DIURNAL, SEASONAL AND SOLAR CYCLE VARIATION OF TOTAL ELECTRON CONTENT AND COMPARISON WITH IRI-2016 MODEL AT BIRNIN-KEBBI

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ABSTRACT

The ionosphere is the major error source for the signals of Global Positioning System (GPS) satellites. In the analysis of GPS measurements, ionospheric error is somewhat assumed to be a nuisance. The error induced by the ionosphere is proportional to the number of electrons along the line of sight (LOS) from the satellite to receiver and can be determined in order to study the diurnal, seasonal, solar cycle and spatial variations of the ionosphere during quiet and disturbed conditions. In this study, we characterize the diurnal, seasonal and solar cycle variation of observed (OBS) total electron content (TEC) and compare the result with the International Reference Ionosphere (IRI-2016) model. We obtained TEC from a dual frequency GPS receiver located at Birnin-Kebbi Federal Polytechnic (BKFP) in Northern Nigeria (geographic location: 12.64° N; 4.22° E; 2.68° N dip) for the period 2011 – 2014. We observed differences between the diurnal variation of OBS-TEC and IRI-2016 model for all hours of the day except during the post-midnight hours. Slight post-noon peaks in the daytime maximum and post-sunset decrease and enhancement are observed in the diurnal variation of OBS-TEC during the equinoxes. On a seasonal scale, we observed that OBS-TEC values were higher in the equinoxes than the solstices only in 2012. Whereas in 2011, September equinox and December solstice recorded higher magnitude followed by March equinox and lowest in June solstice. In 2013, December solstice magnitude was highest, followed by the equinoxes and lowest in June solstice. In 2014, March equinox and December solstice magnitude were higher than September equinox and June solstice magnitude. June solstice consistently recorded the lowest values for all the years. OBS-TEC is found to increase from 2011 to 2014, thus revealing solar cycle dependence.

KEYWORDS: TEC; diurnal; seasonal; variation; solar cycle 24; IRI-2016.

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1 INTRODUCTION

Ionospheric irregularities as a result of inhomogeneity in electron density leads to variations in the intensity of radio signals (Somoye, 2010; Ogwala et al. 2018, Ogunmodimu et al. 2018). Akala et al., (2011) posted that the variable nature of the equatorial/ low latitude ionosphere do adversely affect communication and navigation/ satellite systems in the region. The equatorial/ low latitude ionosphere exhibits unique features such as the seasonal anomaly, semi-annual anomaly, equinoctial anomaly, noon bite-out, spread-F, equatorial electrojet (EEJ) and equatorial plasma bubbles (EPB) (Stankov, 2009; Maruyama et al., 2004; Jee et al., 2004; Codrescu et al., 1999).

For many decades, scientists have been studying these peculiar ionospheric features and their roles in trans-ionospheric electromagnetic radio wave propagation using different techniques and instruments. One of the instruments often used is the GPS receiver. The GPS receiver provide direct measurements from satellites. Their sounding capacity extends to the topside of the ionosphere, and is affected by time and space constraints (Ciraolo and Spalla, 2002). Recently, dual frequency GPS receiver is the most efficient method used to eliminate the effect of the ionosphere on radio signals. This method combine signals in different L band frequencies, L1 (1575 MHz) and L2 (1228 MHz) (Bolaji et al., (2012; Alizadeh et al., 2013).

Almost all space geodetic techniques transmit signals in at least two different frequencies for better accuracy (Alizadeh et al., 2013). The signals are then combined linearly in order to eliminate the effect of the ionosphere on radio signals. The ionospheric effect on radio signal is proportional to the total electron content (TEC), which is defined as the number of electrons per square meter from satellite in space to receiver on ground as shown in Eq. (1).

$$TEC = \int n_e(s)ds \quad (1)$$

It is measured in multiples of TEC units (1 TECU = 10^{16} el/m^2). Due to the dispersive nature of the ionosphere, there is a time delay between the two frequencies of a GNSS signal as it propagate through the ionosphere as shown in Eq. (2) as $\Delta t = t_2 - t_1$. Thus,

$$\Delta t = \left(\frac{40.3}{c}\right) \times \frac{TEC}{\left[\left({}^{1}/_{f_2^2}\right) - \left({}^{1}/_{f_1^2}\right)\right]} \qquad (2)$$

Where c is speed of light and f is frequency. Hence, Δt measured between the L1 and L2 frequencies is used to evaluate TEC along the ray path.

When Global Navigation Satellite System (GNSS) signals propagate through the ionosphere, the carrier experiences phase advance and the code experiences a group delay due to the electron density along the line of sight (LOS) from the satellite to the receiver (Bagiya et al., 2009; Tariku, 2015). Thus, the carrier phase pseudo ranges are measured too short, and the code pseudo ranges are measured too long compared to the geometric range between the satellite and the receiver. This results in a range error of the positioning accuracy provided by a GPS receiver. The range error due to TEC in the ionosphere varies from hundreds of meters at mid-day, during high solar activity when the satellite is near the horizon of the observer, to a few meters at night during low solar activity, with the satellite positioned at zenith angle (Bagiya et al., 2009). By measuring this delay using dual frequency GPS receivers, properties of the ionosphere can be inferred and used to monitor space weather events such as GNSS, HF communications, Space Based Observation Radar and Situational Awareness Radar, etc. Ionospheric delay (proportional to TEC) is the highest contributor to GPS positioning error (Alizadeh et al., 2013; Bolaji et al., (2012).

TEC in the ionosphere can also be studied using empirical ionospheric model such as the International Reference Ionosphere (IRI). IRI is a joint undertaking by the Committee on Space Research (COSPAR) and International Union of Radio Science (URSI) with the goal of developing and improving an international standard for the parameters in earth's ionosphere (Bilitza et al., 2014). An updated version has been recently developed to cater for lapses of previous models. IRI provides the vertical TEC (VTEC) from the lower boundary (60 – 80 km) to a user-specific upper boundary (Bilitza et al., 2016).

In the past few decades, studies on the temporal and spatial variations of TEC have gained popularity in the scientific community (Wu et al., 2008). However, understanding the variability of TEC will also go a long way in obtaining the positioning accuracy of GNSS under disturbed and quiet conditions. As such, previous studies (e.g. Ayorinde et al., 2016; Bhuyan and Borah, 2007; Maruyama et al., 2004; Jee et al., 2004; Balan et al., 1994; Rama Rao et al., 2006a, b, c; Rama Rao et al., 1985; Bolaji et al. 2012; Wanninger, 1993; Akala et al., 2013; Komjathy et al., 1998; Langley et al., 2002 Sunda et al., 2013; Torr and Torr, 1973; Tsai et al., 2001 and references therein) investigated the global distribution of TEC variations and its characteristics at all latitudes, during different solar cycle phases under disturbed and quiet conditions.

Studies of Rama Rao et al. (2006a, b) in the Indian sector and Wanninger (1993) in the Asian sector reported maximum day-to-day variability in TEC at the Equatorial Ionization Anomaly (EIA) crest regions, increasing peak value of TEC with increase in integrated equatorial electrojet (IEEJ) strength, maximum monthly average diurnal variations during equinox months followed by winter months and lowest during summer months. They also reported positive correlation of TEC and EEJ and the spatial variation of TEC in the equatorial region. Titheridge (1974) and Langley et al. (2002) attributed the lowest TEC values during the summer seasons to low ionization density resulting from reduced O/N_2 ratio (production rates) as a result of increased scale height. Bhuyan and Borah (2007) working in the Indian sector and Komjathy et al. (1998) and Lee and Reinisch (2006) while studying in the American sector compared TEC derived from

GPS receivers with IRI model in the equatorial/ low latitude sector and inferred that the diurnal amplitude of TEC is higher during the equinoxes followed by December solstices and lowest in June solstice, i.e., observing winter anomaly in seasonal variation. They further reported discrepancies between IRI model and their measured values during most hours of the day at their various locations. Malik et al. (2016) on their studies over the Malaysian peninsular reported higher IRI values than observed maximum useable frequency (MUF) values but behaves similarly diurnally and seasonally with no clear trend. Akala et al. (2013) on the comparison of equatorial GPS-TEC observations over an African station and an American station during the minimum and ascending phases of solar cycle 24 reported that seasonal VTEC values were maximum and minimum during March equinox and June solstice respectively, during minimum solar cycle phase at both stations. They also reported that during the ascending phase of solar cycle 24, minimum and maximum seasonal VTEC values were recorded during December solstice and June solstice respectively. They further showed that IRI-2007 model predicted better in the American sector than the African sector.

The aim of this paper is (i) to characterize TEC on diurnal, seasonal and solar cycle scales in the Nigerian Equatorial ionosphere (ii) to compare OBS-TEC with IRI-2016 model in order to find if the model underestimates or overestimates TEC values at the African longitudinal sectors. In section 2, we describe the data and methodology. Section 3 shows the result and discussion while concluding remarks are in section 4.

2 DATA AND METHODOLOGY

2.1 DATA

The Receiver Independence Exchange (RINEX) Observation GPS data files were downloaded daily from NIGNET website (www.nignet.net) and processed using Bernese software and GPS TEC analysis software. The RINEX file contains 60 iteration data (i.e. in 1 minute time resolution). The GPS-TEC analysis software was designed by Gopi Seemala of the Indian Institute of Geomagnetism. The summary of this application is to read raw data, processes cycle slips in phase data, reads satellite biases from the International GNSS services (IGS) code files (and calculates them if unavailable), and calculates receiver bias, inter-channel biases for different satellites in the constellation, and finally plots the VTEC values on the screen and writes the ASCII output files (*CMN) for STEC and (*STD) for VTEC in the same directory of the data files. Effect due to multipath is eliminated by using a minimum elevation angle of 50°.

Observation GPS-TEC obtained from the TEC analysis software is the slant TEC (STEC) and vertical TEC (VTEC). STEC is polluted with several biases that must be eliminated to get VTEC. VTEC is calculated from the daily values of STEC using Eq. (3).

$$VTEC = (STEC - [b_R + b_S + b_{RX}])/S(E) \quad (3)$$

Where b_R, b_S, and b_{RX} are receiver bias, satellite bias and receiver interchannel bias respectively. S(E), which is the oblique factor with zenith angle, z at IPP (Ionospheric Pierce Point) is expressed in Eq. (4).

$$S(E) = \frac{1}{\cos(z)} = \left\{1 - \left(\frac{R_E \times \cos(E)}{R_E + h_S}\right)^2\right\}^{-0.5} \quad \text{Bolaji et al. (2012)} \quad (4)$$

R_E = the mean radius of the earth in km and h_S = ionospheric height from the surface of the earth. According to Rama Rao et al., (2006c), ionospheric shell height of approximately 350km is appropriate for the equatorial/ low latitude region of the ionosphere for elevation cut off angle of > 50°. This is valid in this study.

Hourly VTEC data obtained from these processing software are averaged to daily TEC values in TEC units (1 TECU = 10^{16} el/m^2). OBS-TEC from Birnin-kebbi, on geographic Latitude 12.47° N and geographic Longitude 4.23° E located in Northern Nigeria, obtained during the period 2011 – 2014, which corresponds to the ascending (2011 – 2013) and maximum (2014) phases of solar cycle 24 were compared with derived TEC obtained from International Reference Ionosphere (IRI-2016) model website (https://ccmc.gsfc.nasa.gov/modelweb/models/iri2016_vitmo.php). The 2016 version of IRI provides important changes and improvements on previous IRI versions (Bilitza et al., 2016). Solar cycle 24 is regarded as a quiet solar cycle which peaked in 2014 with maximum sunspot number (103) occurring in February. Values of sunspot number, Rz, in Text format were obtained from Space Physics Interactive Data Resource (SPIDR) website (www.ionosonde.spidr.com) shortly before it became unavailable. Table 1 shows the years used in this study and their corresponding sunspot number, Rz.

Table I: Table of years, solar cycle phase and sunspot number, Rz [Source: Author].

Years	**Solar Cycle Phase**	**Sunspot Number, R_Z**
2011	Ascending	55.7
2012	Ascending	57.6
2013	Ascending	64.7
2014	Maximum	79.6

2.2 METHODOLOGY

Diurnal variations of hourly OBS-TEC and hourly IRI-2016 model (NeQuick topside option) were plotted using the monthly mean values of OBS-TEC and monthly mean of IRI-2016 model against local time (LT) on the same Figure. The corresponding percentage deviation (percentage Dev or % DEV) of IRI-2016 from OBS-TEC were also analysed using the monthly mean values of OBS-TEC and monthly mean values of IRI-2016 against local time (LT). Percentage Dev is obtained using Eq. (5) below:

$$\%DEV = \left(\frac{OBS-IRI}{OBS}\right) \times 100 \quad (5)$$

where OBS represents Observation-TEC values and IRI represents TEC derived by IRI-2016 model.

The OBS-TEC data was grouped following Onwumechilli and Ogbuehi (1964) into four seasons namely: March equinox (February, March and April), June solstice (May, June and July), September equinox (August, September and October) and December solstice (November, December and January), in order to investigate seasonal variation. Finally, Annual variation of OBS-TEC and sunspot number, Rz were also analysed by plotting mean OBS-TEC and mean Rz against each month of the year.

3 RESULT AND DISCUSSIONS

Figures 1 to 4 show the diurnal variation of OBS-TEC and IRI-2016 model in the Nigerian Equatorial Ionosphere (NEI) for the years 2011 to 2014 respectively. OBS-TEC were obtained from the GPS receiver installed at Birnin-Kebbi station. The diurnal variation of OBS-TEC and IRI-2016 model TEC reveals the typical characteristics of an equatorial/ low latitude ionosphere. We show the day-to-day variation of OBS-TEC with error bar showing the standard deviation from mean values. The study reveals that day-to-day variation of OBS-TEC is higher during the daytime than night time for all the years. It well established known fact that during the day, the sun causes variations in temperature, neutral wind, electron density and electric field thereby modulating the structure and evolution of the ionosphere and thermosphere (Gorney, 1990; Forbes et al. (2006). These Figs. show a steep rise in OBS-TEC from a minimum of ~2 TECU between 03:00 – 05:00 LT in 2011, ~3 TECU (04:00 – 05 LT) in 2012, ~3 TECU (03:00 – 05:00 LT) in 2013 and 2014.

OBS-TEC increased to a broad daytime maximum between 12:00 LT – 14:00 LT for all years before falling to a minimum after sunset. The diurnal variation of IRI-2016 model shows TEC increasing from a minimum of ~ 2 TECU in 2011, ~ 4 TECU in 2012 and 2013, and ~ 5 TECU in 2014 between 03:00 – 04:00 LT for all years, to a broad daytime peak between 08:00 – 14:00 LT, before falling steeply to minimum before sunset. Hence the IRI-2016 model attained its peak before OBS-TEC. Dabas et al. (2003); Somoye et al. (2011); Hajra et al. (2016); D'ujanga et al. (2017) attributed the steep increase in TEC to the upward $\mathbf{E} \times \mathbf{B}$ vertical plasma drift and the rapid filling up of the magnetic field tube at sunrise due to solar EUV ionization. During daytime, an eastward electric field at the equator causes plasma to be lifted to greater heights. This dynamo-generated eastward electric field combined with the northward geomagnetic field lifts the equatorial ionosphere from 700 km to 1000 km, resulting in additional ionization (D'ujanga et al., 2017; Somoye et al., 2011). Suranya et al., 2015 further mentioned that upward vertical $\mathbf{E} \times \mathbf{B}$ drift could lead to equatorial ionization anomaly (EIA) and meridional winds. The magnetic field tubes then collapse after sunset due to low thermospheric temperature and Rayleigh Taylor Instability (RTI) (Berkner and Wells, 1934) giving rise to the minimum TEC values after sunset. These results are similar to findings of Bolaji et al., (2012), Fayose et al., (2012), Okoh et al., (2014), Eyelade et al., (2017) who have explored the NEI.

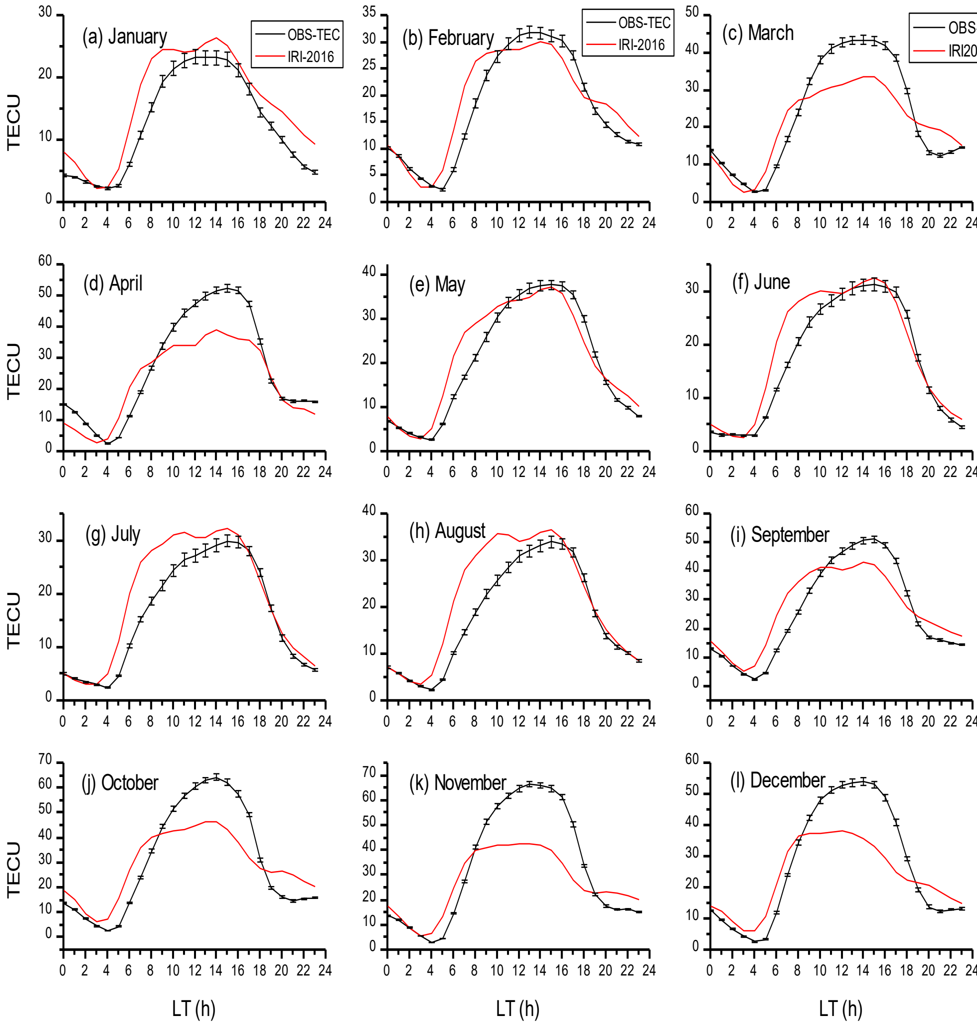

Fig. 1: Diurnal variation of OBS-TEC showing error bar and IRI-2016 model of each month during January – December 2011 at Birnin-Kebbi

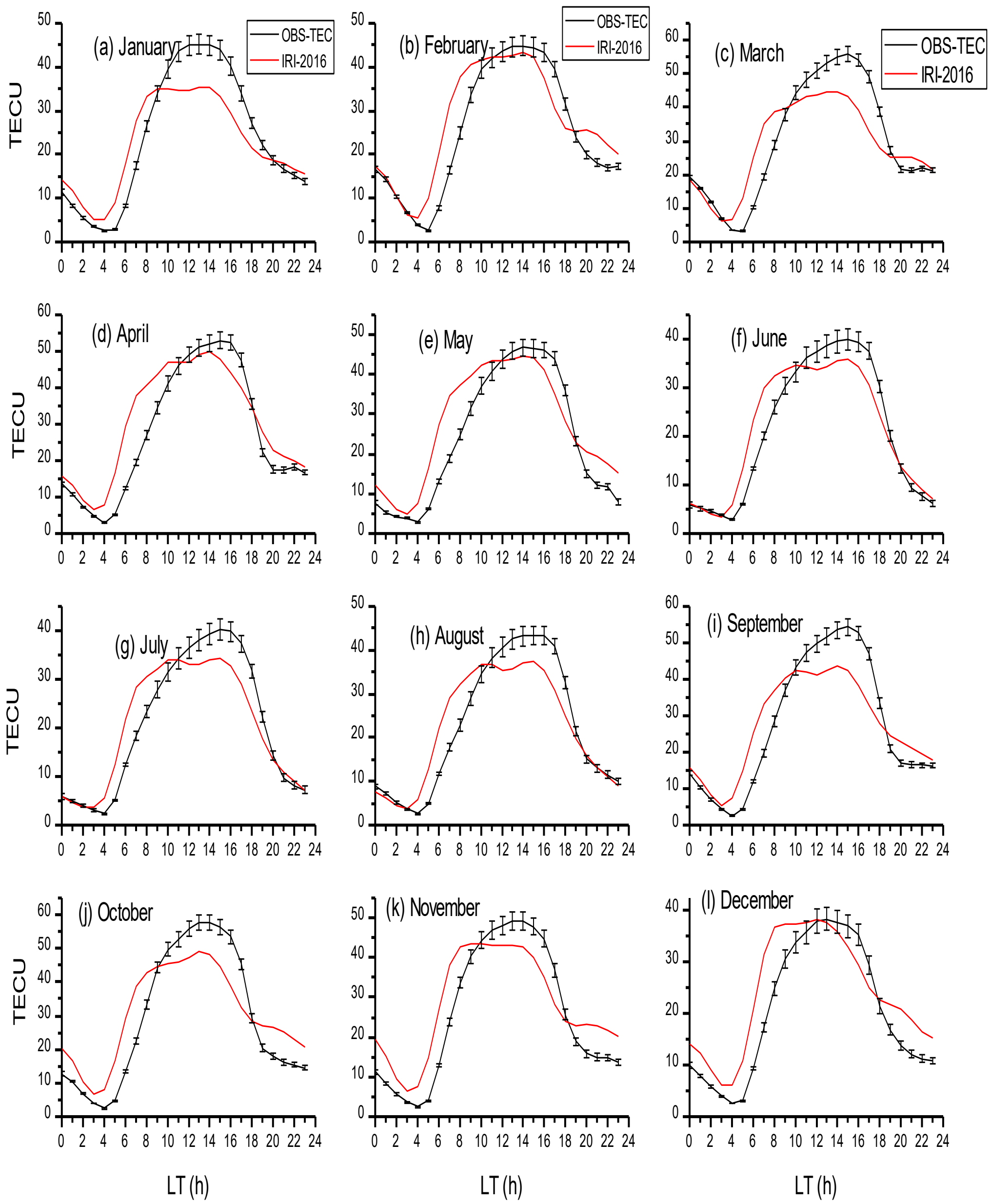

Fig. 2: Same as Figure 1 for 2012.

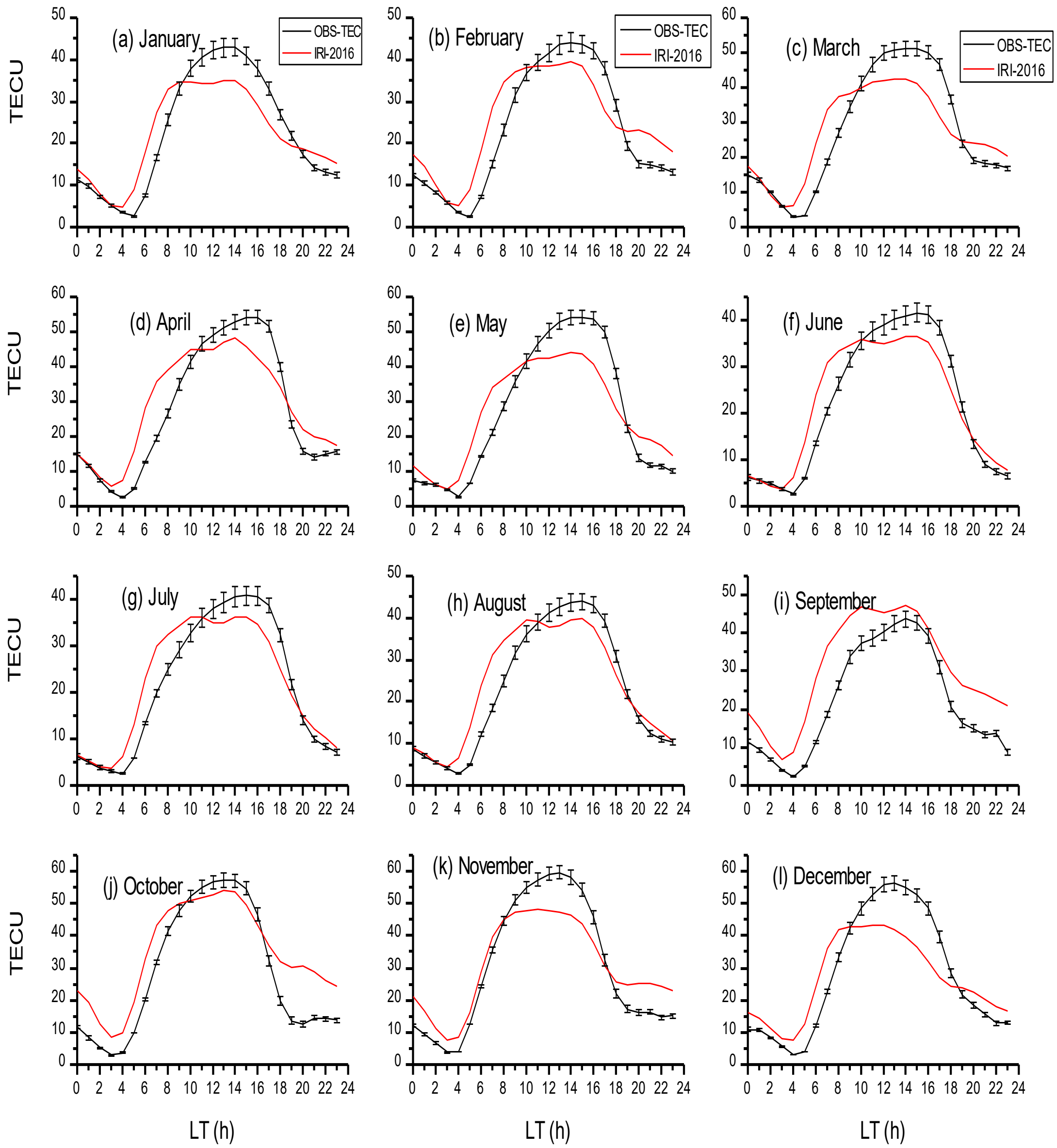

Fig. 3: Same as Figure 1 for 2013.

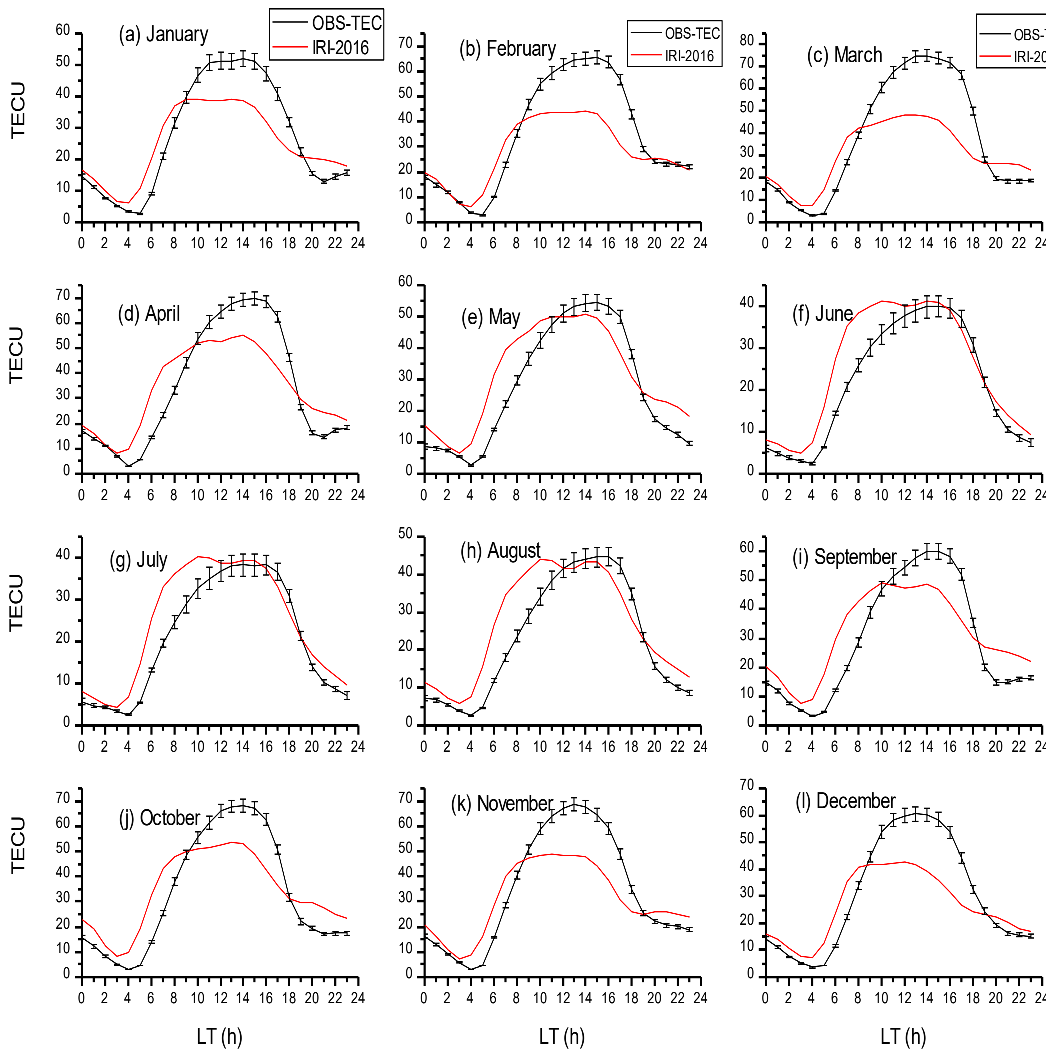

Fig. 4: Same as Figure 1 for 2014.

It can be seen that OBS-TEC is much higher in 2014 with maximum value up to 70 TECU in March compared with IRI-2016 maximum of 54 TECU in the month of October, 2014. The diurnal variation reveals that the peak of OBS-TEC of majority of the months for all years shifted to slightly post-noon hours (13:00 – 14:00 LT). This type of peak shifting is peculiar to equatorial/ low latitude regions and the Polar Regions of the ionosphere and it is found to depend on the equatorial ionization anomaly and solar zenith angle respectively (Rama Rao et al., 2009; D'ujanga et al., 2017). Another key observation seen in the diurnal variation of OBS-TEC is the post-sunset decrease and slight enhancement in some months. The night time enhancement of TEC, for example, March, April and October of the year 2011, March and April of the year 2012, March, April, September and October of the year 2013, January, April and September of the year 2014 was documented by previous researchers like Rama Rao et al., 2009; D'ujanga et al., 2017 and Ayorinde et al., 2016. They attributed it to the product of eastward and westward directed electric field which produces an upward and downward motion of ionospheric plasma during the day and night respectively.

Figures 5 to 8 show the diurnal variation of percentage deviation of IRI-2016 model from OBS-TEC in the Nigerian Equatorial Ionosphere (NEI) for all years respectively. On a general note, IRI-2016 model only presented suitable predictions for the post-midnight hour between 00 – 03 LT of the day for all years. All other hours from 04 – 23 LT show some discrepancies. In fact, for some of the months: October, November and December of 2012, October and December, 2013, and September and October of 2014, these discrepancies lasted throughout the day. Whereas in some other months: June, July and August of 2011, June, July and August of 2012, June and August of 2013 and February, June and July of 2014, these discrepancies collapsed during the pre-midnight hours (18 – 23 h). It is also important to mention that IRI-2016 model either over estimated or under estimated TEC in the NEI especially during daytime hours as shown in the plots.

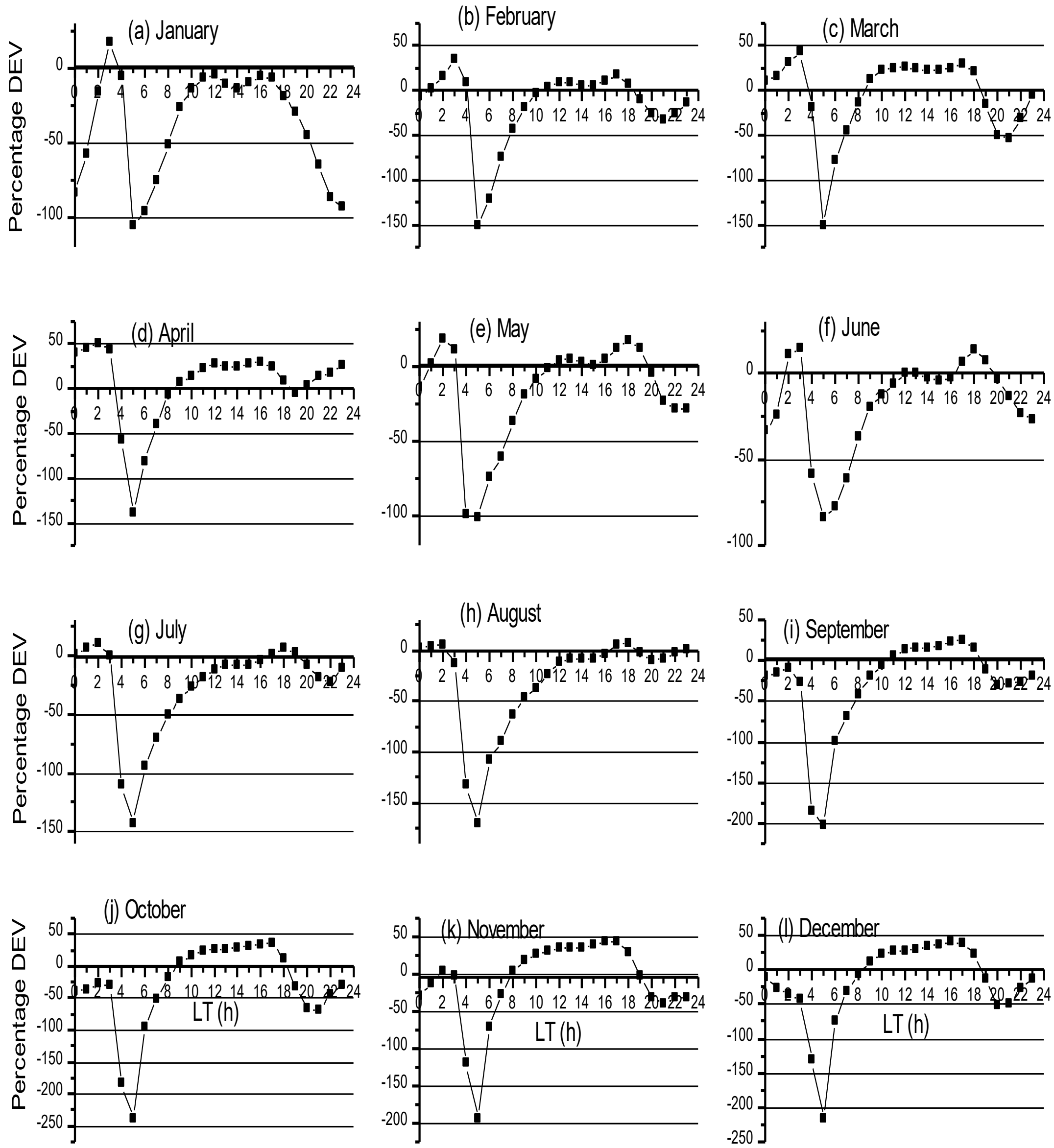

Fig. 5: Percentage deviation of IRI-2016 from OBS-TEC for year 2011

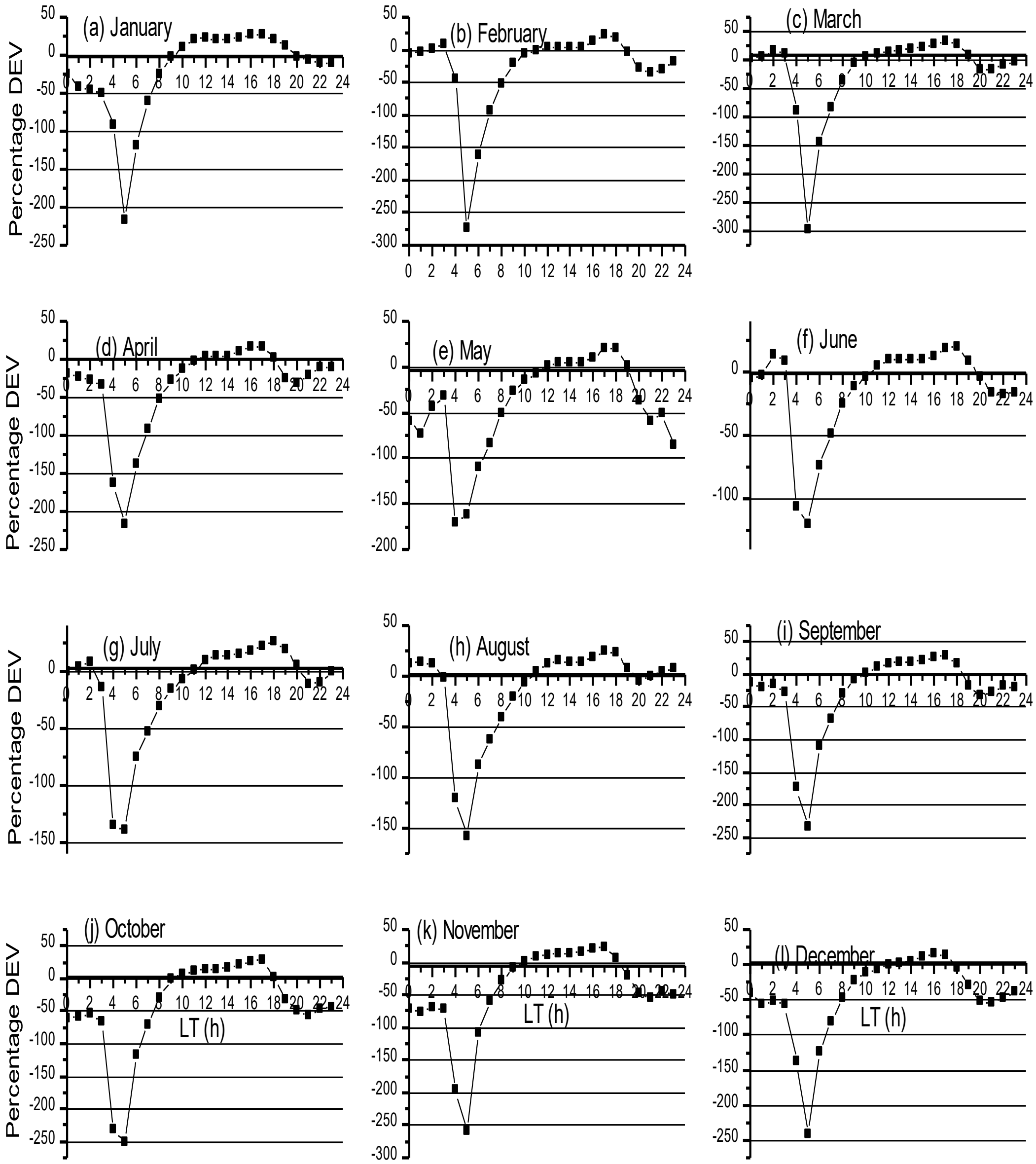

Fig. 6: Percentage deviation of IRI-2016 from OBS-TEC for year 2012

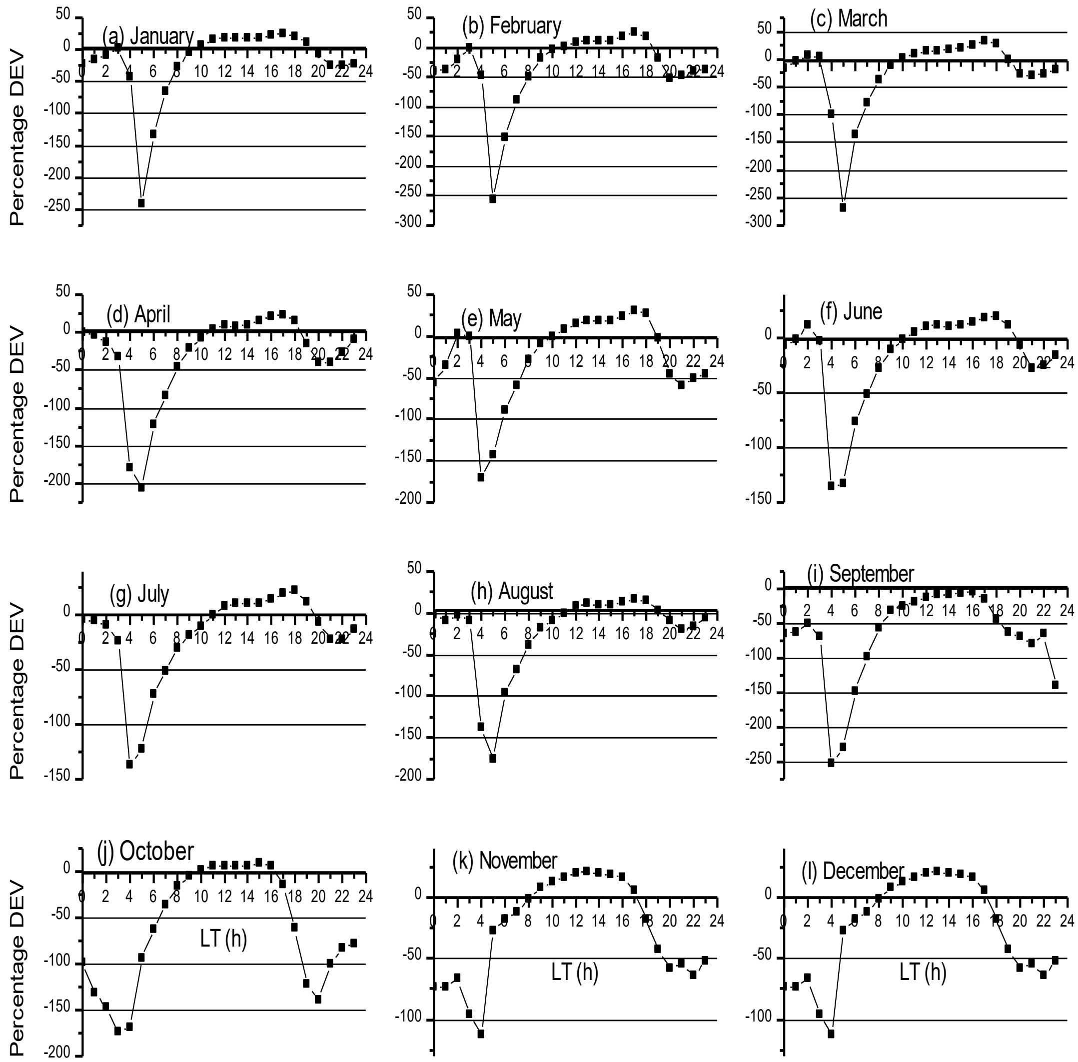

Fig. 7: Percentage deviation of IRI-2016 from OBS-TEC for year 2013

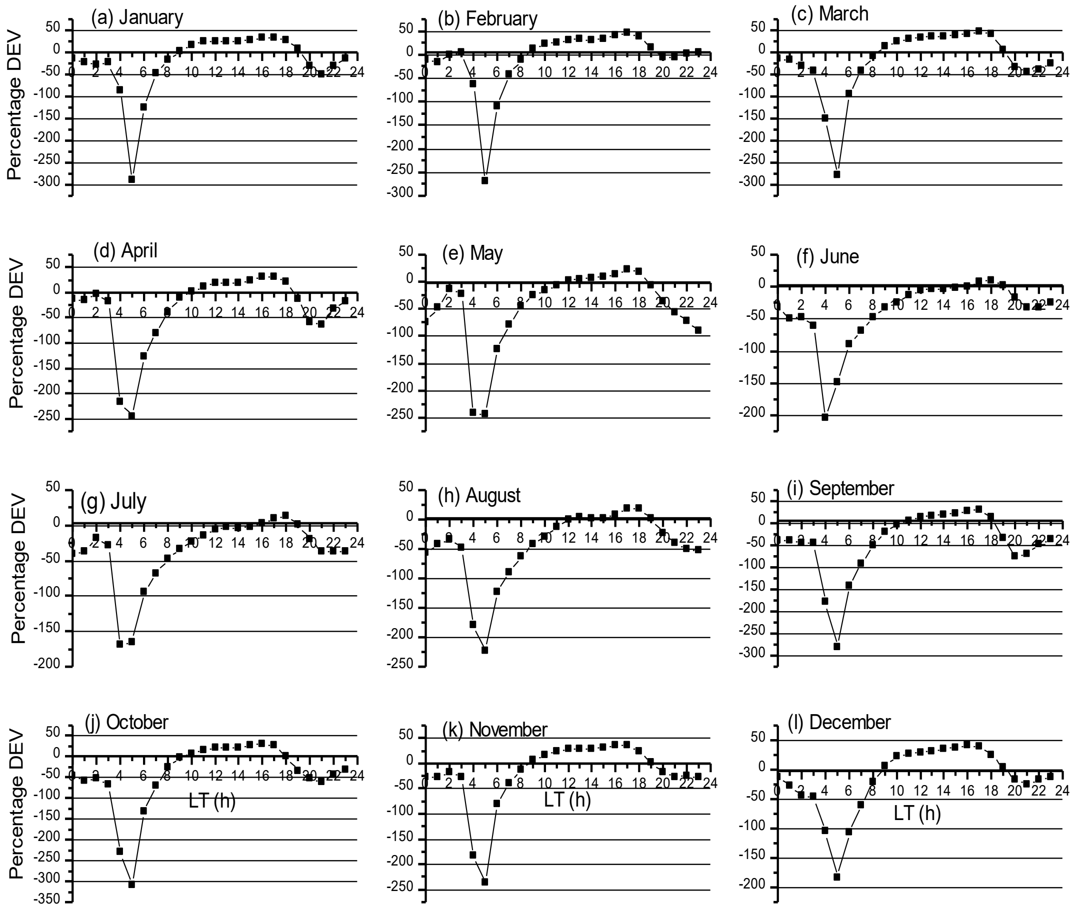

Fig. 8: Percentage deviation of IRI-2016 from OBS-TEC for year 2014

The mass plots in Fig. 5 – 8 further reveal that negative percentage deviation shows higher values of IRI-2016 than OBS-TEC values. The reverse is the case for positive percentage deviation. Highest negative percentage deviations are seen between 04 – 05 LT for all months throughout the years in this study. Highest Negative percentage deviation of ~ 300% was recorded in the month of October, 2014 at 05 LT. Table II shows the summary of months with daytime over- or under-estimate of IRI-2016 in the NEI.

Table II: Months of daytime estimate of IRI-2016 model in NEI [Source: Author]

YEAR	OVER ESTIMATE	UNDER ESTIMATE	SAME RANGE
2011	January, July, August	February – April, September - December	May - June
2012		January - December	
2013	September	January – August, October - December	
2014		January - December	

Therefore, it is clear from Fig. 1- 4, Fig. 5 – 8 and Table II that IRI-2016 model did not predict well in the NEI. This may be attributed to insufficient data which is as a result of the sparse distribution of GPS infrastructure in this region. Our result agree with those Komjathy et al. (1998); Lee and Reinisch (2006); Malik et al. (2016). Bhuyan and Borah (2007) reported higher IRI TEC than their measured values at about all local time in their location. Mosert et al. (2007) and Sethi et al. (2010) also reported discrepancies between of IRI TEC predictions and GPS TEC during high solar activity (HSA) and low solar activity (LSA) respectively at equatorial/ low latitudes.

Figure 9 show the seasonal variations of OBS-TEC for the four years investigated. The change in concentration of Oxygen and molecular Nitrogen has been reported to be the main cause of seasonal variation of ionospheric parameters. Seasonal variation of OBS-TEC in this study depicts semi-annual variation with equinoctial maximum (~ 52 TECU) and solsticial minimum (~ 44 TECU) in 2012. D'ujanga et al., (2017) reported that since the sun passes through the equator during the equinox, both March and September equinox experience the same solar radiation. It is also a well-established fact that March 20 and September 23 are the only times in the year when the solar terminator is perpendicular to the equator, giving rise to the equinoctial maximum. The semi-annual variation resulting from the effect of equatorial ionization anomaly (EIA) in the ionosphere has been attributed to the effect of solar zenith angle and magnetic field geometry (Wu et al., 2008; Rama Rao et al., 2006a). Another important feature of ionospheric parameters (known as equinoctial asymmetry) which is reported in the work of Bolaji et al., (2012); Akala et al., (2013); Eyelade et al., (2017); D'ujanga et al., (2017); Aggarwal et al., (2017), is clearly seen in all years used in this work. Akala et al., (2013) also reported minimum and maximum seasonal VTEC values during June solstice and December solstice respectively, during ascending phase of solar cycle 24. Equinoctial asymmetry is a strong phenomenon that occurs at low latitudes (Aggarwal et al., 2017), which has been explained in terms of the differences in the meridional winds leading to changes in the neutral gas composition during the equinoxes.

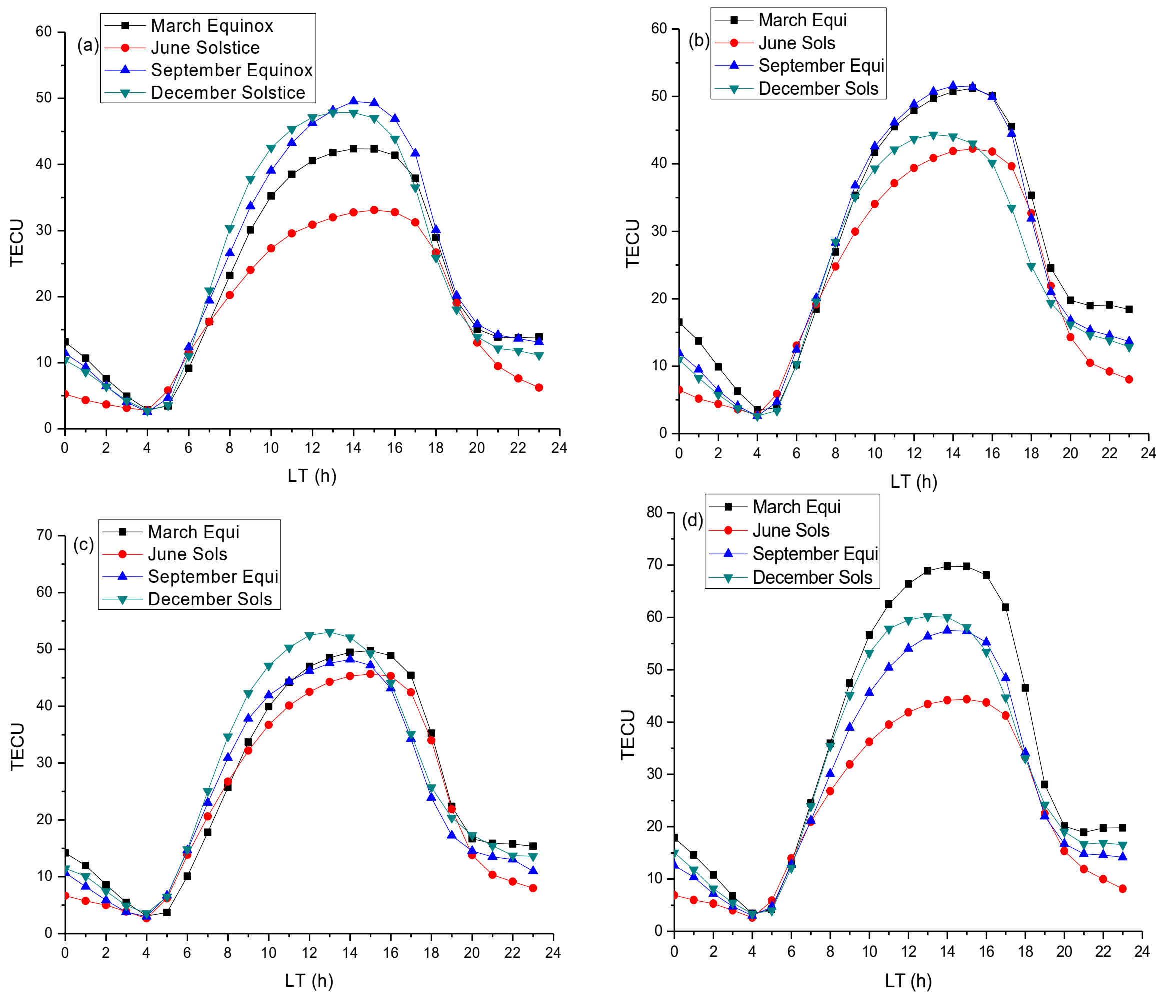

Fig. 9: Seasonal variation of observed OBS-TEC during (a) 2011 (b) 2012 (c) 2013 and (d) 2014

In 2011, September equinox and December solstice recorded higher magnitude, followed by March equinox; the lowest was in June solstice. In 2013, December solstice magnitude was highest, followed by the equinoxes, March and September respectively and lowest in June solstice. This corresponds to result obtained by Akala et al. (2013), which they attributed to increase in ion production rate in winter season and anti-correlation between December and June Solstice pre-reversal velocity enhancement. In 2014, March equinox magnitude was highest, December solstice and September equinox magnitudes were about same range while June solstice magnitudes were least. December solstice magnitude is found to occur between the magnitudes of the equinoxes in 2011 and 2014. The September equinox magnitude and March equinox magnitude are observed to interchange in 2011 and 2014. Overall, June solstice magnitudes were lowest during all the years. Titheridge (1974) attributed the June solstice least magnitudes to low ionization resulting from reduced production rates, i.e. O/ N_2 ratio.

Also, for all seasons, pre-midnight (18 – 23 LT) values of TEC are higher than post-midnight (00 – 05 LT) TEC values for all years. In 2011, pre- midnight TEC values are in the range of 8 – 30 TECU while post-midnight TEC values ranges from 3 to 13 TECU. In 2012, pre-midnight TEC values are in the range of 9 – 35 TECU while post-midnight TEC values are between 3 to 17 TECU. In 2013, the pre-midnight TEC values are between 9 – 35 TECU while post-midnight TEC values ranges from 3 – 15 TECU. Finally in 2014, pre-midnight TEC values are between 9 to 47 TECU while the post-midnight TEC ranges from 3 to 18 TECU. Furthermore, the maximum OBS-TEC values in 2011 (49 TECU) and 2012 (52 TECU) were recorded in September Equinox season. In 2013, OBS-TEC reached a maximum of 53 TECU in December solstice while in 2014, the maximum OBS-TEC (70 TECU) was recorded in March Equinox season in the NEI (West African sector). This result agrees in general with those of D'ujanga et al. (2017) who obtained higher TEC values during the equinoxes than during the solstices in Ethiopia (East African sector). This same result was observed by Bagiya et al. (2009) that reported higher TEC values in equinoctial months than solsticial months in the Indian sector. While the former authors reported maximum TEC of ~ 58 TECU during the equinox months, the latter authors reported maximum TEC ~ 50 TECU during the equinoxes. Seasonal variation of TEC is dependent on thermospheric neutral compositions since during the day the equator is hotter than the pole. Meridional winds therefore flows from the equator towards the pole. This flow cause a change in the neutral composition resulting in the decrease of the ratio of O/ N_2 at the equator. The decrease of O/ N_2 ratio increases the electron density, and thus resulting in TEC increase during the equinoxes (Bagiya et al., 2009). The corresponding annual range error (meters) of the season with maximum OBS-TEC using 1 TECU variation to represent an error of 0.16 m in position is summarized in Tables III.

Table III: Season of maximum OBS-TEC and their corresponding range error.

YEAR	**SEASON OF MAXIMUM OBS-TEC**	**VALUE (TECU)**	**CORRESPONDING ERROR (m)**
2011	September Equinox	49	8
2012	September Equinox	52	8
2013	December Solstice	53	8
2014	March Equinox	70	11

Figure 10 shows the comparison of the monthly mean OBS-TEC and monthly mean sunspot number, Rz from 2011 – 2014, showing an increase and decrease of TEC following the solar cycle variations. Our result is in good agreement with those of Chakrabarty et al. (2012) and D'ujanga et al. (2017), which reported a direct solar cycle effect on TEC measurements. Solar cycle dependency of ionospheric parameters such as TEC provides useful information to study the behavior and variations of the physical and photochemical processes in the ionosphere (Liu et al. 2006). It is well documented that the variability of solar activity results in huge variations in the temperature, neutral wind, neutral density, ion and electron densities and electric fields in the ionosphere (Forbes et al. 2006).

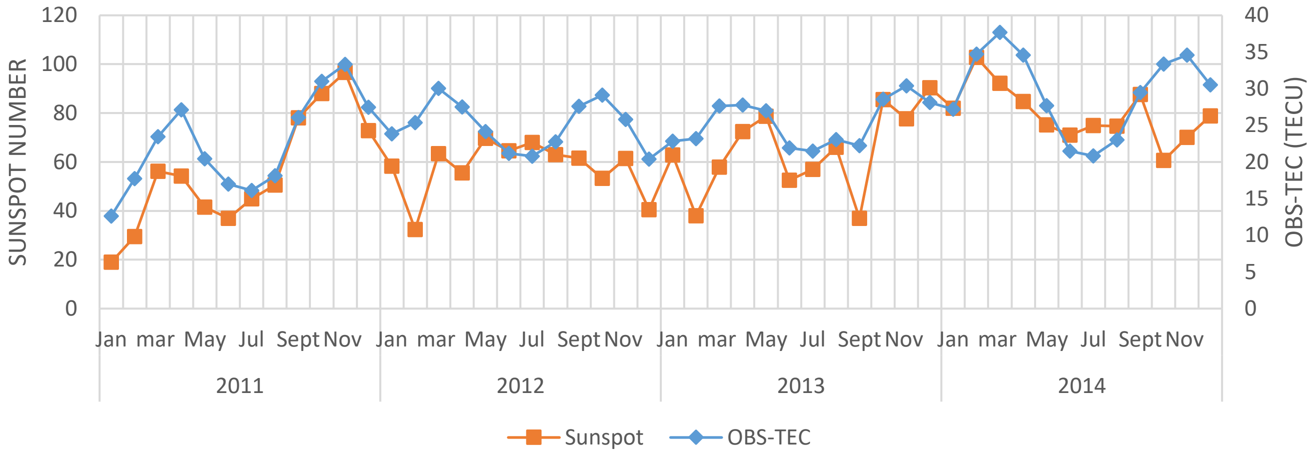

Figure 10: Monthly variation of OBS-TEC with sunspot number, Rz at Birnin-Kebbi

The present result also agrees with that of Rama Rao et al. (1985) who reported a direct solar control on TEC. Balan et al. (1994); Liu et al. (2011) and Liu et al. (2006) and many other works reported the same results during low and moderate solar activity, TEC and N_mF_2 increases linearly with solar proxies, but the linearity collapse during high solar activity. This agrees with our result except for July month of 2012 and 2014 which shows saturation effect on TEC i.e decrease in TEC with increase in solar activity. The saturation effect on TEC was reported in the work of Balan et al. (1994, 1996), which concluded that the saturation effect has not been clarified and hence might be due to other factors near the earth's environment and not as a result of the influence of solar activity. We could not establish the cause of the saturation effect on TEC in this study, however, saturation effect will be further investigated in future studies.

4 CONCLUSIONS

Studies on OBS-TEC and IRI-2016 model at Birnin-Kebbi in Northern Nigeria during the ascending and maximum phases of solar cycle 24 have been carried out. Our result shows that OBS-TEC and IRI-2016 model rising from a minimum in the early hours of the day to a broad daytime maximum before falling steeply to a minimum after sunset for all years, due to photoionization increase produced by solar extreme ultraviolet (EUV) radiation (Anderson et al., 2004; D'ujanga et al., 2017). The diurnal variation reveals that the peak of OBS-TEC is often delayed when compared with IRI-2016 model, with the maximum occurring afternoon, showing dome-like shape while noon bite-out, a special feature observed in equatorial/ low latitude is seen in the peak of majority of the plots of IRI-2016 model. On a general note, we concluded that IRI-2016 model cannot be used as proxy for TEC measurements for most hours of the day for the years investigated. Our result agree with those of Komjathy et al. (1998); Lee and Reinisch (2006); Malik et al. (2016); Bhuyan and Borah (2007); Mosert et al. (2007) and Sethi et al. (2010) at their respective locations. For all seasons, pre-midnight (18 – 23 h) values of TEC are higher than post-midnight (00 – 05 h) TEC values during all years. Seasonal variation shows an asymmetry in the equinoxes and solstices in the NEI as also reported by Fayose et al. (2012) and Eyelade et al. (2017). Maximum OBS-TEC values in 2011 and 2012 were recorded in September equinox. In 2013, OBS-TEC reached its maximum during the December solstice while in 2014, the maximum OBS-TEC was recorded in March equinox. This result agrees in general with those of D'ujanga et al. (2017) in the East African sector and Bagiya et al. (2009) in the Indian sector, who obtained higher TEC values during the equinoxes than during the solstices. Thermospheric neutral compositions is a major cause of seasonal variation of ionospheric parameters such as TEC, since during the day the equator is hotter than the poles. Finally, monthly OBS-TEC varies linearly with annual sunspot number, Rz, thus revealing strong dependence of TEC on solar activity (sunspot number). This linearity collapsed in the month of July of 2012 and 2014. OBS-TEC and sunspot number were found to increase gradually from 2011 to 2014 in agreement with Rama Rao et al. (1985) showing that there is a direct solar control on TEC.

AUTHORS' CONTRIBUTIONS

Aghogho Ogwala designed the study, obtained the data and wrote the first draft of the manuscript. Oluwole Oyedokun assisted in data processing. Emmanuel Olufemi Somoye and Olugbenga Ogunmodimu analyzed the data and wrote the protocol. Rasaq Adewemimo Adeniji-Adele and Eugene Oghenakpobor Onori managed the literature searches, read through the manuscript. All authors approved the final manuscript.

COMPETING INTEREST

We declare that we have no conflict of interest.

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