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VARIATION OF TOTAL ELECTRON CONTENT WITH SUNSPOT NUMBER DURING THE ASCENDING AND MAXIMUM PHASES OF SOLAR CYCLE 24 AT BIRNIN-KEBBI

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ABSTRACT

Satellite radio signals are affected by the presence of electrons in the earth's upper atmosphere (ionosphere). The more electrons in the path of the satellite radio signals, the more the impact on the accuracy of satellite navigation systems such as the Global Positioning System (GPS)/ Global Navigation Satellite System (GNSS) and GLONASS. These electrons introduce several meters of error in position calculation. Total Electron Content (TEC) is used to monitor possible space weather impacts on satellite to ground communication and satellite navigation. 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-Kebbiin 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,

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seasonal and solar cycle dependence of GPS-TEC. The result shows that TEC increases from a minimum at 0400 local time (LT) to maximum daytime peak between 1300 – 1600 LT and then decreases to a minimum value after sunset for all the years. Slight post-noon peaks in the daytime maximum and post-sunset decrease and enhancement is observed in some months. We observed that TEC 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.

KEYWORDS: TEC; variation; ascending phase; maximum phase; sunspot number; solar cycle 24.

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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). 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 being carried out using different techniques and instruments. Some of the instruments are: (i) ionosonde: which provides worldwide determination of ionospheric parameters with high reliability, but these are limited to the bottom-side of the ionosphere (Ciraolo and Spalla, 2002), (ii) incoherent scatter radar: a technique for detecting and studying remote targets (elections) by transmitting radio waves in the direction of the target at high speed. They are also limited to the bottom-side of the ionosphere (Zhang and Holt, 2008) and (iii) GPS receivers: provide direct measurements from satellites. Their sounding capacity extends to the topside of the ionosphere, but are affected by time and space constraints (Ciraolo and Spalla, 2002). Recently, GPS receivers are 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. 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). 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).

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 temporal and spatial variation 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 many researchers (Bhuyan and Borah, 2007).It is reported that the differential carrier phase advance on single frequency carrier phase observations can be at the decimeter level for baseline lengths of 40 km (Kleusberg, 1986). In 1995, the US Department of Defence (DOD) developed a GPS receiver which operates two simultaneous frequency bands (L1 and L2) to augment the single frequency receiver (Bolaji *et al.* 2012).

Due to the dispersive nature of the ionosphere, the time delay between the two frequencies of a GNSS signal as it propagates through the ionosphere is given Equation (1) as $\Delta t = t_2 - t_1$.Thus,

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

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

TEC from satellite to receiver in the ionosphere is defined by Equation (2). It is measured in multiples of TEC units (1 TECU = 10^{16} el/m^2)

$$TEC = \int n_e(s)ds \quad (2)$$

Rama Rao *et al.* (2006a, b) reported maximum day-to-day variability in TEC at the 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

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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.

In this research, the result obtained in 2012and 2013which 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.

DATA AND METHODOLOGY

2.1 DATA

The Receiver Independence Exchange (RINEX) GPS data files were downloaded daily from NIGNET website (www.nignet.net) and processed using Bernese software and GPS TEC analysis software. The GPS TEC analysis software 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. Effect due to multipath is eliminated by using a minimum elevation angle of 20°.

GPS TEC obtained from the TEC analysis software is the STEC. 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).

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

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).

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

R_E = the mean radius of the earth in km and h_S = ionospheric height from the surface of the earth.

Hourly VTEC data obtained from these processing software are averaged to daily TEC values in TEC units (1 TECU = 10^{16} el/m^2).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 used. 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). 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 were analysed using the monthly mean values of VTEC with respect to local time (LT). The annual variation of TEC 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 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 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 GPS 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. The diurnal variation of GPS TEC reveals the typical characteristics of an equatorial/ low latitude ionosphere. Generally, day-to-day TEC variation is higher during the daytime than nighttime for all the years. The diurnal variation shows 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). TEC is found to increase to a broad daytime maximum between 00:12 LT – 00:16 LT in all years before falling to a minimum after sunset. 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 (Suranya *et al.*, 2015).These magnetic field tubes collapse after sunset due to low thermospheric

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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.

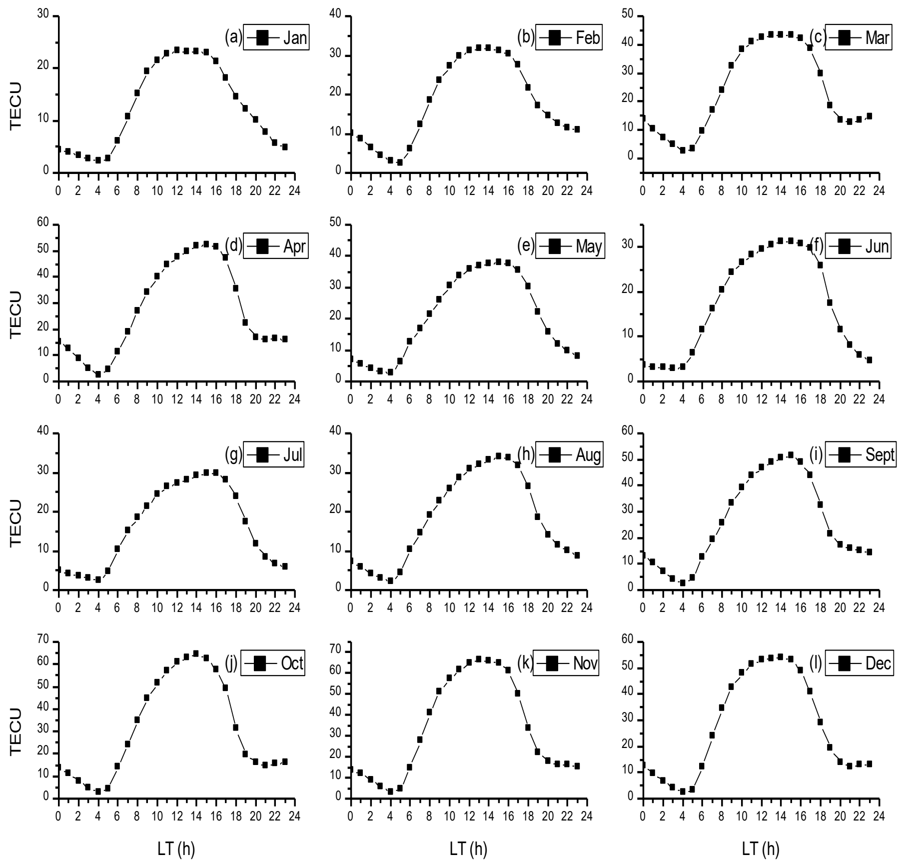

Figure 1: Diurnal variation of VTEC in each month during January – December 2011 at Birnin-Kebbi

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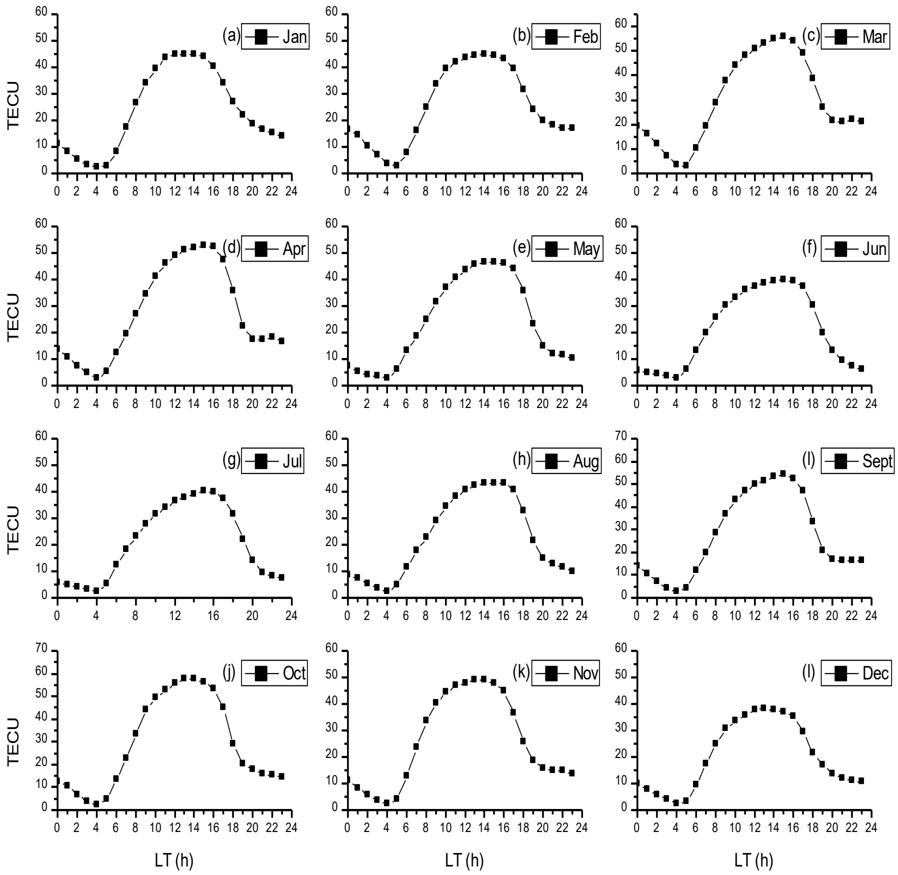

Figure 2: Diurnal variation of VTEC in each month during January – December 2012 at Birnin-Kebbi

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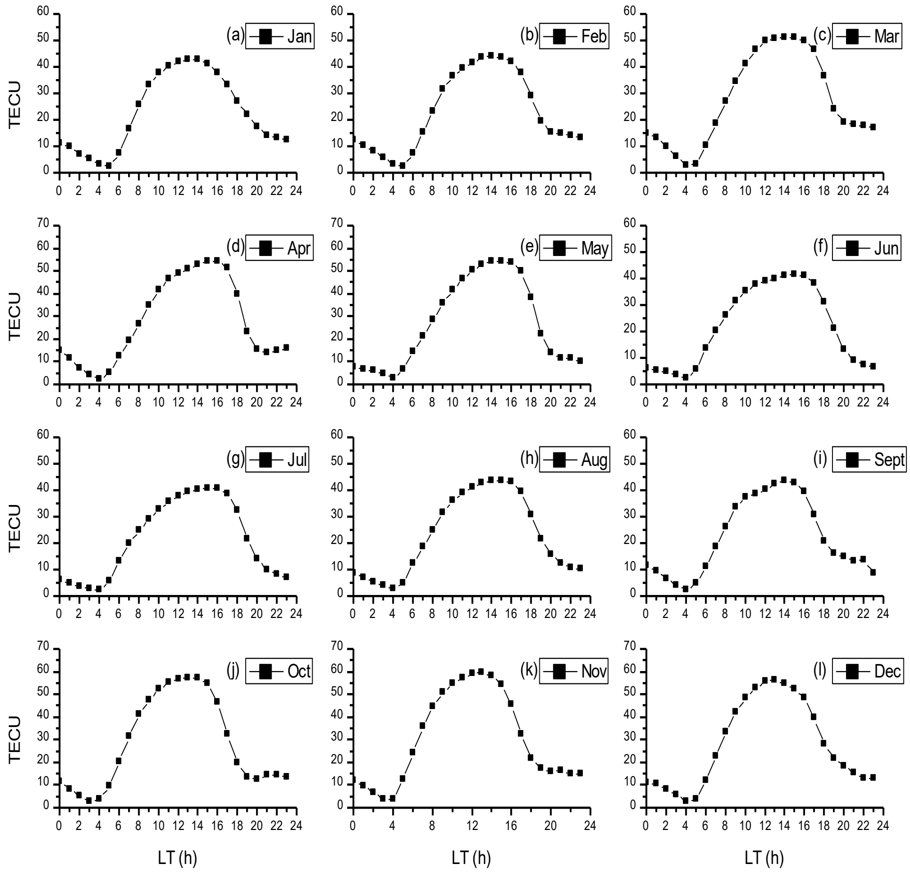

Figure 3: Diurnal variation of VTEC in each month during January – December 2013 at Birnin-Kebbi

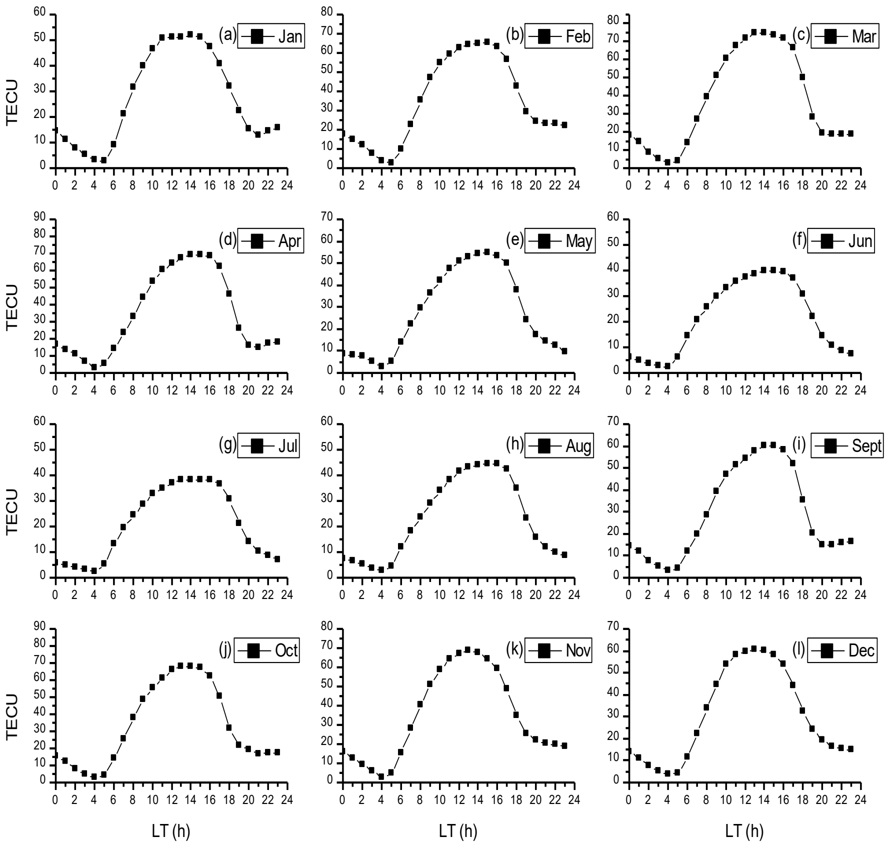

Figure 4: Diurnal variation of VTEC in each month during January – December 2014 at Birnin-Kebbi

It can be seen from the Figures that TEC was much higher in 2014 with maximum values up to 75 TECU in March. The diurnal variation reveals that the peak of TEC of some months were 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 2013had delayed peak. The delayed TEC peak 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

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the solar zenith angle. Another major phenomenon seen in the diurnal variation of TEC is the post-sunset decrease and slight enhancement in some months. The nighttime 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.

Figure 5 plots the seasonal variations of TEC for the four years under investigation. The change in concentration of Oxygen and molecular Nitrogen have been reported to be the main cause of seasonal variation of ionospheric parameters. Seasonal variation of TEC in this study depicts semi-annual variation with equinoctial maximum (~ 51 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) as 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) and others, 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

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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.

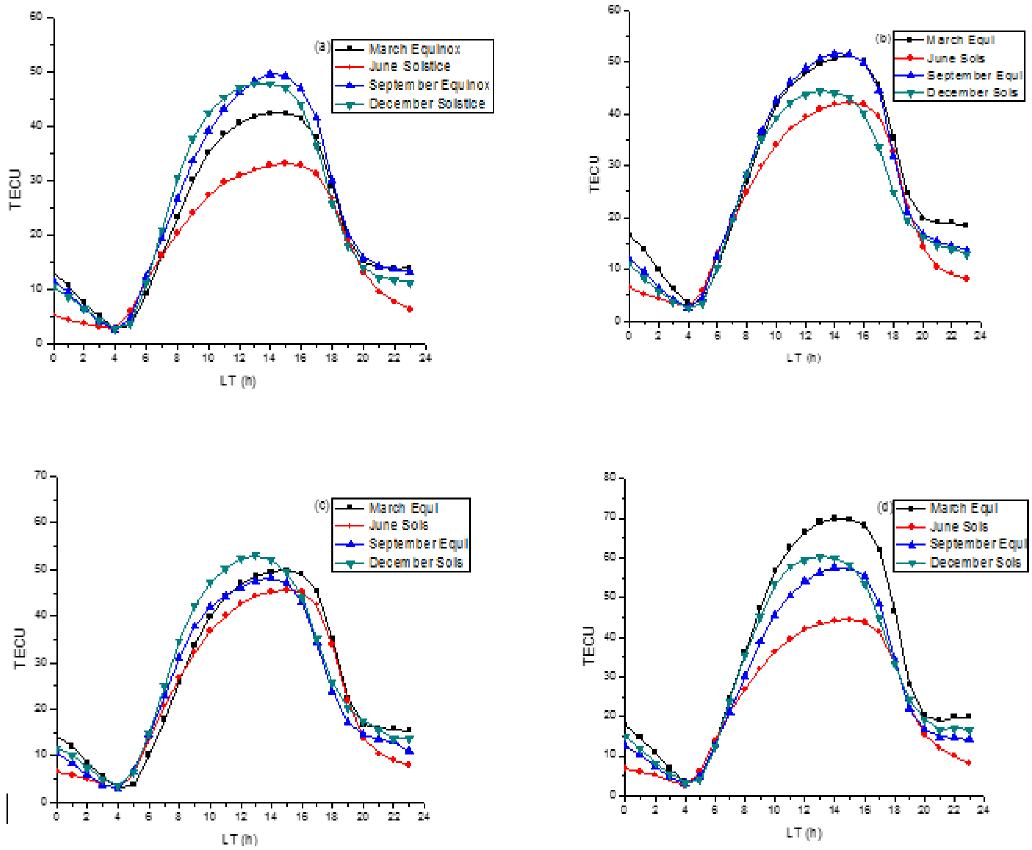

Figure 5: Seasonal variation of TEC during (a) 2011 (b) 2012 (c) 2013 and (d) 2014

In 2011 and 2014, the seasonal variation of 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.*

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(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).

Figure 6 shows the plot of annual variation of TEC and sunspot number, Rz against the months of the year for the four years. The plots reveal the strong dependence of 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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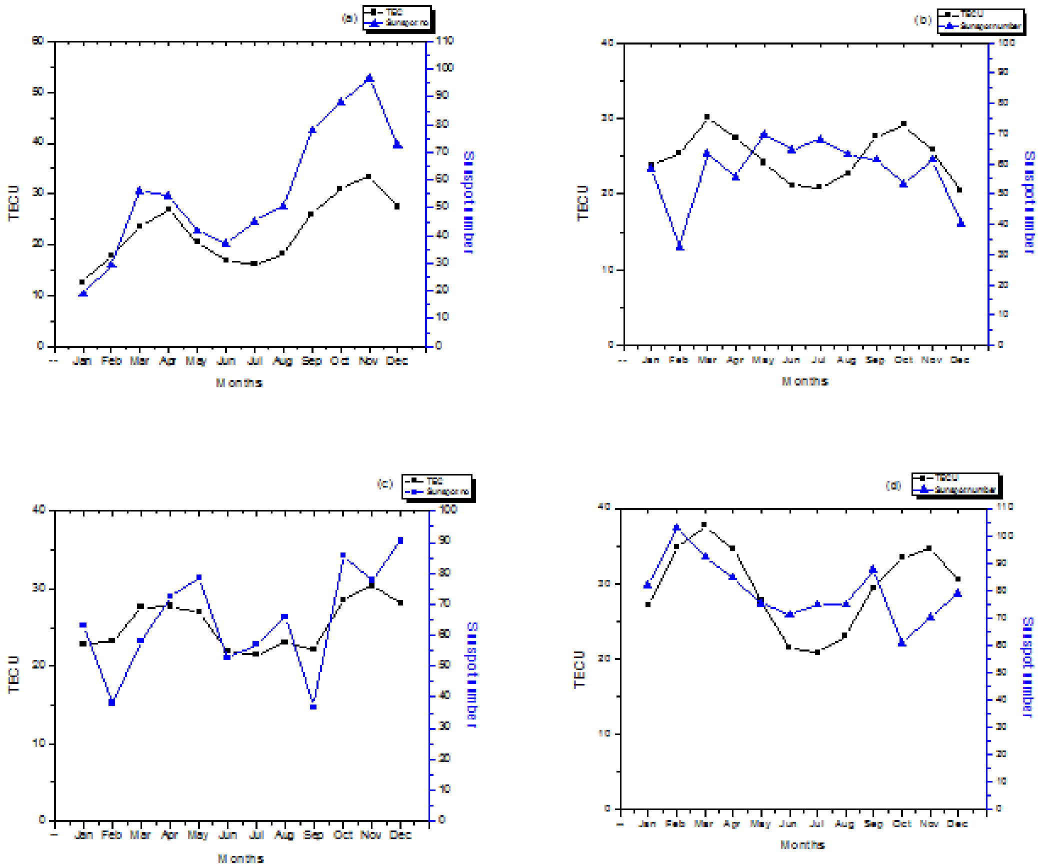

Figure 6: Annual variation of TEC and sunspot number, Rz during (a) 2011 (b) 2012 (c) 2013 and (d) 2014.

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 TEC variations at Birnin-Kebbiin 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 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). 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.
2. The diurnal variation reveals that the peak of TEC of some months were delayed till after-noon. Post-sunset decrease and enhancement were also observed in the diurnal variation of TEC in some months.
3. Seasonal variation of TEC in this study depicts semi-annual variation with equinoctial maximum (~ 51 TECU), followed by December solstice magnitude (~ 44 TECU) and least in June solstice seasons (~ 41 TECU) in 2012. This seasonal trend was not the case for 2011, 2013 and 2014, though June solstice consistently recorded the lowest value for all years.

4. Finally, annual variation of 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).TEC and sunspot number were found to increase gradually from 2011 to 2014.

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