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

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ABSTRACT

Total Electron Content (TEC) is an important ionospheric parameter used to monitor possible space weather impacts on satellite to ground communication and satellite navigation system. TEC is modified in the ionosphere by changing solar Extreme Ultra-Violet (EUV) radiation, geomagnetic storms, and the atmospheric waves that propagate up from the lower atmosphere. Therefore, TEC depends on local time, latitude, longitude, season, geomagnetic conditions, solar cycle activity, and condition of the troposphere. A dual frequency GPS receiver located at an equatorial station, Birnin-Kebbi in Northern Nigeria (geographic location: 12.64°N; 4.22°E), has been used to investigate variation of TEC during the period of 2011 to 2014. We investigate the diurnal, seasonal and solar cycle dependence of observed (OBS) TEC and comparison with latest version of International Reference Ionosphere (IRI-2016) model. On a general note, diurnal variation reveals discrepancies between 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 of some months. On a seasonal scale, we observed that OBS-TEC values were higher in the equinoxes than the solstices only in 2012. Where as 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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INTRODUCTION

The ionosphere causes a variation in the intensity of radio signals – fading – as a result of irregularities (inhomogeneity in electron density) (Somoye, 2010; Ogwala *et al.* 2018, Ogunmodimu *et al,* 2018). Akala *et al.*, (2011) reported that the variable nature of the equatorial/ low latitude ionosphere threatens communication and navigation/ satellite systems. The equatorial/ low latitude ionosphere exhibits many unique features such as the seasonal anomaly, semi-annual anomaly, equinoctial anomaly, noon bite-out, spread-F, equatorial electrojet (EEJ), equatorial plasma bubbles (EPB), etc.

For many decades, scientists have been studying these ionospheric features and the role they play in trans-ionospheric electromagnetic radio wave propagation. These studies are carried out using different techniques and instruments. One of the instruments used is the GPS receiver, which provide direct measurements from satellites. Their sounding capacity extends to the topside of the ionosphere, but is affected by time and space constraints (Ciraolo and Spalla, 2002). Recently, GPS receiver is the most efficient method used to eliminate the effect of the ionosphere on radio signals. This method combines signals in different L band frequencies, L1 (1575 MHz) and L2 (1228 MHz).

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

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

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 propagates through the ionosphere shown in Equation (2) as $\Delta t = t_2 - t_1$. Thus,

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

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. It is documented that ionospheric delay which is proportional to TEC is the highest contributor to GPS positioning error (Alizadeh *et al.*, 2013; Akala *et al.*, 2013).

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

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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 developed recently 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. The global distribution of TEC variations and its characteristics at all latitudes, during different solar cycle phases under disturbed and quiet conditions have been investigated by some researchers (Bhuyan and Borah, 2007).

Rama Rao *et al.* (2006a, b) 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) attributed the lower TEC values during the summer seasons to low ionization density resulting from reduced O/ N_2 ratio (production rates) which is a result of increased scale height. Bhuyan and Borah (2007) compared TEC derived from GPS receivers with IRI in the Indian 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. 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.

In this research, the result obtained in 2012 and 2013 which corresponds to the result of these researchers. However, the result we obtained in 2011 and 2014 did not follow the trend reported by these researchers, who explored the equatorial/ low latitude during different solar cycle epochs. We also observed discrepancies between the OBS-TEC and IRI-2016 almost throughout the day for all the years in this research.

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 are, reads 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 equation (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 receiver interchannel bias respectively. S(E), which is the oblique factor with zenith angle, z at IPP (Ionospheric Pierce Point) is expressed in equation (4).

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

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) 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

Comparison of diurnal variations of OBS-TEC with error bars and IRI-2016 (NeQuick topside option) model, and their corresponding percentage deviation (percentage Dev or % DEV) were analysed using the monthly mean values of VTEC with respect to local time (LT). % DEV was obtained using equations (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.

The annual variation of OBS-TEC and IRI-2016 model were plotted against all hours from the first day of January to the last day of December for the years under investigation (2011 – 2014). The OBS-TEC data was grouped following Onwumechilli and Ogbuehi (1964) into four

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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 TEC and mean Rz against each month of the year.

RESULT AND DISCUSSIONS

Figures 1 to 4 shows the diurnal variation of OBS-TEC in the Nigerian Equatorial Ionosphere (NEI) for the years 2011 to 2014 respectively, were represented by data obtained from the GPS receiver installed at Birnin-Kebbi station and IRI-2016 model. The diurnal variation of OBS-TEC reveals the typical characteristics of an equatorial/ low latitude ionosphere. Generally, top and bottom error bar is used to show day-to-day TEC variation. The study reveal day-to-day variation of TEC is higher during the daytime than night time for all the years. The diurnal variation shows OBS-TEC rising rapidly from a minimum just before sunrise between 03:00 – 05:00 LT (~2 TECU) in 2011, 04:00 – 05 LT (~3 TECU) in 2012, 03:00 – 05:00 LT in 2013 (~3 TECU), and 03:00 – 05:00 LT in 2014 (~3 TECU). OBS-TEC is found to increase to a broad daytime maximum between 00:12 LT – 00:16 LT for all years before falling to a minimum after sunset. The diurnal variation of IRI-2016 model shows TEC rising from a minimum of ~ 2 TECU in 2011, ~ 4 TECU in 2012 and 2013, and ~ 5 TECU in 2014 between 03:00 – 04:00hr, to a broad daytime peak between 08:00 – 14:00hr, before falling steeply to minimum before sunset. Hence the IRI-2016 model attained its peak before OBS-TEC. The steep increase in TEC has been attributed to the solar EUV ionization together with the upward vertical E × B resulting from the rapid filling up of the magnetic field tube at sunrise (Dabas *et al.*, 2003; Somoye *et al.*, 2011; Hajra *et al.* 2016; D’ujanga *et al.*, 2017) and meridional winds

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(Suranya *et al.*, 2015). These magnetic field tubes collapse after sunset due to low thermospheric temperature and Releigh Taylor Instability (RTI) (Ayorinde *et al.*, 2016) 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.

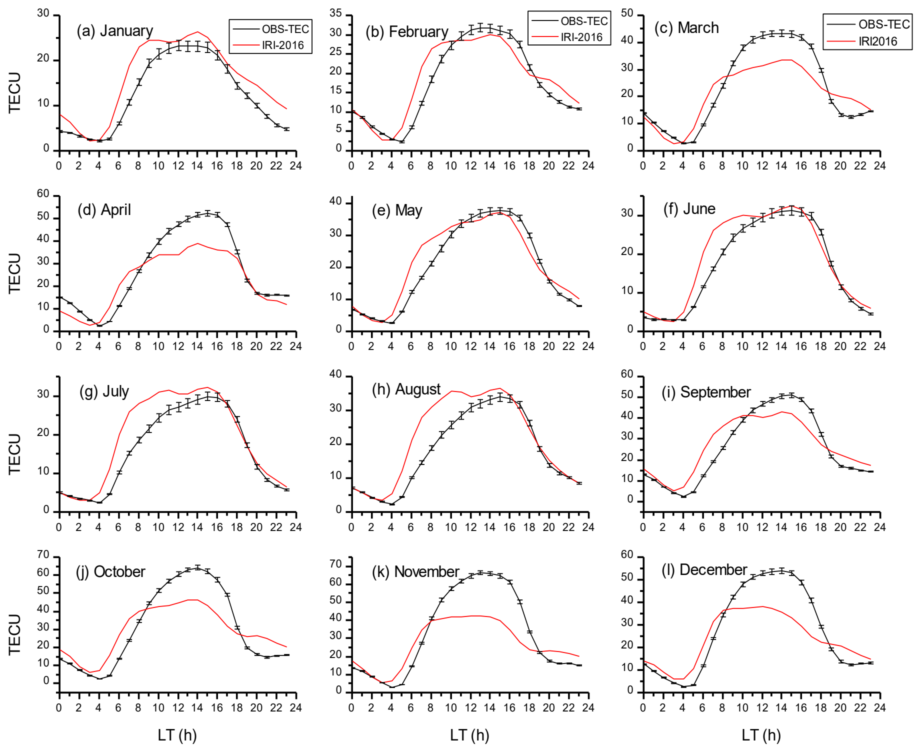

Figure 1: Diurnal variation of OBS-TEC and IRI-2016 model of each month during January – December 2011 at Birnin-Kebbi

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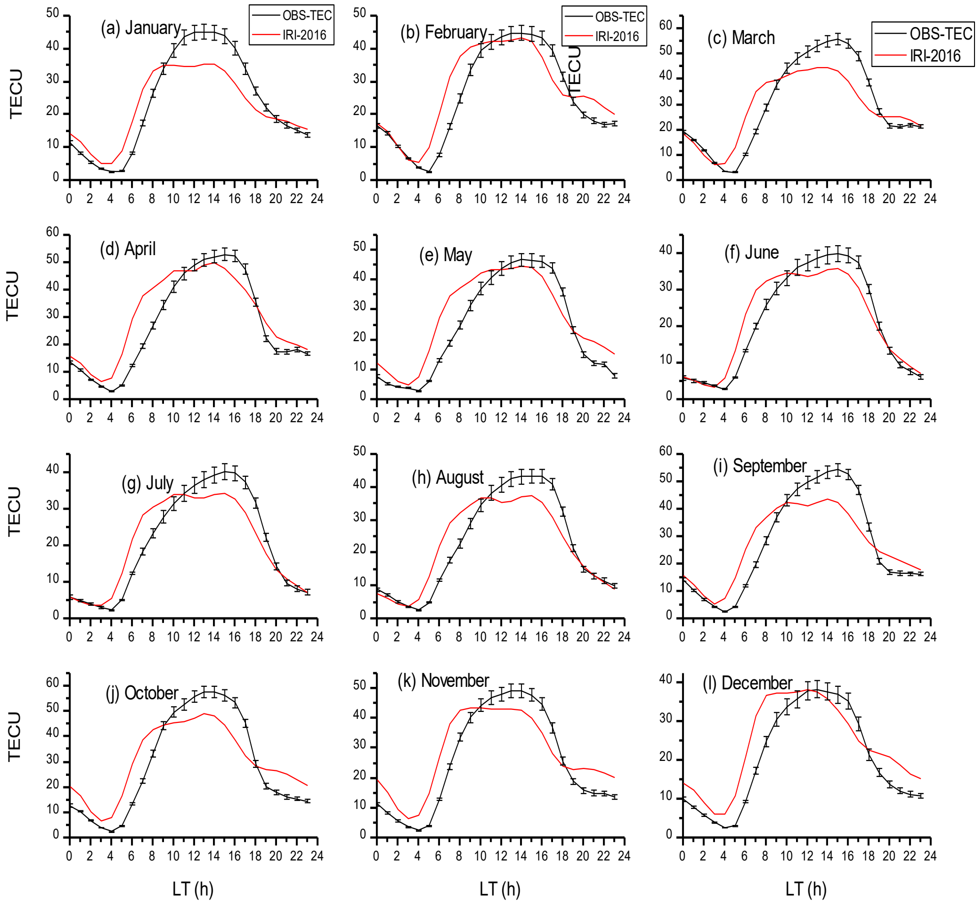

Figure 2: Diurnal variation of OBS-TEC and IRI-2016 model of each month during January – December 2012 at Birnin-Kebbi

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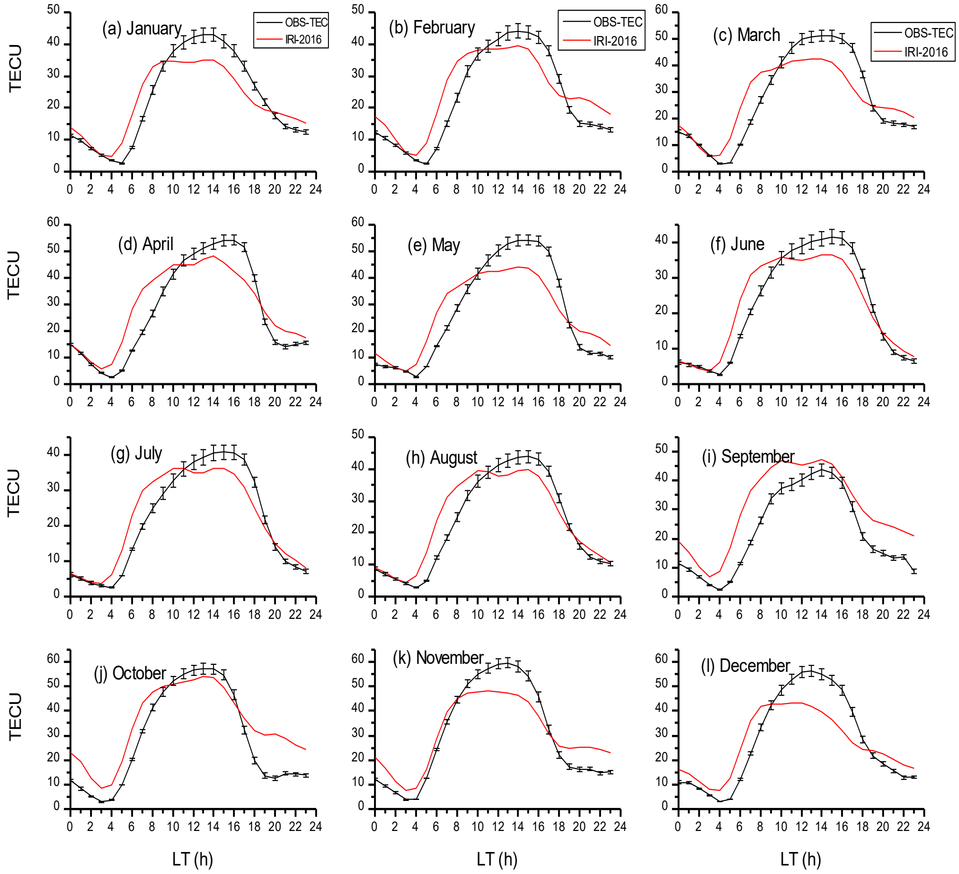

Figure 3: Diurnal variation of OBS-TEC and IRI-2016 model of each month during January – December 2013 at Birnin-Kebbi

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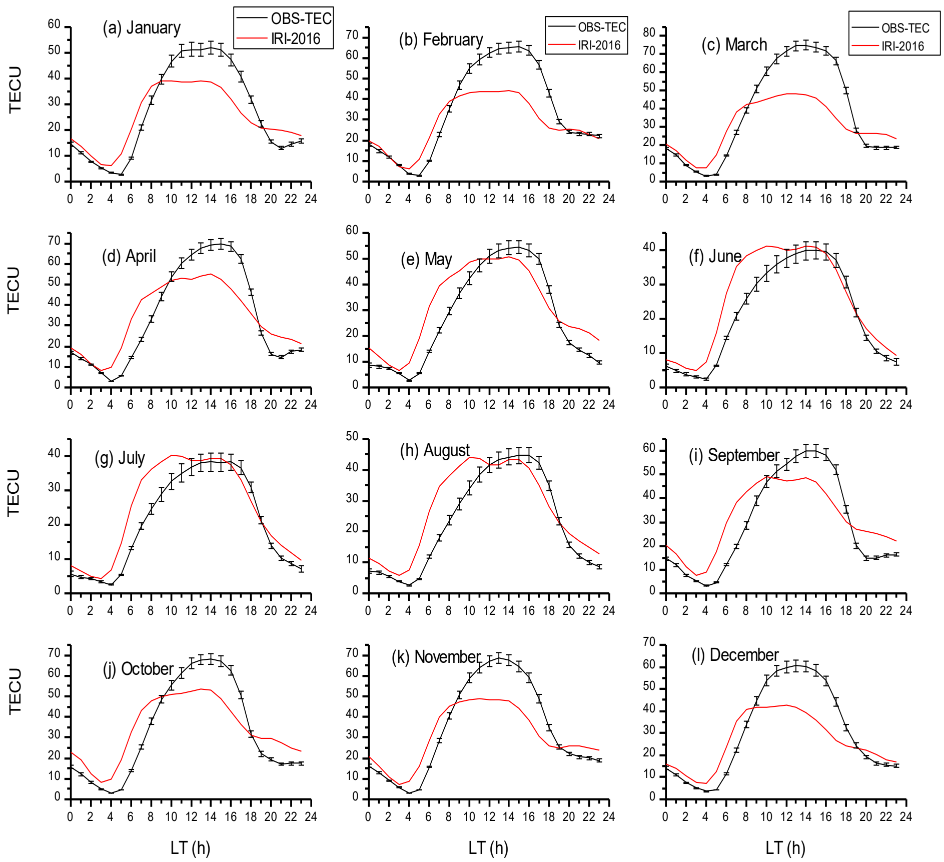

Figure 4: Diurnal variation of OBS-TEC and IRI-2016 of each month during January – December 2014 at Birnin-Kebbi

It can be seen that OBS-TEC is much higher in 2014 with maximum values 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 some months was delayed till after noon. For example, the months of April, July, August and September in 2011, March, April, June and September in 2012, April, June, July and September in 2013 had delayed peak. The delayed OBS-TEC peaks were also seen in April, May, June, August and September of 2014. This type of peak shifting is peculiar to the Polar Regions and it is found to depend on the solar zenith angle. Another major phenomenon 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. 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 shows 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 – 04hr of the day for all years. All other hours from 05 – 23hr shows some discrepancies. In some months, these discrepancies lasted throughout the day for example, in the months of October, November and December of 2012, October and December, 2013, and September and October of 2014, while in some other months these discrepancies collapsed during the pre-midnight hours, for example, in the months of June, July and August of 2011, June, July and August of 2012, June and August of 2013 and February, June and July of 2014. 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 plots.

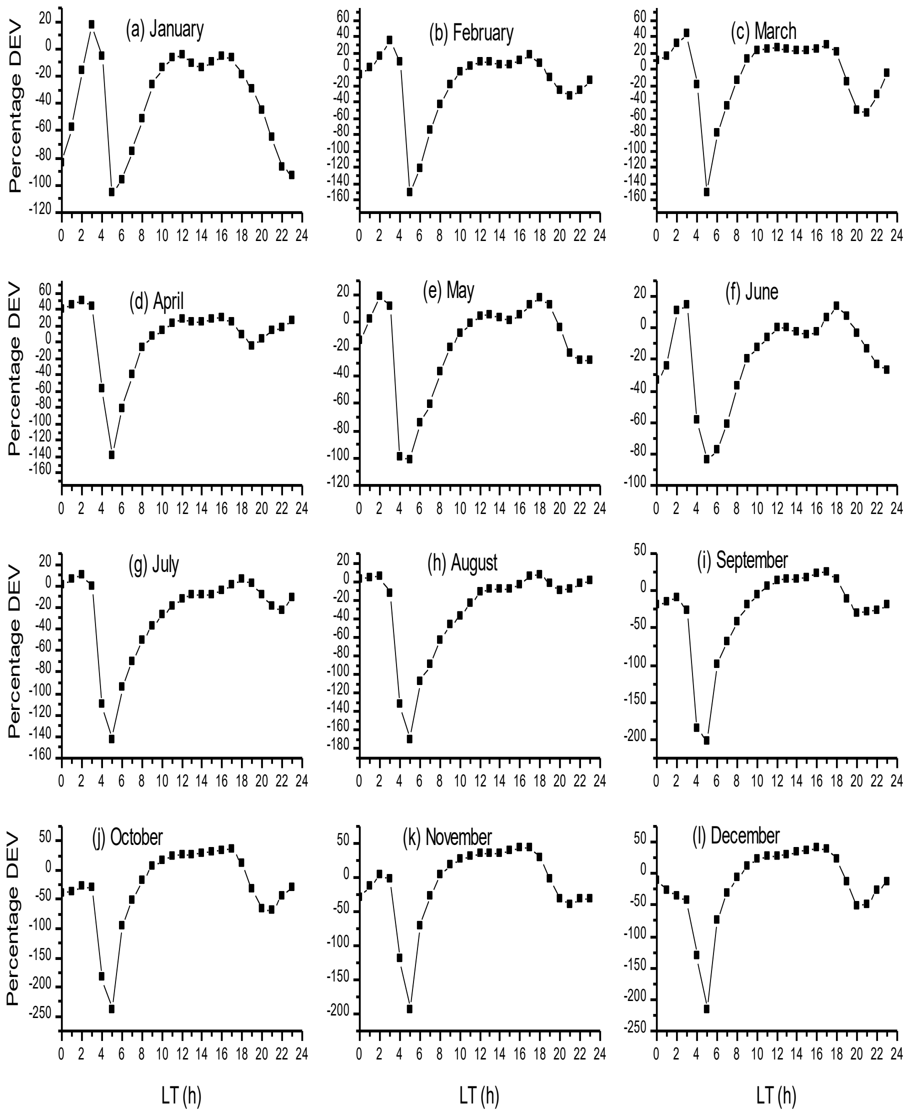

Figure 5: Percentage deviation of IRI-2016 from OBS-TEC for year 2011

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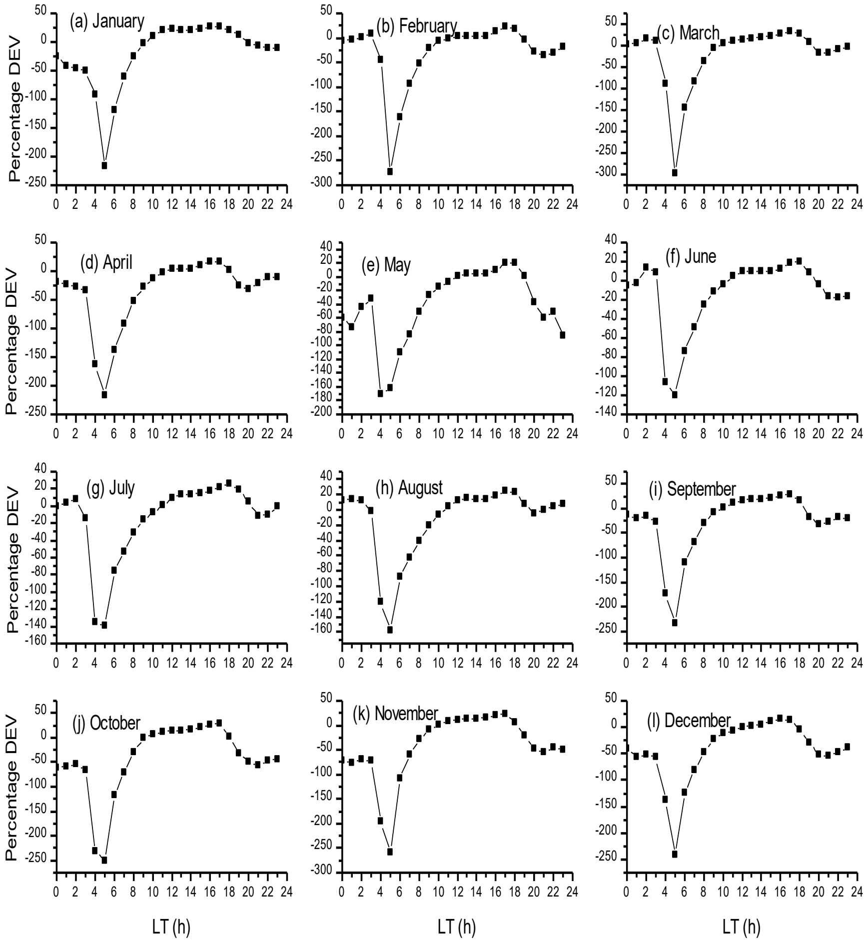

Figure 6: Percentage deviation of IRI-2016 from OBS-TEC for year 2012

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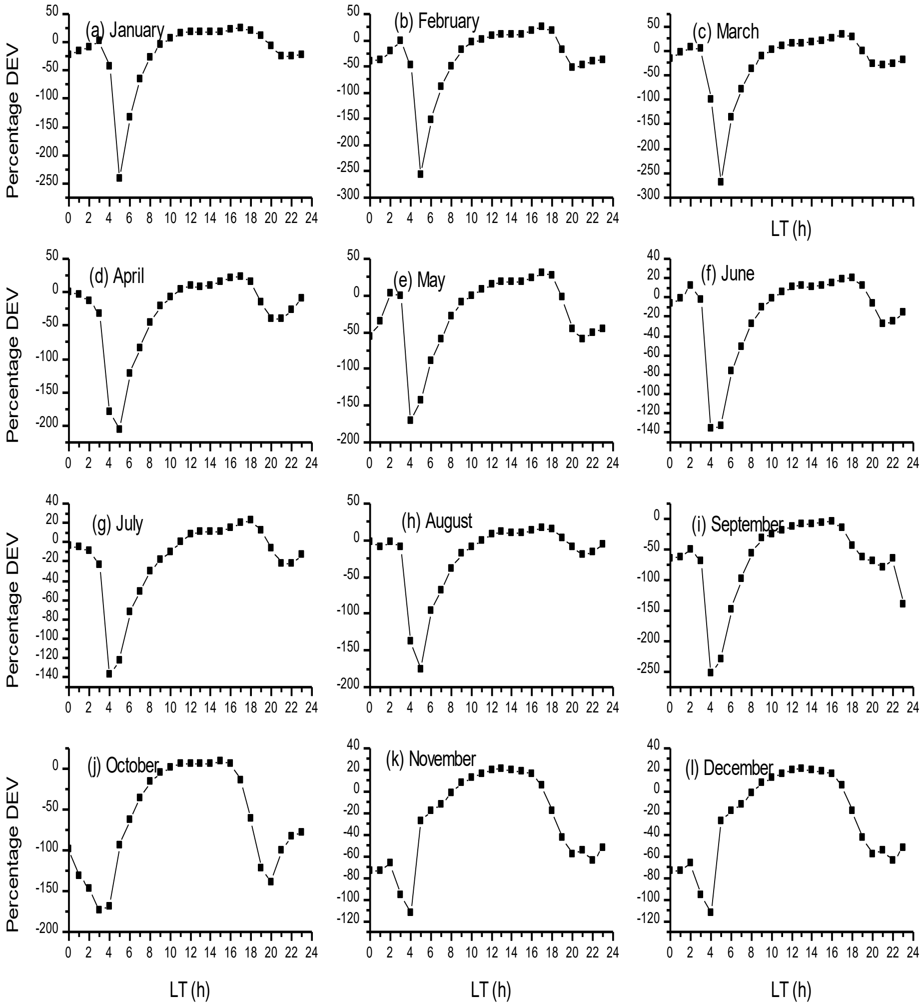

Figure 7: Percentage deviation of IRI-2016 from OBS-TEC for year 2013

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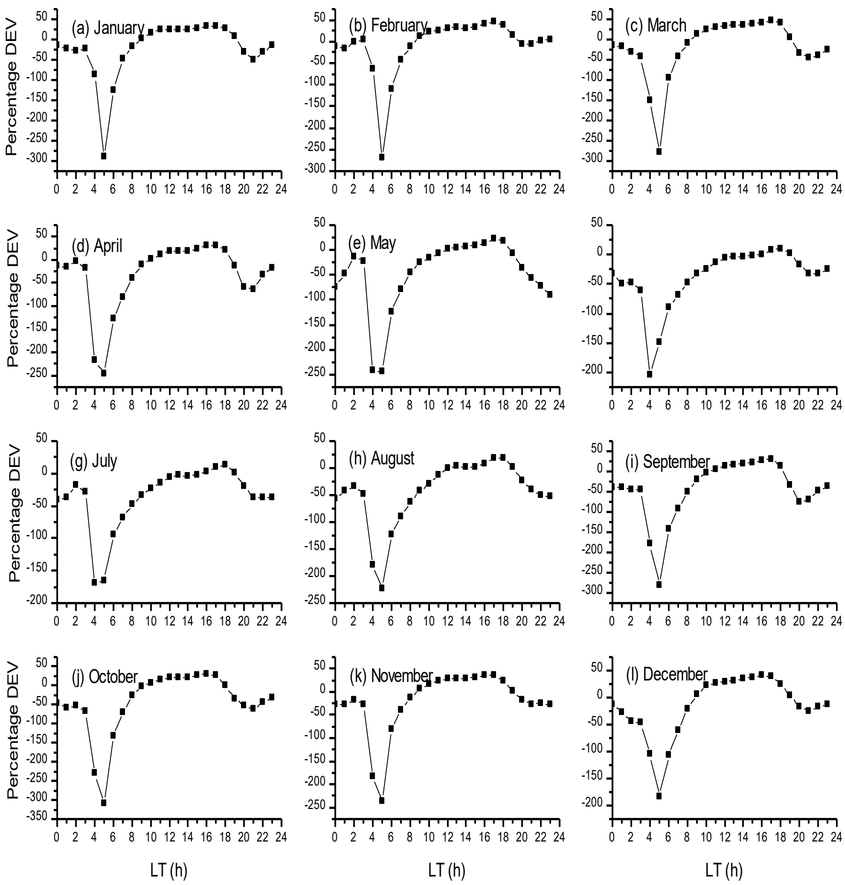

Figure 8: Percentage deviation of IRI-2016 from OBS-TEC for year 2014

The mass plots in the Figures 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 – 05hr for all months throughout the years in this study. Highest Negative percentage deviation of ~ 300% was recorded in the month of October, 2014 at 05hr. Table II shows the summary of months with daytime over- or under-estimate of IRI-2016 in the NEI.

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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 the Figures 1- 4, Figures 5 – 8 and Table II that IRI-2016 model did not predict well in the NEI. This could be attributed to the scarce GPS infrastructure and data in the region.

Figure 9 plots the seasonal variations of OBS-TEC for the four years under investigation. 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 has been attributed to the effect of solar zenith angle and magnetic field geometry (Wu *et al.*, 2004; Rama Rao *et al.*, 2006a). Another important feature of ionospheric parameters (known as equinoctial asymmetry) which is reported in the

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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 December solstice and June solstice respectively, during ascending phase of solar cycle 24. Equinoctial asymmetry is a strong phenomenon in low latitudes (Aggarwal *et al., 2017*). The equinoctial asymmetry has been explained in terms of the differences in the meridional winds leading to changes in the neutral gas composition during the equinoxes.

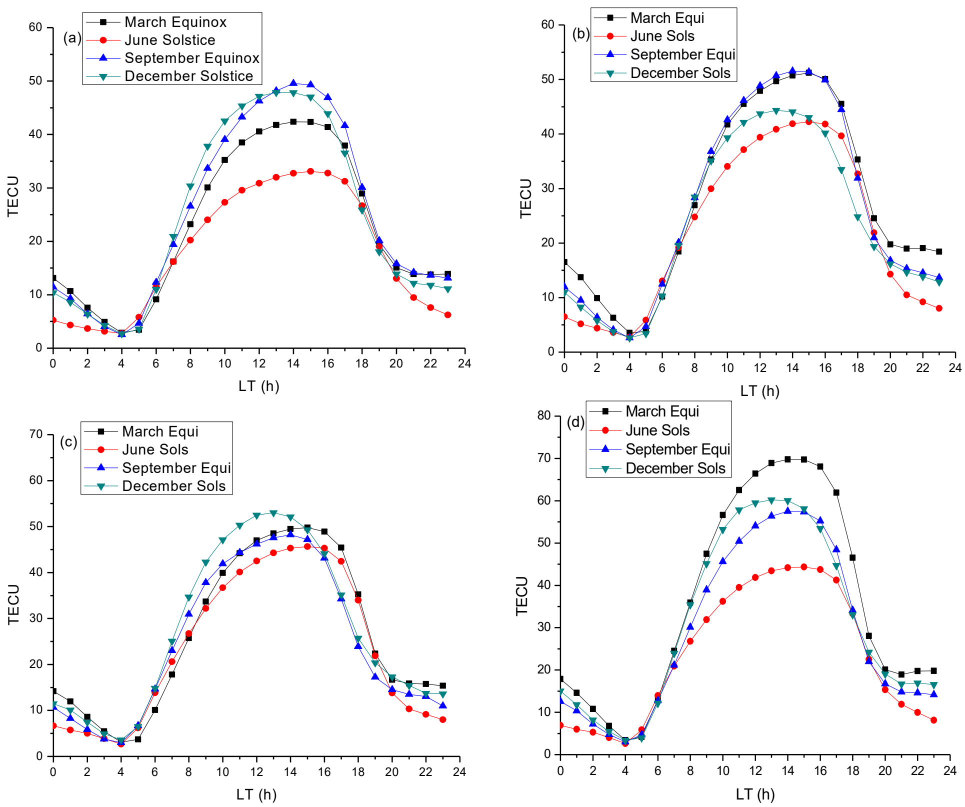

Figure 9: Seasonal variation of observed OBS-TEC during (a) 2011 (b) 2012 (c) 2013 and (d) 2014

In 2011 and 2014, the seasonal variation of OBS-TEC in the ionosphere did not follow the pattern reported by these researchers. 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 and December solstice magnitudes were higher than September equinox and June solstice magnitudes. 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. This is due to low ionization resulting from reduced production rates, i.e. O/ N_2 ratio (Titheridge 1974). Also, for all seasons, pre-midnight values were higher than post-midnight values as follows: In 2011, pre- and post-midnight values range from 8 – 30 TECU and 3 – 13 TECU respectively. In 2012, pre- and post-midnight values are in the range of 9 – 35 TECU and 3 – 17 TECU respectively. 2013 recorded pre-midnight values in the range 9 – 35 TECU and post-midnight values in the range 3 – 15 TECU. While, 2014 pre-midnight value is between 9 and 47 TECU and its post-midnight range is 3 – 18 TECU.

Furthermore, the maximum OBS-TEC values and the corresponding annual range error for all the seasons can be up to 49 TECU (September equinox) which is ~ 8m in 2011. 2012 and 2013 recorded annual range error of ~ 8m which corresponds to the maximum OBS-TEC value of 52 TECU (September equinox) and 53 TECU (December solstice). While in 2014, maximum OBS-TEC is 70 TECU (March equinox) which is approximately equals to 11m of delay.

Figure 10 shows the plot of annual variation of OBS-TEC and sunspot number, Rz against the months of the year for the four years. The plots reveal the strong dependence of OBS-TEC on solar activity (sunspot number). TEC and sunspot number increased gradually from 2011 to 2014.Although solar cycle 24 is regarded as a quiet solar cycle, which peaked in 2014, the sun erupted with some few major flares in February and October of the same year (Kane, 2002).Hence, February, October and November 2014 were months of highest TEC values. An X-class type solar flare was reported in February of 2011, resulting in a high value of sunspot number. Increase in the sun's activities increases the number of electrons along the line of sight (LOS) from a satellite to receiver on ground.

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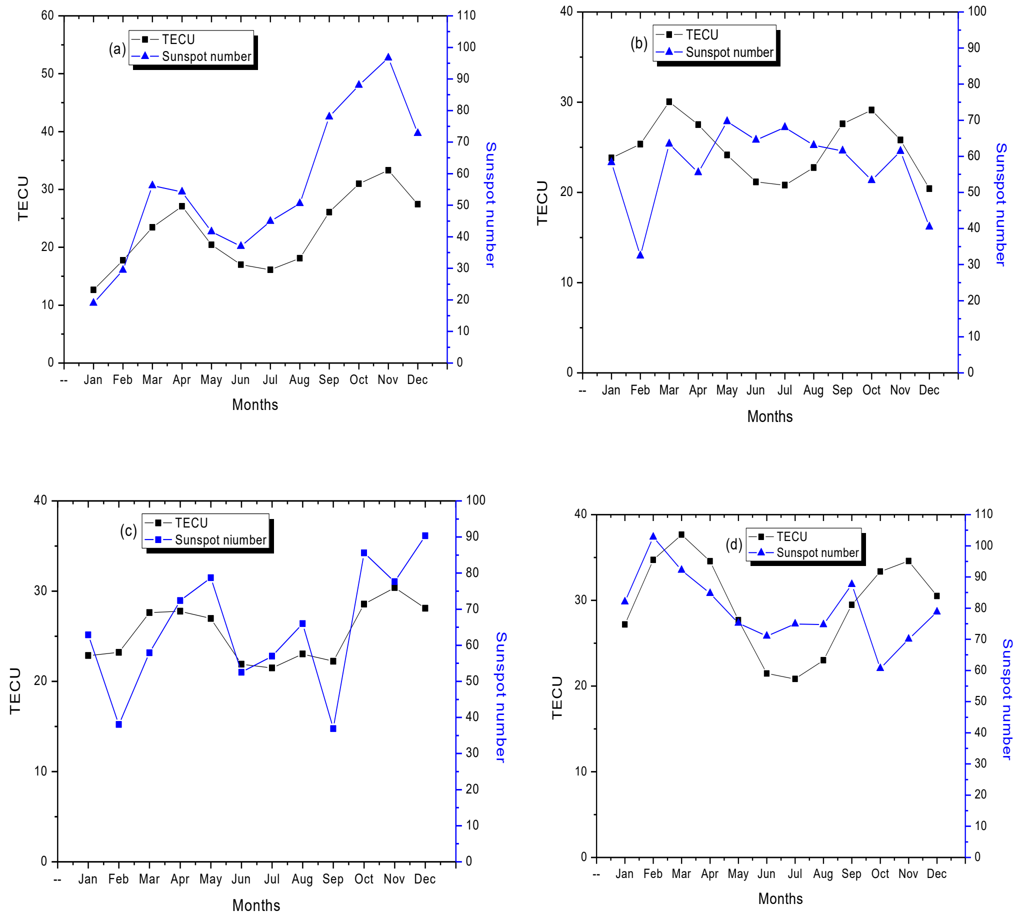

Figure 10: Annual variation of OBS-TEC and sunspot number, Rz during (a) 2011 (b) 2012 (c) 2013 and (d) 2014.

High solar activity produces solar flares of varying classes. As solar particles crash with nitrogen and oxygen atoms in the upper atmosphere, these classes of flares produce waves of ionization in the ionosphere that briefly alters the propagation of radio signals (Kane, 2002). When solar flares become very intense, their electric field impulses, caused by disruption in the earth's magnetic field due to ionization particles, may damage infrastructure such as power grids and telephone lines not adequately protected against the geo-magnetically induced current (GIC), leading to wastage of economic resources. Several earth-orbiting satellites may be in similar danger. Hence, efforts are being made to develop tools and models from scientific results, to forecast localised GIC impacts in national infrastructure. This forecasting capability will provide operators with the information required to make swift operational decision, which may include cancelling maintenance work or re-routing load in order to protect national infrastructure. Operators will also advice when it is considered safe to resume normal operations.

CONCLUSIONS

Studies on OBS-TEC variations at Birnin-Kebbi in Northern Nigeria during the ascending and maximum phases of solar cycle 24 have been carried out. The result obtained reveals the following:

1. Higher TEC day-to-day variations during the daytime than nighttime for all the years were observed. The diurnal variation shows OBS-TEC rising rapidly from a minimum just before sunrise between 03:00 – 05:00 LT (~2 TECU) in 2011, 04:00 – 05 LT (~3 TECU) in 2012, 03:00 – 05:00 LT in 2013 (~3 TECU), and 03:00 – 05:00 LT in 2014 (~3 TECU). OBS-TEC is found to increase to a broad daytime maximum between 00:12 LT – 00:16 LT for all years before falling to a minimum after sunset. While the diurnal variation of IRI-2016 model shows TEC rising from a minimum of ~ 2 TECU in 2011, ~ 4 TECU in 2012 and 2013, and ~ 5 TECU in 2014 between 03:00 – 04:00hr, to a broad daytime peak between 08:00 – 14:00hr, before falling steeply to minimum before sunset
2. The diurnal variation reveals that the peak of OBS-TEC of some months were delayed till after-noon. Post-sunset decrease and enhancement due to pre-reversal zonal electric field after sunset, were also observed in the diurnal variation of TEC in some months.

3. On a general note, it can be concluded that IRI-2016 model did not predict well throughout the day except during the post-midnight hours (00 – 04hr) in the NEI.
4. For all seasons, pre-midnight values were higher than post-midnight values. In 2011, pre- and post-midnight values range from 8 – 30 TECU and 3 – 13 TECU respectively. In 2012, pre- and post-midnight values are in the range of 9 – 35 TECU and 3 – 17 TECU respectively. 2013 recorded pre-midnight values in the range 9 – 35 TECU and post-midnight values in the range 3 – 15 TECU. While, 2014 pre-midnight value is between 9 and 47 TECU and its post-midnight range is 3 – 18 TECU.
5. Maximum OBS-TEC values and the corresponding annual range error for all the seasons recorded 49 TECU (~ 8m) in 2011. 2012 and 2013 also recorded annual range error of ~ 8m corresponding to the maximum GPS-TEC value of 52 TECU and 53 TECU respectively. While in 2014, maximum GPS-TEC is 70 TECU which is approximately equals to 11m of delay.
6. Finally, annual variation of OBS-TEC and sunspot number, Rz against the months of the year for the four years were plotted. The plots reveal the strong dependence of TEC on solar activity (sunspot number). OBS-TEC and sunspot number were found to increase gradually from 2011 to 2014.

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