intensity of radiation at any geographical location. Usually, the whole year is categorized into four seasons, i.e., December solstice (November, December and January), 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 occurs above the equatorial region. The amplitude of the diurnal maximum is higher in the equinoxes and lower in the solstices, thus exhibiting the semiannual variation. Further, the relatively higher TEC during the winter than the summer solstice 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. 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 electrodynamics over the region . Fig. 2 depicts seasonal variation of TEC at (a) Bangalore, (b) Hyderabad, (c) Mumbai, and (d) Lucknow during the period November 2011 to October 2012 [43]. The plots show a semiannual mode, maxima in equinoxes and minima in the solstices. The September equinox shows slightly higher value, i.e., $\sim$ 61 TECU (Bangalore), $\sim$ 70 TECU (Hyderabad), $\sim$ 69 TECU (Mumbai), and $\sim$ 55 TECU (Lucknow), than the March equinox and are consistence with the reports of Galav et al. [23] as studied at Udaipur (24.6 N, 73.7 E, Mag. Lat. 15.6 N) during 2005-2010. However, Bagiya et al. [4] have reported that descending period of solar cycle-23 (2005-2007) at anomaly crest Rajkot station, March equinox shows larger value than the September equinox.

Although results at different latitudes during the similar solar activity period do agree, still there is spatial inconsistency depending on various background parameters at different latitudes. During the equinoxes, the morning rise and afternoon decay of TEC is sharp compared solstice seasons. Further, TEC is higher in the December solstice (winter anomaly) compared to that in the June solstice. In practice, the December solstice shows higher TEC than June solstice 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. The increased value of December solstice than June solstice has been explained earlier; however similar studies during certain low solar activity period do report reversely. However, there is a direct impact of solar activity over the spatial TEC variation along with other electrodynamic parameters over the low latitude region. In general, the day-to-day variation of TEC at low latitudes depend on: (a) solar ionizing flux; (b) sunspot activity; (c) magnetic activity; (d) EEJ strength ; and (e) neutral atmospheric temperature, composition, and winds. The prevailing EEJ intensity is the dominant factor for variation of TEC near the anomaly crest while the solar ionizing flux has a greater impact near the equatorial latitudes. The daytime variability is less at and near the equator than the anomaly crest. Nighttime variability is more than daytime variability in all seasons and at all latitudes except for Delhi where TEC exhibits the highest variability in the evening hours. The double-hump structure of diurnal TEC plots with the second maximum during evening hours are prevailing features of near-equatorial ionosphere that are distinctly visible during the equinoctial season and solar activity periods.

4.3. Latitudinal variation

As latitude increases from the equator towards the 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 the electric field is eastward during the 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 through the $(E \times B)$ drift of plasma which then diffuses along the slope of magnetic field lines at approximately $\pm 15^\circ$ geomagnetic latitudes forming crests on both the hemispheres (equatorial ionospheric anomaly region). Larger the EEJ strength at the equator, the higher is the plasma drift and greater is the strength of anomaly with the crest at farther latitude from the equator. Hence, the TEC is believed to be increased gradually towards the anomaly crest regions, beyond which the value further decreases to attain lower value at mid-latitude regions. Fig. 3 as borrowed from Rama Rao et al. [49], represents the typical contour plots of TEC with its diurnal variation on an equinoctial day (23 Oct 2004), a winter day (3 Dec 2004), and a summer day (22 Jun 2004) as derived from seven Indian GPS stations with common latitude of 77° E.

The Fig. 3 clearly shows gradual increase of TEC from equator to the anomaly crest beyond which it again decreases significantly. The magnitude of diurnal peak TEC is highest on the equinoctial day followed by winter day and the least value on the summer day which tallies well with the integrated EEJ strengths. The latitudes of crest development is also remarkably varies with strength of EEJ indicating that the equatorial electrodynamics plays a major role in distribution of plasma over the equatorial and low latitude Indian region. The region just above the EIA crest manifest abnormal daytime variation of TEC and the day



(a) (b) (c) (d)

Figure 2. Seasonal variations of GPS-TEC at (a) Bangalore, (b) Hyderabad, (c) Mumbai, and (d) Lucknow during the period November 2011 to October 2012 [43].

maximum also occurs slightly later than equatorial region. This is possibly due to the time lag between peak of EEJ strength and maximum intensity of fountain effect. The latitude of crest development varies with the strength of EEJ, season of the year, and the solar activity condition. Nevertheless, the TEC above mid-latitude region varies less during the day unlike the low and high latitude regions which are susceptible to the solar-terrestrial disturbances.

5. Storm-time disturbances of TEC over Indian region

Geomagnetic storms are temporary disturbances of the Earth's magnetosphere, associated with coronal mass ejections (CMEs), coronal holes, or solar flares, which changes the magnetosphere-ionosphere-thermosphere coupling processes. During the storm, interplanetary electric field (IEF) gets mapped to the polar ionosphere through magnetic reconnection and directly penetrate (prompt penetration electric field;PPEF) towards the

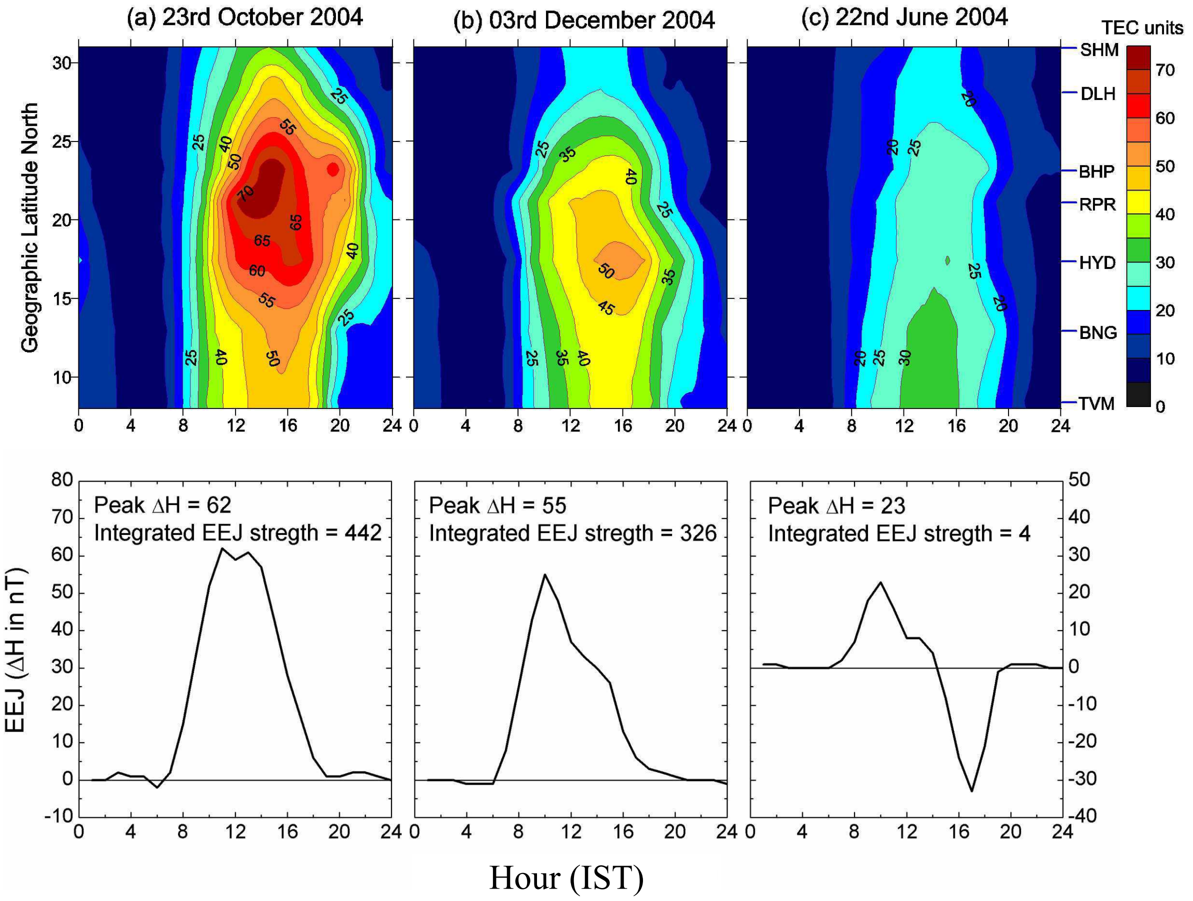
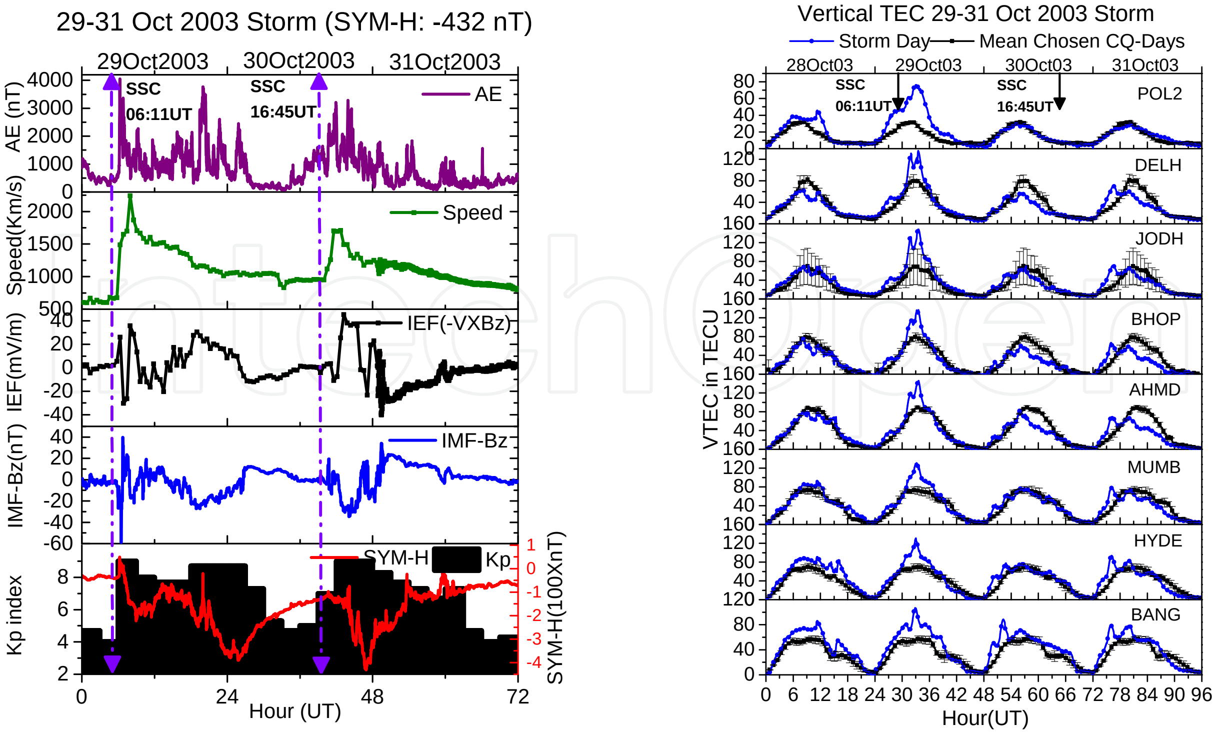


Figure 3. Typical contour plots of TEC (top) showing its diurnal variations as a function of the geographic latitude on (a) an equinoctial day (23 Oct 2004), (b) a winter day (3 Dec 2004), and (c) a summer day (22 Jun 2004) derived from seven GPS stations with a common longitude of 77°E across Indian region along with the respective variations of integrated EEJ strengths (bottom) (Source: Rama Rao et al. [49]).

equatorial region manifesting enhanced daytime E-region electric field. This electric field is eastward (westward) during the daytime (nighttime) and may sustain for short duration or even for few hours. In addition, Joule heating at the auroral thermosphere owing to particle precipitation, causes high-velocity meridional neutral winds to travel towards the equatorial region, consequently generating the disturbance dynamo electric field and the traveling ionospheric disturbances. Unlike PPEF, the zonal component of the manifested electric field due to disturbance dynamo, is westward (eastward) during the daytime (nighttime) and may last for several hours. During severe geomagnetic disturbances, the EIA crest may shift towards (negative ionospheric storm) or away (positive ionospheric storm) from the geomagnetic equator depending on the arrival time of Storm Sudden Commencements (SSCs), and participation of PPEF, and disturbance dynamo electric fields. However, recent studies demonstrate that during daytime penetration electric field (eastward), an equator-ward neutral wind is required to produce positive ionospheric storms, profoundly affecting the distribution of F-layer plasma in the equatorial low and mid-latitude ionosphere [61]. Unlike the typical quiet days, the penetrating electric fields (magnetospheric origin) intensifies the plasma fountain (super fountain) at the dip equator and develops the anomaly crest at relatively higher latitudes. Earlier studies suggests the necessary condition for an intense (peak $Dst < -100$ nT) geomagnetic storm is that the IMF-Bz must be large (< -10 nT) and sustained (> 3 hrs). Large geomagnetic storms typically begin with a sudden impulse (SSC) indicating arrival of an interplanetary shock (the initial phase), followed by sustained southward interplanetary magnetic field (the main phase), and later restoring to the normal conditions (the recovery phase). However, appearance of such sudden impulses immediate before the main phase is neither sufficient nor necessary for occurrence or development of geomagnetic storm [24].

Ionospheric response to geomagnetic storms of different disturbance level has been investigated by many researchers in the low latitude Indian region with different techniques of theoretical, experimental, and model predictions. Most of the studies are based on the comparison of ionospheric conditions during the storm period with the control days (preceding, succeeding or any other quiet day), or mean quiet days, or monthly median values. However, it has been now proved that while considering the control/quiet days for understanding the effect of the storms, the EEJ strength and pattern of these days should be checked as existence of CEJ on the control/quiet days may change the nature of the anomaly and the ionization distribution in the low latitude ionosphere leading to erroneous interpretations [44]. The GPS-derived TEC above various locations across the Indian longitude sector during the Halloween Storm event (28-31 Oct 2003) and the mean of best quiet days are shown in Fig. 4 after Panda et al. [44]. The figure depicts the highest positive deviation of TEC during this event from the mean chosen quiet days at Jodhpur (108%, Geographic 26.26 N, 73.05 E). Earlier results of Manju et al. [38] also depict positive deviations of 120 (↑ 50%), 130 (↑ 85%) and 115 (↑ 92%) TECU by comparing with a single control day (5 Nov 2003) at Ahmedabad, Jodhpur, and Delhi respectively, confirming the poleward movement of anomaly crest on the storm day. Notable to say, all the stations from equator to anomaly crest latitude witnessed night-time depressions pretty below mean chosen quiet days level and this concur well with global ionospheric reports of Perevalova et al. [45] pointing $50 - 100\%$ reduction at mid and low latitudes. Dabas et al. [15] analyzed the characteristics of the Ionosphere over equatorial (Trivandrum) and low latitude regions (Delhi) of India during three most severe storms of the solar cycle-23 (on 29 Oct and 20 Nov of 2003, and 7 Nov 2004) and concluded immediate increase in F-layer height beyond the daytime EIA crest, at both the equatorial and low latitude locations, associated with the disturbance eastward electric field. With a dense distribution of Korean GPS network (KGN) of stations along with supplementary ionosonde networks, Jin et al. [31] have studied the ionospheric F2-layer parameters (NmF2 and hmF2) due to the 20 Nov 2003 super storm, through the GPS ionospheric tomography technique over South Korea, conforming strong associated eastward electric field.

During the severe geomagnetic storm of 15 May 2005 (M8 class X-ray) and 24 Aug 2005 (M5.6 class X-ray), 68-70% deviation in VTEC from the mean quiet days is confirm by Jain et al. [27] at Bhopal, a station close to anomaly crest. During the geomagnetic storm of 9 Nov 2004 far lower value of storm TEC (negative deviation) at Udaipur than the mean quiet days is due to the weakened plasma fountain and pronounced disturbance dynamo electric field at the equator as the main phase started at night [17]. Similar studies of Panda and Gedam [40] during the same event report storm day deviations of 178%, 50%, and 38% at Bangalore, Hyderabad, and Mumbai respectively. During the extreme event of 15 May 2005, Trivedi et al. [59] and Malik et al. [37] also reported positive enhancements of 68% and 57% at Bhopal (23.2 N, 77.4 E, Mag. lat. 14.2 N) by comparing storm TEC with a single



(a)

(b)

Figure 4. (a) One minute averages of geomagnetic and interplanetary parameters and (b) diurnal variation of TEC at different latitudes over Indian region during storm period 29-31 Oct 2003 (blue curve), and suitably chosen quiet days (CQ-Days; black curve with SD error bar) of the month [44].

control day and monthly averages respectively. Similarly, Dashora et al. [18] observed an increment of 100% from mean quiet days at Udaipur during the same event. Kumar and Singh [35] at near crest Varanasi station observed slight decrease in TEC during the main phase and significant increased value ($\sim$ 17 TECU) in the recovery phase of the storm of 20 Nov 2007 (Dst-index -71nT). Reports of Panda et al. [43] explains enhanced value of TEC on the storm day (9 Mar 2012) at Bangalore, Hyderabad, and Lucknow are observed to be $\sim$ 71 (20%), $\sim$ 82 (22%), and $\sim$ 105 (94%) respectively. The relatively larger deviation of the storm TEC at Lucknow is possibly due to the poleward forcing of the fountain effect following the daytime prompt penetration at the equator. Reviews confirm that the consequences of the weak storms are low at the equatorial and low latitude region as there is hardly any penetrating electric field reach at the equator. However during intense storms the prompt penetration, disturbance dynamo, traveling ionospheric disturbances may alter the regular nature of equatorial electrodynamics and thereby changing the spatio-temporal distribution of TEC over the low latitudes.

6. Solar eclipse effects on TEC over Indian region

In the low latitude EIA region, eclipse obscuration effects overlap the regular electrodynamics of the equatorial ionosphere. The ionospheric responses to different solar eclipses have been studied extensively by various research groups with different methods, such as the Faraday rotation , incoherent scatter radar (ISR), ionosonde, GPS, and other satellite measurements, as well as theoretical modeling. Studies confirm remarkable depletions in electron density/TEC and electron temperature during various solar eclipse events. Although a major portion of the F-layer electron density refers to the TEC, their behavioral changes may differ as the former is restricted to the bottom side of the ionosphere. However, effects at the low-latitude and equatorial ionosphere are essentially unique and different from those in the middle ionosphere because of the background equatorial electrodynamics.

The effects associated with a solar eclipse is always unique, since it may occur during different solar activity and geomagnetic conditions, at various geographic latitudes and longitudes, and varied season as well as local times of the day. However, a morning or noontime solar eclipse has a major effect on ionosphere over the low latitude region as the daytime equatorial electrodynamics plays an important role in the distribution of plasma in the low latitudes. Eclipses provide a unique opportunity to study the atmospheric and ionospheric effects of the obscuration caused by the rapidly moving shadow of the Moon over the Earth. An eclipse does not repeat in any recognizable pattern due to diverse Sun-Moon-Earth alignment geometries and different lunar orbital characteristics; hence the study of individual eclipses becomes necessary. Moreover, it directly affects the Earth´s ionosphere, hence has a great impact on satellite-based trans-ionospheric radio-telecommunication and navigation signal propagations. The obscuration of solar radiation during partial, annular or total solar eclipse consequences spatial and temporal ionospheric and thermospheric variations with reduced production of electrons and accelerated recombinations [53]. It is very difficult to separate out the eclipse induced ionospheric effects in the equatorial low latitudes as there is most possibility of associated CEJ occurrences during the events that has a major role in altering the regular variations. Greater occurrences of CEJ effects around New and Full Moon are pointed by Rastogi [51], indicating its lunar tidal dependence. As the solar eclipses by definition only occur at New Moon, the occurrence of CEJ around the eclipse day is most favored. Tomás et al. [58] have studied a set of eclipses during the period from 2001-2006, suggesting favorable occurrences of CEJ after the transition of the eclipse shadow across the dip equator. Mayaud [39], from the thorough review of earlier reports, suggested that the seasonal variation of the equatorial lunar effect reaching maximum during winter months and the exceptional global enhancement of the geomagnetic lunar tide during January month can abnormally modulate CEJ effects. For the event of 15 Jan 2010, St.-Maurice et al. [57] described the associated local electrodynamics highlighting that during December-January the solar heating associated high pressure being developed about $> 30^\circ$ south of the magnetic equator, eventually driving the Sq currents for both hemispheres, and thereby resulting weakening of the EEJ over Indian sector. Furthermore, local counter-Sq current over the magnetic equator generated by passage of the lunar shadow during the eclipse may exaggerate pronounced CEJ effect. All these expressions make it crucial to discriminate the alterations in the equatorial ionosphere owing to eclipse associated reduced radiation or weakened EEJ strength in the low latitude equatorial region.

Some important solar eclipses over Indian region during the past two decades are the total solar eclipses of 11 Aug 1999 (sunset hours) and on 22 Jul 2009 (morning time) passing through the center of the country, and the annular solar eclipse of 15 Jan 2010 (early afternoon hours) crossing through the southern tip of India. The major attraction of the 15 Jan 2010 eclipse is that it occurred during the peak ionization time over the Indian EIA region and the path of the annularity crossed the dip equator where the manifestation of equatorial electrodynamics are at play during the period. The photographs of the Sun at different instances of this solar eclipse as taken from Rameswaram, solar-geomagnetic and interplanetary parameters during the period, path of the solar eclipse through Indian peninsular region, and the ground track of GPS satellite of opportunity over Indian region are pointed by Panda et al. [41]. The substantial decrease in TEC at different locations across Indian region due to the annular solar eclipse of 15 Jan 2010 is shown in Fig. 5 along with their counterparts during the preceding and nominal quiet days. Though the depletion of TEC is a common phenomenon, the associated CEJ effects over the equatorial region driving downward forcing of plasma has been described by researchers limiting it to be a low latitude phenomena. Although the obscuration of solar radiation do impact ionization production and recombination processes, the associated electrodynamics has the foremost role in altering the equatorial and low latitude ionospheric distributions [14].

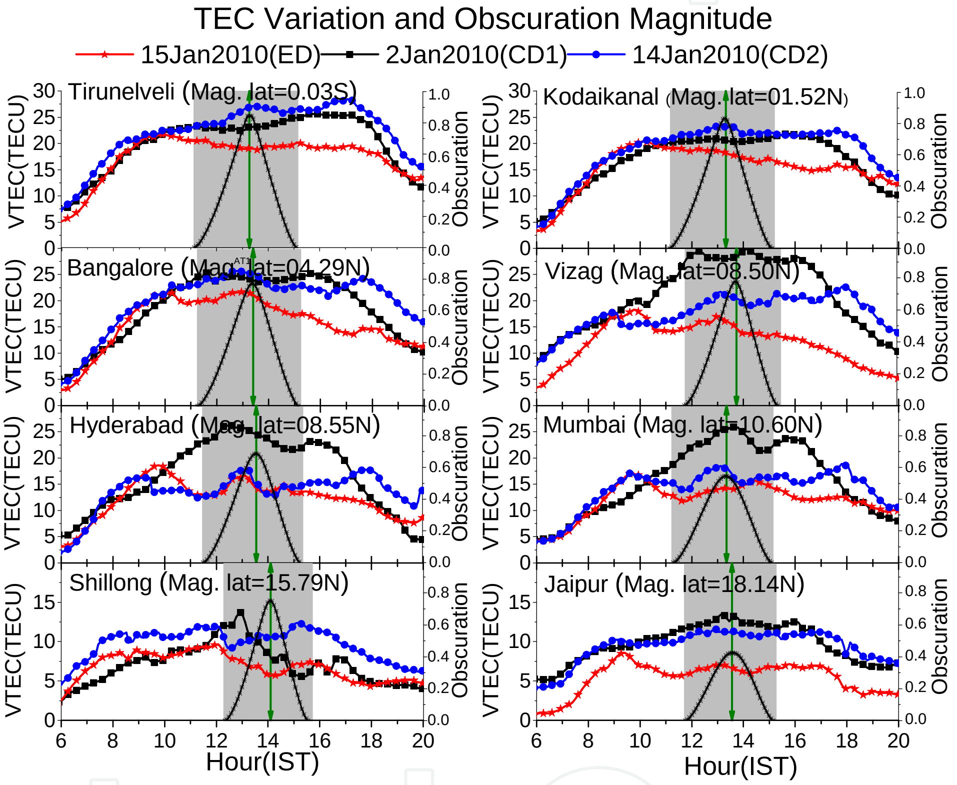


Figure 5. Variation of TEC and obscuration magnitude at different locations during the eclipse day (15 Jan 2010), normal EEJ control day (2 Jan 2010), and the preceding control day (14 Jan 2010).

7. Seismic-ionospheric disturbances over Indian region

Apart from solar and magnetospheric disturbance, effects of solid Earth-related perturbations like earthquakes may cause changes in the regular ionosphere through generation of seismic surface waves. Earthquakes are abrupt violent shaking of the ground, mostly caused by sudden breaking and movements within the earth's crust and releasing in the form seismic surface waves which may travel large distances in all directions. Recent studies with numerous observation data during various earthquake events demonstrate clear anomalous variations in the ionosphere around the seismically active regions apparently existing few days or hours before (possibly due to penetration of vertical electric field) and after (mostly due to acoustic waves) the occurrence of seismic shocks of large intensity (M>5). There might be two major potential mechanism manifesting the seismo-ionospheric disturbances, (1) penetration of anomalous vertical electric field from the lower atmosphere over the seismic zone into the ionosphere and thereby causing irregularity through ion drifting, (2) generation of atmospheric gravity waves (AGW) by earthquakes which propagate upward causing ionospheric disturbances. However, the mechanism of ionospheric perturbation prior to the arrival of shock is still under review as different hypothesis are given for its physical generations. Studies show the surface gravity waves propagating obliquely upward with increased wave amplitude at the upper atmosphere due to the exponential decrease of the atmospheric density, and manifests as Travelling Ionospheric Disturbances (TID) in the ionosphere [16]. The GPS derived TEC results of Liu et al. [36] with about 20 earthquakes ($M \geqslant 6.0$) in the Taiwan region shows ionospheric anomalies appearing within 5 days prior to 16 (about 80%) of the considered events suggesting that the GPS TEC is very much useful for registering the ionospheric anomalies before the earthquakes as precursors of the shock arrivals. Similarly, comparative studies of Afraimovich et al. [1] for TEC response to various strong earthquakes confirms the theory of propagation of co-seismic atmospheric disturbance within a narrow cone of zenith angles up to ionospheric heights and its subsequent diverges in a spherical wave form with the radial velocity close to that of sound at these heights. The amplitude, direction, speed, and propagation pattern of seismic ionospheric disturbances and its evolution is described by [32] with the dense network of GPS Earth Observation Network (GEONET) data in Japan following the Tohoku earthquakes (M=9) during March 2011. Their results also pointed disturbances in ionospheric TEC in a range of more than 4 TECU for period is around 10-20 min and the propagation velocities of disturbance TEC decreased beyond 400-600 km away from the epicenter. The phrenological features of the ionospheric precursors of earthquakes and a clear demonstration of the working of the global electric circuit for transmitting signals from ground surface up to the ionospheric height through the alteration of the electric properties is explained by Pulinets and Davidenko [47] and references therein.

The research communities are mostly focusing to find out the abnormalities in the ionosphere as precursors of the earthquake events and to model the intensity of the effects for practicing early measures before the shocks as the later cause great damage to the existing infrastructures, and may cause tsunamis, landslides, and volcanic eruptions etc. Numerous data from the ground and satellite based measurements have been analyzed by many scientists to evident the ionospheric precursors of earthquakes from the ionospheric parameters such as F2 layer critical frequency (foF2), occurrences of sporadic E layers (foEs), total electron content (TEC) etc. The large network of ionosonde and GPS stations has provided enormous opportunity for statistical study and modeling the effects for appropriate short-term prediction of the earthquakes. Ionosonde studies of Sharma et al. [55] over five locations in the equatorial and low-latitudinal Indian ionosphere, during the Koyna earthquake (December 11, 1967) demonstrate seismogenic variations of foF2 parameters detected within two days prior to the main shock and maximum value being observed on the preceding day. They also found anomalous changes in the ionospheric behaviour with straddling increased and decreased variability during the preceding five days of the earthquake. The precursory signatures in the F-region ionospheric parameters at Delhi (28.6 N,77.2 E), India, showing severe perturbations in foF2 and hmF2 before several hours of the 26 December 2004 Sumatra earthquake (M= 9.0) was observed by Dutta et al. [21] supporting the coupling at far away from the epicenter through the seismogenic electric-field generation prior to the event. They also noticed post earthquake wavelike perturbations in foF2 for several days. Anomalous depletions in the GPS TEC over Varanasi, India, was confirmed by Priyadarshi et al. [46] within 6 days prior to the two recent major earthquakes ($M > 5.0$) of 25 February and 12 March 2010 in Andaman and Myanmar with supporting results from the VLF (15 Hz-17.4 Hz) and ELF (15 Hz-1 kHz) spectra of from the DEMETER satellite. With the Indian GAGAN network of stations GPS TEC data during the same event, DasGupta et al. [16] report significant perturbations of 1.5 to 2 TECs over a smooth variation of TEC in the morning hours. The propagation direction of the disturbance was found to be northwestward with its origin situated about 2° northeast of the epicenter. TEC studies of Singh et al. [56] at Agra (27 N, 78 E) for 43 moderate and high magnitude earthquakes ($M \geqslant 5.0$), report that in 23 cases both depletions and enhancements of TEC occurred, in 14 events either of enhancement or depletion was seen within 0-9 days before the earthquakes pointing the features as the ionospheric precursors of the earthquakes. Fig. 6 shows variation of TEC at Agra station (27.2 N, 78 E) in India, with abnormal enhancements followed by depletion between 02 and 06 June 2007, and unusual depletions and enhancements between 13 and 18 June 2007 referring to the respective moderate earthquakes of 06 June 2007 ($M = 5.1$) and 23 June 2007 ($M = 5.2$) [56]. Recently an integrated Seismic and GNSS Network (ISGN) has been initiated in India by the Earth System Sciences Organization (ESSO) for real time acquisition, processing and analyzing of the of seismic and GPS data to observe the ionospheric precursors of the earthquakes and their predictions.

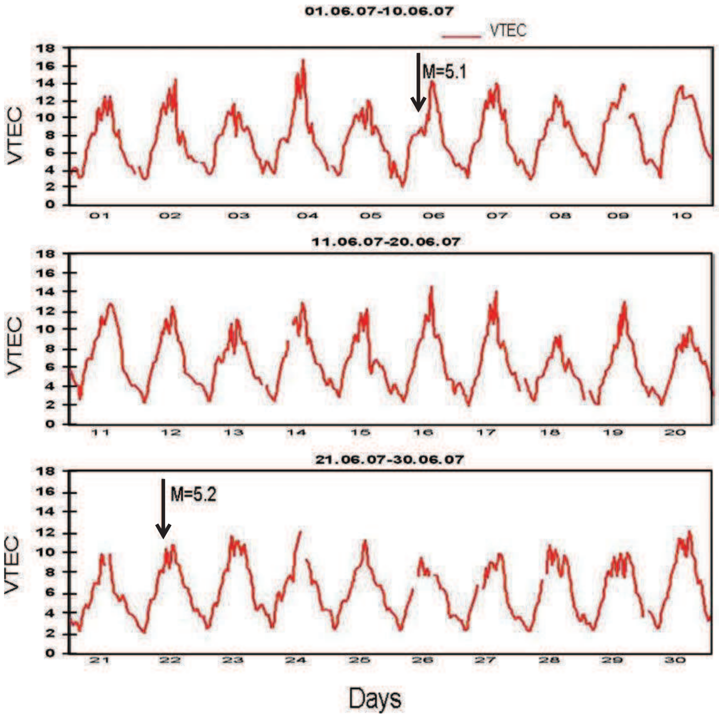


Figure 6. Variation of TEC at Agra station (27.2 N, 78 E) in India with abnormal enhancements followed by depletion between 02 June and 06 June, and unusual depletions and enhancements between 13 June and 18 June referring to the moderate earthquakes of 06 June 2007 ($M = 5.1$) and 23 June 2007 ($M = 5.2$) respectively. The downward arrows (↓) indicate the occurrence of earthquakes.(Source:[56])

8. Model predictions of TEC over Indian region

Although there developed number of models for predicting electron density/TEC variations, the results hardly match the regional measurements specifically over the low latitude region. The different ionospheric models considerably tested and being used in the low latitude Indian region are discussed as follows.

8.1. International Reference Ionosphere (IRI)

The standard International Reference Ionosphere (IRI) is the most widely accepted global ionosphere model developed by the joint project of International Union on Radio science (URSI) and Committee on Space Research (COSPAR). The outputs of this model is based on worldwide network of experimental stations providing estimates of ionospheric parameters in the altitude range from 50 km to 2000 km. However the IRI predictions are most accurate in Northern mid-latitudes due to dense network of experimental stations, whereas at low and high latitudes, accuracy is less due to unavailability of adequate monitoring stations and high variability of space weather. 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). Several research papers and reports have been published on the simultaneous measurements of foF2/TEC, its noontime bite-out, secondary peak during evening, winter anomaly, solar activity dependence, and corresponding model predictions in the equatorial and low latitudes.

Long-term studies report that 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 region. The model deviation from the actual value is maximum in equinox and minimum in summer. Also, it has been proved 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. [22] confirmed that IRI underestimates the observed electron density by 50% and 60% during equinox and winter, and overestimated by as much as 150% in summer. Also, Bhuyan et al. [9] reported failure of the IRI model to produce the secondary peak of electron density during the low solar activity period (1994-1997). Greater efforts have been made by Bhuyan and Borah [7] through comparison of IRI-TEC with measured GPS-TEC at various latitudes across Indian region, concluding overestimation of IRI-TEC than the actual value. However exploitation of a set of foF2 coefficients from the regional ionosonde stations (IRI-2), resulted in more accurate IRI-TEC predictions over the region. Efforts are being made to update and improve the model since its development in 1969, with newer data and better modeling techniques.

8.2. Standard Plasmasphere - Ionosphere Model (SPIM)

The recently established International Standard Plasmasphere - Ionosphere Model (SPIM) 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 [25]. Few studies have been performed on its reliability and credibility with in-situ ground measurements at different parts of the globe, even in the Indian region by [43]. All these literatures suggest overestimation of the SPIM predictions than the in-situ measurement as well as IRI predictions during low and moderate solar activity condition. It could be either due to the plasmasphere addition to the IRI or the (top side + plasmasphere) estimates. It is already known that IRI overestimates across the low latitudes, again by adding the Russian SMI model which is of high latitude nature may speculate the overestimation characteristics of the present SPIM model.

8.3. Global Ionospheric Map (GIM)

The global vertical TEC maps are published by the International GNSS Service (IGS) in association with few Analysis centers those take measurements from the IGS network of GPS stations with their own approach which are integrated together to publish a reliable daily 2 hourly combined global ionosphere maps (GIMs) in an official format Ionosphere Map Exchange (IONEX) with a spatial resolution of $5^\circ \times 2.5^\circ$ in longitude and latitude, respectively and was approved in 1996 IGS workshop. The maps are two-dimensional grid in a single layer at height 450 km by adopting the Earth radius of 6371 km. At present, there are three types IGS GIMs available for free access: the final, rapid, and predicted GIM. The latencies of the IGS ionospheric final and rapid products are 11 days and <24 hrs, respectively. The predicted GIMs are generated for 1 and 2 days in advance, currently based on forecasts prepared by the Technical University of Catalonia (UPC) and European Space Agency (ESA). The weekly self-consistency validation test and substantiation with VTEC from dual-frequency altimeter data (Envisat data, TOPEX and Jason data) is performed for maintaining the reliability of the maps. The accuracy of ionospheric TEC grid in IGS-GIM varies between 2-8 TECU. 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. The VTEC above a location can be extracted from the IGS-GIM by using bilinear spatial interpolation of VTEC values from four nearest grid points [54]. Notable to say there are only 3-4 IGS stations across the Indian region of which at present data from 2 stations are being used in the GIM subject to their regular availability. Reports of Ho et al. [26] suggests the vertical TEC error level of the IGS-GIM diurnal maximum TEC remains 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 suggest 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.

Fig. 7 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 Nov 2011 to Oct 2012 referring to low-medium solar activity condition. Both the IRI and SPIM models overestimates than the in-situ measurements in almost all seasons. 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. However, the difference between IGS-GIM and GPS-TEC seems to be consistently low or steadily varying at most of the locations.

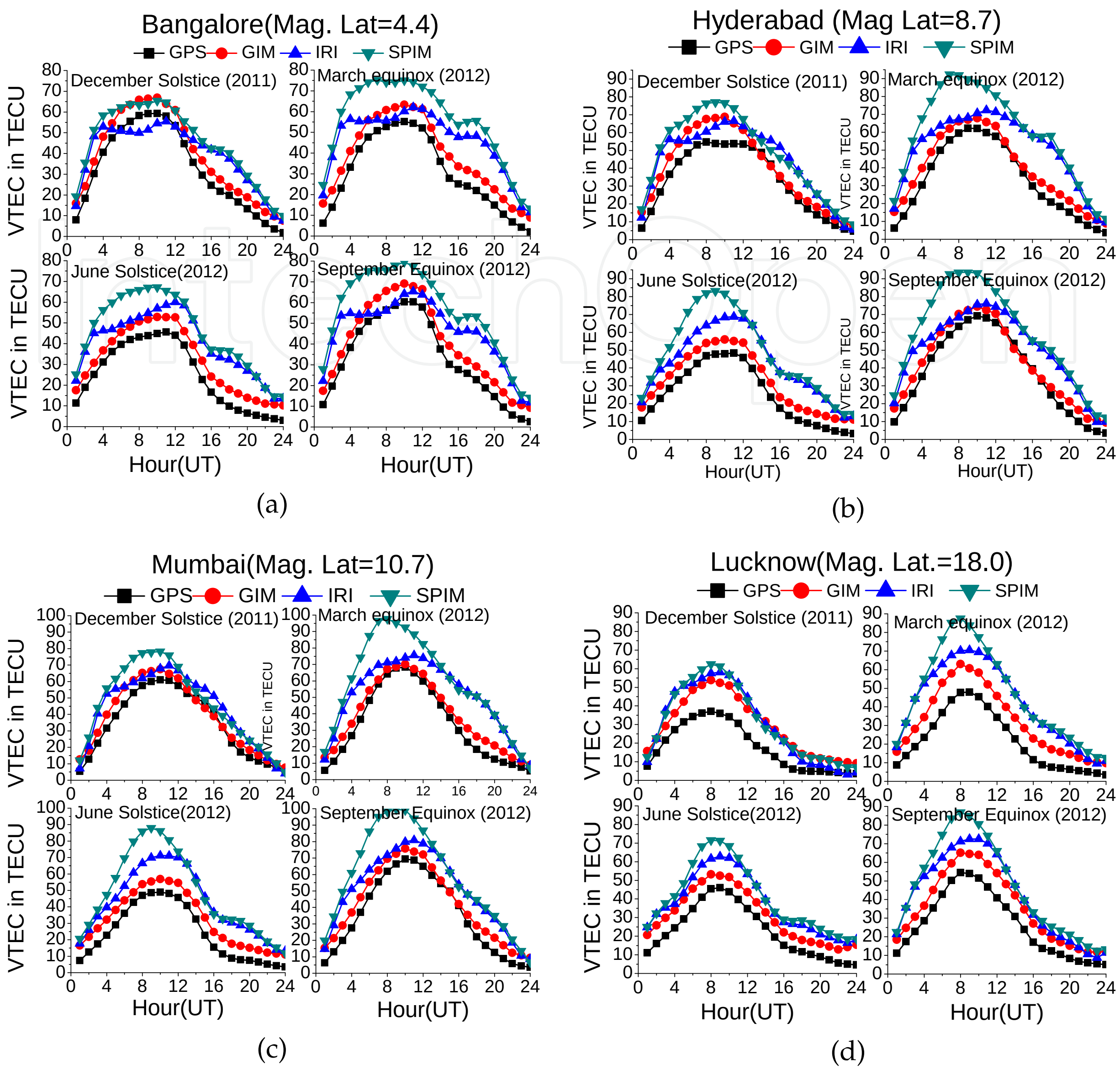


Figure 7. Comparison of seasonal variations of GPS-TEC with IGS-GIM, IRI, and SPIM model estimated TEC at (a) Bangalore, (b) Hyderabad, (c) Mumbai, and (d) Lucknow during Nov 2011 to Oct 2012 Source: Panda et al. [43].

8.4. Indian Regional TEC Model

As the global TEC maps could not be able to provide small scale ionospheric changes due to their low resolution data receiving stations, countries have came forward for establishing their own regional ionospheric maps based on their own dense network local GPS stations for providing the parameters on real-time/near real-time basis similar to that developed through the Shanghai Comprehensive GPS Application Network [29], GPSnet-Victorian Continuously Operating Reference Stations (CORS) system[62]. Similarly India is now on the verge of developing its regional TEC map from the network of GPS stations across the country. Using the measurements of TEC at 18 different stations across the India subcontinental region (covering the crest and trough of the EIA) under GAGAN (GPS Aided Geo Augmented Navigation), a model has been developed by Indian Space Research Organization (ISRO) in collaboration with the Airports Authority of India (AAI), which would successfully predict the TEC between 8-30 N latitude and 60-100 E longitude zone [63, 64]. In this model, observations at 77 E longitude zone are considered as a reference and the solar zenith/neutral wind control are applied to estimate changes in TEC at different longitude sectors from that at 77 E longitude emphasizing a first principle based on the Parametric Ionospheric Model (PIM). This is a new multi-layer grid-based model which uses data fusion technique and provides ionospheric delay corrections as vertical delay on L5 (GIVD) and their 99.9 % accuracy, called the Grid Ionosphere Vertical Error Indicator (GIVEI) at 350 km altitude are provided at each specified ionospheric grid points (IGPs), which is applicable to the signals on L5 band in the the single frequency receiver users over the Indian landmass. Given three or four nodes of a cell of the IGP grid surrounding the user's ionospheric pierce point to a satellite, the user can interpolate from those nodes to his pierce point using the four-point or three-point interpolation algorithms. Additionally, the TEC model would provide TEC maps over the Indian region on real-time data from the GAGAN TEC stations combined with physics based semi-empirical model. The ionospheric corrections for Indian Regional Navigation Satellite System (IRNSS) would be a region specific coefficient based model based on GAGAN TEC and Indian Reference Station (INRES) data [66]. For single frequency GPS users, a Klobuchar like coefficients is to be broadcasted at 5-minute intervals for the Indian region. The ISRO TEC model has now been modified to include the variabilities in Kp and F10.7 cm flux to represent the impact of geomagnetic storms at low latitude. A case study for the severe geomagnetic storm of Aug 24, 2005 (Dst -158 nT; Kp 9) revealed that ISRO-TEC model successfully predicted temporal variations in TEC even at longitudes far away from the reference longitude zone at 77 E. The model is now being used to generate super-truth data for GAGAN certification process and soon will be activated to represent the real Indian ionosphere.

9. Summary

The ionospheric TEC is an important aspect for studying morphology of ionosphere as well as precise positioning, navigation and electromagnetic wave propagations. Experimental studies during different solar-terrestrial events provide an opportunity for understanding and modeling the responses of the ionosphere. This knowledge will help in establishing comparatively more accurate regional ionospheric model over the low latitudes. The low latitude and associated phenomena certainly different from that of the other parts of the globe due participation of equatorial electrodynamics. It is very hard to define a typical representative ionosphere map of the low latitude ionosphere as the parameters appear to differ from day to day and their ease of susceptibility to any solar-terrestrial phenomena. However, the decades of long-term investigations of the low latitude ionosphere starting from early 1962 till the present, has indeed contributed deep insight into the equatorial and low latitude ionosphere over Indian region. Moreover, the availability of GPS satellite signals complemented by other ground and space-based instruments have made it possible for imaging the substantial characteristics of the highly varying equatorial and low latitude ionosphere through 3D-tomographic reconstruction from dense GPS observables complemented/supplemented by other ground and space based observations. At present, number of institutions/organizations in India, like Indian Space Research Organization (ISRO) and its regional centers and space physics laboratories, National Physical Laboratory (NPL), Physical Research laboratory (PRL), National Atmospheric Research Laboratory (NARL), Indian Institute of Geomagnetism (IIG) along with its observatories and regional centers, Indian as well as International Universities and research centers are being actively involved in theoretical, experimental, and modeling tasks on upper atmosphere and ionospheric characteristics. Nevertheless, deployment of GAGAN and IRNSS program encouraged the detailed experimental, observational analysis and regional ionospheric modeling exercises across Indian region. Subsequent up-gradations in the present models are applied day-by-day with sufficient number of experimental datasets and mathematical analysis for their relatively improved estimations over the equatorial and low latitude ionosphere.

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