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Variation of Vertical Total Electron Content (TEC) Over West Africa during Geomagnetic Storms

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Authors' contributions

All authors contributed significantly to the completion of the manuscript. All authors read and approved the final manuscript.

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ABSTRACT

Changes in vertical total electron content (VTEC) over West Africa which were associated with four geomagnetic storms in 2015 have been studied. The spatial evolution of the quiet time TEC over West Africa for four months (vis; March, June, October and December) which may give rise to unique features of the storm TEC were also evaluated. Quiet-time VTEC (i.e Sq VTEC) was obtained using the hourly means of the international quietest days for each month when a storm of interest occurred. The change in TEC ($\Delta VTEC$) was obtained after removing the quiet time VTEC from the storm day VTEC. A significant latitudinal variation in VTEC was observed at 22:00LT over West Africa and this was accompanied by the usual broad peak at about 14-17UT. The latitudinal disparity observed in the Sq $VTEC$ at 22.00LT was likely driven by the intesification of the fountain effect. The maximum $\Delta VTEC$ observed during the storms in 2015 were of the other of $\pm$16 TECU. These results have important implications for our present understanding of TEC evolution during a geomagnetic and its direct effect on the technologies that depend on it.

Keywords: Total electron content; geomagnetic storm; solar quiet day; Ionosphere.

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1. INTRODUCTION

Total electron content (TEC) is the number of electron in a column of $1m^2$ cross section that extend all the way up from the ground through the ionosphere. It's variation (i.e seasonal, diurnal and other transient form) has significant implication for several technology dependent on it. Many authors [1,2,3,4] have determined TEC using different method. Davies and Hartman [3] did a comparison of ionospheric TEC, they made use of GPS and geostationary(GOES II) satellites data in 1994 and 1995 at Boulder (40°N, 105.2°W), Colorado. They used Faraday rotation of 136 MHz signal from GOES II satellite to obtain TEC and compared that with GPS TEC and found that diurnal variations were in overall agreement. However, the nighttime GPS TEC was higher when compared to TEC obtained using GOES II satellite data. Aghogho et al. [1], studied Observed Total Electron Content (OBS-TEC) and the International Reference Ionosphere (IRI-2016) model at Birnin Kebbi in northern Nigeria during the ascending and maximum phases of solar cycle 24. Their results showed OBS-TEC and the IRI-2016 model rising from a minimum in the early hours of the day to a broad daytime maximum before falling steeply to a minimum after sunset for all years.

The temporal TEC evolution has been studied by many authors [1,2,5,6,7]. Wu et al. [7] studied TEC over Taiwan using 9 observational sites covering the latitudes between 21.9° – 26.2° N and the longitudes between 118.4° – 121.6°E, in the Equatorial Ionization Anomaly (EIA) region from September 1996 to August 1997. They found a major diurnal peak at around 15:00LT and a minor peak around 18:30LT. The seasonal maximum of TEC occurred in spring (April) and autumn (October) and minimum in winter (January) and summer (July). They also found that EIA crest appears earlier in winter than in summer while Gupta and Singh [5] studied TEC at Dehli (28.63°N, 77.2^{o}E), India, for the period of 1975-1980 and 1986-1989 and found a diurnal maxima at 14:00LT and specifically, in winter and equinox, a post sunset secondary maximum around 20:00LT. The diurnal peak in equinoctial months is greater than that in the summer and winter months, on the other hand Kumar and Singh [6] studied the variation of TEC at Varanasi (25.28° N,82.97°E), in Indian EIA, from May 2007 to April 2008, a solar minimum period. They found peak VTEC at around 13.46LT and maximum TEC values during the equinoctial months and minimum TEC during solstice months.

The diurnal variation reveals that the peak of TEC of some months was delayed till after-noon. Post-sunset decrease and enhancement were also observed in the diurnal variation of TEC in some months.

Many authors [8,1,9,10] have studied the spatial variation of TEC. Rama Rao et al. [10] studied Daytime variation of TEC at the equatorial region of India and he showed a minimum of 5 TEC units and maximum of 50 TEC units. In the Indian EIA region the minimum TEC was 5 TEC units and maximum was 90 TEC units. This corresponds to a range delay of 8 m at equator and 15 m in EIA as far as GPS ranging error is concerned. Seasonal variation showed maximum TEC in the equinoctial months (September and October) and in the winter month of November. The latitudinal variation revealed that the daytime maximum value of TEC increases from the equator to the anomaly crest region (Raipur: 21.18°N, 81.62°E and Bhopal: 23.28°N, 77.41°E) and decreases significantly at stations outside the anomaly crest regions (Dehli and Shimla) Das Gupta et al. [9], studied TEC under the GPS Aided Geo Augmented Navigation(GAGAN) project covering a latitude of 8° to 32° N in India and found a sharp latitudinal gradient in diurnal peak TEC with maximum around 13:00 - 15:00LT recorded near Pune (19.1°N, 74.05°E and dip: 24°N).

The aim of this study is to investigate the variation of TEC during geomagnetic storm over the West Africa region. The specific objectives include;

- To determine the quiet time diurnal variation of TEC over West Africa for the different month associated with the occurrence of the 4 geomagnetic storm in 2015.
- To calculate the change in TEC associated with each intense geomagnetic storm in 2015.
- To map the storm time change in TEC across West Africa during the 4 intense geomagnetic storms in 2015.
- To identify the key features of change in TEC associated with the 4 intense geomagnetic storm in 2015.

2. METHODS AND ANALYSIS OF DATA

The data for the TEC maps was obtained in the Iono Sphere Inter Exchange (IONEX) format, the files available at ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex. The TEC values are to an accuracy of 0.1 TECU. The TEC files were courtesy IONEX TEC maps generated by the NASA Jet Propulsion Laboratory (JPL) in conjunction with other global analysis centres. The quietest day's value were obtained from World data centre (WDC) for geomagnetism kyoto Japan. The five international quietest days represent the days in a month with the least geomagnetic measured disturbance during a given month.

GPS satellites operate on two different frequencies *f*1 and *f*2, which are derived from the fundamental frequency (*fo*) of 10.23 MHz: *f*1 = 154*fo* = 1575.42 MHz and *f*2 = 120*fo* = 1227.60 MHz. The observables from GPS satellites at these two frequencies *f*1 and *f*2 usually show a differential bias due to different hardware paths inside the transmitter. According to Wanninger [11], the phases also experience offsets as a result of unknown carrier phase ambiguities and differential equipment phase delays. Satellites are mostly observed along oblique signal paths which pierce the ionosphere at an assumed ionospheric thin shell height. The point of intersection of the ray path with the ionosphere is usually called the ionospheric pierce point (IPP). The IPP corresponds to the height typically associated with the peak electron density in the ionosphere (450 km for this study).The hieght of 450km as IPP has been shown to be adequate for equatorial or near equator regions (see [10]). The TEC along the signal path (slant path) between the receiver and the GPS satellite, commonly referred to as slant TEC (STEC), is defined as

$$STEC \;= \int_{reciever}^{satellite} H_s H_R N \, ds \qquad (2.1)$$

where TEC is measured in TEC Units (TECU) with 1 TECU = 10^{16} electrons per m^2, N is the electron density, H_R and H_s denote the receiver and satellite positions respectively in km and ds is the range from S to R. The line integral is assumed to include all the electrons in a column having a cross-section of 1 m^2 and extending from receiver to satellite. The VTEC is modeled using a mapping function and the geographical position of IPP as follows

$$\text{VTEC} \;=\; \text{STEC x COS (z')} \qquad (2.2)$$

where,

z' is the zenith angle (in degree) at the IPP, the zenith angle can also be expressed as

$$\text{Sin(z')} = \frac{R_E}{R_E + H}\sin(\text{z}) \qquad (2.3)$$

where,

R_E is the radius of the earth (~6400km), H is the estimated single layer model of 450km, z' and z are the zenith angles of the satellite (in degree) at the ionospheric pierce point (IPP) and at the observation site respectively. For a known satellite position, z can be calculated and the approximate coordinates of the IPP can be determined.

The quiet (reference ionosphere) was obtained by using the five international quietest days of each month of interest after earlier work by Okpala and ogbonna [12]. The months in 2015 used in this work are March, June, October and December. Table 1 gives the list of the quietest day of each month as provided by WDC for geomagnetism Kyoto. The average of the those ith hour of those 5 days are obtained from this equation:

$$\text{TEC}_\text{Q} = \frac{1}{5}\sum_{j=1}^{5} C_{ij} \qquad (2.4)$$

where,

C_{ij} is the raw VTEC for a particular hour i (1 to 24), for a given quietest day day j (1 to 5).

The geomagnetic storm is often identified by its signature in the Disturbed storm time index (Dst). In this study to better appreciate the geomagnetic storm evolution, the storm profile included the signature of the Dst a day before the storm main phase onset and a day after the storm main phase onset, because some geomagnetic storms can even last for more than 2 days. The geomagnetic storm profiles for the four storms are presented in Fig. 1. The profile includes the day preceeding the storm and the day after the storm. The TEC for the disturbed days is denoted by TEC_S.

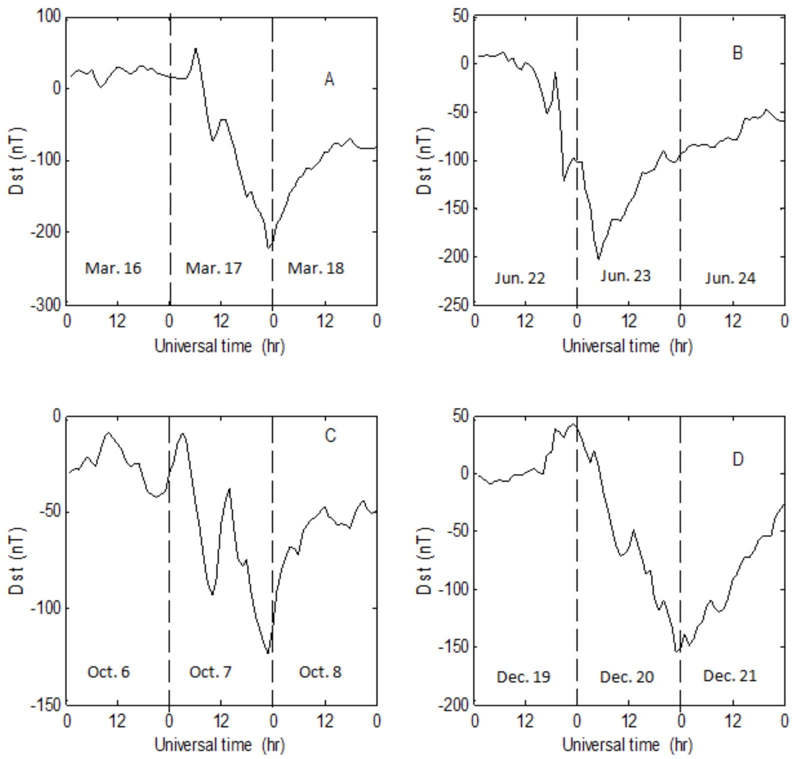

Fig. 1. The disturbance storm time (Dst) index signatures for (A)-March (16-18), (B)-June (22-24), (C)- October (6-8) and D-December (19-21), 2015. The vertical dashed line indicate the beginning of a new day

Table 1. Five international quietest days of the months of interest in 2015

Month	Days
MARCH	10,30,5,14,9.
JUNE	20,5,2,4,3.
OCTOBER	26,28,27,19,29.
DECEMBER	30,3,4,28,18

2.1 TEC Variation

The TEC variation which is generally denoted as change in the TEC (or ΔTEC) is obtained by subtracting the quiet or reference ionosphere for the month from the disturbed ionosphere given in equation 2.5

$$\Delta TEC = TEC_S - TEC_Q \quad (2.5)$$

The root mean square error of the TEC_Q for the entire gridded data was calculated using equation 2.6

$$RMSE = \sqrt{\sum_{i=1}^{5} \frac{(\hat{y}_i - y_i)^2}{n}} \quad (2.6)$$

where,

y_i are the weighted means of the five international quietest days and $\hat{y}_i$ are the values for the individual days.

3. RESULTS AND DISCUSSION

3.1 Event 1 (March 16-18, 2015)

Event 1 is the storm of March 16 to 18 2015.The disturbed storm time (Dst) index signature for the storm is presented in Fig. 1A As evident from Fig. 1A, this storm is an intense storm, it showed a sudden storm commencement (SSC) at about 06UT, the storm peaked at about 23UT with a minimum Dst of -222nT. The solarquiet (Sq) day diurnal variation for March 2015 is presented in Fig. 2A. It shows a typical signature for 0° longitude and latitude 10°,15 and 20°. The profile shows a peak Sq VTEC value of $80.0 \pm 2.4TECU$ between 15 UT – 17 UT (generally 2 to 4 hours after local noon). Similar observation of VTEC peak had been recorded by earlier researchers (e.g [8,1,7]. In addition, the local night time enhancement of VTEC was observed in all the stations. This night time enhancement of VTEC was observed by Su et al. [13], using ground based data. It is evident that there is more significant variation in VTEC at night than during the day time peak. The strength of the night time enhancement was observed to strongest at the peak of the expected region of the fountain effect which results from evening $E \times B$ drift, but may also be associated with the effect of the neutral wind on the plasma distribution [13]. The peak of the night time Sq enhancement was observed (with highest latitudinal disparity) around 22UT local time.

The difference between the storm day VTEC and Sq VTEC (ΔTEC) was computed using equation (3.5). The computation was done bin wise and it represents the change in VTEC associated with the geomagnetic storm of 16 -18 March and are presented in Fig. 3 for hour 00 UT, 06UT, 12UT, 18 UT, 21 UT. During the main phase of the geomagnetic storm (06 UT to 23 UT), there was a general reduction in the VTEC value, this was particularly noted for hour 12 UT to 21 UT. In general the reduction was intense in the western sector of the region with VTEC of 12TECU. However the equatorial ionization anomaly (EIA) crest did not receive equivalent enhancement as shown in Fig. 3D and Fig. 3E during the peak of the storm. In addition, the extent of the western sector peak was pushed beyond the boundary of the map during the storm. Hence it is possible that the night time neutral wind moved the plasma beyond the shore of West Africa towards the Atlantic Ocean. At the storm time there was equatorward reduction and poleward enhancement in VTEC.

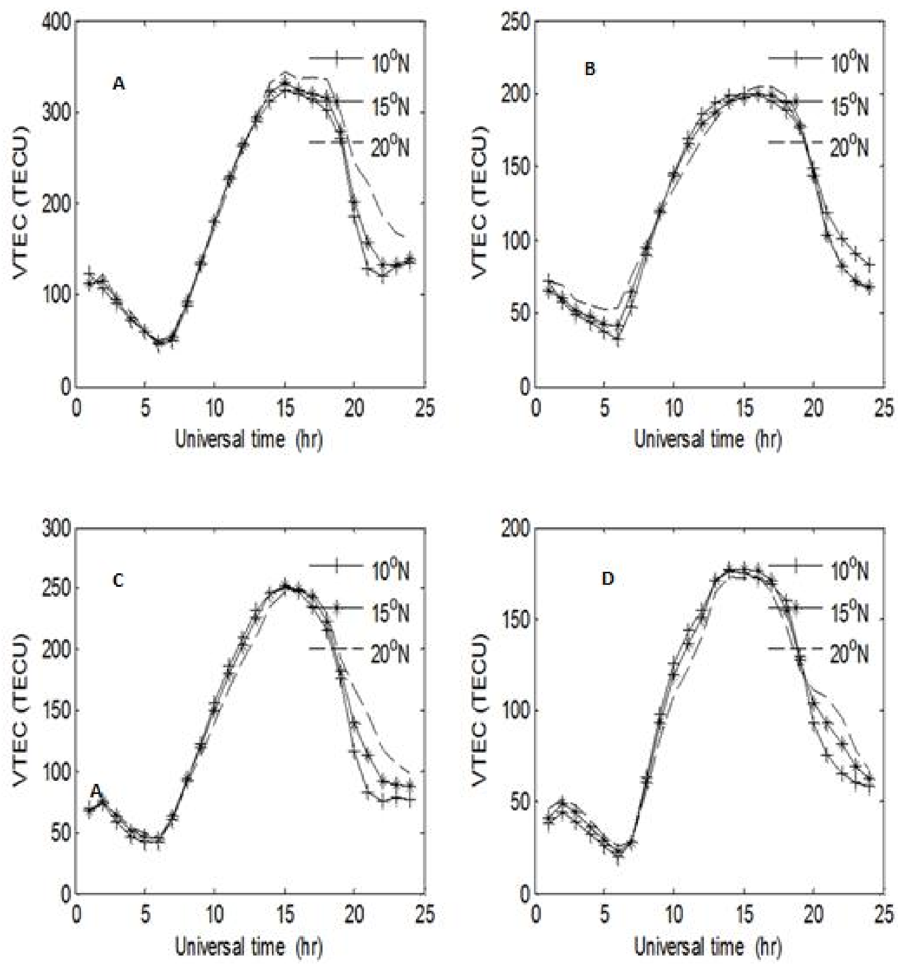

Fig. 2. The Sq diurnal VTEC variation at longitude 0° latitude showing latitudinal (10°,15°,20°) variation for A-March, B- June, C- October and D- December 2015

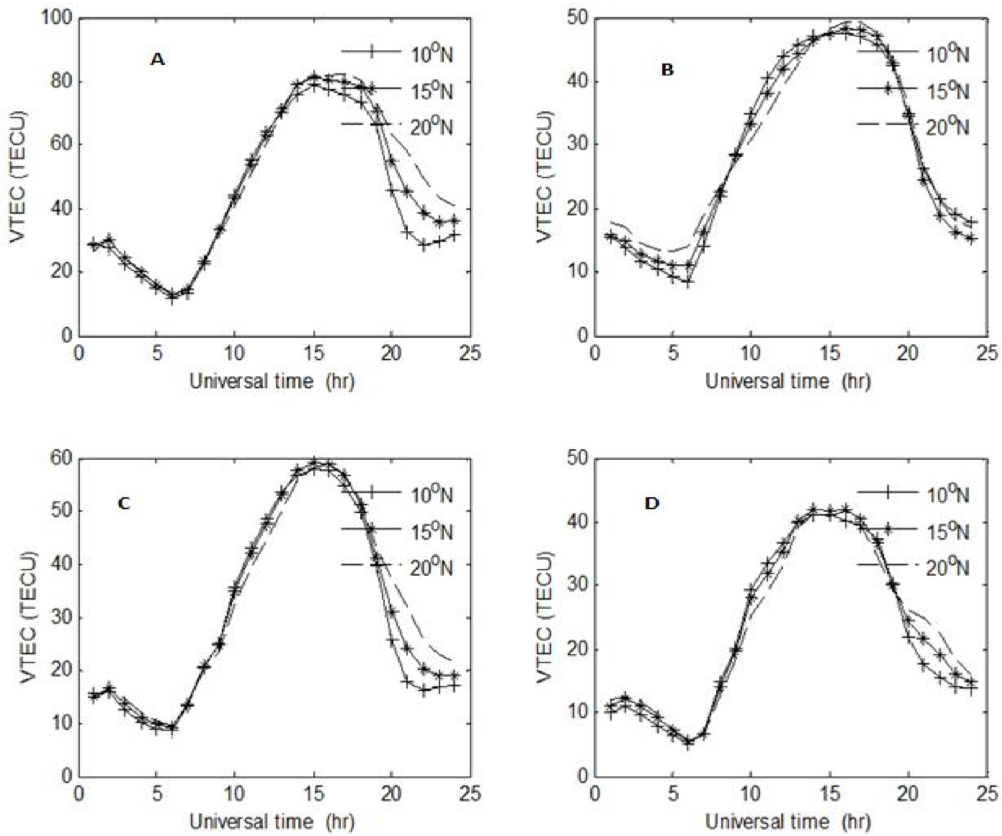

Fig. 3. The Sq diurnal VTEC variation at longitude 0° latitude showing latitudinal (10°,15°,20°) variation for A-March, B- June , C- October and D- December 2015

3.2 Event 2 (JUNE 22 -24 2015)

The storm of June 22-24, 2015 is the second event of interest. Event 2 is the storm of June 22 to 24 2015. The disturb storm time (Dst) index for the storm signature is presented in Fig. 1B, This storm did not show any SSC, the storm peaked at about 05UT with a minimum Dst of -204 nT. The Sq diurnal variation of June 2015 is presented in Fig. 2B. It shows a typical signature for 0°longitude and latitude 10°,15°,20°. A peak TEC_Q value of 50.0 ± 2.1 TECU was observed between 15UT - 17UT (again generally 2 to 4 hours after local noon), similar observation of VTEC peak has been recorded by earlier researchers like Das Gupta et al. [9] and Aghogho et al. [1]. In addition, the local night time enhancement of VTEC was observed in all the stations. A similar night time enhancement of TEC_Q had been reported by Adewale et al. [14]; using ground based data. It is evident that there is more significant night time variation in VTEC than during the day time peak.

ΔVTEC between the storm day 23 June and the quiet condition was computed using equation 3.5. The computation was done bin wise and it represents the change in VTEC associated with the geomagnetic storm of June 22-24, 2015 and is presented in Fig. 4. During the main phase of the geomagnetic storm (i.e 00 UT to 18 UT, of June 23), there was a general reduction in the VTEC value, this was particularly noted for hour 18UT because it recorded the highest reduction in VTEC. In general the reduction was stronger in the eastern sector of the map with ΔVTEC of -9 TECU but there was a little enhancement in VTEC at hour 12UT in Fig. (3C) but the enhancement is of 1TECU which is negligible when compared with the reduction of -9TECU of hour 18 UT in Fig. 3D. At the storm time there was equatorward reduction and poleward enhancement in VTEC.

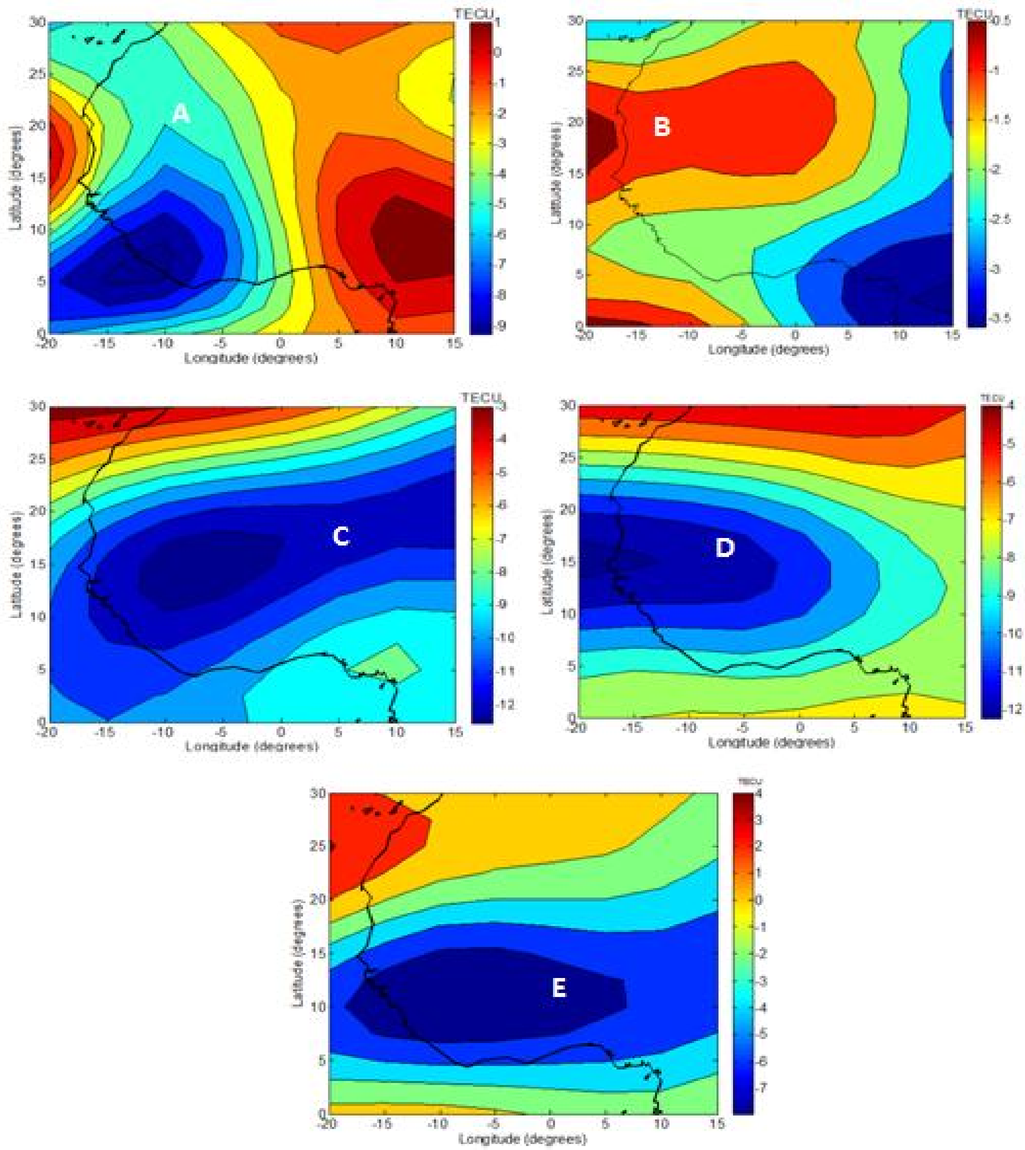

Fig. 4. $\Delta VTEC$ Map for March 17, 2015. A, B, C, D and E represents condition during 00 UT, 06 UT, 12 UT, 18 UT and 21 UT respectively

3.3 Event 3 (OCTOBER 6 -8 2015)

Fig. 1C is the time series profile of the Dst index for event 3, which is the storm of October 6 - 8 2015 The geomagnetic storm sigature shows two peaks. The first peak was -90nT and recovered to -40nT before the second peak at about 23UT with a minimum Dst of -124 nT. The Sq diurnal variation for October 2015 is presented in Fig. 2C. It shows a typical signature for three bins centered on 0° longitude and latitude 10, 15°and 20°. It shows a peak Sq VTEC value of 46 TECU between 15UT - 17UT (generally 2 to 4 hours after local noon, similar observation of VTEC peak has been recorded by earlier researchers like Galav et al. [15]. Event 3 followed the similar trend in the night time TECQ observed in events 1 and 2 with marked difference in the value at about 22 LT. Such large difference across latitudes is an indication of northward drift of plasma.

The ΔTEC between the storm day and Sq day across the region is shown in Fig. 5 for 00 UT, 06 UT, 12 UT, 18 UT and 21 UT. During the main phase of the geomagnetic storm (06 UT to 21

UT), there was a general reduction in the VTEC value, this was particularly observed in Fig. 5C-5E for hour 12 UT, 18 UT and 21 UT respectively. The reduction was up to 16 TEC at 18 and 21 UT. ΔTEC values for this storm was the strongest while the geomagnetic storm was not the strongest among the storms considered. Hence the storm strenght and the associated electrodynamic changes do not drive the changes in the ΔTE. Such changes in the TEC during geomagnetic storm may be associated with the seasonal factors. However it is beyond the scope of the present study.

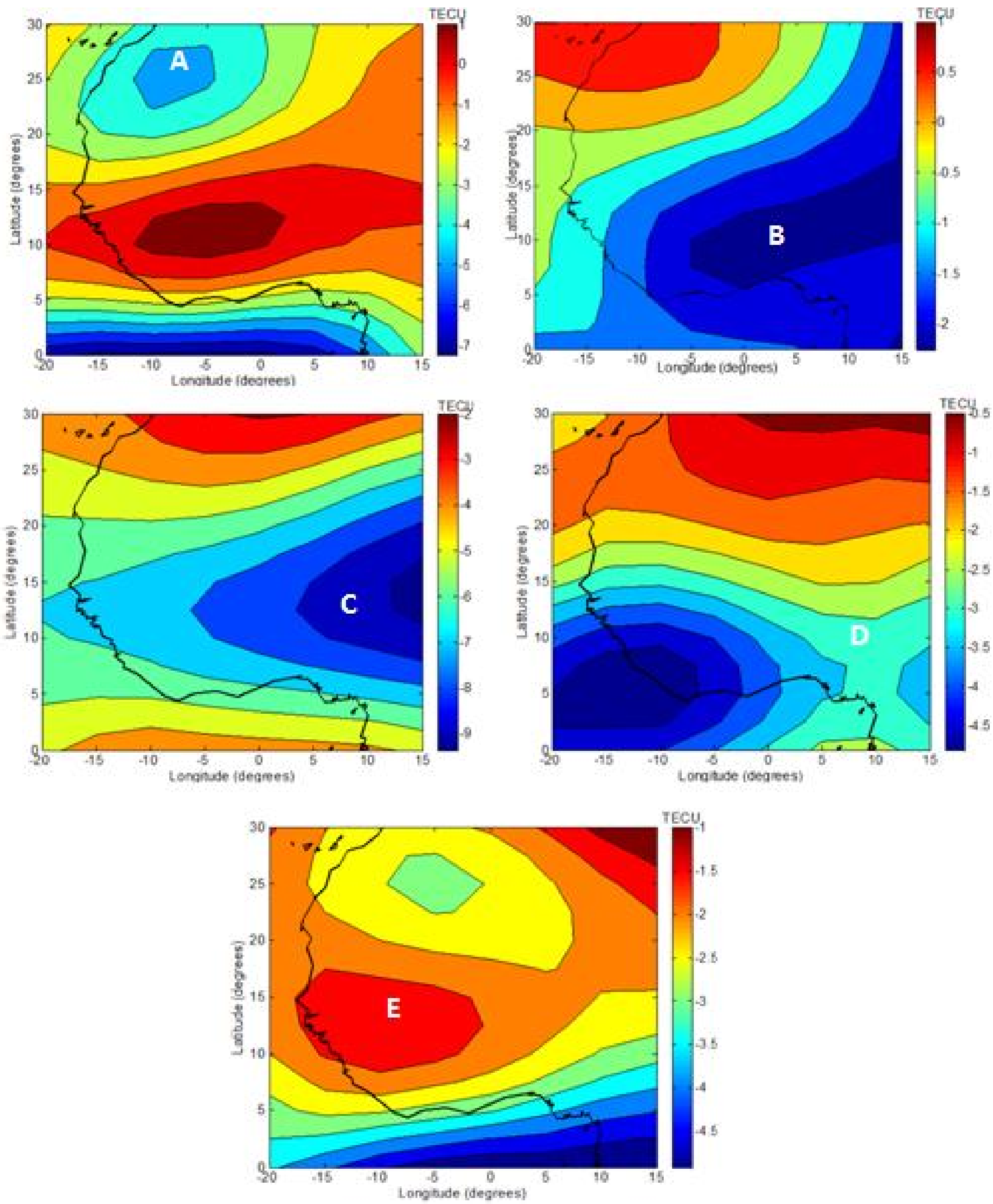

Fig. 5. $\Delta VTEC$ Map for June 23, 2015. A, B, C, D and E represents condition during 00 UT, 06 UT, 12 UT, 18 UT and 21 UT respectively

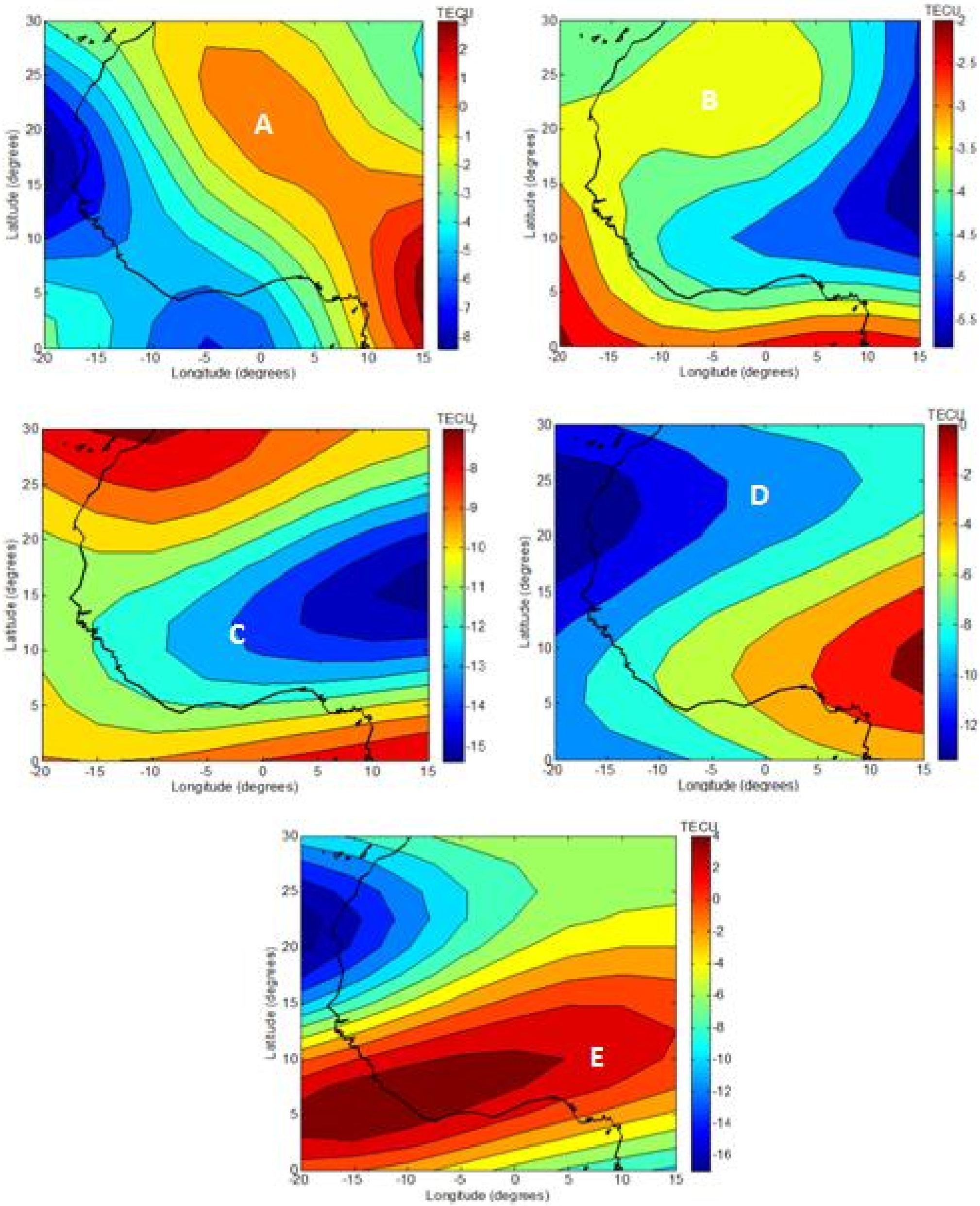

Fig. 6. $\Delta VTEC$ Map for October 7, 2015. A, B, C, D and E represents condition during 00 UT, 06 UT, 12 UT, 18 UT and 21 UT respectively

3.4 Event 4 (DECEMBER 19 -21 2015)

The Dst profile for event 4 is shown in Fig. 1D. It consists of three days as discussed in section 3. The main phase of the storm occurred on 20th of December, 2015. The storm was associated with a sudden storm commencement and peaked at 23 UT with a minimum Dst of -155 nT. The TEC solar quiet (Sq) day diurnal variation for December 2015 is presented in Fig. 2D. It shows a typical signature for 0°longitude and latitude 10°, 15° and 20°. Again, Fig. 2D shows a peak TECQ of 180TECU at a similar time with the earlier events (i.e 2-4 hour after local noon). The accompanying night time enhancement was also visible. The latitudinally dependent features of this diurnal variation is evident in the evening/night period around 22LT. Again the difference between the nor then most latitude (20°N) and the 10°N station is about 40 TEC at this period. Such large disparity in the TEC_Q values across the latitudes was not observed in earlier hours of the day. In comparison, the latitudenal dependent features of the TEC_Q variation of this month (December) is similar to those of the months of March and October (equinocial months), but quite difference from the diurnal variation observed for June. Therefore, this feature may be related to seasonal effects on the TEC over West Africa and requires further investigation.

The $\Delta VTEC$ map for event 4 is shown in Fig. 6. Fig. 6 shows five snap shots of $\Delta VTEC$ at 00 UT, 06 UT, 12 UT, 18 UT and 21 UT and it reflects how TEC changed in the region at those times. It is evident that the largest enhancement in TEC occurred during this event. Also unlike the large negative changes in TEC observed in the storms of equinocial months (event 1 and 3), this event was characterized by positive changes or enhancemens) throughout the day of the storm. The centre of the peak enhancement constantly changed in response to other dynamical processes that governed the Sq variation such as the nuetral wind effect on the plasma distribution during the day.

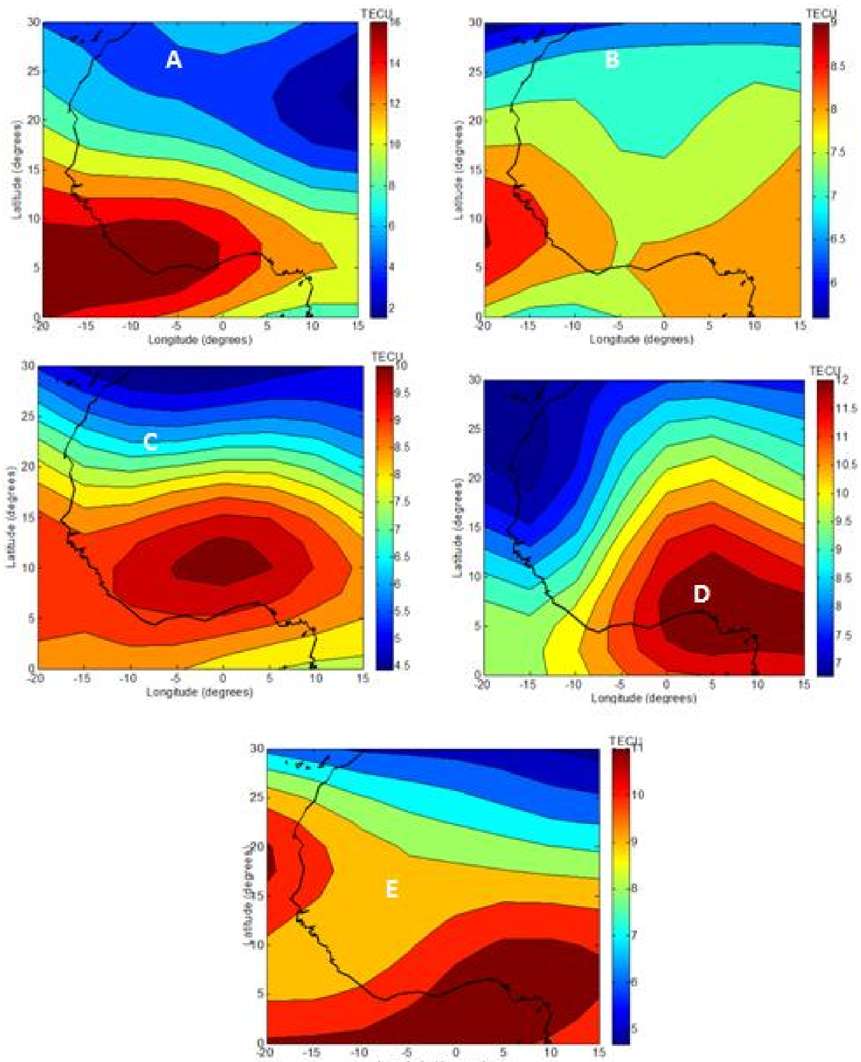

Fig. 7. $\Delta VTEC$ Map for December 20, 2015. A, B, C, D and E represents condition during 00 UT, 06 UT, 12 UT, 18 UT and 21 UT respectively

4. CONCLUSION

The changes in VTEC associated with the four intense geomagnetic storm in 2015 have been studied. These storms were studied for unique features of its spatial variation across West Africa. To achieve this, quiet-time baseline was obtained from the five (5) international quietest days for all the months during which the storms occurred. The VTEC during individual storms was obtained after removing the baseline conditions. From the analysis and discussions, the following conclusions were reached;

- The diurnal variation of quiet time (Sq) VTEC over West Africa is local time dependent. It shows a crest at about 06LT - 07LT and a broader peak at about 14 to 17LT. This profile is accompanied by a very significant latitudinal variation in VTEC during 22LT.
- The intensification of the fountain effect is the most probable mechanism for the wide disparity in the Sq VTEC values at 22LT across West Africa.
- The ΔVTEC associated with geomagnetic storm tend to vary from storm to storm and on the time of occurrence within the year. There are no disenable seasonal trend in the ΔVTEC during the evolution of geomagnetic storms.
- The change in vertical electron content (ΔVTEC) observed during geomagnetic storm of 2015 are generally of the range -16 TECU≤ ΔVTEC ≤ 16TECU in West Africa.

AVAILABILITY OF DATA AND MATERIAL

TEC data used is freely available at ftp://cddis.gsfc.nasa.gov/pub/gps/products/ionex, while the disturbance storm time index and the quietest days data are courtesy of the World Data Centre for Geomagnetism, Kyoto Japan and available at http://wdc.kugi.kyoto-u.ac.jp/

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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