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# On the Pre-Magnetic Storm Signatures in NmF2 in Some Equatorial, Low- and Mid-Latitude Stations

B. W. Joshua<sup>1</sup> , J. O. Adeniyi<sup>2</sup> , C. Amory-Mazaudier<sup>3,4</sup> , and S. J. Adebisi<sup>2</sup> 

<sup>1</sup>Department of Physics, Kebbi State University of Science and Technology, Aliero, Kebbi State, Nigeria, <sup>2</sup>Department of Physics, Landmark University, Omu-Aran, Kwara State, Nigeria, <sup>3</sup>Sorbonne Université, Ecole polytechnique, Institut Polytechnique de Paris, Université Paris Saclay, Observatoire de Paris, CNRS, Laboratoire de Physique des Plasmas (LPP), Paris, France, <sup>4</sup>T/ICT4D, Abdus Salam International Centre for Theoretical Physics, Trieste, Italy

## Key Points:

- Pre-Magnetic Storm Signatures (PMS) on NmF2 were observed to be maximum at the equatorial ionosphere
- Ionospheric Responses during PMS were observed to be similar to the effect of geomagnetic storms
- There is a need to consider a certain threshold of the aurora indices (AE, AL, and AU) in the definition of a geomagnetic quiet day

## Correspondence to:

B. W. Joshua,  
benjaminjoshua7@gmail.com

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**Abstract** In this paper, the ionospheric quiet-time disturbances otherwise known as Pre-Magnetic Storm Signatures (PMS) have been studied using the F2-layer peak electron density (NmF2) data obtained from 12 Digisonde/ionosonde stations distributed across equatorial, low and mid-latitudes. The datasets used spans the years 2010–2012. Results from this study reveals strong PMS in NmF2 with percentage deviations ( $\Delta$ NmF2) ranging from  $-91\%$  to  $500\%$  at the equatorial, low and mid-latitudes, with maxima occurring at the equatorial region. Significant effects on the peak height of the F2-layer (hmF2) were also observed, and they are correlated with the variations in NmF2 particularly at the equatorial station during the PMS. The duration of a PMS is found to be 12–48 h. Although, it was difficult to state clearly the connection between the PMS and the geomagnetic storm that usually follows within 24–48 h; but the NmF2 and hmF2 responses during the PMS were quite similar to those observed during geomagnetic storms. A slight increase in the Solar-wind-plasma speed ( $>20$  km/s) was also observed during PMS. The PMS occur under a southward IMF-Bz, moderate aurora activity (AE ranging from 114 to 560 nT) and quiet ring current (Dst  $>-10$  nT). Therefore, it is pertinent to consider a certain threshold of the aurora indices (AE, AL, and AU) in addition to the Dst, ap, and Kp in the definition of a geomagnetically quiet day. This may eliminate the ambiguity in explaining the ionospheric variability that occurs few days before Sudden Storm Commencement (SSC).

## 1. Introduction

The ionosphere is characterized by peaks of ionization, known as layers, with the highest concentration of ions formed near the ionospheric F2 peak height (Rishbeth & Edwards, 1989). Ionization production in the ionosphere is mainly due to the action of extreme ultraviolet (EUV) solar radiation, while the electrodynamic action of ExB drift or/and neutral wind controls its transportation (Balan & Bailey, 1995; Hanson & Moffett, 1966; Henderson et al., 2005). The ionosphere responds markedly to varying inputs of solar and magnetospheric energy, leading to a disturbance (enhancement or depletion of electron density) in the ionosphere otherwise referred to as ionospheric storms. One of the major causes of ionospheric storm is the geomagnetic storms. During geomagnetic storms, enhanced solar winds, and the southward interplanetary magnetic fields (IMF-Bz) induce global disturbances on the geospace or earth environment, causing the magnetosphere, thermosphere, and ionosphere to deviate from their normal state (Liu et al., 2008).

The intensity of a geomagnetic activity is usually defined by the minimum value of the disturbance storm (Dst) index (Gonzalez et al., 1994; Kamide, Baumjohann, et al., 1998; Kamide, Yokoyama, et al., 1998). The Dst is a magnetic-based index that describes the depression in the horizontal (H) component of the magnetic field, which usually occurs as a result of the intensification of the ring current that surrounds the earth during a geomagnetic storm event. Kamide, Baumjohann, et al. (1998), Kamide, Yokoyama, et al. (1998) has shown that one of the main signatures of any geomagnetic storm is the development of a ring current and its consequent recovery. The response of the Ionosphere to geomagnetic storms has been studied extensively by previous and recent authors like: (Adeniyi, 1986; Akala et al., 2013; Blagoveshchensky & Sergeeva, 2017; Buonsanto, 1999; Chigomezzyo et al., 2012; De Abreu et al., 2014; Fejer, 2002; John et al., 2013; Joshi et al., 2016; Joshua, et al., 2014a, 2014b, 2018, 2021; Kane, 1973; Lin et al., 2005; Liu et al., 2008; Mikhailov et al., 1994; Olawepo & Adeniyi, 2012; Onwumechili et al., 1973, Rishbeth, 1977; Sastri et al., 2002; Sharma et al., 2012; Shimeis et al., 2012, 2015; Sobral et al., 2001; Tsurutani et al., 2004, and much more). In spite of

the increasing number of studies in this area, there are still features and mechanisms of some ionospheric disturbances that have not been fully understood. One of such features is the unusual increase in the F2 layer critical frequencies (foF2) or electron density (NmF2) during the supposed quiet periods (two to three days) that precede geomagnetic storms. This phenomenon was called pre-storm enhancement by Buresova and Lastovicka (2007) and hereafter referred to as *Pre-magnetic storm signatures (PMS)*.

The subject of (or the debate on) PMS has existed for decades and were said to have been formulated for the first time by Danilov (Mikhailov and Perron, 2009) and has appeared in so many literatures since then (Adebesin & Adekoya, 2013; Adebisi et al., 2014, 2015; Adekoya, et al., 2012; Bagiya et al., 2009; Blagoveshchensky et al., 2006; Buresova & Lastovicka, 2007, 2008; Chukwuma, 2007, 2011; Danilov, 2013; Danilov, 2001; Danilov & Konstantinova, 2019; David, 2013; Joshua et al., 2014a, 2014b, 2018; Kane, 2005; Lin et al., 2012; Liu et al., 2008; Mikhailov & Perrone, 2009; Saranya et al., 2011, and many more). Negative phases or decreases of critical frequency (foF2), NmF2, and TEC were also reported for low and mid latitude stations during the PMS (Adebesin & Adekoya, 2013; Adebisi, et al., 2015; Adekoya, et al., 2012; Lin et al., 2012). The PMS is a quiet time ionospheric or geomagnetic disturbance that precedes geomagnetic storms. For the purpose of this study, a typical PMS is characterized by either an enhancement or depletion in the ionospheric electron density (with a percentage change of  $\Delta\text{foF2} \geq 20\%$ , and  $\Delta\text{NmF2} \geq 44\%$ ) that occurs under southward IMF Bz, a moderately enhanced aurora electrojet ( $\text{AE} \geq 100$  nT), a quiet ring current ( $\text{Dst} \leq -10$  nT,  $\text{Kp} < 3$ ,  $\text{Ap} < 6$ ), and must not be connected to any previous geomagnetic storm. It is also important to note that slight changes in the solar wind speed are occasionally observed during a PMS. A PMS can occur both during the day and night time, with an interval of 12–48 h before the geomagnetic storm that follows. It can also occur during all classes (Moderate, strong or intense) of geomagnetic storms either with or without SSC.

The possible cause of PMS and its relationship to the geomagnetic storm has been a great challenge in the study of ionospheric responses to geomagnetic storms (Chukwuma, 2011; Liu et al., 2008) and was earlier considered by Danilov (2001) as one of the open or unsolved problems of the physics of the F2 region. The complex nature of PMS has forced some researchers to avoid the use of few days before the commencement of geomagnetic storm events, focusing mostly on the geomagnetic storm days only (Joshua et al., 2014b). Buresova and Lastovicka (2007) have also shown that the phenomenon of PMS is given less attention than the geomagnetic storm-time behavior. This has accounted for the limited studies on the subject reported in literatures and might have contributed greatly to a lot of unanswered or lingering questions on the possible cause of PMS and its relationship to the geomagnetic storm that follows. In an attempt to unravel the problem of PMS, Mikhailov and Perrone (2009) have raised meaningful questions that were used as a guide for their studies. Some of these questions include: (a) Are PMS in any way connected to the geomagnetic storm event that follows? (b) What sort of NmF2 behavior/signature should be referred to as PMS? The signature referred to consist of the magnitude, duration and time of occurrences of the changes. They studied cases of PMSs that appeared in literatures from the period of Danilov and Belik (1992) and Danilov (2001). The summary of their findings revealed that: “There are no convincing arguments that the observed cases of NmF2 enhancements at middle and sub-auroral latitudes bear a relation to the following magnetic storms.” They further affirmed that the PMSs were due to previous geomagnetic storms, moderate auroral activity or a class of positive quiet time events (Q-disturbances). Thereby, concluded that it is likely there was no such an effect as the PMS that is, directly associated with the geomagnetic storms that usually occurs (Mikhailov & Perrone, 2009).

One thing that is, still common about these recent and previous observations of PMSs is that they were observed under intense or moderate auroral activities and a relatively quiet ring current. This is usually followed by geomagnetic storms which may be observed either immediately or some hours later. However, none of these studies has successfully established any link between the PMSs and the geomagnetic storm that follows.

The study of PMS is of significant importance in improving our understanding of the ionospheric day-to-day variability, which will enhance the modeling of the storm time ionosphere. It can also be of great importance in the prediction of ionospheric weather (Liu et al., 2008) if properly understood. Consequently, this paper is aimed at investigating the PMS features at Ilorin (1.87°S/76.67°E geomagnetic latitude/Longitude), an African equatorial station, and also compare the results with those observed in other regions. This is an

**Table 1**  
*List of Stations, Station Codes and Their Geographic and Geomagnetic Coordinates*

S/No.	Station	Station code	Geographic		Geomagnetic	
			Latitude	Longitude	Latitude	Longitude
1	Kwajelein, Marshall Island	KWJ	9°N	167.2°E	3.72°N	238.11°E
2	Okinawa, Japan	OKN	26.3°N	127.8°E	19.25°N	199.30°E
3	Del'ebre, Spain	DLB	40.8°N	0.3°E	33.87°N	76.40°E
4	San Vito, Italy	SVT	40.6°N	17.8°E	34.68°N	87.13°E
5	Pruhonice, Czech Republic	PRN	50.0°N	14.6 E	45.66°N	90.38 E
6	Ilorin, Nigeria	ILN	8.5°N	4.5°E	1.87°S	76.67°E
7	Ascension Island, UK	AIS	7.9°S	14.4°W	12.37°S	55.76°E
8	Darwin, Australia	DWN	12.5°S	131°E	21.97°S	202.73°E
9	Jicamarca, Peru	JCM	12.1°S	77°W	22.23°S	146.63°E
10	Cocos Island, Australia	CIS	12.18°S	96.83°E	22.72°S	168.56°E
11	Niue Island,	NIS	19.1°S	169.9°E	24.70°S	245.35°E
12	Townsville, Australia	TWS	19.7°S	146.9°E	28.49°S	220.6°E

important contribution to the limited studies on PMS in the African sector. The study is structured under the following objectives: (a) to Investigate the type of NmF2 behavior that should be regarded as PMSs, (b) to Investigate the possible cause(s) of PMSs, (c) to establish the possible relationship (if any) between geomagnetic storm and PMSs and, (4) to verify if PMSs are effects of previous geomagnetic storms. Sixteen (16) different cases of PMSs were investigated. However, for better clarity, we have extensively discussed only three peculiar cases of these PMSs that occurred from 2010 to 2012 (years of low/moderate solar activity). These three cases were carefully selected to represent typical features of PMSs.

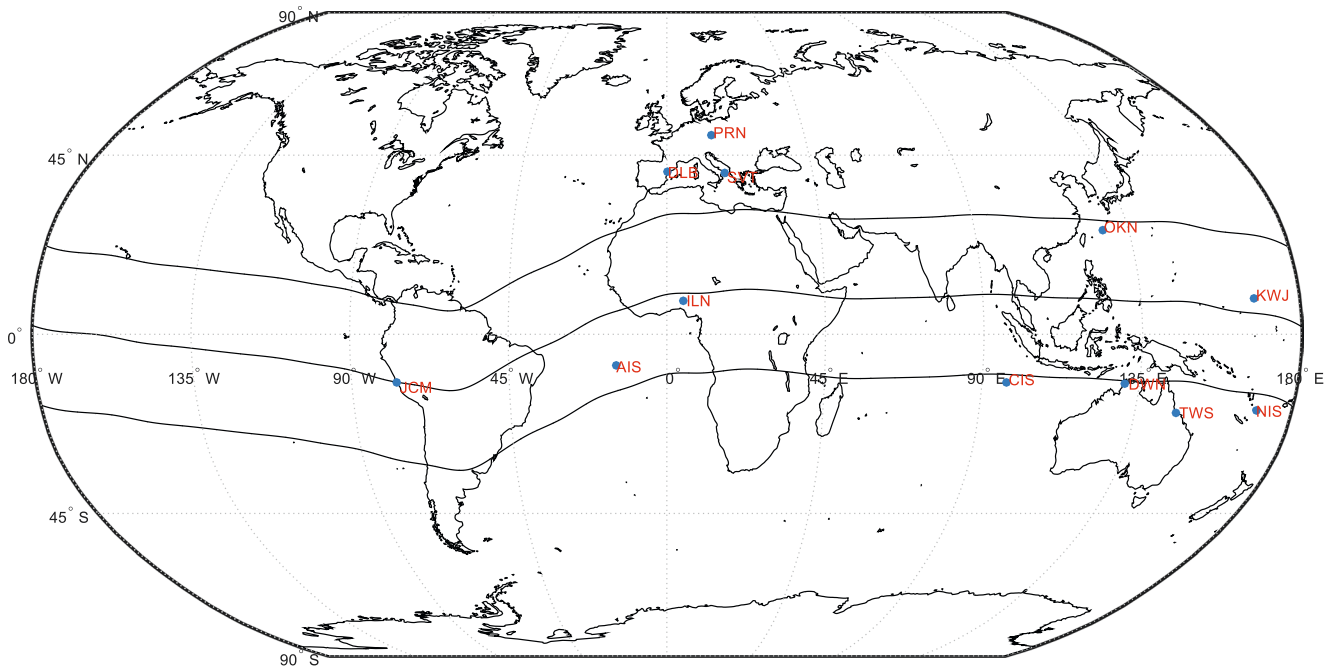
## 2. Data and Method of Analysis

The study compares the features of the PMS observed at Ilorin (1.87°S/76.67°E geomagnetic latitude/Longitude), an African equatorial station to those of other regions. Diurnal variation of Dst, Kp, Ap, AL, and AE ( = AL + AU) indices were employed for the study. Other parameters like the solar wind speed, Interplanetary Magnetic Field (IMF) Bz and electric field (Ey) were also considered. In addition, the study investigated Solar flares as possible cause of PMSs. For this study, ionospheric stations were selected from the equatorial-, low- and mid-latitudes on both hemispheres. Studies with this kind of coverage of latitude on pre-magnetic storm signatures or pre-storm enhancements are not common. The hourly values of the F2-layer critical frequency (foF2) used for this study were obtained from different sources which include: (a) the Standard Archiving Output (SAO) format files obtained from the Digisonde Portable Sounder (DPS 4.2 version) at the University of Ilorin Ionospheric Observatory, (bi) the University of Massachusetts Lowell center for atmospheric research, the Digisonde data were archived at the Global Ionospheric Radio Observatory (GIRO) database and can be obtained from the website: <https://www.digisonde.com/stationlist.php>. The current DPS 4.2 version versions use the latest version of ARTIST (version 5) ionogram auto scaling program. This version has a number of improvements compared to the older versions and results obtained from it have been shown to have high level of accuracy (Galkin et al., 2008). The Digisonde Data set for all the stations used for the PMS study can be accessed at <http://doi.org/10.5281/zenodo.5082129> and that of the University of Ilorin Digisonde can also be accessed at <https://eprints.lmu.edu.ng/2765/>

The NmF2 ( $\text{NmF2} \times 10^{-6} \text{ e/cm}^3$ ) values were calculated from their values of the foF2 using Equation 1:

$$\text{NmF2} = \frac{(\text{foF2})^2}{80.5} \quad (1)$$

The stations were selected based on the availability of data for the period considered, the list of stations and their geographic and geomagnetic coordinates are shown in Table 1, while the map showing the geographic



**Figure 1.** World map showing the locations of the stations used for this study.

location of the stations is shown in Figure 1. The stations used in the analysis of each PMS, varies from one Figure to the other. This is as a result of insufficient data or data gaps from some of the ionosonde/digisonde observatories. For a better understanding of the result, the stations are arranged based on their longitude. There are more stations with sufficient data mostly in the southern hemisphere than we have in the northern hemisphere.

In order to remove the effect due to the day-to-day quiet-time variability, the monthly average values of each parameter (QNmF2 and QhmF2) are used. The monthly average value is calculated from the average value of five quietest days for a particular month. The selection of these quietest days was done using the GFZ Potsdam quiet day selection criteria available at <http://www.gfz-potsdam.de/en/section/earths-magnetic-field/data-products-services/kp-index/explanation/qd-days/>. The quietest days depict when the geomagnetic variations are minima in each month, thus, the selection criteria only give a relative indication of the ionospheric activity in those days with respect to the other days of the same month. This served as a reference point in identifying the intensity of the PMSs. In the present study, geomagnetically disturbed days were considered as days for which  $Dst \leq -30$  nT,  $Kp \geq 3$  and  $Ap > 15$ .

In order to quantify the deviation of NmF2 from its average quiet day's pattern due to the PMSs, Equation 2 is used to calculate the percentage deviation of NmF2 ( $\Delta NmF2$ ).

$$\Delta NmF2 = \frac{NmF2 - QNmF2}{QNmF2} \times 100 \quad (2)$$

where NmF2 represents the measured NmF2 and QNmF2 is the quiet-time monthly average value.

Earlier works such as Forbes et al. (2000), Rishbeth and Mendillo (2001) and so on, have used different threshold values in describing the occurrence of PMS or storm-induced related disturbances. For example, Forbes et al. (2000) used a standard deviation value between  $\pm 25$  and 35 to describe the maximum allowable quiet time NmF2 variability at high frequencies and a value between  $\pm 15$  and 20 at low frequencies for all latitudes. The quiet-time variability of NmF2 has been quantified by Rishbeth and Mendillo (2001) to have a standard deviation maximum limit of 20% during the daytime and 33% at night time. In this paper, we have adopted the values used in Buresova and Lastovicka (2007). Buresova and Lastovicka (2007) have used the percentage deviation of  $\pm 44\%$  (i.e.,  $\Delta NmF2 > \pm 44\%$ ) to indicate the occurrence of PMS. This indicates that a quiet time NmF2 enhancement can only be considered to be a PMS if the peak  $\Delta NmF2$  value for the

**Table 2**  
Peak Values for Dst, AE, Bz, Kp, and  $\Delta NmF2$  for Each Station During the Pre-Magnetic Storm Signatures

Date	Geomagnetic indices					Maximum percentage change in NmF2 ( $\Delta NmF2$ )											
	Minimum		Maximum			Equatorial, low-and mid-latitude							Mid latitude				
	Dst (nT)	Bz (nT)	AE (nT)	Ap	Kp	ILN	OKN	JCM	AIS	NIS	CIS	KWJ	TWS	DWN	SVT	DLB	PRN
2010																	
April 30	-4	-2.1	244	3	1+	117	97	*	101	67		288	104	71	41	87	48
May 27	-3	-2.2	135	2	1+	143	93	*	63	100	27	-39	38	31	47		-62
August 02	-16	-2.1	250	5	2	71	85	*	101	81	-45	-53	-51	107	103	27	26
October 09	-18	-1.8	292	4	2	56	*	*	51	160	-41	-54	144	*	*	49	30
2011																	
February 02	-21	-2.2	344	6	3	*	-79	-64	-35	-70	79	48	*	-83	*	-69	-40
February 27	-2	-2.9	139	2	1	*	65	-50	53	*	176	93	*	-52	*	-59	55
March 08	-24	-3.4	277	5	2	*	96	87	*	*	*	50	57	136	*	-47	40
April 10	-17	-3.2	292	2	1	*	43	*	195	39	89	*	94	66	*	-42	-40
May 26	-18	-4.5	427	6	2	*	61	74	99	-71	*	-45	*	93	*	54	
August 04	-6	-3.9	238	4	3	*	*	*	60	-60	-48	69	-41	-54	*	32	31
September 24	-12	-2.5	143	4	2	*	72	*	581	127	70	34	60	86	*	*	44
October 22	-7	-3.3	231	2	1	*	*	*	*	80	35	53	50	55	*	*	*
October 30	-24	-5.3	557	6	3	*	*	-65	*	-25	-51	43	-34	-66	*	*	*
2012																	
January 20	-2	-2.3	164	4	2	*	-83	58	-60	-28	-53	*	73	53	*	*	33
March 26	1	-2.2	114	4	1+	*	74	-38	*	76	80	*	30	93	*	-31	52
September 29	-6	-2.7	153	0	1+	*	154	44	*	178		*	57	67	*	*	120

Note. \* indicates the absence of data from the stations on those days.

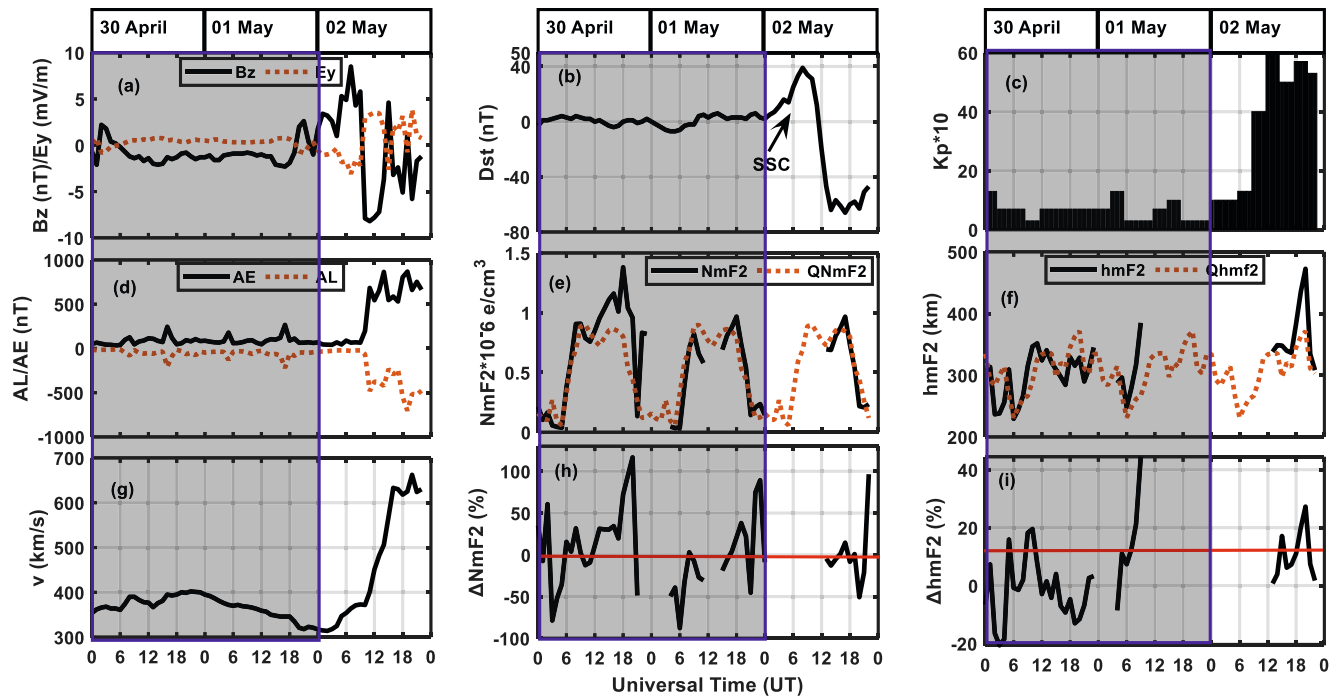
period is greater than 44% and it also precedes a geomagnetic storm. Using adequately large percentage deviations prevent the inclusion of arbitrary perturbations and disturbances of neutral atmospheric origin in the PMS observations (Adebesin, 2012).

Since our focus is on the PMSs, we have considered two days before the commencement of each of the selected geomagnetic storm event. However, in order to confirm if the PMSs observed were as a result of previous geomagnetic storms, a separate section is used to discuss the variation of some magnetic parameters (IMF Bz, IEF Ey, AE and AL, Kp, ap, Dst, and the solar wind plasma speed) considering 6 days before the occurrence of PMS. This is to enable us:

1. Observe if there exist any relationship between the PMS with the geomagnetic storm that follows, and
2. Determine the interval between the PMS and the geomagnetic storm event.

The geomagnetic storm events considered in this study are those that have a clear main and recovery phase, the initial phase of the geomagnetic storms varies as some of them do begin with a sudden storm commencement (SSC).

The data for the: (a) Interplanetary magnetic field (IMF) Bz in nT, interplanetary electric field (IEF Ey) in mV/m, Solar wind plasma Speed (v) in km/s and, (b) Geomagnetic indices: Dst, AE, AU, AL all in nT,  $Kp \times 10$  and ap; were obtained from NSSDC's OMNI database (<https://omniweb.gsfc.nasa.gov/form/dx1.html>). The Kp values used in Table 2 were provided from GFZ Helmholtz Center Postdam and were downloaded at the WDC website (<http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html>). (c) the results of the occurrence of solar flares for the periods considered in this study, were obtained from the Laboratory of X-ray Astronomy of the Sun, LPIRAS, Russia database ([http://tesis.lebedev.ru/en/sun\\_flares.html](http://tesis.lebedev.ru/en/sun_flares.html))



**Figure 2.** Diurnal variation of: (a) the interplanetary magnetic field (IMF Bz) and Electric field (Ey), (b) Aurora electrojet (AE and AL), (c) Solar wind speed (v), (d) Kp index, (e) Disturbance storm time (Dst) index, the arrow with SSC in this figure, denotes the onset time of the sudden Storm Commencement (SSC), (f) Electron density of the F2-layer (NmF2), (g) percentage change of NmF2 ( $\Delta$ NmF2), (h) Peak height of the F2 layer (hmF2), (i) percentage change of hmF2 ( $\Delta$ hmF2). The ionospheric parameters (NmF2, hmF2) and their respective percentage changes are for Ilorin an African equatorial station. The plots are for April 30–May 02, 2010 (DOY 120–122). The dark shaded indicates the period of pre-magnetic storm signature (PMS).

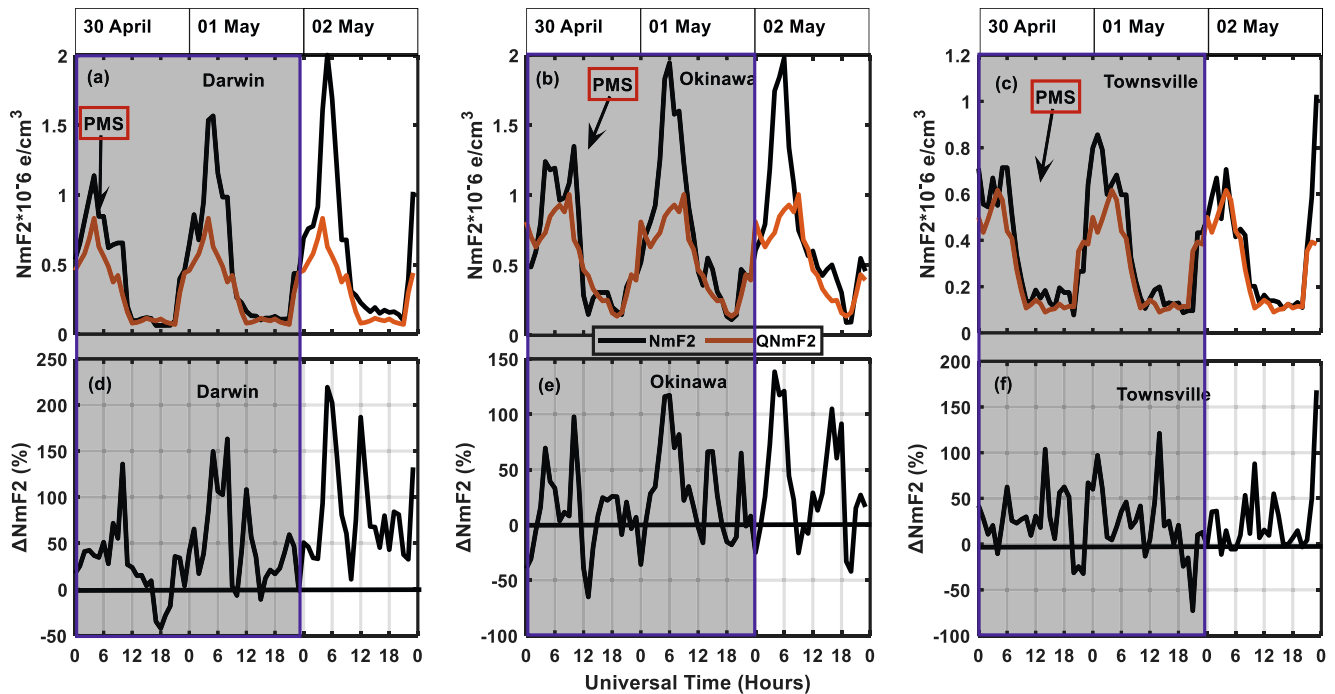
### 3. Results

#### 3.1. Pre-Magnetic Storm Signature of April 30, 2010

Figure 2 show the diurnal variation of: (a) the interplanetary magnetic field, Bz and interplanetary Electric field, Ey, (b) Disturbance storm time (Dst) index in nT, (c) Kp index (d) Aurora electrojet (AE and AL) in nT (e) Electron density of the F2-layer (NmF2  $\times 10^{-6}$  e/cm<sup>3</sup>), (f) Peak height of the F2 layer (hmF2 in km), (g) Solar wind speed (v) in km/s, (h) Percentage change in NmF2 ( $\Delta$ NmF2 in %), (i) percentage change in hmF2 ( $\Delta$ hmF2 in %). The ionospheric parameters (NmF2, hmF2) and their respective percentage changes are for Ilorin, Nigeria an African equatorial station. Figure 3 on the other hand show the diurnal Variation of NmF2 over (a) Darwin, (b) Okinawa and (c) Townsville. Their respective Percentage Change in NmF2 ( $\Delta$ NmF2) is shown in (d) Darwin, (e) Okinawa, and (f) Townsville. The plots span April 30–May 02, 2010 which is equivalent to the day of the year (DOY) 120–122 with solar flux (F10.7 ranging from 79.8 to 80.8).

Observations from Figure 2 show that the geomagnetic storm event began with the arrival of the high speed solar wind (HSSW) as shown in Figure 2g, traces of which can also be seen in the rapid oscillations of the IMF Bz starting from around 23.00 UT of 01 May (Figure 2a), thus leading to the observed SSC (Figure 2b) on May 02, around 08.00 UT. The PMSs were seen at this station beginning about 25 h before the SSC (Figures 2e and 2f, for NmF2 and hmF2 respectively). These Figures revealed that the PMS appeared as a simultaneous enhancement in the NmF2 and a decrease in the hmF2 at different intervals. After the SSC, the Dst index reached a minimum depression of  $-66$  nT at 17.00 UT on May 02, and then recovered gradually (Figure 2b).

The Dst index had a minimum depression of  $-4$  nT on April 30, and  $-11$  nT on May 01, 2010, with maximum Kp and ap values below the reference value, thus indicating a geomagnetically quiet condition on the two days. However, April 30–May 01, 2010 were characterized by simultaneous decrease and increase in NmF2 and hmF2, with peak values occurring on April 30, 2010. April 30 is the fifth day in the range of the most magnetically quiet days as displayed on gfz potsdam website, (<http://www.gfz-potsdam.de/en/>



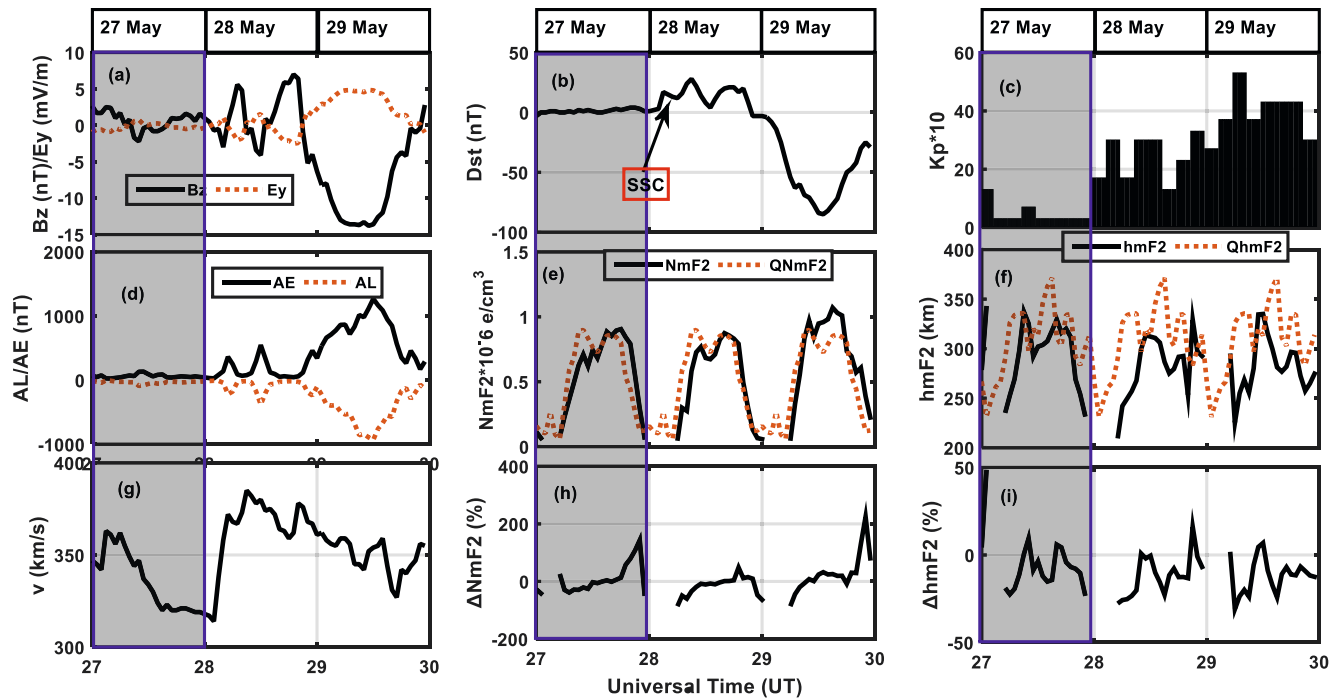
**Figure 3.** Diurnal Variation of NmF2 over (a) Darwin, (b) Okinawa, (c) Townsville and Percentage Change of NmF2 ( $\Delta$ NmF2) over (d) Darwin, (e) Okinawa, (f) Townsville for April 30–May 02, 2010. The dark shaded rectangle indicates the period of pre-magnetic storm signature (PMS).

section/earths-magnetic-field/data-products-services/kp-index/explanation/qd-days/). The difference in the NmF2 observed on that day is possible since the QNmF2 values were average values for the five geomagnetically quiet days. A close look at (Figures 2h and 2i), shows a large enhancement ( $\Delta$ NmF2 > 100%) in NmF2, alongside a decrease in hmF2 over Ilorin on April 30. Earlier, positive NmF2 deviation of about 61% was observed around 02.00 UT, this was accompanied by a concurrent decrease in NmF2 and hmF2 (−78% and −20% respectively) at 0300 UT. Intermittent rise and fall in the AE index which began around 08.00 UT to 22.00 UT (Figure 2d) was consistent with a series of positive deviations in NmF2 (with a peak value of 117% at 20.00 UT) over Ilorin (Figures 2e and 2h) on this day. During this period (of Peak NmF2 deviation), the hmF2 deviations were below the reference value. The IMF Bz was southward through the day with a minimum southward excursion of −2.1 nT, there was however no significant enhancement in the IEF Ey (Figure 2a) on this day.

However, as seen in Figure 3, there was a large positive deviation in NmF2 ( $\Delta$ NmF2 > 70%) on April 30, which appeared early at Darwin and Okinawa (Figures 3a and 3b, respectively) during the pre-noon period, followed by Townsville (Figure 3c) but during the post-noon period. This positive phase was immediately accompanied by a negative phase ( $\Delta$ NmF2 < −40%) over Darwin and Okinawa on the same day. Averagely, maximum NmF2 deviations were observed at the equatorial latitudes. Similar observations (positive phase) were also made on 01 May at Darwin, Okinawa and Townsville with  $\Delta$ NmF2 > 100% that occurred during the day time. A negative and positive phase was observed at Ilorin with  $\Delta$ NmF2 > 70% during the day- and night time respectively, although there was a data gap during the daytime period. Positive phases dominate the onset of the SSC at all the stations, except Ilorin due to data gaps. The variations observed in the time and nature of occurrence of PMS in these stations could be as a result of their latitudinal locations.

It is also worthy of note that the maximum NmF2 enhancement recorded at Okinawa and Darwin occurred during the geomagnetic storm event. The positive phase dominates the entire geomagnetic storm period. Simultaneous NmF2 and hmF2 increases were observed at Ilorin during the main phase of the geomagnetic storm on May 02, 2010.



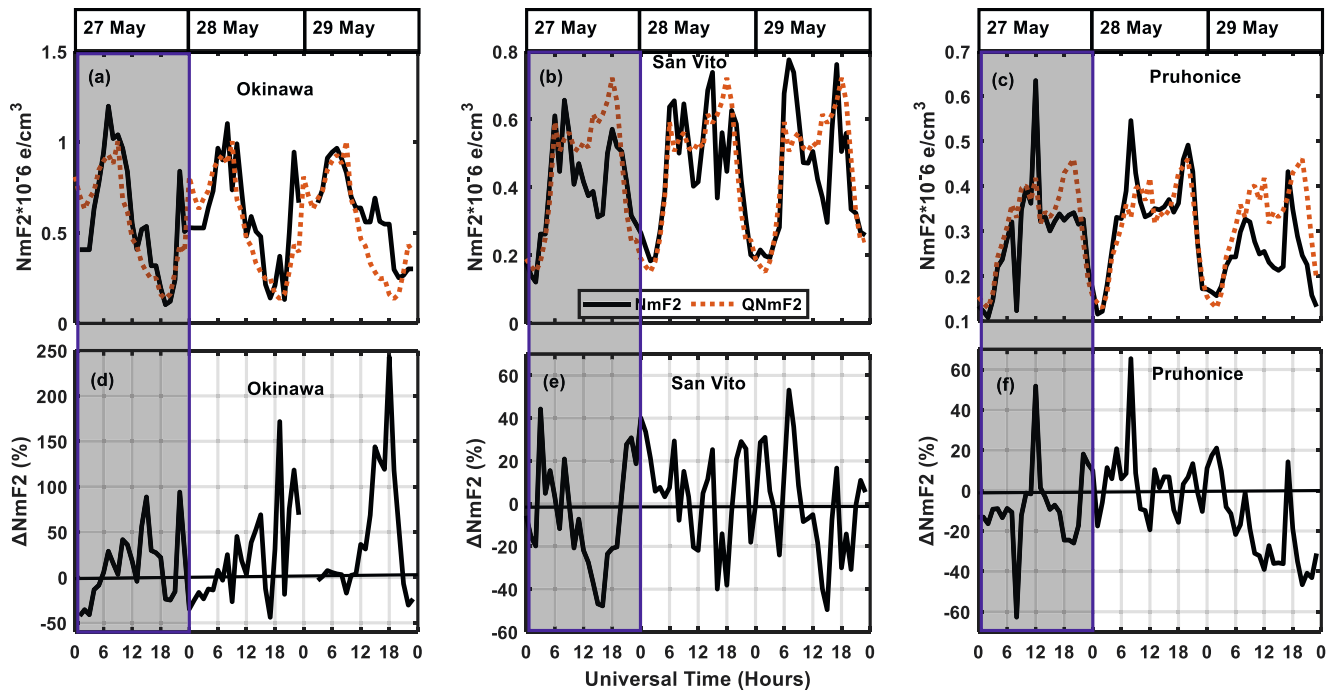


**Figure 4.** Diurnal variation of: (a) the interplanetary magnetic field (IMF Bz) and Electric field (Ey), (b) Aurora electrojet (AE and AL), (c) Solar wind speed (v), (d) Kp index, (e) Disturbance storm time (Dst) index, the arrow with SSC in this figure, denotes the onset time of the sudden Storm Commencement (SSC), (f) Electron density of the F2-layer (NmF2), (g) percentage change of NmF2, ( $\Delta$ NmF2), (h) Peak height of the F2 layer (hmF2), (i) percentage change of hmF2 ( $\Delta$ hmF2). The ionospheric parameters (NmF2, hmF2) and their respective percentage changes are for Ilorin an African equatorial station. The plots are for May 27–29, 2010 (Days 147–149). The dark shaded rectangle shows the period of the pre-magnetic storm signatures (PMS).

### 3.2. Pre-magnetic Storm Signature of May 27, 2010

Figure 4 show the diurnal variation of: (a) the interplanetary magnetic field, Bz and interplanetary Electric field, Ey, (b) Disturbance storm time (Dst) index in nT, (c) Kp index, (d) Aurora Electrojet (AE and AL) in nT, (e) Electron density of the F2-layer ( $\text{NmF2} \times 10^{-3} \text{ e/cm}^3$ ), (f) Peak height of the F2-layer (hmF2 in km), (g) Solar wind speed (v) in km/s, (h) Percentage change of NmF2 ( $\Delta$ NmF2 in %), (i) percentage change of hmF2 ( $\Delta$ hmF2 in %). The ionospheric parameters (NmF2, hmF2) and their respective percentage changes are for Ilorin, Nigeria an African equatorial station. Figure 5: depicts the diurnal Variation of NmF2 over (a) Okinawa, (b) San Vito, (c) Pruhonice, (d)  $\Delta$ NmF2 over Okinawa, (e)  $\Delta$ NmF2 over San Vito, (f)  $\Delta$ NmF2 over Pruhonice. The plots are for May 27–29, 2010, with solar flux (F10.7 ranging from 74.6 to 75.7).

The PMSs were observed during the early hours of May 27 (Data gaps occurred at Ilorin between 02.00 and 04.00 UT on this day, thus the first two hours (00–01.00 UT) were not clearly seen in the Figure). They appeared as a depletion in NmF2 ( $\Delta$ NmF2 =  $-41\%$ , although below the threshold value) as seen in Figures 4e and 4h, with a corresponding increase in the peak height of the F2 layer ( $\Delta$ hmF2 =  $47\%$ ) over Ilorin around 01.00 UT (Figures 4f and 4i). This observation was consistent with the slight increase in the solar wind speed from 345 km/s at 01.00 UT to 365 km/s at 03.00 UT (Figure 4g). The Bz was northward until around 08.00 UT, it turned southward reaching a minimum excursion of  $-2.2$  nT, with a little increase in the Ey (0.76 mV/m) around 10.00 UT (Figure 4a). The solar wind speed decreased from 362 km/s around 03.00 UT to 319 km/s around 22.00 UT (Figure 4g). During this period, a simultaneous depletion in NmF2 and increase in hmF2 were observed, the NmF2 however attained its peak value ( $\Delta$ NmF2  $> 100\%$ ) for the day around 22.00 UT (Figures 4e and 4h). The variation in the ionospheric F2 layer was observed to be consistent with the fluctuations in the solar wind speed on this day. Increases/decreases in AE and AL indices (133 and  $-90$  nT respectively) were also observed around 10.00 UT on May 27. All these occurred before the onset of the SSC around 03.00 UT on May 28, 2010 (Figure 4b). The northward turning of the IMF-Bz around 03.00 UT was simultaneous with the increase in the Dst index from 2 to 17 nT and consequently 28 nT (Figures 4a and 4b), thus signaling the commencement of geomagnetic storm. The Dst Index reached



**Figure 5.** Diurnal Variation of NmF2 over (a) Okinawa, (b) San Vito, (c) Pruhonice and Percentage Change of NmF2 ( $\Delta$ NmF2) over (d) Okinawa, (e) San Vito, (f) Pruhonice for May 27–29, 2010. The dark shaded rectangle shows the period of the pre-magnetic storm signatures (PMS).

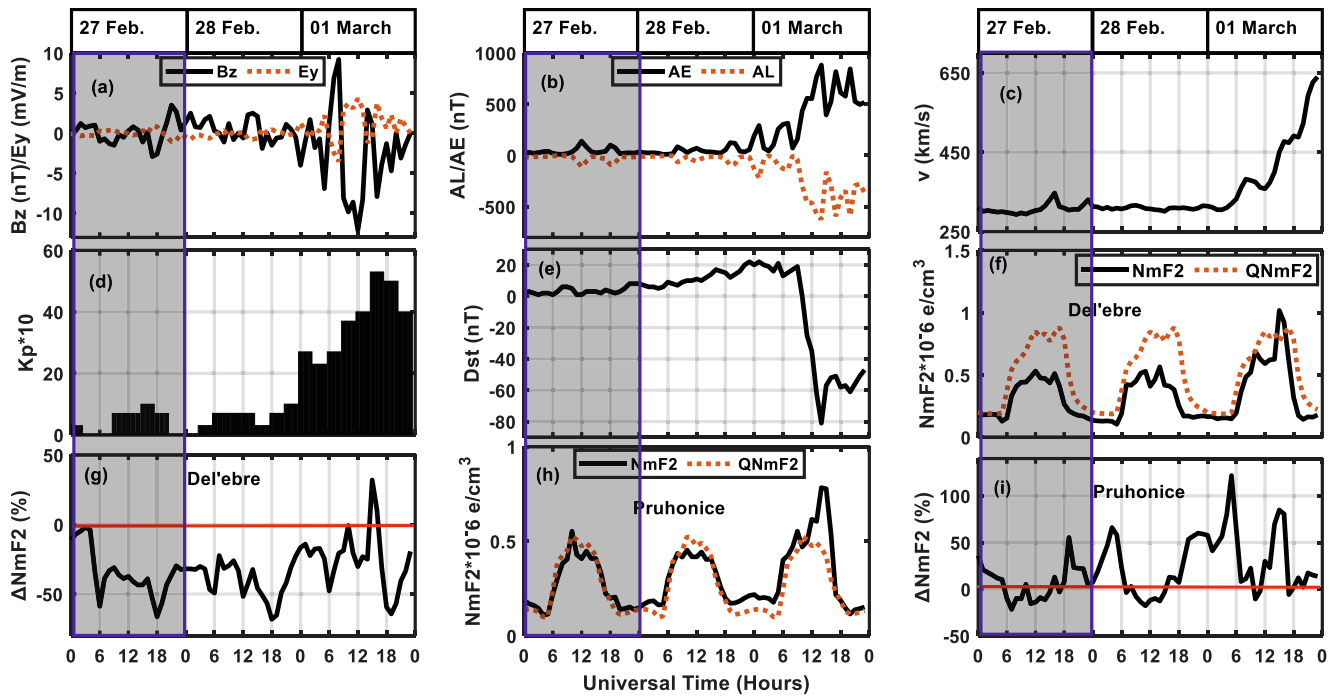
a minimum depression of  $-85$  nT around 13.00 UT, all other indices also attained their maximum values on May 29. NmF2 enhancement that is, consistent with the decrease in hmF2 was observed over Ilorin during the main phase of the geomagnetic storm. This signifies a decrease in the eastward electric field during the day, resulting in the decrease in the drift of ionization from the equatorial F2 layer (Adeniyi, 1986). Results from Figure 5 shows that the PMS appeared as NmF2 enhancements ( $\Delta$ NmF2  $> 70\%$ ) at Okinawa (Figures 5a and 5d), decrease in NmF2 ( $\Delta$ NmF2  $< -45\%$ ) at San Vito (Figures 5b and 5e) and NmF2 enhancement ( $\Delta$ NmF2  $> 50\%$ ) at Pruhonice (Figures 5c and 5f) all occurring between 1,200 and 1800 UT on May 27. Both positive and negative deviations characterize the geomagnetic storm period (May 28–29, 2010) as shown in Figure 5.

### 3.3. Pre-magnetic Storm Signatures of February 27, 2011

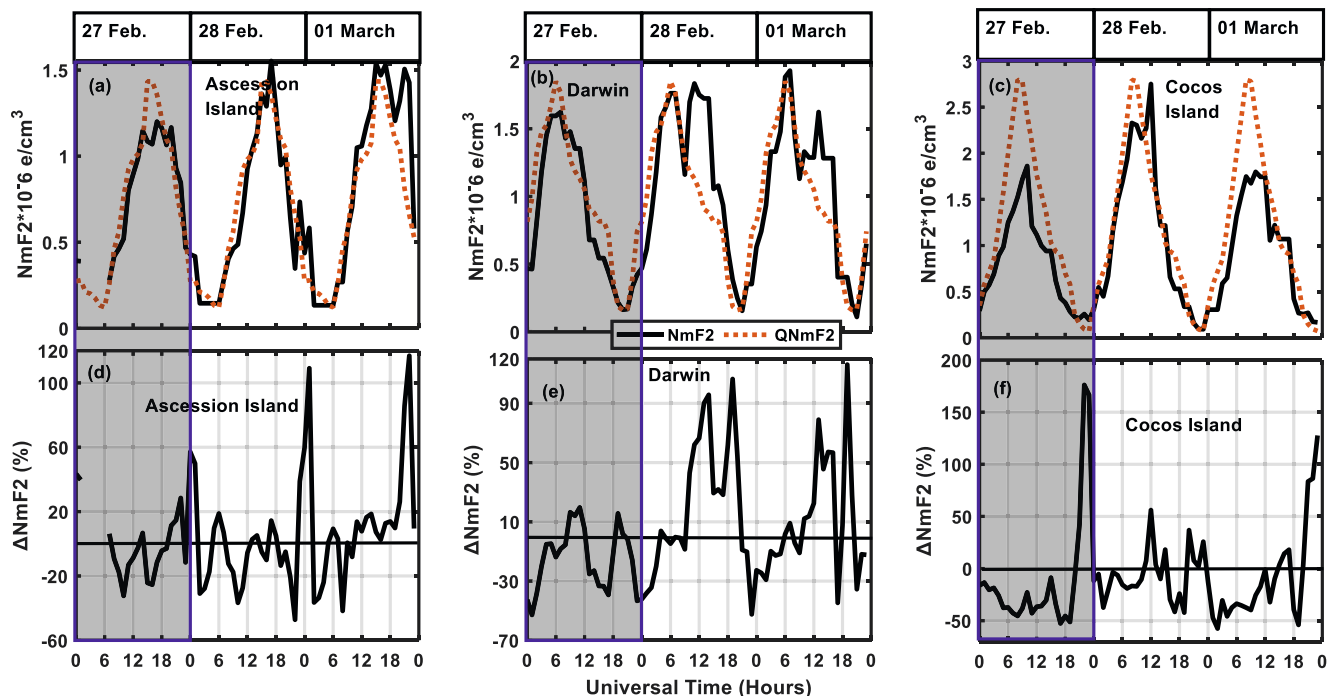
Figure 6 show the diurnal variation of: (a) the interplanetary magnetic field, Bz, and Interplanetary Electric field, Ey, (b) Aurora electrojet (AE and AL), (c) Solar wind speed (v), (d) Kp index, (e) Disturbance storm time (Dst) index, (f) Electron density of the F2-layer (NmF2) over Del'ebre, (g)  $\Delta$ NmF2 over Del'ebre, (h) Electron density of the F2-layer (NmF2) over Pruhonice, (i)  $\Delta$ NmF2 over Pruhonice. The change of format in this plot is as a result of absence of data from the Ilorin Digisonde observatory during this period. Figure 7 illustrate the diurnal Variation of NmF2 over (a) Ascension Island, (b) Darwin, (c) Cocos Island, (d)  $\Delta$ NmF2 over Ascension Island, (e)  $\Delta$ NmF2 over Darwin, and (f)  $\Delta$ NmF2 over Cocos Island. All these plots are for February 27–March 01, 2011 with solar flux (F10.7 ranging from 88.7 to 108.5).

In addition to the above observation, the February 27, 2011 PMS appeared as a strong negative phase at Del'ebre (Figures 6f and 6g). It began as a positive phase and later negative phase over Pruhonice (Figures 6h and 6i). It appeared as a negative phase over Ascension Island (Figure 7a) and Cocos Island (Figures 7c and 7f), and was later followed by a positive phase during the Post sunset period (after 18.00 UT). The positive phase over Darwin on this day was below the reference value (Figures 7b and 7e).

The Kp and Dst indices (Figures 6d and 6e, respectively) indicates a quiet geomagnetic condition, an enhancement in the auroral indices with peak values of 139 and  $-111$  nT for AE and AL respectively, was observed on February 27, 2011 (Figure 6b). The solar wind speed was generally low on February 27–28,



**Figure 6.** Diurnal variation of: (a) the interplanetary magnetic field (IMF Bz) and Electric field (Ey), (b) Aurora electrojet (AE and AL), (c) Solar wind speed (v), (d) Kp index, (e) Disturbance storm time (Dst) index, (f) Electron density of the F2-layer (NmF2) over Del'ebre, (g) percentage change of NmF2, ( $\Delta$ NmF2) over Del'ebre, (h) Electron density of the F2-layer (NmF2) over Pruhonice, (i) percentage change of NmF2, ( $\Delta$ NmF2) over Pruhonice. The plot is for February 27–March 01, 2011. The dark shaded rectangle shows the period of the pre-magnetic storm signatures.



**Figure 7.** Diurnal Variation of NmF2 over (a) Ascession Island, (b) Darwin, (c) Cocos Island and Percentage Change of NmF2 ( $\Delta$ NmF2) over (c) Ascession Island, (d) Darwin, (f) Cocos Island for February 27–March 01, 2011. The dark shaded rectangle shows the period of the pre-magnetic storm signatures.

2018 (Figure 6c). Figure 6a reveals that the positive phases observed during the post sunset periods were consistent with the Northward turning of Bz from its southward orientation.

Observation from Figure 6e reveals a special case of a gradual development of geomagnetic storm without a clear cut SSC. The northward turning of the IMF Bz from  $-2.9$  nT at 17.00 UT to a maximum value of about  $3.5$  nT at 21.00 UT on February 27, 2011; was observed to be consistent with the gradual increase in the Dst index that began around 18.00 UT (one hour later) from  $3$  nT on February 27, 2011 to a maximum amplitude of  $22$  nT around 23.00 UT on February 28, 2011. After this peak, the Dst began a gradual descend, and later a sharp decrease until it attained a minimum amplitude of  $-81$  nT at 14.00UT on March 01, 2011.

The gradual but consistent increase observed on the Dst index (Figure 6e), could have caused an increase in the eastward electric field during the day, which also led to an increase in the ExB force and consequently an increase in the drift of ionization away from the equatorial F2 layer. This may be responsible for the negative deviations that dominated the dayside over Del'eburu, Ascension Island and the pre-noon period over Darwin and Cocos Island (Figures 6g, 7d, 7e and 7f). A strong negative phase was seen at Del'eburu during this period. A strong positive phase was observed at Pruhonice (Figure 6i) during the early hours of February 28, 2011. This cannot be unconnected with the drift of electrons from the equatorial and low latitudes to the mid latitudes. High solar wind speed was observed on March 01 around 03.00 UT, signaling the commencement of the main phase of the geomagnetic storm, which was characterized by both positive and negative deviations.

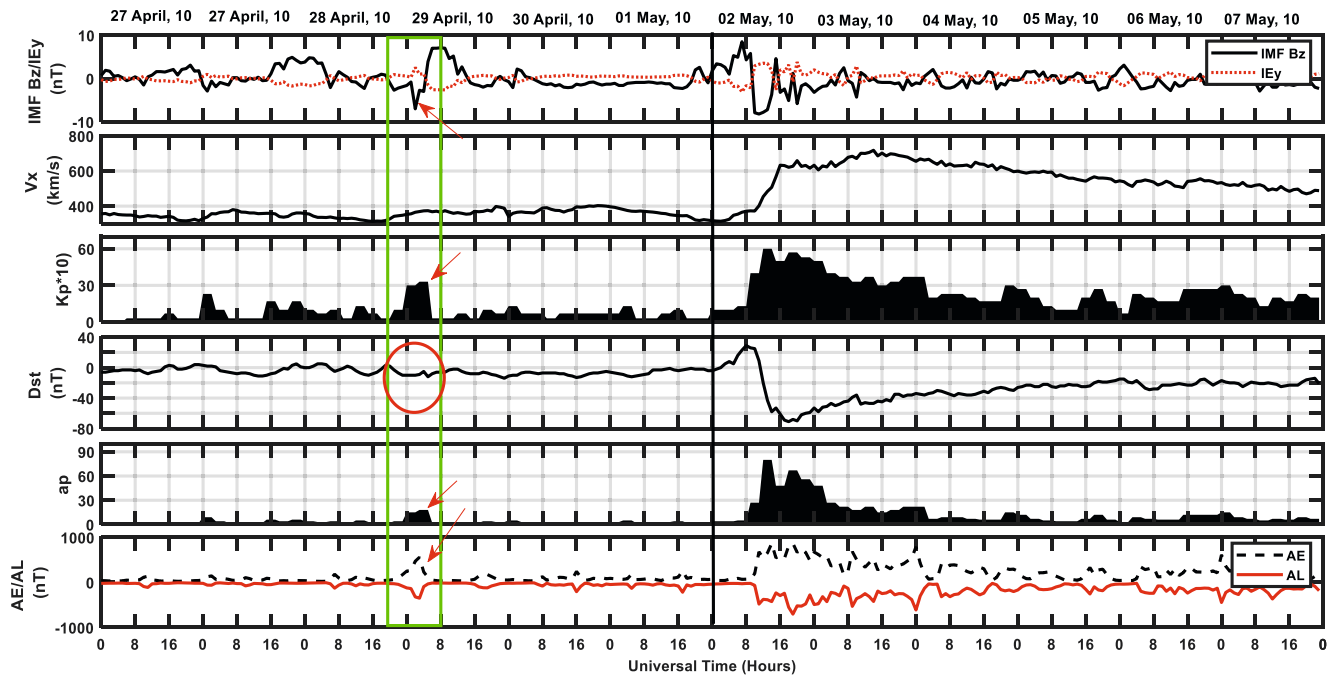
### 3.4. Maximum Deviation of NmF2 During the Pre-Magnetic Storm Signatures

The summary of findings during the 16 cases of PMSs investigated in this study is shown in Table 2. The table, shows the peak values of Dst, AE, IMF Bz, Ap, Kp, and  $\Delta$ NmF2 from all the stations and events investigated, the stations are represented by codes as earlier shown in Table 1. The results are specifically for the day's PMSs were observed in 2010, 2011, and 2012 respectively. These values were obtained from all the events studied and are presented for easy comparison. Results from these Table have further reveal that: (a) the observed NmF2 percentage deviations occurs under a quiet ring current (Dst  $> -25$  nT), (b) PMSs occur under moderate auroral activity indicated by the AE index (AE  $> 100$ ), (c) PMSs occur under a southward Bz, (d) PMSs occur under a quiet geomagnetic activity (Ap  $< 7$ , Kp  $> 3$  and Dst  $> -30$  nT). (e) Averagely, the stations around the equatorial and low latitude show higher percentage deviations of NmF2 than those of the mid-latitudes. Koba et al. (2000), has shown that magnetic disturbance associated to the penetration of the magnetospheric convection electric field decreases from high to middle latitudes and then increases at equatorial latitudes due to the Cowling conductivities. The strength of the Equatorial Electrojet increases and this can be a cause of the larger NmF2 deviations observed at low latitudes.

### 3.5. Pre-magnetic Signatures and Previous Geomagnetic Storms

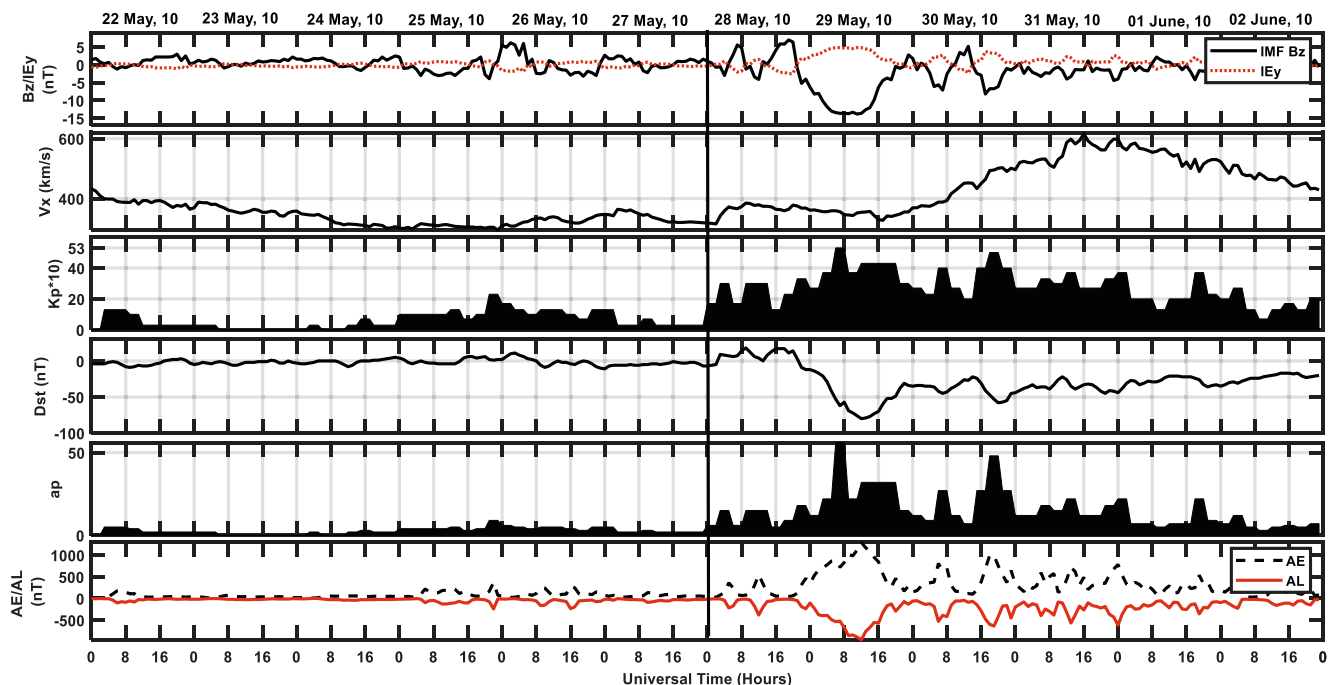
Figures 8 and 9 depict the plot of the diurnal variation of (from top to bottom); the interplanetary magnetic field Bz and Interplanetary Electric field (Ey), Solar wind speed (Vx), Kp index, Disturbance storm time (Dst) index, ap index, and Aurora electrojet (AE and AL). The dates were carefully selected to cover a minimum of 6 days before the commencement of the geomagnetic storms. This is to enable us observe if the PMSs observed were as a result of previous geomagnetic storm events, and also to study the variations or features of these parameters before geomagnetic storms. Observations from these Figures reveal no sign of geomagnetic storm before any of the PMSs recorded, although, significant changes were seen in most of the parameters considered.

Figure 8 shows an occurrence of an event (green rectangle) 72 h before the geomagnetic storm (April 29, around 00–06 UT). There were increases in the values of AE and AL, Ap and Kp, slight increase in the solar wind plasma speed beginning from  $327$  to  $374$  km/s and later  $400$  km/s; gradual but sudden southward turning of the IMF Bz which got to a minimum value of  $-7$  nT. With all these observations, there was no indication of a geomagnetic storm based on the Dst observation. This indicates a quiet condition. However, the observed North-South fluctuation of the IMF Bz, enhancement in the interplanetary electric field (to a peak value of  $2.5$  mV/m) as well as the enhancement in the aurora electrojet (AE =  $558$  nT, AL =  $-350$  nT), and the corresponding slight increase in the solar wind speed, are indications of injection of plasma into



**Figure 8.** Temporal variation of (From top to bottom): the interplanetary magnetic field (IMF Bz) and Electric field (Ey) (b) Solar wind speed (v), Kp index, Disturbance storm time (Dst) index, ap index, Aurora electrojet (AE and AL) all plots are for April 27–May 07, 2010. The ring between April 28 and 29, is indicative of the quiet Dst in spite of southward Bz, increase in Kp and Ap values, and enhanced aurora activity, while the vertical line on May 02, shows the time of SSC.

the Magnetosphere which occurred during the night time. This could have caused modification of the zonal electric field, thus leading to significant changes in the ionospheric electron density of the equatorial, low and mid latitudes as earlier observed, without any geomagnetic storm necessary occurring. After this



**Figure 9.** Temporal variation of (From top to bottom): the interplanetary magnetic field (IMF Bz) and Electric field (Ey) (b) Solar wind speed (v), Kp index, Disturbance storm time (Dst) index, ap index, and Aurora electrojet (AE and AL) all plots are for May 22–June 02, 2010. The vertical line shows the time of SSC.

particular event, it was observed that the IMF Bz remained majorly southward until the commencement of the SSC on May 02, around 00 UT. Increases in AE/AL indices were also observed at certain intervals during this period. This also is indicative of the pressure exerted on the magnetosphere few days before the SSC, thus making it difficult to rule out the possibility of a connection between PMSs and the geomagnetic storm that followed. Similar observations were also made from May 25, on Figure 9. North and southward fluctuations in the IMF Bz, increases in the Plasma speed, Kp and Ap index as well as increases in the aurora indices were observed within 72 h before the commencement of geomagnetic storms. These variations were all observed under a quiet ring current. Observations from these Figures show clearly that *PMSs and their respective effects on the ionosphere are not as a result of previous or earlier geomagnetic storms. They are independent events that could likely pave way for the occurrence of a geomagnetic storm.*

#### 4. Discussion

Many recent and past studies (e.g., Adebisi et al., 2014; Bagiya et al., 2009; Blagoveshchensky, et al., 2017; Buresova & Lastovicka, 2007; Chukwuma, 2011; David, 2013; Danilov, 2013, 2001; Danilov & Konstantinova, 2019, 2021; Danilov et al., 1985; Liu et al., 2008; Joshua et al., 2014b; Kane, 1973; Mikhailov & Perrone, 2009, 2020; Saranya et al., 2011; Zhang et al., 2021) have reported/studied enhancement in foF2/NmF2 during quiet days that precede geomagnetic storm commencement. These increases or decreases in NmF2 are normally not expected under geomagnetically quiet conditions, considering the Dst value. The feature of this phenomena and the mechanism responsible for its occurrence has been a challenge for decades now. The present study presented an analysis of the PMSs over some equatorial, low and mid latitude region. The possibility of PMSs observed as a result of previous geomagnetic storms has also been considered. Our observations in this study have also revealed that PMS is not an after mat of a previous geomagnetic storm as shown in Figures 8 and 9.

There is sufficient evidence that a significant portion of the day-to-day changes observed in the ionospheric parameters (NmF2, TEC, and hmF2), cannot be explained by some of the key or well established drivers like solar ionizing flux and geomagnetic activity (Goncharenko et al., 2010). It has been shown by Forbes et al. (2000), Rishbeth and Mendillo, 2001, Mendillo et al. (2002) that about 20% and 33% respectively of day and night time observed changes/variability in the F-region electron density are not accounted for by these drivers. Many studies (Chau et al., 2012; Goncharenko et al., 2010; Lastovicka, 2006; Mendillo et al., 2002; Mikhailov et al., 2009; Lin et al., 2012; Liu et al., 2011; Rishbeth, 2006) have attributed the day-to-day ionospheric variability to direct or indirect effect of some meteorological processes such as planetary waves, tides and gravity waves (Goncharenko et al., 2010). The Earth's ionosphere is known to be influenced by solar wind dynamic pressure from the top and also by the lower atmospheric waves originating from the bottom, thus making the understanding and modeling of the day-to-day variability highly complicated (Sripathi & Bhattacharyya, 2012 and the references there in).

The present study has further confirm that PMSs (though a relatively quiet time phenomena) mostly occur under a southward IMF Bz, moderate enhancement in the auroral indices ( $AE > 100$  nT); thus suggesting a possibility of the ionosphere being influenced by the solar wind dynamic pressure. There is no clear evidence that the PMSs are caused by some of the meteorological processes; this is however left open for further studies. Notwithstanding, the NmF2 and hmF2 deviations observed during the PMSs are quite similar to the ionospheric disturbances observed during the geomagnetic storms. This suggests a possibility that the two events may be driven by the same/similar mechanism. Bagiya et al. (2009), has earlier attributed PMSs to the increase in the zonal electric field on vertical drift, which could be as a result of many factors, some of which includes; the effect of the previous geomagnetic storm, direct mapping of the interplanetary electric field to the equatorial electric field or as a result of the planetary wave activity (Adebisi et al., 2014; Liu et al., 2008). However, the major PMSs presented in this study (Figures 2, 4 and 6) are clearly separated from any effect arising from any previous geomagnetic storms.

The present study also shows the occurrence of frequent north-south fluctuations of the IMF Bz with more hours of southward orientation, increase in the aurora activity that is, consistent with either an increase or decrease in the solar wind speed, a slight increase in the ap and Kp indices in some cases, though not significant enough to indicate the occurrence of any geomagnetic storm few days before the SSC. These suggest

an increase in the geomagnetic activity prior to the SSC that is, capable of causing the observed changes in the ionosphere.

Mikhailov and Perrone (2009, 2020), have shown that there are no convincing arguments that the observed cases of PMSs at middle and sub-aurora latitudes considered by other researchers established any relation between PMS and the magnetic storms that follow. It is however evident that after every PMS, geomagnetic storm usually follows, either immediately or within 24–48 h. Earlier works like, Liu et al., 2008, have shown that the study of PMS could be of great importance in the prediction of ionospheric weather. Blagoveshchensky and Kalishin (2009) have also noted that PMS could be used to predict geomagnetic storms. Similarly, Adekoya et al. (2012), pointed out that moderate ionospheric F2-layer disturbance that usually occurs during the PMS are indicative of strong ionospheric disturbances during the main phase of geomagnetic storms. Danilov and Konstantinova (2019) and Konstantinova and Danilov, (2020), referred to PMS as ionospheric precursors of geomagnetic storms. Although, there is no clear or established connection between PMSs and the geomagnetic storms that follows, it could be argued that the PMS may likely serve as a pointer to the occurrence of geomagnetic storms when properly understood. This cannot be unconnected with the fact that they always precede geomagnetic storms (irrespective of the class of the storm), this is however, open for further studies.

Interestingly, the Southward orientation of the IMF Bz that is, known as one of the key determinant for the connection of interplanetary plasma parameters with geomagnetic storm, is also a major factor in the occurrence of the PMSs. In most cases, the IMF Bz remains southward even after the PMS, until the commencement of the proceeding geomagnetic storm. This in principle suggests a likelihood of a connection between the two events, although not fully established in this study.

Furthermore, in most cases where these PMSs were observed, increases in the AE and a decrease in AL indices were also obvious during such periods. During some PMSs, the IMF Bz was also observed to have experienced a long duration of the southward orientation (Figure 2a). At other times, they occur with the Bz having a north-south fluctuations, although with Bz value that is, greater than  $-3$  nT, hence not significant enough to cause any geomagnetic disturbance (Gonzalez, et al., 1998). Lei et al. (2008) in Liu et al. (2018), has earlier reported the occurrence of geomagnetic perturbations during geomagnetically quiet conditions. They associated these perturbations with the solar coronal holes and High Speed Solar Wind streams. These two events are known to cause significant changes in the earth's ionosphere. The southward Bz opens the magnetosphere and energy is being transmitted from the solar wind to the magnetosphere even when there are no geomagnetic storms. Slight changes in the IEF Ey were also observed during PMSs. In Figure 6a, Ey exhibit a decrease of about  $-1.07$  mV/m on February 27, 2011; although its magnitude is very small, but it could have produced an observable effect on the ionosphere.

Manju et al. (2009) and Joshi et al. (2016) has also shown that during the southern IMF Bz, the prompt penetration into the ionosphere over the equatorial and low latitude occurs, leading to the modulation of the quiet time ionospheric zonal electric field. Therefore, it could be suggested that PMSs are connected to the southward orientation of the IMF Bz, moderate enhancement in the aurora electrojet and a slight variation in the solar wind plasma speed, which may not necessary be as a result of geomagnetic storms.

It has been shown by Mikhailov and Perrone (2009) that; when AE is greater than 100 nT (i.e.,  $AE > 100$  nT), it indicates an increase in the aurora activity which may be as a result of the southward Bz. This suggests a possibility of penetration of the auroral electric field to the equatorial and low latitudes during such periods leading to the modification of the equatorial electric field pattern and consequently the ExB drift (Joshua et al., 2014a; Liu et al., 2008). Many studies (Adebisi et al., 2014; Danilov & Belik, 1992; Danilov et al., 1985; Joshua et al., 2014b) have also attributed PMSs to neutral composition due to the modification of the day-side cusp as a result of particle precipitation.

It is also pertinent to note in this study that, PMSs could also be associated with sub-storms. This is because a sub-storm is considered as a brief disturbance in the Earth's magnetosphere leading to the release of energy from the "tail" of the magnetosphere and injected into the high latitude ionosphere. This shows that both magnetic storms and sub-storms occur as a result of an increase in the geomagnetic activity. Whereas geomagnetic storms are characterized by the Dst index, sub storms, on the other hand, are measured by AE index (Lakhina et al., 2006). Dobias and Wanliss (2009) have further shown that the AL index in particular

is the most suitable index for studying the dynamics of magnetospheric sub-storms. Thus, the perturbations observed in the AL and AE indices during some PMSs cannot be unconnected with the occurrence of a sub-storm during such periods. Results from this study (e.g., Figures 2d and 4d) have shown a simultaneous response of the AL and AE indices with that of the ionospheric F2-layer electron density during the PMS. Most of the disturbances observed on AL and AE indices during PMSs in this study, mostly occur within the space of an hour, although they may be repeated but each of them reached its maxima within an hour. However, the effect on the F2-layer takes more than an hour as earlier mentioned. It is then apparent that PMSs occur as a result of disturbances in the auroral region. They are only referred to as Quiet time disturbances because their traces were not captured by the Dst, Kp, or ap indices.

Therefore, based on the results from this study, we can infer that there could be a possibility of sub-storms causing a variation in the equatorial and low latitude electric field, leading to the observed NmF2 enhancement or depletions referred to as PMSs at that region. Kikuchi et al. (2000), has shown that penetration of electric field during sub-storms is a complex process. An electric field associated with the field aligned-currents (FACs) tends to shield the equator ward penetrating convection electric field (Crooker & Siscoe, 1981). However, the shielding can be broken during a rapid variation of the convection electric field (Kikuchi et al., 2000), which usually occur during sub-storms. Bounsanto, 1999, have earlier observed that, disturbance in the magnetospheric convection electric fields can penetrate to the equator before they are opposed by effects of shielding in the inner magnetosphere (Gonzales et al., 1983; Sastri et al., 1992). Koba et al. (2000) found the existence of an over shielding effect related to the field aligned currents of region 2.

Nevertheless, both our analysis and that of Liu et al. (2008) indicates that the PMSs are not caused by solar flares. Most of the solar flares observed during the cases considered were minor flares that hardly last up to one hour and they occur mostly after the PMSs were observed, and as such lack the capacity to drive the observed ionospheric variation. Tsurutani et al. (2005) and Le et al. (2007) cited by Liu et al. (2008) have also shown that solar flares effects are at daytime and generally last for less than one hour. Our results have shown that PMSs occur both during the daytime and night time and can sometimes last for more than 24 h (Figures 2–4).

Figure 2, shows that April 30, 2010 was characterized by large enhancements ( $\Delta\text{NmF2} > 100\%$ ) in NmF2, alongside an increase in hmF2 (Figures 2h and 2i) over Ilorin; thus, indicating the lifting of the ionospheric F2-layer by the fountain effect at this station during PMS. Similarly, the PMSs observed during the early hours of May 27, 2010 (Figure 4) appeared as a depletion in NmF2 ( $\Delta\text{NmF2} = -41\%$ ), with a corresponding increase in the peak height of the F2-layer ( $\Delta\text{hmF2} = 47\%$ ) over Ilorin around 0100 UT (Figures 4f–4i). Later in the day, a simultaneous depletion in NmF2 and increase in hmF2 were also observed. The NmF2 however attained its peak value ( $\Delta\text{NmF2} > 100\%$ ) for the day around 2200 UT. This is attributed to the effect of the vertical plasma drift or modifications of the zonal electric field during such times.

## 5. Summary and Conclusion

This paper has compared the occurrence of PMSs at the equatorial and low latitude with those of the mid-latitudes. Results from this study can be summarized as follow:

- PMSs occur mostly during geomagnetically quiet days that precede geomagnetic storms and can last for a period between 12 and 48 h and sometimes even more.
- They occur under a quiet ring current energy, usually before the commencement of geomagnetic storm events regardless of it severity (moderate, strong, extreme and severe). Furthermore, the occurrence of storm events that followed PMSs is usually seen within 24–48 h. Although the evidences available suggest that, there is a likely connection between PMSs and the geomagnetic storms that follows, it is difficult to clearly state how this is done.
- Although the Dst, Kp, and the ap indices indicates a geomagnetically quiet condition during PMSs. The southward IMF Bz, enhancement in the aurora indices ( $\text{AE} > 100$  nT), ionospheric variability and occasional increase in the solar wind speed observed during PMSs, as well as the geomagnetic storms that follows, shows the complexity in explaining the phenomenon and dynamics of PMSs. It can be suggested that PMS is not an absolute quiet time phenomenon but rather signatures that precedes geomagnetic storm events and usually occur under an enhanced auroral activity and a southward IMF Bz. Therefore,



it is important to consider a certain threshold value for the aurora Electrojet (AE) in addition to the Dst, ap, and Kp in the definition of a geomagnetically quiet day. These would eliminate the ambiguity in explaining the ionospheric variability that usually occurs few days before the commencement of geomagnetic storms.

- Again this study has also shown that PMSs are independent of previous geomagnetic storms. It is evident from this study that north-south fluctuations of IMF-Bz and auroral activity increases 2–3 days before the SSC, thus indicating an increase in geomagnetic activity. PMSs may however, be considered as some preliminary events that may likely pave a way for geomagnetic storms to occur.
- Lastly, the magnitudes of NmF2 deviations during PMSs are observed to be generally higher at the equatorial and low latitudes than those of the mid-latitudes. The hmF2 variation is observed to be consistent with the NmF2 deviations during the PMSs. The increase in the hmF2 is an indication of the lifting of the F2-layer. The changes observed in these parameters during the PMSs were quiet similar to those observed during geomagnetic storms, thus, suggesting a possibility of the duo been driven by the same mechanism.

### Data Availability Statement

The available data used for this study: (a) University of Ilorin, Nigeria (<https://www.unilorin.edu.ng/>), (b) National Space Science Data center (NSSDC) (<https://omniweb.gsfc.nasa.gov/form/dx1.html>), (c) University of Massachusetts Lowell, Center for Atmospheric Research (<https://www.digisonde.com/stationlist.php>) (d) the World Data Center (WDC) for geomagnetism, Kyoto, Japan (<http://wdc.kugi.kyoto-u.ac.jp/>) (e) The German Research Center for Geosciences (<http://www.gfz-potsdam.de/en/section/earths-magnetic-field/data-products-services/kp-index/explanation/qd-days/>) and (f) the Laboratory of X-ray Astronomy of the Sun, LPIRAS, Russia database ([http://tesis.lebedev.ru/en/sun\\_flares.html](http://tesis.lebedev.ru/en/sun_flares.html)).

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