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Geomagnetic field H, Z and electromagnetic induction features of coronal mass ejections in association with geomagnetic storm at African longitudes

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Abstract

The largest geomagnetic disturbance caused by a coronal mass ejection (CME) of solar cycle 24 recorded on both 17 March and 22 June 2015 with minimum Dst values of -223 and -195 nT respectively was investigated. This study examines the effect of coronal mass ejection (CME) on Earth's geomagnetic field which include the time derivatives of horizontal (H) and vertical (Z) components of the geomagnetic field and the rate of induction $\Delta Z/\Delta H$ at African longitudes (AAE, MBO, HBK, HER and TAM). The results demonstrated enhancement of dH/dt and dZ/dt in the daytime over the equatorial zone (AAE and MBO) and mid latitudes (TAM, HER and HBK) on 17 March 2015. Nighttime enhancement was observed on 22 June 2015 over the equatorial zones and mid-latitudes. Wavelet spectrum approach is used to investigate $\Delta Z/\Delta H$ variation observed at AAE, MBO, HBK, HER and TAM. The CME may have influence on time derivatives of geomagnetic field H, Z and electromagnetic induction at the African longitudes which might be associated with perturbations in electric fields and currents in the equatorial and low latitude magnetic field linked with the changes in magnetospheric convection.

Keywords: Coronal mass ejection, geomagnetic storm, geomagnetic field and wavelet spectrum.

1.0 Introduction

Sun is the major cause of space weather as a result of variability in term of mass, particles and photon emissions on different time scales. The emission of electromagnetic includes the quasi-steady irradiance and flares. The solar wind, coronal mass ejections (CMEs), and solar energetic particles (SEPs) are the emission from the Sun. The coronal magnetic field can be carried into the heliosphere by CMEs and solar wind. CMEs are heavy expulsions of the charged plasma

released from the solar atmosphere. They are referred to as interplanetary CMEs (ICMEs) moving into interplanetary space which have influence on geo-effectiveness. These CMEs arrive the Earth and interact with the Earth's magnetosphere resulting to geomagnetic storms, which have influence from the magnetosphere to the ground.

During the geomagnetic storm, the strong electric currents flowing within the both magnetosphere and ionosphere have an influence on geomagnetic field, which extends to low magnetic latitudes. The disturbance storm time (Dst) is one of the major parameters used to measure the strength of geomagnetic storm, the Dst is obtained from the geomagnetic H component. The variation of the geomagnetic field is usually expressed through a magnetometer of declination (D), vertical intensity (Z) and horizontal intensity (H). [1] investigated the variations of H, Z and Y components of the geomagnetic field at the equatorial electrojet station in Sri Lanka, Peredinia. It was observed that abnormal features of Z variations at electrojet stations in India-Sri Lanka are caused by a direct effect of the ionospheric electrojet current and the induced current in the local subsurface conductor. [2] examined the features of geomagnetic sudden commencement (SC) in middle and low latitudes using the H component of the geomagnetic field. It was noted that the negative impulse superposed on the main impulse of SC in H component after the onset, at mid to high latitude stations in the local time range from the morning to the early afternoon. The geomagnetic disturbance in H, D and Z of the geomagnetic field at Japan observatories chain was investigated. The diurnal variation patterns in the H and D of the geomagnetic field components during storm time were observed [3]. [4] used longitudinal survey of H and Z field in Nigeria and [5] in Central African longitudes, the results exhibited full similarity with the prediction on the Chapman model of EEJ (Equatorial Electrojet current). [6] analysed the D component of the geomagnetic field to show the existence of EEJ at low latitudes.

In this research, we considered the time derivative of the geomagnetic field (dB/dt) as a potential indicator of induction current occurrence; we analyze the time derivatives of dH/dt and dZ/dt . The magnitudes of time derivatives of the geomagnetic field determine the geoelectric field which drives the GICs. Variation exceeding 30nT/min of the X or Y components appears to be

significant causing undesirable consequences in power grids [7-10]. [11] presented the induced effects of the geomagnetic disturbances in the equatorial electrojet (EEJ) influence area in West Africa. The variability in the north to south (E_x) and east to west (E_y) components of the geoelectric field were examined, alongside with the three components of the geomagnetic field (H , D and Z) during the geomagnetic disturbance of 17 February 1993 and the solar flare observed on 4 April 1993.

The present work aims at examining the time derivatives of the geomagnetic field components of H and Z . The ratio $\Delta Z/\Delta H$ of electromagnetic induction effects of space-weather-related geomagnetic disturbances in the Africa longitudes during the largest geomagnetic storms of solar cycle 24 so far occurred on 17 March 2015 and 22 June 2015 with Dst minima of -223 and -195 nT, respectively were investigated due to coronal mass ejection.

2.0 Data Analysis

The magnetic observatories, stations codes, the geographic and geomagnetic coordinates of the stations are depicted in Table 1. The Geomagnetic data, at 1 min resolution, are obtained from International Real Time Magnetic Observatory Network (<http://www.intermagnet.org/>) [12]. The 1-min differences are formed as an approximation to the time derivative (dH/dt and dZ/dt) in the horizontal northward (H) eastward (D) and vertical (Z) components of the geomagnetic field.

We focused on the largest geomagnetic storms of solar cycle 24 occurred on 17 March 2015 and 22 June 2015 with Dst minima of -223 and -195 nT due to a coronal mass ejection [13]. The purpose of the present study is to analyze the effects of geomagnetic disturbances in the time derivatives and induction current variations at African longitudes. There is a missing data in Addis Ababa on 22 June 2015.

Table 1 List of stations whose data are used together with geographic and geomagnetic coordinates.

2.1 Time derivatives of the horizontal geomagnetic field variations during the 17 March and 22 June 2015 geomagnetic storm.

Figure 1 (a-f) compares the solar wind signatures with dH/dt across the selected geomagnetic observatories, there is an increase between 4:00 h and 5:00 h which is due to the shock ahead of the ejecta and the strong variations between 12:00 noon and 15:00 h which are generated by the enhanced magnetic field as well the enhanced variations in the field of the ejecta (ejecta means interplanetary flows and coronal mass ejections observed through the corona with a coronagraph). On 17 March 2015, the effect of this geomagnetic storm was clearly observed at the ground measurement of the time derivatives of the horizontal geomagnetic field (dH/dt) variation at AAE, MBO, HBK, HER and TAM. At 05:00 h, the sudden storm commencement (ssc) manifests itself in the sharp increase with amplitude of 26 nT/min, another peaks was noticed at 12:00 noon with the value of 23.05 nT/min at AAE. At MBO, the time derivative was noticed at 13:00 h with amplitude 33.18 nT/min. The same signature and trend of variation are observed at HBK and HER with amplitude of 23.3 nT/min and 21.3 nT/min respectively (see Figure 1d and 1e). The maximum value recorded for TAM in 5:00h is 28.10 nT/min (Figure 1f).

Figure 1 (a-f): Solar wind speed and time derivatives of the horizontal geomagnetic field variation on 17 March 2015 magnetic storm at African sector.

Fig. 2 (a-e) presents a characteristic scenario in the development of the geomagnetic disturbance from a quiet period to a highly fluctuating one during the phase of investigation. On 22 June, the solar wind signature with dH/dt was observed between 5:00 h and 6:00 h, another peak was noticed around 18:00 h and 19:00 h produced by shock in the solar wind. Nighttime enhancement of time derivatives of the horizontal geomagnetic field was observed at MBO, HBK, HER and TAM with values of 60.37 nT/min, 24 nT/min, 18 nT/min and 58 nT/min at 19:00 h respectively. The time derivatives of the horizontal geomagnetic field exhibit the same pattern of variation during the geomagnetic storm (Figure 2 (a-e)).

Figure 2 (a-e): Solar wind speed and time derivatives of the horizontal geomagnetic field variation on 22 June 2015 magnetic storm at African sector.

2.2 Time derivatives of the vertical geomagnetic field variations during the 17 March and 22 June 2015 geomagnetic storm.

The same pattern of variation in Figure 1 (a-f) was observed in Figure 3 (a-f). The southward turning of magnetic field usually found within the ejecta reaches the Earth in the form of an interplanetary CME (ICME) with a shock leading to a geomagnetic storm. The variations of time derivatives of the vertical geomagnetic field (dZ/dt) on 17 March 2015, at AAE, HBK, HER, MBO and TAM were depicted in Figure 3 (a-f). At AAE, MBO, HBK, HER, and TAM, dZ/dt respond to geomagnetic disturbance of 17 March 2015 with maximum values 5.73 nT/min, 5.37 nT/min, 14.40 nT/min, 16.10 nT/min, and 2.0 nT/min respectively. The dZ/dt increases from morning time and maximizes after the noon time. The dZ/dt variations are enhanced at HBK and HER at the post-noon hours.

Figure 3 (a-e): Solar wind speed and time derivatives of the vertical geomagnetic field variation on 17 March 2015 magnetic storm at African sector.

Figure 2 (a-e) shows similar pattern of variation with Figure 4 (a-e). Magnetospheric shock associated with sudden impulse or sudden storm commencement was noticed between 18:00 h and 19:00 h on 22 June. Figure 4 (a-e) shows the plot of time derivatives of the vertical geomagnetic field (dZ/dt) at MBO, HBK, HER and TAM. It was observed that dZ/dt impulse decrease as the stations get close to the dip equator. Also the fluctuations of the dZ/dt components are observed during the nighttime. The geomagnetic field variations at low latitudes evidently show the effectiveness of the time derivatives observations. The Z component of the geomagnetic field variation produces the stations of the currents compared to the stations of observation. It is established that the effect of geomagnetic disturbance at low latitudes, in respect of amplitude, is enhanced at high latitudes than low latitudes [14].

Figure 4 (a-e): Solar wind speed and time derivatives of the vertical geomagnetic field variation on 22 June 2015 magnetic storm at African sector.

2.3 Variations of electromagnetic induction $\Delta Z/\Delta H$ during geomagnetic disturbances at African longitudes.

The geomagnetic disturbances are associated with geoelectric fields of the electromagnetic induction on the earth, produce information on the formation of the earth, on the ionosphere and magnetospheric current system. The conducting earth's interior has an influence on the electromagnetic induction as a result of geomagnetic variation deduced from geomagnetic Z-H or magneto-telluric E-H relations [15-16]. The wavelet method was applied to analyze the electromagnetic induction ($\Delta Z/\Delta H$) time series observed in a sequential time scales using the sampling intervals [17- 18]. Figures 5 (a-c) -9 (a-c) depict the electromagnetic induction variation on 17 March using wavelet analysis based approach.

Fig5. (a) dZ/dH data from Addis Ababa observatory for 17 March 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 256-512 min bands. The dashed line signifies the 95% confidence.

Fig6. (a) dZ/dH data from Mbour observatory for 17 March 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 256-512 min bands. The dashed line signifies the 95% confidence.

Fig7. (a) dZ/dH data from Hermanus observatory for 17 March 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Fig8. (a) dZ/dH data from Hartebeesthoek observatory for 17 March 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Fig9. (a) dZ/dH data from Tamanrasset observatory for 17 March 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum

while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Figures 10 (a-c) – 13 (a-c) also display the wavelet transformation to produce information on the maximum of periodic signals within the series and how those peaks vary with time of the electromagnetic induction on 22 June 2015.

Fig10. (a) dZ/dH data from Mbour observatory for 22 June 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 256-512 min bands. The dashed line signifies the 95% confidence.

Fig11. (a) dZ/dH data from Hartebeesthoek observatory for 22 June 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Fig 12. (a) dZ/dH data from Hermanus observatory for 22 June 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Fig 13. (a) dZ/dH data from Tamanrasset observatory for 22 June 2015 (b) depict the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 256-512 min bands. The dashed line signifies the 95% confidence.

3.0 Discussion of Results

Geomagnetic field measurements are very important for studying magnetospheric dynamics and dynamic processes determining the energy transfer from the solar wind to the Earth's magnetosphere. We analyze the variation of time derivatives of the geomagnetic field and electromagnetic induction observed in the African sector during the largest geomagnetic storms of solar cycle 24 occurred on 17 March 2015 and 22 June 2015. The high and low latitudes are

associated with neutral and electrodynamics processes during the geomagnetic storm cause significant alteration at the equatorial and low latitudes. At the global scale equatorial regional electric field is generally eastward during daytime and westward during the nighttime; this alteration during the geomagnetic disturbance can significantly have an influence on the equatorial electrodynamical processes.

The variation of dH/dt showed a large peak after the noontime (Figure 1(a-f)). Our results demonstrated that the large dH/dt is more prevalent during daytime hours at AAE and MBO, and are evidently associated to Equatorial electrojet current. The daytime enhancement of dH/dt shows eastward induction effects at AAE and MBO expected to increase as they get closer to the geomagnetic dip equator. The coronal mass ejection occurred during the strong eastward currents at low latitudes produce strong impulse in the dH/dt field at the stations. The equatorial daytime enhancement of geomagnetic field time derivatives is linked to the influence of Cowling conductivity effects. The alteration in the intensity and distribution of the ring currents, auroral electrojets, and field-aligned currents can affect the time derivatives of the geomagnetic fields at HBK, HER and TAM [19] (see Figure 1 (a-f)). Figure 2 (a-e) depicts time derivatives of the horizontal geomagnetic field variation on 22 June 2015. Nighttime enhancement was noticed around 19:00 h through 24:00 h, this implies that there is a visible nighttime enhancement of geomagnetic disturbance variation in dH/dt . The westward electric field can influence the nighttime enhancement of dH/dt at both the low and mid latitudes.

Figures 3 (a-f) and 4 (a-e) shows the time derivatives of the vertical geomagnetic field variation on 17 March and 22 June 2015 respectively during the magnetic storm at African sector. The dZ/dt of the field is very sensitive to the local inhomogeneities of the earth's internal conductivity [20]. The dZ/dt also gives daytime enhancement impulse reveals the influence of the equatorial electrojet in dZ/dt components at AAE and MBO on 17 March. While Figure 4 (a-d) depicts the nighttime enhancement of dZ/dt at near the equatorial stations and outside the equatorial stations in African sector. It is well known fact that the absence solar radiation at the nighttime implies no dissociation of ions in the ionosphere. The enhancement of dZ/dt obtained at the nighttime at different stations comes from other sources like distribution of electrical

conductivity, geomagnetic pulsation and sudden storm commencement might be responsible for large induction current.

We built a simple numerical model based on wavelet transform to examine the dZ/dH at the African region. The Wavelet Power Spectrum produces analysis on the relative power at a certain scale and a certain time. The colour bars of the wavelet power spectrum range from blue (low power) to red (high power), and the significant regions are the ones associated with red, orange, and yellow, right display the numerical strength of coupling between two variables. The red colour stipulates maximum frequency contributing to the energy of signal over that interval (see Figure 5-12). The global wavelet spectrum (GWS) can be used to examine the geomagnetic disturbance signal to produce information on the frequency or scale variations about induction due to its features of identifying the restriction of these structures in time and in space [21].

Figure 5 (a-c) presents the wavelet power spectrum (WPS) of the AAE induction series. Fig. 5b shows the power of the wavelet transform for the dZ/dH in AAE presented in Fig. 5a. It was noted that there is more concentration of power between the 256–512 min bands, which shows that this time series has a strong annual signal of dZ/dH (Fig. 5b). The GWS in Fig. 5c was used to study the dominant periods of the signals of the dZ/dH data for the different conditions during the 17 March 2015. Fig6 (a-c) depicts dZ/dH data from Mbour observatory for 17 March 2015, it was noted that there is more concentration of power between the 256–512 min bands. Figures 7(a-c) and 8 (a-c) shows the same pattern of variation of dZ/dH , this plot are obtained respectively by the average of Figs 7b and 8b, concentration of power between 512 and 1024 min, which give a measure of the average variance versus time. The reductions of the power within the band represent the weak variation of dZ/dH . Figs 9c also present an almost significant peak with concentration of power between 512 and 1024 min at TAM dZ/dH series.

On 22 June 2015, Figure 10b illustrates that the periodic oscillation is predominant at the larger time scales of 256-512 min band during the geomagnetic storm events. The variation trend and phase of the dZ/dH at HER is identical with those of the HBK (see Figures 11b and 12b). In Figure 11c and 12c, the global wave spectrum power decreases with increasing in the period.

Fig13. Illustrate the dZ/dH data from TAM observatory for 22 June 2015. The spectrum in Fig. 13b shows a strongest wavelet power area from 20:00 h to 23:00 h. The physical implication responsible for the wavelet power appears to have period between 512 and 1024 min. This dZ/dt was detected between 20:00 h and 21:00 h. The dash line denotes 95% confidence level marked on the GWS. The significance of the signal can be ascertained by the identical strength of GWS. When the magnitude of GWS is comparatively small, the signals can be regarded as residuals [22]. Global wavelet spectra could be employed to examine rate of induction variability in non-stationary hyetographs. For the locations that do not show long-term changes in hyetograph structures, global wavelet spectra are useful for summarizing a location, temporal variability and comparing it with the rate of induction in other locations. The CME may have influence on time derivatives of geomagnetic field H , Z and electromagnetic induction at the African longitudes which might be associated with perturbations in electric fields and currents in the equatorial and low latitude magnetic field linked with the changes in magnetospheric convection.

Conclusion

During the largest geomagnetic disturbance of solar cycle 24 occurred on both 17 March and 22 June 2015 with Dst minima of -223 and -195 nT respectively. This paper describes the influence of coronal mass ejection on the time derivatives of horizontal (H) and vertical (Z) components of the geomagnetic field and the rate of induction $\Delta Z/\Delta H$ at African sector (AAE, MBO, HBK, HER and TAM). Enhancement of dH/dt and dZ/dt were observed in the daytime over the equatorial zone (AAE and MBO) and mid latitudes (TAM, HER and HBK) on 17 March 2015. Also, nighttime enhancement was observed on 22 June 2015 over the equatorial zones and mid-latitudes. The induction variability analysis, the main frequency components in the time series are studied by the global wavelet spectrum, exhibiting the $\Delta Z/\Delta H$ variation at AAE, MBO, HBK, HER and TAM. The wavelet power spectra showed that HBK and HER have similar rate of induction patterns

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Figure Captions

Figure 1(a-f): Solar wind speed and time derivatives of the horizontal geomagnetic field variation on 17 March 2015 magnetic storm at African sector

Figure 2(a-e): Solar wind speed and time derivatives of the horizontal geomagnetic field variation on 22 June 2015 magnetic storm at African sector

Figure 3(a-f): Solar wind speed and time derivatives of the vertical geomagnetic field variation on 17 March 2015 magnetic storm at African sector.

Figure 4 (a-e): Solar wind speed and time derivatives of the vertical geomagnetic field variation on 22 June 2015 magnetic storm at African sector

Fig5. (a) dZ/dH data for Addis Ababa observatory for 17 March 2015 (b) depicts the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 256-512 min bands. The dashed line signifies the 95% confidence.

Fig6. (a) dZ/dH data for Mbour observatory for 17 March 2015 (b) depicts the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 256-512 min bands. The dashed line signifies the 95% confidence.

Fig7. (a) dZ/dH data for Hermanus observatory for 17 March 2015 (b) depicts the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Fig8. (a) dZ/dH data for Hartebeesthoek observatory for 17 March 2015 (b) depicts the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Fig9. (a) dZ/dH data for Tamanrraset observatory for 17 March 2015 (b) depicts the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

Fig10. (a) dZ/dH data for Mbour observatory for 22 June 2015 (b) depicts the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 256-512 min bands. The dashed line signifies the 95% confidence.

Fig11. (a) dZ/dH data for Hartebeesthoek observatory for 22 June 2015 (b) depicts the wavelet power spectrum of dZ/dH using Morlet wavelet. (c) Shows the global wavelet power spectrum while the dashed line denotes 5% significance level of the global wavelet spectrum and (d) Scale-average time series of the power wavelet over the 512-10124 min bands. The dashed line signifies the 95% confidence.

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Table 1 List of stations whose data are used together with geographic and geomagnetic coordinates.

Stations	Abbrev	Geog. lat. (deg)	Geog. Long. (deg)	Geomag. lat. (deg)	Geomag. Long. (deg)
Addis Ababa	AAE	9.03	38.77	0.16	110.47
Mbour	MBO	14.38	343.03	2.06	58.24
Hermanus	HER	34.43	19.23	42.39	82.15
Hartebeesthoek	HBK	25.88	27.71	36.31	94.72
Tamanrasset	TAM	22.79	5.53	9.22	78.37