Characterization of Equatorial Ionization Anomaly at the African Southern Hemisphere during a High Solar Activity Period

Abstract: This study was carried out using Total Electron Content (TEC) data from Global Navigation satellite systems (GNSS) situated in the equatorial-low latitudes region to characterize the quiet-time equatorial ionization anomaly (EIA) over African sector during high solar activity year 2013. The day-to-day (TEC) and monthly (MTEC) variations generally exhibits minimum pre-sunrise (0400-0500 LT) hrs magnitudes that start rising gradually at sunrise (0600 LT) hrs to reach their peak around (1200-1700 LT) hrs respectively. The TEC generally exhibit random spread that is mild at the magnetic equator and intensified with increasing geomagnetic latitudes. MTEC magnitudes appear weak in summer months and increase through winter months with greater intensity in equinoctial months. At any particular month, the MTEC at the magnetic equator (BJCO) exhibit daytime flat surface in summer months and consistently maintained lower magnitudes relative to low-latitude stations considered in the study. The noontime bite-out peculiar to the equatorial region is not realistic at the magnetic equator (BJCO) of this study. This could be attributed to stronger daytime EXB drift associated to stronger fountain effect. Seasonal appearance of EIA crests were observed earlier in winter and at latter hours in summer solstice across all latitudes exception of MAL2. The results also reveal the presence of equinoctial asymmetry across the latitudes. The equinoxes had the highest TEC values and the least magnitudes in summer solstice across all the latitudes. The prevalent MTEC and seasonal nighttime TEC enhancements across all the latitudes is not realistic at the magnetic equator (BJCO) indication of possible interplay between pre-reversal enhancement of EXB drift and other mechanism. All other latitudinal characteristics of EIA in the African sector of this study are discussed in light of the potential source mechanisms and implications.

Keywords: Ionosphere, Total electron content (TEC), Equatorial ionization anomaly (EIA), winter anomaly.

1 Introduction

The ionosphere is a distinguished layer of the atmosphere that extends from 90 km to ∼1000 km above the Earth’s surface hosting sufficient amount of ions and electrons that are highly variable caused by different mechanisms. Some of these mechanisms include solar ionizing flux and geomagnetic activity [1]. Lower atmospheric processes such as planetary waves, gravity and tudes that propagate into the ionosphere also make significant contribution to ionospheric variability [2]. Thus makes it a complex physical system that affects propagation of radio signals. The characteristic and dynamics of the ionosphere has been widely studied for several decades using different probing techniques, such as ionosonde measurement, trans-ionospheric radio signals [3]. In the last two decades, Global Positioning System, GPS systematically deployed across the globe have provided some basic ionospheric characteristics [4,5,6]. The GPS which is a satellite based positioning system has a wide range of uses in navigation, relative positioning system and time transfer [7]. The ionosphere been a dispersive medium in nature, as GPS signals are transverse, it depict the signature of the ionospheric variability and thus offer ample opportunity for ionospheric research. Total electron content (TEC) which is a measured data from the GPS under ideal situation is expected to show a regular occurring pattern from one day to the other because its source of formation exhibit both diurnal and seasonal variations. In a normal ionospheric condition, during sunrise or just after sunrise the ionization gradually starts building-up due to slow solar insolation and reaches its peak just after midday (afternoon) and decreases slowly to its base at sunset hours (1800 LT) in response to the decreasing effect of solar radiation. Generally, the ionosphere exhibit strong diurnal and seasonal variability since its main source of ionization is the photo-ionization, thus any change in solar radiation, the ionosphere tends to reflect these changes. Generally, the ionospheric effect on GPS signals provide useful information necessary for understanding temporal and spatial variations of the ionosphere and its subsequent effect on both navigation and satellite communication system.

The unique configuration of the geomagnetic field and the eastward electric field (EEF) at the dip magnetic equator gives rise to the vertical EXB drift that initiates the plasma transport. This lifts plasma vertically upward to an altitude (with minimal loss rate) where gravity and pressure gradient forces are stronger, hence caused a downward diffusion of the plasma along the magnetic field lines, a process known as the equatorial fountain effect. This process produce an enhanced ionization (plasma concentration) known as the crest at about ± 17° magnetic latitude and a reduced or minimized plasma density called the “trough” at the magnetic equator. This phenomenon is known as equatorial ionization anomaly (EIA) The features and characteristic of the EIA has been widely studied [8,9,10]. For example, [11] observed pre-midnight enhancement in TEC in the Brazilian region during low solar activity. In another study, [12,13] observed day-to-day variability of TEC with higher intensity in equinox and their minimum values in summer.

Even though studies have shown that under certain geophysical conditions the ionospheric ionization and the crest position varies from day-to-day, season and solar cycle but the explanation regarding the latitudinal characteristic and formation of equatorial ionization particularly in the African sector with largest land mass thereby making it more susceptible to ionospheric effect arising from the equatorial anomaly is in-adequate. The lack of comprehensive knowledge of EIA in the African region may likely be due to inconsistent TEC measurement and lack of GPS stations compared to South American region with dense of GPS network stations. Hence, in this study concerted effort has been made to study the latitudinal diurnal, monthly and seasonal variations of ionospheric TEC during period of moderate solar activity year 2013 across different latitudes in the African sector. We believe that the result from this study will complement the ongoing global studies to establish a more reliable and accurate regional and global model and also serve as a means of verifying the already existing ionospheric models.

Methodology:

The data used in the present study were obtained from the international GNSS services (IGS) receivers at 5 different locations in the southern hemisphere in the African sector during high solar activity year 2013. The list of the stations and their coordinate systems are presented in table 1. The stations span from the equator to low latitude region known for its vulnerability to changes in solar radiation. These satellites used identical dual frequency GPS receivers that form part of the University NAVSTAR Consortium (UNAVCO) network accessible at (http://unavco.org.) and IGS website (**ftp://cddis.gsfc.nasa-gov/products/ionex/igsg**). For each station used in the study, the receiver-independent exchange (RINEX) observation downloaded from the IGS website (http://igscb.jpl.nasa.gov/.) the raw data were processed using the GPS-TEC analysis application software developed by Gopi seemala, [14,15]. The detail on the estimates of GPS TEC have been reported in the works of [16,17,18]. To ensure that only quiet days are used, the magnetic activity index (Ap) that depict the level of magnetic activity are obtained from the World Data Centre, Kyoto (http://wdc.kug.kyoto-u-ac.jp/). Only days with Ap≤6 are used in this study, hence provide to a larger extent the quiet ionospheric characteristics of the TEC variations. The average daily hourly values with Ap≤6 for each particular day of the month through the year are engaged in the study. These daily average values of TEC between 0600 LT and 1800 LT hrs is assumed to reflect the signature of the daytime TEC variability. Knowing that the solar radiation which is the main source of ionization exhibit seasonal variations, the seasons are classified into four namely; spring (March, April), summer (May, June, July, August), autumn (September, October) winter (December, November, January, February). Matlab 2018a software was used throughout the analysis.

Table 1. Coordinates of GPS receiver locations (arranged in order of increasing geomagnetic latitude)

Stations	Station Code	Geographic		Geomagnetic	
		Latitude (°N)	Longitude (°E)	Latitude (°N)	Longitude (°E)
Cotonou, Ben. Rep.	BJCO	6.38	2.45	-3.08	74.54
Debarek, Ethiopia	DEBK	13.15	37.89	-4.48	109.48
Mbarara, Uganda	MBAR	-0.65	30.74	-10.22	102.36
Malindi, Kenya	MAL2	-2.99	40.19	-12.43	-111.86
Dodoma, Tanzania	DODM	-6.2	35.8	-16.10	107.27

3 Results and Discussion

3.1 Diurnal variability of Total Electron Content (TEC)

Figure 1 shows the histogram of the number of available quiet days (Ap≤6) for each of the month used in the study. From the Figure, the month of January had no data at BJCO and other stations have quite a reasonable data to characterize the features of the EIA in the African sector. The lack of data at BJCO could possibly result from power interruption or system failure. However, it obvious that the highest number of days (11) was recorded each at BJCO, DEBK, MAL2 and DODM in September. The quiet days ranged between 5 and 11 with least observed at MBAR in March. Generally, the quiet days used in the study provided both the diurnal and seasonal EIA signature that is mostly peculiar to the equatorial-low latitude region.

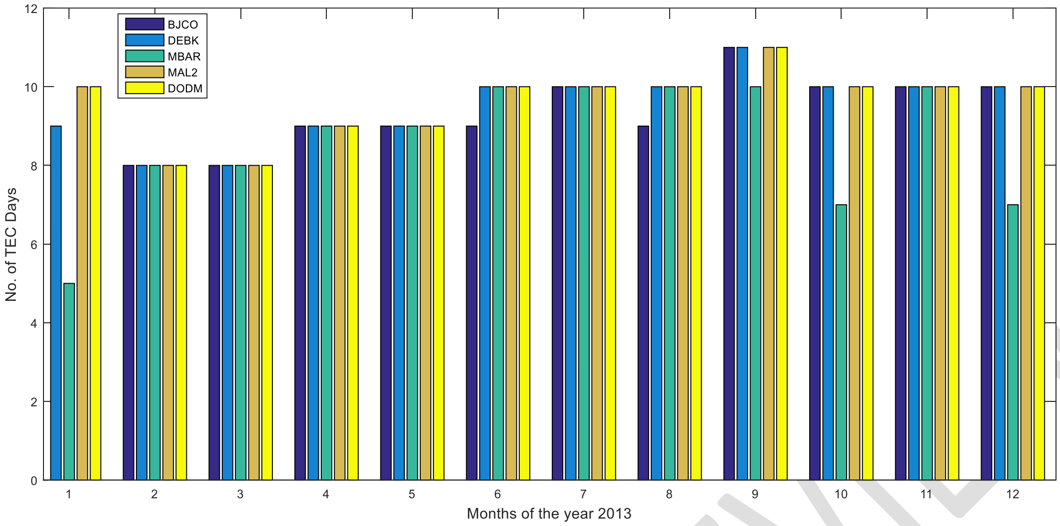

Figure 1. Histogram depicting the number of available quiet days with Ap≤6 used in the study

Figures 2a and 2b show a time series plot of the TEC diurnal variations TEC across the equatorial-low latitudes. It is obvious that a significant day-to-day randomness in the variations of ΔTEC during the daytime (0600-1800 LT) hrs exist across all latitudes except BJCO located at the magnetic equator. This is a rare phenomenon for magnetically quiet days; hence pose a serious concern not only to space scientist in forecasting but also for navigation system users and modeling. The randomness is particularly prominent at MBAR, MAL2 and DODM. The random spread in TEC seems to indicate some level of dependence on latitude as it's noticeably absent at BJCO, relatively calm at DEBK and became intensified with increasing latitudes (see Figures 2a and 2b). This finding in the African sector validate earlier effort by [19,20, 21] who observed day-to-day randomness in their studies and attributed it to changes in solar activity. We suggest that changes in the fountain effect may also contribute to the random changes in TEC that is so eminent across the African latitudes of this study.

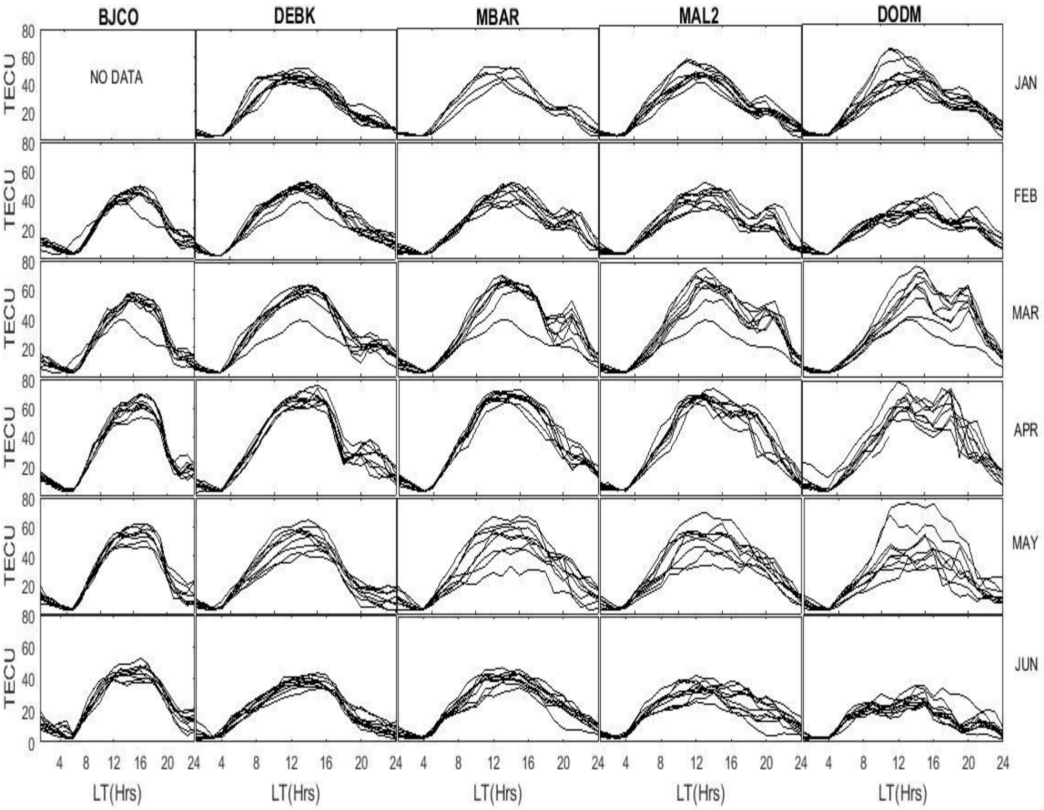

Figure 2a. Diurnal variation of TEC for January to June 2013

Aside these variations, TEC consistently maintained short-lived minimum amplitude during the pre-sunrise (0400-0500 LT) hrs and start rising gradually at sunrise (0500-0600 LT) hrs marking the beginning of photo-ionization with incoming solar radiation. Exception to this is BJCO located at the magnetic equator whose sunrise increase occurs nearly 1-2 hours later in all the days considered in the study. The delay in the morning rise of TEC at BJCO relative to other stations is purely a local factor that needs to be addressed. We assert that the smaller magnitudes of TEC around pre-sunrise period depict lesser electron density associated with weaker fountain effect caused by weak solar ionizing effect around these periods.

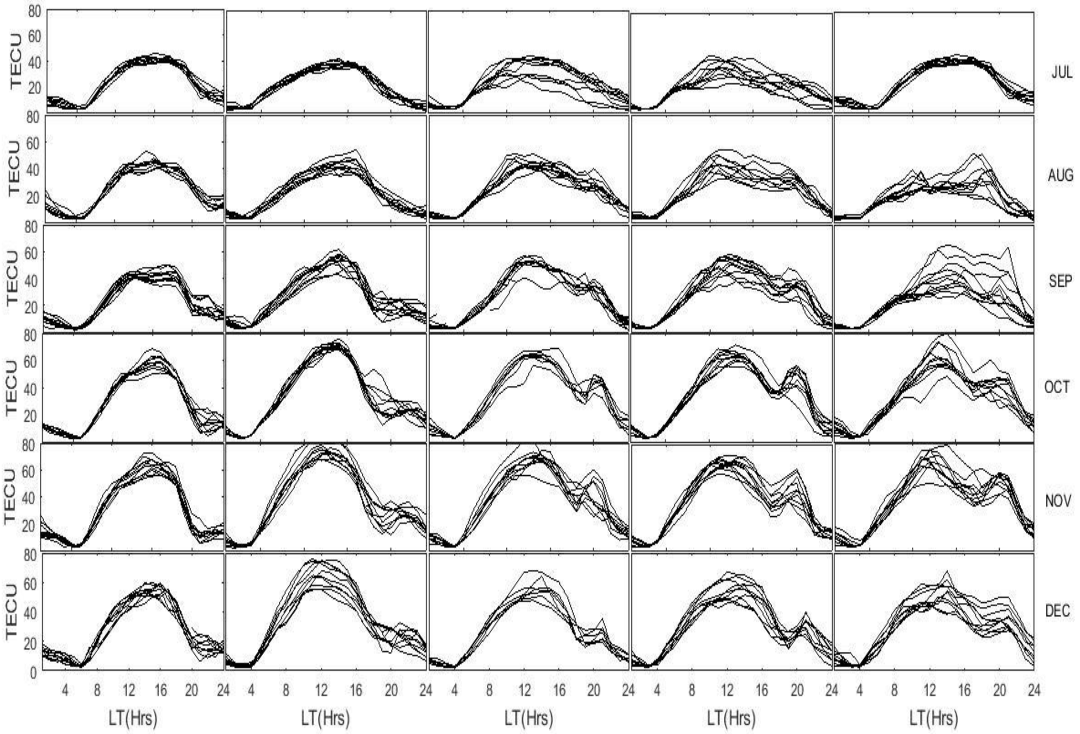

Figure 2b. As figure 2a above but for July to December

These pre-sunrise TEC were generally observed to reach their maximum around (1200-1600 LT) hrs in most cases and gradually fall to a minimum just after sunset (1800 LT) hrs. The afternoon decrease of TEC marks the gradual reduction in the intensity of solar radiation and the associated weakening of the evening fountain effect leading to decrease in ionization intensity across all the latitudes. The delay in the morning increase at BJCO shifts its daytime peak to latter hour of the day (1300-1700 LT) hrs. The daytime TEC maximum amplitudes ~78, 83, 82, 79 and 80 TECU are generally seen at BJCO, DEBK, MBAR, MAL2 and DODM in November exception of the latter two that were seen in March and April respectively. Generally, the daytime maximum TEC values are consequences of intense photo-ionization under the influence of solar EUV radiation which inturn generate sufficient electrons that subsequently enhanced the background electron density at each latitude location [22] coupled with the upward EXB drift at the magnetic equator driven by the F-region electrodynamic processes. These greater daytime TEC are consistence with earlier findings from other regions of the world, [23,24,25.26]. These authors attributed this phenomenon to combined effect of solar EUV that initiate stronger upward EXB drift velocity which lift plasma to a height where recombination rate is minimal thereby enhancing more ionization production rate around these periods as obviously seen in Figures 2a and 2b respectively. Generally, TEC exhibit lower values in May, June, July and August across all the stations indication of weaker fountain effect. The weaker EIA formation in these months (May, June, July and August) is a reflection of strong evidence of lesser transport of plasma to a height of maximum loss rate caused by weaker EXB drift. It is conspicuously seen that at any particular day in each month, the TEC at BJCO consistently maintained lower magnitude relative to other stations considered in the study. This is no surprise knowing that at the magnetic equator there is reduced electron density caused by the transport mechanism of EXB plasma drift.

On average, the stations located outside the equatorial region exhibit larger TEC relative to the equatorial station (BJCO) and this could possibly be due to stronger vertically upward EXB plasma drift during the sunlight hours. Careful observation of Figures 2a and 2b reveal the absence of midday bite-out at the equatorial latitude (BJCO), in contrast to result obtained by [27]. It is worthy to note that the year used by these authors was during minimum solar activity associated to weak upward vertical EXB drift of plasma during the daytime relative to the present study that engaged high solar activity year 2013.

Apart from these daytime maximum and random variations observed in Figures 2a and 2b, TEC is characterized by a pre-midnight (1900-2400 LT) hrs enhancement that is commonly seen across all the stations exception of BJCO at the magnetic equator. These nighttime enhancement starts building up at DEBK which lies at the fringe of the magnetic equator and gradually intensify with increasing latitude. This feature clearly revealed that just like the daytime, the nighttime enhancement in TEC exhibits latitudinal variation with local time. We assert that there may possibly be some mechanism for their prevalence at different latitudes. Ideally at sunset or just after sunset (1800 LT) hrs, the TEC is expected to gradually wane irrespective of location and latitude to reach minimum just before the following sunrise but this is not the case at DEBK, MBAR, MAL2 and DODM latitudes of this study. A substantial increase in TEC lasting for about 2-4 hrs centered around 1900 and 2400 LT. Evidently, these nighttime enhancement were prevalent in equinoctial months (March, April, September and October) closely followed by winter months (January, February, November and December) and only traceable increase in summer months (May-August). Our prevalent nighttime TEC enhancement in winter months agrees with earlier findings by [28,29] but our summer months are contrary to their observation revealing regional differences do exist in ionization distribution. The pre-midnight ΔTEC magnitudes of this study are higher in equinoctial months than winter month indication of variations in the intensity of the nighttime source mechanism. Different mechanisms have been inferred to explain the anomalous nighttime enhancement of TEC. For example, earlier studies by [30,31] have all associated the enhanced nighttime electron density to the downward propagation of plasma flux. [32,33] attributed the nighttime TEC enhancement to presence of meridional wind which propagate equatorward, hence transport plasma to a higher altitudes during nighttime. [34] conducted latitudinal variation of nighttime TEC enhancement over Indian sector and they attributed it to downward diffusion of plasma from the plasmasphere resulting from the cooling of the filled tube after sunset.

3.2 Monthly Variability of TEC (MTEC)

As seen in Figures 3a and 3b, the monthly diurnal variation of total electron content (MTEC) exhibits similar features as the ΔTEC characterized by minimum amplitudes that ranged between ∼2 and 4 TECU during the pre-sunrise (0400-0500 LT) hrs. These minimum MTEC were later observed to rise sharply in most cases around (0500-0600 LT) hrs to reach their peak amplitudes around (1100-1500 LT) hrs respectively. Exception to this is BJCO seen to rise about 2 hours later thereby shifting its afternoon peak to latter hour of the day (1300-1700 LT) hrs. The sharp steep increase observed at other latitudes is not so obvious at DODM particularly in summer months (May, June, July and August), indication that the fountain effect may likely be suppressed by downward plasma drift during these months. Our results revealed that MTEC peak amplitude exhibit variability that appears earlier in winter months (November-February) closely followed by equinoctial months (March, April, September and October) then at latter hours in summer months (May-August). During these periods, the MTEC is characterized by daytime broad phase lasting for about 2-4 hours seen at equatorial latitude (BJCO) during the summer months (May-August). These broad phases may be associated to prolong ionization by solar radiation during these months (May-August). At each particular hour of the day, the MTEC exhibit different level of unprecedented magnitudes. This may be due to the fact that at each hour of the day, the photo-ionization changes slowly with local time in response to the complex orientation of the northward magnetic field and zonal electric field. For Instance, the daytime MTEC amplitudes 78, and 63 TECU are observed at MBAR and DODM each in November. Other stations had their amplitudes 75, 62 and 63 seen at MAL2, BJCO and DEBK all in April exception of DEBK that occurred in March respectively. We suggest that the reduced daytime MTEC values at BJCO depict the maximum rate of removal of plasma (ionization) from the equatorial zone. MTEC magnitudes generally appeared weak in summer months (May- August) relative to other months of the year at all latitudes. The possible mechanism responsible for this would be discussed in terms of seasonal variation in the following section.

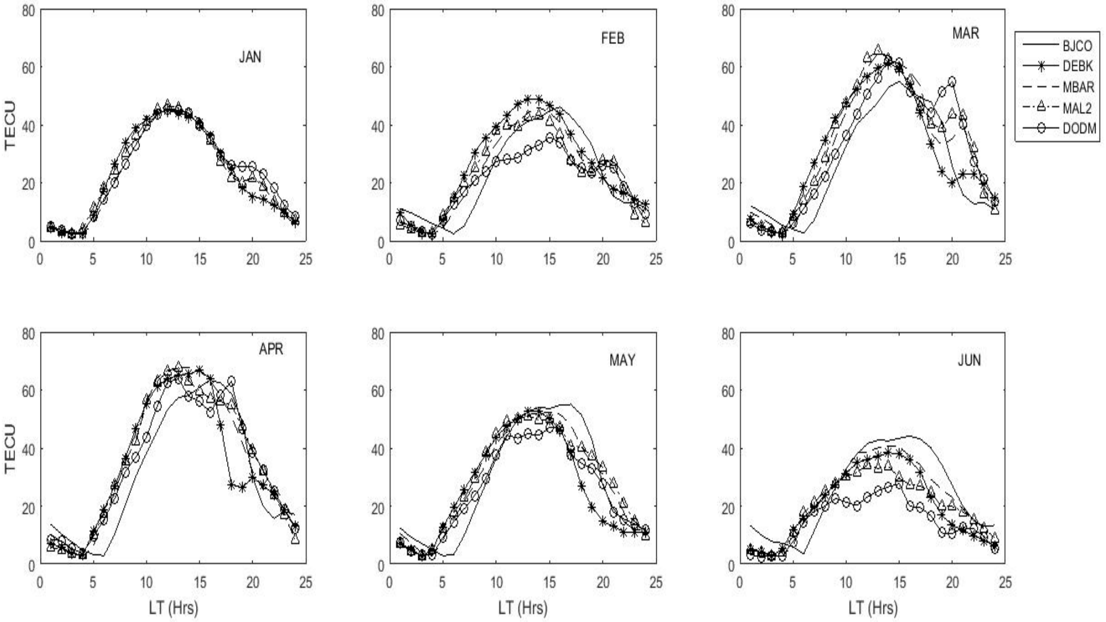

Figure 3a. Monthly diurnal TEC for January to June during moderate solar activity year 2013

Careful observation of Figures 3a and 3b shows that the weakened MTEC at sunset (1800 LT) hrs suddenly becomes intensified again around 1900 and 2400 LT hrs. These nighttime magnitudes seems to start almost at the same local time (1900 LT) hrs with few cases in summer months, increases through the winter month and intensified in equinoctial months. Amazingly, these nighttime TEC magnitudes are absent at the equator (BJCO) and seems to increase with increasing latitude in contrast to what is earlier reported by [35].

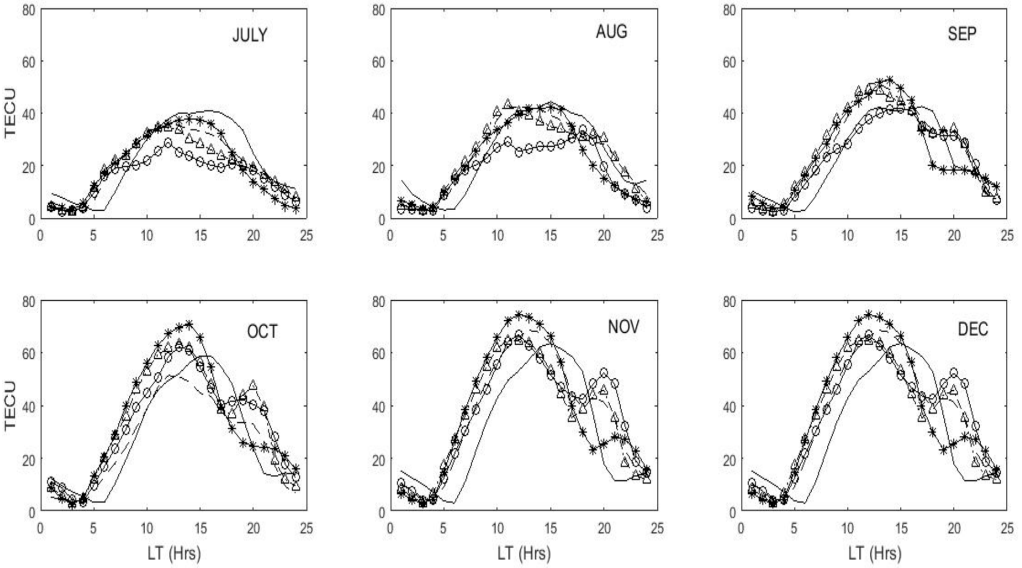

Figure 3b. As Figure 3a but for July to December 2023

They observed that the TEC is strongest at the equator and became weaker with increasing latitudes. Regional changes in solar activity coupled with variable fountain effect may likely cause the differences between this present study and the earlier ones. Aside from the earlier mentioned reasons for the nighttime TEC magnitudes, other mechanisms could likely contribute to the observed nighttime TEC enhancement. In the paper by [36] suggested the reverse fountain effect coupled with the pre-reversal strengthening of the forward fountain as the main cause of the nighttime TEC enhancement. [37] explained that the zonal wind and the ratio between the Pedersen conductivity in the E and F region that are mapped by the magnetic field may influence the formation and development of the nighttime MTEC enhancement. [38] asserted that the faster decay of the ionospheric E region conductivity relative to the F region provide conducive atmosphere for the nighttime TEC variations to developed. We suspect that the lack of TEC nighttime enhancement at BJCO may be associated to early decay of E-region conductivity relative to the F-region ionosphere. Evidences from [39,40,41] explained that solar radiation plays a significant role in the vertical pre-reversal drift enhancement and the subsequent nighttime TEC magnitude.

3.3 Seasonal Latitudinal Variation of TEC

It is now certain that the ionosphere exhibit strong seasonal variability because its main source of ionization is the photo-ionization hence, any slight changes in solar radiation caused corresponding changes in the ionosphere. For example, Figure 4 show that the seasonal variation does not show any regular ionization distribution with increasing latitude but thus indicates strong EIA characteristics with maximum values at the equinoxes (spring and autumn) than other seasons across all the latitudes, a phenomenon known as semiannual variation in the ionization distribution. Exception to this is BJCO located at the magnetic equator whose winter EIA crest value is higher than its autumn as shown in Figure 4 and well tabulated in table 2. The reason for this phenomenon will be discussed later.

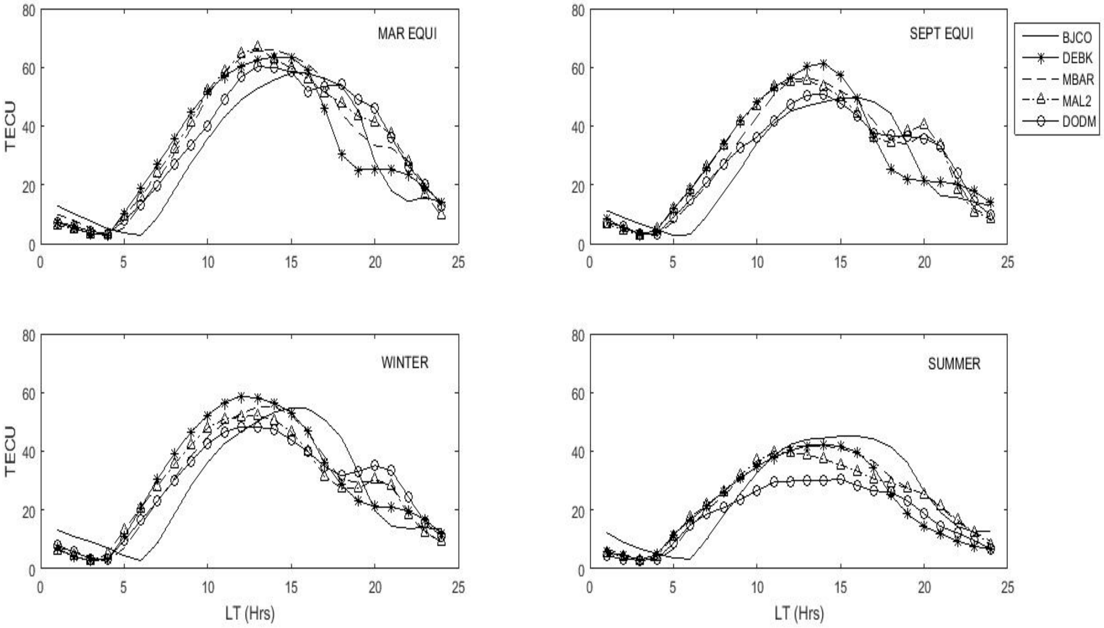

Figure 4. Seasonal variation of TEC in the year 2013

The salient feature to note in Figure 4 is that, during the summer solstice, the value of TEC at the equator (BJCO) is slightly higher than the low latitude stations particularly around 1100-2000 LT hrs and opposite is the case in other seasons. This is a rare phenomenon and not a common one knowing that during the summer solstice, the sun is away from the equator implying less plasma is expected to be transported to a height that support recombination rate thereby reducing the amount of electron density (ionization) at this latitude (BJCO) but rather a seemingly higher ionization is observed relative to other latitudes. We suspect that the wind and trans-equatorial wind which are more effective with solar activity may likely optimize the ionization at the BJCO than other latitudes in summer solstice of the African sector.

The higher ionization in equinoxes (spring and autumn) than in solstices agrees with the earlier findings in the Brazilian and Asian sectors by [42,43]. Various mechanisms have been inferred to explain this semiannual variation TEC pattern. For example, [44] attributed this phenomenon to combined effect of solar zenith angle and orientation of magnetic field. [45] suggested changes in neutral composition O/N_2 may likely cause the semiannual variation in TEC at low latitude. Studies has shown that during equinoxes, the sun is directly towards the equator leading to higher ionospheric conductivity and stronger eastward electric field in the E region of the ionosphere thereby strengthening the equatorial fountain effect, hence the overall consequences of this is that more plasma will be lifted to greater height with minimal recombination rate (loss rate). This processes leda to a well-developed EIA in equinoxes (spring and autumn) relative to the solstices as rightly observed at each latitude location in this study.

Table 2. Highest seasonal values and their occurrence local time

Station	Spring (TECU) / LT	Summer (TECU) / LT	Autumn (TECU) / LT	Winter (TECU) / LT
BJCO	58 / 1500 LT	48 / 1600 LT	50 / 1600 LT	55 / 1500 LT
DEBK	64 / 1400LT	42 / 1400 LT	60 / 1300 LT	59 / 1200 LT
MBAR	66 / 1300 LT	42 / 1400 LT	56 / 1300 LT	53 / 1200 LT
MAL2	66 / 1300 LT	39 / 1100 LT	55 / 1300 LT	52 / 1300 LT
DODM	60 / 1300 LT	31 / 1500 LT	51 / 1400 LT	48 / 1200 LT

Another seasonal variation observed in this study is the equinoctial asymmetry in the latitudinal ionization distribution with higher intensity (crest) in spring relative to the autumn (see table 2). The equinoctial asymmetry of this study validates earlier works by prominent research workers [46]. Despite the fact that the sun is directly towards the equator in spring and autumn, the ionospheric plasma distribution thus present a conspicuous ionization differences as identified in the African sector (see table 2). The salient feature to note in table 2 is that irrespective of season, TEC crest peak value does not show any remarkable difference between MAL2 and MBAR. The reason could be attributed to the fact that the distance between them is just about 230 km (see table 1) which seem to be too small to produce any significant difference.

Apart from the equinoctial asymmetry, TEC also show annual variation with maximum (minimum) ionization in winter (summer) solstices that is contrary to the expectation of solar zenith angle variability with higher intensity in summer solstice, [47,48] . This phenomenon is known as winter anomaly and occurred across all latitudes of this study. Different mechanisms have been inferred to explain the biased ionization between the solstices. For instance, [49] explained that the Earth's magnetic field strength that drives plasma from the summer to winter hemisphere may likely contribute to the unequal distribution of the electron concentration with higher (lower) density in winter (summer) solstice. Studies over the years have shown that the vertical winds are upward (downward) in summer (winter) hemisphere resulting in decrease (increase) of O/N_2 ratio. Higher O/N_2 ratio does not only generate excess production of ionization but minimizes the electron loss rate, thereby weakens the recombination in the winter hemisphere. This process may also contribute to the higher electron concentration in the winter solstice over the summer as rightly observed in this study. The plausible explanation for the higher TEC value in winter solstice over the autumn at BJCO of this study could be that there is presence of large O/N_2 ratio that yield excess ionization in winter that supersede the ionization at the autumn under the direct influence of solar EUV radiation. This phenomenon could probably reflect lesser recombination rate in electron density in winter than in autumn at BJCO latitudes. We suspect that the higher crest value in winter solstice relative to the autumn at BJCO could possibly result from the fact that the low molecular ratio (or low nitrogen) is too insignificant (weak) to reduce the electron density below the ionization densities caused by photo-ionization under the influence of direct solar radiation. On average, the ionization is higher in equinoxes compared to the solstices.

The nighttime monthly TEC enhancement observed in other region of the world inclusive of this present study is seasonally obvious across some latitudes in the African sector of this study, thus indicate strong dependence on local time, season and latitude. For instance, the pre-midnight (1900-2400 LT) TEC peak enhancement occurred more frequently across all latitudes in equinoxes (spring and autumn) and winter solstice but rarely seen in summer solstice. Amazingly these nighttime seasonal TEC magnitudes exhibit large variability that is more prevalent in equinoxes (spring and autumn) and winter but rarely observable in summer solstice of this study. These results are in contrast to what was earlier reported by [50,51,52] that observed frequent occurrence of nighttime enhancement of TEC in summer and rare in winter and equinoctial seasons. The unique finding from this study is that these nighttime enhancement are completely absent in any of the seasons at the equator (BJCO). This shows that the post-sunset enhancement in TEC may not be associated to the well-known pre-reversal enhancement (PRE) or the PRE of EXB drift is too insignificant to cause any the nighttime fountain effect, thus resulting to absence of nighttime TEC enhancement at BJCO located at the magnetic equator. The occurrence of nighttime electron density with varying magnitudes in the African sector is a clear revelation of various mechanisms for their prevalence at different latitudes. [53,54] explained that the equatorward neutral wind at nighttime may likely be a potential mechanism for the formation of nighttime ionospheric electron concentration. [55] explained the downward diffusion plays no significant role, but the presence of neutral wind and electric field may likely be significant source mechanism for the nighttime TEC enhancement.

4 Conclusions

This paper used the total electron content (TEC) from 5 GPS receivers to characterize the equatorial ionization anomaly (EIA) over the African sector during high solar activity year 2013. The main results from this study are summarized as follows:

1) The TEC exhibit random spread that seem to indicate some level of dependence on latitude and seasons as its noticeably absent at the magnetic equator (BJCO), relatively calm at DEBK and intensified with increasing latitudes.
2) The TEC and MTEC consistently maintained short-lived minimum amplitude during the pre-sunrise (0400-0500 LT) hrs and start rising at sunrise (0500-0600 LT) hrs marking the beginning of electron density production with incoming solar radiation. Exception to this is BJCO located at the magnetic equator whose pre-sunrise increase occurs about 2 hours later.
3) The TEC generally exhibit maximum amplitudes∼73, 83, 82, 78 and 80 TECU around (1200-1700 LT) hrs seen at BJCO, DEBK, MBAR, MAL2 and DODM in November exception of the latter two that occurred in March and April respectively. These daytime maximum amplitudes are product of solar photo-ionization under the strong influence of solar EUV radiation which in turn generates electrons that subsequently enhanced electron density at each latitude.
4) Generally TEC exhibit lower amplitudes across all latitudes in May, June, July and August indication of weaker fountain effect in these months. This evidently reflects that lesser plasma is transported to a height of maximum loss rate.
5) The noontime bite-out peculiar to the equatorial region is not realistic at the magnetic equator (BJCO) of this study. This could be attributed to stronger daytime EXB drift associated to intense fountain effect.

6) The MTEC at BJCO located at the magnetic equator is characterized by a flat surface lasting for about 2-4 hours prevalent in summer months. These flat surfaces may be associated to prolong daytime ionization caused by intense solar radiation during these months.
7) The sharp steep increase in of MTEC observed across other latitudes is not so apparent at DODM in summer month's indication of weakening of fountain effect at this latitude location.
8) Seasonal appearance of EIA crest were observed at earlier (latter) hours in winter (summer) across all the latitudes exception of MAL2.
9) The results also reveal the presence of equinoctial asymmetry across the latitudes. The equinoxes had the highest values of TEC and the summer solstice recorded the least across all the states.
10) Nighttime seasonal enhancement of TEC were observed to start almost at the same local time (1900 LT) hrs in winter, increases in equinoctial seasons (spring and autumn) and rarely traceable in summer solstice
11) The prevalent nighttime TEC enhancement at other latitudes is not obvious at any of the seasons at BJCO, indication that if pre-reversal enhancement is ever present, then it is too weak to cause any significant nighttime TEC enhancement at BJCO.

Disclaimer (Artificial intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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