ISSN 0016-7932, Geomagnetism and Aeronomy, 2021, Vol. 61, No. 4, pp. 647–657. © Pleiades Publishing, Ltd., 2021.

The Response of the Equatorial Ionosphere over Nigeria to a Geomagnetic Storm Event

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Received October 20, 2020; revised January 11, 2021; accepted January 28, 2021

Abstract—The total electron content (TEC) data obtained from the ground-based GPS receiver stations of the Nigerian GNSS network of stations (NIGNET) have been used in this study to analyse the response of equatorial and low-latitude ionosphere to strong geomagnetic storms that occurred on October 25, 2011. The stations and their respective geomagnetic latitudes are Lagos (−3.03°), Yola (−1.32°) and Birnin Kebbi (0.72°). The storm caused enhancements in TEC (positive storm effect) in comparison with the quiet condition's TEC across all the stations during both the main and the recovery phases. During the storm of October 25, recorded maximum enhancements in TEC were 181.86%, 142.34% and 181.24% in Kebbi, Yola and Lagos respectively.The magnitude of the ionospheric irregularities was higher at the night (October 25) of the main phase of the geomagnetic storm than the night (October 24) before the storm onset.

Keywords: Geomagnetic storm, equatorial ionosphere, Ionospheric TEC, latitudinal TEC variability, geomagnetic disturbances, seasonal variability

DOI: 10.1134/S0016793221040022

1. INTRODUCTION

The global age-long interest in the ionospheric research is apparently being sustained due to its robust applications in man-made technologies such as satellite communications, navigation, space crafts, power grids, pipelines, etc. (Rama Rao et al., 1997; Rabiu et al., 2013). A highly dynamic ionosphere can severely affect the performance and reliability of our space- and ground-based technologies with attendant economic and societal impacts if not properly studied and understood (National Research Council (NRC) Report, 2008).

The ionosphere along the equatorial (low-latitude) is highly dynamic and consequently constitutes serious threats to communication and navigation systems (Akala et al., 2010).

One of the very important ionospheric parameters to be considered in the planning and operation of satellite navigation and communication systems is the total electron content, TEC (Akala et al., 2013a), and it is defined as the quantity of electrons in a column of 1 unit cross-section along the signal path from a satellite to a ground station (Davies and Hartman, 1997). This is directly related to the ionospheric electron density which is the major origin of signal degradation (Olwendo et al., 2016). The range errors in GPS signals are directly proportional to TEC; therefore, any variations thereof become a matter of concern (Galav et al., 2010).

Increased dissipation of solar wind energy in the near-Earth environment compresses the magnetosphere. According to Gonzalez et al. (1999) and Kumar et al. (2005), the southward turning of the meridional component (*Bz*) of the Interplanetary Magnetic Field (IMF-*Bz*) for a substantial length of time will lead to reconnection process between the Earth's magnetic field lines and IMF lines at the magnetopause. Hence, energetic particles (mainly protons) can be transferred from the solar wind to the Earth's magnetosphere. These particles increase the density of the ring current which creates a magnetic field in the direction opposite to that of the Earth's magnetic field and thus causes a rapid drop in the Earth's magnetic field strength. These disturbances include large plasma and neutral wind velocities, high plasma and neutral gas temperatures and changes in the neutral gas composition.

These temporal disturbances of the Earth's magnetosphere are commonly referred to as geomagnetic storms (Dungey, 1961; Retterer and Kelley, 2010; Schunk and Nagy, 2000).

The strength of the geomagnetic storm is characterised by the minimum Disturbance storm-time (Dst) index and IMF-*Bz* (Gonzalez et al., 1994). The Dst index is a quantitative measure of the energy injection into the ring current by the solar wind disturbance (Gonzalez et al., 1994).

A typical geomagnetic storm usually consists of three major phases: storm sudden commencement (SSC) phase, which is characterised by an abrupt increment in *Dst* due to the compression of the magnetosphere by the shock wave hitting the Earth's environment; the storm main phase, which is characterised by the build-up of the intensified ring current by high energetic particle injection and energisation. This is connected with a decrease of the *Dst* values down to a minimum value which marks the end of the main phase and the beginning of the storm recovery phase which normally takes a little longer than the main phase; the recovery phase, when *Dst* returns to its pre-storm values. Recovery phase can last for several days (Tsurutani, 2001).

During geomagnetically disturbed conditions, the direct prompt penetration of a down-dusk electric field (PPEF) to equatorial and low latitude ionosphere and the ionospheric disturbance dynamo electric field (DDEF) have been identified as the two principal origins of electric fields responsible for the perturbations of the ionospheric electric fields and currents at these regions (Sastri et al., 1997; Fejer, 1997; Chakraborty et al., 2015). The perturbation in field affects the distribution of ionospheric plasma (Chakraborty et al., 2015).

The direct prompt penetration of solar wind electric fields to equatorial and low-latitudes has been observed to be short lived (time scale <1 h) (Kelley et al., 1979; Kikuchi et al., 1996). It creates a dawn-dusk electric field in the equatorial ionosphere which is in general, eastward during the daytime and westward in the night-time, therefore enhancing the daytime eastward dynamo electric field and vertical drifts at equatorial and low latitude ionosphere which lifts the plasma to higher altitudes (Rastogi and Klobuchar, 1990), where the ratio of production to loss is larger. This leads into enhanced electron density in the dayside sector. Hence, dayside ionospheric response to the prompt penetration electric field has been observed to be associated with a marked enhancement in TEC in the daytime (Maruyama et al., 2004; Tsurutani et al., 2004). On the other hand, the ionospheric disturbance dynamo electric field from geomagnetic storm is long lived (time scale from about 2 h to about 30 h) (Blanc and Richmond, 1980; Fejer, 1997; Fejer and Scherliess, 1997). DDEF is westward during the day, thus opposing and causing a decrease of the daytime ionospheric dynamo electric field. This reduces the vertical drift leading into a depletion of TEC in the daytime (Tsurutani et al., 2004).

Adequate knowledge of the behaviour of TEC during geomagnetic storms particularly along the equatorial latitudes where the ionosphere is highly dynamic (Akala et al., 2010) will provide proactive platforms for planning space-based radio, communication, positioning, navigation, and all other space-based technological applications which are prone to ionospheric alterations (Moses et al., 2020).

A number of regional networks of GPS stations have been established in order to provide real-time forecasting of ionospheric TEC variations for aviation applications, with the primary aim of mitigating positioning errors in global navigation satellite system (GNSS) operations (Akala et al., 2013). However, the equatorial TEC is still not well studied (Mendillo and Klobuchar, 2006), particularly in the African sector partly because there are not yet many ionospheric research observatories and consequently there is a dearth of data. The goal of the establishment of NIGNET among others is to provide the much-needed data for this region of the African sector.

The aim of the present work is to investigate the impact of the geomagnetic stormof October 25, 2011 on the GPS-TEC across different latitudes over Nigeria using NIGNET data. The results obtained in this study will constitute an invaluable contribution to understanding the dynamics of the equatorial ionosphere during geomagnetically disturbed periods by providing useful data which may assist system operators to take necessary actions in advance.

2. METHODOLOGY

The data used for this work are categorised into two. The first category of data are ionospheric Total Electron Content (TEC), which were obtained from the ground based GPS receivers located in Nigeria network of stations (NIGNET, www.nignet.net). NIGNET equipment is being operated by the Office of the Surveyor General of the Federation (OSGoF) of Nigeria. Rabiu et al. (2014) and Ayorinde et al. (2016) have described the NIGNET network and the agency managing the project. The period of study covered the year 2011, a year of low solar activity with average Sunspot number (SSN) 55.7 (https://www.sws.bom.gov.au/Educational).

The second category of data are solar-geomagnetic parameters, which were obtained from http://omniweb.gsfc.nasa.gov/. These comprise the Interplanetary Magnetic Field (IMF) along *z*-axis (*Bz*, nT), Interplanetary Electric Field (IMF) along *y*-axis (*Ey*, mV/m), Solar wind plasma speed (*Vp*, km/s), Plasma Temperature (K) and Plasma pressure (nPa), Disturbance storm time index (*Dst*, nT) and Planetary K index (*Kp*, nT).

Table 1. List of stations and their coordinates

ID	Station	Geographic Latitude (°N)	Geographic Longitude (°E)	Magnetic. Latitude (°N)	Magnetic Longitude (°E)
BKFP	Kebbi	12.47	4.23	0.72	76.62
FUTY	Yola	9.35	12.50	−1.32	84.31
ULAG	Lagos	6.52	3.40	−3.03	75.45

However, focus was on the strong/intense geomagnetic storm of October25, 2011 with minimum *Dst* value of -147 nT.

The International quiet days (IQDs) were obtained from (www.ga.gov.au/oracle/geomag/pqdform.jsps) In order to investigate the influence of the solar-geomagnetic structures on the storm event, and the role they played during the day(s) before and after the storm, the data sets covered a day before the storm event and a day after the storm event.

The study locations consist of three stations distributed across Nigeria. Table 1 displays the details of the locations and their geographical and geomagnetic coordinates. Fig. 1 shows the spatial distribution of the stations used in Nigeria.

In this work, the slant TEC, sTEC, which is the raw GPS data, is estimated using two frequencies GNSS receivers in which the first carrier frequency f_1 is centred at 1.57542 GHz and the second carrier frequency f_2 is centred at 1.22760 GHz. Following Carrano and Groves (2006), the code and carrier phase measurements obtained from GNSS network were used to compute the sTEC along the signal path from the satellite to the receiver using the expression,

$$\mathrm{sTEC_P} = \frac{f_1^2 f_2^2}{40.3\left(f_1^2 - f_2^2\right)} \times \left[(P_2 - P_1) - (B_s + B_r + \varepsilon_P)\right], \quad (1)$$

$$\mathrm{sTEC_L} = \frac{f_1^2 f_2^2}{40.3\left(f_1^2 - f_2^2\right)} \times \left[(\lambda_2 L_2 - \lambda_1 L_1) - (\lambda_1 A_1 + \lambda_2 A_2 + \varepsilon_L)\right], \quad (2)$$

where P_1 is the code-delay measurement on frequency f_1 (m), P_2 is the code-delay measurement on frequency f_2 (m), B_s is the satellite differential code biases (m), B_r is the receiver differential code biases (m), L_1 is the carrier phase measurement on frequency f_1 (cycles), L_2 is the carrier phase measurement on frequency f_2 (cycles), A_1 is the ambiguity integer measure on the carrier phase on L_1 frequency (cycles), A_2 is the ambiguity integer measure on the carrier phase on L_2 frequency (cycles), ε_P is the noise wthin the frequency channel and multipath associated with the code-delay measurements (m), ε_L is the noise and multipath associated with the carrier phase measurements (cycles), λ_1 and λ_2 are the wavelengths corresponding to f_1 and f_2, respectively (m).

The $\mathrm{sTEC_P}$ obtained in equation 1 is much noisy due to the inbuilt noise in the frequency channel while the $\mathrm{sTEC_L}$ obtained in equation 2 is much ambiguous due to some cycle slips and many loss of lock (inability of the receiver to track the signals). The noisy but unambiguous $\mathrm{sTEC_P}$ was used to level the $\mathrm{sTEC_L}$ to arrive at a logical sTEC that is neither noisy nor ambiguous.

However, the slant TEC obtained above at every one-minute interval were converted to vertical TEC (vTEC) using the expression

$$\mathrm{vTEC} = \frac{\mathrm{sTEC}}{S(E)}, \quad (3)$$

where $S(E)$ is the obliquity factor with Zenith angle (Z) at the ionospheric pierce point (IPP), E is the elevation angle of the satellites in degrees and vTEC is the vertical TEC at the IPP (Bolaji et al., 2012). According to Mannucci et al. (1993) and Langley et al. (2002), the S(E) is defined as follows:

$$S(E) = \frac{1}{\cos(Z)} = \left[1 - \frac{R_E \cos^2(E)}{R_E + h_s}\right]^{-1/2}, \quad (4)$$

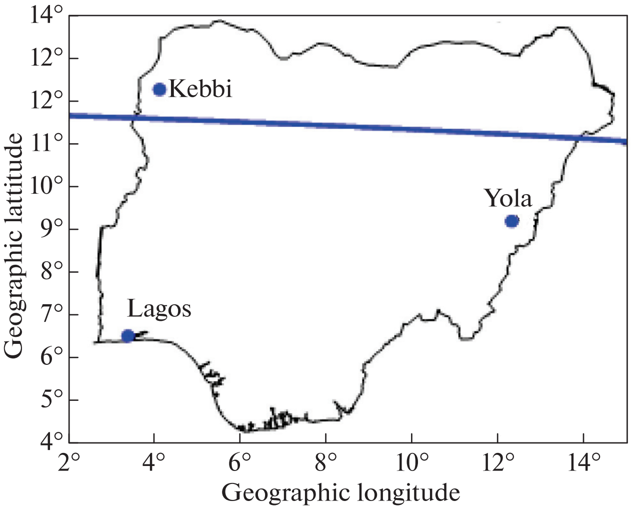

Fig. 1. A map of Nigeria showing magnetic equator (blue line) and the spatial distribution of the TEC observatories.

where R_E is the mean Earth's radius in km and h_s is the height of the ionosphere from the surface of the Earth, which is approximately equal to 350 km (Bolaji et al., 2012).

These analyses, equations (1) to (4) were implemented by using the 2.9.5 version of the GPS-TEC retrieval analysis software to obtain the vertical TEC (vTEC) data. The GPS-TEC program was developed at the Institute for Scientific Research, Boston College, USA (Krishna, 2011). The software and other necessary retrieval information can be obtained from http://seemala.blogspot.com/. Other considerations to ensure the reliability of the data is the elimination of multipath error by excluding sTEC data from all satellites whose elevation angle is lower than 30° and the exclusion of hardware biases. The software also removes hardware biases by processing the satellite and receiver bias files retrieved from Center for Orbit Determination in Europe (CODE) (ftp://ftp.unibe.ch/aiub/CODE/).

In order to quantify the degree of responses of the TEC over the stations to each geomagnetic storm, the mean TEC values for the ten quietest days of the month in which the storm occurred was calculated and used as a background TEC for comparison. Furthermore, the % deviation of TEC (% ΔTEC) was obtained and plotted during each storm as well as a day before and a day after using equation 5.

$$\%\,\Delta\mathrm{TEC} = \left(\frac{\mathrm{TEC}_s - \mathrm{TEC}_Q}{\mathrm{TEC}_Q}\right)\times 100, \tag{5}$$

where % ΔTEC represents the percentage deviation in TEC from its quiet condition, TECs represents the value of TEC for a of day storm while TEC_Q represents the values of TEC on quiet days. From equation 5, positive values of %ΔTEC indicate enhancements while negative values indicate depletions. According to Cander (2016), a geomagnetic storm is considered to produce an ionospheric storm if %ΔTEC exceeds ±25% for more than three consecutive hours.

Also, the transient variation of rate of change of TEC (ROT) and the rate of change of TEC index (ROTI) were estimated using equations 6 and 7.

$$\mathrm{ROT} = \frac{\mathrm{TEC}_k^i - \mathrm{TEC}_{k-1}^i}{t_k - t_{k-1}}, \tag{6}$$

$$\mathrm{ROTI} = \left[\left(\mathrm{ROT}^2\right) - (\mathrm{ROT})^2\right]^{-1/2}, \tag{7}$$

where i is the visible satellite and k is the time of epoch, TEC is the total electron content, ROT is the rate of change of TEC and ROTI is the rate of change of TEC index (five minutes standard deviation of ROT at a sampling interval of 30 s)

3. RESULTS AND ANALYSIS

3.1. The Storm Event of October 25, 2011

Figure 2 shows the comparison between the peak hourly mean values of the average TEC values of the ten quietest days of October and those of October 25, 2011 across all the stations. It is obvious from Fig. 2 that for the quiet condition, themaximum hourly mean values of TEC are 65.72, 52.04 and 50.04 TECU respectively at Kebbi, Yolaand Lagos. On the day of storm, the peak hourly mean TEC values are 79.05, 82.89 and 82.95 TECU for Kebbi, Yola and Lagos, respectively. Therefore, the % enhancement of TEC with respect to the quiet condition's TEC on the day of storm (October 25) across the stations are 20, 59 and 66% respectively at Kebbi, Yolaand Lagos, implying significant positive TEC response to the geomagnetic storm in all the stations.

Figure 3a-e presents the interplanetary parameters and geomagnetic indices of the storm of October 25, 2011. An observation from the Figure reveals an obvious north-ward orientation of the IMF-Bz around 19:00UT on October 24, 2011. This was observed to be simultaneous with the increase in the Dst index from 1 nT to about 20 nT, otherwise known as the storm sudden commencement (SSC); thus flagging the initial phase of the geomagnetic storm. During this period, an increase in solar wind speed from about 330 km/s to about 500 km/s as well as a decrease in the interplanetary electric field (Ey) to a value of about -2.6 mV/m was also recorded. Consequently, an increase in the solar wind plasma temperature from about 86199 K to a peak of 446721 K and the flow pressure increased from about 2.00 nPa to about 14.00 nPa were equally observed during this phase of the geomagnetic storm. The initial phase of the storm occurred around 19:00 UT. The gradual but consistent decrease in the Dst is indicative of the commencement of the main phase of the geomagnetic storm. The Dst decreased gradually to a minimum value of –147 nT around 01.00 UT on 25 October, thus indicates a strong geomagnetic storm. This was consistent with the abrupt north-south orientation of the Bz until it attained a minimum value of –13 nT, which was consistent with the peak value of IEFy (6.63 mV/m). However, the peak values of *Bz* and *Ey* were observed about 2 hours before that of *Dst* index. It is evident that the south-ward turning of *Bz* corresponds well with the increase in the IEFy. The recovery phase started around 2.00 UT after the *Dst* index reached its minimum excursion. A gradual rise in the *Dst*, a gradual decrease in solar wind speed as well as a north-ward turning of the *Bz* characterise this phase of the geomagnetic storm.

Figure 4 depicts the plots of the diurnal TEC profiles (red curve) from October 24 to 26, 2011 (i.e., a day before, the actual day and a day after the storm) along with the temporal variation of the mean TEC values of the ten quietest days of the month of October

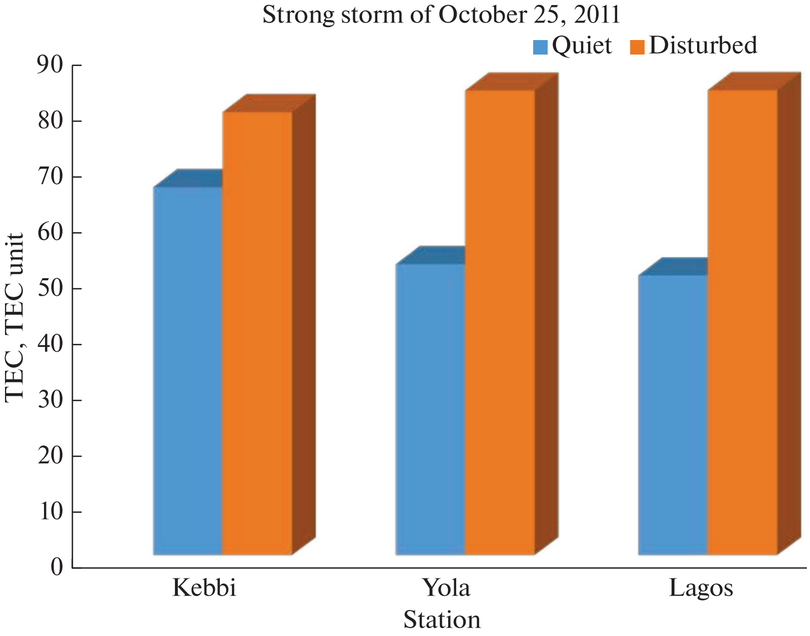

Fig. 2. Peak hourly mean TEC values of the average ten quietest days of October (blue chart) and those of October 25, 2011 (red chart) across all the stations.

2011 (blue curve) at (a) Kebbi, (b) Yola, and (c) Lagos.The magnitude of the error bar indicates the standard deviation of the averaged values of TEC which represent day-to-day variations in TEC. The standard deviation for quiet conditions during the daytime at all stations ranged from 4–23%. According to Schaer et al. (1998), the error of vertical TEC for each Global Ionospheric Map (GIM) is about 10–20%.

Figure 5 on the other hand shows the hourly percentage deviation from the quiet time's variation of TEC at each of the stations respectively for the three days. The Figs. 4 and 5, reveal positive TEC responses to the storm of 25 October in all the stations during both the main and recovery phases. However, the positive responses exhibited during the main phase across all the stations were comparatively higher in magnitude than those exhibited during the recovery phase.

It is clearer from Fig. 5 that during the main phase of the geomagnetic storm, the peak percentage enhancement of TEC and corresponding time of occurrence (in bracket) were 181.87% (2000 UT), 117.06% (04:00 UT) and 181.24% (05:00 UT) at Kebbi, Yolaand Lagos, respectively. Highest (181.87%) and least (117.06%) being recorded at Kebbi and Yola, respectively. On the other hand, during the recovery phase of the storm, peak percentage enhancement of TEC and corresponding time of occurrence (in bracket) were 161.05% (0400 UT), 56.12% (19:00 UT), and 169.24% (04:00 UT) respectively at Kebbi, Yola and Lagos. Highest (169.24%) and least (56.12%) being recorded at Lagos and Yola, respectively.

Figure 6 illustrates the ionospheric irregularities over the stations considered using ROTI for the geomagnetic storm of October 25, 2011. It was observed that the magnitude of the ionospheric irregularities was higher at the night (October 25) of the geomagnetic storm compared with the night (October 24) before the storm occurrence. This showed that magnetic storm affect the usual night-time ionospheric irregularities over the region considered. This result is in agreement with the Aaron's criteria, which states that ionospheric irregularities could be increased or enhanced over low- and equatorial-latitudes when geomagnetic storm occurs after the local sunset to local midnight. This shows that the geomagnetic storm that occurs after sunset does favour the Rayleigh-Taylorinstability (Aaron, 1991).

3.2. Discussion

Observations from the present study have shown that the TEC and its fluctuations over Nigeria, in general, responded positively to the geomagnetic storms of October 25, 2011. Figures 4, 5, revealed enhancements in TEC during the main and recovery phases of the storm.

According to Zhao et al. (2005), at the equator, the disturbance dynamo electric field is eastward at night but westward during the day. Meanwhile, the ambient electric field at ionosphere is eastward during the night but westward during the day. The action of the DDEF produce remarkable effects in the ionosphere of the low-and equatorial latitudes to the extent that the east-

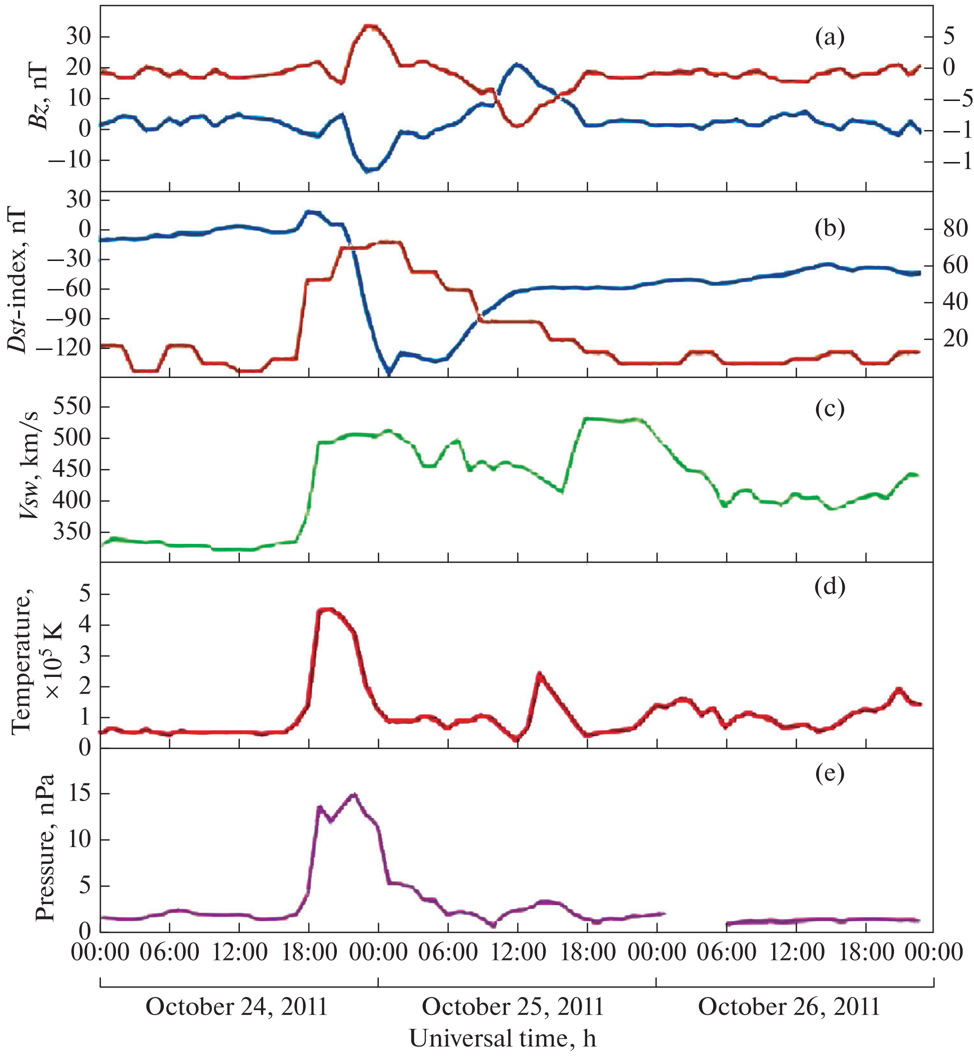

Fig. 3. The interplanetary parameters and indices of the strong geomagnetic storm of 25 October 2011. Panels: (a) IMF-*Bz* (nT) and IEFy, (b) *Dst* (nT) and *Kp* index, (c) Solar wind bulk velocity, *Vp* (km/s), (d) Solar wind temperature (K) and (e) Solar wind dynamic pressure, *P* (nPa).

ward component of the quiet Zonal electric field tends to diminish or even reverse. This results in lower TEC during the day. On the other hand, the direct prompt penetration of solar wind electric fields to equatorial and low-latitudes creates a dawn-dusk electric field in the equatorial ionosphere which is in general, eastward during the daytime and westward in the nighttime, therefore enhancing the daytime eastward dynamo electric field and vertical drifts at equatorial and low latitude ionosphere which lifts the plasma to higher altitudes (Rastogi and Klobuchar, 1990), where the ratio of production to loss is larger. This leads into enhanced electron density in the dayside sector.

The observed overall TEC enhancements during the main phase of the storm considered in this work could then be attributed to enhancements in the electric field, which in turn produces prompt penetration effect (Abdu et al., 1991). This observation is in agreement with some reports in the literatures.For instance, Mannucci et al. (2005) reported low- and equatorial ionospheric positive response to the super storm that occurred during October 29–30, 2003 and attributed the TEC enhancement to the penetration of Interplanetary Electric Field to the low- and equatorial ionosphere. The daytime TEC enhancements observed by Kelley et al. (2003) was explained with the penetration of strong high latitude electric field to the mid and low latitudes. It was observed from Figures 4 and 5 that on the day prior to the onset of geomagnetic storms (October 24), substantial TEC enhancement with respect to the average quiet days' TEC occurred at Kebbi and Yola stations. This significant enhancement in TEC a day before the onset of geomagnetic activity was observed and termed "pre-storm enhancement" by Buresová and Lastovicka (2007). Ratosvky et al., (2020) described pre-storm enhancement as an

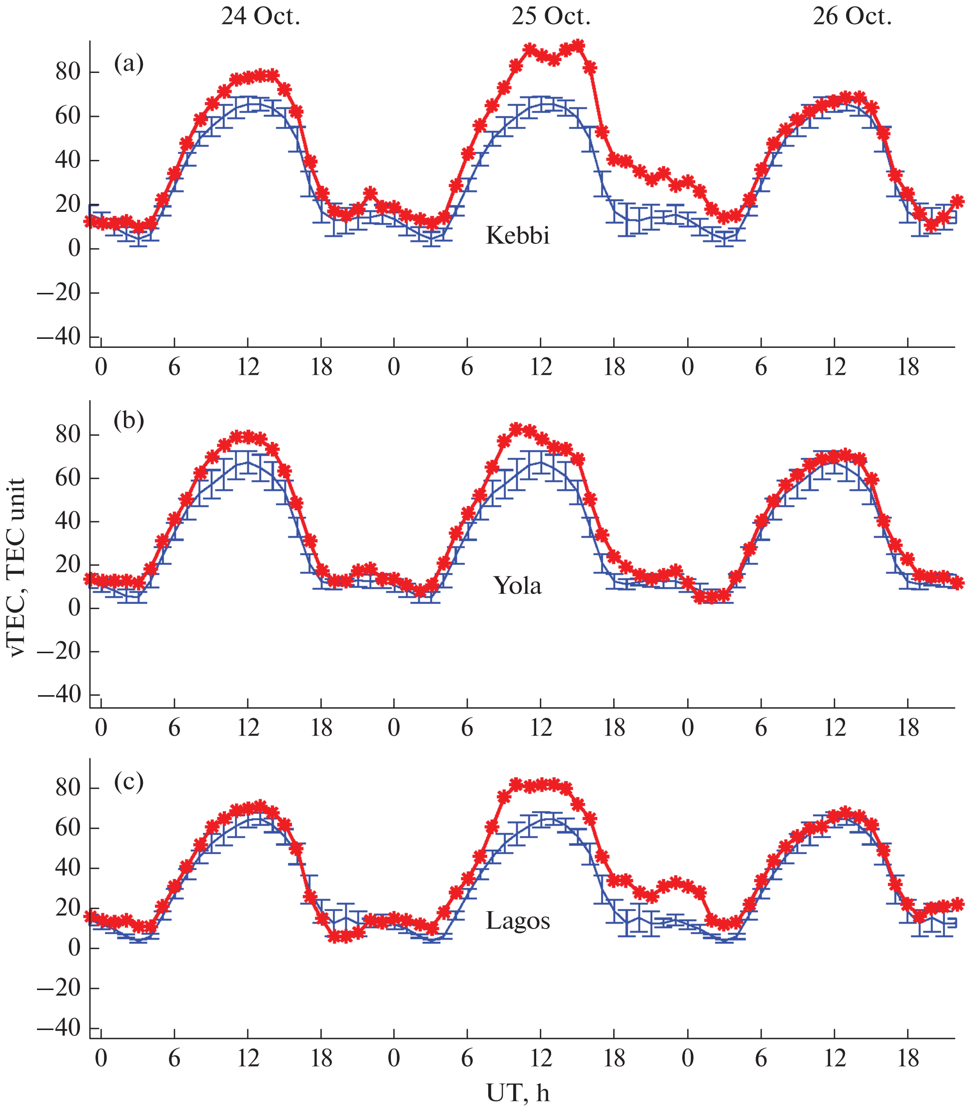

Fig. 4. Variations of the mean TEC of the ten quietest days of October 2011(blue curve) and TEC variations from October 24 to 26, 2011 (days associated with the storm) (red curve).

increase in electron density with manifestation as an increase in the F2-layer critical frequency (fo F2) or TEC during the period prior to the onset of the geomagnetic storm. Liu et al., (2008) suggested vertical plasma drift or zonal electric drift as a possible cause of pre-storm enhancement at low-latitude. The increase in the vertical plasma drift or zonal electric field could be associated with either an aftermath of a previous geomagnetic activity or directly mapping to the equatorial ionosphere from the solar wind electric fields (Ratosvky et al., 2020). Danilov et al. (1985) observed pre-storm enhancements and attributed the events to neutral composition due to variations caused by particle precipitation into the dayside cusp.

Other factors that could be used to explain the observed positive storm effect during geomagnetic storms are the changes in O/N2 ratio (de Jesus et al., 2010; de Abreu et al., 2011) and the storm enhanced wind lifting effects (Lin et al., 2005; Kumar and Singh, 2010). According to Pedatella et al. (2009), the injection of energy into the high latitude may result to equatorward neutral winds which pushes the plasma up the magnetic field lines, resulting in an increase in the F-layer height and consequential to reduction in plasma loss rate and an increase in electron densities towards the equator from the poles. Another relevant physical mechanism engaged in the explanation of TEC enhancement as a result of geomagnetic storm is the ionosphere—plasmasphere exchange of plasma. According to Schunk and Nagy (2000) and Buonsanto (1999), during geomagnetic storms, the outer plasmasphere is convected away due to enhanced magnetospheric electric fields and is refilled by ionospheric upflow. This resultant redistribution of plasma results

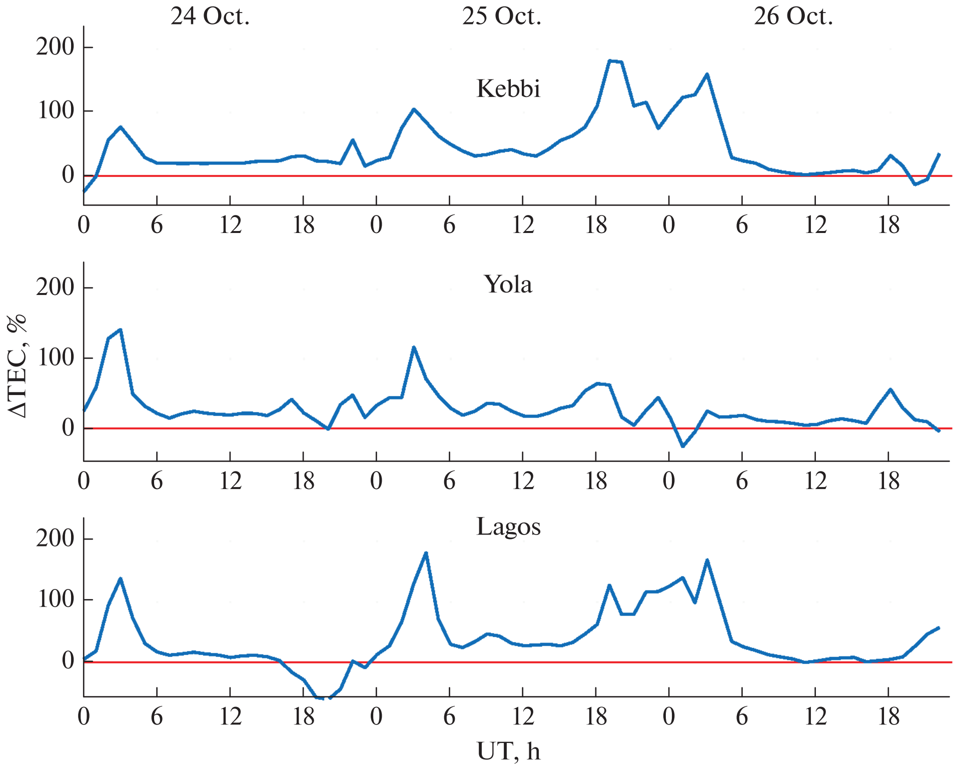

Fig. 5. ΔTEC (storm-time TEC-mean quiet TEC) (%) at (*a*) Kebbi (b) Yola and (c) Lagos from October 24 to 26, 2011.

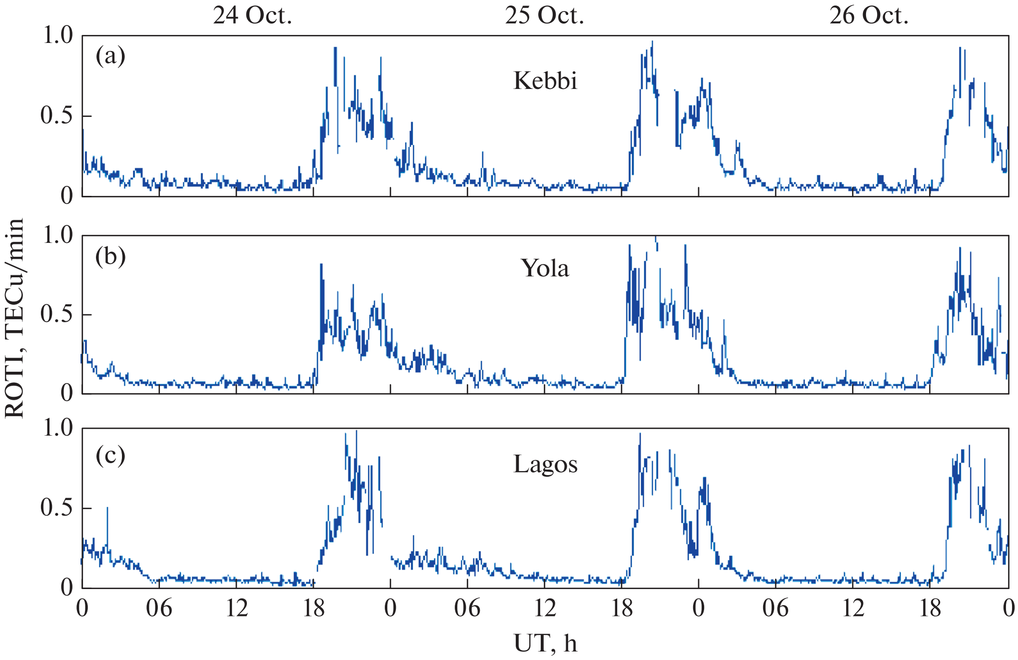

Fig. 6. ROTI at (a) Kebbi, (b) Yola and (c) Lagos from October 24 to 26, 2011.

in a decrease in the rate of loss of electrons resulting in a relative increase in electron densities and TEC in comparison with quiet time condition (Akala et al., 2013b).

4. CONCLUSION

The present work has used the strong stormof October 25, 2011 as a case study to investigate the effect of geomagnetic disturbances on the variation of the ionospheric total electron content (TEC) across three stations in Nigeria, a region within the African sector of the equatorial and low-latitudes. The storm revealed significant TEC enhancement in comparison with the quiet days' condition in all the stations. During the storm of October 25, the enhancements in TEC during the main phase were of higher in magnitudes than those of the recovery phase in all the stations. The results of this work will provide useful data which may assist system operators.

5. ACKNOWLEDGMENTS

The authors are grateful to the Office of the Surveyor General of the Federation, OSGOF, for making the GPS RINEX data used for this research freely available for the public. OSGOF is responsible for operation and maintenance of the Nigerian GNSS reference network NIGNET CORS. Our profound gratitude also goes to Gopi Krishna Seemala and the Institute for Scientific Research, Boston College, Boston, MA, USA, for making the GPS TEC analysis software available. We acknowledge the technical support provided by Stephen Ikubanni and Benjamin Joshua in course of this very work. The anonymous reviewers are greatly appreciated for their positive review that has improved the quality of this manuscript.

FINANCIAL SUPPORT

No grant or any other financial support was received for this research.

CONFLICT OF INTEREST

No conflict of interests

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