Induction Effects of Geomagnetic Storms in the Geo-Electric Field Variations at West African Dip Equatorial Latitudes

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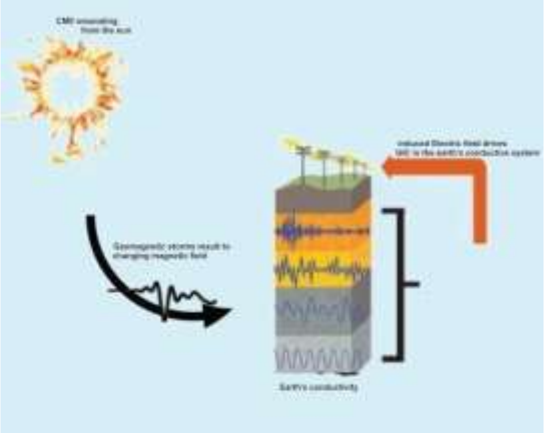
ABSTRACT

Geomagnetic Storms caused by perturbations of the Earth's magnetic field, induce currents within the Earth's crust. The induced currents yield measurable variations in geo-electric field at dip equatorial latitudes in West Africa. The induced effects of geomagnetic storms in the geo-electric field variations at dip equatorial latitudes in West Africa was studied using data obtained from ten West African geomagnetic and telluric electric field stations during the International Equatorial Electrojet Year (IEEY) between 1992 and 1994. Disturbance storm time (Dst) index value of less than -100nT were used to characterize the storm. The analysis was conducted using hourly mean values of the horizontal component (H), the magnetic declination (D) and vertical component of the geomagnetic field (Z) along with the north-south (E_x) and east- west (E_y) components of the geo-electric field obtained from 1992 and 1994 using telluric Field lines operated along the meridian chains of stations across the geomagnetic dip equator in West Africa. The results reveal that the magnitude of the geo-electric field responses due to geomagnetic storms varies depending on the observational station and the daytime enhancements in the telluric field noticeable between 08:00 hours Universal Time and 16:00 UT with slight increase near the dip equatorial stations.

Keywords: Geomagnetic storms: Induction effects: Telluric electric field: Dip Equatorial latitude: West Africa.

Graphical Abstract



- Ejected coronal mass ejection (CME) from the Sun causes geomagnetic disturbances.
- Geomagnetic storms lead to rapidly varying magnetic field which induces geoelectric field.
- The induced geoelectric field drive geomagnetically induced currents in the Earth’s conductive systems like power grids**.**

INTRODUCTION

Solar activity creates geomagnetic storms when the Sun ejects burst of charged particles such as corona mass ejections (CMEs) and high speed of solar wind streams that interact with the Earth's magnetosphere. The interaction between the solar wind and Earth's magnetic field are the primarily cause of the magnetospheric and ionospheric currents. The changes in the ionospheric and magnetospheric currents yield short term temporal variation in the geomagnetic field during the space weather events. These space weather events like geomagnetic storms cause rapid fluctuations in the Earth's magnetic field which are obvious at all the latitudes, but more prominent at auroral and equatorial regions because of the abnormal ionospheric conductivities in these regions (Rastogi, 2006). The intense fluctuations of the geomagnetic field during the geomagnetic storms induced electric field and currents within the Earth (Bolduc, 2002). The induced currents which are referred to as geomagnetically induced currents (GICs) flow in the Earth's conductive systems such as power grids, telecommunication, pipelines and other infrastructure thereby causing disruptions in these systems.

At the dip equatorial latitudes, the Earth’s magnetic field lines are nearly horizontal and relatively weak. This configuration makes the region susceptible to the induction effects of the geomagnetic storms. The electric fields induced can be significantly amplified and measurable. The strength and characteristics of the induced electric field can vary across different locations within the low latitude regions. The induced electric field can drive geomagnetically induced currents (GICs) in the critical infrastructure like power grids, telecommunication cables, pipelines, thereby potentially causing damage and disruptions in these technological systems. The geo-electric field variations during the geomagnetic disturbances at dip equatorial latitudes in West Africa have not been thoroughly investigated compared to other regions. Although, few studies have been carried out which includes the works of (Doumouya *et ai.,* 1988: Vassal *et a*l., 1988: and Akamigwo, 2021). In view of this lag, this study focused on the induction effects of the geomagnetic storms in the geo-electric field variations at dip equatorial latitudes in West Africa using data from the International Equatorial Electrojet Year (IEEY).

Objective of the study

The following objectives are achieved in the study resulting how solar event like coronal mass ejection drives rapid changes in the geomagnetic field at West African dip equatorial latitudes, which in turn induce geoelectric field in the surface of the Earth leading to potentially damaging geomagnetically induced currents (GICs) in conductive systems such power grids and pipelines;

i. Evaluate the variations in the geomagnetic field components (H, D, Z)

ii. Determine the variations in the north-south (E_x) component of the geoelectric field

iii. Determine the variations in the east-west (E_y) component of the geoelectric field

iv. Evaluate the induced effects of the storms on the geomagnetic field components

Organization

This paper is structured into five sections namely: Section 1 contains the Introduction of the geomagnetic storm induced effects on the geoelctric field variations. Section 2 contains the related works of geomagnetic disturbances and their impacts on ground-based conductive systems. Section 3 deals with procedure used in carrying out the analysis (Materials and Methods). Section 4 encompasses the Results and Discussion while Section 5 contains the Conclusion.

Related Work

The relationship between the geomagnetic storms and Equatorial Electrojet has long been a subject of intense study. Rastogi, (1977) used direct measurements of the equatorial electric field during geomagnetic storms to demonstrate that significant decreases in the electric field near the dip equator was as a result of counter equatorial electrojet (CEEJ). Elaborating on this basis, Ngwira *et al*.,(2013) studied the global behaviour of geomagnetic and geoelectric field fluctuations during extreme geomagnetic storms. Their findings highlighted enhanced electric field perturbations within the EEJ influence areas, stressing that these events are not exclusive to high latitudes, but are critical phenomenon at low latitudes as well. Further investigations into the mechanisms of these disturbances have used different geomagnetic field components. Falayi *et al*., (2015) utilized horizontal (H) and vertical (V) components of geomagnetic field to examine the response of the ionospheric disturbance dynamo and electromagnetic induction. The study observed that a high ratio of Z/H occurred at night time due to reduced E-region conductivity, which allows the F-region electric field to dominate. This underscores that the induction effects and vertical component of the geomagnetic field are vital for capturing the full scope of ionospheric responses during geomagnetic storms. The practical consequence of these induction effects is the production of geomagnetically induced currents (GICs). While the impacts of GICs on technological systems are felt globally, historically, research has concentrated on high-latitude regions (Botela *et al.,* 1998; kappernman, 2005; Pirjola, 2005: Pulkkinen *et al*., 2017: and Zawawi *et al*., 2020). However, a growing body of evidence which include the reports by Ngwira *et al*., (2008), Kouassi *et al.,* (2021), Ansor and Hamidu (2022), Zheng *et al*., (2022) and Tarana *et al*., (2023) indicates significant impacts of GICs at mid- and low latitudes. The risk associated with GICs is high following large geomagnetic impulses such as storm sudden commencements (SSC) (Kappernman, 2003; Doumbia *et al.,* 2017). These risks are directly dependent on the time derivatives of geomagnetic and geo-electric fields. For instance, Zheng *et al*., (2022) evaluated the induction effects of geomagnetic disturbances at low latitude in Malaysian power station and observed that GIC can result to transformer saturation, voltage instabilty and reactive power losses. These findings accentuate the exigency of localized data to mitigate the GICs impacts on critical infrastructure like power grids and telecommunication networks in low-latitude regions.

MATERIALS AND METHOD

The dataset utilized in this analysis contains hourly mean values of the horizontal component (H), the magnetic Declination (D) and the vertical component (Z) of geomagnetic field along with the north-south (E_x) and east-west (E_y) components of the geo-electric obtained from ten geomagnetic and telluric electric field stations during the International Equatorial Electrojet Year (IEEY) in West Africa. These stations are located between Mali in the North and Ivory coast in the South. The stations cover a latitudinal range from the dip equator to beyond the equatorial Electrojet belt. Table 1 shows the coordinate of the geomagnetic stations which include Tombouctou (TOM), Mopti (MOP), San (SAN), Koutiala (KOU), Sikkaso (SIK), Nielle (NIE), Khorgo (KOR, Katiola (KAT), Tiebisso (TiE) and Lamto (LAM).

Table 1, Coordinate of the geomagnetic stations during the IEEY

		GEOGRAPHIC		
Stations	Stations Code	Latitude (°N)	Longitude (°W)	Dip Latitude (°N)
Tombouctou	TOM	16.73	3.00	6.76
Mopti	MOP	14.51	4.09	4.02
San	SAN	13.24	4.88	2.45
Koutiala	KOU	12.36	5.45	1.38
Sikasso	SIK	11.34	5.71	0.12
Nielle	NIE	10.20	5.64	-1.30
Korhogo	KOR	9.34	5.43	-2.38
Katiola	KAT	8.18	5.043	-3.85
Tiebissou	TIE	7,22	5.243	-5.04
Lamto	LAM	6.23	5.02	-6.30

In the data analysis, moderate storms with Dst index values of less than -100nT were selected using one hour Dst index values obtained from the website of World Data Centre. Table 2 shows the geomagnetic storm characterization. The geomagnetic storms are classified based on their intensity and primarily determined by the Dst index values using Gonzalez *et al.,* (1994)_nomenclature.

Table 2, Nomenclature used in classification of geomagnetic storms (Gonzalez *et al.,* 1994)

Storm classification	Minimum Dst (nT)
Weak	–30
Moderate	–50
Intense	–100
Super intense	–500
Extreme	< –500

For this present study, moderate storms were selected with Dst intensity of less than -100nT having different phases of the storm which include the initial phase, main phase and the recovery phase. The initial phase has the maximum Dst amplitude accompanied by the main phase. The main phase has the minimum Dst values within the 24 hours proceeding the peak, while the end of the recovery phase was determined by locating the maximum Dst value within the 96 hours after the peak. The Dst index profiles of the selected disturbed days were plotted showing a day before the storm, the stormy day and the day after the storm.

From the data available, the geomagnetic field components (H, D, Z) and the geo-electric field components (E_x and E_y) profiles of those disturbed days were plotted across the selected stations and the effects of these storms were examined.

RESULTS AND DISCUSSION

Four geomagnetic storms were considered in this work, which include the geomagnetic storms of 17 February, 9 March, 11 March and 5 April, 1993. Figure 1 depicts the Dst index from 16 to 18 February, 1993, during which a sharp increase occurred around 03:00 hours UT indicating the storm sudden commencement (SSC). During the main phase of the geomagnetic storm, the Dst minimum value reached -110nT which occurred at 16:00 hours UT.

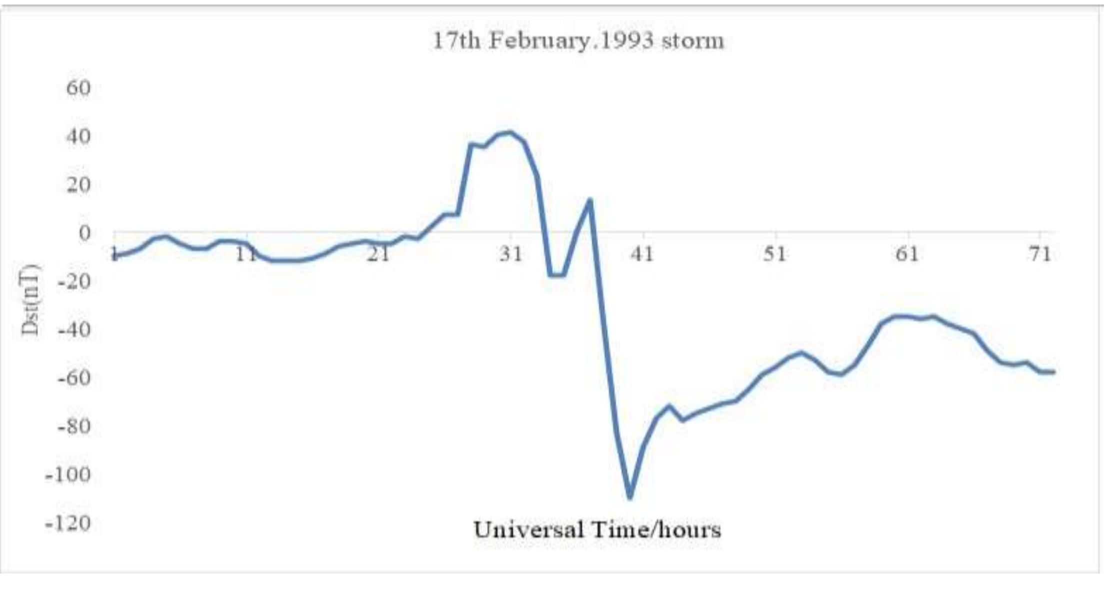


Figure 1: Dst index profiles from 16 to 18 February 1993

Figure 2 illustrates the Dst index from 8 to 10 March, 1993 indicating the storm sudden commencement (SSC) that started at 21:00 hours UT. During the main phase of the geomagnetic storm, the Dst index attained the minimum value of -137nT around 07:09 hours UT before entering the recovery phase around 07:00 hours UT

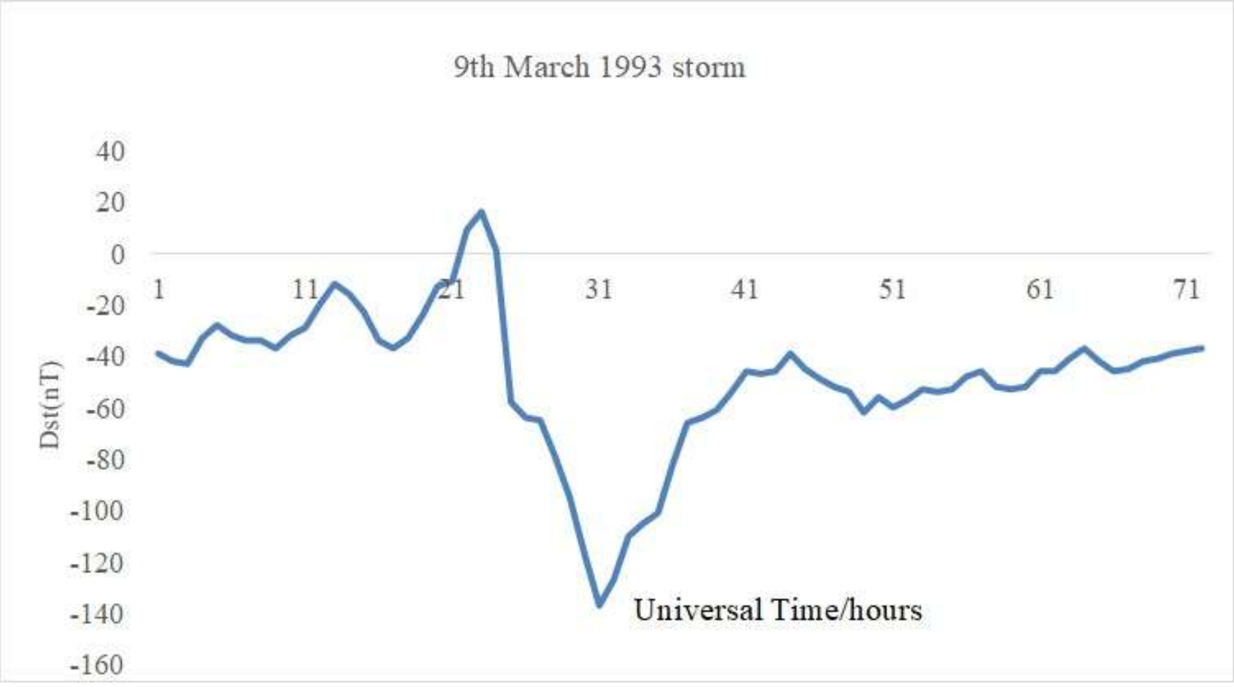


Figure 2: Dst index from 8 to 10 March, 1993

Figure 3 shows the Dst index profile from10 to12 March, 1993. The storm showed an SSC at 38nT around 01:00 hours UT. The Dst index fell to a minimum of -120nT at 19:00 hours UT depicting the main phase of the geomagnetic storm. The recovery phase started around 19:03 hours UT with a Dst index of 61nT.

Figure 3: Dst index profile from 10 to 12 March, 1993

Figure 4 shows the Dst index profile from 4 to 6 April, 1993. The main phase of the storm reached the minimum value of -165nT around 07:00 hours UT on 5th April, 1993 before the recovery phase commenced.

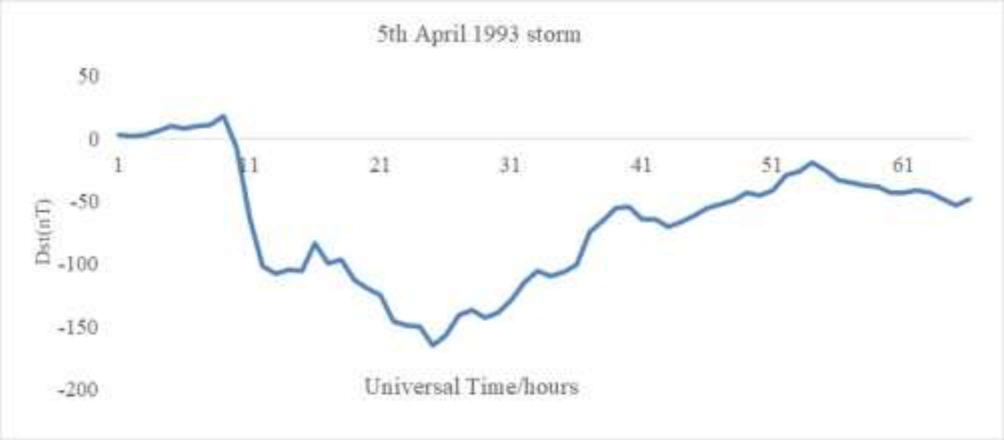


Figure 4: Dst index profile t4 to 6 April, 1983

Geo-electric responses to the 17 February, 9 March, 11 March and 5 April 1993 geomagnetic storms

The variations of geo-electric components (E_x and E_y) measured during the four geomagnetic storms at different stations in West African dip equatorial latitudes are analyzed in this section. The geomagnetic storms which occurred on 17 February, 9 March, 11 March and 5 April, 1993 were intense having the magnitudes of -110nT, -137nT, -120nT and -165nT respectively. The geoelectric field responses to these storms were examined and discussed as follows;

Geo-electric field response due to 17 February, 1993 geomagnetic storm

Figure 5 shows the fluctuations of the geo-electric field components (E_x and E_y) associated to the geomagnetic storm that happened on 17 February, 1993. Here, the geo-electric field components show rapid fluctuations, and the magnitude of the fluctuations of geomagnetic field show a diurnal pattern with most amplified amplitudes observed during the daytime. It could be observed that this geomagnetic storm with a minimum Dst index of -110nT at 16:00 hours UT, had a storm sudden commencement which occurred at 03:00 hours UT reached it's peak value. From Figure 5, there was a secondary impulse around 11:00 hours UT

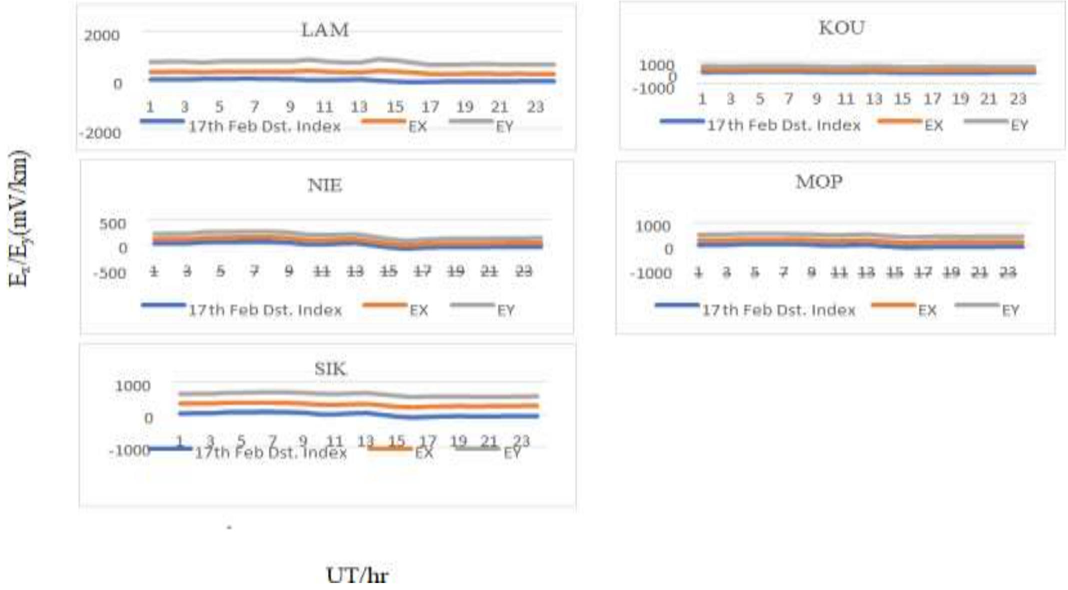


Figure 5: Geo-electric field response to the 17 February, 1993 geomagnetic storm

Across the stations, the fluctuations of the geo-electric field to geomagnetic storm that occurred on 17 February, 1993 was observed. During the SSC at 03:00 hours UT, at KOU, E_x = 209.4 mV/km and E_y = 265.9mV/km. At LAM, E_x = 411.8mV/km and E_y = 432.7mV/km. At MOP, E_x = 307.7mV/km and E_y = 221mV/km. For Station NIE, E_x = 87.5mV/km and E_y = 105.7mV/km. At SIK, E_x = 300.6mV/km and E_y =

320.3 mV/km. Observe that LAM (a southern station) shows stronger amplitude at E_x than those of the dip Latitude stations such as SIK, NIE with E_x = 300mV/km and 87.5 mV/km respectively. NIE has the weakest amplitude with E_x = 87.5 mV/km and E_y = 195.7mV/km. The geo-electric field variations are amplified at LAM with the amplitude of E_x and E_y about 411.8mV/km and 432.7mV/km. The SSC effects decrease from LAM to MOP. The latitudinal trend of the storm signature in the geo-electric field variations show the influence of subsolar point location 5.13^0N which is 1.10^0N south of LAM. Also, lateral resistivity contributed to the changes from one station to another. These observations indicate that the magnitude of the geo-electric field response to the geomagnetic storm depend on the observational locations. This change in the storm time geo-electric field amplitude from one station to another could be as a result of lateral resistivity (Vassal *et al.*, 1998).

Geo-electric field response to the geomagnetic storm on 9 March, 1993

Figure 6 shows the response of geo-electric field to the storm that occurred on 9 March, 1993. This storm has the minimum Dst index value of -137nT at 07:00 hours UT with an SSC having it's peak value of 16nT.

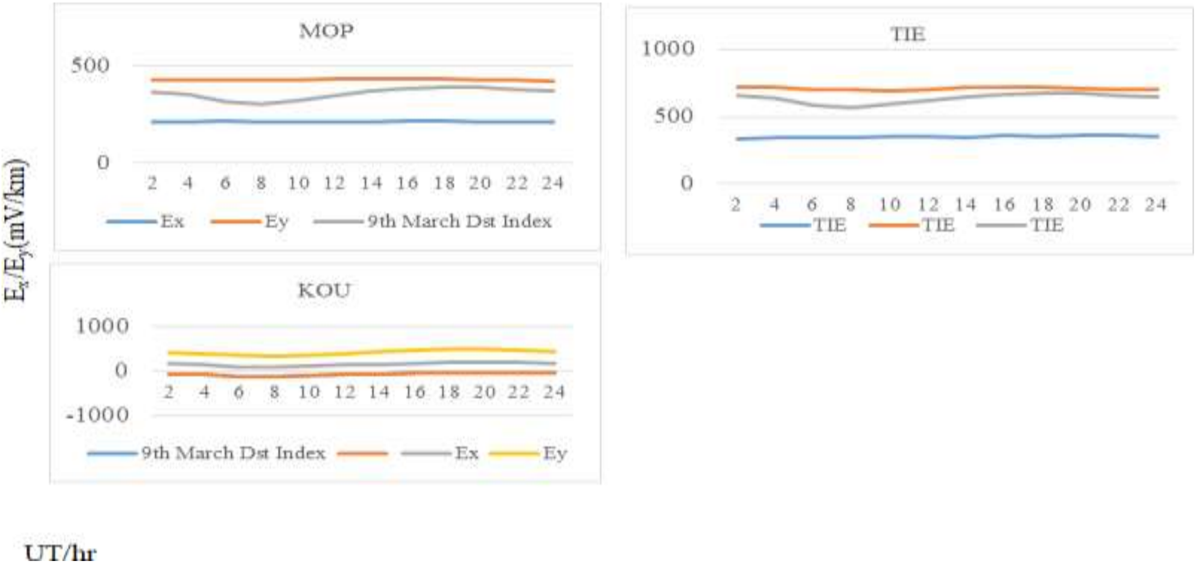


Figure 6: Geo-electric field response to the 9 March, 1993 geomagnetic storm

The geo-electric field response to the geomagnetic storm that occurred on 9 March, 1993 observed during the main phase of the geomagnetic storm across the selected stations MOP, TIE and KOU. At MOP, E_x = 219mV/km and E_y = 217.5mV/km. At TIE, E_x = 319mV/km and E_y = 368mV/km. The amplitude of E_x and E_y at station KOU are 215mV/km and 284mV/km respectively. TIE has the strongest amplitude while MOP has the weakest amplitude. Here, the amplitude of the geo-electric field components decreases from TIE (south) to MOP (north) with slight enhancement at the KOU (a dip latitude station). This enhancement at KOU could be attributed to high cowling conductivity due to the influence of equatorial electrojet currents.

Geo-electric field response to geomagnetic storm on 11 March, 1993

Figure 7 illustrates the response of geo-electric field to the geomagnetic storm that occurred on 11 March, 1993. The geo-electric field response corresponding to the storm that occurred on 11 March, 1993 was observed during the SSC across the selected stations- At KOU: E_x = 218.8 mV/km, E_y = 284.1 mV/km, MOP: E_x = 213.7 mV/km, E_y = 222.2 mV/km. At TIE: E_x = 337.3 mV/km, E_y = 359.9 mV/km

During the main phase around 18:00 hours Universal Time;

KOU: E_x= 279.1 mV/km, E_y = 225.4 mV/km. At MOP: E_x =211.4 mV/km, E_y = 212.9 mV/km, TIE: E_x = 341.4 mV/km, E_y = 322.3 mV/km

During the recovery phase around 18:00 hours Universal Time;

At KOU: E_x = 269.8 mV/km, E_y = 226.6 mV/km, MOP: E_x = 212.5 mV/km, E_y = 211.6 mV/km, TIE: E_x = 333.6 mV/km, E_y = 330.5 mV/km. The three stations have similar latitudinal pattern, but TIE is more elevated than MOP and KOU

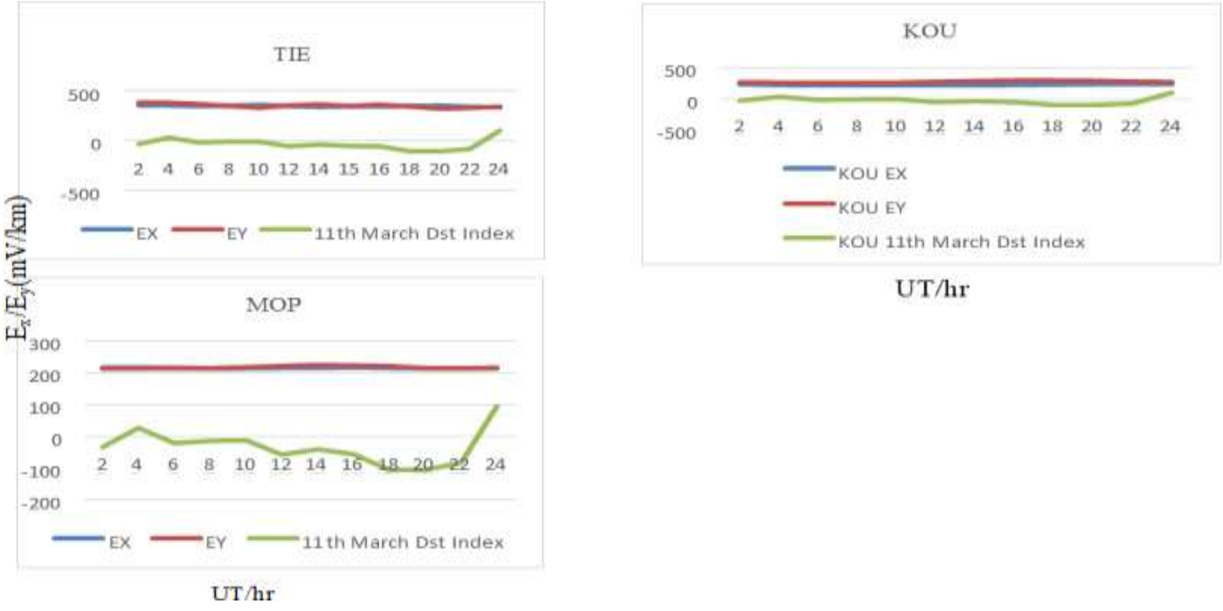


Figure 7: Geo-electric field response to the 11 March, 1993 geomagnetic storm

Geo-electric field response due to the storm on April 5, 1993

For the April 5 storm, with a Dst Index of -165nT, **No SSC was observed**

The geo-electric field responses during the main phase around 08:00hours Universal Time: NIE: E_x = 243.2 mV/km, E_y = 230 mV/km, TOM: E_x = 330.4 mV/km, E_y = 347 mV/km

During the recovery phase at about 08:00hours Universal Time;

NIE: E_x =242mV/km, E_y = 228.7 mV/km, TOM: E_x = 330.2 mV/km, E_y = 346.6 mV/km

TOM, a non-dip latitudinal station, exhibited higher amplitudes compared to NIE, with no distinct latitudinal pattern observed

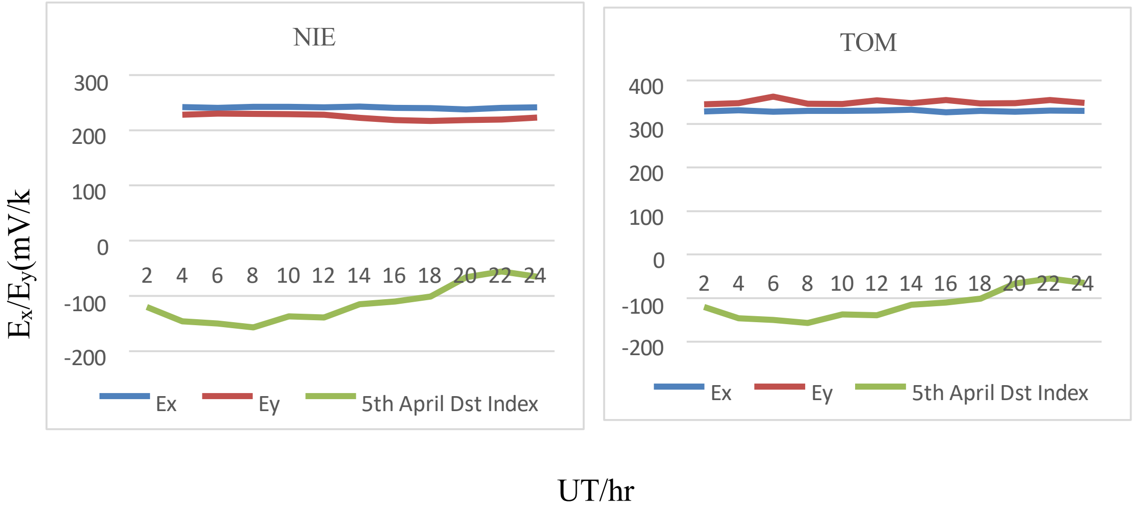


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Figure 8: Geo-electric Field Responses for April 5, 1993

The observations are in agreement with the works of (Akamigwo, 2021: Doumbia *et al.,* 2017: and Vassal *et al*., 1998). They attributed this non-latitudinal trend from one location to another to lateral resistivity and geological conditions such as sedimentary rocks, cratonic shield and coastal areas which could contribute to the electrical conductivity of the location.

CONCLUSION

The induction effects of the geomagnetic storms in the geo-electric field variations at West African dip equatorial latitudes has been studied using ten geomagnetic stations at dip latitudes in West Africa. The following deductions were drawn from the results obtained in this study;

(i) Geomagnetic storms yield rapid changes in the geomagnetic fields which induce substantial geo-electric fields and associated GICs. The magnitude of the response of the geo-electric field to the geomagnetic storm depends on the observational site relative to the dip equator.

(ii) The amplitude of the geo-electric variations are enhanced during the daytime due to increased conductivity of the ionospheric E- layer which is at it's peak in the daytime.

(iii) The effects of the geomagnetic storms are more noticeable at the stations near the dip equator compare to those stations further away from the dip equator.

Data Availability- The data generated is included in the manuscript.

Conflict of Interest- The author declares no potential conflict of interest.

Funding Source- None

Authors Contributions- Obiekezie T.N : Theory of method, reviewing and editing

Udevi B.A.- Calculation, manuscript writing with figures presentation.

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AUTHOR'S PROFILE

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