EFFECT OF SOLAR WIND PRESSURE ON GEOMAGNETIC NORTHWARD COMPONENT OVER SOME SELECTED LOW-LATITUDE AFRICAN STATIONS

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Abstract

The geomagnetic field is a magnetic field that extends into space, interacting with the solar wind, a stream of charged particles emanating from the sun. The geomagnetic (H) component data used for this project were obtained from Magnetic Data Acquisition System (MAGDAS) magnetometer at five different stations in Africa covering magnetic latitudes (MLAT) from 21.13^0 in the northern hemisphere to -39.21^0 in the southern hemisphere and magnetic longitude (MLON) between 69° to 120° The stations are Fayum, Egypt (21.13° MLAT, 102.38° MLON), Ilorin, Nigeria (-1.82° MLAT, 76.80° MLON), Hermanus, South Africa (-42.29° MLAT, 82.20° MLON), Dal Es Salaam, Tanzania (-16.26° MLAT, 110.59° MLON), Abidjan, Ivory Coast (6.32° MLAT, 69.23° MLON). The daily variation of the geomagnetic H component (ΔH) is calculated by subtracting the baseline values. The baseline value is the average value of the nighttime flanking hours. The study examines the effect of solar wind pressure on geomagnetic fields across different hemispheres at different seasons. The outcomes of this study demonstrate geomagnetic disturbances of hemispheric asymmetry which varies with seasons for some selected African stations. After a close study of low-latitude geomagnetic disturbances caused by solar wind pressure enhancements, it is found that there is a significant hemispheric asymmetry of the geomagnetic disturbances and that this hemispheric asymmetry depends on the season and interplanetary magnetic field (IMF) orientation.

Keywords: Geomagnetic field, solar wind, interplanetary magnetic field, magnetometer

Introduction

The condition of the Sun, solar wind, magnetosphere, ionosphere, and thermosphere and their impact on satellite communication and ground-based technological systems can be referred to as space weather (Schwenn, 2006). The concept of space weather is complex and difficult to understand. Nevertheless, space weather variations vary over different timescales from hours to 11-year solar cycles and beyond (Lockwood, 2012). By implication, human life and our technology are vulnerable to disturbances from ~150 million km away (Shea and Smart, 1998) and in a particular way to those initiated by the explosive events on the Sun such as solar flares, solar energetic particles (SEPs) and coronal mass ejections (CMEs). The observed disturbances of the Earth's geomagnetic field at low latitudes are caused by several factors such as solar wind pressure enhancements, reorientations of the interplanetary magnetic field (IMF), and magnetospheric substorms (Sibeck *et al*., 1998, Huang and Yumoto, 2006). The Earth's magnetic field is known to originate from inside the Earth itself (internal) and outside (external). The geomagnetic field's internal sources originated from the Earth's core and lithosphere. The field from the core (main field) accounts for 95% of the Earth's geomagnetic field strength. This main field is generated from a self-sustaining dynamo process in the Earth's fluid outer core field (Hulot *et al.* 2015). The external sources originate in the ionosphere, and the magnetosphere, and electrical currents couple the ionosphere and magnetosphere (Mandea and Chambodut, 2020). The Earth's dipole field can be perturbed by the external current system (e.g., magnetopause current, the ring current, magnetic field-aligned currents, and the neutral sheet or cross-tail current.) resulting from the coupling of the time-varying solar wind and its interactions with the Earth's magnetic field (Singer *et al*., 1996).

Generally, the main field maintains the diversion of the time-varying solar wind flows around the Earth's magnetosphere. This causes the magnetosphere to compress and as the solar wind pressure increases, the dayside magnetospheric content becomes intense resulting in an increase in the geomagnetic field at low latitudes. Mead and Beard (1964) calculated the boundary of the geomagnetic field (magnetopause) in a solar wind using a self-consistent method. The reorientations of the IMF can impact the low-latitude geomagnetic field through the penetration process of the electric field (Fejer et al., 1979; Kelley *et al.*, 1979; Huang and Yumoto, 2006). Unless there is a magnetic reconnection of the IMF and the geomagnetic field, the solar wind particle cannot enter the magnetosphere. However, if the IMF orientation changes from northward to southward, the eastward electric field in the dayside ionosphere can be triggered by the penetration of the interplanetary electric field which will cause a disturbance in both the ionospheric current and the Earth's geomagnetic field. The ionospheric current system can greatly affect the electron density in the bottomside ionosphere (Bello *et al*., 2017; Bello *et al*., 2019; Bello *et al*., 2021).

Numerous reports have been on the statistical relationship between geomagnetic disturbances and solar wind pressure or with other sources such as IMF reorientations and substorms. Wintof (2005) uses solar wind data to develop a model to forecast the time difference between the local north-south (X) and east-west (Y) magnetic fields in Southern Sweden. They found these geomagnetic components have a strong dependence on the IMF, solar wind velocity and standard deviation of the proton number density. Huang and Yumoto (2006) described the geomagnetic disturbances caused by solar wind pressure. They demonstrate that hemispheric asymmetry exists in the geomagnetic disturbances which vary with seasons.

In this study, we examine the impact of solar wind pressure under different IMF conditions on geomagnetic field records of some selected African stations.

Data and methodology

The geomagnetic H component data used for this project were obtained from Magnetic Data Acquisition System (MAGDAS) magnetometer (Yumoto, 1996; Yumoto and CPMN Group, 2001; Yumoto and the MAGDAS Group, 2006; Yumoto and the MAGDAS Group, 2007) at five different stations in Africa covering magnetic latitudes (MLAT) from 21.13° in the northern hemisphere to -39.21° in the southern hemisphere. The stations are Fayum, Egypt (FYM), Ilorin, Nigeria ILR), Hermanus, South Africa HER), Dal Es Salaam, Tanzania (DES), Abidjan, and Ivory Coast (ABJ). The location of these stations is described by geographical latitude (GLAT) and longitude (GLON) as well as magnetic latitude (MLAT) and longitude (MLON) in Table 1.

Table 1. List of stations shown their geographical and magnetic locations

Code	Station Name	Nation	GLAT	GLON	MLAT	MLON	Install
ABJ	Abidjan	Ivory Coast	5.35°	-3.08°	6.32°	69.23°	10/08/07
DES	Dal Es Salaam	Tanzania	-6.47°	39.12°	-16.26°	110.59°	08/09/10
FYM	Fayum	Egypt	29.30°	30.88°	21.13°	102.38°	08/01/14
HER	Hermanus	South Africa	-34.34°	19.24°	-42.29°	82.20°	07/09/14
ILR	Ilorin	Nigeria	8.50°	4.68°	-1.82°	76.80°	10/03/25

There are many MAGDAS stations between 21.13° and -39.21° MLAT and beyond this latitude range, and the measure of geomagnetic disturbances of all low-latitude magnetometers in response to solar wind pressure enhancements have similar characteristics. This study covers the period of the year 2009 to 2010. The initial data resolution of the geomagnetic H component in a minute was converted to hourly data. The daily variation of the geomagnetic H component (ΔH) is calculated by subtracting the baseline values.

The baseline value is the average value of the nighttime flanking hours which is given as

$$\Delta \mathrm{H} = H_{LT} - \sum \frac{H_n}{4} \qquad (1)$$

The baseline value, $\sum \frac{H_n}{4}$ is subtracted from the raw values (in minutes) H_{LT} of the geomagnetic H component to give the daily geomagnetic variation of ΔH. The term Hn is the sum of the nighttime flanking hours of the geomagnetic field around the universal times 0000, 0100, 2200, and 2300 hours, respectively. The reason for subtracting the baseline value from the H component is that the changes noticed on the raw values (in minutes) were not significant enough.

The sudden increase of solar wind was matched with the impulse of the geomagnetic field across the stations, though there are some propagation delays. The impact of geomagnetic disturbance on these stations was observed using an interplanetary magnetic field (IMF Bz) and solar wind pressure (SWP) obtained from the OmniWeb website which can be accessed at https://omniweb.gsfc.nasa.gov/form/dx1.html. The screenshot of the OmniWeb user interface is shown in Figure 1.

Figure 1. Shows the picture of the website where the (IMF B_Z) and (SWP) were obtained.

Results and Discussion

The solar wind and the geomagnetic data are classified into three categories according to IMF orientations namely northward IMF, fluctuating IMF and southward IMF.

Case I- Northward IMF

Case one is described by the sudden increases of the low-latitude geomagnetic field northward (H) component caused by solar wind pressure enhancements during northward interplanetary magnetic field (IMF) and is illustrated in Figures 2 to 4. These figures show the three cases during the northward IMF in winter, summer and equinox respectively. For the case of northward IMF, the IMF must be continuously northward for at least 1 hour before the solar wind pressure enhancement and remain northward after the solar wind pressure enhancement. The magnitude of the IMF B_Z may change at the time of solar wind pressure discontinuity, but the direction of the IMF must remain unchanged.

Winter case was examined which occurred on 19th February 2009, as shown in Figure 2. From the top to bottom are the IMF B_z, solar wind pressure, and geomagnetic field northward (H) component measured at three magnetometer stations. The change in the orientation of the IMF B_Z (see the red dotted line) lead to a sudden increase in the solar wind pressure from 0.77 nPa at 0700 UT to 2.17 nPa at 14 UT and enhancement of the geomagnetic H component across the stations except at HER station. It is observed that the geomagnetic H-component at HER had already increased before the onset of the change in the orientation of IMF at 0700 UT and this is due to propagation delay. The maximum increase of the geomagnetic field is 13 nT at FYM, 56 nT at ILR and 11 nT at HER. The net increase of the geomagnetic field at ILR is 4.3 times that at FYM and 5.1 times that at HER.

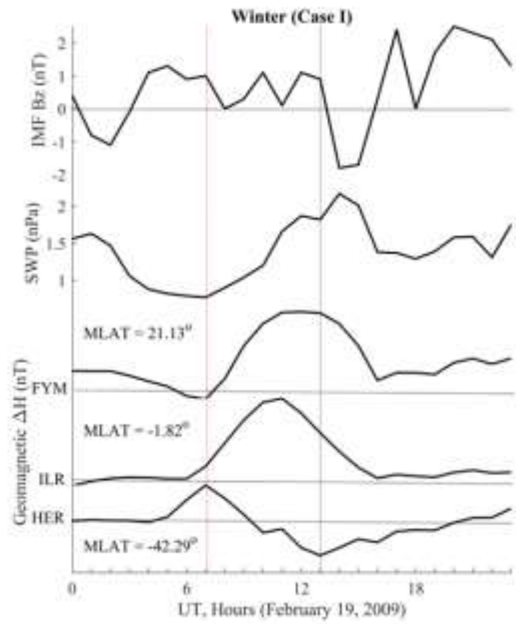

Figure 2: The northward IMF B_Z, solar wind pressure (SWP) and geomagnetic H field measurement at Fayum (FYM), Hermanus (HER), and Ilorin (ILR) during the winter season of 2009.

Figure 3 shows the summer case that occurred on 19th June 2009 for the typical case I northward IMF. The geomagnetic field shows a sudden increase at 0600 UT in response to solar wind pressure enhancement. The peak values of the geomagnetic field during the solar wind enhancement are 31 nT at FYM, 49 nT at ILR and 9 nT at HER. The ratio of the magnetic field increase at ILR and FYM is 1.6, and the ratio of the magnetic field increase at ILR to that at HER is 5.4.

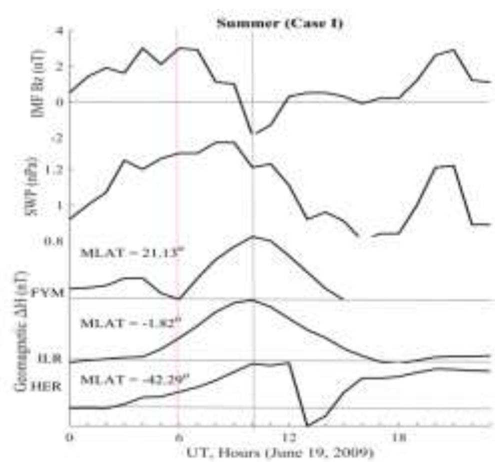

Figure 3: Same as Figure but for the summer season June, 19th 2009.

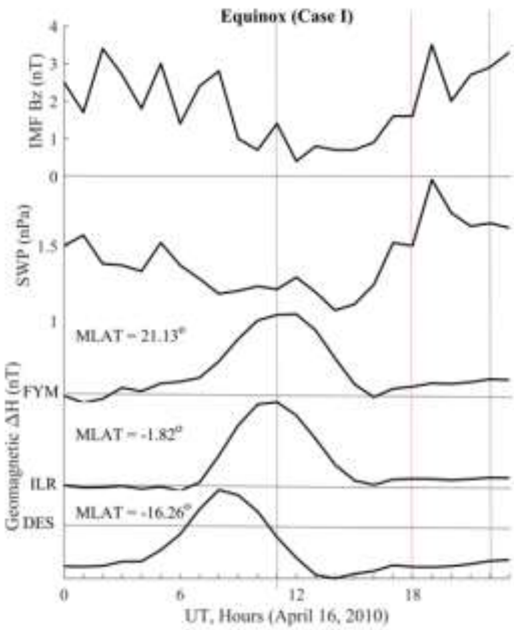

Figure 4. The northward IMF B_Z, solar wind pressure (SWP) and geomagnetic H field measurement at Fayum (FYM), Dal Es Salaam (DES), and Ilorin (ILR) during the equinox season of 2009.

The Equinox case that occurred on 16th April 2010 is shown in Figure 4. In this case, no data is available at the HER station and data at DES (-16.26° MLAT) station is used to describe the geomagnetic field variation in the southern hemisphere. At 1900 UT (see the red dotted line) there is a sudden increase in the orientation of the IMF B_Z field which leads to an increase in the solar wind pressure. The magnitude of the geomagnetic field decreases at this point. However, the strength of the magnetic field is greater during the daytime with peaks around the local noon across the three stations. Both the neutral winds and local conductivities in the ionospheric E -region has be found to be dominant factors that control the variation of the geomagnetic northward components (Pedatella et al., 2011; Bello et al., 2017).

Case II - Fluctuating IMF

The sudden increases of the low-latitude geomagnetic field northward (H) component caused by solar wind pressure enhancements during fluctuating interplanetary magnetic field (IMF) for case II is shown in Figures 5 to 7. These three figures show the cases during the fluctuating IMF in winter, summer and equinox respectively. For the case of fluctuating IMF, the IMF Bz may be very small or change direction across the solar wind pressure discontinuity.

Figure 5 shows the changes in the geomagnetic caused by the change in the orientation of the IMF and the solar wind pressure at 0400 UT. The variation in the geomagnetic field at ILR is higher than the stations in the northern and southern hemispheres. The noon time peak of geomagnetic H components is 30 nT at the ILR, 14 nT at FYM and -22 nT at HER. A similar observation can be seen during the summer case (Figure 6). In this case, the solar wind pressure enhancement is much higher at ILR which is close to the equator than FYM and HER which is away from the equator. The daytime geomagnetic field is 43 nT at ILR, 17 nT at FYM and with two peaks at HER. The pre-noon peak at HER occurs at 0700 UT with a magnitude of 12 nT and -8 nT at 14000 UT. For the case of the equinox (Figure 7), the change in IMF caused the amplitude of solar pressure to increase from 2 nPa at 0600 UT to a peak value of 2.4 nPa at 1000 UT. The solar wind pressure enhancement can be seen to trigger the changes in the magnetic field in the three stations and ILR higher than northern and southern hemispheres with a ratio of 1.33 increase in geomagnetic field at ILR to that at FYM and 8 at ILR to that of HER.

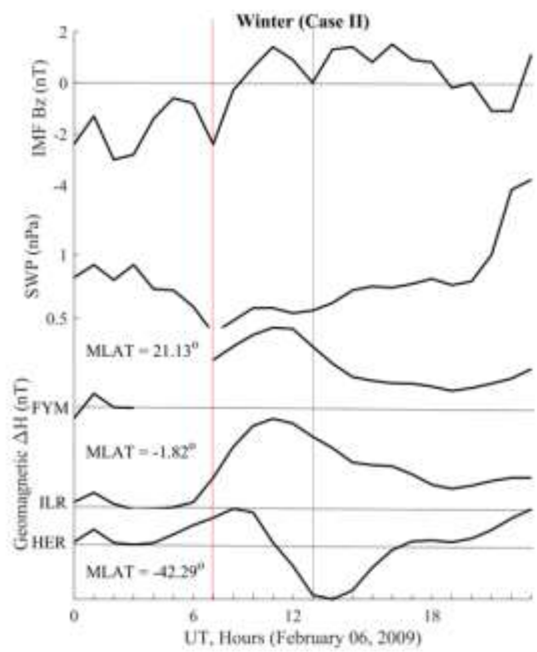

Figure 5. The fluctuating IMF B_Z, solar wind pressure (SWP) and geomagnetic H field measurement at Fayum (FYM), Hermanus (HER), and Ilorin (ILR) during the winter season of 2009. The magnetic latitude(MLAT) for each station is given in the figure.

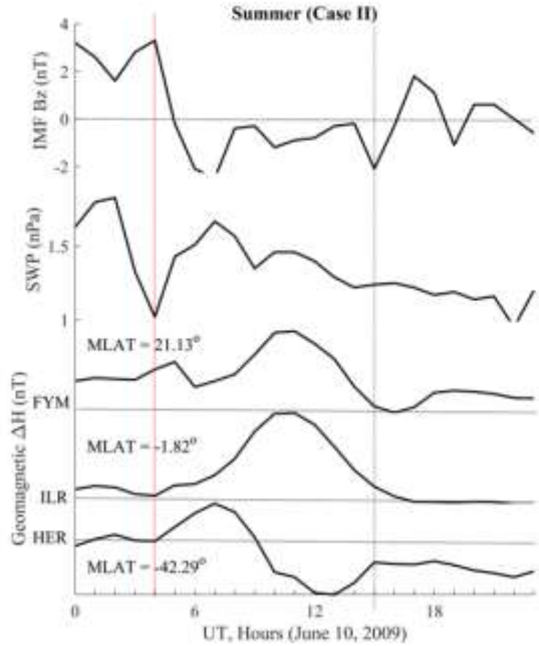

Figure 6. Same as Figure 5 but for the summer season of the year 2009

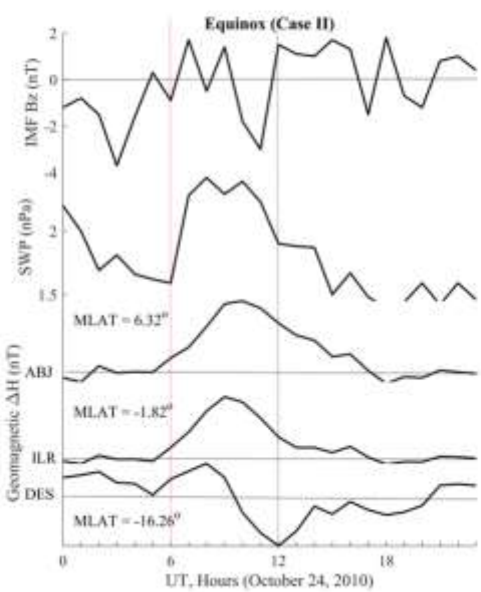

Figure 7. The fluctuating IMF B_Z, solar wind pressure (SWP) and geomagnetic H field measurement at Abidjan (ABJ), Hermanus (HER), and Ilorin (ILR) during the equinox season of 2010. The magnetic latitude (MLAT) for each station is given in the figure.

Case III - Southward IMF

Figures 8 to 10 describe the three cases that occurred during the southward IMF. In this case, the orientation of the IMF is continuously southward for a minimum of 1 hour before an increase in solar wind pressure and remains southward across the solar wind discontinuity. In Figure 8, there is a rapid increase in the geomagnetic field at FYM and ILR stations at 0800 UT, and the magnitude of the field at HER decreases until a minimum value of -18 nT at 1300 UT. The ratio of the net increase in the geomagnetic field at ILR 9 to that FYM. In summer (Figure 9), the changes of the geomagnetic field at the stations follow the solar wind enhancement from 0.5 nPa at 0200 UT to a maximum value of 1.6 nPa at 0700 UT. This occurrence in turn causes an increase in the geomagnetic field to be around 11 nT at FYM, and 38 nT at ILR while at HER there are two peaks during the pre-noon at 0900 UT with a magnitude of 14 nT and -23 nT at 1400 UT.

For the equinox case shown in Figure 10, the magnitude of the solar wind pressure increases from 0.6 nPa at 0800 UT to 1.6 nPa at 1400 UT. Within this period, IMF continues to maintain a southward orientation with a significant increase in the geomagnetic field in the northern and southern hemispheres. The magnitude of the field is 37 nT at FYM, 8 nT at ILR and 30 nT at DES. The values of the field at ILR appear constant during the daytime.

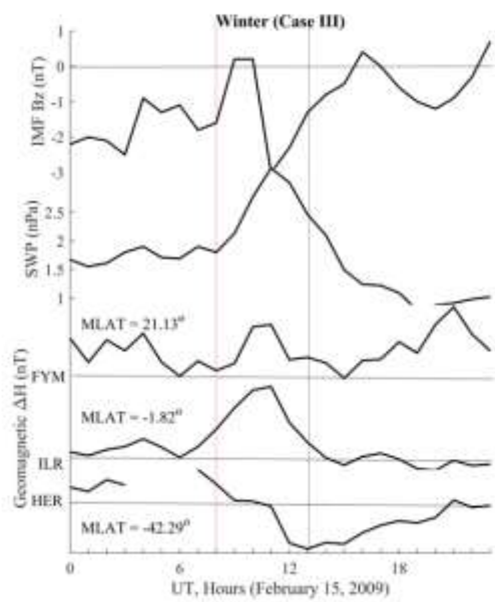

Figure 8. The southward IMF B_Z, solar wind pressure (SWP) and geomagnetic H field measurement at Fayum (FYM), Ilorin (ILR) and Hermanus (HER) during the winter season of 2009. The magnetic latitude (MLAT) for each station is given in the figure.

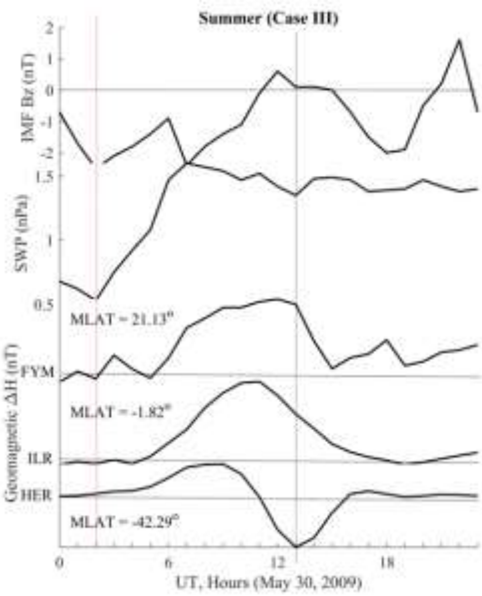

Figure 9. Same as Figure 8 but for the summer season of the year 2009.

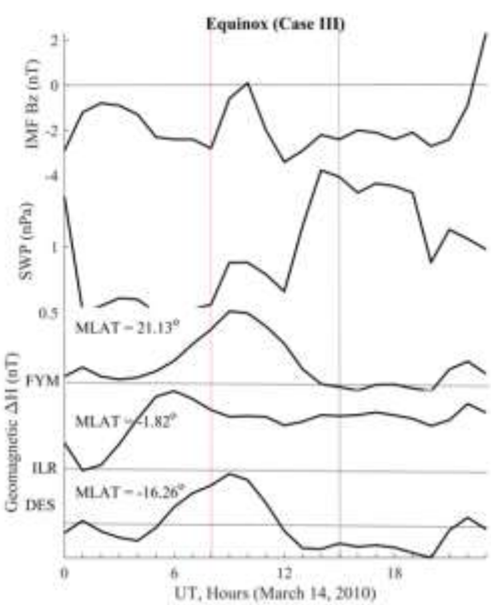

Figure 10. The southward IMF B_Z, solar wind pressure (SWP) and geomagnetic H field measurement at Fayum (FYM), Ilorin (ILR) and Dal Es Salaam (DES) during the equinox season of 2009. The magnetic latitude (MLAT) for each station is given in the figure.

The results obtained demonstrated that the response of the low latitudes geomagnetic field to the changes in the IMF orientations and the solar wind pressure enhancements are significantly larger in the equatorial stations than those in the northern and southern hemispheres. According to the works presented by Huang and Yumoto (2006), this variation in the responses of the geomagnetic field across these stations during different seasons is related to the tilt of the Earth's magnetic axis

Conclusion

In this study, an analysis of low-latitude solar wind disturbances caused by solar wind enhancement under different IMF conditions and seasons was examined. The orientation of the IMF is observed to play an important role in the energy transfer from the solar wind to the magnetosphere and only events with prolonged and sufficiently strong southward IMF can drive intense magnetospheric storms. The outcomes of the study demonstrate geomagnetic disturbances of hemispheric asymmetry which varies with seasons for some selected African stations. The observed disturbances near the equatorial region are found to be larger than regions far away from the dip equator irrespective of being in the northern or southern hemisphere.

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