Annals of Geophysics, 63, 2, GM214, 2020; doi:10.4401/ag-8127

Influence of geomagnetic storms on the mid latitude D and F_2 regions

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Article history: received February 15, 2019; accepted August 18, 2019

Abstract

The signal amplitude of 22.1 kHz Very Low Frequency (VLF) waves, transmitted from the radio station Skelton, UK (GQD at 54.7^0 N, 2.8^0 W) and received at South France station (SID, Sudden Ionospheric Disturbance monitoring station at 46^0N, 2^0E) is studied for the effect of geomagnetic storms on the lower ionosphere. The VLF parameters, D-Layer Preparation Time (DLPT) depth and Mid-Day Peak (MDP) have been used to study the response of D-region to the geomagnetic storms occurred during the equinox months of 2012-2015. The two parameters recorded enhancement on the storm day and subsequent days. A shift in the sunrise Terminator Time is observed for the geomagnetic storms for which Sudden Commencement (SC) occurred during the day lit hours on the previous day. The observed effect of the geomagnetic storms on the mid latitude D-region is due to the precipitation of high energy particles. The response of F_2-region to geomagnetic storms is studied using the f_oF_2 data at Dourbes (50.1^0 N, 4.6^0 E), Belgium which is near the mid-point of the GQD-South France VLF path. The percentage of deviation of f_oF_2 from the quiet day values, Df_oF_2 is found to undergo positive and negative changes. The positive storm effect during daytime is mainly due to the penetration electric field and strong negative phase during both day time and night time is due to depleted $[O]/[N_2]$ ratios.

Keywords: D-region, VLF wave propagation, Geomagnetic storm, F_2-region, Solar wind.

1. Introduction

The Very Low Frequency (VLF) signals (3-30 kHz) have been used for investigating the response of the lower ionospheric D-region to solar events like X-ray flares and geomagnetic storms [Kumar et al., 2015; Selvakumaran et al., 2015; Kumar and Kumar, 2018]. These waves propagate in the earth-ionosphere waveguide and their propagation path completely lies in the D-region. Therefore, their propagation characteristics are sensitive to changes in the electron density and conductivity of the D-region. These D-region parameters undergo change during the sunrise and sunset times. When an X-ray flare occurs, the D-region conductivity changes resulting in signatures in the amplitude and phase of the VLF waves [Kumar and Kumar, 2018]. The space weather events like geomagnetic storms modify the high latitude ionosphere through solar wind driven particle precipitation, Joule heating and thermospheric circulation [Venkatesh et al., 2017].

During the geomagnetic storms, the solar wind interacts with the ionospheric plasma at high latitudes and electric fields are developed. These fields are mapped to mid and low latitudes and modify the existing electric fields [Uma et al., 2012 and references therein]. From the study of the phase variations of VLF signals transmitted from OMEGA-ALDRA (at 13.6 kHz), GBR (at 16.0 kHz) and OMEGA-NORTH DAKOTA (at 13.6 kHz) and received at Inubo, Japan, Kikuchi and Evans (1983) concluded that the high energy (>300 Kev) electron precipitation into the atmosphere during magnetically disturbed days is the main source of D-region ionization responsible for the observed phase anomalies. Lastovicka [1996] observed that the lower ionosphere at high latitudes readily respond to geomagnetic storms and the mid-latitudes show a delayed effect. The study also revealed that there is a correlation between geomagnetic storms and total ozone density under special conditions. Cummer et al. [1996] observed VLF phase and amplitude perturbations at the edge of auroral zone due to enhanced electron density caused by high energy precipitating electrons. From the study of VLF amplitude data from Holographic Array for Ionosphereic Lightning Research (HAIL) stations in United States and another station from Antarctica with L shell contours 2-3, Peter et al. [2006] observed a reduction in night time VLF amplitudes during geomagnetic storms. Clilverd et al. [2010] showed that VLF amplitude variations can be used to estimate the flux of energetic electrons entering the upper atmosphere. Using the amplitude of 24 kHz VLF waves transmitted from NAA, Maine, USA and received at sodankyla, Finland, they found that electron density varies by three orders during geomagnetic storms. Sokolov [2011] studied the variability of D-region electron density and the precipitation electron flux at L shell contours 3-8 during the different types of geomagnetic storms. This study revealed that during the recovery phase of intense magnetic storms, the electron precipitation extends over long latitudinal interval and VLF phase anomalies are observed at mid-latitudes due to this effect. Choudhury et al. [2015] found that the change in the VLF amplitude at the sunrise time decrease during the geomagnetic storms indicating the reduction in day-night asymmetry. Many investigators [Kumar and Kumar, 2014; Kumar et al., 2015; Nwankwo et al., 2016] reported anomalies in VLF amplitude during geomagnetic storms associated with solar flares. The enhancement in the electron density at D-region altitudes due to the high energy electron precipitation during geomagnetic storms is responsible for the signatures observed in VLF parameters.

Studies on the response of E-region to geomagnetic storms at mid latitudes are very scarce. The ionospheric E-region electron density reduces slightly after a geomagnetic storm leading to reduction in f_oE (critical frequency of E-layer) at auroral latitudes and this response is very weak at mid latitudes [Danilov and Lastovicka, 2001]. The effect of geomagnetic storm on the ionospheric F_2 region is indirect and is through the disturbance dynamo electric fields (DDEF), prompt penetration electric field (PPEF) and neutral composition changes [Uma et al., 2012; Danilov, 2013]. The variations of electron densities and also the dynamics at the ionospheric F_2-region altitudes are due to the mapping of PPEF, DDEF and the storm time thermospheric wind circulations which can generate Travelling Atmospheric Disturbances (TADs) and Traveling Ionospheric Disturbances (TIDs) [Kumar and Kumar, 2019 and references therein]. The critical frequency of the F_2 layer, f_oF_2 and Total Electron Content (TEC) have been studied widely for the response of this region to the geomagnetic storms [Venkatesh et al., 2017; Kumar and Kumar, 2019]. The effect of geomagnetic storm on f_oF_2 known as ionospheric storm has positive and negative phases. The positive and negative phases of f_oF_2 variation refer to enhancement and depletion of maximum electron density respectively during the storm. Mansilla [2014] observed the negative storm effects at equatorial anomaly crest regions and positive storm effects at equatorial and low latitudes which are attributed to the DDEF developed due to the disturbance winds. The positive storm effect observed at mid latitudes during daytime can be due to abundance in [O]/[N_2] ratio [Klimenko et al., 2015]. The long-duration negative storm effect at southern hemisphere mid latitude station, Hobart during the St. Patrick storms of 2012, 2013 and 2015 were observed by Kumar and Kumar [2019]. They indicated that these negative phases are caused by the storm induced DDEF, depleted [O]/[N_2] ratios and TIDs of high latitude origin penetrating to mid latitudes. In a detailed study of the geomagnetic storm effect on the total atmosphere and ionosphere, Danilov and Lastovicka [2001] observed that the effect of geomagnetic storms is through the strong Joule heating leading to disturbance winds in F-region and the enhancement of particle precipitation resulting in enhancement of electron densities at the D-region altitudes. The aim of the present work is to study the response of mid latitude D and F regions to a few geomagnetic storms which occurred during the equinoxial months of February, March and August months of 2012-2015.

2. Data and Analysis

The amplitude of VLF signals at 22.1 kHz transmitted from Skelton (Station code GQD), UK (54.7^0 N, 2.8^0 W) and received at SID monitoring station in South France (46^0N, 2^0E) is obtained from the website https://sidstation.loudet.org/data-en.xhtml. The great circle distance between GQD and the receiving station is 1024 km. The magnetic storms considered in the present study are listed in Table 1.

S.NO	Event Date	Sudden Commencement Time	Minimum Dst Value (nT)
1	09-03-2012	1100 UT on 08-03-2012	-145
2	17-03-2013	0600 UT on 17-03-2013	-132
3	19-02-2014	1300 UT on 18-02-2014	-116
4	27-02-2014	1700 UT on27-02-2014	-94
5	17-03-2015	0600 UT on 17-03-2015	-223
6	27-08-2015	0600 UT on 26-08-2015	-91

Table 1. Details of the geomagnetic storms considered in the present study

The VLF amplitude for seven days (3 days prior to and after the event day) has been analysed for calculating the VLF parameters, D-Layer Preparation Time (DLPT) depth and Mid-Day Peak (MDP). At the time of sun rise and sun set, the VLF amplitude undergoes drastic changes. The first minimum in VLF amplitude graph during sun rise time is denoted by sunrise terminator. The difference in night time VLF amplitude at the time where the sun rise effect starts and that at sunrise terminator time is taken as DLPT depth. The average of day time signal amplitude from 1200 UT to 0200 UT is designated as MDP. The sun rise and sun set terminator times are important parameters since the lower ionospheric condition can be monitored by these Terminator Times [Maekawa and Hayakawa, 2006].

The effect of the geomagnetic storm on F_2 region can be studied using the critical frequency f_oF_2. The mid latitude station, Dourbes (50.1^0 N, 4.6^0 E) is in the same time zone of Skelton (GQD) and has been selected for studying the response of mid latitude F_2 region to the geomagnetic storms. The f_oF_2 at Dourbes is obtained from the website http://ulcar.uml.edu/DIDBase/. Df_oF_2 indicates the deviation of foF2 from the quiet day values and is given by

$$Df_o\,F_2 = \frac{[f_o\,F_2 - f_o\,F_2\,(\text{quiet day})]}{f_o\,F_2\,(\text{quiet day})} \times 100 \qquad (1)$$

The quietest day of the corresponding month is taken from website http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html. The geomagnetic indices Dst and AE are taken from the website https://omniweb.gsfc.nasa.gov/form/dx1.html.

3. Results and Discussion

During the sunrise time, the D-layer undergoes significant change in its electrical conductivity due to the onset of photoionization. The DLPT depth being the index of the day-night asymmetry in VLF propagation, responds to the space weather events [Choudhury et al., 2015]. This parameter calculated for seven days for all the events has been plotted in Figure 1. There is an increase in the parameter by an amount of 2 to 4 dB on the storm day for all the events except for the event of August 27, 2015. There is a dip of 3.5 dB on August 27, 2015 when compared to the previous day. Using the amplitude data of 19.8 kHz VLF signal transmitted from Northwest Cape, Australia and received at Tripura, India, Choudhury et al., [2015] studied the variation of DLPT during the long duration storm days. They reported a dip in the parameter on the storm day and the subsequent day. They also observed a negative correlation between A_p index and DLPT depth parameter. In the present study, only for one storm event, dip in the DLPT depth is observed on the storm day. From the rocket measurements of electron concentration in the altitude range 70 – 110 km at mid latitude station, South Uist, Scotland (57.3^0 N, 7.3^0 W), Dickinson and Bennett [1978] observed that the electron density on the post storm days is 10 times the average quiet time value. They concluded that the enhancement occurs below 85 Km during the early morning hours. This results in the lowering of reflection height of the VLF waves and increase in the absorption of radio waves. The DLPT depth which depends on the amplitude of VLF waves at the time of night to day transition, increases due to decrease in amplitude of these waves.

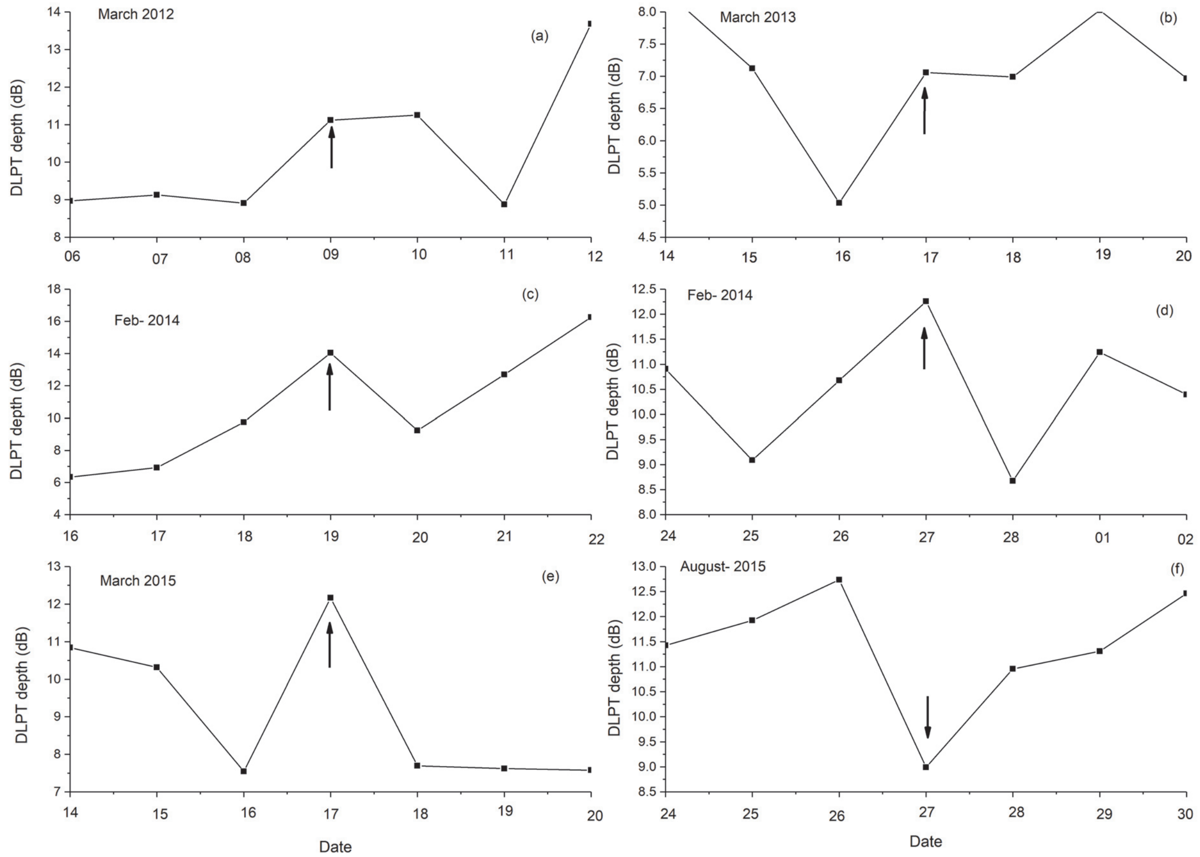

Figure 1. Variation of DLPT depth for the six geomagnetic storms (the arrows indicate the day of minimum Dst).

The day time D-region electron densities are mainly controlled by the photoionization. The day time amplitude parameter, MDP evaluated for seven days (including pre and post storm days) for the six events is shown in Figure 2. No sharp dip in the MDP is observed on storm day for all the events except for August 27, 2015 event. The MDP was low on August 27, 2015 and decreased on subsequent days. There have been reports of reduction in day time VLF amplitude during geomagnetic storms. Kumar et al. [2015] observed reduction in day time signal amplitudes of VLF waves transmitted from NWC – Harold E. Holt, North West Cape, Exmouth, Australia and NPM – Pearl Harbour, Lualuahei, Hawaii, and received at Suva, Fiji on the storm day when compared to quiet days. Analysing the diurnal amplitude of the VLF signal transmitted from GQD (UK) at 22.1 kHz, ICV (Italy) at 20.27 kHz and DHO (Germany) at 23.4 kHz received at A118 SID monitoring station at South France, Nwankwo et al. [2016] reported dip in MDP within 1-2 days of geomagnetic storm. But in the present study, both the parameters (MDP and DLPT) are behaving differently for August 27, 2015 event from the other events as disturbed conditions with indices A_p> 40 and Dst< -40 nT and the interplanetary magnetic field component B_z< 0 prevailed on the days from August 26 to August 28, 2015. The study revealed that the D-region is responding in a different way when the disturbed condition prevailed for 3 to 4 days. Lastovicka [1996] mentioned that northward B_z for several days after the storm is not favourable for development of post storm effects in mid latitude lower ionosphere. The enhanced X- ray flux emitted during a flare results in extra ionization at D-region altitudes and causes signatures in amplitude and phase of VLF waves during the daytime. Day time VLF amplitude is sensitive to X-ray flares and these signatures affect the parameter MDP. A M-Flare (of intensity 6.3) on March 9, 2012 and a C-flare (of intensity 6.8) on February 27, 2014 could be responsible for higher values of MDP on those days.

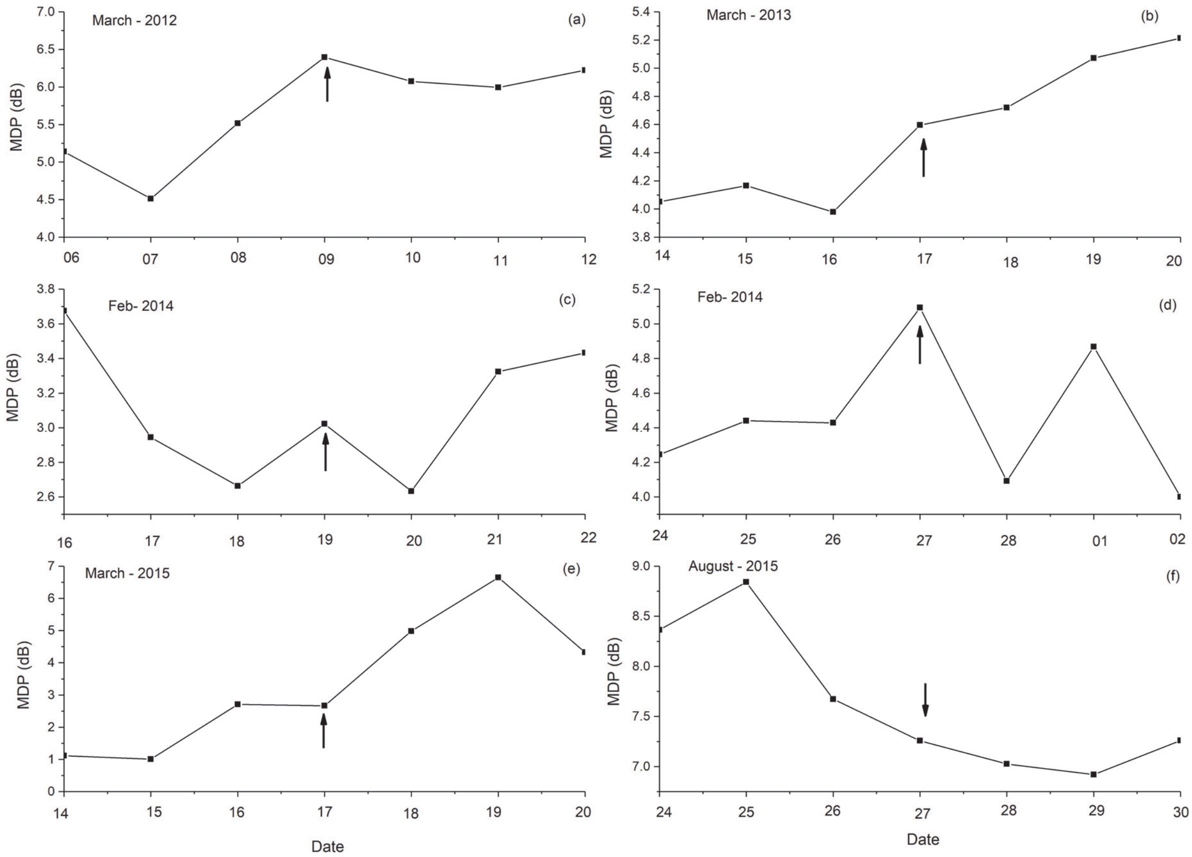

Figure 2. Variation of MDP for the six geomagnetic storms (the arrows indicate the day of minimum Dst).

There exists minima during sunrise or sunset times in the diurnal variation of VLF amplitude. The generation mechanism for such minima is mainly the mode conversion at the sunrise/sunset terminator [Maekawa and Hayakawa, 2006]. From the full wave computation, Soloviev et al. [2004] concluded that any perturbation in the lower ionosphere results in significant change in the Terminator Time of the VLF propagation. The study of shift in Terminator Time known as TT method is applicable to East-West Propagation path. This method is useful in monitoring the lower ionospheric condition even for North South short paths [Maekawa and Hayakawa, 2006]. In the present study, the TT method is applied to the VLF path between GQD and South France station, being a North-South short path. The sunrise terminator timings for the corresponding months are shown in Figure 3 for all the events. A remarkable shift in the sunrise terminator time is observed for four events i.e March 9, 2012; February 19, 2014; February 27, 2014 and March 17, 2015 and no change is observed for the two events i.e March 17. 2013 and August 27, 2015. There are reports of shift in Terminator Time before seismic events which occurred near the Great

Circle Path [Ray and Chakrabarti, 2013; Sasmal et al., 2014; Latha et al., 2014]. No seismic events were reported near the propagation path during the period of study for all the events. The shift in morning terminator time is present when the Sudden Commencement (SC) occurred during day time on previous day. The morning Terminator Time is not deviating from the quiet time value when the SC occurred during sun rise period or pre sun rise period as in the case of other two events.

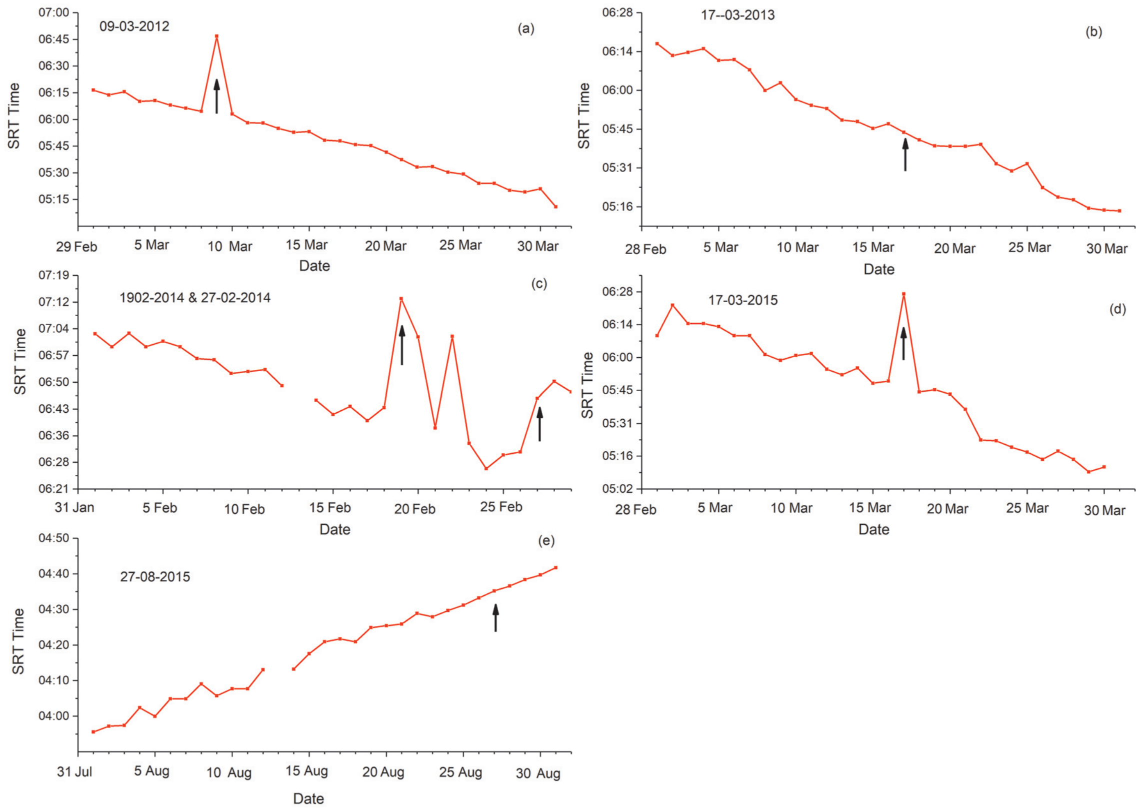

Figure 3. Monthly variation of Sunrise Terminator Times for the six geomagnetic storms (the arrows indicate the day of minimum Dst).

In the lower ionosphere mainly D-region, the electron concentration is considerably enhanced in the auroral zone during a geomagnetic storm [Lastovicka, 1996]. Danilov and Lastovicka [2001] opined that a delayed post storm effect at mid latitudes is due to the loss of energetic electrons from the trapped regions. Dickinson and Bennett [1978] reported enhancement of electron densities in the early morning at South Uist, Scotland on post storm days of the geomagnetic storm on April 1, 1973. The enhanced electron density during the morning hours lowers the reflection height indicating the lowering of D-region. The observed shift in morning Terminator Time towards daytime (Figure 3) indicates that the night to day transition is being delayed. The storm induced enhancement in electron densities causes this delay in terminator occurrence. From the theoretical model calculations, Spjeldvik and Thorne [1975] found that the loss of precipitated electrons during the recovery phase of the storm results in enhanced D-region ionization at the mid-latitudes. The Morning Terminator Time varies continuously following the variation in local sun rise time and season [Maekawa and Hayakawa, 2006]. The decreasing or increasing trend in Terminator Time variation (Figure 3) is due to this effect. No deviations in the evening Terminator Time are observed during the days of these events.

During the geomagnetic storms, the critical frequency of F_2-region (f_oF_2), undergoes positive and negative change from the quiet time values. For studying the response of the F_2-region to the geomagnetic storms, the authors have selected three events of February 08, 2012, March 17, 2013 and March 17, 2015. The Df_oF_2 parameter evaluated using f_oF_2 observed at Dourbes, Belgium has been plotted for three days of the storm period for these events in Figure 4 (a, b and c).

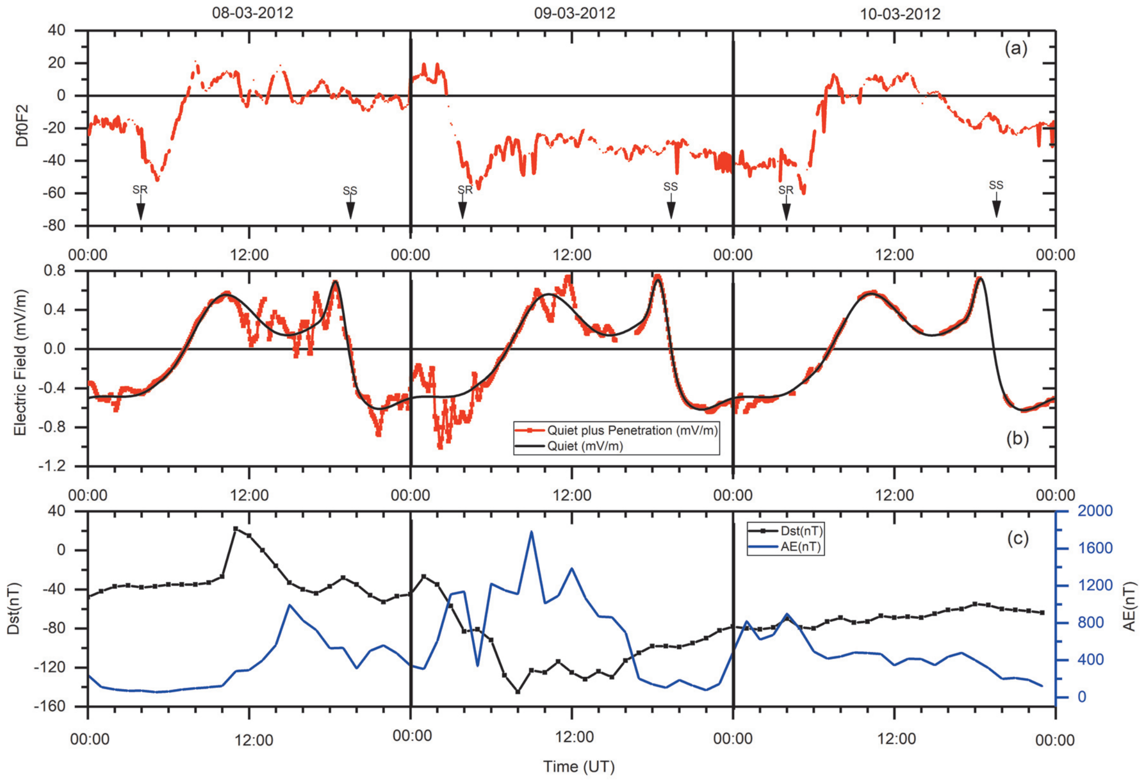

Figure 4 (a). Variation of the $D_f o_F 2$ (upper panel), PPEF (middle panel) and Dst & AE index (lower panel) for the period from March 8, 2012 to March 10, 2012.

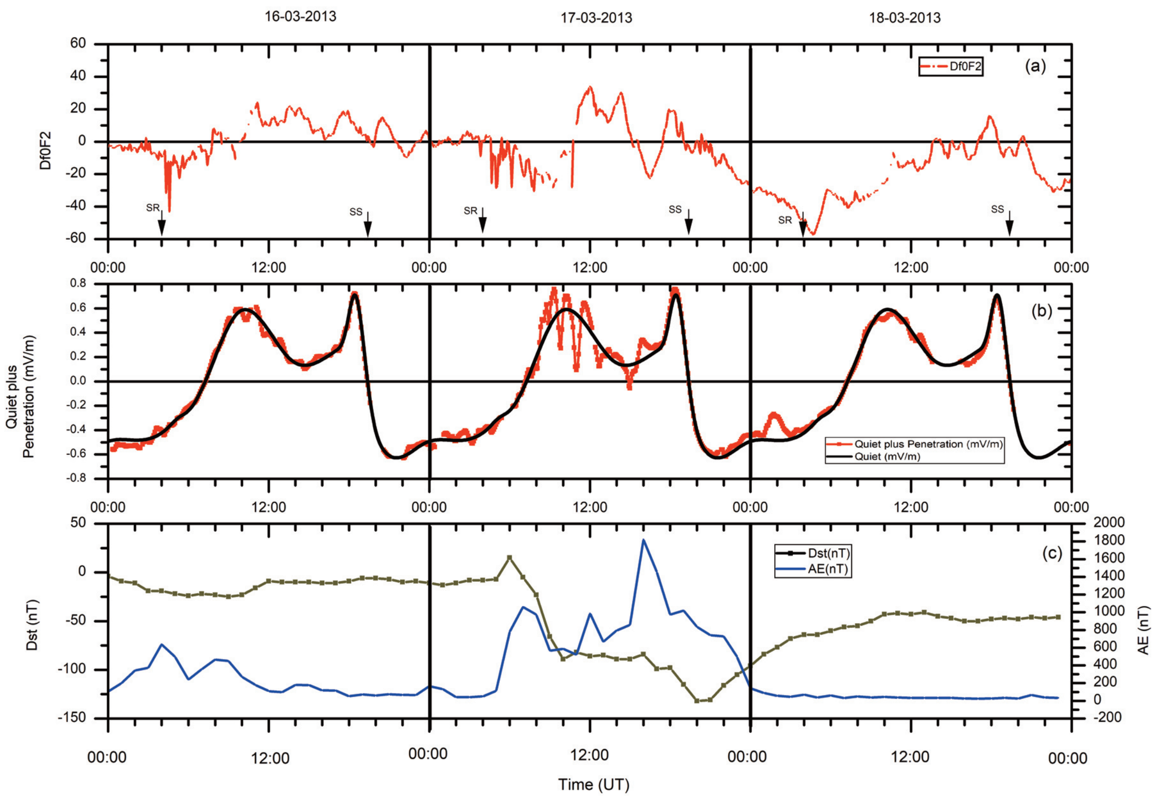

Figure 4 (b). Same as FIGURE 4a for the period from March 16, 2013 to March 18, 2013.

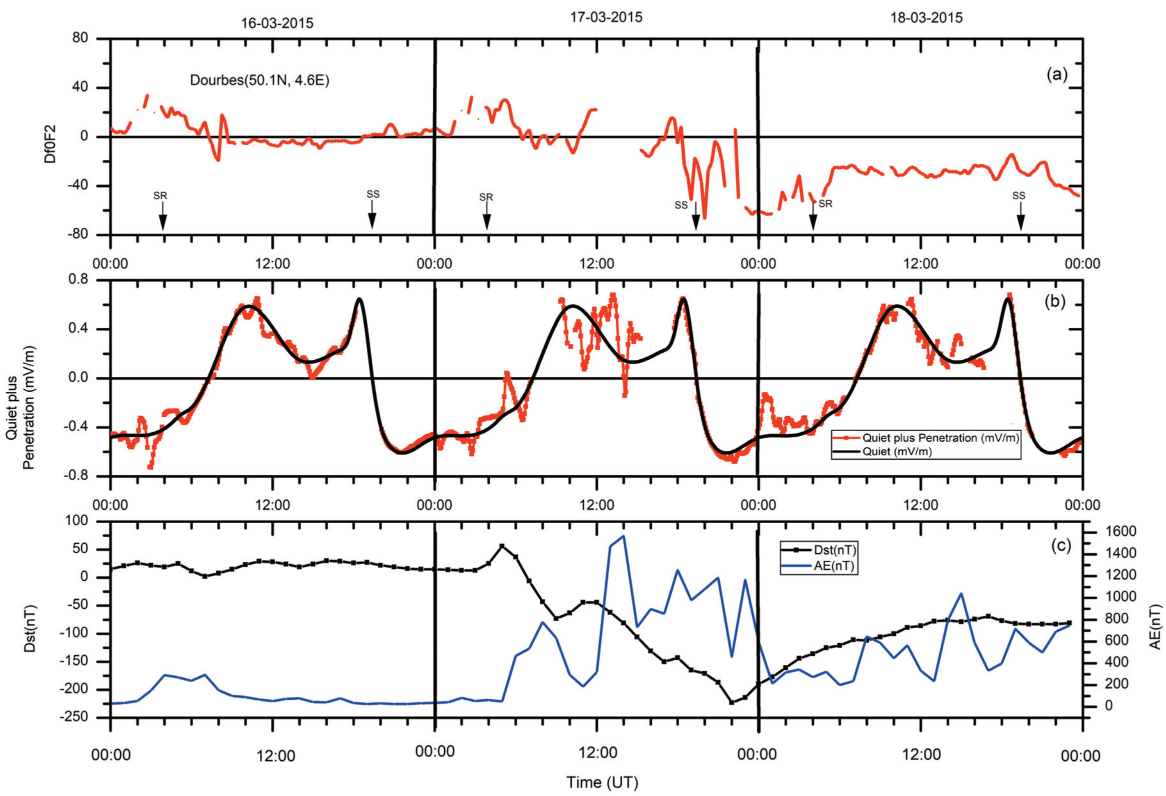

Figure 4 (c). Same as FIGURE 4a for the period from March 16, 2015 to March 18, 2015.

The variation of Df_oF_2, Prompt Penetration Electric Field (PPEF), Dst and AE during the period March 8-10, 2012 are shown in Figure 4a. The PPEF is evaluated for the longitude(4.6^0 E) of Dourbes, using the model available on the website http://geomag.org/models/PPEFM/RealtimeEF.html . The Sudden Commencement (SC) of the storm occurred at 1100 UT on March 8, 2012. The Dst variation showed multiple minima during the next 20 hours and reached a minimum of -145 nT at 0800 UT on March 9, 2012. During the period from the SC to 0300 UT on March 9, 2012, Df_oF_2 (~20%) exhibits wave like positive storm effect. The sudden energy input into polar atmosphere during a geomagnetic storm launches Travelling Atmospheric Disturbance (TAD) which propagates towards equator [Blagoveshchensky et al., 2003]. The daytime eastward electric field combined with the penetration field along the magnetic field lines can result in upward movement of plasma where the recombination is less. This results in positive storm effect at mid latitudes. During the main phase of the strong magnetic storm on March 13, 1989, Mansilla [2004] observed positive variation of N_mF_2 at mid latitude stations where the sudden commencement is during local daytime. From the Millstone Hill (42.6^0 N, 288.5^0 E) Incoherent Scattered Radar measurements on April 3, 2004, Huang et al. [2005] observed strong positive storm phase in the variation of F-region electron density after the sudden commencement of storm at 1412 UT on the same day. They explained that the daytime eastward electric field lifts the plasma to higher altitudes where the recombination is less resulting in increase of electron concentration. From the study of global TEC maps and radio occultation data, Habarulema et al. [2015] concluded that positive storm phase observed at southern hemisphere mid latitude during the March 8-10, 2012 magnetic storm is due to expansion of equatorial Ionospheric Anomaly to mid latitudes. The positive storm effect observed in Df_oF_2 after SC can be due to combined effect of TADs and PPEF.

The negative storm effect is prominent from 0300 UT on March 9, 2012 to 0600 UT on March 10, 2012. During this period, strong and long-lasting negative phase of (~50%) Df_oF_2 is observed. Mansilla [2004] explained that the long-lasting negative storm effects are due to storm induced thermospheric winds with reduced $[O]/[N_2]$ ratio. The AE index reached maximum value of 1800 nT at 0900 UT on March 9, 2012 indicating the strong auroral electrojet during the local daytime of Dourbes. The GUVI Maps on March 9, 2012 shown in Figure 5(a) shows depleted $[O]/[N_2]$ ratios at mid latitudes in the European sector where Dourbes is situated. In his review on response of F-region to

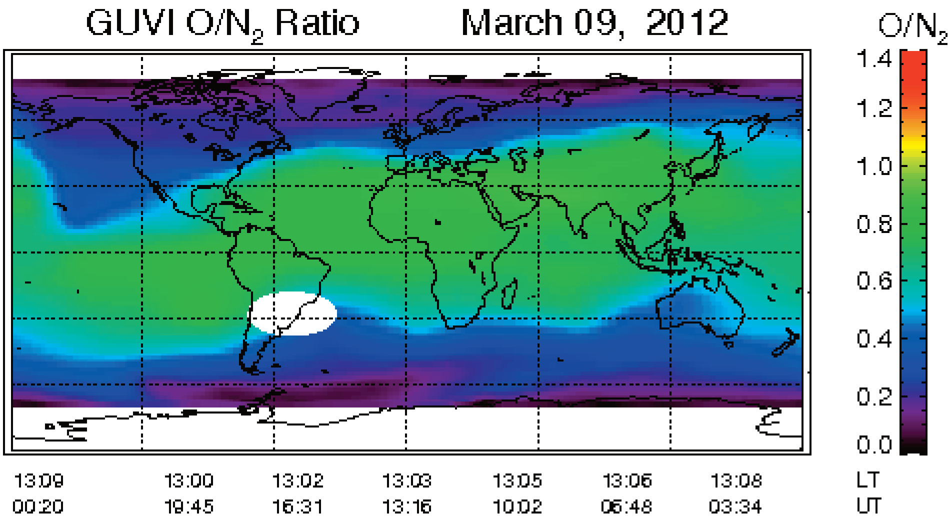

Figure 5 (a). GUVI map showing [O]/[N_2] ratio on March 9, 2012.

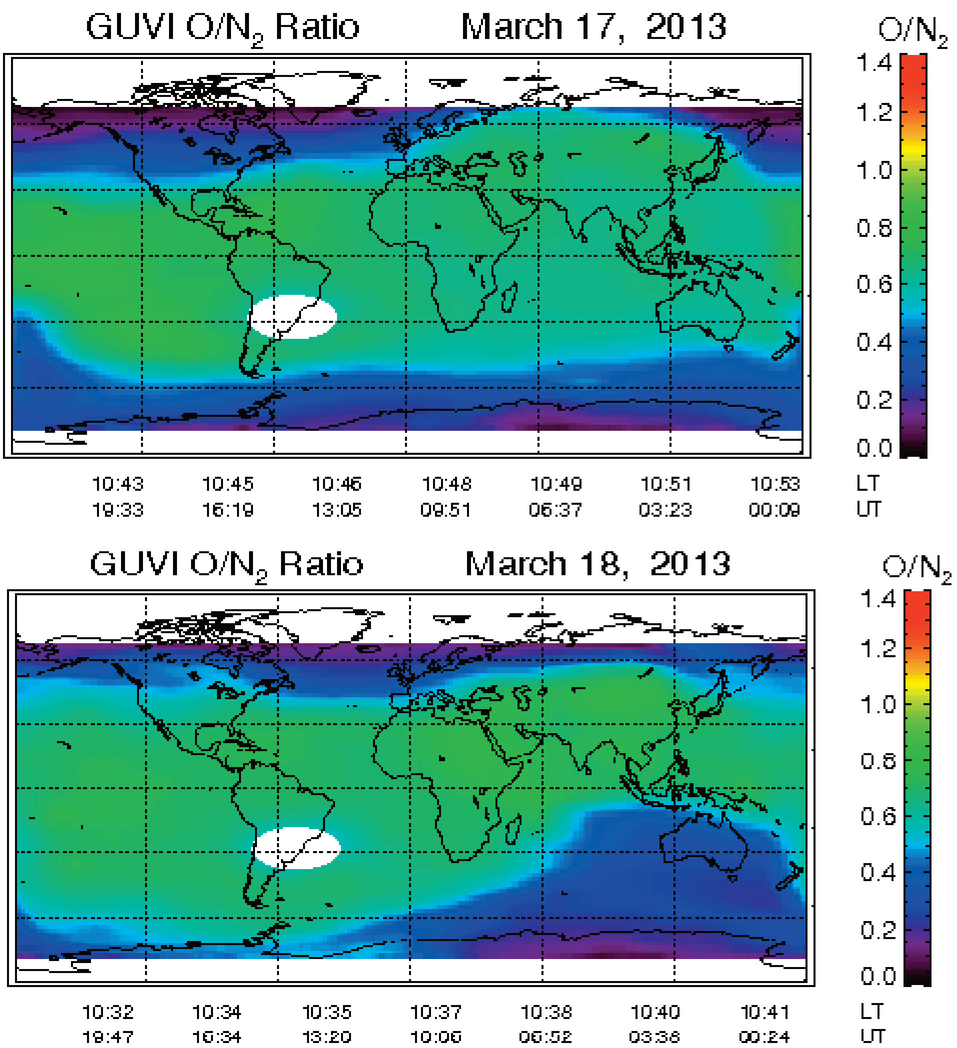

Figure 5 (b). GUVI map showing [O]/[N_2] ratio on March 17, 2013 (upper panel) and March 18, 2013 (lower panel).

geomagnetic storms, Danilov [2013] suggested that long lasting negative storm effect can be due to the storm time equatorward disturbance meridional winds. The decrease of [O]/[N_2] ratio produces the negative storm effect at mid latitudes. Mansilla [2007] observed that the strong and long-lasting negative storm effect in summer hemisphere is due to depleted [O]/[N_2] ratio. On March 10, 2012, the Df_oF_2 turned positive during the period from 0600 to 1400 UT beyond which the parameter recorded negative values. The storm induced electric fields and Joule heating at high latitudes create Disturbance Dynamo Electric Fields (DDEF) which map to mid and low latitudes [Huang, 2013]. The DDEF exhibits delayed effects at mid and low latitudes which can last for more than a day after SC [Richmond et al., 2003]. These fields are westward during the day and eastward during the night at equatorial latitudes [Scherliess and Fejer, 1997]. DDEF can be the cause for weak positive and negative storm effects during the period starting from 0600 UT on March 10, 2012. The storm induced thermospheric winds which are not rich in [O_2] can be the cause for the weak negative storm effect observed beyond 1400 UT of the same day.

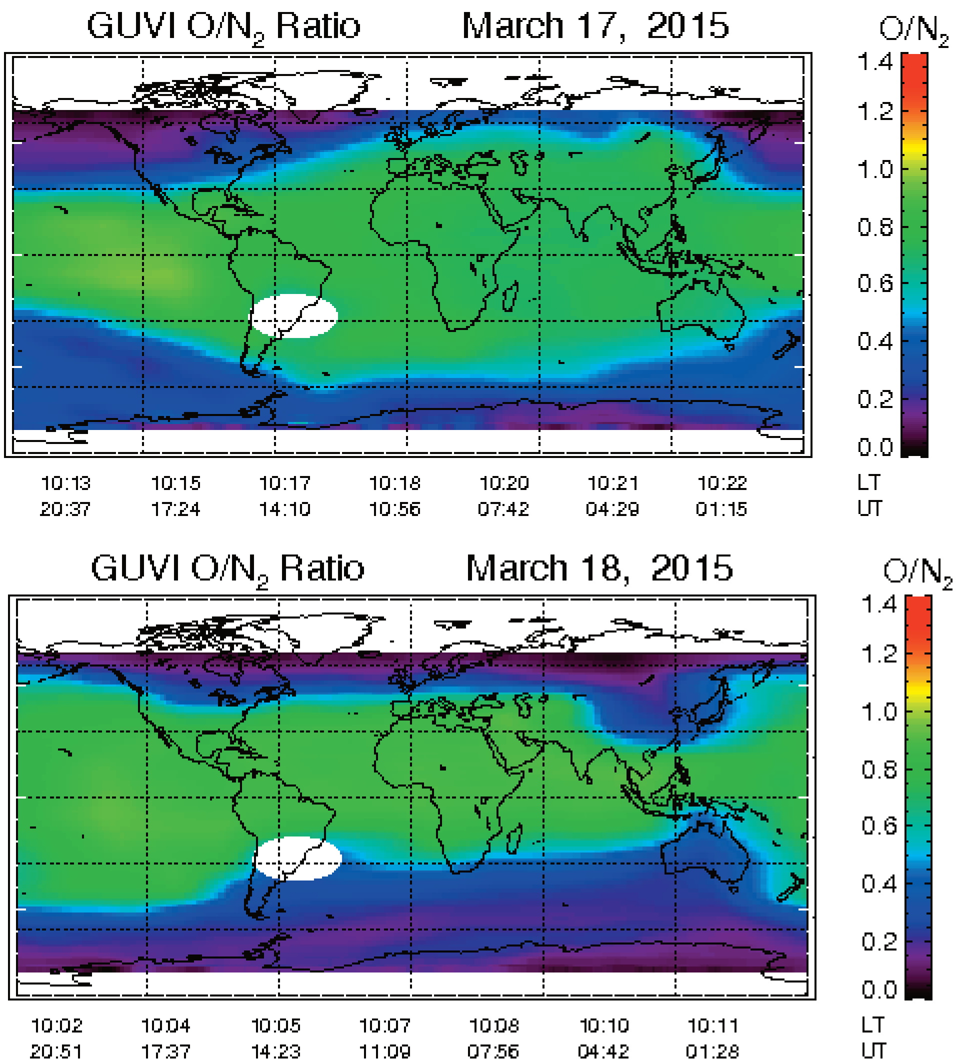

Figure 5 (c). GUVI map showing [O]/[N_2] ratio on March 17, 2015 (upper panel) and March 18, 2015 (lower panel).

The variation of Df_oF_2, PPEF, Dst and AE during the period of March 16, 2013 to March 18, 2013 are shown in Figure 4b. The SC of the storm is at 0600 UT on March 17, 2013. After the SC, AE index reached 1060 nT at 0700 UT which can give rise to disturbance winds. These result in negative storm effect at mid latitudes. The negative storm effect observed after SC up to 1040 UT on March 17, 2013 can be due to the disturbance winds. The eastward PPEF (middle panel of Figure 4b) during day time can lift the plasma to higher altitudes where the recombination rate is less [Wang et al., 2010]. This results in positive storm effect which is evident in Df_oF_2 variation during midday hours. The penetration field reduced during the afternoon hours resulting in negative Df_oF_2. From the model calculations, Huang [2013] found that during equinox conditions, the equatorward and westward disturbed winds present at high latitudes produce disturbance dynamo electric fields (DDEF). Disturbance Dynamo Electric fields can be responsible for the positive Df_oF_2 observed just after sunset time (1650 UT) on March 17, 2013. The GUVI map (upper panel of Figure 5b) on this day shows depleted [O]/[N_2] ratios in the European sector. The AE index of 1822 nT can result in the negative Df_oF_2 observed around 1600 UT. On March 18, 2013, the [O]/[N_2] ratio is depleted to a large extent as evident from the GUVI map presented in Figure 5b (lower panel). The disturbed winds during the geomagnetic storm are equatorward and the depleted [O]/[N_2] ratio results in reduction of electron density which leads to negative Df_oF_2 on March 18, 2013.

For the third magnetic storm under consideration, the variation of Df_oF_2 for the period of March 16, 2015 to March 18, 2015 along with PPEF, Dst and AE indices is shown in Figure 4(c). The SC occurred at 0500 UT on March 17, 2015. Eastward penetration electric field was set up and the positive Df_oF_2 observed during the onset time can be due to the upward drift of plasma. The strong eastward penetration field varying rapidly can result in the positive Df_oF_2 observed beyond 1000 UT on this day. The GUVI map on March 17, 2015 [upper panel, Figure 5(c)] shows depleted ratios of [O]/[N_2] at Dourbes. The high AE index of 1600 nT can cause Joule heating at auroral latitudes triggering disturbance winds [Mazaudier et al., 1987]. The disturbance winds from the auroral latitudes are equatorward and can result in negative Df_oF_2 at the mid latitudes [Danilov, 2013]. The [O]/[N_2] ratio is more depleted on March 18, 2015 (lower panel, Figure 5c) which results in negative storm effect. The long-lasting negative phase in Df_oF_2 observed on March 18, 2015 is due to the effect of these disturbance winds. The AE index is high on this day reaching 1100 nT indicating disturbed conditions.

The three geomagnetic storms considered in the foregoing analysis occurred during the month of March. There is similar behaviour between the March 2012 and March 2015 storms. During the beginning of main phase, the Df_oF_2 is positive and during the recovery phase, strong long-lasting negative Df_oF_2 is recorded. But for the March 2013 storm, negative and positive Df_oF_2 are observed during main phase and during the recovery phase, the negative storm effect is not so strong. For all the three storms, B_z is maintained southward for a period of 16 hours.

4. Conclusions

The response of mid latitude D and F_2 regions to intense geomagnetic storms which occurred during equinox months of 2012-2015 has been studied using the VLF amplitude data of Skelton (GQD) U.K -South France SID station path and f_oF_2 data at Dourbes. The results of the study are summarized below.

1. The DLPT depth evaluated using the VLF amplitude of 22.1 kHz waves propagating over the path of GQD (UK) and South France station showed an increase on the storm day (Dst minimum). This can be due to the reduction in the reflection height of VLF waves caused by the enhanced electron densities during the geomagnetic storm. But a dip in the parameter is observed for the event of August 27, 2015 for which the disturbed conditions prevailed for a period of 3 days from August 26, 2015 to August 28, 2015.
2. The Mid Day Peak (MDP) in VLF amplitude recorded a dip on storm minimum day for August 27, 2015 event and an enhancement on storm day for the remaining events. The day time amplitude of VLF waves normally increases when a solar flare occurs which results in the enhancement in the MDP.
3. A remarkable shift in the sunrise Terminator Time is observed for geomagnetic storms whose sudden commencement occurred during the local day time hours on the previous day. This is due to the precipitating high energy electrons causing enhanced D-region ionization at mid-latitudes.
4. The day time positive storm effects observed in Df_oF_2 at mid latitude station Dourbes are due to the PPEF. The long-lasting strong negative phase observed in Df_oF_2 is due to the disturbance equatorward winds. These winds transport air with depleted [O]/[N_2] ratios to mid latitudes causing reduction in the electron density. This results in negative variation of Df_oF_2.

Acknowledgements. The authors wish to express their sincere thanks to the following websites for making the data available on internet. https://sidstation.loudet.org/data-en.xhtml, http://ulcar.uml.edu/DIDBase/, http://wdc.kugi.kyoto-u.ac.jp/wdc/Sec3.html, http://geomag.org/models/PPEFM/RealtimeEF.html, http://guvitimed.jhuapl.edu/data_products, https://omniweb.gsfc.nasa.gov/form/dx1.html. One of the authors, Mr. P. Peddi Naidu gratefully acknowledges the University Grants Commission, New Delhi, India for the financial assistance through the award of Senior Research Fellowship under the scheme 'Basic Science Research Fellowship for Meritorious Students'.

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