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Ionospheric Response to Intense Geomagnetic Storms and Pre-storm

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ABSTRACT

In this study, the investigation of the ionospheric response to the geomagnetic and interplanetary, pre-storm and storm phenomena was concerned with variation in foF2 during Oct. 19-23, 2001 covering the three phases of the storm. The storm was chosen on the criteria of its intensity and also it is a double step storm. Analysis of the changes in foF2 was conducted using a normalized deviation of critical frequency (δ(foF2)) on the ionosphere of 3 low and 6 mid-latitude stations from 3 sectors of the earth ionosphere. Analysis of a vertical error bar on δfoF2 was also used to investigate the vivid effect of positive and negative storm on the aforementioned parts of the ionosphere. The upper error bar represents the positive storm while the lower error bar presents the negative storm. The result of the study showed that the enormity of Bz turning into southward from northward direction and the variation in F2 layer parameter at the time of geomagnetic storm strongly depends on the intensity of the storm. There was no significant difference between the ionospheric F2 response of low and middle latitude ionosphere any newly burst of storm activity is associated with a newly generated disturbance at the ionospheric F2 layer of the ionosonde stations. The pre-storm period was preceded by intense positive and negative ionospheric storms. Furthermore, the variations in ionospheric F2 in the pre-storm period suggest the impending large ionospheric disturbances at the main phase and increase ionospheric variation exceeding the main phase signified the storm recovery. Also, the record intense ionospheric storm was recorded at the initial phase despite the low geomagnetic storm activity in the period. Correspondingly, the error bar showed clearly the contribution of both negative and positive storm to the stations along the same narrow longitude.

Key words: Ionospheric response, geomagnetic storms, pre-storm, Ionospheric F2, geomagnetically induced currents

INTRODUCTION

A geomagnetic storm is the main interruption of the earth magnetosphere phenomena that occur due to eruption of energy from the solar wind to the neighbouring space around the Earth[1,2]. These storms are as a result of variation in the solar wind that causes significant changes in the earth magnetosphere current system, its plasma and field. These processes resulted in a storm of high intensity that was connected with solar Coronal Mass Ejections (CMEs). In this case, billion tones plasma from the sun, with its embedded magnetic field is released into the Earth. The flow of the high-speed solar stream into the slow solar wind, thereby creating a Co-rotating Interaction Region (CIRs) is, also, another favorable circumstance for a geomagnetic storm, but of lesser intensity[3]. Geomagnetic storm has three phases an initial phase, the main phase and a recovery phase[1]. Each phase is demarked in the Dst and with different associated solar wind properties and geomagnetic processes.

It is worthy to note that the geomagnetic storm also generates a so-called ionospheric storm in the ionosphere. This ionospheric storm has a parallel evolution and phases as a geomagnetic storm, but with a faster course, are now recognized as part of significant natural hazards that perturbed the ionosphere[4]. The possibilities of severe disturbances of terrestrial environment caused by solar activities which may threaten infrastructures are of great concern for the scientific community and government entities as a whole. The geomagnetic phenomena are connected with several space weather events such as Solar Energetic Particle (SEP) events, Geomagnetically Induced Currents (GIC), ionospheric disturbances may also result to radio and radar scintillation, damage of electric power grid, damage of satellites, hazardous to human health disruption of navigation by magnetic compass and aurora displays at much lower latitudes than normal[5].

In the early days of ionospheric research, it was observed that geomagnetic activity is accompanied or quickly followed by significant changes in the F2-layer. These changes are a great deviation from the ionospheric behavior at low and middle latitude ionosphere. There is some general elemental response of the low latitude ionosphere to particular geomagnetic storms. This irregular behavior was structured as enhancement of the foF2 critical frequency, but more often appears as severe depletion of the foF2. These phenomena were termed positive and negative ionospheric storms respectively[6].

The equatorial region of the ionospheric foF2 response to storms events during the night-time and post-midnight hours designate negative responses of the ionospheric foF2, while that of the daytime hours indicates positive responses to storm event[7]. The two mechanisms responsible for the positive ionospheric storm were downwelling of neutral atomic oxygen and uplifting of the F layer due to winds[8]. According to Mikhailov *et al.*[9], this mechanism works best during the daytime, while increases in O density caused positive storm effects at night. It was also, discovered that an increase in the O density was more important than an increase in the O/N_2 ratio is causing positive storm effects. The negative phase was due to decreases in the O/N_2 and O/O_2 neutral density ratios. Although Seaton[10], first suggested that the changes in the neutral composition definitely leads to increased in O_2 density. This could be the cause of the observed decreases in NmF2 during geomagnetic storms. It is worthy to note that the period of both negative phase and positive phase has distinct latitudinal, seasonal and Magnetic Local Time (MLT) dependence[11].

One of the observed magnificent effects of geomagnetic storm at middle latitude is Ionospheric holes. These holes were identified by precipitous depletion of the electron density to very low values. Other phenomena such as photo-production, chemical loss and transport by thermal expansion, neutral winds, waves, tides and electric fields of internal and external origin were to be considered in assessment at the mid-latitude ionosphere, during geomagnetic storms[12,13]. The equator shift from aurora latitudes to middle latitudes during a geomagnetic storm is also one of the noteworthy features of the negative phase. This negative phase was demonstrated by well-pronounced depletion depending on the intensity of the magnetic storm disturbance as expressed by various geomagnetic indices such as Dst and Ap indices. However, the positive phase sometimes was observed several hours before the beginning of the magnetic disturbance, which caused this particular ionospheric storm[14].

Several studies on the phenomena responsible for ionospheric responses during the pre-storm and geomagnetic storm have been conducted. For example Chukwuma[15] reported that the driver of ionospheric responses in the main phase could be designated neither to prompt penetration electric fields and the local time effect does not initiate pre-storm phenomena, but the magnetospheric electric field that manifested in the form of foF2 enhancement at two widely separated longitudinal zones seem to play a major role. He also suggested that pre-storm ionospheric phenomena exist but remain an unresolved problem.

The unresolved problem of ascertaining the ionospheric response to geomagnetic storm becomes more complex by describing the begin of the ionospheric disturbance as Sudden Storm Commencement (SSC) or Main Phase Onset (MOP). As this confines the explanation of ionospheric storms signature/s to post-onset time thereby foreclosing the presented ionospheric response limiting preceding the onset reference time[16,17]. In regards to the true response of the ionosphere to storm and pre-storm, Mikhailov and Perrone[18] suggested that foF2 enhancement of about a 24 h before SC should be selected as pre-storm period if this period is developed in quiet geomagnetic mode.

Moreover, a persistent electric field can also cause strong foF2 enhancement or positive storm phases near midnight at middle latitude[19]. Furthermore, as a result of the local time variation of winds and neutral composition changes at middle latitudes, negative ionospheric storm effects are most frequently seen within the morning sector and positive storm effects in the afternoon and evening[20]. Also, at middle latitudes, positive storm effects are typically seen or last longer in winter and negative storm effects prevail in summer because of the larger latitude penetration of the equator ward winds and the composition disturbance zone than in winter[21,11]. The source of the high-density plasma seen during the positive storm phase implies that, there was a magnetospheric electric field with an eastward component that penetrates to mid-latitudes. This may results to an increase in local production on the dayside to a degree that was sufficient to account for the storm time density increases that have been observed. According to Buresova and Lastovicka[22,23] only 20-25% of magnetic storms were accompanied by pre-storm NmF2 enhancements.

The dynamical response of ionosphere during a geomagnetic storm creates a serious problem to communication and navigation system[24,25]. The effect of Ionospheric response to a geomagnetic or ionospheric storm, on the Global Navigation Satellite Systems (GNSS) that employs radio signals propagating through the ionosphere, may be fierce. This is because the ionospheric storms induce rapid and large variation changes on the electron density. This causes changes in the velocity of radio wave propagation thereby introducing a propagation delay. As a result, there are fluctuations of phase and amplitude of GPS signals, also known as ionospheric scintillations, which may, eventually, result in cycle slips and losses of carrier lock[26, 27].

The aim of this research was to determine the effect of intense geomagnetic storm and pre storm on low and mid latitude ionospheric F2. And also, investigate the interplanetary phenomena responsible for intense geomagnetic storms and pre-storm. This will promote better understanding of the ionospheric response during pre-storms and storm. To achieve this aim, statistical analysis, such as change in foF2 using a normalized deviation of critical frequency (d(foF2)) will be performed on ionospheric F2 parameters of the low and the mid latitude regions during an intense storm of October 19-23, 2001 and their geomagnetic parameters also will be analyzed.

MATERIALS AND METHODS

The geomagnetic indices, interplanetary and solar wind parameters such as disturbance storm time index Dst (nT), the interplanetary magnetic field index (IMF) southwards orientation Bz (nT), the interplanetary electric field, the proton number density, the solar wind flow speed, the plasma flow pressure, the plasma temperature and plasma beta used in this research were obtained from National Space Science Centre's NSSDC OmniWeb Service[28]. The ionospheric data used in this study consists of hourly values of foF2 obtained from Space Physics Interactive Data Resource (SPIDR's) network[29] of ionosonde stations located in the equatorial/low and mid-latitude region. These stations are located in the Australian sector (Darwin, Townsville), European-African sector (Rostov, Juliusruh/Rugen and Grahamstown) and American sectors (Goose Bay, Point Arguello, Jicamarca and Boulder). Table 1, highlighted the Geographic coordinates of the stations and their respective local time differences.

Table 1: List Ionosonde stations with their geographic coordinates

	Geographic coordinates		Difference between
Station and their code	Φ	Λ	LST and UT (h)
Euro-African sector			
Rostov (RV149)	47.20° N	39.70° E	+3
Juliusruh/Rugen (JR055)	54.70° N	13.40° E	+1
Grahamstown (GR13L)	-33.30° N	26.50° E	+2
American sector			
Jicamarca (JI91J)	-12.10° N	-77.00° E	-5
Goosebay (GSJ53)	53.30° N	-60.40° E	-4
Point Arguello (PA836)	35.60° N	-120.60° E	-8
Boulder (BC840)	40.00° N	-105.30° E	-7
Australian sector			
Darwin (DW41K)	-12.50° N	131.00° E	+9
Townsville (TV51R)	-19.70° N	146.90° E	+10

The present study ionospheric response to the geomagnetic and interplanetary and pre-storm phenomena forcing was concerned with variation in foF2 during Oct. 19-23, 2001 covering the initial, main and the recovery phase of the storm. However, the F2 region response to geomagnetic storms was conveniently described using a modified form of the analysis of Chukwuma[30], in terms of δfoF2 that was, the normalized deviations of the critical frequency foF2.

$$\delta foF2 = \frac{foF2 - (foF2)_{ave}}{(foF2)_{ave}} \times 100\%$$

The δfoF2 variations were described in terms of the percentage change in amplitude of critical frequency foF2 which was depicted by the upper error bar from the reference. The storm was positive when the upper error bar was large i.e., when the absolute maximum value of deviation exceeds 20% compared with the average quiet days represented by the lower error and negative storms occur if otherwise. This limit was sufficiently large to prevent inclusion of random perturbation and disturbances of neutral atmospheric origin, such as gravity waves, thereby making the indicated positive and negative storms represent a real change in electron density not simply redistribution of the existing plasma. The reference day is the respective average hourly values of foF2 of the most geomagnetic quiet days in October 2001 (i.e., 15, 16, 17 and 18). The adoption of δfoF2 instead of foF2 presents a first-order correction for temporal, seasonal and solar cycle variation, therefore, the effects of the geomagnetic storm are better recognized Chukwuma[30]. The reference period was chosen with the criteria that these days must be free from both significant geomagnetic activity and solar activity; this was because Chukwuma[15] have shown that the high solar flares activity results in ionospheric disturbances due to their effects on thermospheric neutral density[31].

RESULTS AND DISCUSSION

Interplanetary and geomagnetic response: In this section, interplanetary and geomagnetic observation during the storm of Oct. 21, 2001 and pre-storm phenomena leading to the intense nature of the geomagnetic storm was presented. This was depicted in Fig. 1 using the low latitude magnetic index Dst, southward interplanetary magnetic field (Bz) and solar wind parameters (i.e., Flow speed, penetrating electric field, plasma flow pressure, proton density, plasma beta and plasma temperature) associated with the disbursement of energy from the surface of the sun corona. The figure presents the aforementioned storm parameters for the period of Oct. 19-23, representing two days before and after the event. This is to enable us the analysis of the pre and aftermath event. The pre-event study was for a proper understanding of the phenomena of the Sudden Storm Commencement (SSC) and the aftermath (i.e., Recovery phase) for the after effect on the terrestrial atmosphere. The SSC period is a period of the sudden increase in magnetic horizontal component (H-field) brought about by the sudden collision of the solar wind with the terrestrial magnetosphere.

Figure 1a presents the Dst index during the storm event period, which was signed with the minimum peak value of -187 nT. The storm was a double steps storm with the second step coming up after about 24 h[32]. The intense nature of the Dst was a measure of the westward ring current encircling the earth, brought about by the high injected geomagnetic energy into the terrestrial magnetosphere. However, storms were classified as weak (when Dst > -50 nT), moderate (when -100 nT < peak Dst ≤ -50 nT) and intense (when Dst < -100 nT)[33] based on the level of westward ring current. That was, the increase/decrease in the westward ring current leads to the enhancement/depletion nature of the horizontal magnetic field which resulted to decrease/increase of Dst index. It is noteworthy that the storm main phase occurs in near coincidence with the sharp southward turning of the Interplanetary Magnetic Field (IMF) Bz at the magnetic cloud boundary. It could be observed from the plot that the storm shows a second decrease of -164 nT at 0:00 UT on Oct. 21 instead of recovery, which depicts double step storm[34] and thereafter, gradually recovered for the rest of the day. The sudden slight increase within 12:00-18:00 UT on Oct. 21 represent the period of sudden storm commencement that signal the arrival of the geomagnetic storm. It is worthy to note that the storm main phase occurs in near coincide with the sharp southward turning of IMF at the magnetic cloud boundary.

The second panel of Fig. 1b shows a Bz plot against time. The northward to the southward orientation of Bz continued with a moderate field record until a sudden large southward turning at about 17.00 UT with the minimum peak value of -16.4 nT which coincide with the period of sudden storm commencement (SSC) termed pre-storm period[18]. After which, it orientates northward with a maximum peak value of 7.5 nT at 21:00 UT on the storm main phase period. Observation confirmed that the peak Bz turning coincides with the time of minimum Dst decrease which lasted for more than 3 h which was affirmed by Gonzalez and Tsurutani[34]. The preliminary studies of moderate storms with -100 nT < peak Dst ≤ -50 nT confirm earlier suggestion made by Rusell *et al.*[35], for associated threshold values of Bz ≥ 5 nT and ΔT ≥ 2 h. The period of the second decrease in the Dst corresponded with northward turning of IMF which coincided with 1.9 nT, this northward turning was heralded with a southward turning of -11.9 nT peak at 14:00 UT. Two interplanetary structures are important for the development of such class of storms; the sheath region just behind the forward shock and Coronal Mass Ejecta (CME) itself. These interplanetary structures often result in the formation of intense storms with two-step growth in their main phase. Occasionally, this may lead to the development of very intense storms, particularly when the set up of another interplanetary shock is coupled with another stream in the sheath plasma of the primary structure[36,37].

The plasma temperature plot (Fig. 1c) shows an abrupt increase in the plasma temperature at the pre-storm period, which signifies the arrival of the storm. Sharply after, it decreases to a minimum temperature value of 59188 K during the main phase and maintains this low value throughout the recovery phase.

The plot of proton density (Fig. 1d) responds with an increase in concentration at the pre-storm phase with a peak value of 17.2 N cm^{-3} at 17:00 UT. And has its maximum proton density

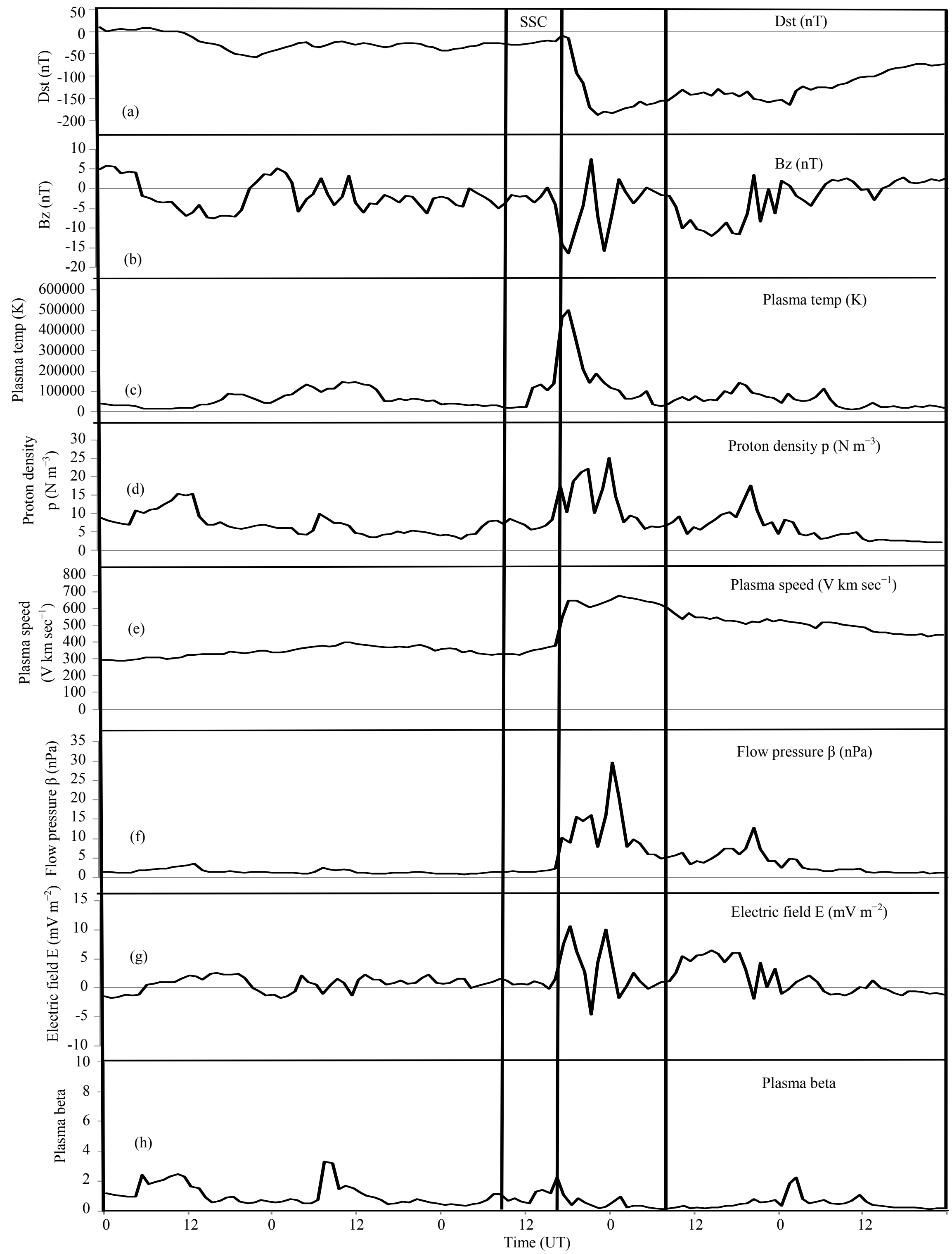

Fig. 1: Geomagnetic, interplanetary and solar wind parameters for the period of October, 19-23 2001

number recorded in the storm main phase with a peak concentration of 21.9 N cm^{-3}. The recovery phase was observed to fluctuate throughout in concentration of proton density number before another increase was recorded at about 20:00 UT with 17.3 N cm^{-3} which signify the arrival of the second storm. Since the pressure term depends on the solar wind density, it has been reported that beside Bz and flow speed, the proton density also plays an important role in the ring current intensification[38].

The flow speed plot (Fig. 1e) shows a low-speed stream till around 2:00 UT on Oct. 20, thereafter the flow speed increases till 649 km sec^{-1}, the period observed as the pre-storm hours. This increase extended to the main phase with the peak value of 676 km sec^{-1} at 1:00 UT on Oct. 21. The coincidence time of minimum Dst and IMF northward turning is recorded with a flow speed increase of 608 km sec^{-1}. According to Gonzalez *et al.*[1], the greater the relative velocity the stronger the intensity of the shock and the field compression. If shock runs into an irregular portion of a high-speed stream, before it, the magnetic fields may be extremely high[37].

The plot of flow pressure initially shows (Fig. 1f) record of a low pressure thereafter, the flow pressure increases and attained a peak pressure value of 10.14 nPa at the storm onset period. The increase extended to the main phase period with a maximum peak of 26.9 nPa at 0:00 UT, the time of minimum depression is recorded with a flow pressure of 15.47 nPa. After the maximum flow pressure, the flow sharply decreases as the Dst was recovering. The higher plasma density and the higher velocity combine to form a much larger solar wind ram pressure. This pressure compresses the Earth's magnetosphere and increases the field magnitude near the equator[32].

The electric field emerges from the southward direction. The low field penetration to the Earth's magnetosphere was continued until when its electric field suddenly increases abruptly to 10.64 mV m^{-1} on the storm Main Phase Onset (MPO) at 18:00 UT. Thereafter, it decreases into the southward direction and then later orientate back to northward after some hours of turning with a peak field value of 10.03 mV m^{-1} at 23:00 UT. It was later orientated southward, this southward to northward orientation was continued with low electric field value below that of the main phase. During the recovery phase, the northward electric field record is higher than that of the initial phase with a peak of 6.41 mV m^{-1} at 14:00 UT. It is evidently shown from the plot that solar wind dawn-to-dusk electric fields directly drive magnetosphere. These fields are caused by a combination of solar wind velocity and northward interplanetary magnetic field.

The plasma beta responds with high value at the initial phase, the pre-storm period recorded a high plasma beta of 2.22 and the main phase shown a low beta of 0.96 at 1:00 UT. This point to the fact that high field region was typically low beta plasma. The field reversals typical within magnetic clouds feature magnetic field reconnection during the period of southward field and general lack of reconnection and solar wind injection into the magnetosphere during the part with a northward field[39].

Ionospheric response of October 20-22, 2001: Figure 2 and 3 presents the plots of δfoF2 the normalized deviation of the critical frequency foF2, against time (UT) with the upper error bar representing the positive storm i.e the disturbed foF2 and the lower error bar representing the negative storm i.e the average of foF2 for quiet days on δfoF2 for both low and middle latitude ionospheric response of October 20-22, 2001. Here, if the deviation of the upper error bar was large compared to the average quiet day represented by the lower error bar, then a positive emerges. If otherwise, a negative storm emerges. Therefore, the observed deviation in response to storm phases shows complimentary remarks to this positive and negative storm.

The observed pre-enhancement at the foF2 before magnetic onset with a reasonable time interval before Sudden Commencement (SC) during quiet geomagnetic condition is called pre-storm phenomenon[18]. The station under study exhibits these aforesaid characteristics. The result also shows that the pre-storm period was mainly controlled by large southward magnetic field component, high plasma temperature, increase in proton density, flow speed stream and high plasma beta and these have no pronounced effect on ionospheric foF2,) but may result to significant ionospheric effect during the main phase. This is in accordance with the earlier reports of Balan and Rao[40], Rishbeth[41] and Vijaya Lekshmi *et al.*[42].

Low latitude response: It could be observed from Fig. 2 that the low latitude ionosphere shows some degree of simultaneity deviation from the sudden commencement of the storm through the main phase to the recovery phase. The low latitude stations, Darwin, Townsville and Jicamarca (Fig. 2ai, aii and aiii) consider in this study shows that positive storm response dominates both the initial and main phase of the storm. The peak deviation of this positive storm corresponds to the main phase with the exception of Jicamarca which its peak deviation does not correspond with the main phase of the storm. However, the anomaly over the ionosphere of Jicamarca may be attributed to the local time difference between the stations. As a result, the main phase was depleted simultaneously across all the stations, which

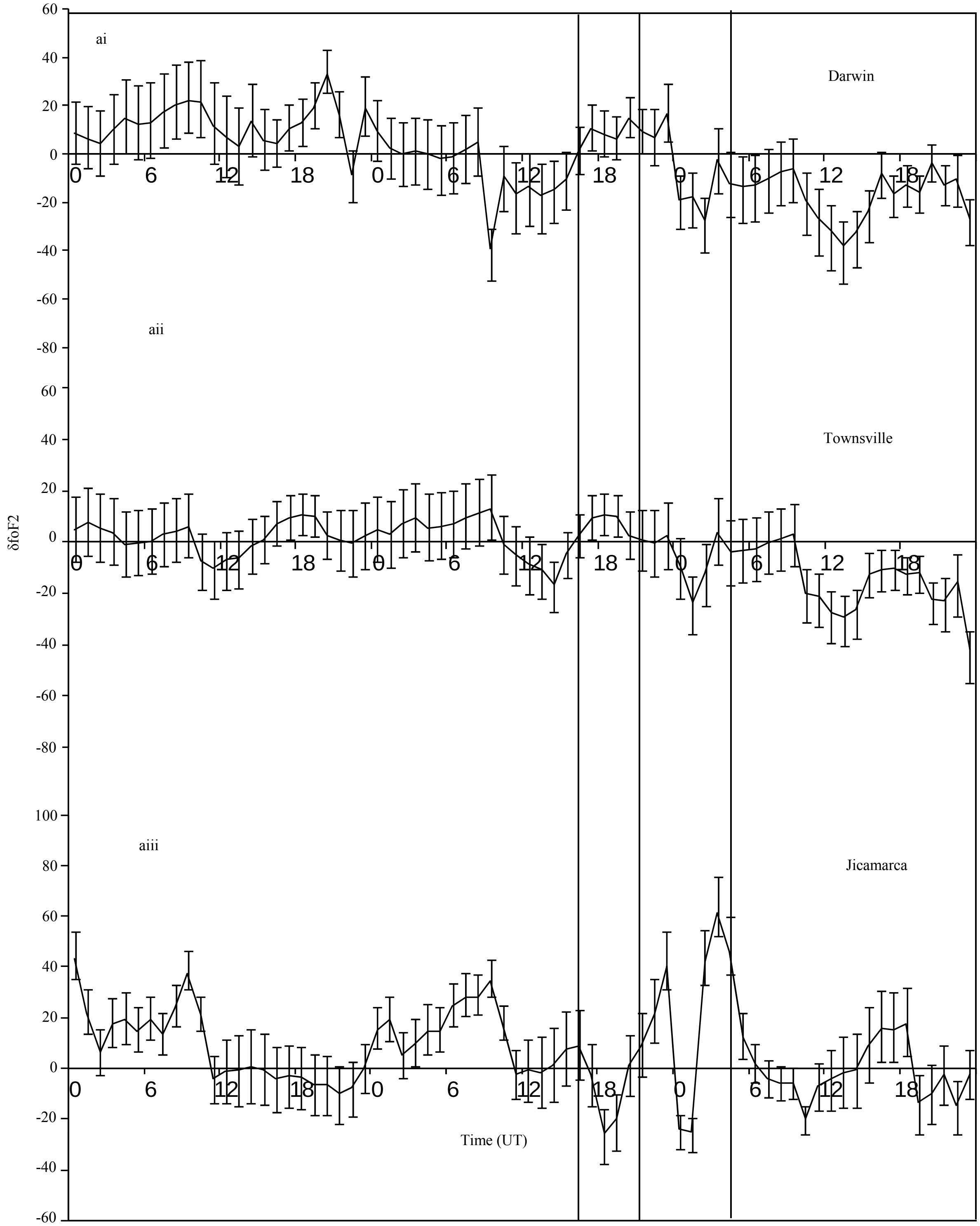

Fig. 2: The normalize percentage deviation of the foF2 of disturbed day from magnetic quiet days at low - (a) and mid-latitude (b) stations for the storm of October 21, 2001. The error bars (vertical bar) upward and downward showing real foF2 covering the initial, main and recovery phases of the storm and the mean of the quietest days in the month

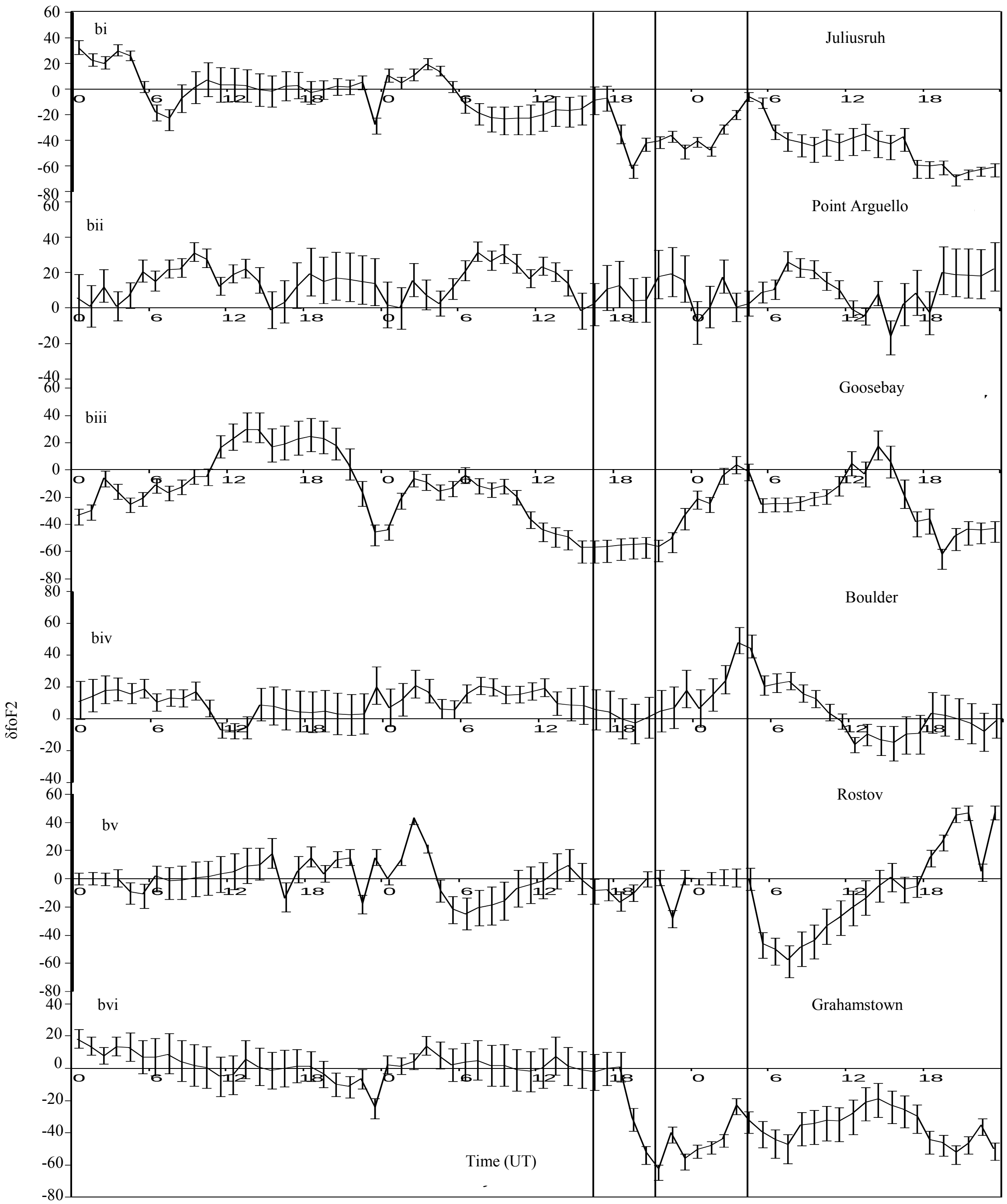

Fig. 3: The normalize percentage deviation of the foF2 of disturbed day from magnetic quiet days at mid-latitude stations for the storm of October 21, 2001. The error bars (vertical bar) upward and downward showing real foF2 covering the initial, main and recovery phases of the storm and the mean of the quietest days in the month

shows that equatorial region ionosphere, cannot be left out with global geomagnetic effects. It was observed that the recovery period is rather quite throughout.

An analysis of the interplanetary and geomagnetic observations of the plot of low latitude region Fig. 1a shows that a moderate ionospheric effect in both southward and northward direction was maintained during the pre-storm period between 0.00 UT of October 20 to7.00 UT of October 21. This implies that an increase in solar wind parameter pre-storm period does not record a large variation in electron density of foF2 which indicate the arrival of the ionospheric storm. The plot indicated the existence of moderate ionospheric storm during the main phase period, the largest response of the ionospheric F2 layer was recorded in the recovery phase and during the initial phase periods. The storm measured majorly positive ionospheric storm with a peak electron density value on the recovery phase. As a matter of fact, the low latitude region ionosphere has confirmed to be largely affected by geomagnetic storm most especially the recovery phase periods.

Middle latitude response: From Fig. 3, it can be seen that the middle latitude station shows some degree of simultaneity deviation from the initial phase of the storm to the recovery phase. The storm sudden commencement period was depleted simultaneously across all the stations. It was observed that the Main Phase Onset (MPO) period depletion signal the intense simultaneous decrease during the main phase in all stations except for Point Arguello and Boulder. Those two stations show that there was a positive storm dominating the phases of the storm. Although, looking at the local time difference between this station. Since the occurrence of positive and negative ionospheric storm effects shows a strong dependence on local time[16] hence the anomalies over the ionosphere of Point Arguello and Boulder, be connected to the local time effect which emanated from longitudinal effect.

In summing-up, to ascertain the effects of geomagnetic storms and pre-storm phenomena on low and middle latitude ionospheric F2, analysis of the changes in foF2 was conducted using normalize deviation of critical frequency (δ(foF2)) on the ionosphere of 3 low and 6 mid-latitude stations from 3 sectors of the earth ionosphere. Analysis of a vertical error bar on δfoF2 was also used to investigate the vivid effect of the positive and negative storm on the aforementioned parts of the ionosphere. Here, the upper error bar presents the positive storm (the disturbed foF2) while the lower error bar presents the negative storm (the average of foF2 for quiet days). The relationship between the Dst and the parameter of the stations under consideration is summarized by showing that the low and middle latitude ionosphere F2 has no significant difference as they both respond to newly burst of storm activity.

CONCLUSIONS

The study also shows a large southward turning of interplanetary magnetic field Bz, high electric field, increase in the flow speed stream, increase in proton number density, high-pressure ram and high plasma beta during pre-storm period. Hence, these could be termed as the pre-storm phenomena that lead to an intense ionospheric storm. The enormity of Bz turning into southward from the northward direction highly depends on the severity/intensity of the storm and the variation in F2 layer parameter at the time of geomagnetic storm are strongly dependent upon the storm intensity. There was no significant difference between the ionospheric F2 response of low and middle latitude ionosphere any new burst of storm activity is associated with a newly generated disturbance at the ionospheric F2 layer of the ionosonde stations. The pre-storm period was preceded by intense positive and negative ionospheric storms. It was also observed that low to moderate variations in ionospheric F2 at the pre-storm period indicate the upcoming of large ionospheric disturbances at the main phase and low ionospheric variation beyond the main phase implied the storm recovery. The initial phase was observed to be recorded with an intense ionospheric storm despite the low geomagnetic storm activity in the period. This follows the fact that the variations of the F2 layer quite disturbances have different formation mechanism and have been interpreted to the concept of thermosphere-ionosphere interaction. Correspondingly, the error bar showed clearly the contribution of the negative and positive to the stations along the same narrow longitude.

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