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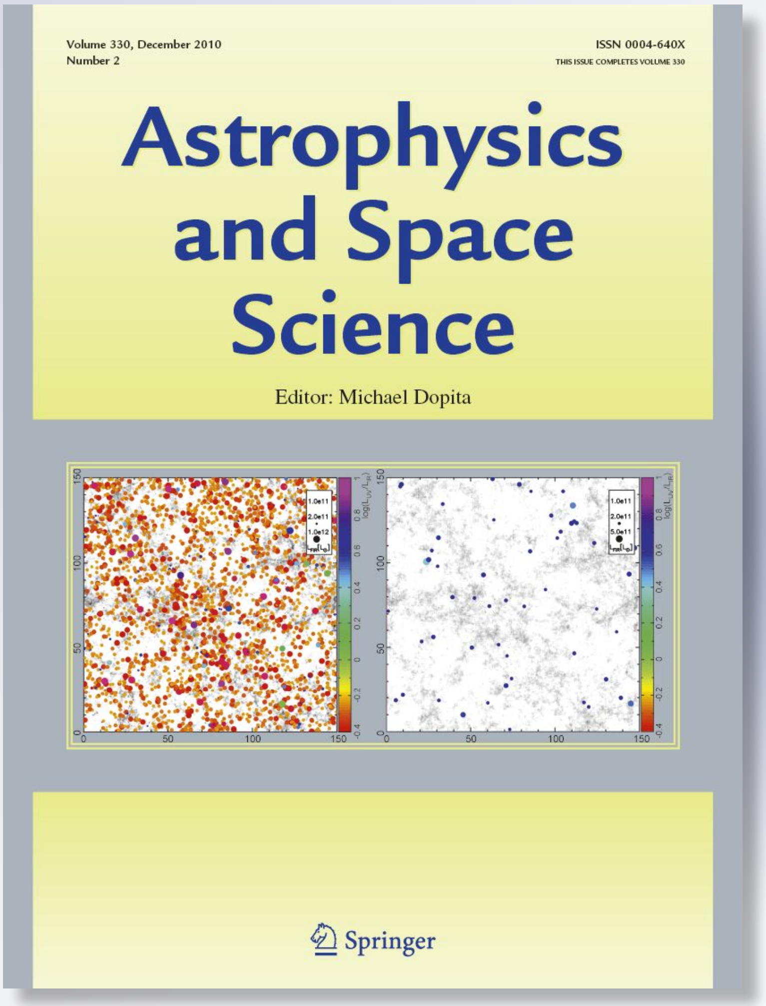

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REVIEW

On the effects of geomagnetic storms and pre storm phenomena on low and middle latitude ionospheric F2

B.J. Adekoya · V.U. Chukwuma · N.O. Bakare · T.W. David

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Abstract This paper presents some features of the ionospheric response observed in equatorial and mid-latitudes region to two strong geomagnetic storms, occurring during Oct. 19–23, 2001 and May 13–17, 2005 and to understand the phenomena of pre-storm that lead to very intense geomagnetic storms. The result point to the fact that pre-storm phenomena that leads to intense ionospheric storm are; large southward turning of interplanetary magnetic field Bz, high electric field, increase in flow speed stream, increase in proton number density, high pressure ram and high plasma beta. The magnitude of Bz turning into southward direction from northward highly depends upon the severity of the storm and the variation in F2 layer parameter at the time of geomagnetic storm are strongly dependent upon the storm intensity. A detailed analysis of the responses of the ionosphere shows that during the storm periods, foF2 values depleted simultaneously both in the equatorial and mid latitude. Observation also shows that low to moderate variations in ionospheric F2 at the pre-storm period may signal the upcoming of large ionospheric disturbances at the main phase. The ionospheric F2response for low and mid latitude does not show any significant differences during the storm main phase and the pre-storm period. The ionospheric response during the pre-storm period is thought very puzzling. The period is observed to be depleted throughout with low-moderate effect across all the stations in the low and mid latitude.

Keywords Ionospheric F2 layer · Ionospheric disturbances · Pre-storm phenomena · Geomagnetic storm · Ionospheric storm

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1 Introduction

During a geomagnetic storm, the solar wind energy deposited into the magnetospheric polar cap region will eventually be dissipated into the ionosphere and thermosphere. Meanwhile, various physical and energy transport processes within the ionosphere become extreme and more complicated (Mendillo 1971; Fuller-Rowell et al. 1996; Buonsanto and Fuller-Rowell 1997). The effects of magnetic storm on the ionosphere are complex and deviate greatly from average behavior. There are some common elements of behavior for most storms, but it has been recognized that in the low latitude regions the ionospheric response to particular geomagnetic storms manifest some irregularities. These irregularities sometimes take the form of increases of the foF2 critical frequency, but more often there are severe decreases of the foF2 constituting phenomena that came to be known as positive and negative ionospheric storms respectively. Even in the early days of ionospheric research, it was noticed that geomagnetic activity is accompanied or quickly followed by marked changes in the F2-layer. The response of the ionospheric foF2 over equatorial region to storms events, during the night-time and post-midnight hours indicates negative responses of the ionospheric foF2, while that of the daytime hours indicates positive responses (Akala et al. 2010). The ionosphere over equatorial latitudes is highly dynamic, and consequently poses serious threats to communication and navigation systems, especially during magnetically disturbed (geomagnetic storm) days (Kumar and Gwal 2000; Basu et al. 2002). Ionospheric holes are one of the most spectacular disturbance effects observed at equatorial latitudes (Prölss 2006). These holes are marked by a steep drop in the electron density to very low values. Conventionally, the strength of a geomagnetic storm is represented by geomagnetic indices (the disturbance storm time (Dst), planetary K (Kp) index, etc.) (Akala et al. 2010). It is possible to measure the strength of a geomagnetic storm by the Dst, because the strength of the surface magnetic field at low latitudes is inversely proportional to the energy content of the ring current, which increases during geomagnetic storms (Ratcliffe 1972). It was found that a geomagnetic storm can be included by a sheath, the leading (i.e front part) region of a cloud, the trailing part of a cloud and both sheath and cloud region (Chin-Chun and Lepping 2002). Furthermore, magnetic cloud (MC) are a principal source of strong, long-lasting, interplanetary, negative Bz fields (in solar magnetospheric coordinate and hence are a major source of geomagnetic activity. The intensity of an onset time of storm activity has been related to the polarity of a magnetic cloud Bz components (Wilson 1990). According to Gonzalez et al. (1999), for CMEs involving clouds, the intensity of the core magnetic field and the amplitude of the speed of the cloud seems to be related, with a tendency that clouds which move at higher speeds also posses higher core magnetic field strengths, thus both contributing to the development of intense storms since those two parameters are important factors in genering the solar wind-magnetosphere coupling via the reconnection process. The typical mechanism phenomena that formed a magnetic cloud are series of most geoeffective interacting CMEs of various sizes which are characterized by high IMF magnitude, low field variance and large scale coherent field rotation, often including large and steady north-south component, the high region is typically a low plasma beta. The low beta values (≈0.1) in cloud imply large Alfven/Magnetosonic speeds which ordinarily prelude the formation of shocks within magnetic clouds (Gonzalez et al. 1999).

The pre storm effect on ionospheric F2 layer has been thought very puzzling, of which Makhailov and Perrone (2009) has shown that there is no such effect as the pre-storm electron concentration of ionospheric F2 enhancement as a phenomenon inalienably related to the following magnetic storm. The observed nighttime electron concentration of ionospheric F2 enhancements at subauroral latitudes may result from plasma transfer from the plasma ring area by meridional thermospheric wind. Enhanced plasmaspheric fluxes into the nighttime F2-region resulted from westward substorm-associated electric fields is another possible source of nighttime NmF2 enhancements. According to Buresova and Lastovicka (2007, 2008), only 20–25 % of magnetic storms are accompanied by pre-storm NmF2 enhancements. Chukwuma (2010) revealed that pre-storm phenomena don't originate from local time effect. He also suggested that pre-storm ionospheric phenomena exist but remain an unresolved problem.

The interest of this research work mainly is to revealing the effect of pre-storm on ionospheric F2 region of the equatorial and mid-latitude region as well as the ionospheric F2 disturbance during a large geomagnetic storm on equatorial region and mid-latitude respectively. Chukwuma (2010) has revealed the mechanism responsible for pre-storm phenomena and those responsible for main phase ionospheric phenomena, especially the role of penetration electric fields. According to Huang (2008), strong penetration electric field during intense storms has profound effects on redistribution of global ionospheric plasma. Also reveal the pre-storm phenomena that lead to intense geomagnetic storms.

2 Methods of analysis

The geomagnetic index and solar wind data used consist of hourly values of the low latitude magnetic index Dst, the interplanetary magnetic field component Bz, interplanetary electric field, the proton number density, the solar wind flow speed, the plasma flow pressure, the plasma temperature and plasma beta. These data were obtained from National Space Science Centre's NSSDC OMNIWeb Service (http://nssdc.gsfc.nasa.gov/omniweb).

The ionospheric data used in this study consists of hourly values of foF2 obtained from Space Physics Interactive Data Resource (SPIDR's) network (http://spidr.ngdc.noaa.gov) of ionosonde stations located in the equatorial and mid latitudes region. These stations are located in the East Asian sector (Kwajalein), Australian sector (Darwin, Townsville), European-African sector (Rostov, Juliusruh/Rugen, Ascension Is., Grahamstown and Louisvale) and American sectors (Goosebay, Point Arguello, Jicamarca, Puerto Rico and Boulder). Table 1 listed the stations showing Geographic and Geomagnetic coordinates.

The present study of global ionospheric response to the geomagnetic and interplanetary and pre-storm phenomena forcing is concerned with variation in foF2 during Oct. 15–18, 2001 and May 14–16, 2005. However, the F2 region response to geomagnetic storms is conveniently described using a modified form of the analysis of Chukwuma (2003), in terms of D(foF2), that is, the normalized deviations of the critical frequency foF2 from the reference

$$\mathrm{D(foF2)} = \frac{\mathrm{foF2} - (\mathrm{foF2})_{ave}}{(\mathrm{foF2})_{ave}} \times 100\ \%.$$

The D(foF2) variation are described in terms of percentage change in amplitude of critical frequency foF2 from the reference and following Chukwuma (2010) and reference therein, positive and negative storms occur when the absolute maximum value of D(foF2) exceeds 20 %. Furthermore, this limit is sufficiently large to prevent inclusion of random perturbation and disturbances of neutral atmospheric origin (gravity waves, etc.), thereby making the indicated positive and negative storms represent real change in electron density not simply redistribution of the existing plasma. Hence, the data that were analyzed consist of D(foF2) of respective hourly values of foF2 for the aforementioned periods, while the reference for each hour is the average value of foF2 for

Table 1 List ionosonde stations with their Geographic coordinates

Station and their code	Geographic coordinates		Difference between LST and UT (in Hours)
	ϕ	λ	
Euro-African sector			
Rostov (RV149)	47.20°N	39.70°E	+3
Juliusruh/Rugen (JR055)	54.70°N	13.40°E	+1
Ascension Is. (AS00Q)	−07.90°N	−14.40°E	−1
Grahamstown (GR13L)	−33.30°N	26.50°E	+2
Louisvale (LV12P)	−28.50°N	21.2°E	+1
East-Asian sector			
Kwajalein (KJ609)	09.00°N	167.20°E	+11
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
Puerto Rico (PRJ18)	18.50°N	−67.20°E	−4
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 hour calculated from the four quite days, Oct. 15–18, 2001 and April 25–28, 2005. The use of D(foF2) rather than foF2 provides a first-order correction for temporal, seasonal and solar cycle variation so that geomagnetic storm effects are better identified Chukwuma (2003). An important criterion used in choosing the reference period is these days must be devoid of not only of any significant geomagnetic activity but also there must be an absence of any considerable solar activity; this follow the fact that Chukwuma (2010) have shown, the high solar flares activity results in ionospheric disturbances due to their effects on thermospheric neutral density (Sutton et al. 2006).

3 Results

3.1 Storm of October 19–23, 2001

3.1.1 Interplanetary and Geomagnetic response

The first panel in Fig. 1 shows a magnetic index Dst, plot against time (UT) for the period of Oct. 19–23, 2001 representing the plot covering two days before and two days after the storm event. The storm is summarized using the low latitude magnetic index Dst and is interpreted using available interplanetary data. However, storms are classified as weak (when Dst > -50 nT), moderate (when -100 nT $<$ peak Dst ≤ -50 nT) and intense (when Dst < -100 nT) (Vieira et al. 2001). From the plot beginning from 0:00 UT the storm was weak till 17:00 UT, immediately at about 18:00 UT the storm increases it intensification from weak to moderate for a period of 4 hours with peak value of −56 nT at 20:00 UT on Oct. 19 before it continued in it weak storm appearance record till around 18:00 UT on Oct. 21 when the Dst greatly decreases to a minimum value of −187 nT at 21:00 UT on Oct. 21, before started to recovered. It is observed that the recovery phase did not completely recovered rather it shows a second decrease of −165 nT at 0:00 UT on Oct. 23 and thereafter, gradually recovered for the rest of the day. It is noteworthy that the storm main phase occurs in near coincidence with the sharp southward turning of interplanetary magnetic field (IMF) Bz at the magnetic cloud boundary. 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 geomagnetic storm.

The Bz plot shows a northward rotation from 0:00–5:00 UT with peak value of 5.9 nT at 1:00 UT, it thereafter, rotate southward with a minimum value of −7.4 nT. It is observed that at the period of Dst first depress with a moderate storm record of −52 nT at 20:00 UT the Bz is in southward orientation before it increases back to the northward. This northward to southward orientation of Bz continued with a moderate field record until a sudden large southward turning with minimum peak value of −16.4 nT which coincide with period of sudden storm commencement (SSC) newly known as pre-storm period (Makhailov and Perrone

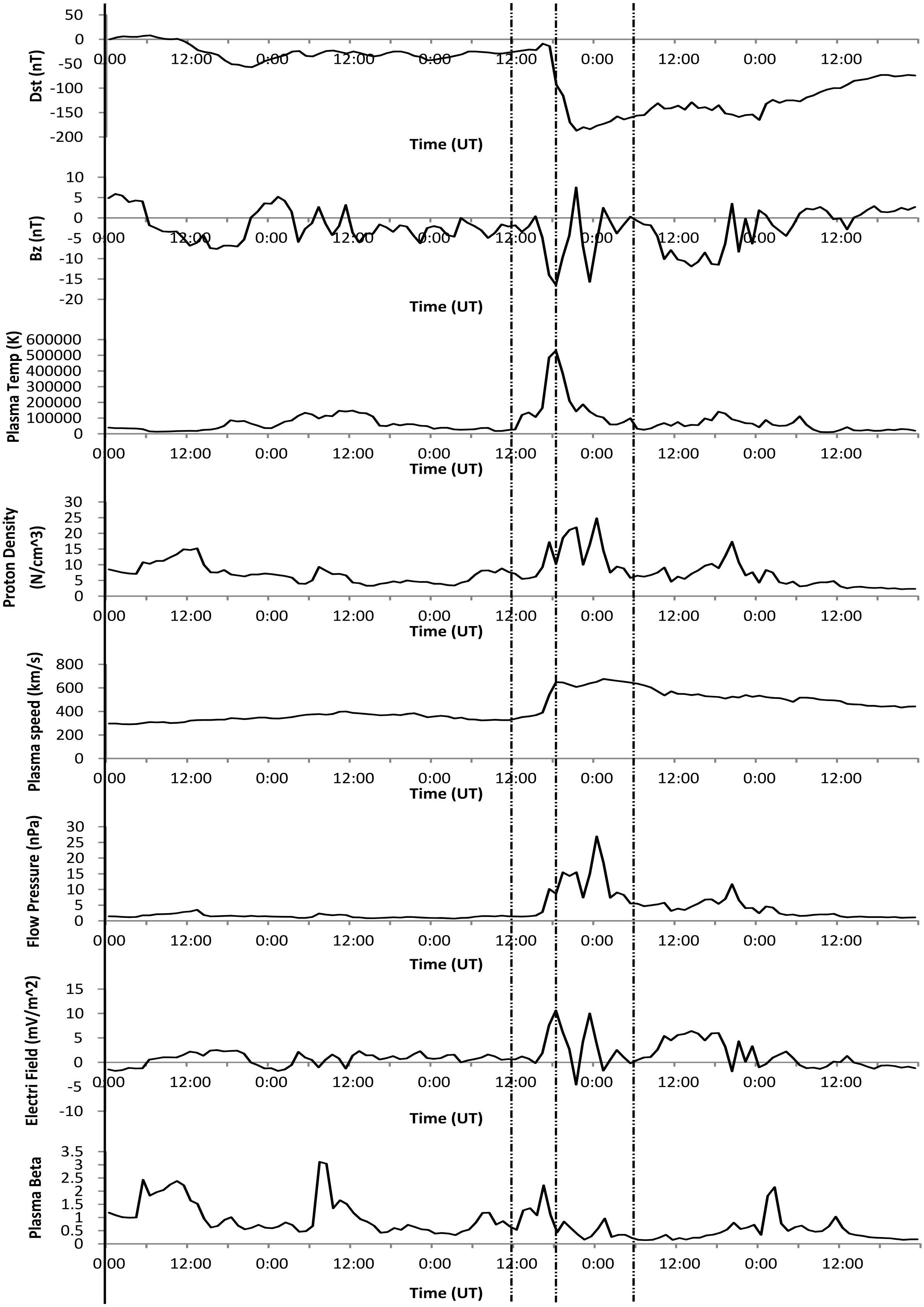

Fig. 1 Composition of interplanetary and geomagnetic observation for Oct. 19–23 2001

2009). Sharply after, it orientate 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 hours which affirmed by Gonzalez and Tsurutani (1987). Also preliminary studies of moderates storms with -100 nT $<$ peak Dst ≤ -50 nT confirm earlier suggestion made by Rusell et al. (1974), for associated threshold values of Bz ≥ 5 nT and $\Delta T \geq 2$ hours. The period of second Dst depression is noted to be coincides with northward turning of IMF at the same time with 1.9 nT, this was preceded with a southward turning of -11.9 nT peak at 14:00 UT. Two interplanetary structure are important for the development of such class of storms; the sheath region just behind the forward shock and coronal mass ejecta (CME) itself. According to Gonzalez et al. (2001), these structures frequency lead to the development of intense storms with two-step growth in their main phase. These structures also lead sometimes to the development of very intense storms, especially when an additional interplanetary shock is found in the sheath plasma of the primary structure accompanying another stream (Gonzalez et al. 2001; Zhao 1992).

The plasma temperature plot shows a low temperature value of the plasma within Oct 19 to around 12:00 UT noon on Oct. 21. Thereafter, the temperature of the plasma increases abruptly to a peak of 529177 K at the pre-storm period, this sudden temperature increases signal the arrival of storm. Sharply after, it decreases to a minimum temperature value of 59188 K during the main phase and maintain this low value throughout the recovery phase.

The plot of proton density responds with low value from 0:00 UT on Oct 19 to around 12:00 UT on Oct. 21, thereafter, at the pre-storm phase there is an increase in the concentration of proton density with peak value of 17.2 N/cm^3 at 17:00 UT. The maximum proton density number is recorded at the storm main phase with peak concentration of 24.8 N/cm^3 at 0:00 UT on Oct. 22, the Dst minimum depression time is observed to increase in proton number density with 21.9 N/cm^3. The recovery phase is observed to fluctuate throughout in concentration of proton density number after an increase record at about 20:00 UT with 17.3 N/cm^3. Since the pressure term depends on 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 (Smith et al. 1986).

The flow speed plot emerged with a low speed stream at the early hour of Oct. 19 till around 2:00 UT on Oct. 20, thereafter the flow speed increases till 649 km/s at 18:00 UT on Oct. 21, the period observed as the pre-storm hours. This increase extended to the main phase with peak value of 676 km/s at 1:00 UT on Oct. 22. The coincidence time of minimum Dst and IMF northward turning is record with flow speed increase of 608 km/s. According to Gonzalez et al. (1994) the higher the relative velocity the stronger the shock and the field compression. If shock runs into a trailing portion of a high-speed stream, preceding it, there may be exceptionally high magnetic fields (Zhao 1992).

The plot of flow pressure was recorded with a low pressure from early hour of Oct. 19 till around 16:00 UT on Oct. 21. 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 flow pressure of 15.47 nPa. After the maximum flow pressure, the flow sharply decreases as the Dst is 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 (Kamide et al. 1998).

The electric field emerges from the southward direction in the early hour of Oct. 19 to the northward with peak field record of 2.51 mV/M at 16:00 UT. The low field penetration to the Earth's magnetosphere was continued till around 15:00 UT on Oct. 21 when its electric field suddenly increases abruptly to 10.64 mV/m on the storm main phase onset (MPO) at 18:00 UT. Thereafter, it decreases to the southward direction and then later orientate back to northward after some hours of turning with peak field value of 10.03 mV/m at 23:00 UT. It later orientate southward, this southward to northward orientation was continued with low electric field value below that of main phase. During the recovery phase the northward electric field record is higher than that of the initial phase with peak of 6.41 mV/m at 14:00 UT. It is evidently show from the plot that solar wind dawn-to-dusk electric fields directly drive magnetospheric. These fields are caused by a combination of solar wind velocity and northward interplanetary magnetic field.

The plasma beta responds with a high value at the initial phase, the pre-storm period recorded a high plasma beta of 2.22 and the main phase shown low beta of 0.96 at 1:00 UT. This point to the fact that high field region is 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 northward field (Tsurutani and Gonzalez 1995).

3.1.2 Ionospheric response of October 20–22, 2001

Low latitude response The D(foF2) plot of Darwin in Fig. 2 response with a low ionospheric storm from 0:00 UT–8:00 UT, starting from the low positive ionospheric storm

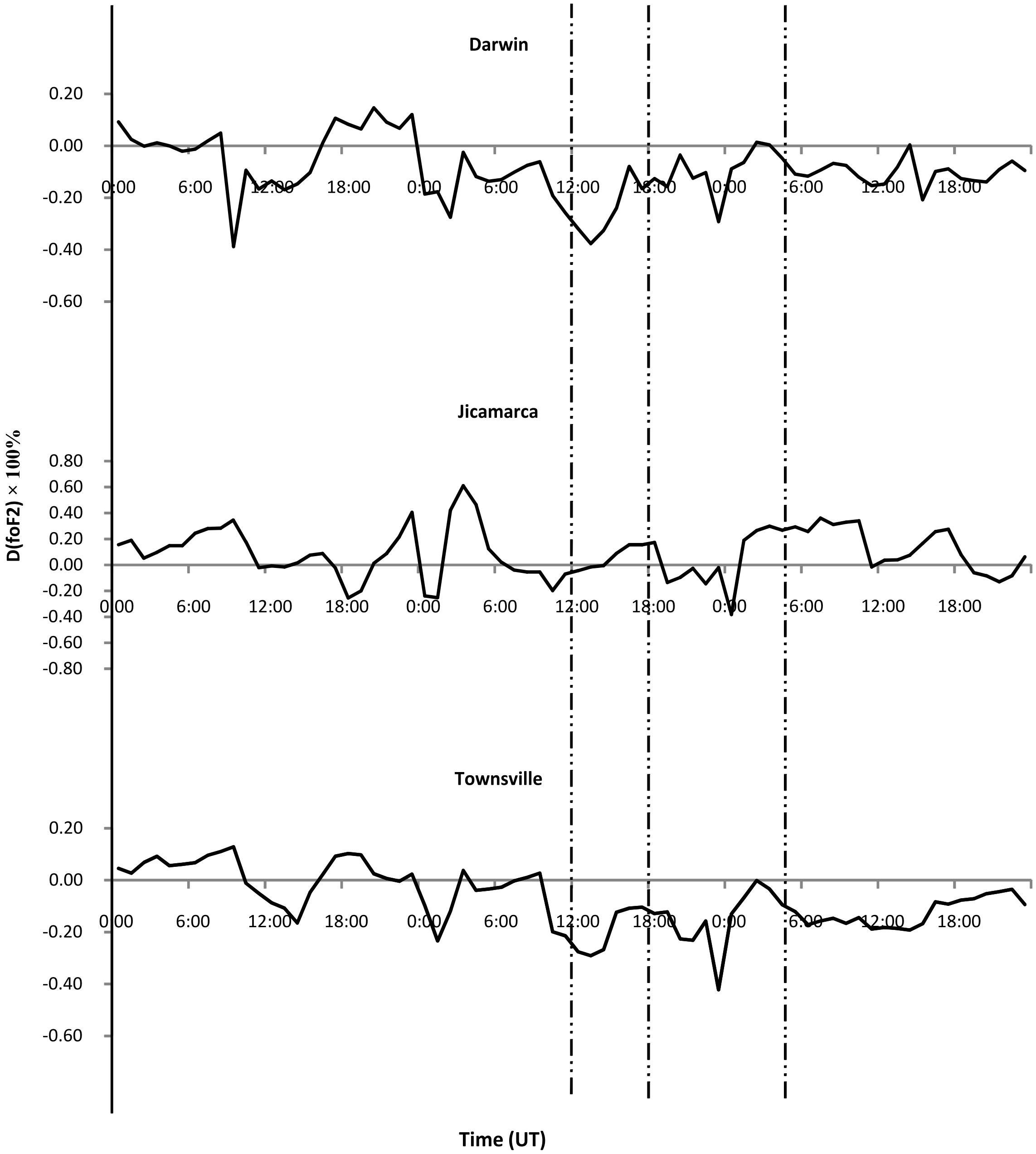

Fig. 2 Variation in D(foF2) for low latitude station for 20–22 Oct., 2001

response at 8:00 UT on Oct. 20, the atmosphere experience a sudden decrease in electron density with 39 % depletion at 9:00 UT on the same day, thereafter, its sharply increases and attained a peak enhancement value of 15 % for the day at 20:00 UT. Starting from 0:00 UT on the activity day the ionosphere response with depletion, this lasted throughout the day with peak depletion value of 38 % which was recorded at the pre-storm period. It is also observed from the station D(foF2) plot that throughout Oct. 22 the foF2 was depleted and no variation of electron density was recorded above the reference value.

The ionosphere at Jicamarca emerges with a positive ionospheric storm starting from 0:00 UT on Oct. 20 with peak electron density variation value of 18 %. This positive response was prolonging for about 17 hours, thereafter it started experiencing a fluctuation to both positive and negative phase. The peak enhancement of 61 % was recorded at 3:00 UT mid night on Oct. 21 on the storm day, during the pre-storm period the ionosphere recorded mostly a positive ionospheric storm of with peak of 16 % enhancement at 16:00 UT. At around 18:00 UT it emerges to a negative phase and fluctuated for a few hours with low response. On

Oct. 22 the atmosphere responds with 38 % depletion which is the highest electron density value throughout the period of storm activities, thereafter it increases and attained an enhancement peak value of 36 % at 7:00 UT. It is observe that recovery phase response with an enhancement mostly than depletion.

The D(foF2) for Townsville shows a low positive storm occurrence within 0:00–10:00 UT on Oct. 20, above this the ionosphere immediately show a negative storm with peak value of 16 % at 14:00 UT. However, beginning from 0:00 UT on Oct. 21, the ionosphere recorded a negative storm of 23 % depletion at 1:00 UT, sharply after it increases and record a low value of 4 % enhancement which indicate no ionospheric F2 effect at the period. This enhancement does not lasted long before it depleted and this was maintained throughout with peak value of electron density during the pre-storm, main phase and recovery phase with 28 % at 12:00 UT, 42 % at 23:00 UT and 19 % at 11:00 UT respectively.

Figure 3 present the mid latitude response to the variation in D(foF2) during Oct. 20–22, 2001. The atmosphere at Point Arguello mostly shows positive storms throughout the storm periods. On Oct. 20, the atmosphere records an enhancement of 31 % at 7:00 UT, thereafter, it decreases in an inconsistence manner in the positive phase. The initial phase period was observed to be mostly control by positive storms with peak values of 31 %, 23 %, and 19 % at 7:00 UT, 12:00 UT and 22:00 UT respectively. The storm main phase does not show any differences compared to that of preceding day except a depletion value of 16 % at 15:00 UT on the main phased onset (MPO). The storm onset period was majorly depleted, and exceeding this is the period of increase in solar wind speed and this period the interplanetary magnetic field flow is northward with peak depression in magnetic index Dst of −185 nT, the ionospheric F2 layer in fact was enhanced with peak increase in electron density value of 20 % at 19:00 UT and the period of peak minimum Dst was recorded with no data by the station (i.e. paucity of data) which lasted almost throughout the recovery phase.

The Goosebay ionosphere responds to this storm with depletion throughout the initial phase of the storm with a consistence peak value of 57 % which lasted for about 3 hours. The ionosphere also response to MPO largely with depletion and a short-time enhancement which record a moderate positive storm with electron density variation value of 17 %. The depletion value during the MPO extended to the Dst main phase period with an intense negative storm record of 62 % at 19:00 UT. Thereafter, it increases to the positive phase and attained a peak enhancement of 16 % at 0:00 UT below reference value on the recovery phase, and thereby, fluctuate through the negative and positive phase throughout.

The ionosphere at Rostov never shows any much difference compared to Goosebay except that the emergence of positive storm from 1:00–4:00 UT on Oct 20, which was preceded with paucity of data. The storm onset period maintain a negative storm record throughout, while the main phase responds with a predictable and consistence positive storm. The recovery period begin with a paucity of data, and lasted for about 2 hours, thereafter a depletion of foF2 is recorded almost throughout the day.

The D(foF2) variation for Juliusruh/Rugen do reveal intermittent phases of weak negative and positive storm in the period 0:00–17:00 UT on Oct. 21. The D(foF2) variation also show a sharp decrease in foF2 at about 18:00 UT which resulted in 62 % depletion at 19:00 UT. It rather increases in fluctuating manner in the southern hemisphere throughout the periods of event. It is observed that D(foF2) variation at this station responds largely with depletion, the only period it experience a positive storm is within 0:00–5:00 UT and in fact, the ionospheric storm at this period was averagely low. The main phase onset (MPO) period still maintain it record of negative storm of 43 % depletion peak value at 15:00 UT, it then later gradually decreases to 69 % at 20:00 UT at the main phase, the period is observed to be most depleted in foF2 which probably be as result of large decrease in Dst and southward turning of Bz.

The D(foF2) variation for Boulder shows a positive phase storm in the period 0:00–18:00 UT, thereafter, it recorded a very weak negative storm phase which do not lasted for more than an hour before it increases back to the positive phase of the storm and attained a peak enhancement of 48 % at 3:00 UT on Oct. 21. Thereafter, it rather gradually decrease and record depletion in foF2 during the storm onset period with 10 % minimum below the reference value at 16:00 UT. The storm main phase also responds with weak negative storm with low foF2 variation value of 14 % at 23:00 UT, after this it fluctuated both in the positive and negative phases with low ionospheric storm record throughout the recovery day.

The D(foF2) plot for Grahamstown appear to shows a low positive ionospheric storm response to the magnetospheric processes during the period 0:00–18:00 UT. the ionosphere thereafter depleted and registered a negative storm with 62 % depletion, the foF2 later reveal a fluctuating negative storm throughout the event periods with peak electron density of 47 %, 19 %, 52 % and 40 % at 7:00 UT, 14:00 UT, 20:00 UT and 7:00 UT during the initial phase storm onset, Dst minimum depression period and recovery phase respectively.

3.2 Storm of May 13–17, 2005

3.2.1 Interplanetary and Geomagnetic observation

Figure 4 shows interplanetary and geomagnetic observation during 13–17 May, 2005. The first panel is the low—latitude

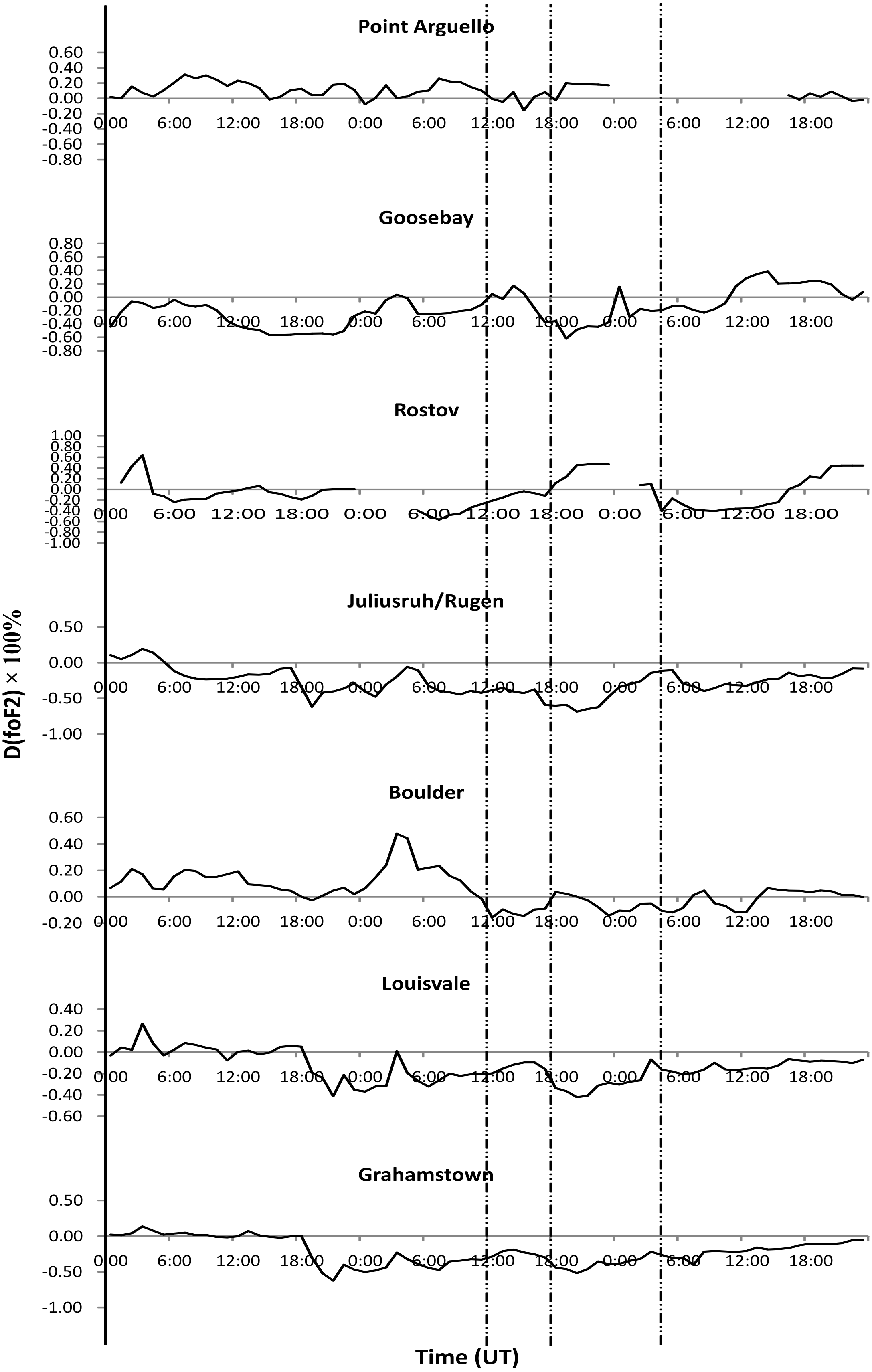

Fig. 3 Variation in D(foF2) for mid-latitude station for 20–22 Oct., 2001

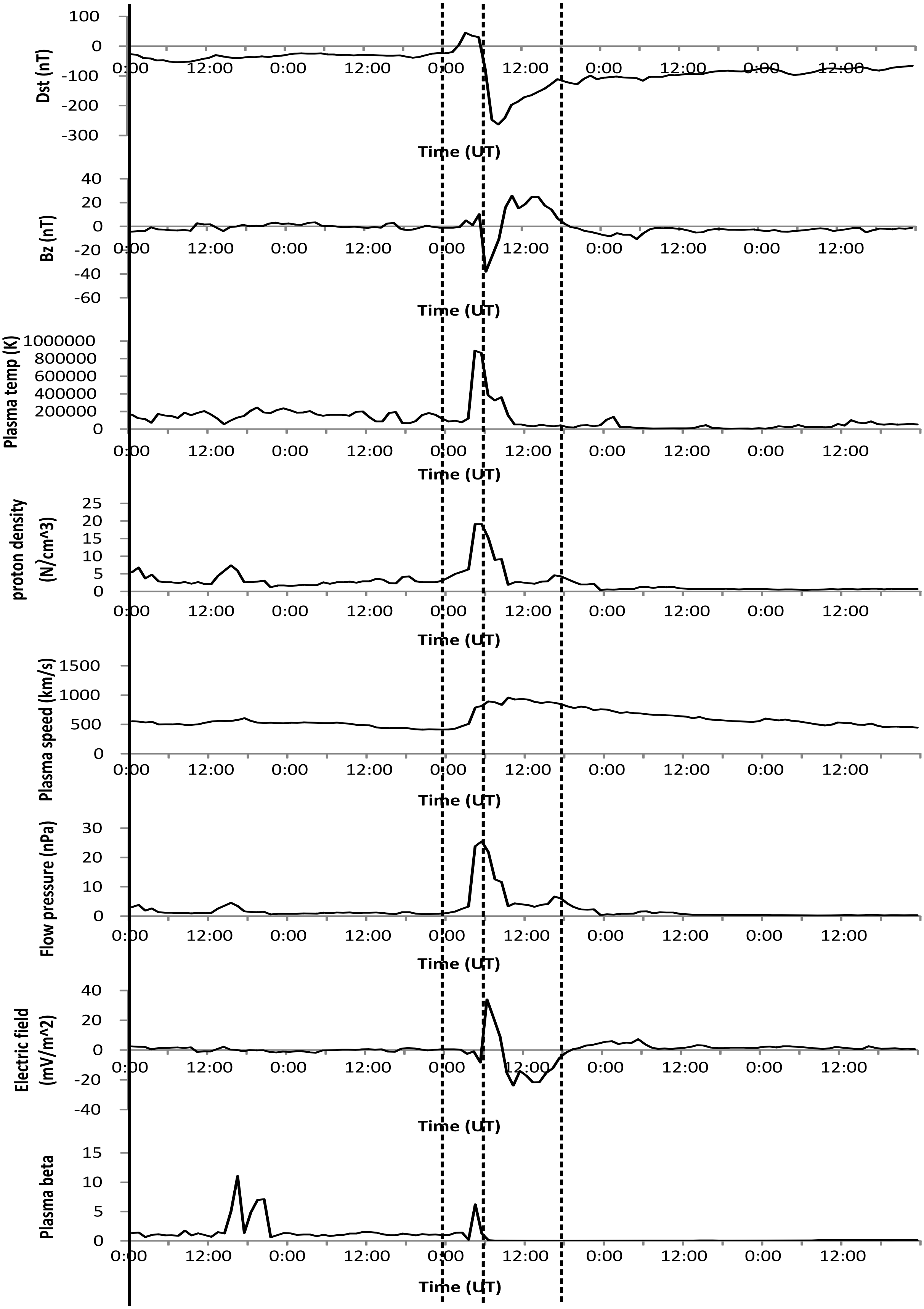

Fig. 4 Composition of interplanetary and geomagnetic observation for May 13–17 2005

Dst. The plot of Dst indicate a moderate to weak geomagnetic storm on 13–14 May. On 15 May around 3:00 UT the Dst experience a sudden shock that orientate to the northward direction with peak value of 45 nT. It was recognized that the initial phase simply represent a period of time after the onset of the sudden storm commencement (SSC) during which the IMF was orientated primary northward (Kamide et al. 1998). It was later discovered that SSC is not a necessary condition for a storm to occur, and hence is not an essential feature (Kamide et al. 1998 and reference therein). In light to the above mentioned the period is regarded as pre-storm Danilov (2001) and that pre-storm phenomena have still some unsolved problems, Chukwuma (2010) and reference therein asserted that the difficulty with explaining these phenomena is because in the studies of ionospheric storms it is assumed that the beginning of the disturbance is defined by storms sudden commencement or main phase onset (MPO) which is as a scheme restricts the geoeffectiveness of the solar wind to post-onset time, thereby foreclosing the explanation of any aspect of the morphology of ionospheric storm. Suddenly it decreases sharply to a minimum peak value of -263 nT at 8:00 UT on May 14. Thereafter, Dst recovers rather gradually throughout May 15–16. Vieira et al. (2001) had classified geomagnetic storm with Dst below -100 nT as intense geomagnetic storms. It is noted that the storm main phase occur in near coincidence s with the sharp southward turning of IMF at the magnetic cloud boundary.

The Bz plot shows that until 01:00 UT on May 15 there was no definite trend in Bz variation. Follow this IMF increases northward with peak value of 10.3 nT at 5:00 UT, this period nearly coincides with the period of pre-storm of Dst. Thereafter, it sharply decreases southward to a peak value of -38 nT at 6:00 UT on May 15, it then rotated back to the northward and record a peak value of 25.8 nT at 10:00 UT on the same day. The period of first southward turning at 4:00 UT to northward at 9:00 UT indicating that IMF has experience about five hour southward component. It is also observed that southward turning of the Bz at 4:00 UT have triggered the large depression at Dst beginning from 6:00 UT. According to Gonzalez and Tsurutani (1987), the IMF structure leading to intense magnetic storm have intense >10 nT and long duration (>3 hrs) southward component.

The plasma temperature was abruptly increased during the pre-storm period with peak value of 891191 °K. Thereafter the plasma temperature decreases sharply and records a peak value of 363196 °K at the same period of Dst minimum before maintaining a low temperature value throughout the recovery phase.

The plot of proton density responds with low value from 0:00 UT to around 15:00 UT on May 13 with increase in proton concentration of 7.4 N/cm^3. It then reduces and maintain a low value not greater than 4.1 N/cm^3 till the day of storm activity. Around 4:00 UT on May 15 proton density increase with a peak value of 19.1 N/cm^3, this was nearly coincides with the pre-storm phase. The maximum proton number density in the plasma during the main phase of the storm (i.e minimum Dst) is 9.2 N/cm^3 which is far reduce to the pre-storm period. This is point of the fact that, increase in proton density at the pre-storm stage signal the arrival of an intense storm. Furthermore, it is noted that as the proton number density is decreasing the storm is recovered.

The flow speed plot emerged with high stream flow at the early hour of May 13 till around 0:00 UT on May 15. Thereafter, the speed increase to a peak of 959 km/s at 9:00 UT. This anonymous increase in stream flow may be as a result of high plasma density and higher velocity that combine to form a much larger solar wind ram pressure. This pressure compresses the earth's magnetosphere and increases the field magnitude near equator (Tsurutani and Gonzalez 1995). According to Gonzalez et al. (2001) intense magnetic storms occur when solar wind speed is substantially higher than the average speed 350 km/s.

The electric field maintained an inconsistence low value from May 13–14, around 6:00 UT on May 15 the field record a peak value of 34.01 mV/m, this then decreases to a negative field value of 23.89 mV/m at 10:00 UT on the same day. This high electric field during the pre-storm with large southward turning of Bz may give indicative for an intense storm.

Plasma beta record a low value from 0:00 UT–13:00 UT on May 13, thereafter, it increases sharply to a peak value of 11.05 at 16:00 UT on the same day. On the day of activity the plasma beta record a high value of 6.23 at 4:00 UT. However, enhancement of the plasma beta and temperature at the same period confirms that the shock produced was follow by ejecta which were not a magnetic cloud type (Dal Lago et al. 2004). The period of Dst minimum is characterized as low plasma, low plasma temperature, and high northward turning of the Bz. A magnetic cloud is a region of slowly vary and strong magnetic field (10–25 nT or higher) with exceptionally low proton temperature and plasma beta typically $\sim$0.1 (Gonzalez et al. 1999 and reference therein). Following the ejecta one can observe a high speed stream, which is overtaking it. According to Dal Lago et al. (2004), the interaction of the high stream and ejecta result in an increase in speed, density and temperature.

3.2.2 Ionospheric response to storm of May 14–16, 2005

Low latitude response The D(foF2) of ascension Is. As shown in Fig. 5 emerges with an enhancement in the electron density from 0:00 UT and fluctuate both in the positive and negative phase till around 10:00 UT on May 14 with peak enhancement value of 43 %. Thereafter, it depleted and remains in the negative phase for about 9 hrs which covered

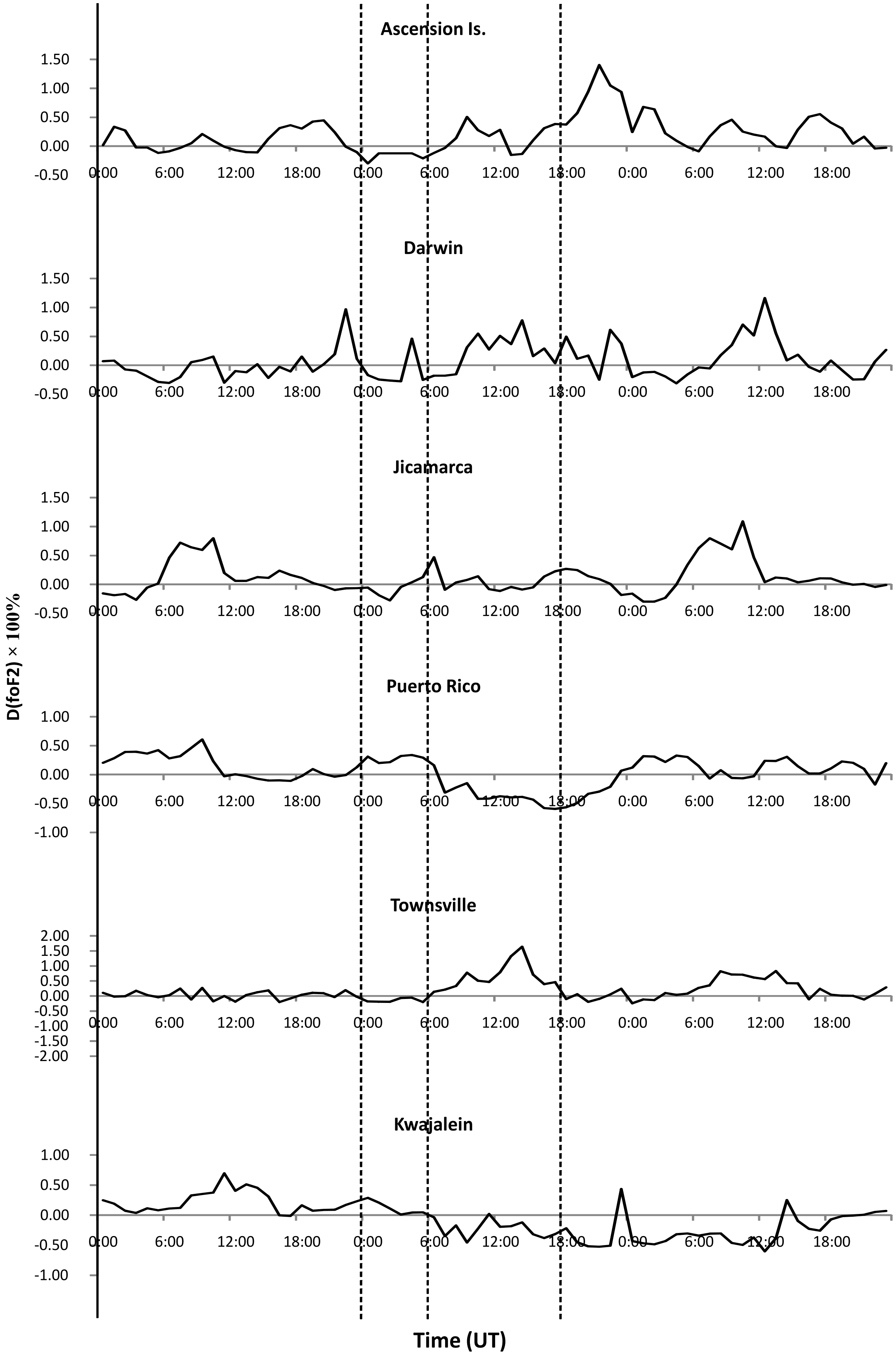

Fig. 5 Variation in D(foF2) for low latitude station for 14–16 May, 2005

the period of pre-storm. The peak value of electron density ever recorded during the main phase is 50 % enhancement at 9:00 UT an hour after the Dst minimum value of −263 nT. It then later fluctuated through the recovery phase till it attained a maximum peak value of electron density ever recorded for the period of geomagnetic storm at 21:00 UT on May 15 with 141 % enhancements.

The ionospheric F2 of Darwin responds to the storm of May 14–16 with low electron density value from 0:00 UT with 7 % enhancement below the reference value till 1:00 UT on May 14, it then depleted to 31 % on the same day around 6:00 UT. Around 22:00 UT mid night the electron density concentration increase to 97 % which signal the arrival of shock, sharply it later decrease to a depleted value of 46 % on May 15 at 4:00 UT. During the pre-storm phenomena the ionosphere at Darwin responds mostly with depletion than enhancement but the peak electron density value at this period is 46 % enhancement at 4:00 UT. The main phase period never show any difference compared to that of Ascension Is. This period is mostly recorded with an enhancement with peak value of 78 % at 14:00 UT. There is no much difference observed at the recovery phase except high enhancement peak of 116 % at 12:00 UT.

The ionospheric response for Jicamarca indicates that at interval 0:00–5:00 UT on May 14 was rather quite, the interval 6:00–10:00 UT shows that foF2 was enhanced by 80 % peak value above the reference level. This positive storm was immediately followed by a weak positive storm. On May 15, at the interval of 0:00–6:00 UT the ionosphere response to pre-storm phenomena largely with depletion, despite this the period record maximum positive ionospheric storm effect compared to depletion with peak enhancement of 47 % at 6:00 UT. At this station the intense geomagnetic storm response with low ionospheric storm, the peak response was at the recovery phase with enhancement of 109 % in electron density.

The D(foF2) versus UT plot for Puerto Rico emerge from 0:00 UT on May 14 with an enhancement. The intense positive earth's ionospheric storm followed immediately by a no significant ionospheric storm which lasted for coupled of hours. The pre-storm period was recorded with a significant positive storm which preceded the negative intense ionospheric storm at the main phase with maximum depletion of electron density value of 58 % at 16:00 UT. The recovery phase is majorly recorded with positive storm, but the foF2 variation fluctuates both in the positive and negative phases with significant effect responses at the positive phase.

The D(foF2) variation of Townville respond differently with positive ionospheric storm of 164 % peak enhancement on May 15 at 14:00 UT. Not just the peak enhancement value of electron density, but it is the period of maximum ionospheric storm effect ever recorded by the station. Preceding this, starting from 0:00 UT on May 14, the foF2 recorded a low to moderate ionospheric till around 6:00 UT when it started increasing. The period of this abrupt ionospheric F2 increase coincide with the main phase period of the minimum geomagnetic index Dst.

The ionosphere at Kwajalein showed a moderate negative storm that occurred at exactly hour of Dst minimum, negative ionospheric response was recorded an hour after with peak depletion value of 45 %. It was observed that no high value of foF2 was recorded beyond this at the period of pre-storm and main phase of the Dst. The maximum positive and negative ionospheric storm was observed at the initial phase with peak enhancement of 70 % at 11:00 UT and depletion of 60 % at 12:00 UT on May 16 respectively.

Middle latitude response The D(foF2) for Juliusruh/Rugen emerge with a negative storm occurrence with peak electron density of 19 % at 1:00 UT on May 14 of Fig. 6, the ionosphere above this station immediately shows a positive storm with peak value of 7 % below reference value at 4:00 UT. It is observed that May 14 was recorded majorly a negative storm. However, beginning at 0:00–6:00 UT on May 15 the period known as pre-storm occurrence, the ionosphere emerge with positive ionospheric storm with peak enhancement record of 16 % at 3:00 UT. Thereafter, it decreases throughout the main phase period and the recovery phase with minimum depletion value recorded at the recovery phase with 51 % and 54 % at 23:00 UT of May 15 and May 16 respectively.

The D(foF2) for Point Arguello shows a low to moderate ionospheric F2 layer response to the ionospheric processes on May 14. Starting from 0:00 UT on May 15 the foF2 depleted with minimum record of 14 % at 2:00 UT, it then sharply increases and recorded a positive storm intensity value of 39 % at 5:00 UT. Thereafter, the foF2 depleted throughout the remaining days with peak negative storm intensity values of 41 % at 9:00 UT, 47 % at 15:00 UT and 43 % at 2:00 UT of May 15 and 16 respectively.

The D(foF2) plot for Goosebay shows am positive ionospheric response during 1:00–9:00 UT on May 15 which emerge from a negative storm phase with 41 % at 5:00 UT. It later decreases and lead to a negative storm with electron density concentration which do not exceed the reference level. Observation also confirm that during the depression of the Dst main phase the ionosphere initially records a positive storm that later decreases with minimum electron density peak of 41 % at 12:00 UT which indicates the recovery of geomagnetic storm.

The D(foF2) variation for Rostov shows a similar characteristics of ionospheric response compared to Juliusruh/Rugen and Point Arguello except on May 15 at the initial and main phase periods that the ionosphere record a depletion value of 44 % at 4:00 UT and enhancement of

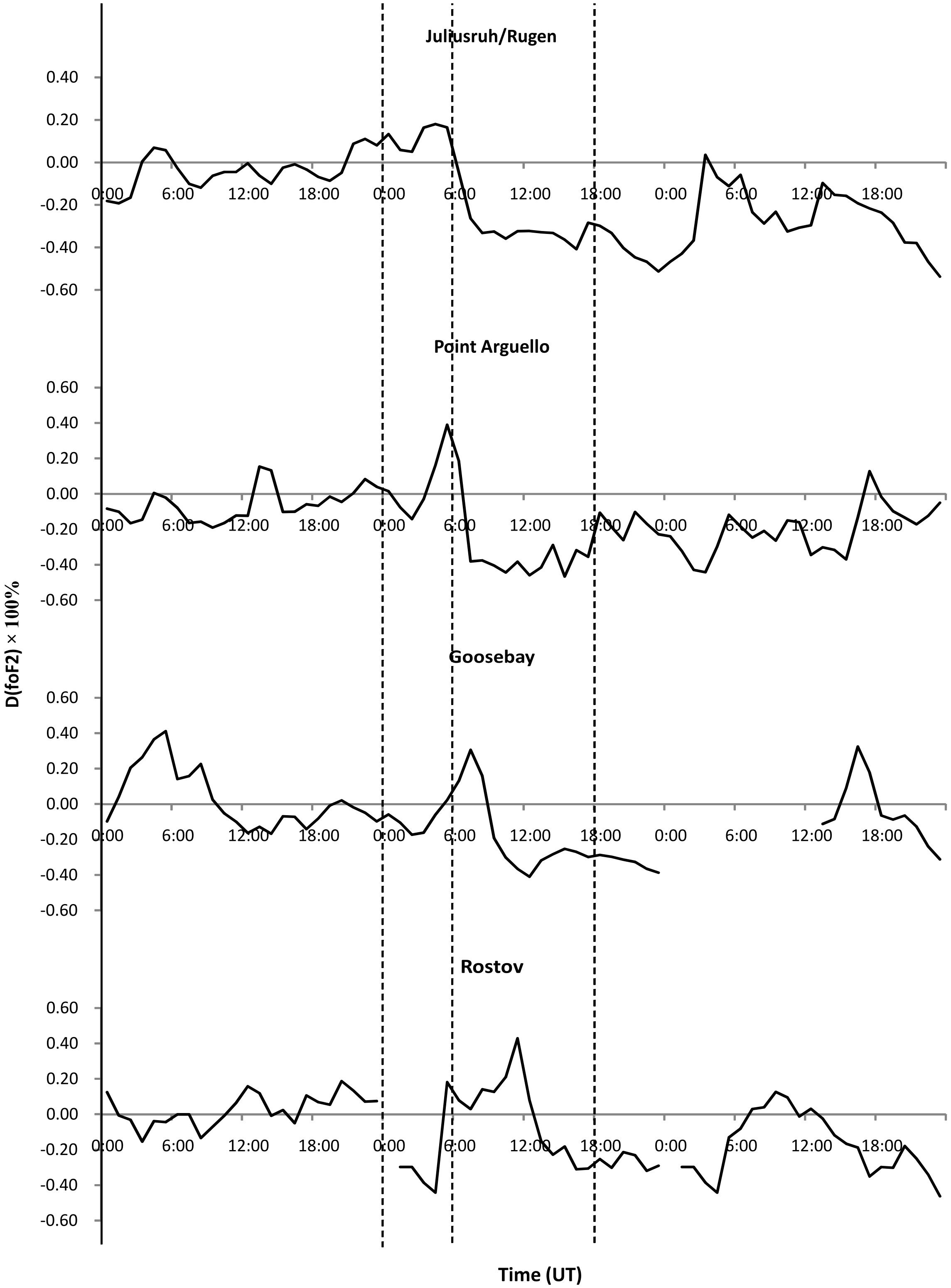

Fig. 6 Variation in D(foF2) for mid latitude station for 14–16 May, 2005

43 % at 11:00 UT. Followed the enhancement at 11:00 UT, the electron density sharply depleted to the negative storm phase which thereafter elongated till May 16 with minimum peak of 44 % at 4:00 UT, thereafter, it enhances with a low positive storm of 13 % at 9:00 UT before it later depleted throughout the remaining period of the day.

4 Discussions

The intense interplanetary magnetic field can be thought of as being associated with essentially two parts of high-speed stream, the intrinsic fields, and plasma associated with the coronal-ejecta (called driven gas fields), and the shocked and compressed field and plasma due to the collision of the high speed stream with the slower solar wind preceding it (Gonzalez et al. 1994). Furthermore, the compression is related to the strength of shock and thus to the speed of high speed stream relative to the upstream (slow) solar wind. The evidence is overwhelming that solar wind dawn-to-dusk electric fields directly drive magnetospheric convection (e.g. Gonzalez et al. 1994; Kamide 1992). However, there are four major mechanisms responsible for this drive: the interplanetary coronal mass ejections (ICMEs), the corotating interacting region effect (CIRs), which is the interaction of fast stream with slow stream ahead creating plasma and field compression, Russel-McPherron effect and the Alfevenic interplanetary magnetic field fluctuations. Of these four, only ICMEs and CIRs can be considered the primary event driving the storms while the other two are modifiers which generally do not produce storms without an ICME or CIR (Kamide et al. 1998). Note that these four mechanisms can interact differently from one event to the other. The dominant interplanetary phenomena causing intense magnetic storm are the interplanetary manifestation (Gonzalez et al. 1999, 2001; Vieira et al. 2001). Two interplanetary structures are important for the development of such class of storms; the sheath region just behind the forward shock and the coronal mass ejecta (CME) ejects itself. However, these structures lead sometimes to the development of very intense storms, especially when an additional interplanetary shock is found in the sheath plasma of the primary structure accompanying another stream (Gonzalez et al. 2001; Zhao 1992). However, Zhao et al. (1993) found that internal interplanetary coronal mass ejecta (ICME) field orientation may indeed exhibit a preference for the prevailing solar field pattern, suggesting that these fields also contribute to the seasonal pattern of geomagnetic storms. The field decrease the equatorial magnetic field strength is directly related to the total energy of the ring current particles and this is good measure of energetic of magnetic storms (Gonzalez et al. 1994; Tsurutani et al. 2003; Vieira et al. 2001). The great (or intense) storm are those with peak of Dst ≤ -100 nT, moderate storms fall between -50 and -100 nT, and weak storms are those between -30 and -50 nT (Gonzalez et al. 1994). With this entire characteristic aforementioned above it is understood clearly that the storms of 13–17 May, 2005 and Oct. 19–23, 2001 is regarded as intense geomagnetic storm and it was drive by magnetic cloud. The orientation of the interplanetary magnetic field (IMF) carried by the solar wind is also a very important factor. Geomagnetic activity is known to increase dramatically whenever the IMF stream is toward negative z-direction (Chaman-Lal 2000). Also the storm driver is characterized by low plasma beta, high magnitude of magnetic field component, large coherent rotations; often include large and steady north-south components and higher proton temperature.

The pre-storm period of both Oct. 19–23, 2001 and May 13–17, 2005 storms is observed to be largely control by large southward magnetic field component, high plasma temperature, increase in proton density, flow speed stream and high plasma beta, and these period has no definite effect on the ionospheric foF2, which support the previous study of Chukwuma (2010), Makhailov and Perrone (2009), Liu et al. (2008), Buresova and Lastovicka (2007, 2008), Balasis et al. (2006) but may result in large ionospheric effect at the main phase period.

The ionospheric response of the equatorial region of the year under consideration can be summarize using a superimpose plot as shown in Figs. 7 and 9. The results reveal some degree of simultaneity at the initial, main and recovery phase of the storm. The increase in solar wind parameter at this period of pre-storm does not record a large variation in electron density of foF2 which indicate the arrival of ionospheric storm.

Around 7:00 UT–12:00 UT on Oct 20 the superimpose plot of Fig. 7 shows that all the stations were depleted simultaneously and the initial phase was more disturbed with large ionospheric storm than the main phase and recovery phase respectively. This points to the facts that ionospheric F2 disturbance at the initial phase signal how intense the geomagnetic and ionospheric storm at the main phase will be. The pre-storm period was registered by depletion except for Jicamarca with weak-moderate ionospheric storm; this may be as result of local time effect (see Vijaya Lekshmi et al. 2011; Balan and Rao 1990). As a result of this the main phase was depleted simultaneously across all the stations, which shows that equatorial region ionosphere, cannot be left out with global geomagnetic effects. And also weak-moderate ionospheric storm on the storm onset period may signal the intensities of ionospheric storm on the event period. It is observed that the recovery period is rather quite throughout. The initial phase of the mid-latitude superpose in Fig. 8 does not shows any difference compare to equatorial region, the storm sudden commencement period is depleted simultaneously across all the stations. It is observed that (MPO) period depletion signal the intense simultaneous decrease during the main phase in all stations except Point Arguello and Rostov whose has a paucity of data. It is clearly observed that the recovery phase is simultaneously depleted throughout.

An analysis of the interplanetary and geomagnetic observations show that the pre-storm phase occurred between

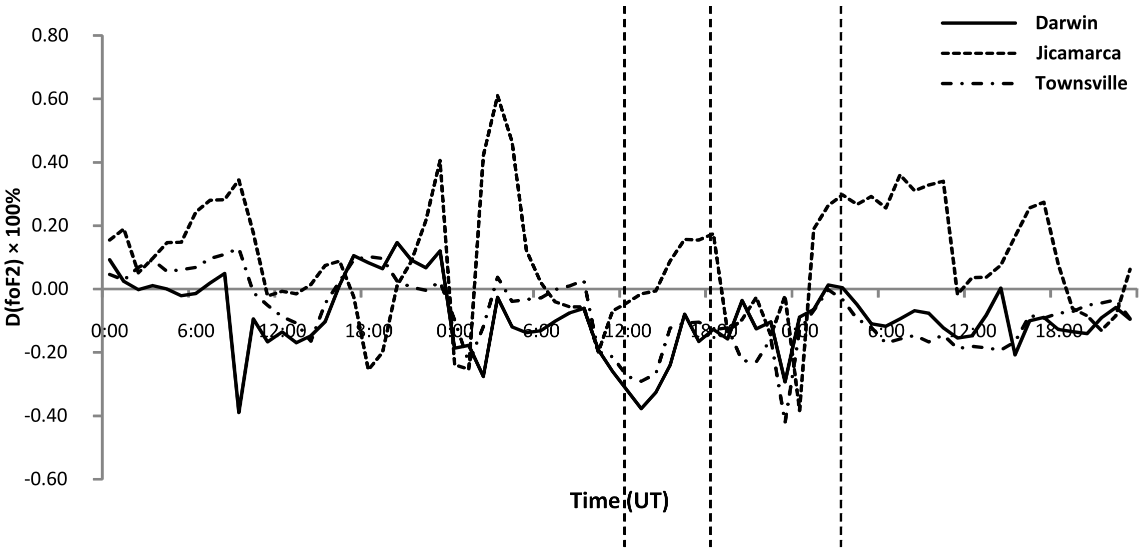

Fig. 7 Variation in D(foF2) superpose for low latitude stations for Oct. 20–22, 2001

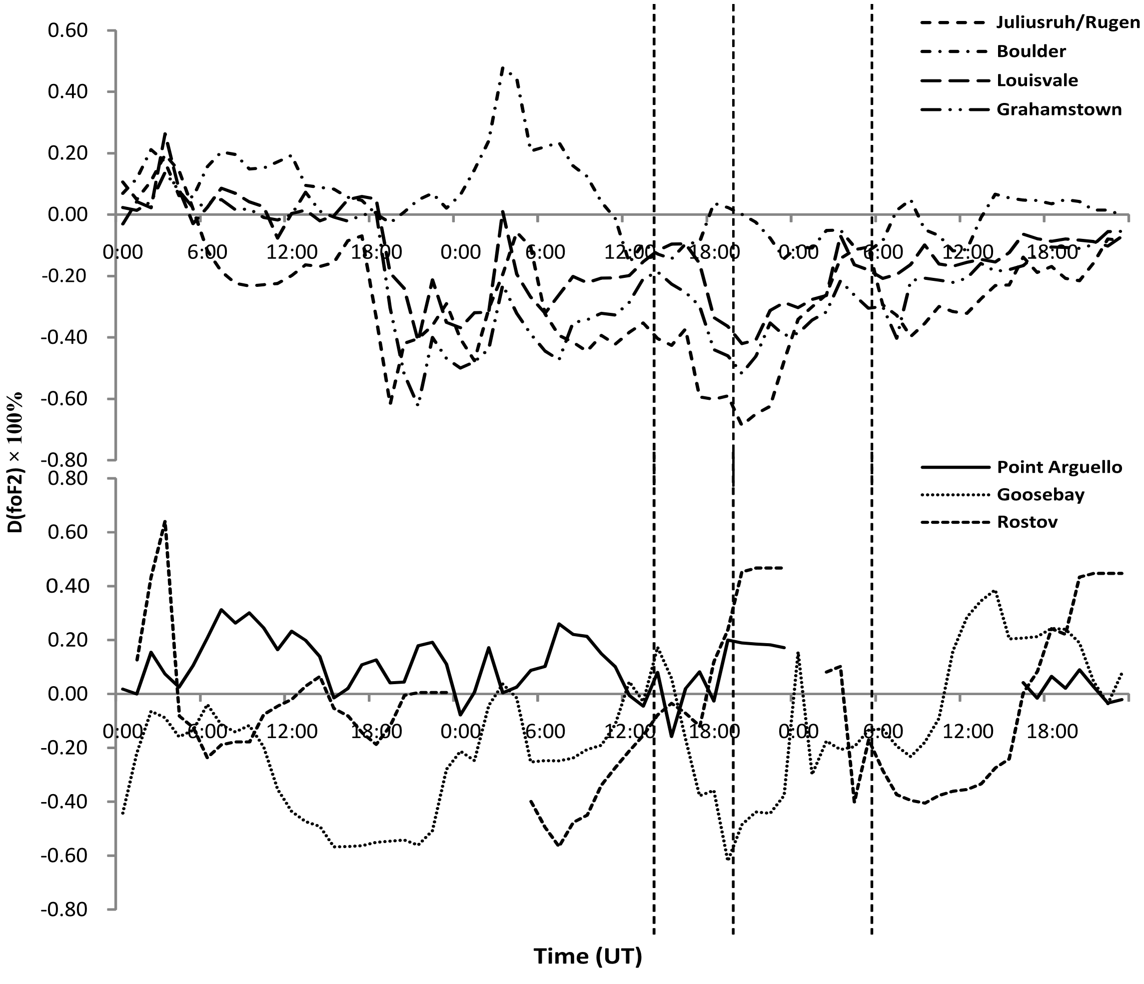

Fig. 8 Variation in D(foF2) superpose for mid-latitude stations for Oct. 20–22, 2001

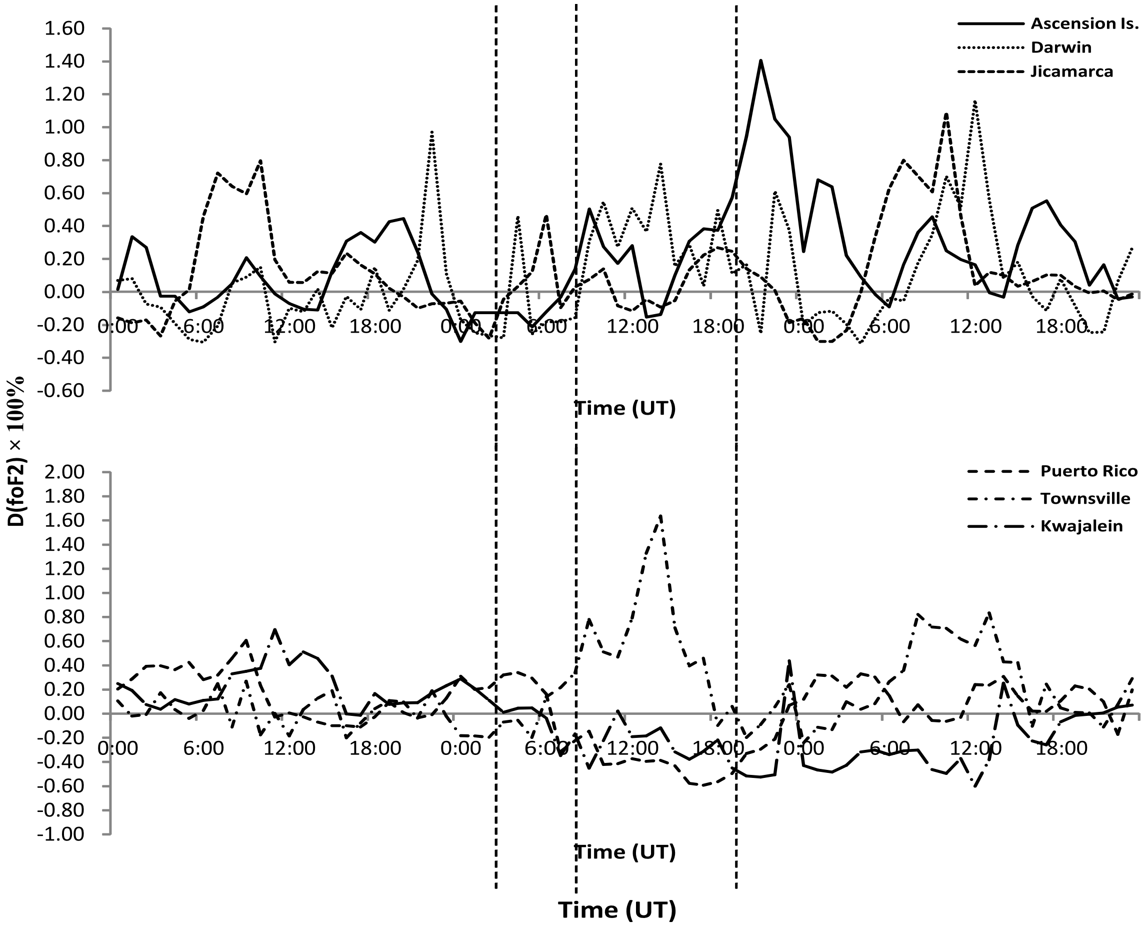

Fig. 9 The superimposed variation in D(foF2) for low latitude stations for 14–16 May, 2005

0:00–6:00 UT, and the main phase between 6:00–16:00 UT. The superimposed plot of the equatorial region in Fig. 9 during the pre-storm maintains a moderate ionospheric effect in both southward and northward direction. This is point of the fact that increase in solar wind parameter at this period of pre-storm does not record a large variation in electron density of foF2 which indicate the arrival of ionospheric storm. The plot indicate an existence of moderate ionospheric storm during the main phase period, the largest response of ionospheric F2 layer was recorded at the recovery phase and during the initial phase periods. Also the storm measured majorly positive ionospheric storm with peak electron density value on the recovery phase. As a matter of fact equatorial region ionosphere has confirmed to be largely affected by geomagnetic storm most especially the recovery phase periods.

The superimpose plot of the mid-latitude in Fig. 10 indicate that all the station responds with a depletion within time interval of 6:00 UT on May 15 to 3:00 UT on May 16 except Goosebay which it take depletion effect at 9:00 UT and Rostov at 13:00 UT on May 15. This non-coincidence of ionospheric response at these stations may be as a result of local time effect (Balan and Rao 1990). The plot further indicate the existence of positive storm during the pre-storm period and preceding this all the station response with a simultaneity of depletion majorly except for Goosebay who records an enhancement value of 41 % at 5:00 UT. This point to the fact that existence of pre-storm lead to negative storm at mid latitude and this period was known as period of prompt penetration of electric field. According to Gonzalez et al. (1994) the primary causes of geomagnetic storm at the Earth are strong interplanetary electric field associated with the passage of southward direction of magnetic field Bs that pass the Earth for a sufficiently long interval of time. The electric field is composed of two factors; the solar wind velocity V_{sw} and southward IMF (Chukwuma 2010). Tsurutani et al. (1993) demonstrated that it is the extraordinary high southward Bz rather than high V_{sw} that is the dominant part of the electric field. The negative storm response during the pre-storm phenomenon in equatorial region and mid latitude may be as a result of large northward value of electric field and large southward turning of interplanetary magnetic field (IMF) Bz.

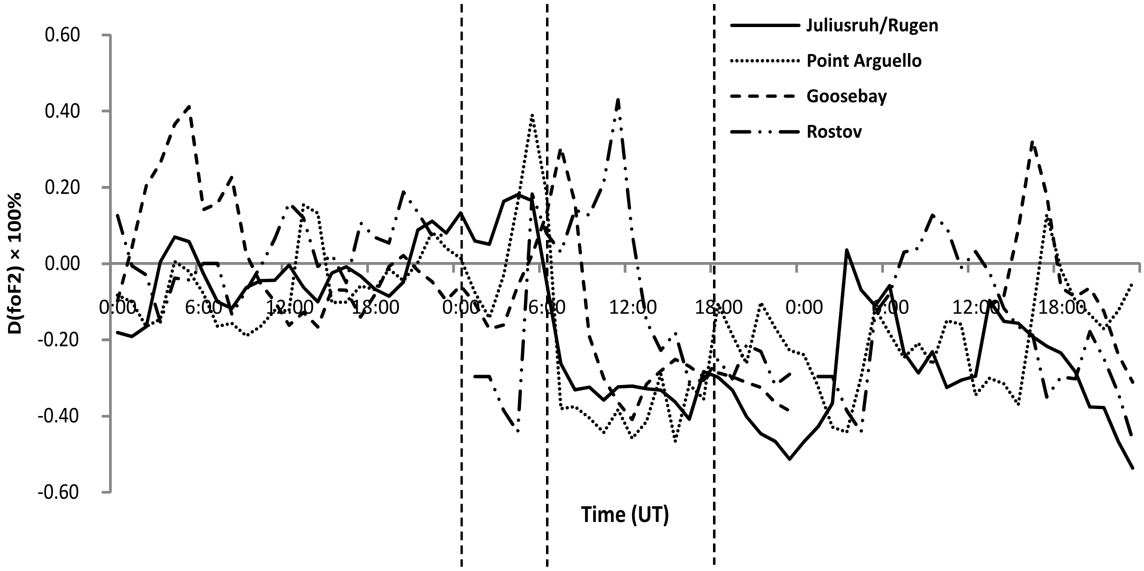

Fig. 10 The superimposed variation in D(foF2) for Mid-latitude stations for 14–16 May, 2005

Many research has been carried out on the positive and negative ionospheric disturbances at the mid- and high-latitude using different modelling and method (Rakhee et al. 2010; Bakare et al. 2010; Mukherjee et al. 2010; Romanova et al. 2008; Rishbeth and Mendillo 2001; Bencze et al. 2004; Tsagouri et al. 2000; Namgaladze et al. 2000; Vasiljevic and Cander 1996), with only few mention on equatorial region (Mansilla 2011; Prölss 2006; Pavlov et al. 2006), the result confirmed prompt effects of geomagnetic disturbances at all latitudes. The recent research on ionospheric F2 region have confirmed a pronounce effect of geomagnetic storm on low latitude ionosphere. In light of this, it is clearly observed from our result that both low and mid latitude ionosphere response largely to geomagnetic storm effects. The result generally reported that negative intense ionospheric storm always preceded by weak-moderate ionospheric storm during the pre-storm.

5 Conclusion

In this research work we conducted an analysis on the changes in foF2 using normalize deviation of critical frequency F2 (D(foF2)) on the ionosphere in other to verify the geomagnetic storm effect on the 9 equatorial and 11 mid latitude region of the earth ionosphere and to investigate the vividly effect of pre-storm on the aforementioned part of the ionosphere particularly equatorial region. Also to understand the phenomena of pre-storm that leads to very intense geomagnetic storms. The result point to the fact that pre-storm phenomena that leads to intense ionospheric storm are; large southward turning of interplanetary magnetic field Bz, high electric field, increase in flow speed stream, increase in proton number density, high pressure ram and high plasma beta.

It is to be noted that magnitude of Bz turning into southward direction from northward highly depends upon the severity of the storm and the variation in F2 layer parameter at the time of geomagnetic storm are strongly dependent upon the storm intensity. The storm is known to be drive by magnetic cloud i.e. the main phase is characterize by low plasma beta temperature, low field variance and large scale coherent field rotation, often including large and steady north-south component, and higher proton temperature (Bakare and Chukwuma 2010).

The foF2 variation at the low and mid latitude thought very puzzling during pre-storm. An interesting point is that any new burst of storm activity is associated to a new generated disturbance at the ionospheric F2 layer of the ionosonde stations. The ionospheric F2 response for low and mid latitude does not show any significant differences during the storm main phase and the pre-storm period are comparable. The result confirmed large ionospheric disturbance at both mid and equatorial region and the pre-storm period was characterize with low-moderate ionospheric storm. The pre-storm period was preceded by intense positive and negative ionospheric storms. Observation also shows that low-moderate variations in ionospheric F2 at the pre-storm period signal the upcoming of large ionospheric disturbances at the main phase and low ionospheric variation exceeding the main phase signified the storm recovery. The initial phase is observed to be recorded with an intense ionospheric storm despite the low geomagnetic storm activity at the period. This follows the fact that the variations of F2 layer quite disturbances have different formation mechanism and have been interpreted to the concept of thermosphere-ionosphere interaction (Mikhailov et al. 2009).

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