Long Term Ionospheric VTEC Variation during Solar cycle 24 as Observed from Indian IGS GPS Station

S. Kundu1*, S. Sasmal2, S. K. Chakrabarti3

1,2,3Department of Ionospheric Sciences, Indian Centre for Space Physics, 43, Chalantika, Garia Station Road, Kolkata - 700084, India

*Corresponding Author: mcqmld@gmail.com Tel.: +91-865360369

Available online at: www.isroset.org

Received: 07/June/2021, Accepted: 20/July/2021, Online: 31/Aug/2021

Abstract— We use the IGS (International Geodesic Survey) dual-frequency GPS data of Indian low latitude IGS Station IISC, Bangalore (13.02 °N, 77.57 °E), to compute the Total Electron Content (TEC) to study the solar activity variation of the ionosphere. To study the TEC variation with solar activity, we choose a complete solar cycle 24 during the period 2007-2020. We study the variation of TEC with sunspot numbers which is the quantitative measure of the solar activity. We observe the variation of TEC with the solar activity parameter such as solar flux and the EUV flux. The estimated TEC gradually increases from a minimum to maximum during 2007 to 2014 and then again decreases during 2015-2020 to a minimum which follows the sunspot numbers variation over the complete solar cycle. We use the EOF decomposition model using GPS-TEC data for the entire solar cycle. The diurnal, seasonal, annual TEC variation and its corresponding trend with solar activity are observed using the EOF-TEC method. The EOF-TEC data is highly correlated to GPS-TEC data with a value of correlation coefficient of 0.9323. The performance of the model is also good with the RMSE value of 5.7891 and the NRMSE value is 16%. We also use the IRI-2016 TEC to study the diurnal, annual variation of TEC with solar activity and verify our observed and model data. The IRI-TEC is comparatively low but the solar activity dependence of TEC matches with the GPS-TEC and EOF-TEC values satisfactorily. The diurnal TEC attains a maximum value at the afternoon 13:00-17:00 IST for this low latitude station which is observed for all TEC throughout the solar cycle. We observe that for seasonal variation, the value of GPS-TEC is maximum for the equinox. The equinoctial GPS-TEC is maximum followed by winter and summer. A similar kind of outcome is found in EOF-TEC. We show the positive correlation between TEC, sunspot, solar flux (F10.7 cm), and EUV flux for the entire solar cycle.

Keywords— Ionosphere – Wave propagation – ,GPS-TEC–, Solar activity–, EOF-TEC–, 24th solar cycle

1. INTRODUCTION

Ionosphere is a thick ionized layer of the upper atmosphere, which spreads from 60 km to 1000 km above the Earth’s surface. It lies between the partly mesosphere, thermosphere and partly exosphere. The main ionization source of the ionosphere or upper atmosphere is solar radiation. Sydney Chapman first proposed a theoretical model to estimate the ionization profile of ionosphere and explained the ionospheric absorption of solar radiation [1-4]. Ionosphere is divided into three layers, namely D, E, and F. F layer is the uppermost layer and most important layer of the ionosphere. F region is mainly used for HF radio communication, which lies between 140-600 km. The F region is divided into two sub layers due to solar radiation named F1 and F2. F1 layer disappears at night but F2 layer remains for the entire day and night. The F1 layer of the ionosphere spreads at an altitude between 140 to 210 km. As F1 layer is a Chapman layer, it highly depends on the solar cycle and solar zenith angle profile. The maximum electron density of the layer is near about 2 × 1011 el/m3. The activity of the F layer is more effective in summer than in winter because during winter sometimes the layer disappears during the daytime also [4-5]. The upper F2 layer of the ionosphere lies between 210-600 km. It has high variability and depends on the 11-year solar cycle. It also has a dynamic variation during space weather phenomenon since the characteristics of the layer depends on solar-terrestrial conditions. The electron density of F2 layer highly depends on the Sun. The electron density starts to increase after sunrise and attains a maximum value near the noon and afternoon and depletes after the sunset. The electron density of the F2 layer is quite high and the major ion-molecule of the region is O and N2. The change in electron density depends on the thermo-ionospheric neutral components like N2 molecule. When a radio wave is propagating through the ionosphere it collides with the free electrons and deviates from its original path. Total Electron Content (TEC) is one of the major parameters to study the ionospheric irregularities by using the concept of signal deviations and positioning error. When the GPS signal passes through the ionosphere, a group path delay occurs which is proportional to TEC. GPS has a dual frequency satellite system with frequencies L1 (1.575)
GHz and L2 (1.227 GHz). The two major parameters of a GPS are the pseudo range(\(\rho\)) and the carrier phase(\(\phi\)). There is a phase advance in the carrier phase and a group path delay is with the code. As a result, a position error occurred in GPS receiver [6]. TEC is defined as the free thermal electron per unit area between the receiver to satellite. To check the ionospheric scintillation, disturbances in space weather phenomenon, positioning error, a bunch of scientists computes a world TEC ionospheric model. They develop a Centre for monitoring global TEC supported GPS receivers called International Geodesic survey (IGS). The computation of TEC can be estimated by using the IGS station GPS data. The GPS receiver stored the information in RINEX format.

Many researchers have started to study ionospheric data using the analytical orthogonal function (EOF) decomposition approach to enable systematic analysis of the spatial patterns and time temporal fluctuations of the TEC and their relationships with influencing factors [7, 8, 9]. The findings of a single station's data analysis, as well as the regional and global TEC, all showed that the EOF approach could be a valuable technique for data compression and isolation of various physical processes [10]. Variation features of various time scales, such as diurnal and seasonal fluctuations, can also be extracted using EOF decomposition.

In this paper we use the IGS station data of IISC, Bangalore (geographic coordinates:13.02 °N, 77.57 °E) located at the low latitude region in India. To analyze the solar activity variation with TEC for the low solar active year 2007, 2009, 2018-2020; moderate solar active year 2010-2013, 2016-2017 and high solar active year 2014-2015 of the 24th solar cycle. We set up a correlation between the solar activity and TEC. In this paper we also use EOF-TEC model and International Reference Ionosphere (IRI)-TEC data over a complete solar cycle to verify our observation results.

II. RELATED WORK

A different variation of TEC such as diurnal, monthly, seasonal, latitudinal, and during solar activity has been computed by various scientists worldwide for different locations using different methods over the past few decades [11-21]. In India, also significant TEC measurements on this variation have been studied by several researchers [11, 22-27].

The temporal and spatial variation of TEC was studied by Rama Rao et al. [22] by using the Indian GPS system GAGAN and observed that TEC is attained the maximum value at 13:00 to 16:00 (Local Time) LT for the Equatorial Ionospheric Anomaly (EIA) region. The maximum diurnal TEC was 50 TECU for the equatorial region and 90 TECU for the EIA crest region. It is also studied in the low solar activity periods for the EIA crest region for India and observed that the diurnal variation of TEC is highly influenced by the season, solar activity, geomagnetic activity, and latitude [23]. For the seasonal variation, it is also observed that the equinoctial Vertical TEC is higher than the solstice TEC during the low solar activity period [23,28,29] and high solar activity period [16]. It is also reported [22] that the seasonal variation of TEC is maximum for the equinoctial month followed by winter and minimum for the summer. Solar zenith angle also plays an important role in ionization. The semi-annual variation of TEC is highly dependent on the noon solar zenith angle as reported by Bagni et al. [23]. TEC measurements using the GAGAN network have been investigated by Rama Rao et al. [22] at Waltair in the equatorial region and [31] at Udaipur near the anomaly crest region. In Rao et al. [27], the GPS-TEC is compared with the IRI-2016 model, and also the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM) during 24 Solar cycles. Spectral, regression, and statistical analysis were used to analyze the short- and long-term variabilities in TEC. In terms of Solar Cycle 24, the current analysis shows a double-hump structure and clockwise hysteresis in TEC. During this time, the solar flux and TEC trend are observed to be uneven and slow. During the fall stage of Solar Cycle 24, the rising is smooth and rapid. The semi-annual anomaly is shown to be seasonal. be a recurring feature throughout the solar cycle, while the winter anomaly appears to be aided by a high degree of solar activity around the solstices.

According to the findings, spatial scale and seasonal fluctuations of many solar-terrestrial phenomena can be determined using EOF research. Time series modeling for the decomposed EOF coefficient terms can be used to construct an analytical model of the ionosphere based on EOF decomposition [32-39]. The development of the EOF analytical model of the ionospheric M(3000)/F2 (a factor that gives the ratio of the maximal available frequency over a distance of 3000 km and vertical critical frequency) for individual and global stations was analyzed by Liu et al. [40], and the analysis of observational and modeled results showed strong agreement. Based on the EOF decomposition of the dataset and the modeling of the corresponding EOF coefficients with harmonic functions describing the annual and semi-annual seasonal variations, Zhang et al. [41] developed a global model of the ionospheric parameter h|mF2. A comparative study has been conducted of various empirical models using various EOF expansion approaches. All of the models fit well with the results, and some of them perform better than the IRI model. It is also studied by Earcha et al. [35], Bouya et al. [36] where the GPS-TEC data is comparing the EOF model and satisfactory results have been observed. In Uwamahoro et al. [37], the EOF TEC model has been used the storm period of 1999-2013 and compared the results with the neural network model. They observed the EOF decomposition method-based model is performed very well during the disturbed condition. In S [42], the authors also studied the long-term variation of GPS-TEC and used the EOF model and compare the results with IRI-2016 over China. They also checked the spatial variation of the EOF coefficient and observed some good outcomes.
III. MATERIALS AND METHODS

It is well known the VTEC can be expressed as:

\[
VTEC = \frac{STEC - TEC_{cal}}{M(\alpha)}
\]  

(1)

where VTEC is the Vertical Total electron content, STEC is Slant Total Electron Content and \( TEC_{cal} = bs + bR + bRX \).

The slant TEC (STEC) records obtained from GPS are contaminated with satellite differential delay (\(bs\) is satellite bias) and receiver differential delay (\(bR\) is receiver bias), attached with receiver inter-channel bias (\(bRX\)). This uncorrected STEC measured at every 30 seconds interval from the GPS receiver derived from all the visible satellites at all the stations is converted to vertical TEC (VTEC) [43].

The Slant Total Electron Content (STEC) is uncorrected as measured by the receiver. To get the corrected VTEC values one needs to include the \(M(\alpha)\) which is the obliquity factor with zenith angle \(\beta\) and \(\alpha\) is the elevation angle at the ground station. After this inclusion, the VTEC can be obtained at Ionospheric Piercing Point (IPP) which is the altitude at 350 km for the Indian region (low-latitude region). This is first validated by Rama Rao et al. [44]. The \(M(\alpha)\) is obtained by Mannuchi et al. [45,46] and Langley et al. [47] as

\[
M(\alpha) = \frac{1}{\cos(\beta)} = \left(1 - \frac{\beta \cos(\alpha)}{h_\alpha + h_{\min}}\right)^{-0.5}
\]

(2)

The TEC is computed from the GPS RINEX data. Receiver Independent Exchange Format (RINEX) consists of three ASCII files. The files are the Observation file, Navigation file, and Code bias file. The observation file mainly consists of GPS measurements data such as frequency, pseudo-range etc. The navigation file consists of orbit information. The Code bias files consist of satellite bias files. Equations (1) and (2) are implemented in a software name “GOPI SEEMALA software”. All bias corrections and calibrations of TEC are performed using the approach described in Seemala and Valladeres [48], which was created and made publicly available by the Institute for Scientific Research at Boston College in Massachusetts, USA, to compute Slant TEC and Vertical TEC. To compute the TEC, first, we collect the GPS RINEX observation and navigation data of IISC, Bangalore from the IGS data archive (https://ccmc.gsfc.nasa.gov/modelweb/modelsviri2016_vitmo.php) [50].

We use the GPS data of IGS station IISC, Bangalore to compute the STEC and the corresponding VTEC. We use the data for the period of 2007-2020. We start our analysis from the end of the solar cycle 23 to the end of the solar cycle 24. The prime difference between the two solar cycles 23 and 24 is that the peak value of the solar cycle 24 is lower than the previous one [49]. The sunspot numbers are the indicator of solar activity. It is found from Figure 1 that the sunspot numbers are minimum for the years 2009 and 2019 and maximum for the year 2014. The year with low sunspot numbers is denoted as a low solar active year and high sunspot numbers are denoted as a high solar active year. Sunspot number data files are taken from World Data Centre for Sunspot Index and Long-term Solar Observation (WDC-SILSO), Royal Observatory of Belgium, Brussels (https://www.sidc.be/silso/datafiles). The solar flux data F10.7 is obtained from OMNIWEB NASA archive (https://omniweb.gsfc.nasa.gov/). The EUV flux data is obtained from Solar EUV Monitor (SEM) data (https://dornsifecms.usc.edu/spacesciencescenter/download-ssem-data/ ). We have used IRI-TEC data taken from CCMC NASA Archive (https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php) [50].

Figure 1 shows the solar activity parameters sunspot number (SSN), Solar flux (F10.7) and EUV flux gradually increases from 2009 and attains the maximum value in 2014 and decreases and attains minimum value in 2019 and again increases.

We compute the value of TEC for the entire period 2007-2017. We use the 21st day of four months March, September, June, and December to study the diurnal variation of TEC. To compute the TEC on a single day, we average all the TEC derived from all visible satellites during the day. We could not analyze the data for 2008 because the IGS data for 2008 is not available for the IISC location. We use March and September for equinox and June and December for the Solstice for the monthly variation of TEC. We divide the whole year into four seasons. We compute the average TEC data of February, March, April as March equinox; May, June, July as June
The contributions of each EOF component are tabulated in Table 1. To develop the EOF, 12 EOF components are used. The total variance of 12 EOF components is 99.90206. Convergence this model is obtained with 6 EOF components with a total variance of 99.61391. For better results, we have used the 12 EOF components. In some previous cases, the f0F2, TEC, and M(3000)F2 during a non-contaminated condition, the convergence reached with 3-4 variables. For disturbed conditions, they observed that the convergence reached 12 EOF components. In our case, we have studied the long-term variation of TEC with solar activity.

Table 1: Percentage of the variances of each EOF component

<table>
<thead>
<tr>
<th>EOF component</th>
<th>Variance (%)</th>
<th>Cumulative variance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_1 \times E_i^1$</td>
<td>98.01195</td>
<td>98.01195</td>
</tr>
<tr>
<td>$A_2 \times E_i^1$</td>
<td>0.698614</td>
<td>98.71056</td>
</tr>
<tr>
<td>$A_3 \times E_i^1$</td>
<td>0.369386</td>
<td>99.07995</td>
</tr>
<tr>
<td>$A_4 \times E_i^1$</td>
<td>0.256061</td>
<td>99.33601</td>
</tr>
<tr>
<td>$A_5 \times E_i^1$</td>
<td>0.158664</td>
<td>99.49468</td>
</tr>
<tr>
<td>$A_6 \times E_i^1$</td>
<td>0.119239</td>
<td>99.61391</td>
</tr>
<tr>
<td>$A_7 \times E_i^1$</td>
<td>0.084243</td>
<td>99.69816</td>
</tr>
<tr>
<td>$A_8 \times E_i^1$</td>
<td>0.058815</td>
<td>99.75697</td>
</tr>
<tr>
<td>$A_9 \times E_i^1$</td>
<td>0.051169</td>
<td>99.80814</td>
</tr>
<tr>
<td>$A_{10} \times E_i^1$</td>
<td>0.037512</td>
<td>99.84565</td>
</tr>
<tr>
<td>$A_{11} \times E_i^1$</td>
<td>0.031629</td>
<td>99.87728</td>
</tr>
<tr>
<td>$A_{12} \times E_i^1$</td>
<td>0.024777</td>
<td>99.90206</td>
</tr>
</tbody>
</table>

The diurnal and long-term variations such as solar cycle, seasonal and annual are represented by the EOF base functions $E_i(H)$ and related coefficients $A_j(D)$. The percentage of the overall variation in the first k EOF components in the initial data set is calculated by

$$
\mu_k = \frac{\sum_{i=1}^{k} \lambda_i}{\sum_{m=1}^{p} \lambda_m} \times 100%,
$$

where $p$ represents the total no EOF components. The percentage of the total variance calculated for the $l$th EOF component is given by

$$
\nu_l = \frac{\lambda_l}{\sum_{m=1}^{p} \lambda_m} \times 100%.
$$

We use the EOF analysis is a mathematical technique for transforming a data set with several highly correlated variables into a current data set with a limited number of uncorrelated variables that retains the majority of the original data set’s information. The primary objectives of EOF research are to reduce the dimension of a data set, uncover hidden structures within it, and classify such structures according to the percentage of variation they account for in the data set. The approach works by manipulating matrices, and the initial step was to construct the TEC data matrix $Y$ with the dimension of 4307 × 24. A total of 4307 days has been chosen from 2007 to 2020 (skip 2008 due to lack of data) for the IGS station IISC, Bangalore. We have considered 24 hourly TEC values. The matrix consists of 4307 rows and 24 columns. The covariance matrix was calculated using the method described in Zhang et al. [40]. The eigenvalue equation is given by

$$
\Lambda = Y^T Y.
$$

where $Y^T$ is represented as the transpose of $Y$, $E_i$ are the EOF base functions, $i$ denotes the hours from 1 to 24. The $E_i$s are the eigenvectors of the covariance matrix $\Lambda$ which is calculated by using the method described in Zhang et al. [40]. The eigenvalue equation is given by

$$
\Delta E_i = \lambda_i E_i
$$

where $\lambda_i$ represents the eigenvalues. After the computation of EOF base functions, the original TEC data set can be decomposed using the EOF base functions and related coefficients. The equation is given by

$$
TEC (H, D) = \sum_{j=1}^{24} A_j(D) \times E_j^T (H)
$$

Where $TEC (H, D)$ indicates the hourly TEC values, $H$ represents the hours from 1 to 24 and $D$ represents the day 1, 2, 3, up to 4307. $E_j^T (H)$ is the transpose of the EOF base functions, $A_j(D)$ denotes the EOF coefficients which is calculated by the (6) as:

$$
A_j = Y E_j
$$

The percentage of the overall variation in the first k EOF components in the initial data set is calculated by

$$
\mu_k = \frac{\sum_{i=1}^{k} \lambda_i}{\sum_{m=1}^{p} \lambda_m} \times 100%.
$$

where $p$ represents the total no EOF components. The percentage of the total variance calculated for the $l$th EOF component is given by

$$
\nu_l = \frac{\lambda_l}{\sum_{m=1}^{p} \lambda_m} \times 100%.
$$

The contributions of each EOF component are tabulated in Table 1. To develop the EOF, 12 EOF components are used. The total variance of 12 EOF components is 99.90206. Convergence this model is obtained with 6 EOF components with a total variance of 99.61391. For better results, we have used the 12 EOF components. In some previous cases, the f0F2, TEC, and M(3000)F2 during a non-contaminated condition, the convergence reached with 3-4 variables. For disturbed conditions, they observed that the convergence reached 12 EOF components. In our case, we have studied the long-term variation of TEC with solar activity.
\[ M_{j3}(D) = [N_{j3} + L_{j3} F10.7P(D) + P_{j3} AP(D)] \cos \left( \frac{4\pi D}{365.25} \right) + [Q_{j3} + R_{j3} F10.7(D) + S_{j3} AP(D)] \sin \left( \frac{2\pi D}{365.25} \right) \]

(11)

\[ M_{j3}(D) \] is expressed as a linear function of AP and F10.7, \( M_{j2}(D) \) and \( M_{j3}(D) \) are expressed as the harmonic function with periods of 1 year and 0.5 year and amplitudes are represented similar to the \( M_{j1}(D) \). The solar cycle, seasonal, annual variation are determined by using the coefficients \( M_{j1}(D), M_{j2}(D) \) and \( M_{j3}(D) \). The unknown coefficients \( N, L, P, Q, R, S \) are calculated by linear regression analysis. After computation of all the coefficients, the final TEC \((H, D)\) is obtained from the (5) by putting all the values of the different coefficients.

The diurnal and long-term variation of the first 12 EOF base functions and the corresponding coefficients are shown in Figure 2(a)-(b). Figure 3(a) shows, The diurnal variation of the first order EOF base function \( E1 \) and the average TEC. The average TEC was computed over the 4307 days. The computation process is done by averaging all the TEC values for a certain time and then divided with number of days. It is obtained the variation of average TEC and EOF base function \( E1 \) are very much similar to each other with a correlation coefficient 0.989. The diurnal variation of TEC is represented by the first EOF base function \( E1 \). The variation EOF coefficients \( A1 \) and \( F10.7 \) are shown in Figure 3(b). The \( A1 \) and \( F10.7 \) also shows a similar kind of variation with correlation coefficient 0.84.

The higher amplitudes are observed from 2011 to 2015 and the maximum value of \( A1 \) is observed in 2014. As we skip 2008 so there are no values. The lowest values of \( F10.7 \) and \( A1 \) are observed in 2009 and 2019. If we compare the \( A1 \) with solar activity, it is observed that the EOF coefficients also follow the solar activity of the 24th Solar cycle.

**IV. RESULTS AND DISCUSSION**

During the period 2007-2014, we find that the solar flux got increased from 70.54 sfu to 145.93 sfu and then again started to decrease from 2015 to 2019 and attained a minimum value of 69.7 sfu (sfu= 1 solar Flux Unit= \( 10^{-22} \) watt m \(^{-2} \) Hz \(^{-1} \)).

**Diurnal variation of TEC:**

The diurnal variation of TEC gradually increases from sunrise and reaches a maximum in the afternoon time and then decreases to a minimum just before the next day of sunrise. The diurnal variation of TEC is known to depend...
on various factors such as solar activity, seasonal solar flux, and geographical latitude. At first, we have compared the diurnal TEC for a quiet March equinox day, June solstice day, September equinox day, and December solstice day. Figures 4 and 5 (a) shows the diurnal TEC variation for March, June, September, and December. From Figure 3 (a)-(c) and 4 (a) it is evident that the diurnal TEC value is quite low for IRI 2016 modeled TEC. Figure 3 (a) suggests that TEC has higher values around 2011 to 2015 on March equinox and from Figure 4 (b)-(c) and 5 (a), it is observed that TEC has again higher values around 2011 to 2014. The higher TEC values are observed during the high solar active for GPS-TEC, EOF-TEC, and IRI-TEC. The values of IRI-TEC are low, but they are also following the same trend. The diurnal variation of TEC is divided into three parts: (1) build-up region: TEC is started to increase just after the sunrise (2) daytime plateau- after the sharp increment of TEC, it attains a maximum value in the afternoon period and (3) decay region- after sunset TEC gradually decrease and attained a minimum value just before the sunrise. The maximum value is attained by the TEC at the afternoon period between 8:00-11:00 UT or 13:00 -16:00 LT for all the days. We also observed the EOF -TEC model residuals and shown in Figure 5. (b). From Figure 5 (b), it is observed that EOF-TEC values are lower than GPS-TEC or March equinox day for all years, while for the other the EOF-TEC values are higher than the observed one. The differential TEC (dTEC) is around -10 to +8 for all the years. To get a comparatively better model performance we also made a day-to-day variation of TEC for GPS-TEC, EOF-TEC, IRI-TEC, and EOF-dTEC which is described in the next section.

Figure 4. Diurnal variation TEC of a) March equinox day, b) June solstice day, c) September equinox day and from 2007-2020. The black lines represent the GPS-TEC, red lines represent the EOF-TEC and blue lines represent the IRI-TEC.

Figure 5. Same as Figure (4) for December solstice day from 2007-2020 e) The differential TEC values for above all the days during 2007-2020 for EOF-TEC and GPS-TEC.

Day-to-variation of TEC:

Figure 6. The temporal variation of (a) GPS-TEC, (b) EOF-TEC, (c) IRI-TEC and (d) EOF-dTEC during 2007-2020.
We have chosen the entire solar cycle GPS-TEC data for a single station IISC, Bangalore. The total no of days is 4307. To check the model performance, we made temporal variation all results which are shown in Figure 6. Figure 6 shows that GPS-TEC, EOF-TEC, and IRI-TEC maximum value around 8:00-12:00 UT for all the year which is already observed in single day variation. The next outcomes are the TEC is maximum around 2012-2015 during the high solar active year and lower values of TEC around the low solar active year. The model performance is also quite good as the dTEC value is ranging in between ±2 for the entire solar cycle. The GPS-TEC and EOF-TEC temporal distribution patterns are quite similar, but the obtained EOF-TEC values are lower than GPS-TEC from 2011 to 2013. We made some statistical analysis to check the model performance discussed in the last section.

**Seasonal variation of TEC:**
The mean diurnal variation of TEC of the March equinox, June Solstice, September Equinox, December Solstice for the year 2007-2020 are represented in Figure 7 (a)-(d). Seasonal variation of TEC shows that the value of TEC is maximum for March Equinox and December solstice for the year 2014 for both GPS-TEC and EOF-TEC. June solstice TEC is maximum in 2013 for GPS-TEC and 2015 for EOF-TEC. September equinox TEC is maximum in 2012 for both GPS-TEC and EOF-TEC. For GPS-TEC equinox TEC is greater than solstice TEC for the year 2007-2010, 2014-2017, and 2020 and for 2011-2013 and 2018-2019 solstice, TEC is higher than equinox one. For EOF-TEC equinox TEC is greater than solstice TEC for the year 2007-2010, 2012, 2014-2020 and for 2011, 2013 solstice TEC is higher than equinox one. From 2011-2013 September equinox GPS-TEC is higher than March equinox GPS-TEC while for EOF-TEC this kind of variation during 2011-2013. December solstice TEC is higher than June Solstice TEC for the year 2010-2012, 2014-2015, and 2020 for both EOF-TEC and GPS-TEC. As the TEC is one of the major parameters of the F region, N₂ attachment or detachment plays a vital role to increase or decrease the electron density. The N₂ attachment or detachment is mainly related to the O molecule. We have also taken the thermo-ionospheric O/N₂ ratio obtained by Global Ultraviolet Imager (GUVI). The possible cause of higher December solstice TEC than June solstice TEC is the winter anomaly during high solar active year generated due to the higher O/N₂ ratio in December. From Figure 1, it is observed that from 2011-2013 the solar activity variation is not steady so this factor can also influence the value of TEC is higher in solstice than equinox. The September equinox TEC is higher than March equinox TEC may be due to higher sunspot value is started after the September month or due to higher O/N₂ during that period. From Figure 8, it is observed that for 2014 (the high solar active year) the O/N₂ ratio (≥0.8) in March equinox and O/N₂ ratio (≥0.6) in December Solstice while for September equinox, the O/N₂ ratio (≥0.6) and June Solstice, the O/N₂ ratio (≥0.4) which are much lesser than March and December. For the same reason, the equinox TEC is higher than the solstice one.
Figure 8. Thermo-ionospheric O/N$_2$ ratio obtained by GUVI for March and September equinox days, and June and December solstice days of 2014 represented as the equinox month and solstice month.

Yearly variation of TEC:
The mean seasonal variation of TEC shows the yearly variation of the same. The yearly variation of TEC is shown in Figure 9. It is found from Figure 9 (a), that the first minimum value of TEC is for 2009 and then the value of TEC is started to increase and attains a maximum value in 2014. After that, the value of TEC slowly decreases and again attains the second minimum value in 2019 and then started to increase in 2020. This same pattern is followed by GPS-TEC, EOF-TEC, and IRI-TEC. The IRI-TEC model values are quite low with respect to the model data and observed data. The EOF-TEC model results are very much similar to the observed one with residual value ±1.5 TECU which are shown in Figure 9 (b).

Figure 9. (a) The annual variation of GPS-TEC, EOF-TEC, and IRI-TEC during 2007-2020. b) The annual residuals of EOF-TEC with respect to the GPS-TEC.

Variation with solar activity:
The sun emits a wide spectrum of radiation along with high-energy particles. The effects of solar activity on the ionosphere can be studied by three parameters which are the sunspot number (SSN), the flux of solar radio emission at a wavelength of 10.7 cm (2.8 GHz), and EUV flux (W/m$^2$×10$^9$). To study the dependency of solar activity, we compare the yearly mean TEC as computed from observed data, EOF-TEC decomposition model, and IRI-2016 model TEC (Figure 5) with the yearly mean solar flux (F10.7), the yearly mean sunspot number (SSN) and EUV solar flux for the year 2007-2020. All the yearly mean TEC values precisely match the solar activity pattern, with a peak in 2014 and depressions in 2009 and 2019 (Figure 10). Though the value of IRI-2016 TEC also follows the same trend. EOF-TEC is slightly higher than the observed GPS-TEC data. GPS-TEC, EOF-TEC, and IRI-2016 TEC show a high positive correlation with solar activity parameters. For EOF-TEC, the correlation coefficients are R= 0.9882, 0.9843, and 0.9600 with F10.7, sunspot number, and EUV flux respectively. Similarly, for IRI-TEC, the correlation coefficients are R= 0.9886, 0.9843, and 0.9600 and for GPS-TEC, the correlation coefficients are R= 0.9869, 0.9857, and 0.9569 with F10.7, sunspot number, and EUV flux respectively. The GPS-TEC, EOF-TEC, and IRI-TEC are also highly correlated with each other with correlation coefficients R= 0.9879 (GPS-TEC and EOF-TEC), 0.9889 (GPS-TEC and IRI-TEC), and 0.9895 (EOF-TEC and IRI-TEC) respectively.
We have computed all the statistical values to check the performance of the Model. Figure 10 shows the histogram of model residuals. The mean error value is 0.2001 TECU, RMSE and STDE=RMSE= 5.7891 and NRMSE=16% which is quite good, and the correlation coefficient between model data and observed data is 0.9323.

V. CONCLUSION AND FUTURE SCOPE

The present paper deals with a comprehensive study of ionospheric TEC variation as observed from the IGS GPS satellites data for the solar cycle 24. We use the low latitude station IISC, Bangalore to study the ionospheric TEC variation. We take the full solar cycle GPS-TEC data to compare the variation with solar activity and its parameters. The diurnal variation of TEC is mainly affected by solar flux and geomagnetic activity. So that we first present the diurnal variation for quiet days. The outcome of our observation as follows:

1. The variation of diurnal TEC attains a maximum value at about 8:00-11:00 UT or 13:00-16:00 LT and a minimum value after the sunset.
2. The value of TEC is minimum around 29-35 TECU for 2007, 2009, and 2019, whereas for 2013 to 2015 it is nearly about 70-80 TECU.
3. As sunspot numbers, solar flux, and EUV flux are low in 2007, 2009, and 2019 and the corresponding TEC is also lower. From 2013 to 2015, as the sunspot number, F10.7 and EUV flux got increase which proportionately increased the value of TEC and it attains the maximum.
4. For seasonal variation, TEC is high in the Equinox period in comparison with summer and winter. For yearly variation, we see that TEC rapidly increases from 2009 to 2014 and then gets depleted from 2015 to 2019 and increases in 2020.
5. The percentage increase in yearly background TEC varies from 1 to 166% in the entire solar cycle for the lowest the solar active year 2019.
6. EOF-TEC model predicted well for the entire solar cycle. From statistical analysis, it is observed that the EOF-TEC model performance is good during entire period, and it is highly correlated with the observed GPS-TEC.
7. The diurnal variation of the first-order base function and the first-order coefficient is highly correlated to average TEC and F10.7.

8. In IRI-2016 model analysis, it also follows the similar kind of trend during the entire solar cycle.

9. The IRI-2016 model TEC value is not comparable to EOF-TEC and GPS-TEC but solar activity variation is verified by it.

This paper gives a vast statistical output of the low latitude TEC variation which can be used as an ionospheric calibration over a complete solar cycle. The variation of TEC is directly proportional to the solar activity which is verified with previous works [14-16, 23-24]. We also get similar kinds of results for the whole solar cycle period for seasonal and annual variations as per the previous works. The correlation between solar flux, EUV flux, and TEC is enhanced for low to high and depleted for high to low solar activity period. To obtain the peculiarities in seasonal variation we mainly checked the O/N2 ratio whose value is mainly responsible to produce the winter anomaly in the low latitude region [23,51]. The EOF-TEC model is highly correlated to solar activity. We also get similar kinds of results for the entire solar cycle with EOF-TEC for the single station IISC like previous work for a region China by Shuhui et al. [43]. We use this model only for a single station in low latitude so in near future we have the scope to study multiple station data and also checked the spatial variation of EOF components. We will also apply this model for polar auroral storm variation in the near future. The present manuscript deals with using the estimated TEC variation as available from GPS-IGS stations. These data have some limitations on biasing errors and data availability. In the future, we will try to eliminate such limitations by using advanced GPS instruments through a network of receivers. Also, this work can be extensively used as a calibration of TEC variation which can be used as a background profile. Such a profile will be very useful to study other terrestrial and solar energetic phenomena for which significant TEC anomalies can be observed [52-53]. We will extensively work on this in the future and will report elsewhere.

ACKNOWLEDGMENT

The authors thank NASA data centre (OmniWeb) for providing the geomagnetic indices, SILSO data archive for giving the sunspot number information, and the IGS network for providing the GPS data. We thank Dr. Gopi Seemala for providing the software to compute the TEC variations. The authors are thankful to DST-INSPIRE, DST-SERB and Govt of West Bengal for the financial supports.

REFERENCES


AUTHORS PROFILE

Mr. Subrata Kundu pursued B. Sc from Malda college, Malda, West Bengal in 2014. He pursued his M.sc from Ramakrishna Mission Residential college, Kolkata in 2016. He is currently pursuing PhD as Senior Research Fellow in Department of Ionospheric Sciences from Indian Centre for Space Physics, sister institute under Calcutta University, Kolkata, since 2017. His main research work focuses on ionospheric irregularities during terrestrial and extra-terrestrial events by using multi-parametric approach. He also got the Young Scientist Award in URSI GASS 2020.

Dr. Sudipta Sasnal received his Ph.D. from Jadavpur University. He is presently working as an Assistant Professor in Indian Centre for Space Physics, Kolkata. His major research topics are ionosphere and upper atmosphere, low-frequency radio wave remote sensing, space-weather, lithosphere-atmosphere-ionosphere-coupling, lightning, polar ionosphere etc.

Prof. Sandip Kumar Chakrabarti received his Ph.D. degree from the University of Chicago. He received DSc from the University of Gour Banga and received “Banga Ratna” award from Government of West Bengal, India. He is presently the Director and Distinguished Professor at Indian Centre for Space Physics, Kolkata. His major research topics are black hole astrophysics, low-cost balloon-borne science, astrochemistry leading to biomolecules, ionospheric sciences, etc.