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A study on the effects of solar wind and interplanetary magnetic field on geomagnetic H-component during geomagnetic storms

S. O. Chiaha[1*], O. J. Ugonabo[1] and K. C. Okpala[1]

Department of Physics and Astronomy, Faculty of Physical Sciences, University of Nigeria, Nsukka, Enugu State, Nigeria.

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During geomagnetic storms, the geomagnetic H component is depressed which is preceded by a sudden storm commencement (SSC) or not and this is categorized as sudden or gradual storms. Using the method of cross correlation analysis, we have studied the associations of geomagnetic H components at four low latitude stations at longitudinal separations of 145° - 215° with solar wind density and interplanetary magnetic field (IMF) B during the four most intense sudden and four most intense gradual geomagnetic storms in solar cycle 23. In addition to dawn-dusk responses, how the ionospheric and magnetospheric currents respond to these variations at low latitudes during geomagnetic storms will be determined. Results show that profiles of cross correlation coefficients against time lags were superposed and had peak associations at zero time lags during each event for both parameters. Also there was no dawn-dusk variation in the profiles which implies that the magnetosphere responds uniquely to sources of external origin during geomagnetic storms at low latitudes..

Key words: Geomagnetic storms, solar wind and interplanetary magnetic field (IMF) parameters, geomagnetic H components.

INTRODUCTION

The study of geomagnetic field variation is necessary especially during geomagnetic storms because it is strongly coupled to the ionosphere, magnetosphere and interplanetary space whose conditions affect space borne, ground based technological systems and human life or health. Interacting with the solar wind from the sun is the magnetosphere that surrounds earth and dominated by its magnetic field. The bow shock, magnetopause, magnetotail are the outer regions of the magnetosphere while the plasmasphere, Van Allen radiation belt and the ring current characterized by the population of charged particles form the inner regions of the magnetosphere (Moldwin, 2008; Campbell 2003). Van Allen radiation belt consist of trapped energetic charged particles with energy extending into the relativistic regime (about 0.86c, where c is the speed of light). The region is the source of magnetohydrodynamic waves from which geomagnetic ultralow frequency pulsations were observed. Global cavity and wave guide modes have been offered as possible sources of such

*Corresponding author. E-mail: shedrach.chiaha.pg77234@unn.edu.ng.

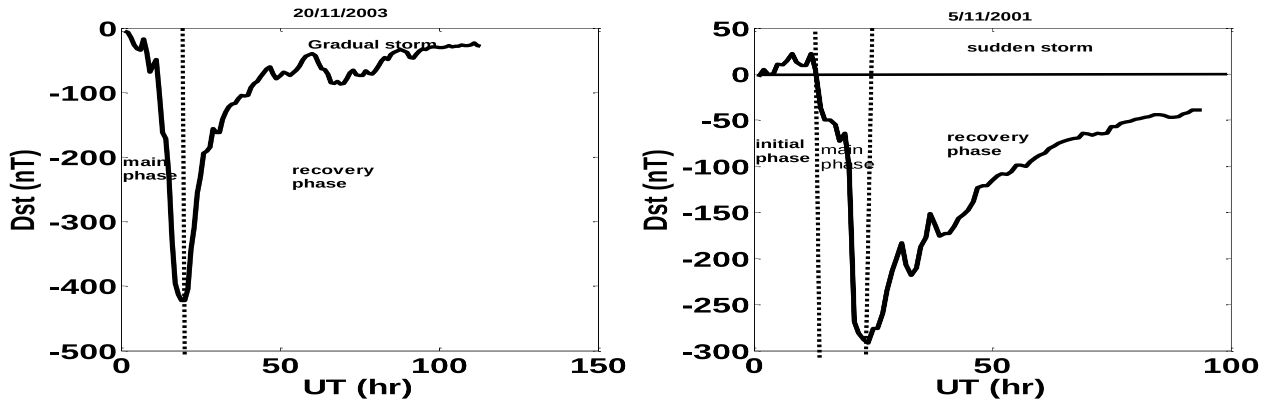

Figure 1. Profiles of gradual and sudden geomagnetic storms.

waves on Earth. In these models, the magnetosphere is presumed to resonate globally at frequencies determined solely by its internal properties such as size, shape, field topology, etc. However, we show in this work that upstream solar wind and interplanetary magnetic field precede and drive magnetic field variations on ground during geomagnetic storms. Observers prefer to describe a vector representing the Earth's field in one of two ways: (1) three orthogonal component field directions with positive values for geographic northward, eastward and vertical into the Earth typically called the X, Y and Z representation or (2) the horizontal magnitude, the eastward (minus sign "-") angular direction of the horizontal component from geographic northward and the downward component called the H, D and Z representation (Campbell, 2003). The compression of earth magnetosphere during geomagnetic storms is observed on depression of the vector component H. A classical geomagnetic storm (Figure 1), which can be divided into initial, main and recovery phases. Geomagnetic storms can be subdivided into sudden and gradual storms depending on whether a sudden storm commencement (SSC) was observed at the onset of the storm or not. Gradual geomagnetic storms (GG-storms) do not exhibit SSC nor have initial phase, with their main phase starting at or below zero.

Owing to the fact that the magnetosphere is a region dominated by Earth's magnetic field and interacts with solar wind from the sun, studies have reported solar wind and IMF parameters as direct drivers of geomagnetic field variations. Kepko et al. (2002) and Vichare et al. (2009) from results of correlations, obtained an association between solar wind and interplanetary magnetic field parameters with geomagnetic field. Vichare et al. (2009) among all solar wind and IMF parameters obtained highest correlation coefficient of 0.46 at time lag of 36 min for dynamic pressure with geomagnetic field at Alibag (~10°N) during sudden geomagnetic storm. This is similar to the strong correlation coefficient (0.9) obtained between dynamic pressure and geosynchronous magnetic field (Kepko et al., 2002). These results preclude a cavity or waveguide explanations, suggesting that the solar wind dynamic pressure affect the size of the magnetosphere. Furthermore, strong correlation between square root of solar wind dynamic pressure and geomagnetic H component during period of northward and southward IMF conditions indicates that the geomagnetic field responds well to a series of stimulations on the magnetopause (Francia et al., 1999; Russell et al., 1992; Russell and Ginskey, 1995). Geomagnetic field H components at L'Aquila station (36.2°N), low latitude stations below 50°, along with 11 subauroral stations at latitudes between 54.1° and 58.2° were studied respectively. The local time dependence (with lower values in the local morning and evening and greater values around local noon and midnight) imply that the magnetosphere is a highly dynamic system which responds very rapidly to external changes. For southward IMF, the magnetic field was about 25% smaller due to the presence of magnetospheric current systems and much greater than that observed for northward IMF at night. Similarly, Vichare et al. (2009) performed day and night cross correlation analysis of geomagnetic H components with solar wind density during six geomagnetic storm events. The result shows no day and night effect in their associations as daytime values were sometimes larger than nighttime values and vice versa. Magnetospheric current variation with local time was also obtained from the work of Wang et al. (2009). Strong correlation coefficient (0.90) was obtained at subsolar region (0900-1500LT) between Symmetric H (SYM-H) and dynamic pressure for 250 interplanetary (IP) shocks. It was observed that 34 IP shocks located on the night side and the dynamic pressure prior to the IP shock arrival were relatively smaller; therefore, significant changes of the geosynchronous magnetic field was not detected. If the magnetosphere does not respond to external influence, the magnetospheric currents would maintain their symmetry at every location and time.

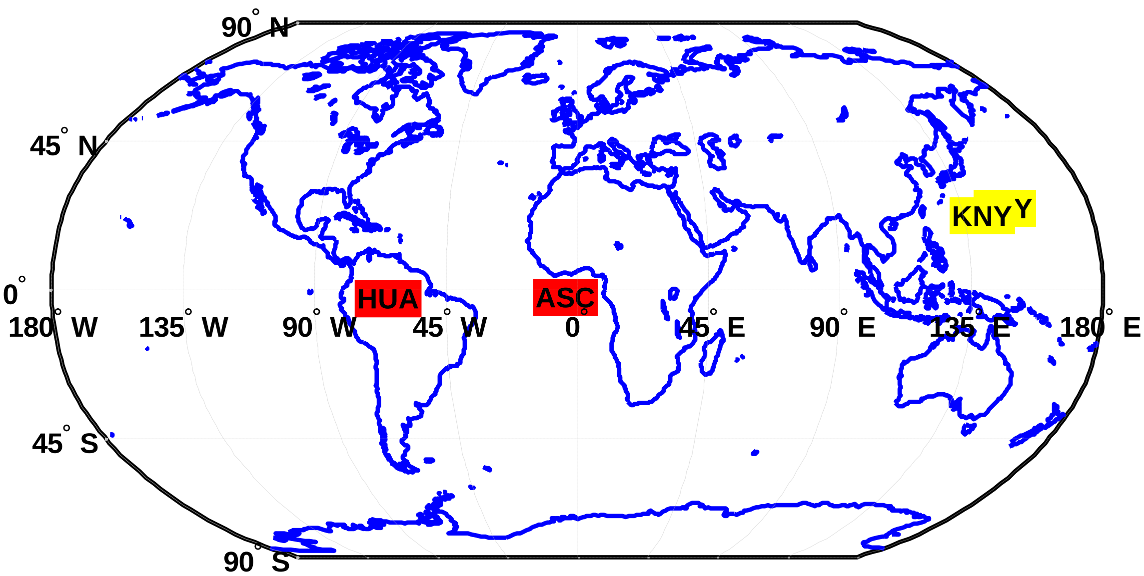

Figure 2. Distribution of geomagnetic stations.

During geomagnetic storm, the magnetosphere responds to solar wind and interplanetary magnetic field as manifested in the decrease of geomagnetic field measured at Earth surface. Such surface variations are created by magnetosphere and ionospheric sources of the magnetic field as well as by conductive currents flowing in the conductive Earth (Kalegaev and Makarenkov, 2005).

Also, disturbed storm time (Dst) which is calculated to estimate the contribution of the ring current on geomagnetic H variation shows the magnetosphere response to solar wind from the sun during geomagnetic storm. From investigations on the influence of the solar wind dynamic pressure on the decay and injection of the ring current, Wang et al. (2003) and Shi et al. (2005) obtained results that the ring current injection was proportional to the solar wind dynamic pressure for southward B_z. This implies that the ring current injection increases when the magnetosphere is more compressed by high solar wind dynamic pressure. The Dst also had strong correlation with solar wind velocity, IMF B but low (0.24) for B_z suggesting that southward magnetic field component B_z has significant growth mainly during (or before) the initial phase of geomagnetic storm (Balveer et al., 2011, 2014). Seemingly, employing method of cross correlation, Ayush et al. (2017) studied the association between IMF B_z with Dst, solar wind density, temperature and velocity. The results obtained strongly suggest that IMF B_z has strong impact for the cause of geomagnetic storms with Dst index of 250, -400 and -300 nT, respectively. However on grounds of results from other works, on the association of geomagnetic field with solar wind and IMF parameters during periods of northward and southward IMF at low and mid latitudes for day and night times, this study intend to identify dawn-dusk response in the association of disturbed geomagnetic H component with sources of external origin (solar wind and IMF parameters). Also of importance, is measuring the association of geomagnetic H component with solar wind and IMF parameters specifically during sudden and gradual geomagnetic storms at low latitudes.

DATA SET AND METHODOLOGY

The data for this work were obtained from two different sources. The first set - ground horizontal magnetic field component for disturbed and quiet days recorded at four geomagnetic observatory stations were obtained from the world data Centre (WDC) for geomagnetism, Kyoto, Japan. The second set of data: disturbed storm time (Dst) index and IMF parameters which includes total magnetic field (B) and density (D) were obtained from www.omniweb.gsfc.nasa.gov. In selection of storm events, eight events were considered which includes four sudden and four gradual storms (GS) in solar cycle 23 as observed by Pandey and Dubey (2009). The initial, main and recovery phases of geomagnetic storm events were employed. Also, four low latitude geomagnetic stations were selected in the range of 0° - 25° geomagnetic latitude (GM). The stations were selected in such a way that two stations separated in longitude by about 145° - 215° would help in identifying dawn-dusk asymmetries (Figure 2 and Tables 1 and 2).

Cross correlation analysis

Cross-correlations help identify variables which are leading indicators of other variables or how much one variable is predicted to change in relation with the other variable. The cross-correlation test of two time-series data sets involves calculations of the coefficient (r) by time-shifting the one data set relative to the other data set. In this case, solar wind and IMF parameters were sliding under the geomagnetic H components to find signatures of them at various time lags (L). The analysis of the variables was done with

Table 1. Selected geomagnetic storm events.

S/N	Date of occurrence	Type of storm	Intensity of storm (nT)	Duration of initial phase (h)	Duration of main Phase (h)
1	7^{th} - 8^{th} Nov. 2004	SS 1	-373	03	10
2	15^{th} - 16^{th} July, 2000	SS 2	-301	01	09
3	5^{th} - 6^{th} Nov. 2001	SS 3	-292	08	12
4	15^{th} - 16^{th} May, 2005	SS 4	-263	04	03
5	20^{th} - 21^{th} Nov. 2003	GS 1	-422	00	17
6	6^{th} - 7^{th} April, 2000	GS 2	-288	00	08
7	11^{th} - 12^{th} May, 2001	GS 3	-271	00	07
8	9^{th} - 10^{th} Nov. 2004	GS 4	-289	00	24

Table 2. Geomagnetic stations showing latitudes and longitudes.

S/N	Station	Lat.(°)	GM Lat.(°)	Long.(°)
1	Ascension Island (ASC)	12.04S	2.28S	14.38W
2	Huancayo (HUA)	7.95S	2.74S	75.32W
3	Hartizyo (HTY)	33.07N	24.59N	139.82E
4	Kanoya (KNY)	31.42N	22.30N	130.88E

the hourly data of each geomagnetic station, solar wind and IMF parameters at 99% confidence level along with 0.01 significance. The cross correlation (r) at time lag (L) (Bourke, 1996) is defined as

$$r = \frac{\sum_{i=0}^{N}[x(i)-mx)*(y(i-d)-my)]}{\sqrt{\sum_{i=0}^{N}(x(i)-mx)^2}\sqrt{\sum_{i=0}^{N}(y(i-d)-my)^2}} \quad (1)$$

Where x(i) and y(i) are two-time series, i = 0,1,2, …., N, delay (d) = 0,1,2, ……., N, mx and my are the means of the corresponding series. If the above is computed for all time lags L = 0, 1, 2… N, it results in a cross correlation series of twice the length as original series and N is the number of variables. In other to verify the normal distributions of the data, a two tail t-test comparing the two averages to obtain t values and how significant the differences are, were obtained.

RESULTS AND DISCUSSION

The profiles of cross correlations coefficient (r) against time lags (L) for the main and initial phase of geomagnetic storms are subsequently shown. For sudden storms, the initial and the main phase profiles were plotted while main phase were plotted for gradual storms. Figures 3 and 4 show that the profiles for the four geomagnetic stations were superposed on each other during all geomagnetic storm events.

Figures 3 and 4 show the profiles of cross correlation coefficients (r) against time lags (L) for various stations at low latitude separated in longitudes of which their peak values were strong, unique without time delays for every station during each gradual and sudden storm event. The profiles of solar wind and IMF parameters were strongly associated with the geomagnetic field in decreasing order as the solar wind density and IMF B were sliding from left to right for all events. Examining the profiles in Figures 3 and 4 as solar wind density and IMF B were shifted to the left, it was observed that the correlation coefficients were decreasing more than that obtained as they were shifted right. Meaningfully, these results portray the magnetosphere response to upstream solar wind during geomagnetic storms and that solar wind density and IMF B have strong peak associations with geomagnetic H components at the onset of intense geomagnetic storms. Furthermore, similar profiles of correlation coefficients for gradual and sudden storms were observed as there was no significant difference. From Table 3, peak correlation coefficients of solar wind density and IMF B for gradual storms had no order but the associations were higher for IMF B (0.76) on average compared to that of solar wind density (0.68). For sudden storms, each correlation coefficient of IMF B was stronger than those of solar wind density, 0.72 and 0.54 on average, respectively. Performing the same analysis for just an event, Vichare et al. (2009) obtained solar wind pressure and density amongst all solar wind and interplanetary magnetic field parameters, the highest weak correlation coefficient of 0.46 at a time lag of 36 min for a storm event. Furthermore, uniqueness in the profiles of correlation coefficients and their time lags for each event indicate there was no dawn dusk responses at low latitudes for station pairs separated with about 145 to 215° in longitude. Similar result was obtained by Vichare et al. (2009) where strong correlation coefficient of 0.8 at a time lag of 2 min between two geomagnetic H components at stations separated by ~17 and ~67° in

Table 3. Peak correlation coefficients.

S/N	Storm	Solar wind density	Time lag (L)	IMF B	Time lag (L)
1	GS 1	0.79	0	0.76	0
2	GS 2	0.57	0	0.73	0
3	GS 3	0.55	0	0.79	0
4	GS 4	0.82	0	0.77	0
5	SS 1	0.56	0	0.78	0
6	SS 2	0.64	0	0.68	0
7	SS 3	0.52	0	0.71	0
8	SS 4	0.47	0	0.71	0

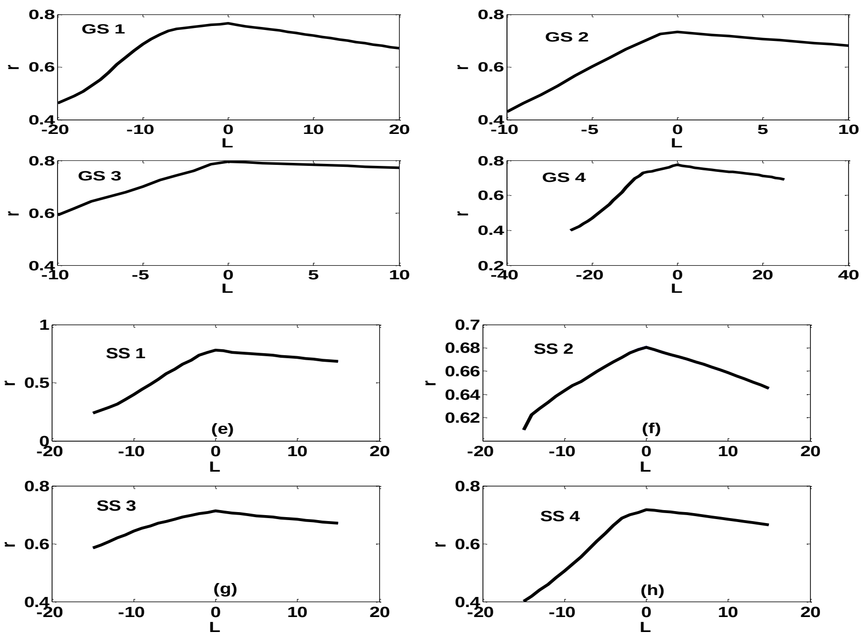

Figure 3. Profiles of correlation coefficient (r) against time lag (L) with IMF B for all station.

latitude and longitude, respectively. Dawn-dusk scenario in location of the stations was done and can clearly be pictured in this work by examining the positions of the stations as the earth rotates eastward. Adding 180° to the longitudes of ASC and HUA, 194.38 and 255.32° would be obtained respectively as their positions on the globe as the earth rotates eastward. Comparing the positions of the stations, using 180° or Greenwich meridian as bench mark for dawn-dusk sectors, KNY and HTY at 139.82 and 130.88° are therefore on the dawn-dusk side of earth at different time as compared to ASC and HUA.

In examining day and night effect, Russell et al. (1992), Francia et al. (1999), Russell et al. (1994), and Russell and Ginskey (1995) found variations in local time in the association of square root of SW dynamic pressure with H component at a particular station, including strong correlation coefficient (0.90) obtained at subsolar point (0900 - 1500 LT) (Wang et al., 2009). However, observations show that for each burst of solar wind during intense gradual and sudden geomagnetic storms, signatures of solar wind and interplanetary magnetic field drive equally the geomagnetic fields irrespective of longitudinal separations of stations and the geomagnetic field responds well to sources of external origin.

Also, Li et al. (2011) identified that when there are no dawn-dusk and day night responses in the geomagnetic H component, the partial ring current and the magnetotail current are not the predominant contributor to the depression seen. Examining the three main current that contribute to geomagnetic H depression, the ring current is the only predominant current left to contribute to this unique correlation coefficient obtained for each storm event. Also, as identified by Bakhmina and Kalegaev (2008) and Kalegaev et al. (2005), the magnetotail current do not contribute to storms of magnitudes above -200 nT and so the non-dawn dusk asymmetry in the

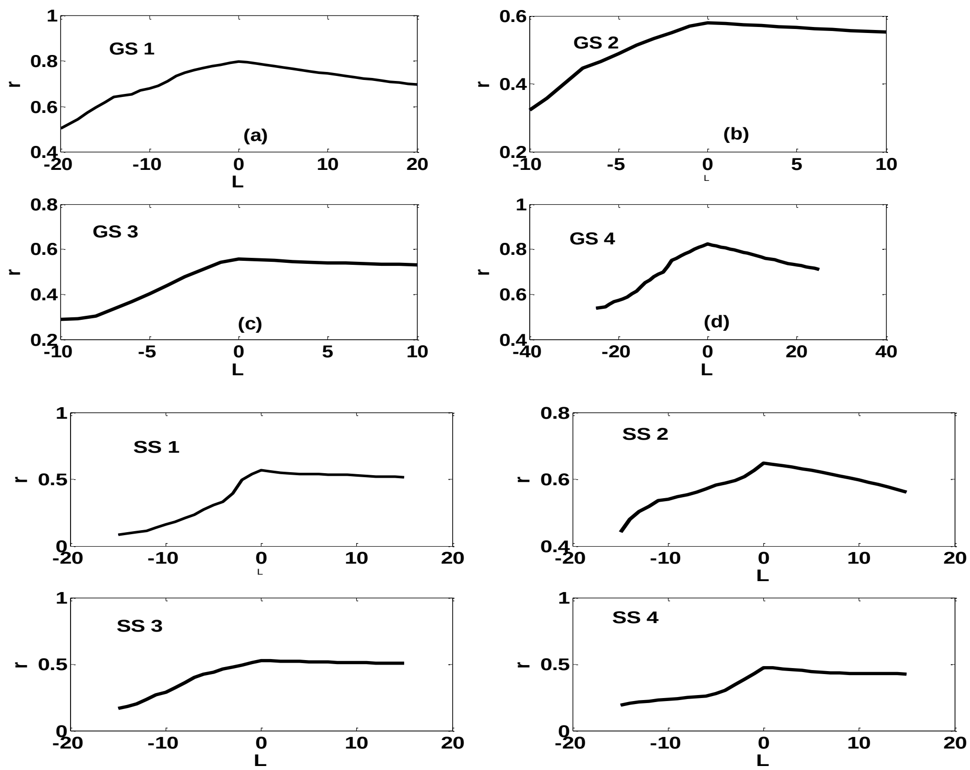

Figure 4. Profiles of correlation coefficient (r) against time lag (L) with solar wind density for all station.

correlation coefficients are definitely from the ring current in the magnetosphere. Ionospheric currents which are masked in the geomagnetic H field during geomagnetic storms (Chapman, 1951; Kane, 1978; Burrows, 1978) and causes less depression as we move from low to mid latitudes during geomagnetic storms (Rastogi, 2005), did not have any or such effect in profiles of the associations. In same vain, Russell et al. (1992), Russell et al., (1994) and Vichare et al. (2009) isolated equatorial electrojet (EEJ) and ionospheric currents in association of square root of solar wind dynamic pressure with geomagnetic H field for period of northward and southward IMF, by measuring the associations 10 min from the peak associations and selecting stations away from EEJ regions. However, results from this work show that the presence of ionospheric currents and selection of stations from EEJ regions have no effect in associations of solar wind and IMF parameters with geomagnetic H components as profiles for low latitude (including ASC & HUA in the EEJ regions) stations were same as that of other stations. These results also signify that the magnetosphere plays a role in signatures of geomagnetic fields observed on ground by the response of its current systems to solar wind and interplanetary magnetic field parameters during geomagnetic storms. Therefore, the global cavity and wave guide modes in which the magnetosphere is presumed to resonate globally at frequencies determined solely by its internal properties such as size, shape, field topology (Kivelson et al., 1984; Kivelson and Southwood, 1985; Samson et al., 1991) is not supported. More so, plots of correlation coefficients (r) against time lags (L) from Figures 3 and 4 show the profiles superposed on one another (that is, the profiles during each event for the four stations were unique after cross correlation analysis) for each gradual and sudden geomagnetic storm irrespective of longitudinal separation of geomagnetic stations. Low latitude profiles for each storm event are presented in the figures and the single profile on each

further depicts the uniqueness in their associations.

Conclusion

We have studied latitudinal and dawn-dusk responses in the associations of disturbed geomagnetic H components, at low latitude stations with solar wind density and IMF B during the four most intense gradual and four most intense sudden geomagnetic storms in solar cycle 23. Cross correlation analysis was used to obtain the correlation coefficients at their respective time lags and profiles of the initial and main phases plotted. The results were all significant at 99% confidence level. From our findings, the following conclusions were reached:

(1) There were no dawn-dusk responses in the correlation coefficients for disturbed geomagnetic field with solar wind and IMF parameters. All the stations had strong correlation coefficients at the onset of the main phase or initial phase for each storm event without time delay. The result portrays the geomagnetic field responds to sources of external origin with the ring current in the magnetosphere been responsible for the pattern of associations.

(2) Also, no significant difference was observed in the correlation profiles of sudden and gradual storms. Both parameters had associations from profiles of correlation coefficients at time lags to the left and right from the peaks at onset of storms.

(3) On average IMF B had the strongest peak correlation coefficients for gradual and sudden storms..

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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