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Investigation on the characteristics of the South Atlantic Anomaly

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Abstract. The South Atlantic Anomaly (SAA) is known for its weak Earth's magnetic field strength. In this research, power spectrum analysis method was applied on the Horizontal intensity of the Earth's magnetic field with data sample rate used at 1 min. Four active periods on 18 March 2012, 10 March 2012, 25 April 2012, and 30 June 2013 which represent the occurrence of geomagnetic storms and 4 normal periods on 25 March 2012, 21 March 2012, 4 April 2012, and 15 June 2013 which indicate no geomagnetic storm event were examined. Research was conducted by analyzing the SAA region where comparisons were made between the middle latitude region and the high latitude region. The results indicate that the SAA region tends to be persistent, and this may be due to the ring current. The middle latitude region experienced a mixture of persistent and antipersistent characteristics and this may be due to the transportation of plasma and seasonal weather variations. The high latitude region tends to be antipersistent. This may indicate that the high latitude region is influenced by geomagnetic storms and the aurora.

1 Introduction

Astronomical observations of the atmospheric environment are valuable for gaining better understanding of the phenomena. In this regard, identifying the phenomena occurring in the solar-terrestrial environment has continued to be of scientific interest. The significance of ionospheric disturbance study is of concern not only in the field of science but is vital for applied problem solving (Blagoveshchensky and Sergeeva, 2019). The winds with strong magnetic fields as well as high densities are oriented by the sun (Umar et al., 2019). It produces solar flare, an eruption of electromagnetic waves (Annadurai et al., 2018). The energy of the sun interacts with the signal of the satellite and influences the signals obtained by Earth's stations, which is identified as sun transit (Vankka and Kestilä, 2014). Solar flares, geomagnetic storms, and high-speed solar wind ejections can occur during periods of increased solar activity which are referred to as disturbed days (Yusof et al., 2020). Occurrence of solar flare as well as coronal mass ejection has the potential as well as the capability to influence the Earth's atmosphere (Bahari et al., 2011).

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The phenomenon of ionospheric disturbance (storms) occurring in conjunction with geomagnetic disturbance is well identified (Danilov and Konstantinova, 2019). One of the most prominent events which can be measured at the Earth's surface is the geomagnetic storm (Papa and Sosman, 2008). Geomagnetic storms have the ability to cause damaging impact on electric grid and other technologies (Okpala and Ogbonna, 2018). These magnetic storms are an indicator of geomagnetic activity (Zaourar et al., 2013). Geomagnetic storm originates from the sun. It is capable of initiating large disturbances in the ionospheric electron densities together with total electron content (Timoçin, 2019). During the occurrence of magnetic disturbance, strong particle precipitations can occupy a large geographical region (Abdu et al., 2005). In general, geomagnetic disturbances are known as major disturbances in space atmosphere (Jr et al., 1992).

There exists on Earth a region which has low magnetic field known as the South Atlantic Anomaly (SAA) region. The SAA region is a region which has the weakest magnetic field on Earth and the reduced magnetic field causes high energy particle precipitation in this region compared to other places on Earth during solar storms (Cilliers et al., 2009).

Research on the drift of an intense electron population occurring during a great magnetic storm in the SAA region revealed that the electrons are trapped in the SAA region rather than drifting past it. Electron fluxes decrease exponentially within the SAA region. Energetic neutral atoms generated by charge exchange of ring current ions with geocoronal hydrogen can influence very low latitudes which create the observed energetic electron population.

A large amount of energy is deposited in the thermosphere at high latitudes during the occurrence of geomagnetic storms. Thus, the high latitude ionosphere has a characteristic feature that has more influence on geomagnetic storms.

1.1 Review on the SAA and Power Spectrum Analysis

Trivedi et al. (2005) conducted a study on the amplitude enhancement of sudden commencement (SC) (*H*) events in the SAA region. They examined the records of geomagnetic horizontal component variations at the time of sudden commencement at two stations, São Martinho da Serra (SMS) and Vassouras (VSS). Both stations are located at around 33^0 dip angle in the SAA region of Brazil (Trivedi et al., 2005). According to the findings, the SC(*H*) amplitudes in general were larger at station SMS, which is closer to the center of the SAA. The differential increase in ionization caused by the continuing loss of ions and electrons from the magnetosphere into the SAA region may be responsible for the amplitude enhancements of the SC (*H*) impulse in this region. Nevertheless, increasing the number of stations analyzed in the SAA region would increase our understanding of the characteristic of the SAA region.

A case study research on the interplanetary medium condition effects in the South Atlantic Anomaly was carried by Mendes et al. (2011). The research aimed to investigate the impact of solar energetic particles as well as interplanetary medium conditions on space and time configuration of the ring current at low latitudes. It was implemented in order to learn how these particles could influence the lower ionosphere in the SAA region (Costa et al., 2011). The research was conducted using wavelet techniques, and the time series studied were related to the geomagnetic disturbance that occurred on August 25-30, 1998. The wavelet analysis of the cosmic noise absorption signals showed that the signal may possibly be sensitive to the ionization created through energetic electrons as well as protons. However, if more comprehensive dataset of cosmic noise

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absorption is available in the SAA region, a more detailed investigation can be carried out. The research therefore inspires new efforts to improve understanding of the peculiarities of the SAA region.

Santis and Qamili (2010) investigated the equivalent monopole source of the geomagnetic South Atlantic Anomaly. Based on the research carried out, they modeled the space-time development of this anomaly for the past 400 years based on the resulting decline of a global axial dipole and a rise of a virtual local monopole source. Several features of this development were studied. In their discussion, the researchers stated that one of the probable conjectures is on the topography of the core-mantle boundary and its probable characteristics underneath the SAA region. Examining SAA is important since it may provide valuable insights regarding our planet (Santis and Qamili, 2010). Nonetheless, there is limitation in the research in that it applied two geomagnetic models, GUFM1 and IGRF. As a result, the local representation in some epochs was oversimplified.

Hamid et al. (2009) conducted an analysis on the geomagnetic horizontal component during the time of quiet as well as active period. The purpose of the research was to define the fractal properties described by the Hurst exponent. In order to implement the research, the geomagnetic horizontal component, H throughout the active day and the normal day at station in Cebu and Davao in the Philippines was analyzed. The fractal parameter could be utilized on the basis that the research was to describe the variation of the geomagnetic horizontal component, H, throughout the time of active as well as quiet period (Hamid et al., 2009). Hamid et al. (2009) indicated that more research needs to be carried out on data from other stations and over longer time periods.

In a subsequent study, Hamid et al. (2010) conducted research on the scaling and fractal properties of the horizontal component of the geomagnetic field. In the research, data were obtained from Davao, Philippines as well as Langkawi, Malaysia. Techniques such as detrended fluctuation analysis, power spectrum analysis and rescaled range analysis were utilized in the study. The presence of scaling was revealed by the use of different fractal techniques in the research. Based on the outcome, the fractal methods can be applied to quantify and characterize the horizontal geomagnetic field component (Hamid et al., 2010). However, the research focused on the method and efficiency and the analysis was limited to the Southeast Asian sector.

Levitt et al. (2018) carried out a study on power spectrum identification for quantum linear systems. In the study, they examined system identification for general quantum linear systems (QLSs) in the condition where the input field was set as stationary (squeezed) quantum noise. In this method, the output field was characterized by the power spectrum. In the study, the power spectrum was influenced by the system's parameters through the transfer function. However, consideration of the issues in the more practical scenario of noisy QLS which is modelled by additional channels that cannot be monitored would be interesting (Levitt et al., 2018).

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2 Methodology

2.1 Method of Power Spectrum Analysis and Hurst Exponent

The power spectrum is a method to identify the scaling properties that can prove the existence of fractal properties of the Earth's magnetic field components of horizontal intensity. The spectrum power density function, characterized as S_m, which is intended for a discrete time series represented by y_n, n = 1,2,3 …., N, can be set as

$$S_m = \lim_{N\to\infty} [2|Y_m|^2/N\delta], m = 1,2,3 \dots \dots ,\frac{N}{2}, \quad (1)$$

where δ is the time amid in the succession, *n*.

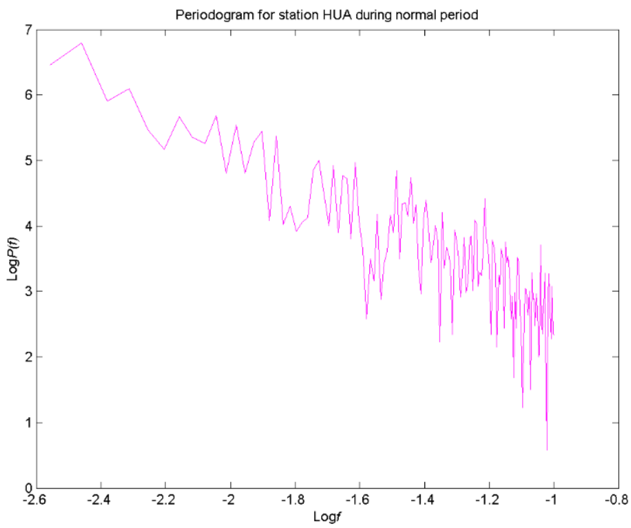

Figure 1: The periodogram for station HUA on 15 June 2013.

From Fig. 1, an example of power spectrum, p(f) versus frequency, f in log scale for the station in the SAA region can be observed. The power spectrum of a time series describes the distribution of power into frequency elements constituting that signal. The periodogram in Fig.1 represents station HUA on 15 June 2013. The value of the spectral exponent, β was obtained from the negative slope of the straight-line plot p (f) versus f in the log scale based on the periodogram. The Hurst exponent was achieved from the spectral exponent, β. Based on the spectral exponent, β, is used in $H_{PS} = (\beta - 1)/2$ when $1 < \beta < 3$ as well as $H_{PS} = (\beta + 1)/2$ for $-1 \leq \beta < 1$. The research carried out compared the period during geomagnetic storm occurrence and the normal period where the Horizontal intensity was chosen based on its sensitiveness toward the geomagnetic activity level.

From the Hurst exponent, H_{PS} the characteristics of a region can be determined. Time series with $0 < H_{PS} < 0.5$ were identified as antipersistent. For antipersistent process, it can mean that a positive anomaly in the past is more likely to be accompanied by a negative anomaly in the time to come, and inversely. H_{PS} = 0.5 means a random series (Nasuddin et al.,

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2019). The events can be interpreted as being uncorrelated. It also suggests that the present does not affect the forthcoming event. The time series with $0.5 < H_{PS} < 1$ were illustrated as persistent. The persistent processes indicate that a positive or negative anomaly in the past is more likely to be followed by the same type of anomaly in the future (Panchev and Tsekov, 2007).

2.2 Description of Stations and Locations

The stations in this study were chosen based on their region. The regions analyzed in this study were the SAA region, the middle latitude region, and the high latitude region.

Table 1. Stations in the SAA region

Station	IAGA Code	Geodetic Latitude (Degree)	Geodetic Longitude (Degree)
Hartebeesthoek	HBK	-25.883	27.707
Hermanus	HER	-34.425	19.225
Keetmanshoop	KMH	-26.541	18.110
Ascension Island	ASC	-7.949	345.624
Huancayo	HUA	-12.038	284.682
Vassouras	VSS	-22.400	316.350
Tsumeb	TSU	-19.202	17.584
Trelew	TRW	-43.266	294.617

Table 2. Stations in the middle latitude region

Station	IAGA Code	Geodetic Latitude (Degree)	Geodetic Longitude (Degree)
Fresno	FRN	37.091	240.279
Ottawa	OTT	45.403	284.447
Newport	NEW	48.271	242.880
Sitka	SIT	57.061	224.669
Victoria	VIC	48.517	236.582
Fort Churchill	FCC	58.760	265.911
Fredericksburg	FRD	38.201	282.630
Meanook	MEA	54.617	246.652

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Table 3. Stations in the high latitude region

Station	**IAGA Code**	**Geodetic Latitude (Degree)**	**Geodetic Longitude (Degree)**
Cambridge Bay	CBB	69.123	254.968
Baker Lake	BLC	64.319	263.988
Thule	THL	77.470	290.770
Yellowknife	YKC	62.483	245.518
Barrow	BRW	71.320	203.380
Godhavn	GDH	69.250	306.470
Resolute Bay	RES	74.690	265.105
College	CMO	64.871	212.139

Table 1, 2 and 3 represent the stations in the SAA region, the middle latitude region, and the high latitude region in this research, respectively. The SAA region is situated at 0º to 50º S and from 90º W to 40˚ E while the middle latitude region is at 30˚ to 60˚ latitude. Meanwhile, the high latitude region is situated at 60˚ to 90˚ latitude.

Figure 2 indicates the position of the stations in the SAA region, the middle latitude region, and the high latitude region. Each region consisted of 8 stations. As shown in Fig. 2, the stations in the SAA region are represented by black circles while the ones in the middle latitude region are in blue circles. The stations in the high latitude region are represented by red circles.

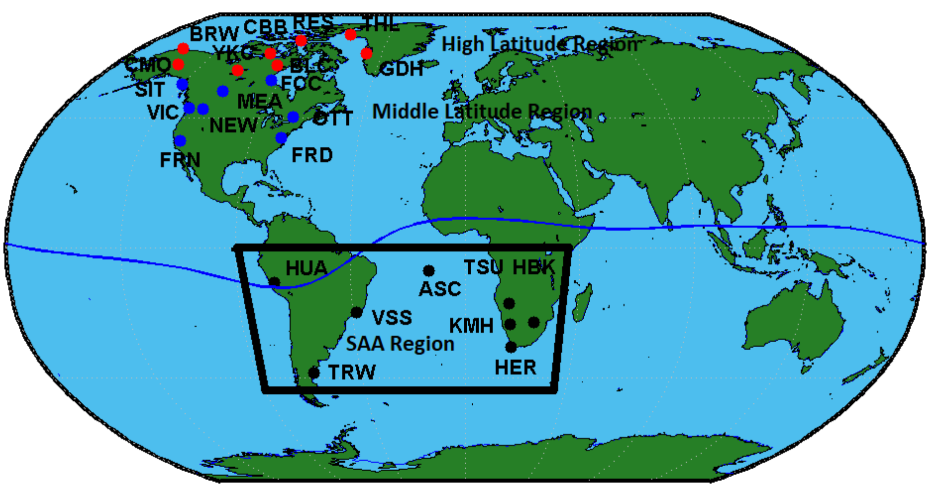

Figure 2: The stations in the SAA region, the middle latitude region, and the high latitude region. The magnetic equator is represented by the blue line.

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2.3 Period of Study During the Active Period and the Normal Period

In this research, two periods were examined, namely the active period and the normal period. In general, an active period is when a geomagnetic storm happens, and a normal period is when there is no occurrence of geomagnetic storms. Geomagnetic storms can be detected by the Dst index. The red line on the Dst index is a benchmark for the occurrence of geomagnetic storms. When the Dst index is below -30 nT, it indicates the occurrence of a magnetic storm. The active period is defined as a period in one day ranging from 1 UT to 24 UT where the presence of a geomagnetic storm is consistently below -30 nT. Meanwhile, for a normal period, it is a period of one day starting from 1 UT to 24 UT where the value is above –30 nT, indicating that there is no geomagnetic storm occurrence on that day. This is because there are days when a geomagnetic storm occurs but its value is inconsistent; for example, during a certain period, a geomagnetic storm occurred and this was then followed by a situation where there was no geomagnetic storm and later continued with the occurrence of a geomagnetic storm. In this study, a total of 4 active periods and 4 normal periods were examined to see the characteristic of the SAA region, the middle latitude region, and the high latitude region. The Dst index of the active period and the normal period is shown in Fig. 3. The red line represents the threshold of the geomagnetic storm event.

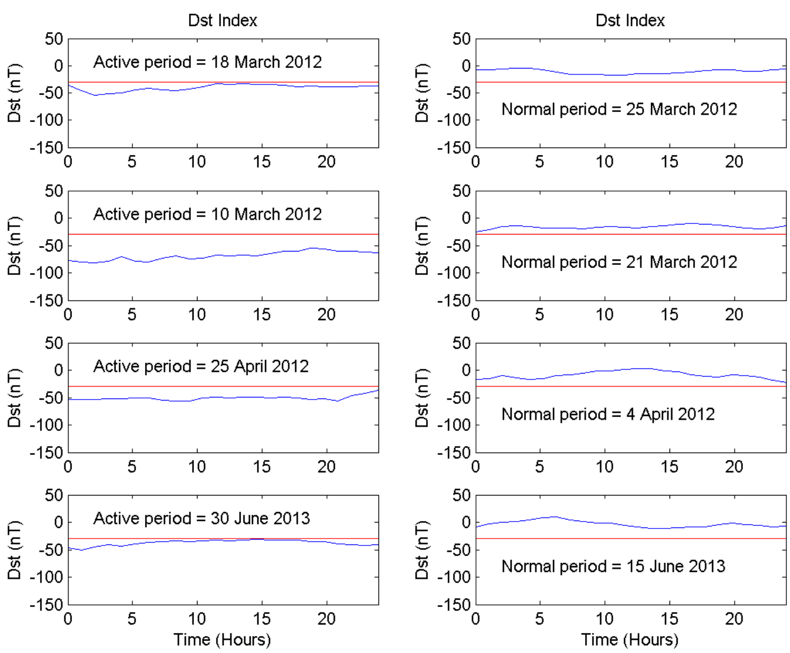

Figure 3: The Dst index of the active period and the normal period.

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3 Results and Discussion

Figure 4 shows the characteristics of the middle latitude region in 2012 and 2013 while Fig. 5 displays the characteristics of the high latitude region in 2012 and 2013. It reveals the result of the region that were analyzed in this research. The station's characteristic is displayed based on its attribute. Comparison was made to study the SAA region in detail.

The stations in the SAA region showed a persistent characteristic throughout the active period as well during the normal period in this research. During the occurrence of the active period, the geomagnetic storm produced may be able to cause a major disturbance to the Earth's magnetosphere.

In this research, the SAA region's characteristics tend to experience persistent values despite the occurrence of the geomagnetic storm. This is more likely to occur in the SAA region compared to other regions. It was observed that based on the strength of such geomagnetic storm, it may not have an effect on the SAA region. The persistent experience indicates that a positive or negative anomaly in the past is more likely to be followed by the same type of anomaly in the future. This may be correlated to a possibility whereby the number of large energetic particles in the region can be said to remain high in the time to come based on the trend of the persistent value that the SAA region exhibits.

The ring current may be one of the potential causes for the SAA region's tendency to be persistent. The ring current has its influence on the effect of the space weather, both in terms of particles, ions and electrons. It is a near-equatorial electric current that travels around the Earth in a toroidal way. The drift movement as well as the charged particle pressure gradients create the ring current. The ring current occurs during geomagnetic quiet times and is significantly enhanced throughout geomagnetic storms, depressing the equatorial horizontal magnetic field strength at the Earth's surface. In quiet times, the ring current mainly consists of protons. During times of storms, a considerable part of the ring current is contributed by the O^+ ions.

Factors such as the weak Earth's magnetic field that the SAA region experience may influence the SAA region's tendency to be persistent during the normal period. It was observed that the Earth's magnetic field in the SAA region is lower compared to other regions in the research and the SAA region also has a great amount of energetic particles compared to the middle latitude region and the high latitude region. The high-energy particles in the SAA region may have an effect on the value of the horizontal intensity of the Earth's magnetic field.

It can be seen that the position of the SAA region which is closer to the inner Van Allen belt resulted in the SAA region to be impacted by a large number of particles. This creates a need for satellites crossing through the region to be careful. The inner belt has a high concentration of electrons and for this reason, it is important to be cautious when passing through the SAA region. Thus, it is important that research is conducted on the SAA region because the SAA region can pose a threat especially to spacecrafts that pass through it. There are instances of such situations, for example, the one where the Hubble space telescope stopped from taking data collection while passing through the SAA region.

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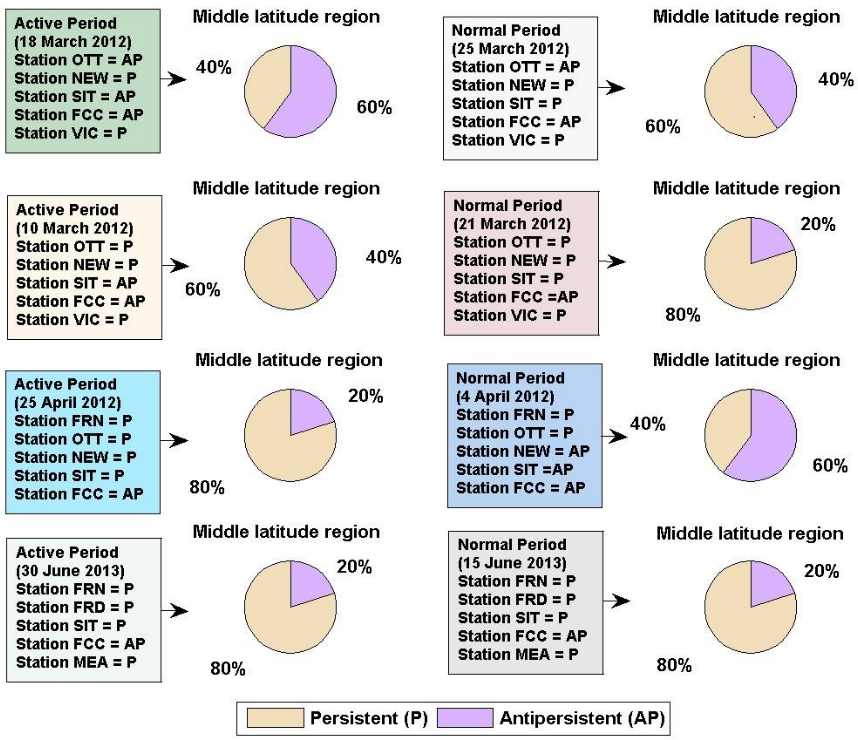

Figure 4: The Hurst exponent characteristics for stations in the middle latitude region in 2012 and 2013.

It was observed that during the active period and the normal period, the middle latitude region tend to be affected by the geomagnetic storm in contrast to the SAA region. It was found that in the middle latitude region, antipersistent characteristic began to appear during both periods. Geomagnetic storm produces a group of charged particles such as solar wind and when it encounters the magnetosphere, it has the ability to charge the magnetosphere, resulting in an effect on the Earth's magnetic field. Depending on the Sun's activity, the solar wind pressure on the magnetosphere can increase or decrease. These variations in solar wind pressure change the electric currents in the ionosphere. It was observed that the geomagnetic storm had an influence in the middle latitude region in this research compared to the SAA region which experienced a tendency to be persistent during both the active and normal periods.

Based on the analysis, another factor that may have caused the middle latitude region to experience this characteristic could be attributed to the transportation of plasma. It is known that the transportation of plasma is due to the geomagnetic field line which is inclined toward the horizontal and the ionospheric plasma that is made to go along the geomagnetic field lines. In addition, electron density is also influenced by seasonal weather variations such as the equinox and the solstice. Seasonal variations may also affect the correlation of electric and magnetic fields, E and B (E x B). This may define the properties of

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electron drift and could influence the rate of electron and ion ionization process since the middle latitude region is more affected by seasonal change.

Furthermore, the Earth's ionosphere is governed by interactions between motions of the neutral winds as well as electromagnetic force. The variation of the ionosphere which is controlled by the interior process because of chemical movement and changes during ionospheric absorption may be a factor for the middle latitude region to experience a mixture of persistent and antipersistent characteristics.

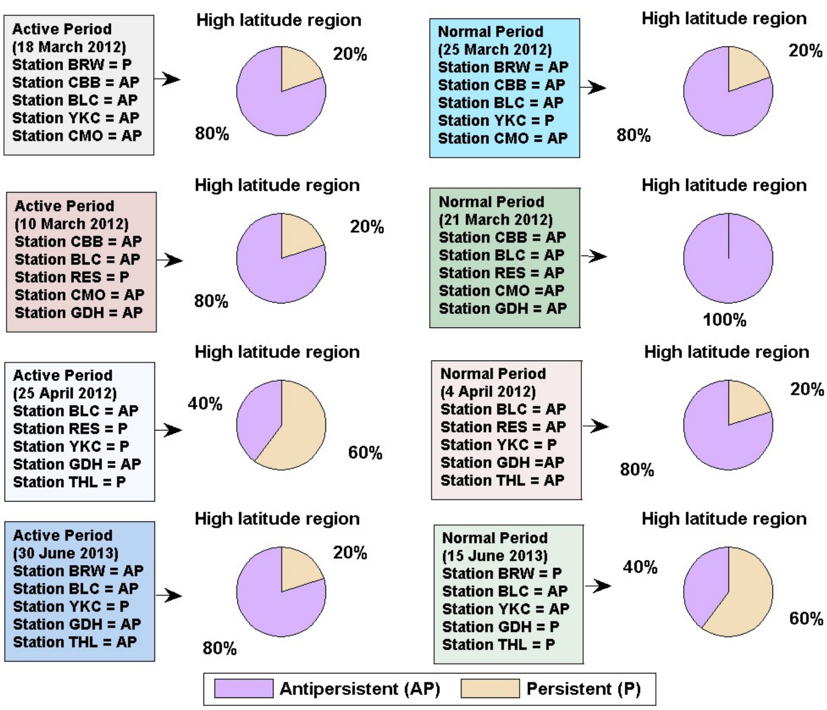

Figure 5: The Hurst exponent characteristics for stations in the high latitude region in 2012 and 2013.

Based on the analysis, the high latitude region tends to be antipersistent during the active and the normal period. It can be observed that geomagnetic storms have high effects in the high latitude region compared to the other regions in this study.

The ionospheric layer consists of D, E, F1 and F2 layers. In the higher latitude, the Earth's magnetic field lines permit solar wind particles as well as plasma to get through into the ionosphere, causing large magnitude irregularities associated with the magnetic field in the ionosphere's E as well as F regions. The high latitude F region is subjected to interplanetary magnetic field as well as solar winds through the Earth's magnetic field; therefore, any solar disturbances are linked to any one which directly or else through the magnetosphere.

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In the high latitudes, a large amount of energy is deposited into the thermosphere during geomagnetic storms. This causes a rise in the neutral gas temperature and variations in the neutral composition, along with a decrease in the atom-to-molecule ratio at F2 heights. Both factors result in a decrease of electron concentration in the high-latitude ionosphere.

Another factor that may have caused the high latitude region to have the tendency to be antipersistent is the presence of aurora in the region. At high latitudes, energetic electrons are coupled into the upper atmosphere along the geomagnetic field lines, resulting in auroras. These may appear together with solar winds as the effect of a solar disturbance.

4 Conclusion

In this research, the SAA region, the middle latitude region, and the high latitude region were examined to study their characteristics. It was observed that the SAA region tend to be persistent during the active and normal period. The SAA region has the tendency to be persistent may be because of the ring current. It could be that the ring current is able to influence the SAA region, making it exhibits this characteristic. It occurs during geomagnetic quiet periods and increases dramatically during geomagnetic storms, affecting and depressing the equatorial horizontal magnetic field's strength. The middle latitude region tends to have a different characteristic compared to the SAA region. The transportation of plasma as well as seasonal weather variations may be a potential cause for the middle latitude region to experience a mixture of persistent and antipersistent characteristics. In contrast, the high latitude region is more influenced by the geomagnetic storm compared to the SAA region. The geomagnetic storm causes the neutral gas temperature to rise and the neutral composition to change while other causes such as the aurora may result in the high latitude region experiencing a tendency to be antipersistent. The strongest effect of the geomagnetic storms is seen at the higher latitudes.

Data Availability

Data for this research can be obtained from INTERMAGNET. It can be accessed at www.intermagnet.org.

Author Contribution

The research was supervised by MA and NSAH. MA contributed in terms of the management of the research and in providing authorization as well as approval for the research. NSAH contributed by inventing the coding for the program on the power spectrum analysis and Hurst exponent, giving permission to carry out the research and providing feedback on the research. KAN conducted the research based on the supervision of MA and NSAH and prepared the manuscript with contribution from all authors.

Competing Interests

The authors declare that they have no conflict of interest.

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