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Inter-Correlation Analysis of Magnetic Activity Indices during Varying Geomagnetic Conditions and Phases

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ABSTRACT

The linear interrelationship between the *Dst*, *AE*, *ap*, and the *IMF-Bz* were presently investigated in pairs and multiples during magnetic quiet ($ap \leq 7nT$), disturbed ($ap > 7\,nT$), and combined activities, as well as for different storm phases using data obtained from 1996-2006. The results from the study indicate the highest correlation percentage ($\%_{corr}$) between pairs of indices was for the *AE/ap* (73%) occurring during the storm onset phase. The Dst/ap $\%_{corr}$ was 21-57%, AE/ap (50-73%), Dst/AE (23-52%), Bz/AE (5-40%), *Bz/ap* (24-60%), and Bz/Dst (7-37%) across various levels of activities. The results for the multiple correlation relationships of the $ap = a(AE) + b(-Dst)$ and $Bz = a(ap) + b(AE) + c(-Dst)$ showed that the magnitudes of the coefficients of best fit are smallest during quiet magnetic activity in comparison to other activities, suggesting that *ap* and *Bz* are well explained by the independent variables carrying the coefficient during the quiet condition and can be better inferred during the same period of magnetic activity. The present results suggest that the *ap* index is well correlated with the Dst as an intermediate index regarding the ap index and can describe the general state of planetary geomagnetic activity. It contains at least two or more major sources, the auroral electrojet (AE) and the ring current; also, by means of a multiple correlation program, a linear fit can be performed for *ap* in terms of AE and Dst. Furthermore, only the AE/ap pair has a $\%_{corr}$ of above 50% for any activity class. For the entire data span, the *AE/ap* pair performed best at 67%, followed by the Bz/ap pair with 59%, and the least was the Bz/Dst pair with 37%. Additionally, the results revealed that the AE/*ap* relationship presents the highest values of 73.25%, 62.16% and 68.56% during the storm onset, main, and recovery phases, respectively.

Keywords:
Geomagnetic indices,
Mid-latitude magnetic index,
Auroral Electrojet,
Disturbance storm time index.

INTRODUCTION

The Geospace, the region of outer space (extending from the Earth's atmosphere to the ionosphere, plasmasphere and magnetosphere) is influenced by Earth's magnetic field and the flow of charged particles from the Sun. Consequently, the understanding of the geospace environment is significant for various scientific activities, including space weather forecasting, satellite communications, and the study of Earth's magnetic field interactions with the Sun. Researchers, therefore, use a combination of ground-based and space-based probing equipment, such as satellites and radar systems, to observe and study the properties and dynamics of geospace. In investigating the dynamics, to be able to forecast the events ahead of occurrence time, specific indices are presented, that serve as indicators or proxies of such activities. Possible causes of variation in the geospace environment, especially relating to the ionospheric F-region are electrodynamics (e.g. plasma convection), neutral atmosphere (e.g. gravity waves), solar ionizing variation (e.g. solar cycle variations) and geomagnetic activity (Rishbeth and Mendillo, 2001; Buresova et al., 2014; Adebesin et al., 2018; Adekoya et al, 2023). Of relevance to the current work is the last causative factor – the geomagnetic activity, which are disturbances in the Earth's magnetic field when it interacts with the solar wind and other external factors through the influence of the Sun's activity including solar flares and coronal mass ejections; whose key manifestations could be in form of geomagnetic storms, substorms and auroras. Monitoring and predicting geomagnetic activity is however of great value in mitigating potential impacts on technological systems. This brings to the fore the introduction of Geomagnetic indices, which are numerical measures used to quantify, track, and provide information about the state of the Earth's magnetic field depicting the different phases/levels of geomagnetic disturbances (Adekoya and Adebesin, 2015; Astafyeva et al., 2015; Adekoya and Chukwuma, 2018).

Numerous geomagnetic indices, which are measures of various magnetic activities, are derived from ground magnetometer measurements (Rostoker, 1972; Menvielle, M. and Berthelier,1991; Menvielle et al., 2011). Some of the geomagnetic indices for analyzing geomagnetic activities include the disturbance storm time index Dst (representing the average deviation of the horizontal component from its normal value reduced to the dip equator, and obtained from four low-latitude stations, measuring the strength of the ring current during the main and recovery phases of a geomagnetic storm); the *SYM-H* (similar to the *Dst*, but with a higher resolution of 1-minute temporal resolution); the *AU/AL* (measures of the maximum eastward/westward auroral electrojets in the auroral zone); the AE (a measure of the auroral electrojet during substorms, and is obtained from about ten stations in the northern auroral zone); the Kp/Ap/ap indices, in which case the K-index quantifies disturbances in the horizontal component of earth's magnetic field at mid-latitudes with an integer in the range 0-9 with 1 being calm and 5 or more indicating a geomagnetic storm. The K index gives the 3-hour range of geomagnetic activity at different observatories and is obtained during each 3-hourly time interval by measuring the difference between the absolute maximum and minimum values for the most disturbed horizontal magnetic field component. The 3-hourly ap index is derived directly from the Kp index and is based only on mid-latitude observations. While the Kp is in the quasi-logarithmic scale, the ap is transformed into a linear scale. The *Ap* is the daily average of ap. The only advantage of ap over Kp is the change from a quasi-logarithmic to a linear scale (Menvielle and Berthelier, 1991). The *Ap* is therefore the planetary index for measuring the strength of a disturbance in the Earth's magnetic field. More information on the earlier derivation of these indices could be obtained from the work of Mayaud (1980) and Rostoker (1972).

Other indices related to the *K, Kp*. and *Ap* are linear versions of *K* and *Kp. Kn, An, Ks*, and *As* are similar to *Kp* and *Ap* except that they are used, respectively, in northern and southern hemisphere observatories; and their global averages are *Km* and *Am*. The *aa* index is similar to the *Kp* except that it utilizes only two, roughly antipodal, observatories, one in the northern hemisphere and one in the southern hemisphere (Menvielle and Bertheiler, 1991; McPherron, 1995; Love and Remick, 2007; Grimald, 2013). Additionally, Geomagnetic indices often include parameters derived from solar wind measurements, such as the solar wind density and interplanetary magnetic field (IMF) measurements. These parameters provide information about the properties of the solar wind and its interaction with the Earth's magnetic field. According to Gonzalez et al, (1994), magnetic field reconnection between the southwardly directed IMF (*IMF-Bz*) and the geomagnetic field has been the most accepted mechanism for magnetospheric energization, and by extension, for geomagnetic storms. Quantitative studies of large-scale magnetopause reconnection have revealed a sufficient understanding of the rate of energy transfer from the solar wind to the magnetosphere during geomagnetic storms (Gonzalez, 1990; Martinis et al., 2005).

Few works have been reported by researchers in finding the relationship between geomagnetic indices. (e.g.Gulyaeva 1993; Saba et al. 1994; Fares Saba et al. 1997; Adebesin and Chukwuma, 2008; Grimald 2013). Saba et al. (1994) investigated the relationship between the Dst and other geomagnetic indices. Peak Dst values correlate best (0.87) to the time integral of AE during the preceding 10 hours from the Dst minimum. During moderate storms, the AE and Dst absolute values grow together linearly. However, for more intense storms, the AE saturates at a level of about 1000 nT due to the shift of the auroral electrojets to sub-auroral latitudes. Fares Saba et al. (1997) established a relationship between the ap and a linear combination of the AE and Dst indices, using two years of data including 1979 and 1974 representing the solar maximum and minimum periods. They reported a higher AE yearly average during solar minimum than in solar maximum, and a reverse of the case for the Dst index for a higher number of intense storms. The correlation coefficient (r) of the AE versus ap was observed to be the highest of AE versus Dst and ap versus Dst. "r" was only highest for the ap versus Dst when relationship during geomagnetic storms, at which time the influence of the ring current was intensified. Stepanova and Pérez (2000) explored the possibility of prediction of Dst variations using previous Dst values obtained through a feed-forward multi-layer perception. They reported that the Dst could be auto-predicted a few hours ahead, as both the main and recovery phases of geomagnetic storms were accurately predicted up to 3 hours. A comparative study of the *Kp, Ap, Km, Am, Dst* and *AE* indices was done by Grimald (2013); using autocorrelation and cross-correlationto investigate the inertia of each index and the probable link that may likely exist between them, and projected that the Kp index may not be the only global magnetic index, the Ap, Km and Am could also be used instead. The Disturbance Storm Time (Dst) index serves as a metric for assessing low latitude magnetic index and provides insights into space weather dynamics. It offers detailed information regarding the potency of the ring current encircling Earth, a consequence of solar protons and electrons.

Various magnetic activity indices were designed to describe/measure the geomagnetic field variation observed during disturbed periods caused by the irregular current system. According to Mayaud (1980), indices were developed in areas of vast data availability for proper investigation and possible interrelationship description. For the purpose of this work, only ap, Dst, AE and *IMF-Bz* indices are considered. This is because the three appear to be most commonly used.

Adebesin (2016) considered eight (8) years of data spanning high-, moderate-, and low-solar activities, and observed that all the pairs (ap versus Dst, AE versus Dst, and AE versus ap) of indices investigated recorded the highest/lowest correlations during LSA/HSA. The Dst is observed to have a greater influence on ap during geomagnetic storm periods. Persai et al., (2019) investigated all Geomagnetic storms occurring between 1996-2013; of which 49.5% are intense and the remaining 50.5% fall within the moderate class. They obtained negative and high correlations for the Dst/Ap (-0.89) and Dst/Kp (-0.89) pairs. Eroglu (2019) in modelling the superstorm of the 24th solar cycle, revealed the importance of the linear relationship between the Dst and Bz and studied the relationship of ap versus Bz, and AE versus Bz using both linear and nonlinear models. He submitted mathematically, that the height level of the nonlinear correlation with the Bz versus ap should not be overlooked.

In the current work, the linear interrelationship between the indices is limited to the *ap, Dst, AE*, and *IMF-Bz* (as they are the most commonly used indices in depicting the level/strength of geomagnetic activities). The period of investigation spans 1996 – 2006 falling within the solar cycle (SC) 23. This study was structured within SC23 because SC23 is characterized by a surprisingly large number of sunspot-less days that are unique in almost a century, very low irradiance, and high cosmic ray flux (Nandy et al., 2021). The implication of this is that this solar cycle presents a nearly stable and fair space weather, good for studying ionospheric and magnetospheric dynamics in comparison to other solar cycles. The investigation is for six major classes of activities including (i) magnetic quiet condition, (ii) magnetic disturbed condition, (iii) combined activity (inclusion of both magnetic quiet and disturbed conditions), (iv) Storm onset phase, (v) Storm main phase, and (iv) storm recovery phase. Both the pairs and the multiple linear relationships are presented. It is believed that the understanding of the interaction between these commonly used geomagnetic indices (*Dst, AE, ap*) together with the *IMF-Bz* during different geomagnetic conditions and phases will further increase our knowledge of the electrodynamics of the ionospheric environment, and also know the best condition during which each pair of indices complement one another. This will be one of the earliest works that will consider the interrelationship between the common magnetic indices under six distinct conditions of magnetic activities.

MATERIALS AND METHODS

Figure 1 presents the flow chart for the methodology. Presently, in this work, only the ap, *Dst* and *AE* indices, together with the IMF-Bz, are considered. This is because these three appear to be the most commonly used among the various indices in use. The ap index has been found to account for planetary geomagnetic activity. This is because it gains support from both the auroral electrojet (measured using the AE index) and the ring current, using *Dst* as an indicator (Rostoker, 1972). Further, the *AE* is measured at high latitudes, the *Dst* at low latitudes and the *ap* is measured at mid-latitudes (Mayaud, 1980; Amory-Mazaudier, 2009). Therefore, investigating the relationship of the *ap* index by a linear combination of the *AE* and *Dst* indices over a wide range of input data, under different geomagnetic conditions (quiet, disturbed, and combined) and storm phases (onset, main and recovery) will be useful for general space weather studies. The data used spans from 1996 – 2006. The indices were obtained from the Space Physics Data Facility (SPDF) of NASA's Goddard Space Flight Centre (GSFC) Heliophysics Science Data Management Policy at the website https://omniweb.gsfc.nasa.gov/form /dx1.html. SPDF additionally provides multi-project and cross-disciplinary access to data at ensuring both correlative and collaborative research across different disciplines. The low-resolution OMNI data are hourly average values of the *Dst, ap, AE,* and *IMF-Bz* spanning 1996-2006. Since the *ap* is computed at every 3-h interval, both the *AE, Dst,* and *Bz* magnitudes have also been averaged over the same 3-h intervals for convenience in computation, as was also depicted in the works of Fara Saba et al. (1997) and Adebesin (2016). The hourly daily values of the indices were plotted for the pairs of *ap versus AE, ap versus Dst* and *Dst versus AE* indices. Thereafter, the multiple correlation relationship between the three indices was carried out using the mathematical relation in Equation 1.

$$ap = a(AE) + b(-Dst) \quad (1)$$

where *'a'*, and *'b'*, are the linear fit coefficients.

In the same manner, the multiple correlation relationship between the *IMF-Bz* and the *Dst, ap,* and *AE* indices was carried out using Equation 2.

$$Bz = a*(ap) + b*(AE) + c(-Dst) \quad (2)$$

where *'a*', 'b*'*, and *'c'* are the linear fit coefficients.

The use of *'a'* and *'b'* for the expression in equation (1) and that of *'a*'* and *'b*'* in equation (2) is to differentiate between the specific linear fit coefficients as related to each equation.

In categorizing the geomagnetic activity, the dataset was treated for extremely quiet conditions by extracting only those *ap*, *AE* and *Dst* data corresponding to $ap \leq 7\,nT$ (Pietrella and Perrone 2008, Pietrella 2012; Adebesin, 2016). $ap > 7\,nT$ is considered magnetically disturbed activity. The data for each of the magnetic quiet and disturbed conditions were extracted through the use of a MATLAB code developed. A total of 13,405 datasets of each magnetic index (*ap*, *Dst*, *AE* and *IMF-Bz*) were used for the disturbed time observation; 16,795 for the quiet time analysis, and 30,200 datasets for the combined activity. A total of 90,600 data set was used all together following works depicted by Fara Saba et al. (1997) and Adebesin (2016) and the *ap* is computed at every 3-h interval, both the *AE*, *Dst*, and *Bz* magnitudes have also been averaged over the same 3-h intervals for convenience in computation. Similarly, the classification of storm phases into storm onset (or storm sudden commencement, SSC), storm main phase, and storm recovery phase for the entire 1996-2006 data were done by first identifying all the seventy-five (75) intense magnetic storms. Thereafter, the onset phase, main phase and recovery phase of the storms are respectively set by two days before the storm, the storm day (or days), and two days after the storm. Finally, these days in the different categories of phases were binned together, and then the normal inter-relationship correlation between the pairs of indices and multiple operations was performed.

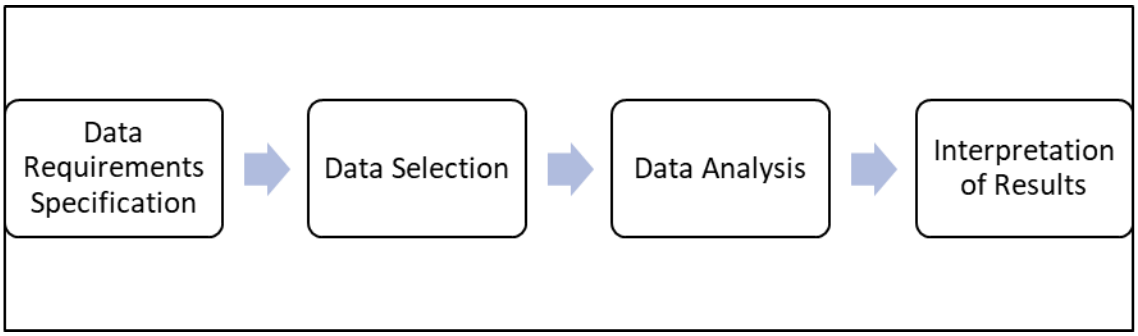


Figure 1: Flowchart for the methodology.

RESULTS AND DISCUSSION

Observations for Quiet, Disturbed and Combined Magnetic Activities

Intercorrelation Relationship between the ap, Dst, AE and IMF-Bz during Quiet magnetic activity

The linear intercorrelation relationship between the *ap*, *Dst*, and *AE* and between the *ap*, *Dst*, *AE* and *IMF-Bz* during Quiet magnetic activity was shown in Figures 2 and 3 respectively. The horizontal red line on the plots indicates the trend line. Inset on each plot is the mathematical equation describing the relationship between each pair of indices. R^2 is the regression coefficient (the correlation coefficient defined $r = sqrt\,(R^2)$. From Figure 2(a)-(c), the regression is quite low for the pairs of *Dst versus ap* (0.0436), *AE versus ap* (0.2546), and *Dst versus AE* (0.0539). From Figure 3, the *Bz versus AE (a)*, *Bz versus ap (b)* and *Bz versus Dst (c)* also present poor R^2relationships during the quiet condition with R^2 values of 0.0023, 0.0581, and 0.0053 respectively. It should be noted that the dataset plotted spans the entire 1996-2006 for which ($ap \leq 7\,nT$), and therefore has many plotted points.

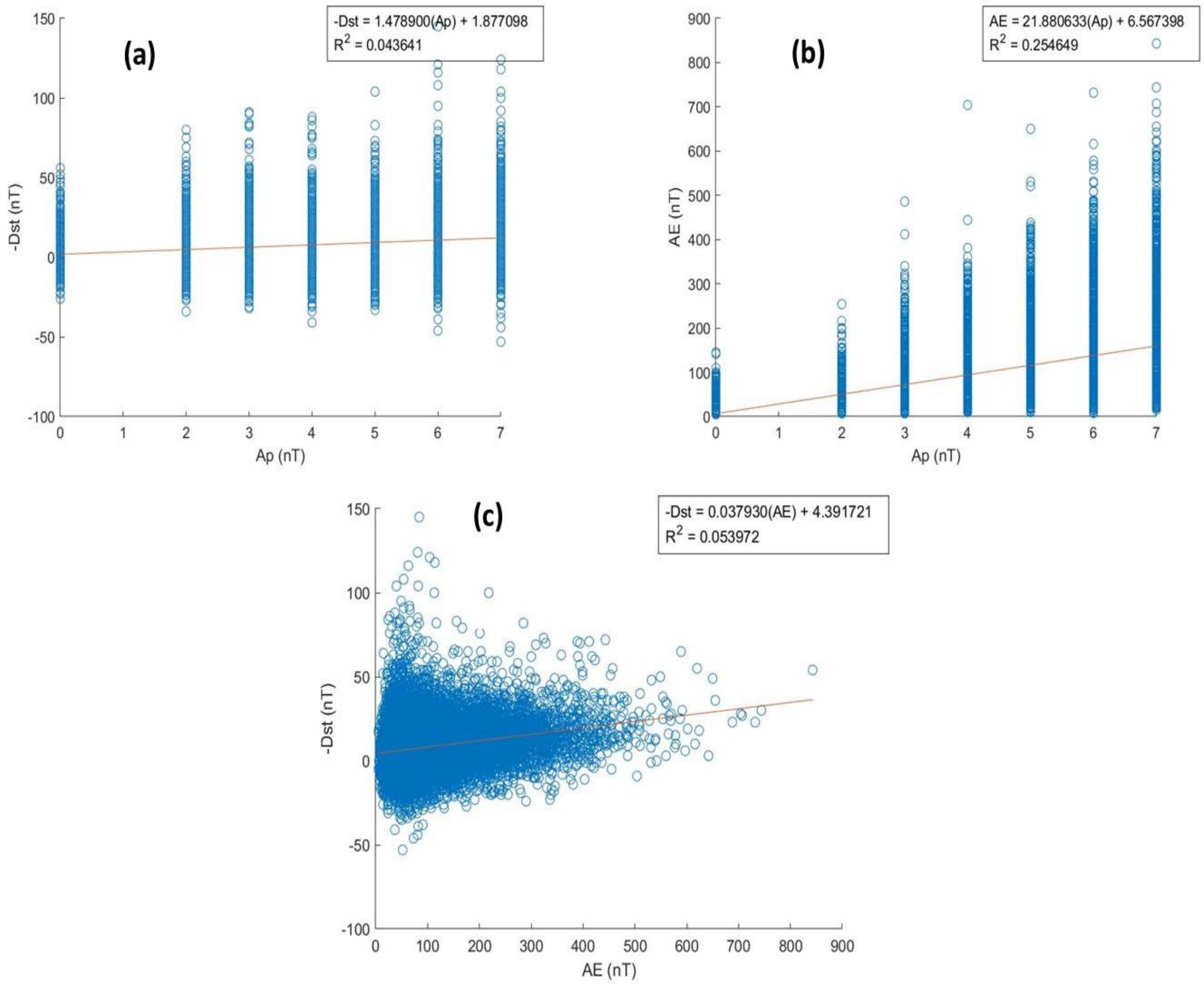


Figure 2: Interlinear relationship between the magnetic activity indices for Quiet magnetic activity condition. Observation is for (a) *Dst versus ap*, (b) *AE versus ap*, and (c) *Dst versus AE*. Note that the positive Dst is plotted in the negative sense for ease of interpretation.

Intercorrelation Relationship between the ap, Dst, AE and IMF-Bz during Disturbed condition

The linear relationship between the *ap*, *Dst*, and *AE* and between the *ap*, *Dst*, *AE* and *IMF-Bz* during Disturbed magnetic activity is shown in Figure 4 and Figure 5 respectively. Inset on each plot is the mathematical equations describing the relationship between each pair of indices, and R^2 is the regression coefficient (the correlation coefficient defined by $r = sqrt\ (R^2)$. From Figure 4(a)-(c), the regression is still low, but better than that of the quiet magnetic activity for the pairs of *Dst versus ap* (0.2895), *AE versus ap* (0.3139), and *Dst versus AE* (0.1783). In a similar manner, the plots in Figure 5 of the *Bz versus AE (a)*, *Bz versus ap (b)* and *Bz versus Dst (c)* present R^2 values of 0.0857, 0.3473, and 0.1155 respectively. Note that the dataset plotted spans the entire 1996-2006 for which ($ap\ > 7\ nT$).

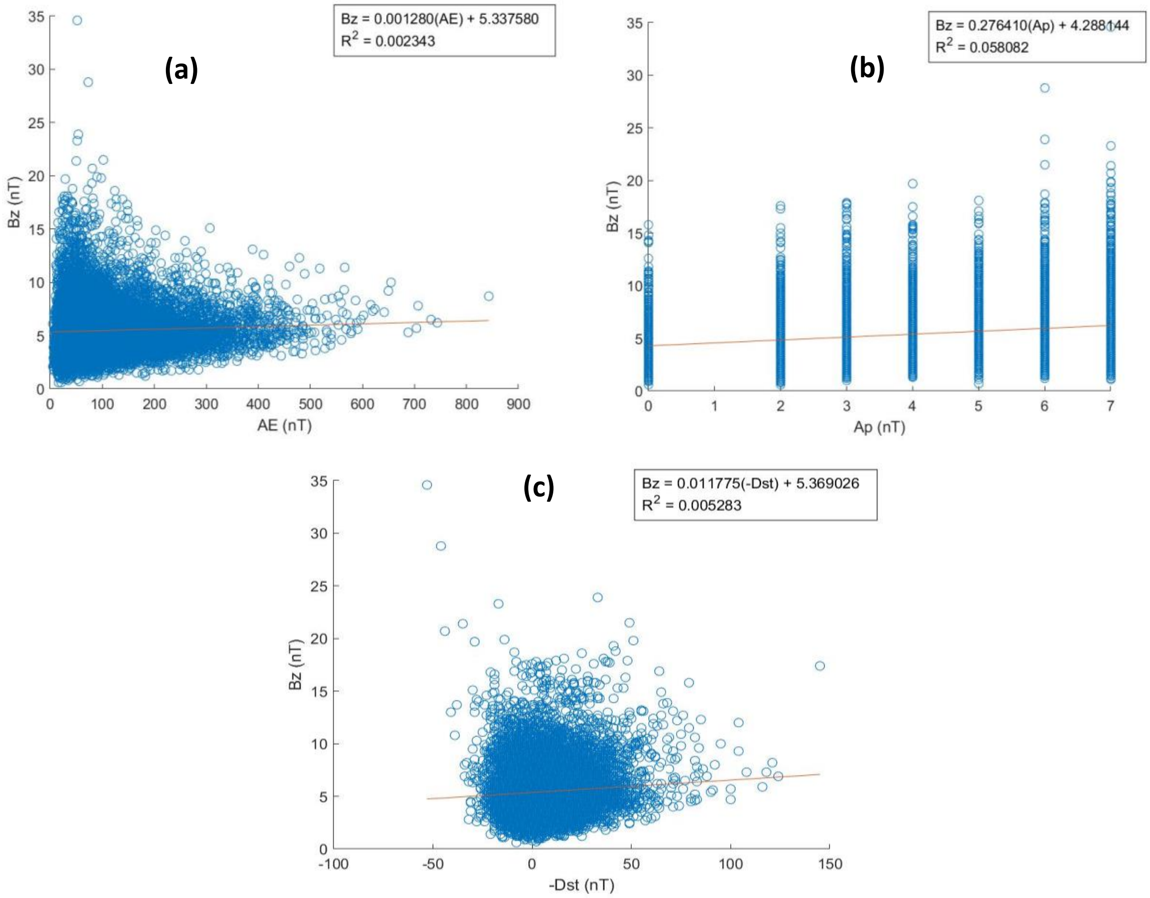


Figure 3: Interlinear relationship between the *IMF-Bz* and the other magnetic activity indices for Quiet magnetic activity conditions. Observation is for (a) *Bz versus AE*, (b) *Bz versus ap*, and (c) *Bz versus Dst*.

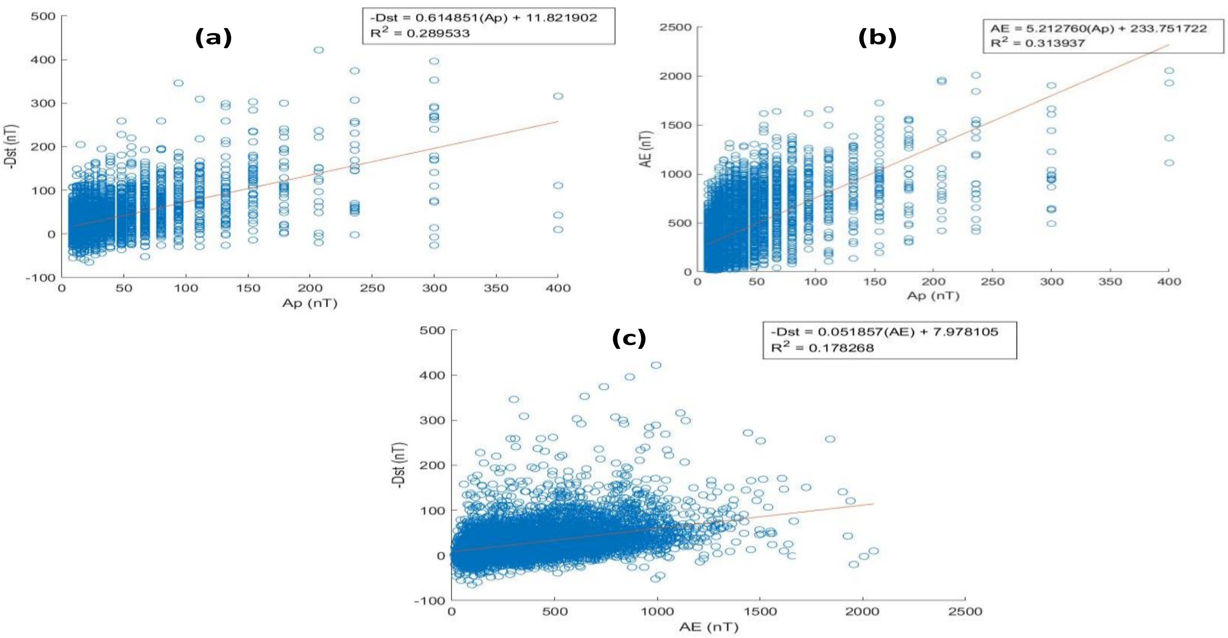


Figure 4: Same as in Figure 1 but for magnetically disturbed activity. Observation is for (a) *Dst versus ap*, (b) *AE versus ap*, and (c) *Dst versus AE*. Note again that the positive Dst is plotted in the negative sense.

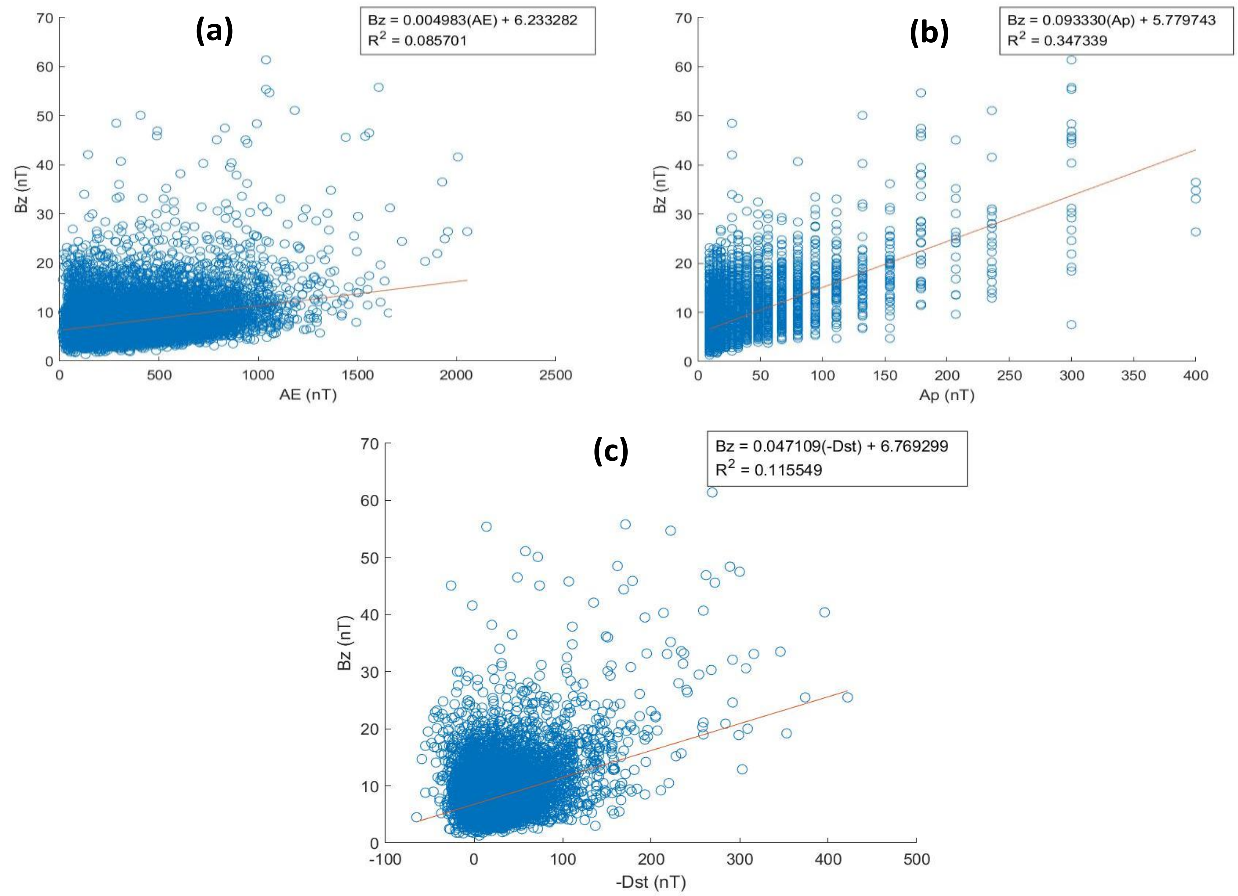


Figure 5: Same as in Figure 2 but for magnetically disturbed activity. Observation is for (a) *Bz versus AE*, (b) *Bz versus ap*, and (c) *Bz versus Dst*.

Intercorrelation Relationship between the ap, Dst, AE and IMF-Bz during combined (Quiet plus Disturbed) magnetic activity condition

For the combined (quiet and disturbed) magnetic activity condition, the *Dst versus ap* (figure 6a), *AE versus ap* (figure 6b), and *Dst versus AE* (figure 6c) present R^2 values of 0.3304, 0.4446, and 0.2633 respectively, which is better than the $R2$ values obtained for the quiet magnetic activity. In a similar manner, the *Bz versus AE*, *Bz versus ap*, and *Bz versus Dst* plots in Figure 6(a), (b), and (c) present R^2 values of 0.1587, 0.3526 and 0.1401 respectively.

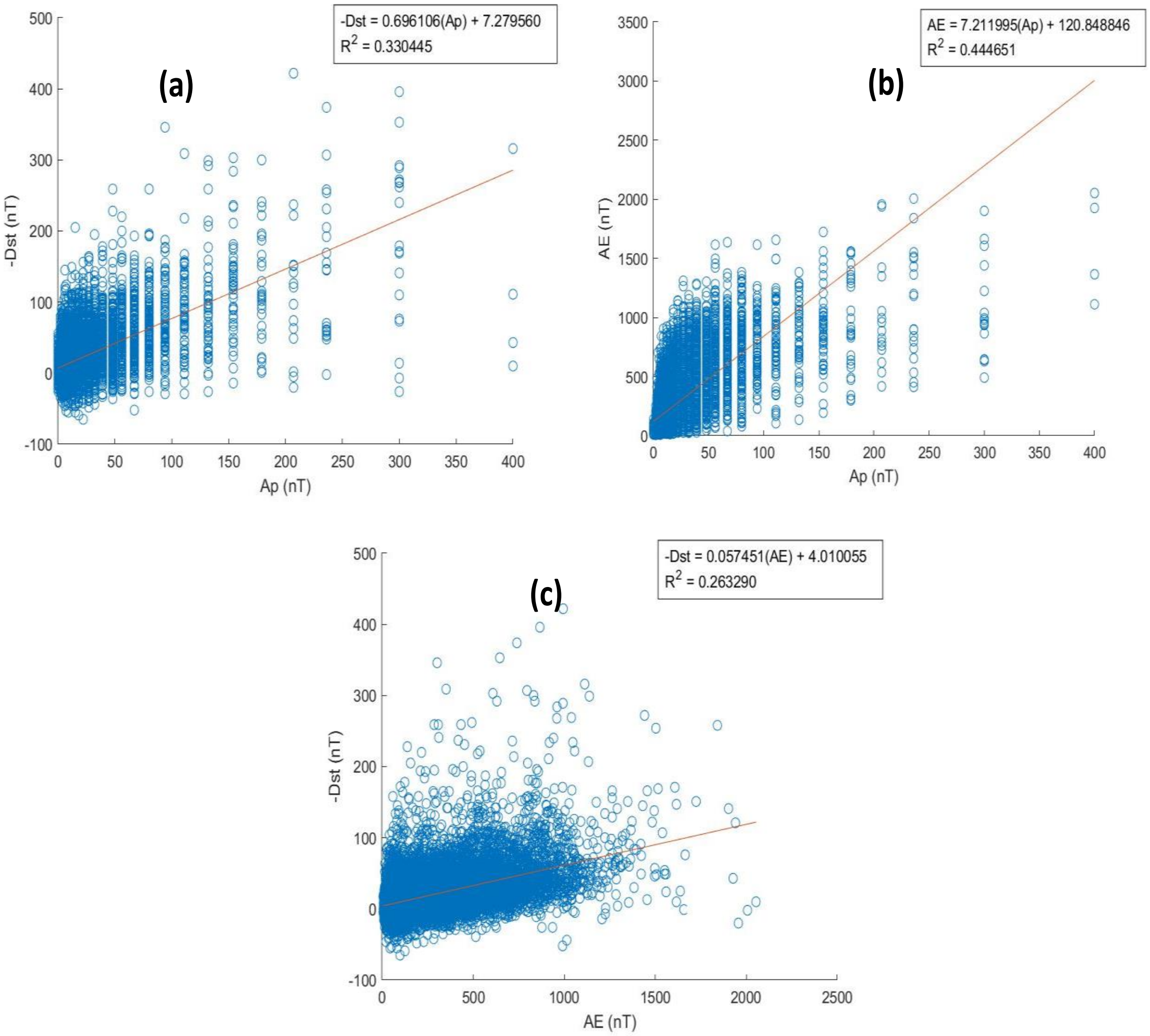


Figure 6: Same as in Figure 1 but for the combined (disturbed and quiet together) magnetic activities. Observation is for (a) *Dst versus ap*, (b) *AE versus ap*, and (c) *Dst versus AE*. Note that the positive Dst is plotted in the negative sense.

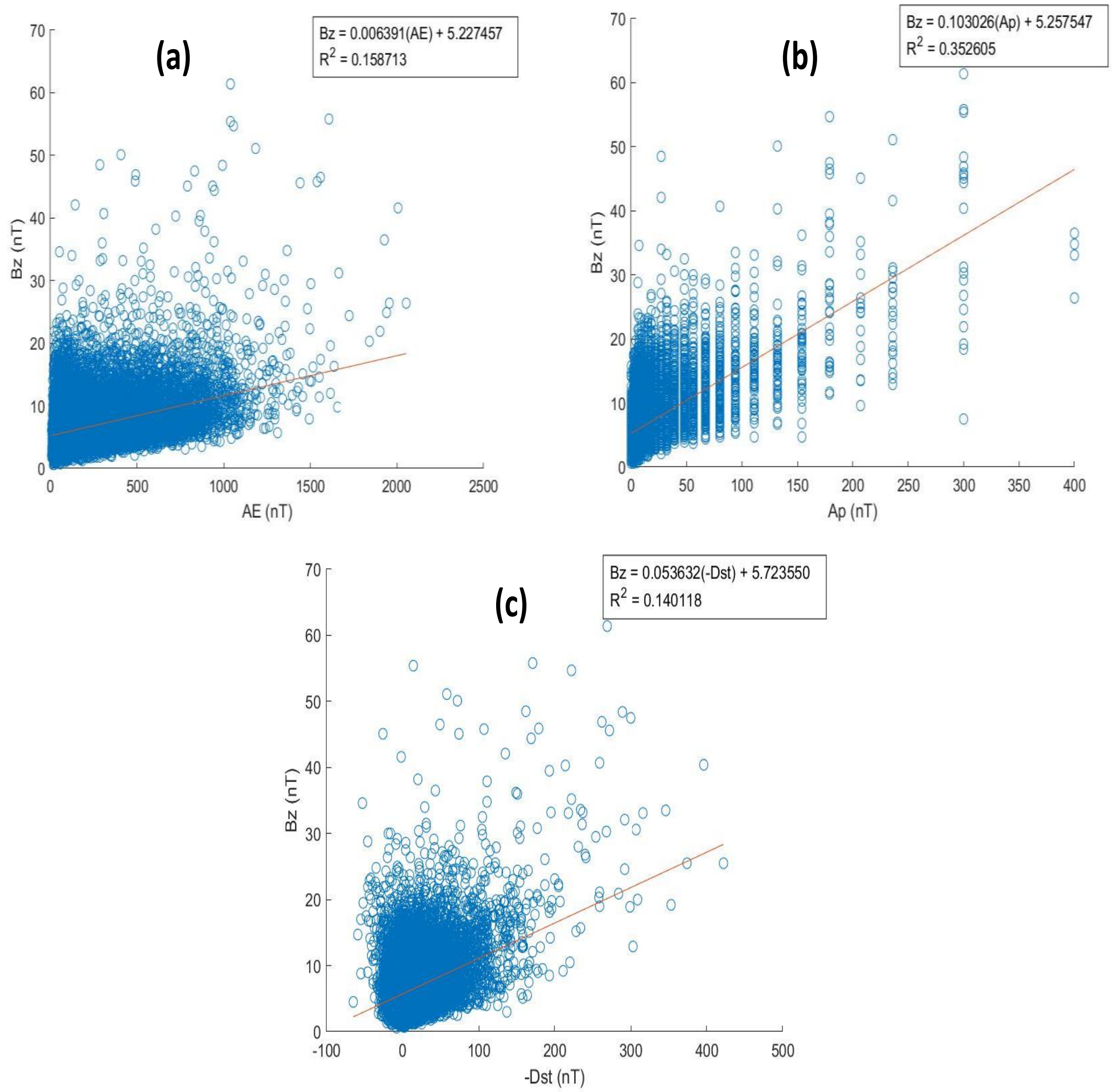


Figure 7: Same as in Figure 2 but for the combined magnetic activity condition. Observation is for (a) *Bz versus AE*, (b) *Bz versus ap*, and (c) *Bz versus Dst*.

In a bid to investigate the magnetic activity condition (quiet, disturbed, or combined) during which each of the geomagnetic indices performed best, a correlation table expressed as a function of percentage is created with the indices placed side by side for better comparison. This is presented in Table 1. From the Table, all the pairs of indices across each row recorded the highest correlation magnitudes during the combined magnetic activity (i.e., at which condition the quiet and the disturbed conditions are not separated) coded with the letter '***h***' depicting the highest correlation percentage across rows. This is closely followed by the observation during the disturbed magnetic activity for all pairs of indices. The least correlation percentage for all pairs of observations was recorded during the quiet magnetic activity. These percentage magnitudes are coded with the letter '***l***' on the table, depicting the lowest correlation percentage across rows.

Table 1: Linear correlation between the geomagnetic indices for different magnetic activities expressed in percentages $[r = sqrt\,(R^2)\; x\; 100\%]$

Pair of indices	Magnetic activity condition (correlation in %)		
	Quiet	Disturbed	Combined
Dst versus ap	20.88^{l}	53.81	57.48^{h}
AE versus ap	**50.46**^{l}	**56.02**	**66.68**^{h}
Dst versus AE	23.23^{l}	42.22	51.31^{h}
Bz versus AE	4.84^{l}	29.27	39.84^{h}
Bz versus ap	24.10^{l}	55.93	59.38^{h}
Bz versus Dst	7.27^{l}	33.99	37.43^{h}

^{h}*depicts the highest correlation percentage across rows*
^{l}*depicts the lowest correlation percentage across rows*

The inference from Table 1 is that the linear relationship between the pairs of geomagnetic indices (*Dst versus ap, AE versus ap, Dst versus AE, Bz versus AE, Bz versus ap,* and *Bz versus Dst*) is better during disturbed magnetic activity in comparison to a quiet condition. The table also revealed that at any level of magnetic activity, be it quiet, disturbed, or combined, the *AE versus ap* pair performed best in terms of the linear relationship. This is indicated in the table with the bolded values of 50.46% for the quiet condition, 56.02% for the disturbed condition, and 66.68% for the combined condition. Following closely behind the *AE versus ap* pair in terms of the highest correlation percentage across the three magnetic activity conditions is the *Bz versus ap* pair with magnitudes of 24.10%, 55.93%, and 59.38% for the quiet, disturbed and combined magnetic activities. The third best-performed pair is the *Dst versus ap* with correlation magnitudes of 20.88%, 53.81%, and 57.48% yet again for the quiet, disturbed, and combined magnetic activities.

The last pair in terms of linear interrelationship is the *Bz versus AE* with magnitudes of 4.84%, 29.27%, and 39.84% for the quiet, disturbed and combined activities. Noting that the best three performed pairs of indices in terms of correlation percentage are *AE versus ap, Bz versus ap,* and *Dst versus ap* irrespective of magnetic activity conditions, it may then be suggested that the mid-latitude magnetic index *ap* is an essential index factor to consider in the description of geomagnetic activities as it has a good relationship with the *AE*, *Bz* and *Dst* indices. Adebesin (2016) noted higher percentage correlations for the *ap/AE* pair at any geomagnetic conditions than for the *ap/Dst* and *AE/Dst* pairs. The same observation was noted in the current study. Persai et al., (2019) while investigating 2,080 geomagnetic storms occurring during solar cycle 23 and the ascending phase of solar cycle 24 spanning 1996-2013 also reported a higher*Dst/ap* linear relationship (89%) compared to the *Dst/Bz* relationship (82%). In the current work, the *Dst/ap* linear relationship is also higher than the *Dst/Bz* relationship by the magnitudes 20.88% higher than 7.27%, 53.81% higher than 33.99% and 57.48% higher than 37.43% for the quiet, disturbed, and combined conditions of magnetic activities respectively. The lower percentage correlation magnitudes experienced in the current work in comparison to those obtained by Persai et al., (2019) could be because Persai et al., (2019) investigated the pairs of indices during specific geomagnetic storm events, whereas the current work under this section considers the work for $ap \leq 7\,nT$ and $ap > 7\,nT$ class of magnetic activities, in which case specific geomagnetic storm periods were considered together with non-geomagnetic storm event periods.

Generally, for all pairs of indices considered, the percentage correlation ranges between 4-50% for the quiet magnetic activity, 29-56% for the disturbed condition, and 37-67% for the combined magnetic activity. The observation in Table 1 is further captured in a plot form in Figure 8a for better clarity at a glance. Additionally, the average percentage correlation magnitudes (mean of the quiet, disturbed and combined magnetic activities) for each pair of indices under investigation is presented in Figure 8b. The figure indicates the percentage levels of correlation with that of the *AE versus ap* having the highest (58%), while that of the *Bz versus AE* recorded the least (25%).

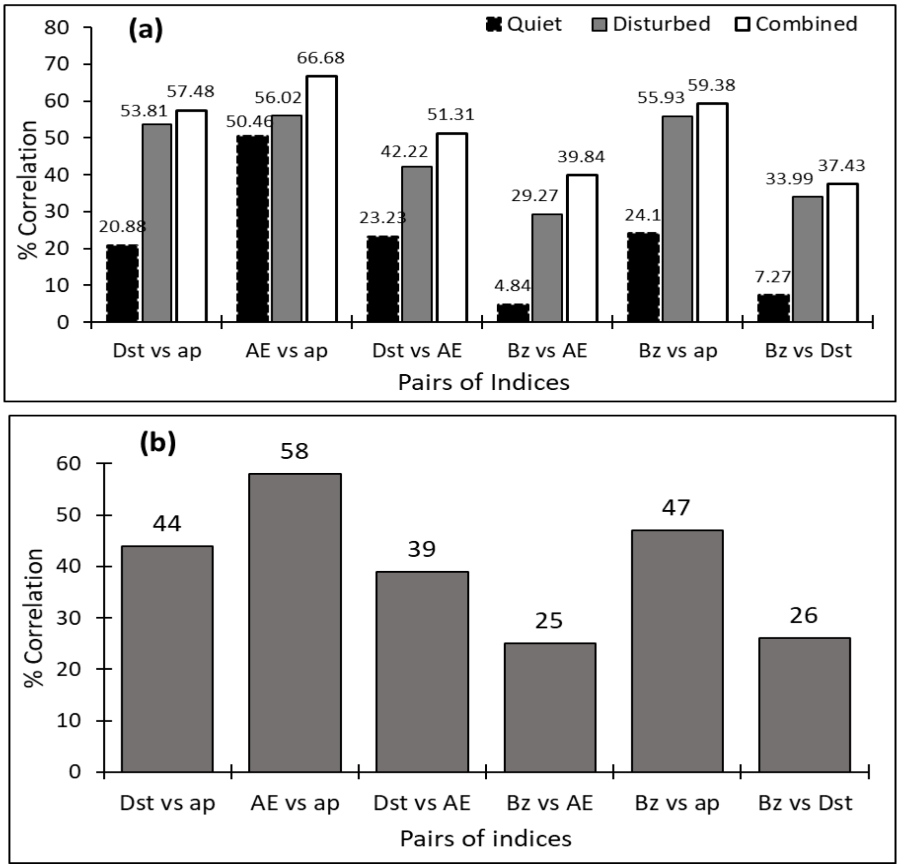


Figure 8: (a)Linear correlation between the geomagnetic indices expressed in percentages (inset are the values) and (b) mean percentage correlation magnitudes (averaged over the quiet, disturbed and combined magnetic activities)

Estimated coefficients for the multiple correlations between the indices

For the first case of *ap* versus *AE+Dst* (of the form of Equation 1 in section 2), a multiple correlation relationship was performed on the indices, first on the relationship between the *ap, AE* and *Dst.* making *ap* the dependent variable, because the *ap* spreads around the *AE* (in high latitude) and *Dst* (in low latitude). Additionally, the *ap* numerical values are related to the magnitude of the disturbance at a standard mid-latitude station (Rostoker, 1972). The coefficients in each case of the quiet, disturbed and combined magnetic activities are presented in Table 2 to see how they vary from one magnetic activity condition to the other. Here, the 'a' and 'b' are the estimated linear fit coefficients. From the Table, the magnitude of both coefficients is the least during the quiet magnetic condition. This observation agrees with the result obtained by Fares Saba et al., (1997). The highest linear fit coefficient is either during the disturbed magnetic activity or during the combined condition. It should be noted that if the magnitude of the coefficient is small, it is suggestive that the dependent variable *ap* is well explained by the independent variable carrying the coefficient (e.g., Fares Saba et al., 1997). Table 2 could then be interpreted that *ap* is better explained with the $AE/-Dst$ relationship during the magnetic quiet condition than during the magnetic disturbed and combined conditions since the least correlation coefficients were obtained for both the AE and Dst during the quiet condition.

Table 2: The ap versus $AE + Dst$ multiple relationships for the $ap = a(AE) + b(-Dst)$ equation

Magnetic activity	**Coefficient 'a'**(*x* 10^{-2})	**Coefficient 'b'**(*x* 10^{-2})
Quiet	2.68[#]	4.29[#]
Disturbed	4.33	32.06[##]
Combined	4.41[##]	25.51

[#] *Coeff. with the least value across the vertical column*
[##] *Coeff. with the highest value across the vertical column*

For the second case of *Bz* versus *ap+AE+Dst* multiple relationships (of the form of Equation 2 in section 2), yet for the quiet, disturbed and combined magnetic activities, the estimated linear fit coefficients 'a*' and 'b*' and 'c' for the observations are presented in Table 3. Here, *Bz* seems to be well explained on the average yet during quiet conditions especially for the *AE* and *Dst* indices, whereas it (*Bz*) is best related to the *ap* during disturbed activity.

Table 3: Bz versus $ap + AE + Dst$ multiple relationships for the $Bz = a*(ap) + b*(AE) + c(-Dst)$

Magnetic activity	Coefficient a*($x\ 10^{-2}$)	Coefficient b*($x\ 10^{-2}$)	Coefficient 'c' ($x\ 10^{-2}$)
Quiet	12.78##	-0.21#	1.30#
Disturbed	9.45	0.90	2.60
Combined	8.21#	1.11##	3.55##

\# *Coeff. with the least value across the vertical column*
\## *Coeff. with the highest value across the vertical column*

Observations for Storm Onset, Main, and Recovery Phases

Intercorrelation Relationship between the indices for the Onset, Main and Recovery Phases of Geomagnetic Storms

Geomagnetic storms are generated on Earth through the action of strong solar wind dawn-to-dusk electric fields which directly drive the magnetospheric convection associated with the passage of southward directed interplanetary magnetic field, IMF-Bz (Adebesin and Chukwuma,2008). Predicting magnetic storms is on the increase because of their profound influence on humans and the environment, particularly communication and satellite anomalies. Geomagnetic storm varies from one event to the other, depending on the magnitude of the solar wind parameters including the flow speed, alpha-proton ratio, ram pressure, the Dst, proton density, temperature, plasma beta, electric field, etc. The geomagnetic storm is often characterized by the hourly disturbance storm time index (Dst) or the 1-minute SYM-H index, which are measures of the variation of the horizontal magnetic field component near the equator as a result of the effect of the symmetric ring current strength. The storms are classified based on the minimum value of Dst (or SYM-H); weak storms (-30 to -50nT), moderate (-50 to -100 nT), strong – intense (-100 to -200 nT), severe (-200 to -350 nT), and Great (< -350 nT) (Loewe and Prolss, 1997, Maimati, 2019). In this work, only intense storms up to great storms were considered, based on the methodology earlier explained in section 2. A typical storm/substorm comprises three phases viz (i) the onset phase, (ii) the expansion/main phase, and (iii) the recovery phase.

The entire seventy-five (75) intense magnetic storms identified during the study period were considered. For these sets of storms binned together, the relationship between the ap, AE and Dst indices, together with the IMF-Bz, during the onset phase, main phase, and recovery phases were determined. The onset phase, main phase and recovery phases of the storms are represented by two days before the storm, the storm day (or days), and two days after the storm respectively, and thereafter bin together for observation. A total of 3,340 datasets (using the Dst signature) were used for obtaining the indices (*Dst*, *Bz*, *AE*, *ap*) during the storm's onset. 2,311 datasets for the main phase and 3,470 datasets for the recovery phase. The highest frequency range of the Dst is 1.0 to 6.3nT, -96 to -122nT, and 35.6 to 40.2nT for the storm's onset, main, and recovery phases respectively.

Additionally, the study period (1996-2006) average values of (a) Dst (b) Bz (c) ap, and (d) AE parameters during the storm's onset, main, and recovery phases are shown in Figure 9. The highest minimum Dst peak magnitude of -99.6nT was obtained during the storm's main phase. In the same manner, the peak Bz, ap and AE magnitudes were also highest during the main phase. This is closely followed by the values obtained during the recovery phase (yet for the Bz, ap and AE) except for the Dst parameter. For the Dst under this condition, the least magnitude was obtained during the onset phase. The observed higher value of the Dst during the main phase is because the Dst is the continuous hourly index that measures the magnitude of the magnetic field induced by near equatorial ring currents (Martins et al., 2005; Hasbi et al., 2011; Ngwira et al., 2013). A large negative value of Dst ($\leq -100\,nT$) therefore indicates the occurrence of geomagnetic storm events.

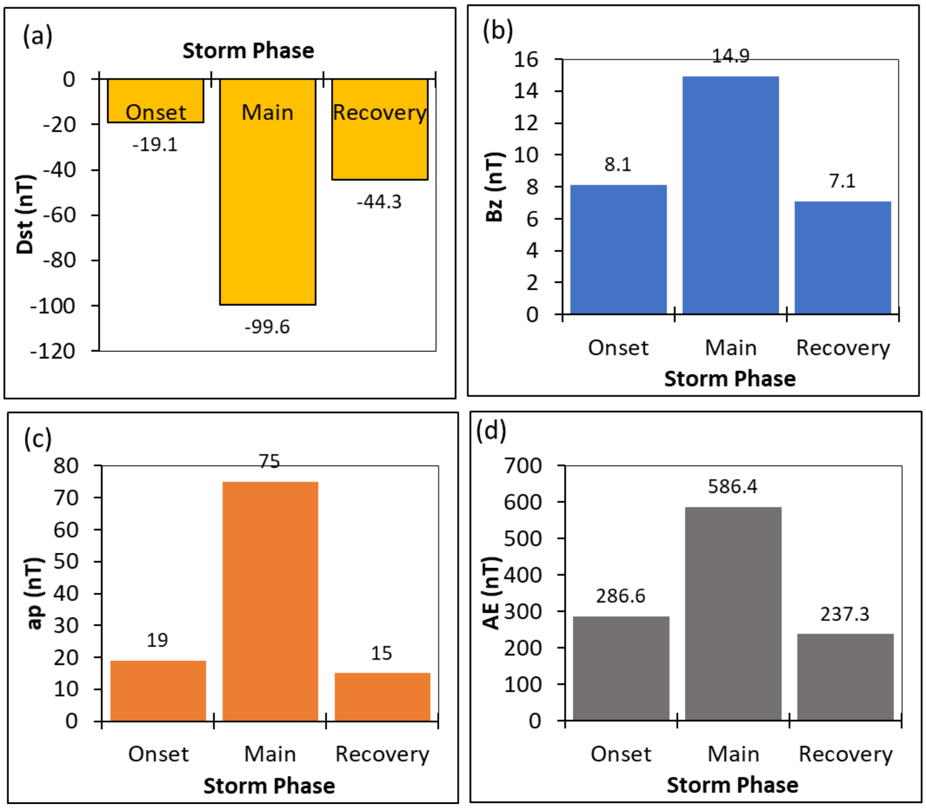


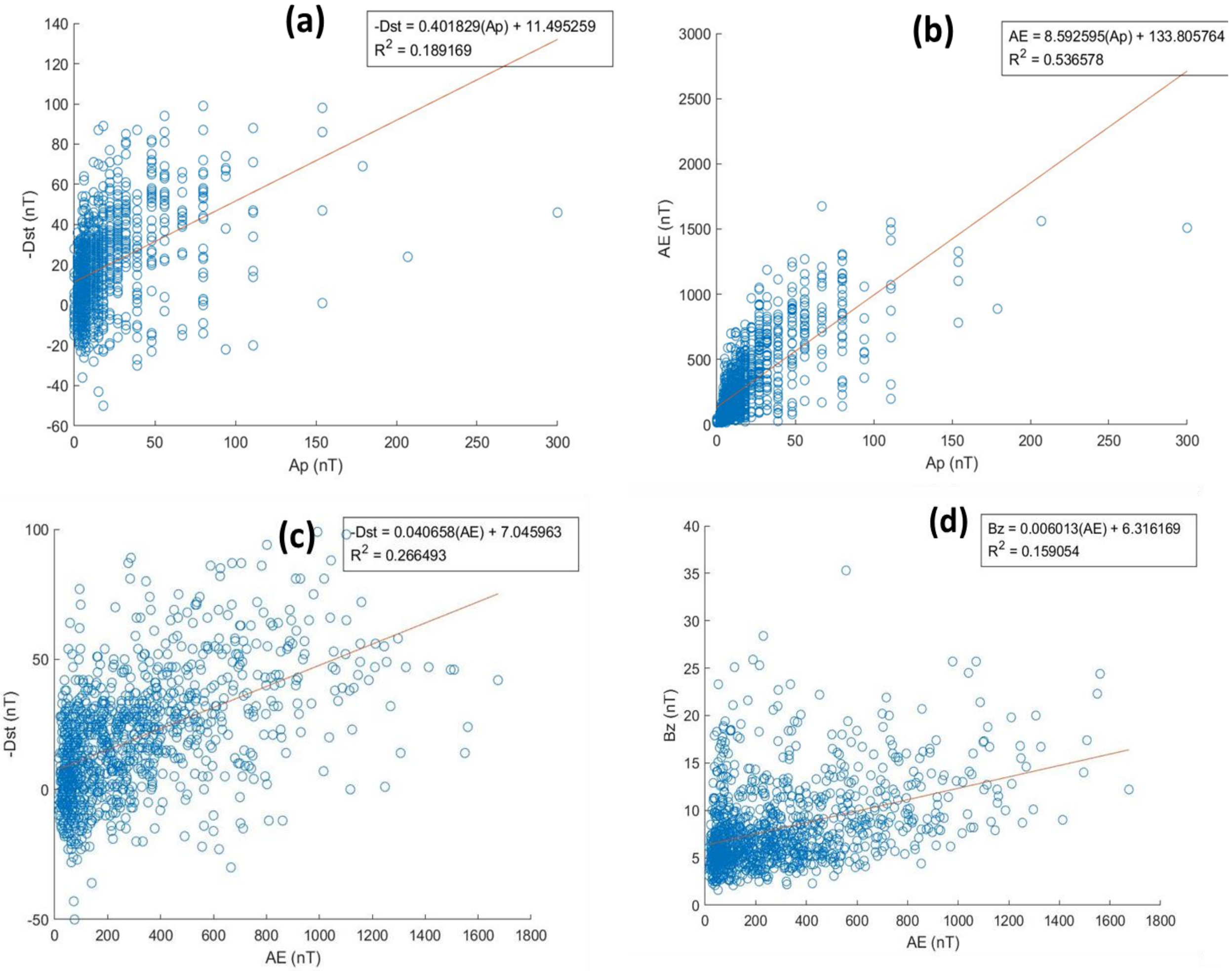
Figure 9: Average values of (a) Dst (b) Bz (c) ap, and (d) AE parameters during the storm's onset, main, and recovery phases.

Figure 10 presents the linear relationship between the magnetic activity indices for the Storm Onset phase of the seventy-five intense storms bin together. The observations are for the Dst versus ap, AE versus ap, Dst versus AE, Bz versus AE, Bz versus ap, and Bz versus Dst pairs. Those of the main and the recovery phases are not shown because of space considerations. However, the percentage correlations of the three phases are presented in Table 4. One observed that the Dst versus ap (with 56.60%), Bz versus ap (with 60.02%), and Bz versus Dst (with 33.64%) pairs had the highest percentage correlation during the main phase in comparison to the onset and recovery phases. On the other hand, the AE versus ap (with 73.25%), Dst versus AE (with 51.62%), and Bz versus AE (with 39.88%) pairs had the highest percentage during the onset phase in comparison to the other two phases. It is interesting to note here that all the pairs of correlation relating to the AE had their highest during the storm onset phase (i.e., AE versus ap, Dst versus AE, and Bz versus AE). In general, the AE versus ap presented the highest values of 73.25%, 62.16% and 68.56% during the storm onset, main, and recovery phases. The least correlation relation was for the Bz versus Dst pair, especially during the onset (10.33%) and the recovery phase (10.50%). According to Chukwuma (2007) and references therein, it is well established that the Bz component of the IMF exerts the most important influence on the magnetosphere and high-latitude ionosphere, as it controls the fraction of the energy in the solar wind, which is extracted by the magnetosphere. When Bz is strongly negative, magnetic reconnection between the IMF and the geomagnetic field produces open field lines, which allow mass, energy and momentum to be transferred from the solar wind to the Earth's magnetosphere (Davies et al., 1997). So, during magnetic reconnection during storm onset, the AE/ap correlation is at its maximum because the magnetometers monitoring both indices are close (Fares Saba et al., 1997). Notably, the solar wind is the source of both the ap index, representing the intensity of planetary magnetic activity as seen at sub-auroral latitudes, and the AE index, which primarily measures the variations in the auroral electrojets.

Table 4: Linear correlation between the geomagnetic indices for different storm phases expressed in percentages [correlation [$r = sqrt\,(R^2)\; x\; 100\%$]

Pair of indices	Storm phase (correlation in percentage, %)		
	Onset	Main	Recovery
Dst versus ap	43.47	**54.60**	44.73
AE versus ap	**73.25**	62.16	68.56
Dst versus AE	**51.62**	23.22	48.41
Bz versus AE	**39.88**	35.17	10.17
Bz versus ap	53.28	**60.02**	25.31
Bz versus Dst	10.33	**33.64**	10.50

The bolded figure across rows signifies the highest correlation percentage



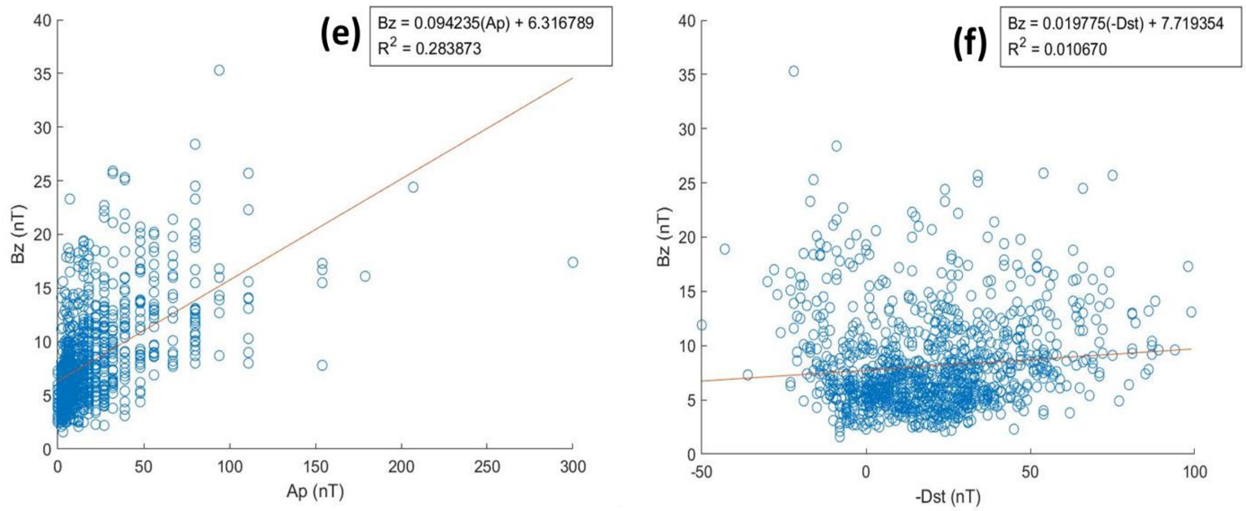


Figure 10: Linear relationship between the magnetic activity indices for the Storm Onset phase of the seventy-five intense storms bin together. Observation is for (a) *Dst versus ap*, (b) *AE versus ap*, and (c) *Dst versus AE*. (d) *Bz versus AE*, (e) *Bz versus ap*, and (f) *Bz versus Dst*.

Multiple Correlation Relationship between the indices for the ap* versus *AE+Dst* and *Bz* versus *ap+AE+Dst.

Table 5(a) presents the ap versus *AE+Dst* multiple relationships. From the Table, the magnitude of 'a' is least during the recovery phase, while 'b' is lowest during the onset phase. The highest coefficients 'a' and 'b' are during the main phase; which is in alignment with the results projected by Fares Saba et al., (1997) and Adebesin et al., (2016); who reported higher linear fit coefficients during disturbed magnetic activities. It is also worth mentioning that the smaller the coefficient magnitude, the better it is suggestive that the dependent variable ap is well explained by the independent variable carrying the coefficient (e.g., Fares Saba et al., 1997). The estimated linear fit coefficients 'a*', 'b*' and 'c' of the multiple correlation plot of Bz versus ap+AE+Dst is as highlighted in Table 5(b). The recovery phase presents the lowest values of 'a*' and 'b*', whereas the lowest coefficient 'c' was presented for the onset phase of geomagnetic activity

Table 5: The *ap* versus *AE+Dst* and *Bz*versus *ap+AE+Dst* multiple relationships for different storm phases.

(a) *ap* versus *AE+Dst* relationship			
Storm activity phase	**Coefficient 'a'** (*x* 10^{-2})	**Coefficient 'b'** (*x* 10^{-2})	
Onset Phase	5.88	8.21#	
Main Phase	7.77##	35.90##	
Recovery Phase	4.77#	9.16	
(b) *Bz*versus a*p+AE+Dst* relationship			
Storm activity phase	**Coefficient a*** (*x* 10^{-2})	**Coefficient b***(*x* 10^{-2})	**Coefficient 'c'** (*x* 10^{-2})
Onset phase	9.37##	1.00##	2.14#
Main Phase	4.77	0.74	5.42
Recovery Phase	4.59#	0.14#	12.58##

\# *Coeff. with the least value across the vertical column*
\#\# *Coeff. with the highest value across the vertical column*

Comparison of Correlation results for the six conditions of magnetic activities and phases considered

The observations are for the pairs of *Dst versus ap*, *AE versus ap*, *Dst versus AE*, *Bz versus AE*, *Bz versus ap*, and *Bz versus Dst*. This was presented under (a) disturbed, quiet and combined and (b) during different storm phases including the onset, main, and recovery phases. A holistic side-by-side representation of all the activities is presented in Figure 11, in which the correlation percentages were rounded up to zero decimal places. From the Figure, the following were noted:

i. Across each row, the highest percentage for the *Dst versus ap* (57%) and *Bz versus Dst* (37%) relationships are during combined magnetic activity;
ii. the highest percentage for the *AE versus ap* (73%) relationship is during the storm onset phase;

iii. the highest percentage for the *Dst versus AE* (51%) and *Bz versus AE* (40%) pairs is during combined magnetic activity;

iv. the highest percentage for the *Bz versus ap* (60%) pair is during the storm's main phase

v. The highest percentage correlation is for the *AE/ap* (73%) pair occurring during the storm onset phase. The *Dst/ap* $\%_{corr}$ ranges from 21-57%, *AE/ap*(50-73%), *Dst/AE* (23-52%), *Bz/AE* (5-40%), *Bz/ap*(24-60%), and *Bz/Dst*(7-37%);

vi. Only the *AE versus ap* relationship has a correlation percentage of above 50% for any class of activity. In essence, of the six (6) magnetic/solar activities considered, the *AE versus ap* pair had above 50% of correlation in all conditions.

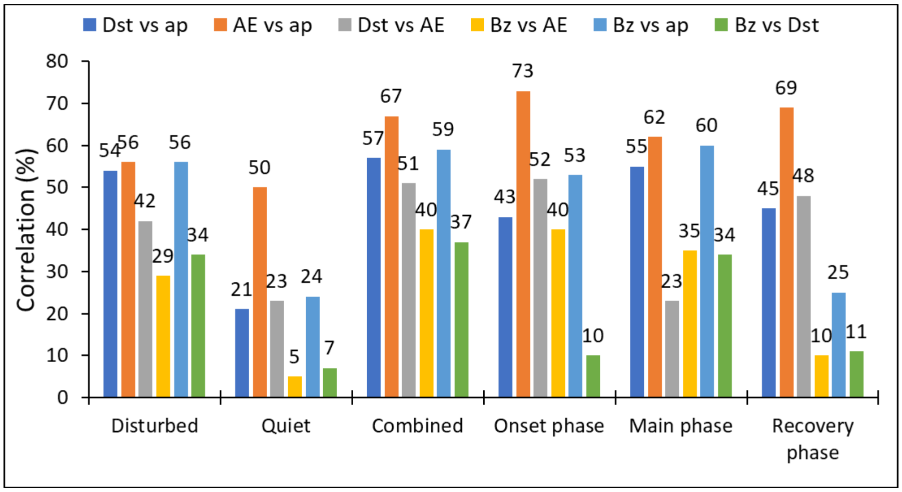


Figure 11: Linear relationship between magnetic activity indices for all 6 conditions considered

The best relationship observed for the *AE versus ap* relationship implies that in specifying the intensity of magnetic activities (especially at high latitudes), the Dst should not be the only magnetic index in use. The AE and ap should also be put into consideration. Dst depicts the average change in the horizontal component of the Earth's magnetic field (obtained from four low-latitude stations during geomagnetic storms) and is a measure of the ring current injection strength. Hence Dst monitors ring current during magnetic storms. The AE index, on the other hand, is obtained from about ten stations distributed in the northern hemisphere auroral zone (e.g., Østgaard, 2009 and the reference therein). AE monitors ionospheric currents during sub-storms. For instance, the periods depicted as quiet periods on the Dst plots by David (2013) yielding higher electron density depletion/enhancement magnitudes are not all quiet periods, going by the corresponding AE and ap magnitudes (which were not shown by David, 2013), but rather a period during which ionospheric sub-storms accumulated. Fares Saba et al. (1997) made a comparison of the ap index averages with a linear combination of the AE and Dst indices. The intent behind their attempt is that since the processes occurring at low and high latitudes are monitored respectively by the Dst and AE indices, then the relationship of the ap versus Dst/AE is expected to influence equally the mid-latitudes where the ap index is measured. Additionally, AE is a measure of the electrojet in high latitudes. This electrojet is a source of a high Electric field that could affect the morphology of the high-latitude ionosphere and also penetrates the mid and low-latitude regions.

Depicted in Figure 12 is the Mean percentage correlation coefficient averaged over the entire six activities of consideration for each pair of observations. The *AE versus ap* pair had the highest value of 64%. This is followed by the *Bz versus ap* pair with 51%, and then the *Dst versus ap* pair with 50%. The least was for the *Bz versus Dst* pair with 27%. This observation revealed that every pair of indices involving the *ap* (i.e., *AE/ap*, *Bz/ap*, and *Dst/ap*) projects better correlation coefficients than the others. This suggests that the ap plays a vital role in the specification of magnetic activity.

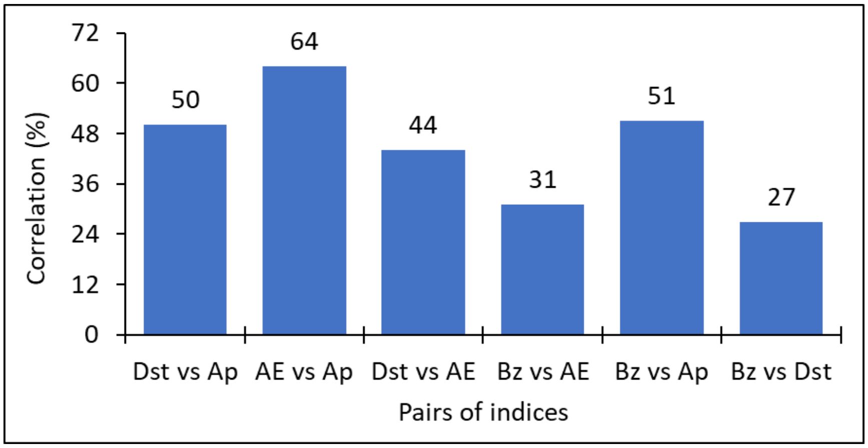


Figure 12: Mean percentage correlation coefficient averaged over the entire six (6) activities of consideration for each pair of observation

Comparison of Linear fit Coefficients for Multiple Correlations of Indices

Table 6 compares the linear fit coefficients for the multiple correlation relationship of (a) *ap* against *AE+Dst* across the six levels of activities. The least coefficient 'a' and 'b' (across each row of the activity denoted by the bolded values) occurred during the quiet magnetic activity. This implies that the *ap* versus *AE+Dst* relationship is best investigated during quiet magnetic activity. Similarly, for the *Bz* versus *ap+AE+Dst* multiple relationships in Table 6(b), the least coefficient for 'b*' and 'c' are yet during the quiet magnetic condition. However, the least value of coefficient 'a*' occurred during the recovery phase of geomagnetic activity. It could still be further inferred that the *Bz* versus *ap+AE+Dst* multiple relationships is also best suited for study under quiet magnetic activity. It should be noted that if the magnitude of the coefficient is small, it is suggestive that the dependent variable *ap* is well explained by the independent variable carrying the coefficient (e.g., Fares Saba et al., 1997), and in this case during the quiet condition in comparison to the other activity periods

Table 6: The *ap* versus *AE+Dst* and the *Bz* versus *ap+AE+Dst* multiple relationships for all six activities

(a) *ap* versus *AE+Dst* multiple relationships						
Coefficient	**Disturbed**	**Quiet**	**Combined**	**Onset Phase**	**Main Phase**	**Recovery Phase**
'a' $x\ 10^{-2}$	4.33	**2.68**	4.41	5.88	7.77	4.77
'b' $x\ 10^{-2}$	32.06	**4.29**	25.51	8.21	35.90	9.16
(b) *Bz* versus *ap+AE+Dst* multiple relationships						
Coefficient	**Disturbed**	**Quiet**	**Combined**	**Onset Phase**	**Main Phase**	**Recovery Phase**
'a*' $x\ 10^{-2}$	9.45	12.78	8.21	9.37	4.77	**4.59**
'b*' $x\ 10^{-2}$	0.90	**0.21**	1.11	1.00	0.74	0.24
'c' $x\ 10^{-2}$	2.60	**1.30**	3.55	2.14	5.42	12.58

Comparison with previous result

The ap numerical values are related to the magnitude of disturbance at a standard mid-latitude station (Rostoker1972). The ap is also useful as it spreads around the AE (in high latitude) and Dst(in low latitude). Fara saba et al., have presented multiple correlation analysis between this above mention indices in a single model equation for different kinds of activities (except otherwise argued). Adebesin (2016) expanded the scope by incorporating data spanning eight years. Employing the same analytical methodology devised by Fares Saba, this extended dataset encompassed 3-hourly average data from 1999, 2000, 2001 (representing high solar activity - HSA), 2004-2005 (reflecting moderate solar activity – MSA), and 2006, 2009, 2010 (pertaining to low solar activity - LSA). The investigation yielded intriguing observations. During LSA periods, all pairs of indices examined (*ap* versus Dst, AE versus Dst, AE versus *ap*) exhibited the highest correlations, while the lowest correlations were observed during HSA phases. Remarkably, the ap/AE pair consistently displayed the highest correlation, ranging from 70% to 78% across all solar activity levels. Moreover, the multiple correlation between ap, AE, and Dst reached 94%, 92%, and 89% for HSA, MSA, and LSA activities, respectively, and 72%, 83%, and 80% during the main phase, recovery phase, and quiet conditions, respectively, underscoring stronger relationships between the pairs during solar activities compared to magnetic activities. Notably, higher percentage correlations were discerned for the ap/AE pair under various geomagnetic conditions than for the ap/Dst and AE/Dst pairs. Ultimately, it became evident that the Dst index wielded a more pronounced influence on ap during geomagnetic storm periods. However, it is important to note that the study was based on a limited dataset spanning the solar cycle 23.

Therefore, the present study aim is to investigate quantitatively and qualitatively, the relationship between the six conditions of magnetic activities and phase considered during multiple correlation during quiet, disturbed and combined (quiet and disturbed together) and determines the onset phase, main phase and recovery phase of the intense storm of solar cycle 23. The present work comparises of 75 intense storms compare to what Fara Saba et al., (1997) and Adebesin (2016) have work on. Fara Saba et al., (1997) had considered 7 intense and 11 moderate storms from 1979 to characterize their magnetic storm activity and Adebesin(2016) had considered and covered some years in solar cycle 23 i.e. High(HSA) span 1999-2001, Moderate(MSA) span 2004-2005 and low solar activity (LSA) covers from 2006,2009-2010 respectively . Hence, the reason for wider gap and my present work covered all years and intense storms of solar cycle 23. Furthermore, both results exhibited the highest correlation values for AE/*ap* pair compared to others pairs of indices and phases.

CONCLUSION

Geomagnetic indices (GIs), which are used to indicate the state of geomagnetic activities, are useful to the Space environment and in forecasting the behaviour of the ionosphere and its effect on radio propagation prediction. Geomagnetic activities have dominant control over the dynamics of the ionosphere and possess the ability to affect man-made technologies. Predictions of geomagnetic indices thus serve two purposes: to provide alerts and warnings of coming events and to serve as inputs to models. Three main reasons for forecast in ascertaining the relationship between geomagnetic indices have been identified from the literature including administrative, economic, and scientific (e.g., Wintoft and Wik, 2018). Administrative reason concerns judging the performance of different forecast systems and their improvement over time. Economic reason deals more with users, where forecasts may be personalized to their requirements and require different verification measures. The Scientific reason is concerned with the understanding and improvements of forecast models, and any method that can expose problems with the forecasts is useful as it may be used to determine the limitations of the forecast capabilities and be used for future developments and progress.

The data presented in this work gave a comprehensive description of both the auto and multiple correlation relationships into some commonly used Geomagnetic indices in the specification of geomagnetic and solar activities at six (6) various levels. These levels include (i) quiet magnetic activity ($ap \leq 7\,nT$), (ii) disturbed magnetic activity ($ap > 7\,nT$), (iii) combined condition, (iv) storm's onset period, (v) storm's main phase and (vi) storm's recovery phase. The magnetic indices used include the disturbance storm time (*Dst*) index, the Auroral electrojet index (*AE*), the mid-latitude magnetic index (*ap*), and the *IMF-Bz*. The data used spans 1996-2006 (with a total of 30,200 datasets). The following results were obtained:

i. The highest correlation percentage ($\%_{corr}$) between pairs of indices was for the *AE/ap* (73%) occurring during the storm onset phase.
ii. The *Dst/ap* $\%_{corr}$ ranges from 21-57%, *AE/ap* (50-73%), *Dst/AE* (23-52%), *Bz/AE* (5-40%), *Bz/ap* (24-60%), and *Bz/Dst*(7-37%);
iii. For all pairs of indices, the magnetic disturbed activity projects a better relationship in comparison to the quiet magnetic condition but is best for the combined condition (involving both the quiet and disturbed conditions together). Generally, for all pairs of indices considered during magnetic activity classification, the percentage correlation ranges between 4-50% for the quiet condition, 29-56% for the disturbed condition, and 37-67% for the combined condition.
iv. The *AE/ap* relationship presents the highest values of 73.25%, 62.16% and 68.56% during the storm onset, main, and recovery phases in comparison to other pairs.
v. The results for the multiple correlation relationships of the $ap = a(AE) + b(-Dst)$ and $Bz = a(ap) + b(AE) + c(-Dst)$ showed that the magnitudes of the coefficients of best fit are smallest during quiet magnetic activity in comparison to other activities, suggesting that *ap* and *Bz* are well explained by the independent variables carrying the coefficient during the quiet condition and can be better inferred during the same period of magnetic activity.
vi. The mid-latitude magnetic index *ap* is observed to be an essential index factor to consider in the description of geomagnetic activities as it has a good relationship with the *AE*, *Bz* and *Dst* indices in general.

The investigated indices, *ap*, AE, Dst and IMF-Bz have highest average values during storm onset storm and this index will be predictable seen as important tool in space weather applications and host of many other fields. As a result, model equations with linear fit correlations coefficients can be developed in magnetic

activity conditions and phases. The results of present work are consistent with previous results. The Dst ring current is observed to have a greater influence on *ap* during geomagnetic storm in accordance with Adebesin(2016). It is hoped that modeling equation will filling gaps and great benefit that may be due to human/machine error in data repositories during solar cycle 23.
The results obtained have improved our understanding of the behaviour between commonly used geomagnetic indices and revealed that quiet magnetic activity is the best condition to study their multiple relationships.

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