Ionospheric TEC from the Turkish Permanent GNSS Network (TPGN) and comparison with ARMA and IRI models

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ABSTRACT

The present study investigates the ionospheric Total Electron Content (TEC) variations in the lower mid-latitude Turkish region from the Turkish permanent GNSS network (TPGN) and International GNSS Services (IGS) observations during the year 2016. The corresponding vertical TEC (VTEC) predicted by Auto Regressive Moving Average (ARMA) and International Reference Ionosphere 2016 (IRI-2016) models are evaluated to realize their effectiveness over the region. The spatial, diurnal and seasonal behavior of VTEC and the relative VTEC variations are modeled with Ordinary Least Square Estimator (OLSE). The spatial behavior of modeled result during March equinox and June solstice indicates an inverse relationship of VTEC with the longitude across the region. On the other hand, the VTEC variation during September equinox and December solstice including March equinox and June solstice are decreasing with increase in latitude. The GNSS observed and modeled diurnal variation of the VTEC show that the VTEC slowly increases with dawn, attains a broader duration of peak around 09.00 to 12.00 UT, and thereafter decreases gradually reaching minimum around 21.00 UT. The seasonal variation of VTEC shows an annual mode, maxima in equinox and minima in solstice. The average value of VTEC during the June solstice is with slightly higher value than the March equinox though variations during the latter season is more. Moreover, the study shows minimum average value during December solstice compared to June solstice at all stations. The comparative analysis demonstrates the prediction errors by OLSE, ARMA and IRI remaining between 0.23 to 1.17 %, 2.40 to 4.03 % and 24.82 to 25.79% respectively. Also, the observed VTEC seasonal variation has good agreement with OLSE and ARMA models whereas IRI-VTEC often underestimated the observed value at each location. Hence, the deviations of IRI estimated VTEC compared to ARMA and OLSE models claim further improvements in IRI model over the Turkish region. Advanced analysis of TPGN data over the region may complement towards the future refinement of IRI model over the lower mid-latitude region.

Keywords: ARMA, IRI, TPGN, VTEC, OLSE

1. Introduction

The ionospheric Total Electron Content (TEC) keeps on to be the largest source of error in the Global Navigation Satellite System (GNSS) positioning, especially for the single frequency users (Panda and Gedam, 2016). Also, the delay effects of TEC on other radio propagation, satellite communication and space-based navigational applications cannot be ignored. Hence, the exploitations of GNSS signals for probing ionospheric TEC over different regions of the globe are practiced by different groups (Panda et al., 2015a; Ratnam et al., 2016; Ansari et al., 2017a). Moreover, the technological development in GNSS based measurements have been expanded with accuracy, availability, integrity and continuity of geodetic position estimation with assured art of safety from natural disasters through probing the ionospheric constraints (Sparks et al., 2011). In Turkey, the Turkish permanent GNSS network (TPGN) is a regional GNSS network established for providing the ionospheric slant delay (ISD) of signals propagating from satellites to the receivers. The network allows the users to mitigate the ionospheric delay error by providing the ionospheric grid delay (IGD) in terms of ionospheric vertical delay (IVD) at each ionospheric grid point (IGP) latitude and longitude. Recently, the vertical delays have been estimated from slant delay measurements for several TPGN stations, by assuming the ionosphere to be a thin shell and located at 350 km altitude above the Earth (Ansari and Corumluoglu, 2016; Ansari et al., 2017a). The researchers have been trying to improve the ionospheric delay predictions from various imperial ionospheric models like Auto Regressive Moving Average (ARMA) model, International Reference Ionosphere (IRI), and Ordinary Least Square Estimator (OLSE) etc. in different parts of the globe. The present study investigates the suitability of ARMA and IRI models at the lower mid-latitude Turkish region with the opportunity of a dense network of high resolution GNSS data availability.

Additionally, the forecasting of ionospheric error carries the most exciting challenge for the ionospheric researchers. The accurate forecasting of ionospheric disturbances is a strong requirement for reliable performance of many applications such as communication, navigation and surveillance system. There are several ionospheric forecasting models such as Autoregressive Model, Advanced Neural Network Model, Holt Winter Method and Kriging etc. which are being used over low, mid and high latitude regions. The ARMA model is successfully applied in medical field, biological field, statistical purpose and signal processing for forecasting applications and is one of the popular techniques for analyzing univariant time series data (Lu et al, 2001). Later, numerous efforts have been made to study the ionospheric TEC distribution by ARMA model in different regions around the world, including Europe, America, Africa, and Asia (see, e.g. Akhoondzadeh 2013; Ratnam et al, 2014; Dai et al, 2015; Mandrikova et al, 2015; Lei et al, 2015; Chen et al, 2017). However, to the best of our knowledge a clear understanding on the TEC distribution over the lower mid-latitude Turkish region and applicability of the ARMA or any other forecasting models are still sparse. Hence, in this work we attempted to investigate the TEC variability and reliability of ARMA model forecasting over Turkish region with a dense network of GNSS data. The applicability of ARMA model algorithm can be summarized as follows:

Let y denote the stationarized time series (the time series having a constant variance over time or has no trend). In technical language, we can say it has constant autocorrelations over the time. The equation for ARMA forecasting y will be given by:

Forecasting of y at time t =
Constant + sum of the weighted last p values of y+ sum of the weighted last q forecast errors

where "p" and "q" are small positive or negative integers called the weighted coefficients. Mostly the value of either p or q is taken as zero, and sum of p and (p +q) is consider less than or equal to 3. In this situation there will not be too many terms on the right side of the equation. The constant term may or may not be taken as equal to zero. The lagged terms of y appeared in the equation are known as "autoregressive" (AR) terms, and the lagged terms of the forecast errors are known as "moving average" (MA) terms (Nau 2014). The equation for the predicted value of y in a period t up to period t-1 based on the observed data is expressed like this (Nau 2014):

$$\hat{y}_t = \mu + \varphi_1 y_{t-1} + \ldots\ldots + \varphi_p y_{t-p} - \theta_1 e_{t-1} - \ldots\ldots - \theta_q e_{t-q} \tag{1}$$

where μ is the constant term, φ_k is AR and θ_k is MA coefficient at lag k. The value $e_{t-k} = y_{t-k} - \hat{y}_{t-k}$ is the error in forecasting which was prepared at period t-k. It is notable that the error terms MA in the model are usually written with a negative sign instead of a positive sign (Nau, 2014).

The mathematical equations of ARMA model in more simple form can be written as

$$\hat{y}_t = \mu + \sum_{i=1}^{p} \varphi_i y_{t-i} - \sum_{j=1}^{q} \theta_j e_{t-j} \tag{2}$$

The intent of this work is to forecast the ionospheric VTEC variations over Turkish regions during the selected period. We selected ARMA model with the order p = 1 and q = 1. The forecasted values of VTEC are evaluated with original VTEC values. The preliminary outcomes point out that ARMA model would be a successful tool for developing early warning ionospheric disturbances.

The consistency of VTEC predictions from IRI-2016 (https://omniweb.gsfc.nasa.gov/vitmo/iri2016_vitmo.html) model is also evaluated over the region. The IRI, sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), is the globally accepted standard empirical model predicting ionospheric parameters. It provides improved and updated monthly averages of critical ionospheric parameters within 60-2000 km altitudes as a function of local time, geographical location, height and sunspot number (Bilitza et al., 2014). The diurnal, monthly, seasonal as well as annual variations in TEC during the periods of 2005-2007, 2007-2008, 2009-2011, 2013-2015 and 2016-2017 have been earlier investigated over the equatorial and low-latitude regions by several authors (Bagiya et al., 2009; Kumar and Singh, 2009; Chauhan et al., 2011; Panda et al., 2015a; Ratnam et al., 2016, Ansari et al., 2017a). Mosert et al. (2007) investigated the diurnal and seasonal variations of IRI-2000 TEC predictions and compared with the GNSS-TEC and ionogram observations. They concluded that IRI is overestimating both GNSS-TEC and ionogram values most of the time. Praveen et al. (2010) conducted the IRI-2007 TEC predictions validation model during the lowest phase of the solar activity period. They revealed there are seasonal and longitudinal discrepancies in IRI predictions. The predicted TEC (IRI-2012 model) have been examined in recent years over different equatorial and low-latitude regions (Tariku, 2015; Kumar et al., 2015; Rathore et al., 2015) and concluded that the IRI-2012 model fails to respond during geomagnetic storms. Tariku (2015) reported that the largest overestimations are being noticed during the low solar activity phase compared to the high solar activity phase. Similar studies on ionospheric variability and validation of different versions of IRI models over equatorial and low-latitude stations are performed by many researchers (Kouris and Fotiadis, 2002; Kouris et al., 2004; Oyekola and Fagundes, 2012; Kumar et al., 2014, 2015; Saranya et al., 2015; Karia et al., 2015, Ansari et al., 2017a).

The TPGN vertical delay estimation has been modeled based on ordinary least square estimator (OLSE) and ARMA model to validate the IRI-2016 model at regional level. The complete description of the proposed OLSE method has been discussed in Sec 2. The paper investigates the variations of ionosphere above the lower mid-latitude Turkish region using the GNSS observables. The spatial, diurnal and seasonal variations of TEC over four IGS and 145 regional stations are presented and compared with ARMA and IRI-2016 models in Sec. 3. Finally, the results are summarized followed by the conclusion drawn from the study in Sect. 4.

2. GNSS Data and Modeling methodology

In the present study, the spatial, diurnal and seasonal variation of TEC over the lower mid-latitude Turkish region has been investigated. The study includes GNSS data from four IGS stations located at Istanbul (ISTA; Geographic 41.10°N, 29.02°E; Geomagnetic 38.31°N), Ankara (ANKR; Geographic 39.89°N, 32.76°E; Geomagnetic 36.54°N), Gebze (TUBI; Geographic 41.14°N, 35.47°E; Geomagnetic 37.35°N) and Armenia (ARUC; Geographic 37.23°N, 39.75°E; Geomagnetic 32.88°N) and 145 regional stations under Turkish permanent GNSS network (TPGN) as shown in Fig 1a. The location of geomagnetic equator and average position of northern equatorial ionization anomaly (EIA) crest contour (15° geomagnetic latitude) with the positions of the Turkish GNSS sites are shown in Fig. 1b. The TPGN was established in 1999 and presents the continuous recorded data in its website in the receiver independent exchange (RINEX) format (Ansari et al., 2017b). Initially the TPGN was established for geodetic measurements across the region, but latter the researchers started using the GNSS data over the region for tropospheric as well as ionospheric estimates (Ansari et al., 2016). The present study examined the behavior of VTEC variation during the year 2016 at selected stations and provides an opportunity for probing the reliability of model estimations over the region. The IGS stations data are downloaded from the CDDIS (ftp://cddis.gsfc.nasa.gov/) data server and TPGN data has been provided by TUSAGA-Aktif (https://www.tkgm.gov.tr/tr/icerik/tusaga-aktif-0). The TUSAGA-Aktif system is a ground based positioning system consisting of fixed GNSS stations and control centers for real-time positioning information that began on May 8, 2006 with the Scientific and Technological Research Council of Turkey (TÜBİTAK) project support and was completed in May 2009. The system is currently in operation with 146 stations and 2 control centers. It continuously provides the near real-time location correction information in the Turkish territory. The system consists of four separate components; fixed earth stations receiving signals from GNSS positioning, system control centers, communication unit for data transmission, and capable single/dual frequency receivers with differential global positioning system (DGPS) and real time kinematic (RTK) features. In addition, within the scope of American GPS, Russian GLONASS and European Union GALILEO systems are used in the TUSAGA-Aktif system. In the present study, the RINEX GNSS data are processed by the GNSS-TEC analysis program (Seemala and Valladares, 2011). The satellite differential code biases (DCBs) P1C1 and P1P2 are used from the Center for Orbit Determination in Europe (CODE), Astronomical Institute, University of Bern. However, the receiver differential code biases (DCBs) are estimated by the program itself by observing the diurnal minimum TEC at each station and then determining the 2-sigma iterated average of all satellites passes over the locations. The geomagnetically disturbed days due to earth and solar events are neglected by considering the days only with geomagnetic Ap indices below 20 nanotesla (Ap < 20 nT). The diurnal minimum slant TEC (STEC) at each station are estimated from differential code and phase observations and then converted to vertical TEC (VTEC) using a single layer model (SLM) mapping function. The SLM mapping function is a thin shell model associated with an ionospheric pierce point (IPP) altitude to determine the VTEC from the STEC (Schaer, 1999). Hence, the VTEC at a given point is calculated from the equation as follows:

$$VTEC = STEC \times \sqrt{1 - \left(\frac{R_E Cos\alpha}{R_E + h_{\max}} \right)^2} \qquad (3)$$

where R_E the radius of the earth (R_E=6378 km), α is the elevation angle, and h_{max} (=350 km) is the approximate ionospheric thin shell altitude above the earth surface. To avoid the multipath, atmospheric effects and change in satellite geometry, an elevation angle of 20° is chosen at all the stations.

The percentage deviation between the GNSS-TEC values and (ARMA or IRI) models has been calculated by equation (4)

$$\Delta TEC\ (\%) = \left(\frac{GNSS_{TEC} - Model_{TEC}}{GNSS_{TEC}} \right) \times 100 \qquad (4)$$

Where, $GNSS_{TEC}$ and $Model_{TEC}$ refer to the GNSS-TEC and estimated TEC from (ARMA or IRI) models.

The VTEC measurements quantile-quantile plot (QQ-plot) around 06.00 UT (Local Time=Universal Time +3 Hours) during March equinox, June solstice, September equinox and December solstice of the year 2016 at each ionospheric grid point (IGP) across Turkey are shown in Figs. 2a to 2d. It is clear from figures that the QQ plots diverge from the straight line indicating the VTEC does not approximate the normal distribution (Lee et al., 1998). This means the VTEC presents a trend; it is probably due to the day to day equatorial electrodynamics and wind dynamics (Crujeiras and Keilegom, 2010). The VTEC trend of ionospheric process can be modeled with an ordinary least square estimator (OLSE) by using a simple polynomial (Crujeiras and Keilegom, 2010). The OLSE residuals are also very useful to construct the variance and covariance matrix. Let us assume that observed GNSS-VTEC value can be expressed as a function of the independent variables latitude, longitude and time (ϕ, λ and t):

$$VTEC = VTEC(\phi, \lambda, t) \qquad (5a)$$

The latitudinal and longitudinal variation of VTEC at 12:00 UT on 13 March 2016 (randomly selected quiet day) has been shown in Figs (3a and 3b). Both figures have some VTEC peak values like 38°N latitude and 32°E longitudes; these peaks corresponds to the diurnal maximum mostly due to local solar radiation and tidal effects with hardly any influence of ionization transportations through the E×B drift from equatorial and low latitudes (Yizengaw and Moldwin, 2008). It is clear from the figures that longitude range is more than double the latitude range for covering Turkey (Fig. 1a, 3a & 3b). Hence, we used first order function for latitude and second order for longitude to model the VTEC in Turkish region.

Let us consider

$$VTEC(\phi,\lambda,t)=\alpha_1(t)+\alpha_2(t)\phi+\alpha_3(t)\lambda+\alpha_4(t)\lambda^2 \tag{5b}$$

Where $\alpha_i\,(t)$ are time dependent coefficients

If the number of observation data is *n,* then by least square approach the polynomial constants of Eq. (5b) can be expressed in the following form:

$$\begin{bmatrix} \Sigma VTEC \\ \Sigma VTEC\times\phi \\ \Sigma VTEC\times\lambda \\ \Sigma VTEC\times\lambda^2 \end{bmatrix} = \begin{bmatrix} n & \Sigma\phi & \Sigma\lambda & \Sigma\lambda^2 \\ \Sigma\phi & \Sigma\phi^2 & \Sigma\phi\times\lambda & \Sigma\phi\times\lambda^2 \\ \Sigma\lambda & \Sigma\phi\times\lambda & \Sigma\lambda^2 & \Sigma\lambda^3 \\ \Sigma\lambda^2 & \Sigma\phi\times\lambda^2 & \Sigma\lambda^3 & \Sigma\lambda^4 \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \end{bmatrix} \tag{6}$$

After calculating polynomial constants (α_i), we can easily model the VTEC variation.

3. Results and discussion

Here, we investigated the behavior of VTEC variations estimated from GNSS stations at the spatial, diurnal and seasonal basis. The GNSS-VTEC results during the year are compared with ARMA and IRI-2016 models to investigate the spatio-temporal behavior of TEC and to evaluate the model predictions during different ionospheric conditions.

3.1 Spatial variation of VTEC

The spatial variations of GNSS-VTEC during March equinox, June solstice, September equinox and December solstice at 12.00 UT of the year 2016 are plotted at two degree interval in latitude and five degree interval in longitude as shown in Fig. 4a. We also estimated spatial variation behavior of VTEC from GNSS stations during March equinox, June solstice, September equinox and December solstice of the year 2016 by using OLSE method. The equations of VTEC spatial variation for TPGN network at 12.00 UT are modeled as:

$$\begin{aligned} DC(\phi,\lambda,t)&=49.5236-0.5489\phi-0.6615\lambda+0.0067\lambda^2 && (Mar\ \ Eqn) \\ DC(\phi,\lambda,t)&=19.3893-0.2291\phi+0.0576\lambda-0.0013\lambda^2 && (Jun\ \ Sols) \\ DC(\phi,\lambda,t)&=8.2900-0.0474\phi+0.0460\lambda+0.0011\lambda^2 && (Sep\ \ Eqn) \\ DC(\phi,\lambda,t)&=8.5836-0.1281\phi+0.2783\lambda-0.0030\lambda^2 && (Dec\ \ Sols) \end{aligned} \tag{7}$$

The corresponding figure of Equations (7) for the VTEC model in terms of OLSE method is shown in Fig. 4b. The Fig. 4b clearly shows an inverse relationship between the longitude and the VTEC during the March equinox and June solstice. It means VTEC values are decreasing from west to east which could be due the relatively longer duration of dusk facing towards the western longitudes than the eastern longitudes resulting in increased recombinations in the eastward direction. On the other hand, the VTEC variation during September equinox and December solstice including March equinox and June solstice are decreasing with increase in latitude. As the latitude increases towards north direction from the geomagnetic equator, the density of free electrons starts decreasing beyond the anomaly crest region.

3.2 Diurnal variation of VTEC

We examined the VTEC variation on a quiet day rather than a storm day because the models generally differ significantly during the storm days. The scatter plot of GNSS-VTEC diurnal variation at different stations for the selected geomagnetically quiet day ($\sum$Kp=5) on 13 March 2016 at three hour interval, is shown in Fig. 5. The temporal and spatial variations in the GNSS-VTEC values obtained from the stations are compared with their corresponding ARMA model VTEC values. These variations are almost similar to that of corresponding ARMA-VTEC over the Turkish region as shown in Fig-6. More interestingly, the interpolated VTEC by ARMA model reproduce the same patterns of GNSS-VTEC from pre-sunset (00.00 UT) to post-sunset (21.00 UT). This indicates that VTEC ingestion into ARMA model corrects the problem of ionospheric estimation between experimental and modeled VTEC. The figures show that the VTEC slowly increases with dawn, achieves a peak at between 09.00 to 12.00 UT and reaches minimum around 21.00 UT (Fig. 5 & 6). The diurnal peak value of VTEC corresponds to the equatorial E×B drift that reach the diurnal maximum strength few hours before the maximum VTEC (Scherliess and Fejer, 1999). The daily maximum value of VTEC during quiet day remains for a longer duration at all locations (09:00-12.00 UT) and then starts decreasing gradually. It is probably because the land part of Turkey cannot expose direct sun light any more at those hours of a day. In general, the diurnal variation of TEC shows low variation at all stations during the quiet day. The net diurnal change in quiet days mostly depends on the photoionization production and recombination losses related to the local solar radiation and the transported electrons through field-aligned diffusion as a consequence of the Fountain effect (E×B drift) that corresponds to the equatorial electrojet (EEJ) strength around the magnetic equator (Panda et al., 2015a; Ansari et al., 2017a). Past reports confer the arrival of diurnal peak VTEC few hours later than the maximum daytime EEJ strength (Scherliess and Fejer, 1999). However, the lesser variation of quiet days VTEC over the region and the broader duration of diurnal peak in the middle of the day indicate that the contribution from the transported electrons is subordinate in presence of the local radiation effects.

The diurnal VTEC contour plots during March equinox, June solstice, September equinox and December solstice of 2016 are shown in Fig. 7. From the figure, it can be observed that the diurnal pattern of TEC over the region follows almost similar to that of under laying low latitudes in March equinox season with the magnitude gradually increasing with sunrise, reaching the day maximum around local midday (10.00 UT) and decreasing thereafter to attain the day minimum value after mid night. However, the June solstice depict an anomalous pattern in TEC with the diurnal peak value remaining for a broader period centering local afternoon (about 15 TECU around 12.00 UT) even beyond the evening hours, eventually raising the daily average value even larger than that of March equinox. The observation agrees well with the past reports over equivalent latitudes in the northern hemisphere illustrating extended duration of maximum magnitudes during the daytime

(Thampi et al., 2009; Yu et al., 2016; Mathew et al., 2017). The September equinox although confirm the presence of primary peak (about 14 TECU) around 10.00 UT, a secondary peak of lesser magnitude is being noticed around 14.00 UT. In case of December solstice, the overall VTEC magnitude is reasonably less with diurnal maximum magnitude about 10 TECU, but nighttime values are somewhat elevated unlike rest of the seasons over the region. In brief, with the gradual weakening of equinoctial characteristics of TEC, the summer-dependent characteristics progressively came into view. The season-dependent characteristics of diurnal VTEC fluctuations prominently occur in the lower-mid-latitude region which gradually weaken or disappear towards higher latitudes (Liu et al., 2016). Nevertheless, the day to day variations over the lower middle latitudes are combined consequences of solar zenith angle, meridional wind circulation and compositional changes in the neutral thermospheric composition during the period (Write, 1962; Karia and Pathak, 2011; Sripathi, 2012).

3.3 Seasonal variation of VTEC

The seasons are caused because the Earth revolves around the Sun and axis of Earth is tilted. The effect of sunrise and sunset are the causes of the photoionization production and recombination losses of electrons in the ionosphere (Ansari et al., 2017a). The whole year is categorized into four seasons, i.e., February to April (March equinox), May to July (June solstice), August to October (September equinox) and November to January (December solstice). The geographical regions of Turkey comprise seven regions (bölge) which were originally defined by the first Turkish geography congress in 1941. These seven regions are subdivided into twenty one sections (bölüm) which are further splitted into numerous areas (yöre) as defined by microclimate and bounded by local geographic formations. The seven official geographical regions are the Marmara Region, the Black Sea Region, the Aegean Region, the Mediterranean Region, the Central Anatolia Region, the Eastern Anatolia Region, and the Southeastern Anatolia Region are identified as showing different geography and climate. We have chosen seven stations from different regions namely ISTA from the Marmara Region, BOYT form the Black Sea Region, IZMI from the Aegean Region, ADAN from the Mediterranean Region, ANKR from the Central Anatolia Region, OZAL from the Eastern Anatolia Region, and MARD from the Southeastern Anatolia Region (Fig 8). In Fig 8, the average VTEC is shown in the Y-axis whereas the top values in the bar diagram describe the variance of daily seasonal values. The plots show an annual mode with maxima in equinoctial seasons of which March equinox showing obvious higher value than September equinox whereas minima in solstice seasons of which December solstice is showing lesser diurnal values than the summer solstice. However, the 24 hour average value of TEC is observed to be with slightly higher values, i.e., ~10 TECU (ADAN and ANKR) and ~9 TECU (BOYT, IZMI, MARD, OZAL and ISTA) during the during the June solstice as compared to the March equinox. In our study, the minimum value is observed at all stations during December solstice compared to June solstice as explained earlier by many authors, such as Chauhan and Singh (2010), Galav et al. (2010) and Bagiya et al. (2011) but some of the reports like Bhuyan et al. (2003), Zhao et al. (2009), and Liu et al. (2012) demonstrate reversely during low solar activity period. It can be observed from Fig 8 that the variation of VTEC at all stations during March equinox is higher than others in spite of lower average VTEC compared to the June solstice. This is attributed to the optimized consequence of the compositional changes in the thermosphere and the solar zenith angle in the northern hemisphere. During the March equinox, the sub-solar point crosses the equator heading northward and the almost perpendicular illumination of solar radiation is expected resulting in photo-ionization and compositional changes in the northern hemisphere. The combined response consequences are the higher variation of VTEC during the March equinox. The top values in each bar diagram is more during March equinox while the average TEC is relatively more during June solstice. The relatively higher value of average TEC during June solstice is due to the extended duration daytime with solar radiation ionization and lesser duration of nighttime for diffusion, resulting in the day-night difference minimal. The apparently comparable diurnal average and the variance magnitude in TEC during the December solstice confirm the elevated nighttime value during winter which is mostly due to the compositional changes in the [O/N2] ratio following convergence of meridional wind and the summer to winter propagation of hemispheric neutral wind..

The seasonal variations from the GNSS-VTEC values obtained from the stations are compared with their corresponding ARMA-VTEC, IRI-VTEC and OLSE-VTEC model values (Fig. 9). The deviations between these model predictions (GNSS-VTEC versus ARMA-VTEC; GNSS-VTEC versus IRI-VTEC; GNSS-VTEC versus OLSE-VTEC) have been calculated by using Eq. (4). The positive and negative percentage deviations of model values illustrate the overestimation and underestimation the observed VTEC respectively. The values derived from IRI model are showing more deviations compared to OLSE and ARMA model at all stations. The percentage deviation of OLSE model is lower than IRI model that means our OLSE modeling using the local data is better estimate than IRI model at all stations at local level. The GNSS-VTEC versus OLSE-VTEC deviation has larger deviation than GNSS-VTEC versus ARMA-VTEC. It means ARMA model is better estimate than our OLSE modeling as in OLSE modeling we have chosen only geographical coordinate dependency but it is obvious that the VTEC variation does not depend only on geographical locations, rather on many additional factors. Moreover, it is remarkable that the underestimation of IRI model is extended up to ~45% over IZMI, BOYT, ISTA, MARD and ANKR in February, and again ANKR in October. The station ISTA and OZAL show lowest deviation ~15% in November. The OLSE model depicts maximum ~12% overestimation deviation in January and other months have less deviation. The maximum underestimation deviation for OLSE is ~8% in several months. The percentage deviation values of IRI derived VTEC compare to observed VTEC as well as OLSE and ARMA models over the Turkish region claims the essentiality of improvement in the IRI model predictions over the lower mid-latitude region.

3.4 Model comparisons

The comparison of VTEC models for GNSS observations plays an important role for forecasting and nowcasting instability in the ionosphere. The GNSS derived VTEC values have been compared with the standard ARMA and IRI-2016 models as well as mathematical models by OLSE method in the study to examine reliability of the models over the lower mid-latitude Turkish region. The spatial distribution of GNSS, ARMA and IRI model as well as OLSE-VTEC estimations at five stations KKAL, KLUU, GEME, TNCE and MURA) in the order of increasing longitude is shown during the five continuous quiet days 09th September to 13th September of 2016 (Fig. 10, Table 1).

The differential calculation between the estimated values indicates the error in the model predictions. We analyzed the suitability of these model predictions covered by TPGN network and at adjacent locations using these techniques. The obtained results from Table-1 indicate the minimum and maximum relative error by OLSE, IRI and ARMA models. The observed minimum relative errors by OLSE, ARMA and IRI models are 0.23%, 2.40% and 24.80% respectively while the maximum relative errors by OLSE, ARMA and IRI models are 1.17%, 4.03% and 25.79 % respectively. These outcomes show the high-potential of stochastic component technique in regional VTEC prediction on the TPGN regional network compared to IRI model in the terms of performance and accuracy. The IRI model underestimated the GNSS-VTEC as well as OLSE-VTEC and ARMA-VTEC estimations. In conclusion, we can say that the IRI model require numerous computational points in the correction stage. These are the limitations of IRI model in VTEC interpolations. Basically, Turkish region is a transition region between low and middle latitudes, but still these estimations are less reliable. This suggests that, the lower-middle latitude Turkish region needs further refinements with more regional data and the TPGN data can be incorporated in the IRI background experimental parameters for better reliability. The other point from the comparison is that OLSE modeling shows lower error than ARMA model but it’s not indicating that OLSE model is better than ARMA. Actually this error is based on average data and we already concluded that ARMA model better estimates the result than OLSE modeling.

We compared the seasonal variation of VTEC with OLSE-VTEC model at selected four stations namely IZMI from western Turkey, ANKR from central Turkey, TRBN from northeast Turkey and SIRN from southeast Turkey (Fig. 11). It is clear from the figure GNSS-VTEC with OLSE and ARMA VTEC models have very good agreement but IRI-VTEC is underestimated. This suggests that the present IRI model needs further improvements over the Turkish regions. There are only three IGS stations and hardly any ionosonde/incoherent radar station available across the region whose data has been incorporated in IRI. Hence, anticipating that the dense network of GNSS data may supplement towards further improvement in the global models above the territory, we attempted to study the VTEC variability with OLSE and ARMA model techniques realizing discrepancies of the existing standard models over the region. The results from this study will help to improve the model estimations over Turkish as well as other analogous lower mid-latitude region.

Conclusion

The ionospheric TEC is studied at the lower mid-latitude GNSS stations across the Turkish region to understand its latitudinal and longitudinal variations in this paper. The spatial, diurnal and seasonal variability of the ionosphere has been investigated using GNSS-derived VTEC more than hundred locations in the Turkish territory. The GNSS-based VTEC observations have been compared with VTEC predicted from mathematical model technique with ordinary least square estimation (OLSE) method as well as the ARMA and IRI models during the year of 2016. The summary of the study is as follows:

i. The spatial behavior of VTEC shows an inverse relationship between the longitude and the VTEC during the March equinox and June solstice. It means VTEC values are decreasing from west to east which could be due the relatively longer duration of dusk facing towards the western longitudes than the eastern longitudes resulting in increased recombinations in the eastward direction. On the other hand, the VTEC variation during September equinox and December solstice including March equinox and June solstice are decreasing with increase in latitude. As the latitude increases towards north direction from the geomagnetic equator, the strength of free electrons production and radiation start to reduce and field aligned transportation is restricted to the low latitude anomaly region.

ii. The figures with diurnal variation of the VTEC show that the VTEC slowly increases with dawn, attains a peak at between 09.00 UT to 12.00 UT and recovers its minimum value around 21.00 UT. The peak value of VTEC corresponds to equatorial E×B drift that usually has its maximum earlier than the daily maximum VTEC.

iii. The daily maximum value of VTEC during quiet day remains for a longer duration at all locations (09.00-12.00 UT) and thereafter starts decreasing gradually. It is probably because the land part of Turkey cannot expose direct sun light any more at those hours of a day and the recombination is at its progressive state.

iv. The seasonal variation of VTEC shows an annual mode, maxima in March equinox and minima in December solstice with intermediate values during June solstice and September equinox. The 24- hour average value of TEC is observed during the June solstice of slightly higher value, i.e., ~10 TECU (Mediterranean Region and Central Anatolia Region) and ~9 TECU (Marmara Region, Black Sea Region, Aegean Region, Eastern Anatolia Region, and Southeastern Anatolia Region) than the March equinox due to elevated magnitude of VTEC over a broader period of the day. The study shows the minimum value at all stations during December solstice compared to June solstice. The variation of VTEC at all stations during March equinox is higher than others which clearly depends on the optimized consequence of the compositional changes in the thermosphere and the solar zenith angle. During the March equinox, the sub-solar point crosses the equator and heads northward and the almost perpendicular illumination of solar radiation is expected resulting in photo-ionization and compositional changes in the northern hemisphere.

v. The percentage deviation of IRI model is extended up to ~45% in February and again in October while the lowest deviation is ~15% in November. The percentage deviation value of IRI derived VTEC compare to OLSE and ARMA models over the Turkish region indicate the necessity of improvement in the IRI models accuracies.

vi. The comparison results of GNSS with the OLSE, ARMA and IRI models show the minimum relative error obtained by OLSE is 0.23%, by ARMA is 2.40% and by IRI is 24.82 %. The corresponding maximum relative errors are 1.17%, 4.03% and 25.79 % respectively. These outcomes show the potential nature of OLSE and ARMA technique in regional VTEC prediction for determining the local ionosphere parameter. The OLSE and ARMA models show very good agreement with the observed value whereas IRI underestimated the observed VTEC at all selected locations almost all through the year. Basically, Turkish region is a transition region between low and middle latitudes, but still the model estimations are less comparable. This suggests that the lower-middle latitude Turkish region in the IRI model needs further improvements with more regional data coverage. Concerning this, the experimental parameters from the TPGN network may be incorporated in the IRI background parameters to further improve its performances over the region.

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