GEOMAGNETIC STORM VARIATION OF VERTICAL TOTAL ELECTRON CONTENT (VTEC) OVER SOME EURO-AFRICAN STATIONS

Abstract

Geomagnetic storms are events which have physical effects on some ionospheric parameters that, to some extent,affects the state and dynamics of the ionosphere with important implications on GNSS applications. Here, the total electron content (TEC) of Brussels (50.80^{o}N, 04.37^{o}E), Madrid (40.43^{o}N, 04.25^{o}W) and Irkutsk (52.22^{o}N, 104.32^{o}E), which are all mid-latitude European stations are compared with Libreville (00.35^{o}N, 09.67^{o}E) and Lusaka (15.43^{o}S, 28.32^{o}E) which are equatorial and low-latitude stations respectively. This study is done over two geomagnetic storms that took place in the solstice period of 2004. Deviations of storm time VTEC from solar quiet (Sq) averages are calculated, analysed and presented. Similarities and differences of storm effects are observed in the European stations with enhancements and depressions. Diurnal solar quiet day variations showed high VTEC during the post-noon hours for all the stations. The VTEC deviations during storm time at Libreville lie within $-21\, TECU \leq \Delta VTEC \leq 25 TECU$, for Lusaka it is $-20\, TECU \leq \Delta VTEC \leq 40 TECU$. For the mid-latitude European stations, the deviations are lower such that $-5\, TECU \leq \Delta VTEC \leq 10 TECU$ is recorded at Brussels while $-5\, TECU \leq \Delta VTEC \leq 20 TECU$ is recorded for both Irkutsk and Madrid. Enhancement of VTEC during the daytime storm period is attributable to the super-fountain effect caused by the prompt penetration electric fields (PPEFs) into the ionosphere and magnetosphere while low VTEC at night-time is attributed to the process of recombination. Understanding the behaviour of the ionosphere during geomagnetic storms is important and necessary for a better understanding of the applications of GNSS.

Keywords: Total electron content, geomagnetic storm, prompt penetration electric fields, recombination.

1. Introduction

Total electron content (TEC) is the number of electrons contained in a 1m^2 cross-section.. Photo-ionization of neutral species in the atmosphere by extremely energetic cosmic radiations represents the major source of the production of electrons in the ionosphere. TEC varies in many different ways. These variations may be temporal such that it could be diurnal, annual, seasonal or even in terms of solar cycles. The variations could be spatial such that the total electron content of the ionosphere in the equatorial region is different from the low-latitude regions, mid-latitude regions and high-latitude regions. However, TEC is expected to have a different variation during geomagnetic events such as geomagnetic storms. Geomagnetic storms are fluctuations which arise as a result of the transfer of solar energy into the magnetosphere following magnetic reconnection between the southward IMF (B_z) component and the antiparallel geomagnetic field at the magnetopause (Dungey 1961; Gonzalez *et al*.,1994; in Okpala and Ogbonna, 2018). During a geomagnetic storm, the solar wind energy deposited into the magnetosphere polar cap region will be dissipated into the ionosphere and thermosphere thereby ensuring many transport processes of matter and energy to become extreme and complicated (Buonsanto and Fuller-Rowell, 1997 in Malik *et al.*, 2010). Therefore, it is important that VTEC variations during geomagnetic storms be studied.

Some scholars (Bagiya *et al.,* 2008; Chakraborty and Hajra, 2010; Malik *et al.,* 2010; Azzouzi, 2015; Edward *et al.*,2019;Okpala*et al.*, 2020) have investigated the variations of VTEC during intense storms (-100nT >Dst> -250nT) and super storms (-250nT >Dst≥ -400nT). For instance, Okpala *et al.* (2020)reached the conclusions that the diurnal variation of quiet time VTEC is local time dependent, with minima occurring during dawn at about 06LT – 07LT and broader maxima occurring at about 14LT – 17LT. This agrees with the work ofUgonabo*et al.* (2020) on the seasonal variability of VTEC in West African StatesofYamoussoukro, Cote d'Ivoire (6.87^{o}N, 354.46^{o}E) and Dakar, Senegal (14.72^{o}N, 342.32^{o} E) from 2016 to 2018, where the diurnal VTEC was always minimum during the dawn hours of the day and maximum in the afternoon hours. Furthermore, Okpala *et al.* (2020) calculated the change in VTEC during the geomagnetic storms of 2015 considered to be generally in the range $-16TECU \leq \Delta VTEC \leq 16TECU$ in West Africa.

The aim of this study is to investigate the variation of TEC during geomagnetic storms in the European region. The specific objectives include to:

- determine the quiet time diurnal variation of TEC over Europe using three (3) stations for the different month associated with the occurrence of two geomagnetic storms in 2004,
- calculate the change in TEC associated with two (2) geomagnetic storms in 2004,
- identify the key features of the profiles showing the change in TEC associated with the (two) 2 geomagnetic storms in 2004 and
- compare the effects of the storms in Europe with two off-stations – an equatorial West African station and the other, a low-latitude South African station.

2. **Methods and analysis of data**

The day to day TEC data for each of the stations used for this study were obtained in Receiver Independent Exchange (RINEX) file format from the online database *ftp://cddis.gsfc.nasa.gov/gps/data/daily*. The Differential Code Biases (DCB) files were obtained from the online database*ftp://ftp.aiub.unibe.ch/CODE/*in the Z-file format. The list of international quietest day's values was obtained from World Data Centre (WDC) for geomagnetism, Kyoto, Japan, (https://omniweb.gsfc.nasa.gov/). The five international quietest days represent the days in a month with the least geomagnetic measured disturbance during a given month.

GPS operates on two different frequencies, that is f_1 and f_2 which are derived from the GPS fundamental frequency, f_0 .

$$f_0 = 10.23MHz$$

$$f_1 = 154f_0 = 154 \times 10.23 = 1575.42MHz$$

$$f_2 = 120 f_0 = 120 \times 10.23 = 1227.60 MHz$$

A dual frequency GPS receiver can measure the difference in ionospheric delays between the L_1 and L_2 of the GPS frequencies which are generally assumed to travel along the same path through the ionosphere. The group delay is given as:

$$P_2 - P_1 = 40.3 \times (TEC) \times \left\{\frac{1}{f_2{}^2} - \frac{1}{f_1{}^2}\right\} \qquad (2.1)$$

where P_1 and P_2 are the group path lengths corresponding to the high GPS frequency ($f_1 = 1575.42 MHz$) and the low GPS frequency ($f_2 = 1227.60 MHz$) respectively. Therefore, the TEC is given by:

$$TEC = \frac{1}{40.3} \times \left\{\frac{f_1{}^2 f_2{}^2}{f_1{}^2 - f_2{}^2}\right\} \times (P_2 - P_1) \qquad (2.2)$$

Slant TEC is a measure of the total electron content of the ionosphere along the ray path from satellite to receiver. Although STEC is measured at different elevation angles, usually the VTEC is modeled (Norsuzila *et al.*, 2010). The single layer model is based on the assumption that the ionosphere is concentrated into a thin shell (Mehmood *et al.*, 2019) at about 350km - 450km (Norsuzila *et al.*, 2010). In this model, TEC measurements are taken from different GPS satellite observed at arbitrary elevation angles. This causes the GPS signals to cross largely different portion of the ionosphere. The electron currents for paths with different elevation angles are transformed into equivalent vertical total electron content (VTEC) for efficient comparison. This is done by dividing the STEC by the secant of the elevation angle at a mean ionospheric height, which is usually taking to be about 350-450km above the earth surface. The relation between STEC and VTEC at any sub-ionospheric point is:

$$VTEC = STEC\ (\cos X')\qquad (2.3)$$

where X' is the difference between 90^{o} and the zenith angle (X), that is $X' = 90 - X$

This process is also called the elevation-dependent single layer (or thin shell) model mapping function (SLM) (Norsuzila *et al.*, 2010). The function is expressed as:

$$F(\chi) = \frac{TEC(\chi)}{TEC(0)} = \frac{1}{\cos\chi'} = \frac{1}{\sin\beta'} = \frac{1}{\sqrt{1-\sin^2\chi'}}\qquad (2.4)$$

And $in\chi' = \frac{R_e}{R_e+h_m}\ sin\chi$, where R_e is the mean earth radius and h_m is the height at the maximum electron density.

$$VTEC = STEC\ \times \sqrt{1 - \left(\frac{R_e}{R_e+h_m}\ sin\chi\right)^2}\qquad (2.5)$$

The months in 2004 used in this work are July and December. The list of the quietest days of each month as provided by WDC for geomagnetism Kyoto is shown on Table1. This minute by minute data was converted to the equivalent hourly data format. The average of the i^{th} hour of those 5 days for each month is obtained from the equation:

$$TEC_Q = \frac{1}{5}\sum_{j=1}^{5} D_{ij}\ \ldots\ldots\qquad (2.6)$$

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

Table 1: Five international quietest days of the months of interest in 2004

Months	**Days**
July	6^{th}, 7^{th}, 8^{th}, 9^{th} and 21^{st}
November	2^{nd}, 5^{th}, 6^{th} ,15^{th} and 18^{th}

For months that do not have a complete data set for the quiet days, the average was calculated over the number of days available for that station in that particular month.

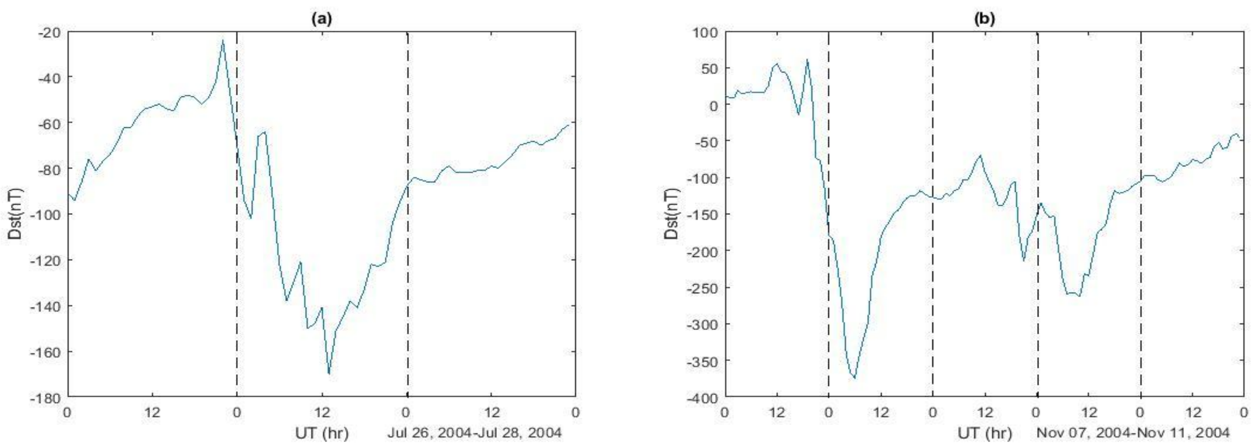

Fig. 1: The disturbance storm time (Dst) index signatures for (a)-July (26-28), (b)-November(07-11), 2004. The vertical dashed line indicates the beginning of a new day.

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 2.7.

$$\Delta VTEC = TEC_S - TEC_Q \qquad (2.7)$$

Table 2:The stations considered and their corresponding geographic coordinates

STATIONS	LATITUDE	LONGITUDE	TIME ZONE
Brussels, Belgium	50.80^{o}N	04.37^{o}E	UTC+2 (July), UTC+1 (Nov)
Madrid, Spain	40.43^{o}N	04.25^{o}W	UTC+2 (July), UTC+1 (Nov)
Irkutsk, Russia	52.22^{o}N	104.32^{o}E	UTC + 08
Libreville, Gabon	00.35^{o}N	09.67^{o}E	UTC + 01
Lusaka, Zambia	15.43^{o}S	28.32^{o}E	UTC + 02

3. Results and Discussion

Geomagnetic storms are often identified and classified using the disturbed storm time index (Dst) which is a quantitative measure of the ring current forming around the earth during a geomagnetic storm. 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. The geomagnetic storm profiles for the two storms are presented in Fig. 1. The profile includes the day preceding the storm and the day after the storm. The TEC for the disturbed days is denoted by TEC_S.

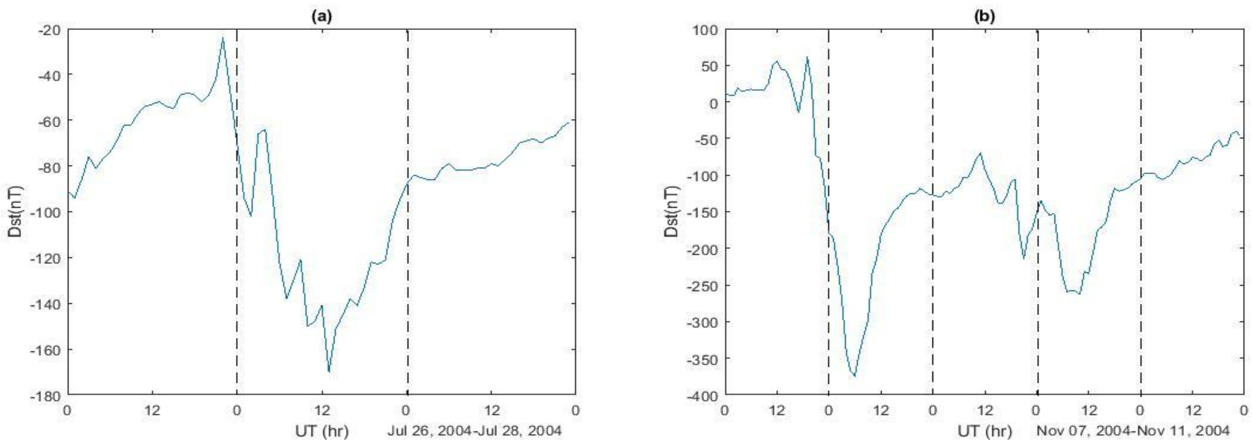

Fig. 2: The disturbance storm time (Dst) index signatures for (a)-July (26-28), (b)-November(07-11), 2004. The vertical dashed line indicates the beginning of a new day.

Event 1 (July 26-28, 2004)

Although Dst levels as shown on Fig. 2(a) were well low throughout July 26 (day before the storm), there was a notable surge which occurred at about 01UT – 02UT where the Disturbance storm time index dropped to -102nT. However, this surge doesn't last for long but was rather temporary as recovery occurs immediately. The main phase of the storm commences proper at about 06UT on the 27th July lasting for about 16 hours. The peak of the storm effect occurred at about 13UT with a minimum Dst value of -170nT. The recovery phase occurred gradually with Dst values becoming moderate throughout the next day, 28th July.

The solar quiet (Sq) days' diurnal variation of VTEC for the month of July together with the storm days diurnal variation of VTEC for all the stations is shown on Fig. 3. The Solar quiet days average for Libreville is observed to be at its lowest levels (1TECu – 4TECu) during night-time between 00UT – 04UT. The values rise steeply from dawn (around 05UT) and reaches its maximum of about 37TECu in the past noon hours. As sunset approaches, the TEC values drop steeply also. This drop may be as a result of reduction in photo-ionization (Ugonabo*et al.*, 2021).

In general, the deviation of the VTEC for the periods just before and after the main phase of the storm from the Sq values lies in the range $0\,TECU \leq \Delta VTEC \leq 20TECU$. However, during the main phase of the storm, an enhancement in VTEC is observed which leads to an increase in $\Delta VTEC$reaching 24TECU. This is presented on Fig. 4. The Sq time TEC values at Lusaka shows a diurnal variation which is much similar to the patterns of Libreville as could be seen on Fig. 3. There is a slow rise in VTEC valuesfrom the minimum values in the early hours of the day. The VTEC values are highest around 12UT which corresponds to post noon period in Lusaka (about 2pm in Local time). However, the VTEC values in Lusaka are relatively low as compared to that at Libreville. From Fig. 4, it is observed that the storm time VTEC deviationfrom the Sq average for Lusaka lies between $-5TECU \leq \Delta VTEC \leq 20TECU$for the days before and after the storm. At around 06UT, when the storm commenced, there was an enhancement in VTEC. This enhancement is evident in the fact that $\Delta VTEC$ of nearly 40TECU is recorded during the main phase of the storm, implying that $\Delta VTEC$ is nearly doubled by the effect of the storm at Lusaka.For the mid-latitude European stations, the Sq diurnal variation is quite different. In Brussels, the Sq diurnal VTEC shows that the minimum is recorded around 02UT. Furthermore, VTEC reaches distinct maximum twice at around 09UT and 18UT respectively, with a slight depression occurring at around 13UT. Hence, the profile for Brussels depicts semi-diurnal variation although the VTEC values are so low that they lie below 10TECu. As displayed on Fig. 4, the deviation from Sq VTEC average by the VTEC values obtained during storm hours lies within the range $-2\,TECU \leq \Delta VTEC \leq 5TECU$ for the days preceding and succeeding the main phase period. During the main phase, this range is widened a little to $-5\,TECU \leq \Delta VTEC \leq 5TECU$.For Irkutsk, the solar quiet values did not exceed 10TECu just as in Brussels. However, the profile shows a nearly sinusoidal curve indicating semi-diurnal variation with peaks at around 00UT and 12UT respectively. An increase in VTEC values during the period of the storm is also observed as shown in Fig. 3 and Fig. 4. The VTEC during the main phase of the storm was enhanced up to 18TECU above solar quiet average.

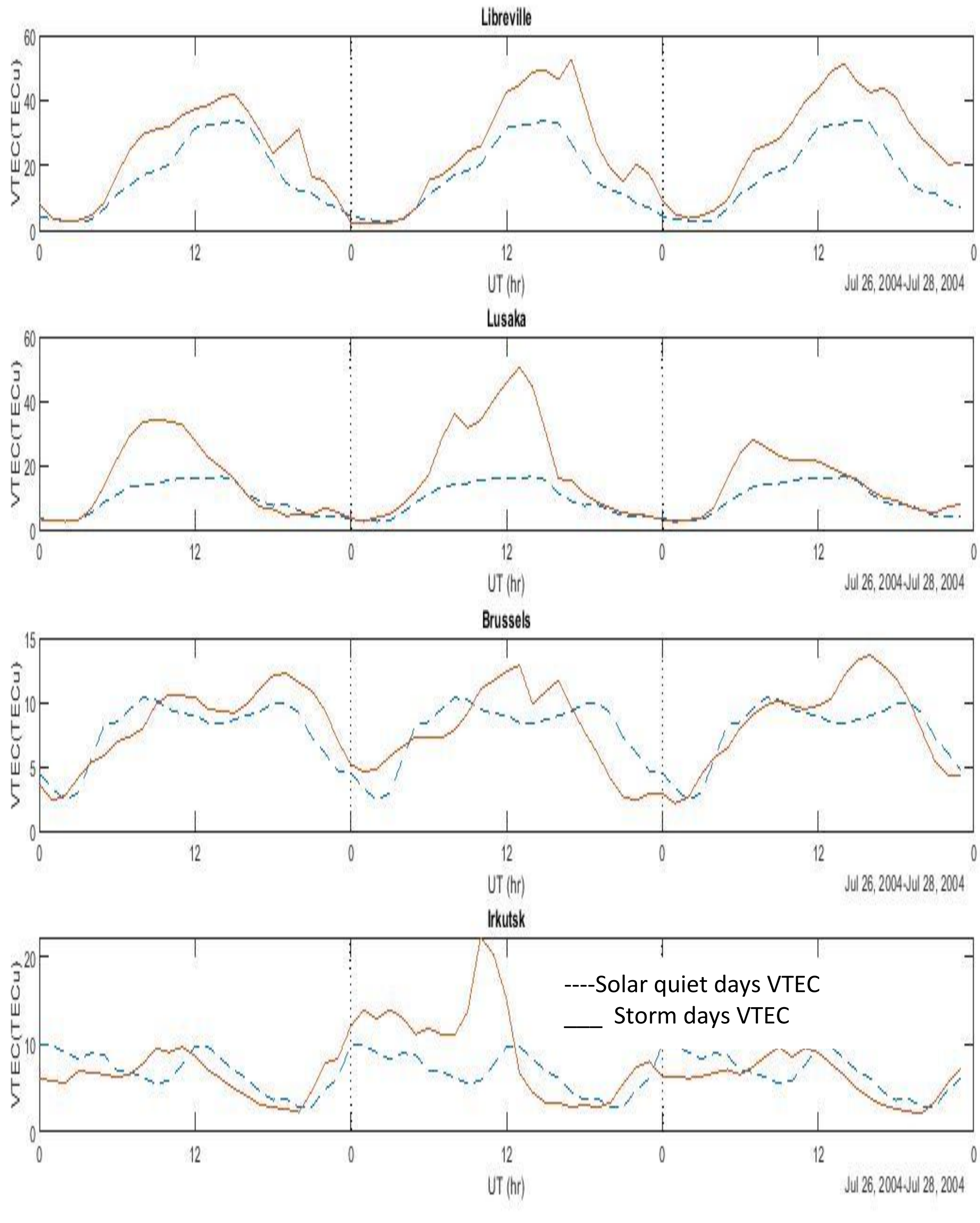

Fig. 3: Profiles of solar quiet day VTEC (on breaking lines) and the storm days VTEC for July 26-28, 2004.

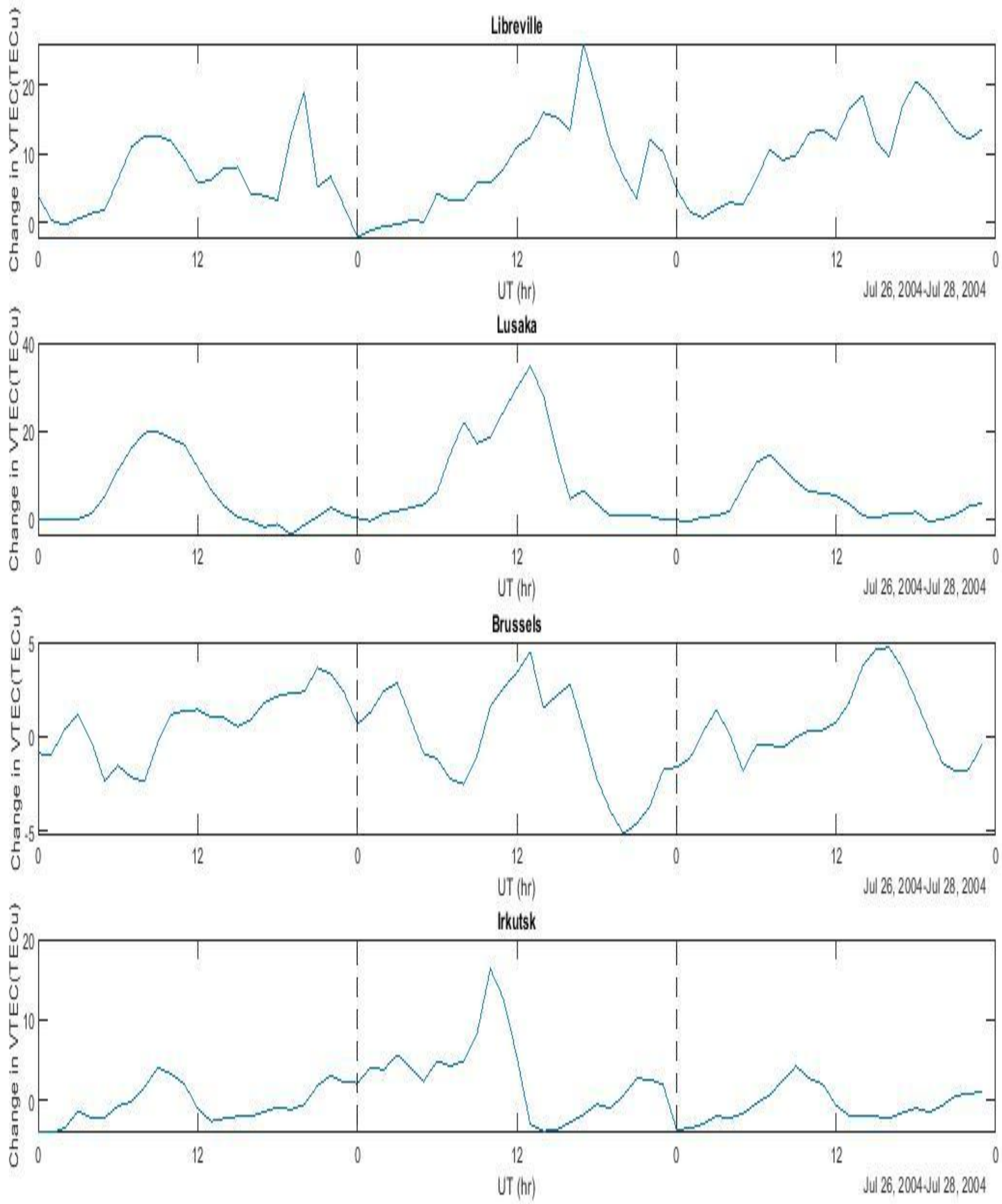

Fig. 4: Plots showing the storm time VTEC deviations ($\Delta VTEC$)for the storm of July 26-28, 2004.

Event 2 (November 7-11, 2004)

The Dst profile on Fig. 1(b) shows that the storm is a double super-storm with the first part of the storm having a greaterintensity than the second. The storm showed a sudden storm commencement at about 23UT on 7th November. The main phase intensified reaching a minimum Dst of -374nT at about 06UT on November 8. The duration of the first superstorm is about 29 hours spanning portions of three days (November 7-9) as the storm attempted to make a recovery at about 05UT on the 9th of November. However, this recovery phase is temporal as it lasted for only 10 hours before another surge occurred at about 15UT on 9th November, serving as the initial phase of a second storm which is not as strong as the first but is also a super-storm with a minimum Dst of -263nT which was recorded at 10UT on 10th November. This second super-storm of relatively lower intensity lasted for about 30 hours spanning portions of twodays. The storm, however, begins its recovery phase at 19UT on November 10.

The solar quiet VTEC variation and storm time VTEC variation are displayed on Fig.5. In Libreville, the Sq diurnal VTEC rises from its minimum during the early hours of the day (02UT – 03UT) which is as low as about 2TECu, rising steadily to its peak around 14UT. VTECvalues around this time gets as high as nearly 60TECu. However, the VTEC values remains nearly constant at 30TECu around 18UT-20UT before going down. The phenomenon of equatorial ionization anomaly is the main reason for such high values observed in Libreville (Ugonabo*et al.*, 2020), which is a station in the equatorial region.The first superstorm which occurred on the 8th of November did not have much noticeable effect on the variation of VTEC at Libreville. Deviation of storm time VTEC values from the solar quiet diurnal average was within the range: $-21\,TECU \leq \Delta VTEC \leq 21 TECU$.The deviation was strongest in the negative direction at about 21UT on November 8, while the peak positive deviation was at 15UT on the 10th of November.

For Lusaka which is located at about 15° south of the equator, the solar quiet diurnal variation is similar to the profile recorded for Libreville. This is largely because both stations are not largely displaced both in latitude and longitude. Minimum VTEC of ~2TECu is recorded at 01UT while at 11UT; VTEC is maximum reaching 35-40TECu. The storm has minimal effect on VTEC variation. The VTEC values are slightly reduced during the storm (especially in the second superstorm). This is shown on Fig.6 which represents the deviations of storm time VTEC from quiet time VTEC. Negative deviations are observed on the 8th and 10th of November (major periods of both storms), thereby indicating a reduction in VTEC values up to about 20TECu.

For Brussels, the solar quiet diurnal variation shows low VTEC values during the early hours of the day, with a minimum around 05UT. VTEC rises to peak value of about 15TECu at around 11UT-12UT before dropping low again at around 17UT. It is obvious that during the storm periods, there is little deviation from the solar quiet values. Enhancement in VTEC occurred only during pre-storm periods (15UT on November 7) and the short recovery period (13UT on November 9). However, minimal negative deviations from Sq averages are observed throughout the storm. In summary, $\Delta VTEC$ lie between $-5\, TECU \leq \ \Delta VTEC\ \leq 10 TECU$.Irkutsk which operates on a UTC+08 time zone, it is observed that the solar quiet VTEC is highest during the past noon hours (04UT – 07UT) with values which are as high up to ~20TECu. However, from 10UT (6pm local time), the VTEC drops and remains low throughout the night. The commencement of the storm coincides with the normal time at which VTEC enhancement occurs at Irkutsk. This coincidence ensures that VTEC during the storm is higher than the observed values for the solar quiet period. A very similar occurrence is observed for the second super-storm. As expected, the VTEC values for the recovery phase follow a perfectly correlated pattern with the solar quiet profile. This observation is evident in the profile on Fig. 6. A near-zero deviation is observed on November 7, while a well-enhanced VTEC value is observed on November 8 (the first super-storm) as positive deviation is high. During the first recovery phase, deviations returns back to insignificantly near-zero values. However, in the second super-storm, an enhanced deviation is observed again but this time, it is lower than the deviations observed during the first super-storm.Deviations return to normal on November 11 marking the end of the storm.

During November, Madrid and Brussels move to Daylight Saving Time mode (UTC +1) which is the same time at Libreville. So there is a similarity in the solar quiet VTEC patterns between Madrid and Brussels as both also lie within the mid-latitude region. Latitudinal differences ensure that Libreville does not have similar pattern as both European stations. The solar quiet profile shows that the VTEC is maximum around noon-time (12UT-13UT). Also, just like in Brussels, the first super-storm causes a drop in VTEC values as compared to the solar quiet VTEC. But there is a slight increase during the recovery phase on November 9 with a sudden greater enhancement on November 10 (during the second super-storm).

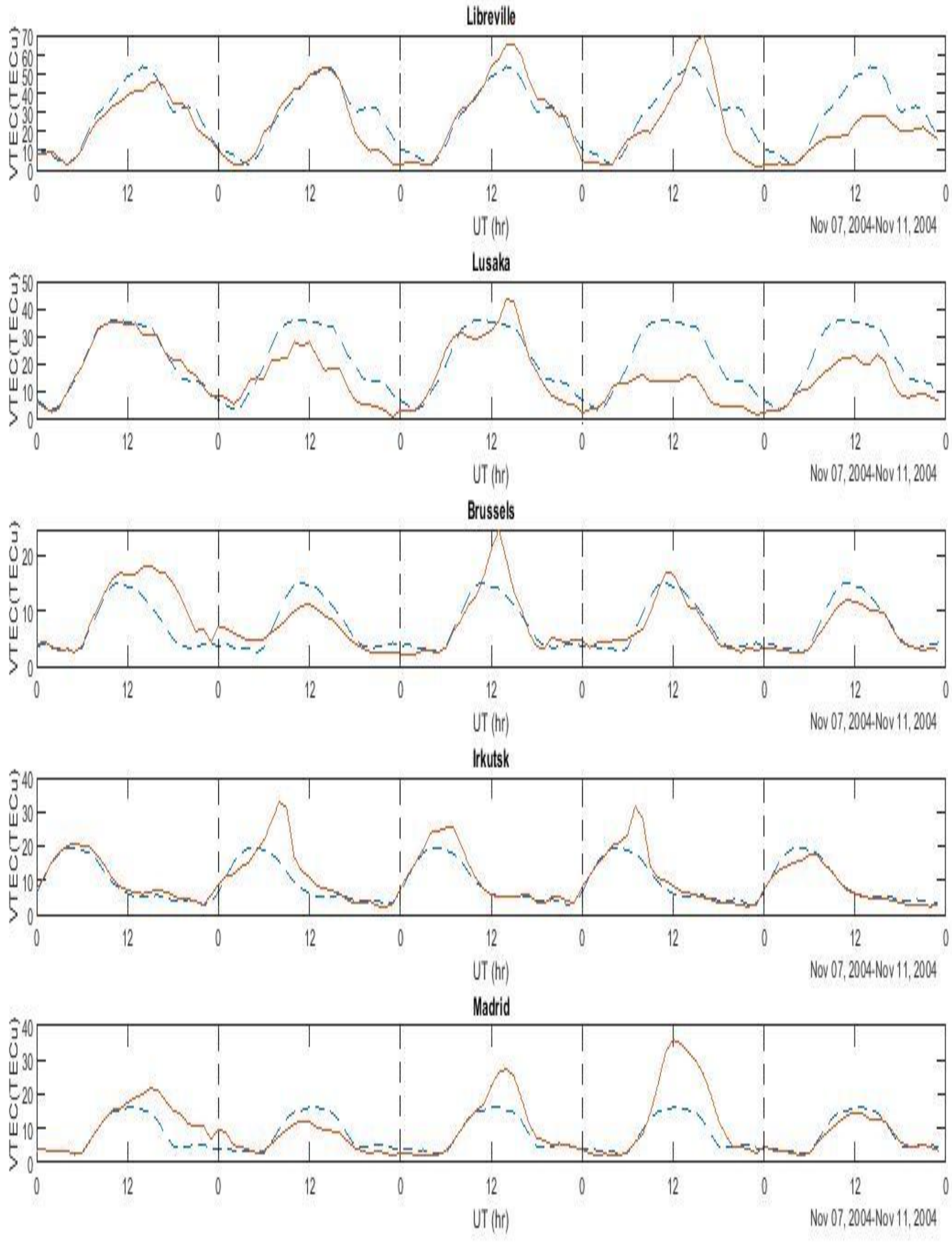

Fig.5 :Profiles of Solar quiet day VTEC (on breaking lines) and the storm days VTEC for November 7-11, 2004.

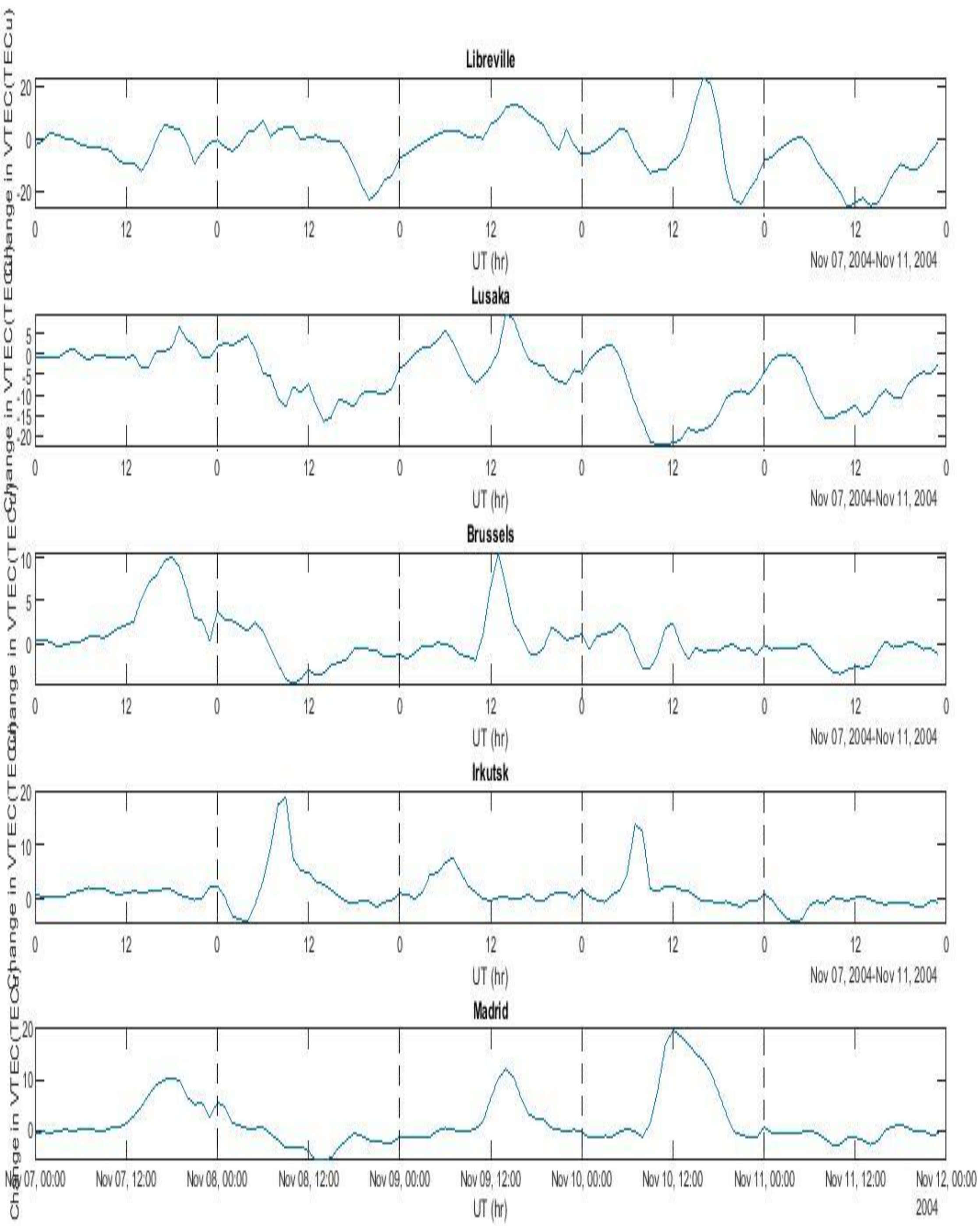

Fig.6:Plots showing the storm time VTEC deviations ($\Delta VTEC$) for the storm of November 7-11, 2004.

Dayside ionospheric superfountain (Dis) caused by prompt penetration of electric fields (PPEF)

Prompt penetration electric fields (PPEF) are sudden interplanetary motional fields that appear in the earth's ionosphere and magnetosphere through convection by solar winds to the magnetosphere (Tsurutani*et al.*, 2008). These fields are notable effects of geomagnetic storms. Dungey (1961) illustrates the actions of these fields and Tsurutani*et al.* (2008) discussed how different directions of the interplanetary magnetic fields will create different magnetospheric and ionospheric PPEFs and the different outcomes of their actions.

During daytime, the sun illuminates through the atmosphere creating a heating effect on the atoms and molecules. Also, it causes the atoms and molecules to be photo-ionized. These thermally agitated molecules expand to higher altitudes dragging more ions with them. This drag, together with the vertical movement of electrons and ions to higher altitudes due to the action of eastward electric field and southward magnetic field ($\vec{E} \times \vec{B}$ - drift)leads to the equatorial ionization anomaly (EIA) (Nambda and Maeda, 1939 in Tsurutani*et al.*, 2008) which manifests as an ionospheric event called "Fountain Effect". This accounts for high VTEC values in low latitude stations like Lusaka. However, a more enhanced event called the "Super-fountain effect" occurs especially during strong geomagnetic storms such as the ones considered in this study. The super-fountain effect is caused by the fast penetration of electric field contained in the solar wind (PPEF) into the equatorial ionosphere and magnetosphere during daytime.Theseelectric fields greatlyenhance the already existing eastward electric field, thereby increasing the intensity of the original Fountain effect. Hence, the plasma (both ions and electrons) is pushed further to higher latitudes and altitudes. This explains the enhancement of VTEC in mid latitude stations (Madrid, Brussels and Irkutsk) during the storm. However, since photo-ionization still takes place at the equatorial region, more electrons and ions are still pushed to low latitudes, hence the sustenance of high VTEC values in Lusaka even during the storm. So, the combination of solar photo-ionization and plasma transport enhances plasma densities including VTEC to values higher than the quiet time averages. This is called a positive ionospheric effect and the overall event is called "the dayside ionospheric super-fountain effect".

Negative Phase ionospheric storms (night-time recombination)

During the night-time of a storm event, the interplanetary magnetic field which is in the southward direction creates a corresponding interplanetary electric field (Tsurutani*et al.*, 2008). Peradventure this IMF gains entrance into the night-time equatorial ionosphere, then the electric field will be in the westward direction. Hence, the ionospheric plasma will move downwards as a result of the $\vec{E} \times \vec{B}$ – drift. At lower altitudes, chemical recombination occurs at a faster rate and this recombination leads to a reduction in plasma density and consequently reduction in VTEC. This is the reason for the low VTEC values during the night time even in the storm periods.

0. CONCLUSION

The variation of VTEC in Brussels, Madrid and Irkutsk have been studied and compared with that of Libreville and Lusaka during two major geomagnetic storm events in 2004 and the following conclusions were reached:

- The diurnal variation of quiet time (Sq) VTEC local time dependent with all the stations considered in this work having minimum VTEC values in the early hours of the day, around 02LT – 05LT and 03LT – 06LT for July and November respectively. However, the minimum VTEC in the mid latitude European stations have minima which are higher than the values observed in the African stations.

- Peaks are observed in all stations at around 12LT – 16LT. The peaks observed at the mid latitude European stations are much lower than the values recorded in the African stations. Peaks were as high as 40TECu in Lusaka and 55TECU in Libreville but does not exceed 25TECU in the mid latitude European stations.
- Storm-time enhancements of VTEC values during the day at mid-latitudes are attributable to the intensification of the Fountain effect in to the Super-fountain effect by the prompt penetration of electric fields into the magnetosphere and ionosphere. Night-time recombination ensures that VTEC during the storm is low at night-time.
- Although both storms occurred in solstice seasons, there is no specific trend in the VTEC variation which is attributable to the seasons.
- The change in vertical electron content (ΔVTEC) observed during geomagnetic storm of July 26-28, 2004lies within$-5TECU \leq \Delta VTEC \leq 25TECU$ for Libreville, for Lusaka it is$-5\,TECU \leq \Delta VTEC \leq 40TECU$, $-5\,TECU \leq \Delta VTEC \leq 5TECU$ for Brussels and $-5\,TECU \leq \Delta VTEC \leq 20TECU$ for Irkutsk.
- The change in vertical electron content (ΔVTEC) observed during geomagnetic storm of November 7-11, 2004lies within$-21TECU \leq \Delta VTEC \leq 21TECU$ for Libreville, for Lusaka it is$-20\,TECU \leq \Delta VTEC \leq 10TECU$, it is$-5\,TECU \leq \Delta VTEC \leq 10TECU$ for Brussels and $-5\,TECU \leq \Delta VTEC \leq 20TECU$ for Irkutsk and Madrid.

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