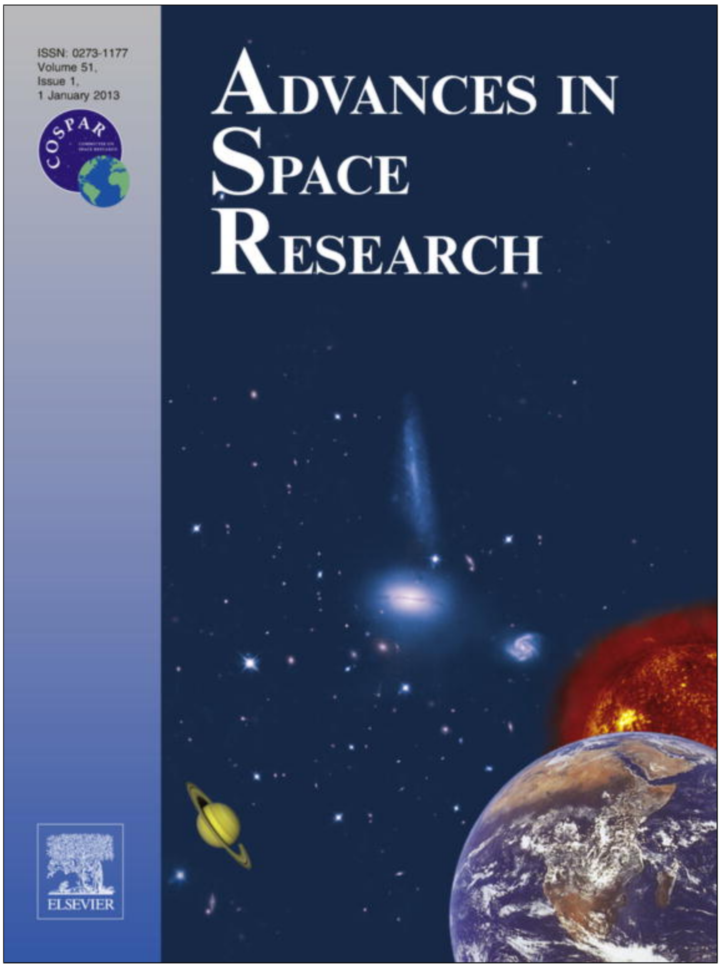
ISSN: 0273-1177
Volume 51,
Issue 1,
1 January 2013
COSPAR
ADVANCES IN
SPACE
RESEARCH
ELSEVIER

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Advances in Space Research 51 (2013) 50–60

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Ionospheric response to the 3 August 2010 geomagnetic storm at mid and mid-high latitudes

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Received 7 June 2012; received in revised form 30 August 2012; accepted 4 September 2012
Available online 12 September 2012

Abstract

The global ionospheric response to the geomagnetic storm occurred of 3 August 2010 is studied in terms of the ionospheric parameter foF2. Data from three longitudinal sectors (Asia/Pacific, Europe/Africa and America) are considered. Some new aspects of the storm time ionospheric behavior are revealed. Results of the analysis show that the main ionospheric effects of the storm under consideration are: (a) prior to the storm, Japanese, Australian and American stations show increases in foF2, irrespective of the local time. (b) During the main phase, the stations of mid latitudes of the American sector show positive disturbances (in the pre-dusk hours), which subsequently change to negative. (c) During the recovery phase of the magnetic storm long-duration positive disturbances are observed at mid-low latitudes of the African chain. Also positive disturbances are observed in the Australian sector. In the European sector long-duration negative disturbances are seen at mid-high latitudes during the last part of the recovery phase while at mid-low latitudes a positive disturbance is seen, followed by a negative disturbance. In general, the ionospheric storm effects show a clear hemispheric asymmetry.

Keywords: Geomagnetic storm; Ionosphere; foF2 critical frequency

1. Introduction

The F2-region response to a geomagnetic storm is known as ionospheric storm. Ionospheric storms represent very large disturbances in the F region electron density. The characteristics of ionospheric storms have been examined in terms of deviations of the F-region critical frequency (foF2) from the median value for the same time of day and changes in the height of the F-region h′F (minimum virtual height) and/or hmF2 (height of the F-peak) (Uma et al., 2012). Basically, ionospheric F-region disturbances are increases or decreases of foF2 (proportional to the square root of the maximum electron density NmF2) from median or quiet time values. At middle latitudes, the ionospheric storms present an initial "positive" phase in which the electron density is greater than normal (median) values and a "negative" phase when the above mentioned quantity is reduced below their normal pre-event values (e.g., Buonsanto, 1999; Prölss, 1995; Förster and Jakowsky, 2000; Danilov, 2001; Mendillo, 2006; Burns et al., 2007 and references therein for a review on these phenomena). The negative storms occur predominantly during night-time hours while the positive ones at daytime hours (Prölss, 1993). From 1950s, there are more than 800 publications on the ionospheric storm study, but do to the

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http://dx.doi.org/10.1016/j.asr.2012.09.001

complexity of ionospheric storms many aspects of their underlying physical processes are still far from being fully understood. The ionospheric response to a particular geomagnetic storm varies significantly with latitude, season, local time, etc.

Penetration of the high-latitude electric field generated into the mid, low and equatorial ionosphere, electric fields generated by the disturbance dynamo mechanism, traveling atmospheric disturbances (TADs) that can travel to low and equatorial latitudes even into the opposite hemisphere which can transport ionized particles from high latitudes to middle, low and equatorial latitudes with increased temperature and [N_2] density leading to a decrease in the [O]/[N_2] ratio have been suggested as some possible physical mechanisms to explain the ionospheric response to geomagnetic storms observed at different latitudes (see e.g., Uma et al., 2012 and references therein).

This paper describes the behavior of the foF2 ionospheric parameter in three longitude sectors around the globe during the storm period 2–5 August 2010. The mechanisms involved are also discussed in this study. The geomagnetic storm started on 3 August at about 19 UT. This geomagnetic storm occurred after several days of relatively quiet magnetic activity which is a favorable condition to observe clearly the ionospheric disturbances caused by the storm. This paper can be considered as a follow up of a previously published paper (Mansilla, 2011), but for middle and moderately high latitudes.

Table 1
The stations used in this study.

	Geog. Lat	Geog. Lon	Geom. Lat
Asia/Pacific			
Wakkanai	45.4	141.7E	35.3
Beijing	40	116.3E	28.8
Kokubunji	35.7	139.5E	25.5
Yamagawa	31.2	130.6E	20.3
Darwin	−12.4	130.9E	−22.9
Townsville	−19.3	146.7E	−28.5
Norfolk	−29	168.0E	−34.7
Brisbane	−27.5	152.9E	−35.7
Camden	−34	150.7E	−42
Canberra	−35.3	149.0E	−44
Hobart	−42.9	147.2E	−51.7
Europe/Africa			
Juliusruh/Ruegen	54.6	13.3E	54.5
Dourbes	50.1	4.6E	51.7
Pruhonice	50	14.6E	49.9
Rome	41.8	12.5E	42.4
El Arenosillo	37.1	6.7W	41.4
Madimbo	−22.4	30.9E	−24.3
Louisvalle	−28.5	21.2E	−28.4
Hermanus	−34.4	19.2E	−33.4
Grahamstown	−33.3	26.5E	−33.7
America			
Qaannaaq	77.5	290.8E	88.8
Sondrestrom	67	310.0E	77.1
Gakona	62.4	214.8E	63.4
Millstone Hill	42.6	288.5E	53.9
Wallops Is	37.9	286.5E	49.3
Boulder	40	254.6E	48.8

The longitudinal zones considered are: Asia/Pacific, Europe/Africa and America. Such a division is convenient for the investigation of the global positive and negative ionospheric storm effects characteristics (longitudinal dependence).

The ground-based hourly foF2 data were provided by the Space Physics Interactive Data Resource (SPIDR) of NOAA (http://spidr.ngdc.noaa.gov/spidr/index.html). Data of SPIDR for h´F were also available. We do not use h´F because this parameter is rather inaccurate during the storm and in summer because of blackout of strong Es or effect of spread-F or absorption. The station names and their geographic and geomagnetic latitudes and longitudes are provided in Table 1. During this disturbed storm period some ionospheric stations present gap in the data. The geomagnetic index Dst was chosen as diagnostic tool of geomagnetic activity. Hourly values of that index were obtained from the World Data Center at the University of Kyoto database: http://swdc.kugi.kyoto-u.ac.jp/dstdir.

2. Observational results

As an index of ionospheric disturbance, the relative deviation of critical frequencies from the quiet level at each station was calculated as follows:

$$\mathrm{DfoF2} = [(\mathrm{foF2} - \mathrm{foF2(q)})/\mathrm{foF2(q)}] \times 100$$

where foF2 is the hourly perturbed critical frequency and foF2(q) represents the reference level (average value of five quiet days of the month: August 01: $\Sigma kp = 7+$, $Ap = 4$; August 02: $\Sigma kp = 11+$, $Ap = 5$; August 07: $\Sigma kp = 7$, $Ap = 4$; August 08: $\Sigma kp = 6$, $Ap = 3$ and August 14: $\Sigma kp = 5$, $Ap = 3$). Positive and negative DfoF2 values correspond to positive and negative ionospheric storm effects.

One of the largest geomagnetic storms during 2010 occurred on 3 August. Fig. 1 shows a summary of the geomagnetic and solar wind conditions for the period 30 July to 10 August 2010. The present storm was characterized by a storm sudden commencement (SSC) at about 19 UT on 3 August, which is indicated by the vertical dotted line (top panel). The index Dst sharply decreased reaching a minimum value of approximately −67 nT at about 23 UT on the storm day (weak storm), after which an irregular recovery started. In the middle panel, the solar wind speed showed an increase up to values of about 600 km/s nearly coincident with the SSC. In the bottom panel, the solar wind density showed values larger than 14 cm^{-3} on 4 August for a short time.

Fig. 2 shows the temporal variation of DfoF2, in percentage, for the Asia/Pacific stations during the period 2–5 August 2010 (the vertical dotted line corresponds to the SSC). For this sector, the storm started in the pre-dawn hours. It can be seen that the Northern Hemisphere stations (Japanese sector) Wakkananai, Kokubunji and Yamagawa present increased DfoF2 values prior to the storm onset. No significant storm effects are observed at these stations, neither following the time of the SSC nor

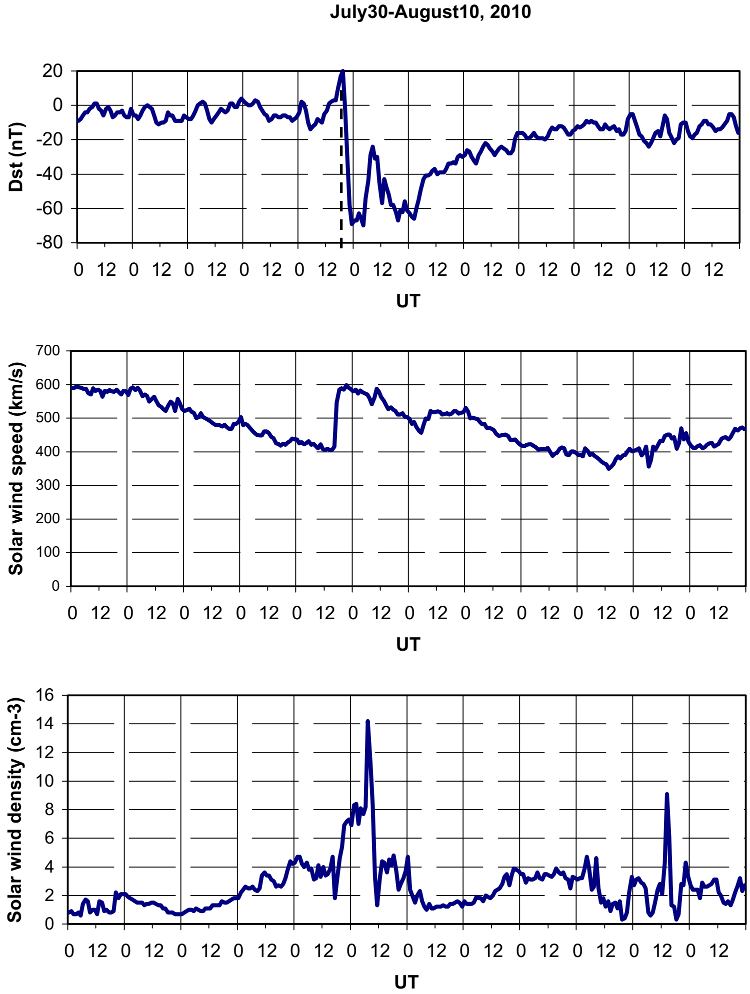

Fig. 1. Dst geomagnetic index for the period 30 July–10 August 2010 (top); solar wind speed (middle); and solar wind density (bottom). In the top panel, the vertical dotted line indicates the SSC.

during the main phase of the storm. During the first part of the recovery phase (in the afternoon and dusk hours) irregular positive ionospheric storm effects are observed over Wakkanai, Beijing and Kokubunji. The sparse data at Yamagawa present an oscillating behavior during this stage of the storm.

Fig. 3 presents the variations of DfoF2 in the South Pacific sector (Australian longitudes). The stations Hobart, Camden and Canberra also present increased DfoF2 values prior to the storm commencement. At Canberra and Candem positive storm effects are observed in response to the storm (during the main phase), which increase their amplitude since the first stage of the recovery. The sparse data from Brisbane, Norfolk and Townsville are also positive on 4 August during the recovery phase (in daytime hours). The trend of available data indicates that these effects seem to have longer duration at lower latitudes. It can be noticed perceptible decreases in foF2 at Hobart and Canberra (∼30–40% change) on 5 August.

Fig. 4 presents the relative deviations DfoF2 at stations of the European sector. For this sector, the storm started in the pre-dusk hours. Short duration negative storm effects are initially observed at Juliusruh, Dourbes and Pruhonice and later at Rome during the first stage of the recovery phase, which occur slightly delayed with decreasing latitude; these effects are followed by periods with foF2 values close to the reference values and later by long duration negative disturbances with greater amplitude than before (∼40–50% change). El Arenosillo presents a positive effect during the first part of the recovery phase (mainly from past noon to midnight), followed by a delayed negative effect on 5 August (∼25–30% change).

Fig. 5 presents the plots of the relative deviations DfoF2 for the African stations. Over the stations Grahamstown, Hermanus and Madimbo small positive storm effects are observed during the storm main phase which are followed by values close to the reference till about 06–07 UT, when started irregular long duration positive effects over all the stations of the sector (∼50–60% maximum change).

Fig. 6 shows the temporal variation of DfoF2 values for the American sector. In this sector, the SSC occurred in daytime hours. It can be observed over Qaannaaq an increase in DfoF2 prior to the storm onset, between about 19 UT on 2 August and 00 UT on 3 August, and also over

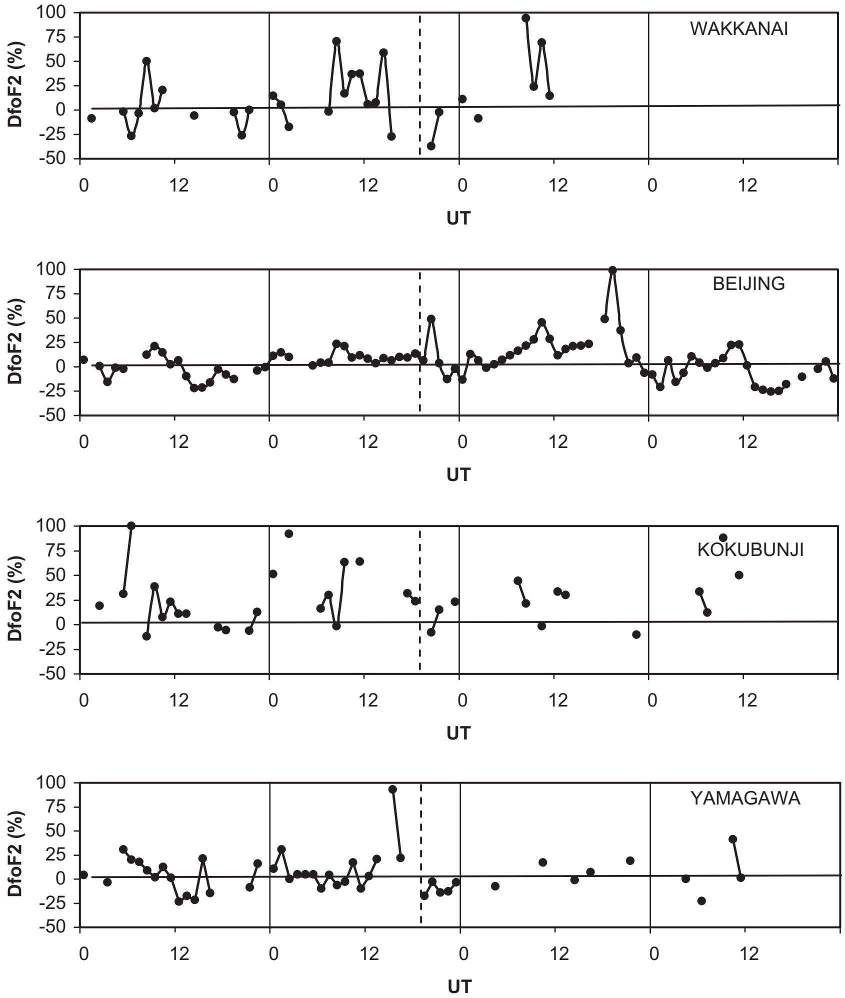

Fig. 2. Time variation of DfoF2, in percentage, at stations of the Asia/Pacific sector during the storm period 2–5 August 2010. The storm sudden commencement is indicated by the vertical dotted line.

Sondrestrom between about 02 and 09 UT on August 3. Qaannaaq, Gakona, Millstone Hill, Wallop Islands and Boulder show short-duration positive storm effects during the main phase (~50% change). These effects change to negative at Qaannaaq, Millstone Hill and Wallops Is since the first part of the recovery phase, or remain predominantly positive at the lower latitude station (Boulder). At Gakona the data gap prevents from determining the ionospheric behavior, however some negative values are observed on August 5 during the recovery phase.

To determine what are the similarities and differences of the storm effects over the Northern and Southern hemispheres simultaneously, we compare the relative deviations observed in both hemispheres at some crucial hours during the different stages of the storm. It is convenient to use the modified magnetic dip X instead of geographic or geomagnetic latitude, because it better organizes solar and geomagnetic effects.

Fig. 7 presents the relative deviation DfoF2 vs. the modified magnetic dip in the Asia-South Pacific sector for several hours after the storm onset: SSC + 5 h (00 UT on 4 August, main of the main phase), SSC + 12 h (07 UT on 4 August, first part of the recovery), SSC + 17 h (12 UT on 4 August, recovery phase) and SSC + 24 h (19 UT on 4 August, recovery phase). During the end of the main phase it can be seen a significant hemispheric asymmetry because the majority of Southern Hemisphere stations present positive ionospheric storms effects, while the Northern Hemisphere stations show positive and negative disturbances, these positive disturbances being observed at the higher modified magnetic dip angles. During the first part of the recovery a hemispheric symmetry is observed, because positive ionospheric storm effects with similar amplitude are presented in both hemispheres. The opposite of the initial situation is seen after 24 h of the storm commencement: decreases of DfoF2 in the Southern Hemisphere and increases in the Northern hemisphere, indicative that different physical processes are acting during this stage of the storm.

Fig. 8 is similar to Fig. 7 but corresponds to the European-South African sector. During the end of the main phase, in this longitudinal sector, a hemispheric asymmetry

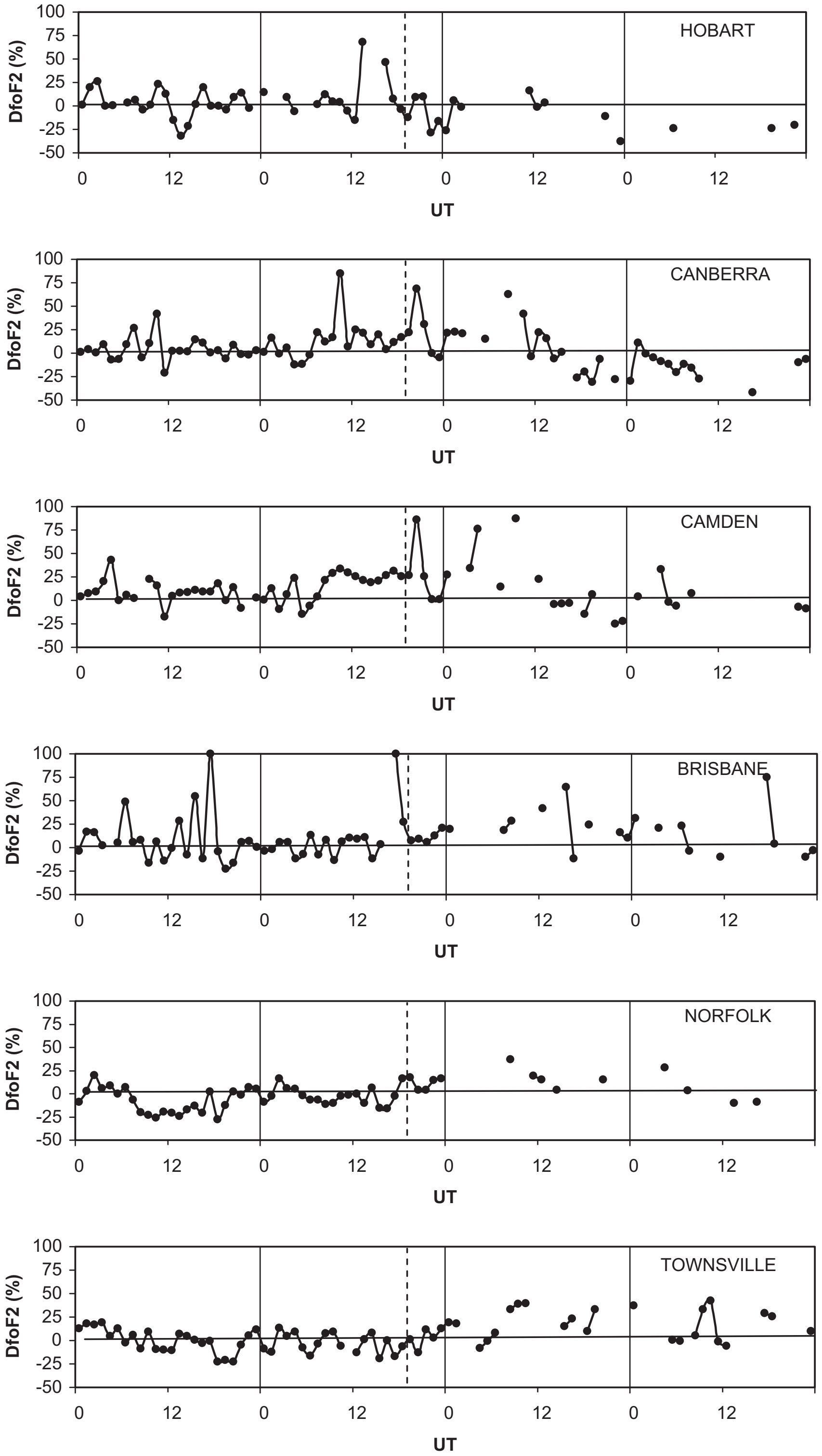

Fig. 3. Same as Fig. 2 but for the South Pacific sector.

is also observed. This is similar to the one observed in the Asia-South Pacific sector, with the Southern Hemisphere stations showing positive effects, and positive and negative effects at the Northern Hemisphere stations. By contrast to the Asia-Pacific sector, the hemispheric asymmetry remains during the recovery phase, with positive effects in the Southern Hemisphere and negative ones in the Northern Hemisphere, which suggests that different physical mechanisms are acting for controlling the morphology of the ionosphere during the storm.

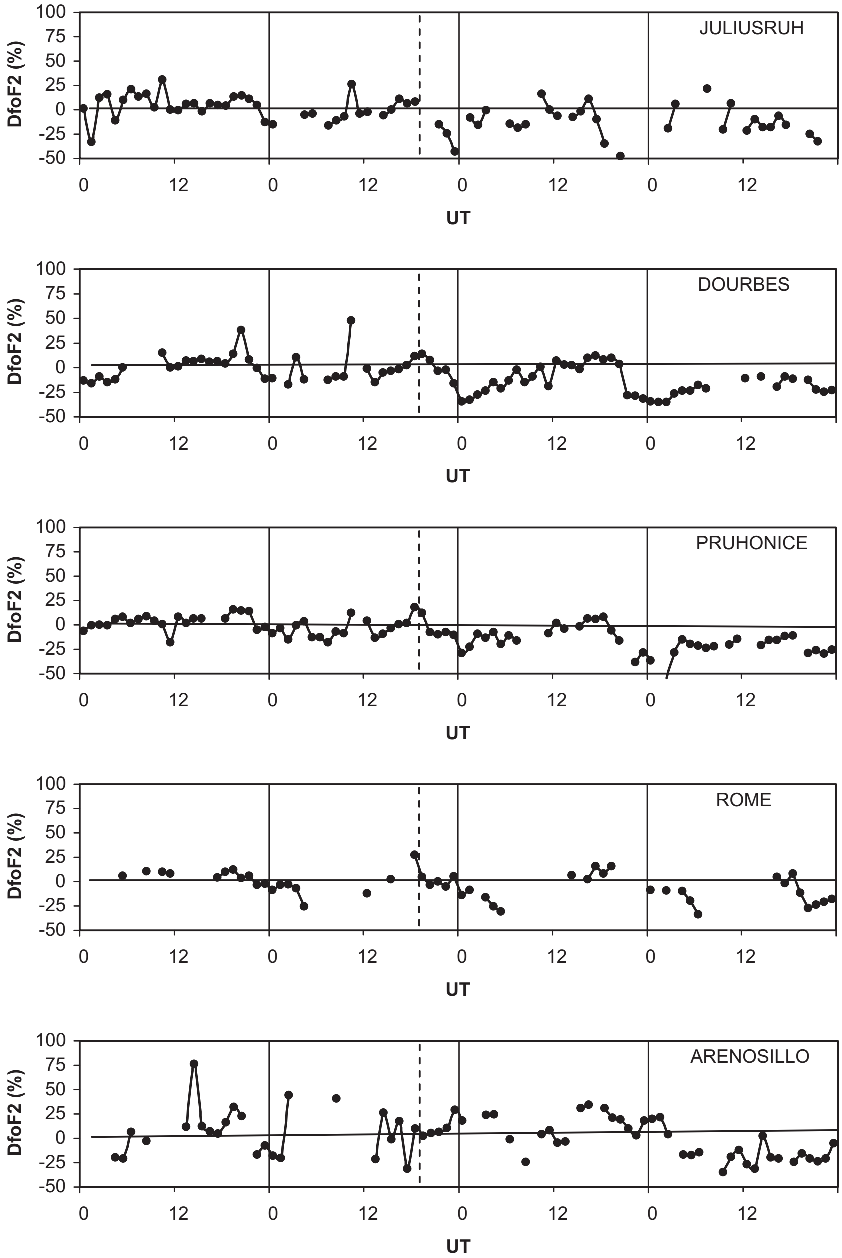

Fig. 4. Same as Fig. 2 but for the European sector.

3. Discussion and conclusion

In this paper, the behavior of the ionospheric parameter foF2 during the geomagnetic storm occurred of 3 August 2010 is reported using data from ionosonde stations located around the globe. Some new aspects of the storm time ionospheric behavior are revealed.

The main observational results can be summarized as follows.

Prior to the storm, Japanese, Australian and American stations showed increases in foF2, irrespective of the local time. During the main phase, at the mid latitude stations of the American sector positive disturbances are observed (in the pre-dusk hours) which subsequently change to negative. Long-duration positive disturbances are seen at mid-low latitudes of the African chain during all the considered recovery phase of the magnetic storm. Also increases are observed in the South Pacific sector during the recovery phase. In the European sector, during the recovery phase long-duration, negative disturbances at mid-high latitudes are seen, while at mid-low latitudes a positive disturbance is seen, which is followed by a negative one.

Analyzing the global response of mid-high and low latitude ionosphere in four longitudinal sectors during two

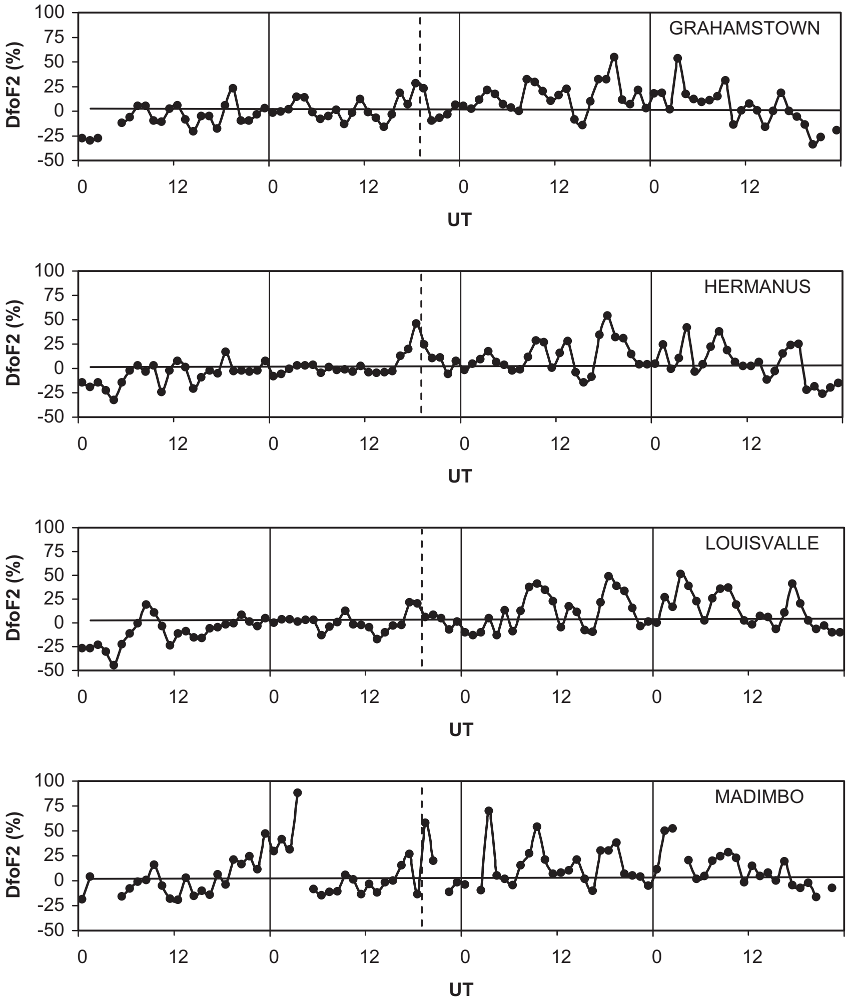

Fig. 5. Same as Fig. 2 but for the African sector.

moderate geomagnetic storms occurred in 2007 (22–25 March, min Dst ~ -70 nT and 19–21 November, min Dst ~ -67 nT), Mansilla (2011) found significant positive storm effects at mid-high latitudes during the main phase/first part of the recovery, positive effects after the onset of the storm followed by negative effects at middle latitudes and delayed positive effects during the night-time hours in the trough of the equatorial anomaly ("dusk" effect). Although the storms occurred in different seasons, it can be seen some similarities between the effects of the present paper and the previous paper, for example the positive effects observed at mid latitudes during the first stage of the storm followed by negative effects, and the delayed positive storm effects during the recovery phase. A difference is that in the storms discussed above presented no significant increases before the storm onset, which could indicate that this is a seasonal effect, however further experimental evidence is needed to confirm this assumption.

Some physical processes that cause the observed effects are analyzed.

Several mechanisms have been considered as a probable source of the positive storm effects because they are definitely the most difficult to be explained in terms of the current understanding. Prölss (1993) considers that the positive ionospheric effects at middle latitudes and the geomagnetic activity effect at low latitudes have a common origin and are both produced by traveling atmospheric disturbances (TADs). Such TADs propagate with high velocity from polar to equatorial latitudes. An essential feature of these TADs is that they carry along equatorward-directed meridional winds of moderate magnitude. It is this transient increase of the meridional wind velocity which is believed to be responsible for the generation of positive ionospheric effects at middle latitudes. This model is applied for daytime positive disturbances, which are the most often reported in the literature. For that reason it is convenient to distinguish between daytime and nighttime positive disturbances. It is necessary to consider a different mechanism to explain the positive disturbances observed in the American sector during the main phase ("dusk effect"). A possible but non

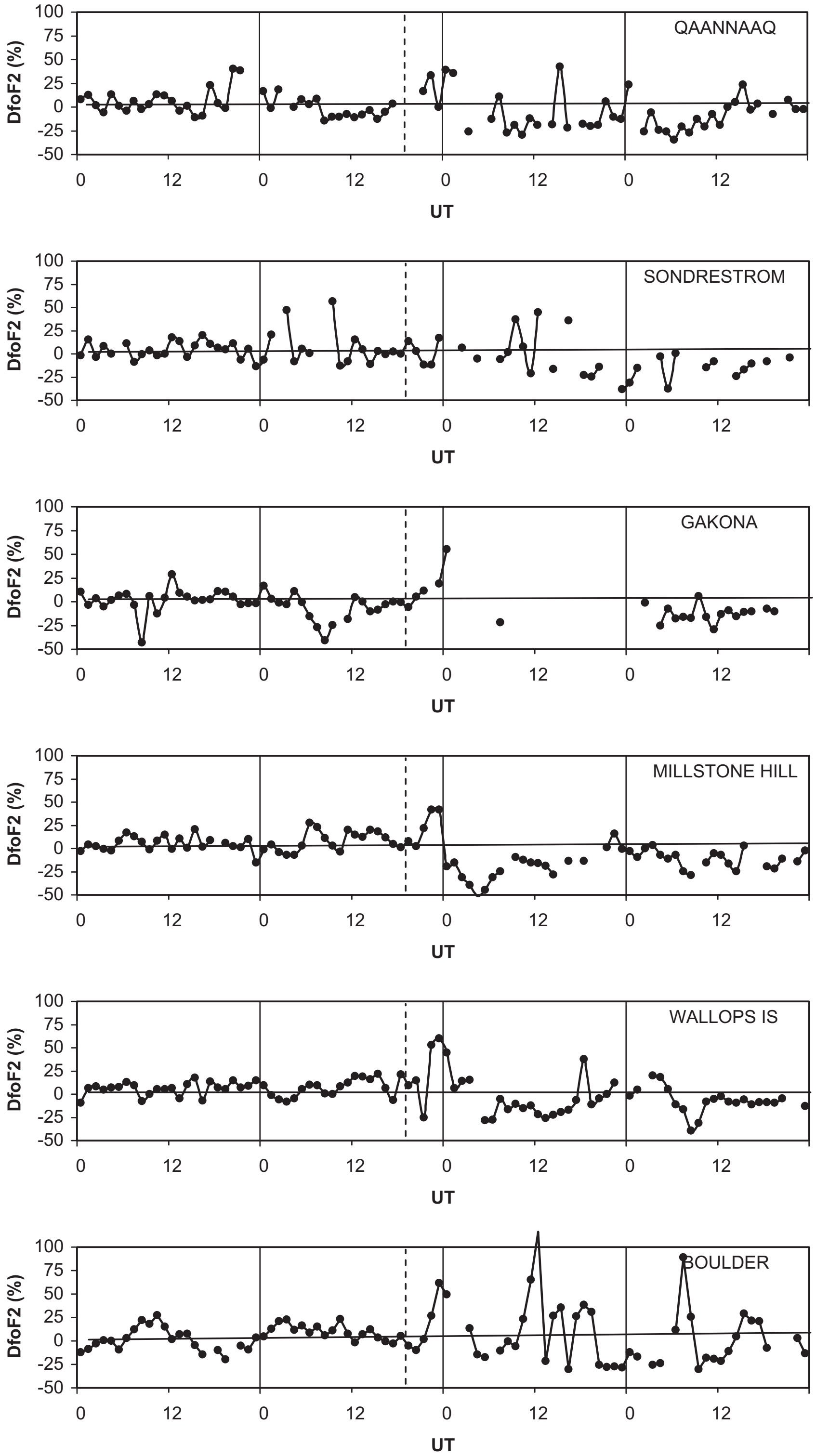

Fig. 6. Same as Fig. 2 but for the American sector.

verifiable explanation of this behavior would be the cessation of the meridional storm-induced circulation or the reversal in wind direction (enhanced poleward winds). However, further experimental evidence is needed to confirm if the mechanism is plausible.

The positive disturbances observed in the African sector during the recovery phase can be attributed to increases of the O density relative to N_2 to O_2 (Chandra and Stubbe, 1971; Mayr et al., 1978; Rishbeth, 1991). The air heated in the Joule heating zone is lifted up to

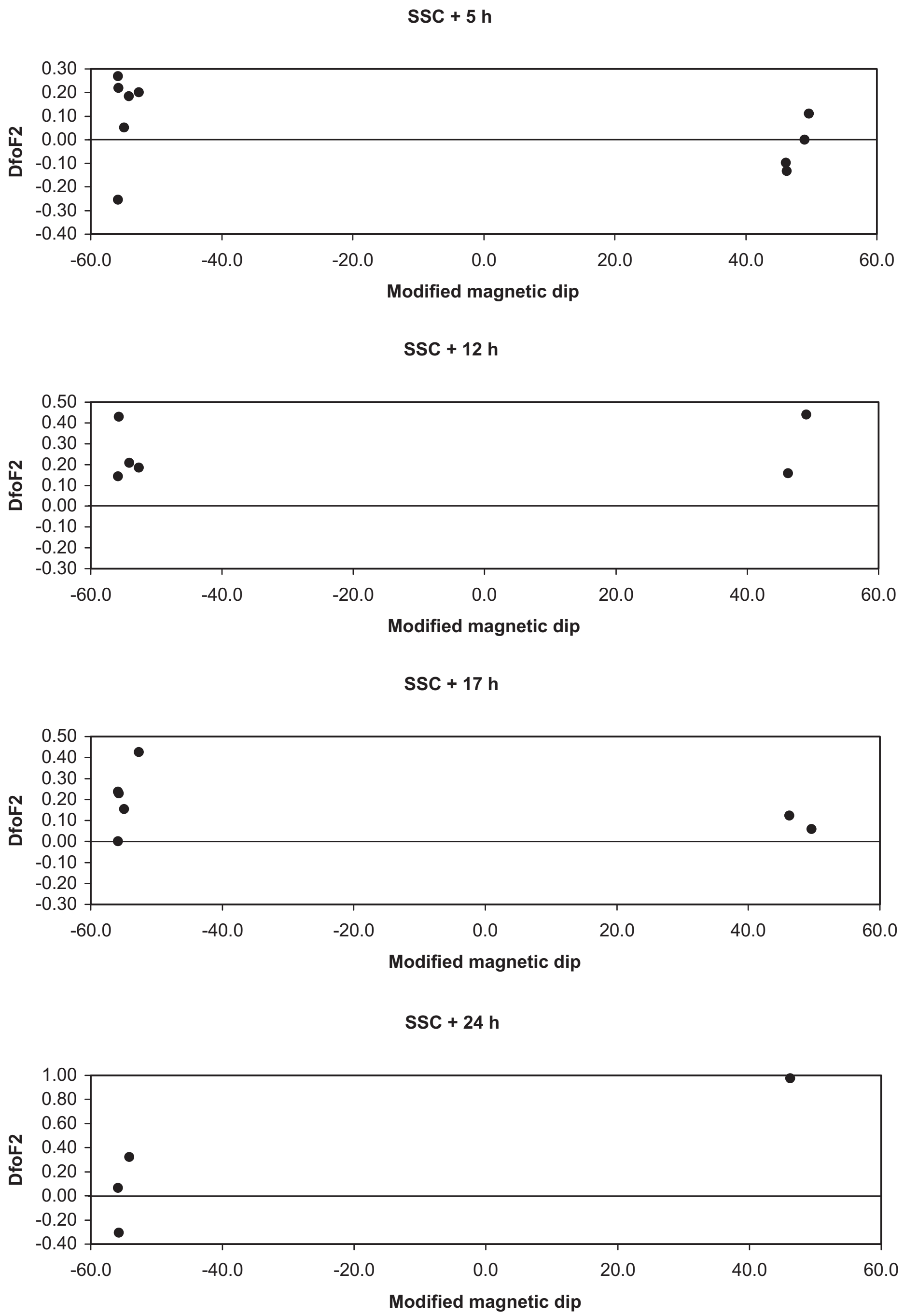

Fig. 7. DfoF2 vs. the modified magnetic dip in the Asia-South Pacific sector for several UT after the SC.

the topside ionosphere, is brought equatorwards by the meridional circulation and then is down-welled to the F2-layer maximum bringing an excess in [O] which produces the positive phase. However, the observational evidence found for these composition changes is not yet conclusive (e.g., Prölss and Von Zahn, 1977; Burns et al., 1995). As Fig. 8 indicates, negative disturbances are observed in the opposite hemisphere (European sector). These effects can also be caused by the storm time circulation, which transports changes in neutral composition as discussed below.

An interesting fact is the occurrence of prestorm positive disturbances in foF2 at Japanese, Australian, and American stations. The ionospheric positive disturbances occurring sometimes before the beginning of the magnetic storm cannot be explained in terms of above mentioned physical mechanisms because there are still neither storm induced circulation nor composition changes. Kane (2005) suggested that the increases in ionization could be the effect of a particle precipitation in the high latitude region. The problem of the prestorm ionospheric disturbances is a very important one. Since it was mentioned

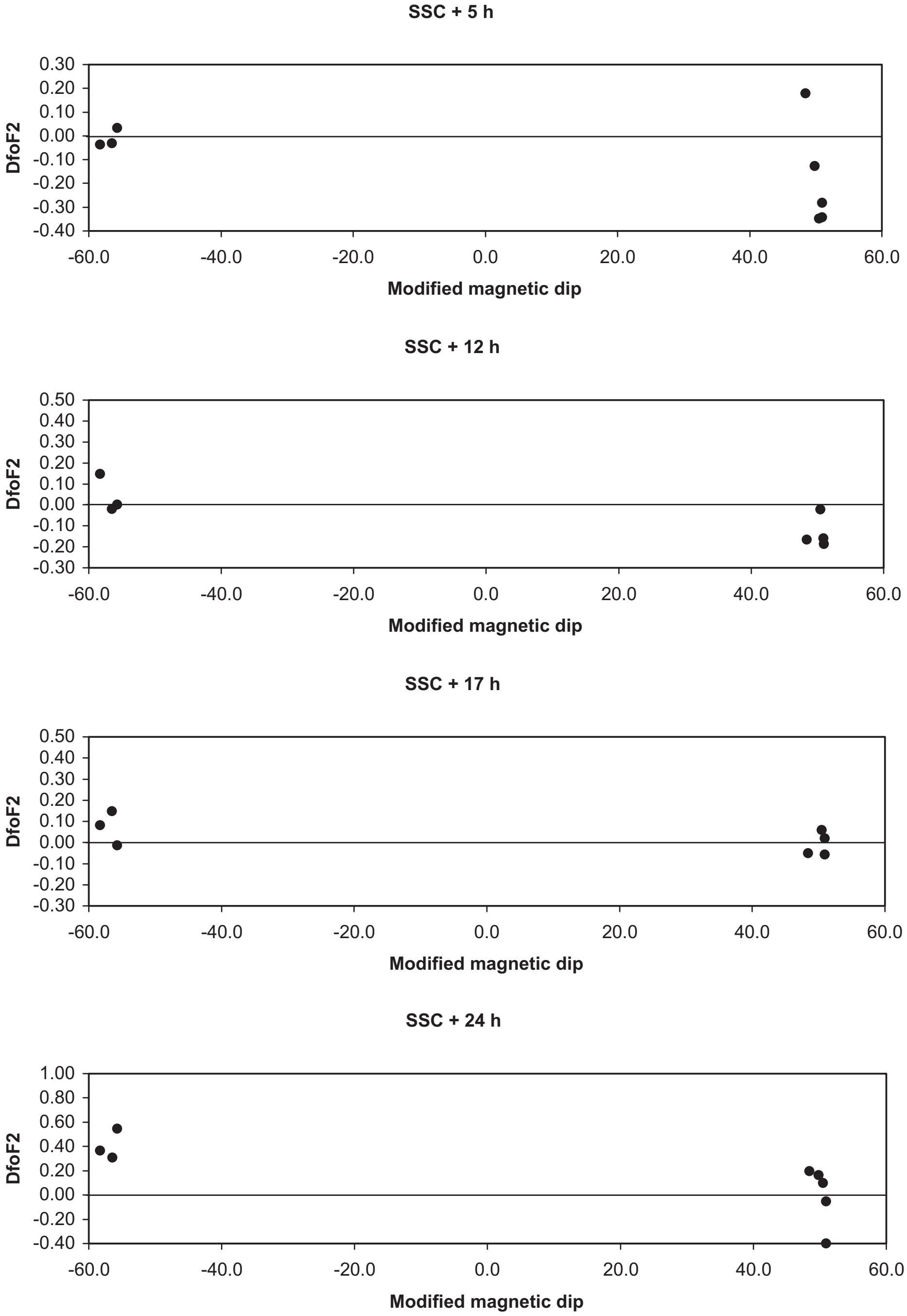

Fig. 8. Same as Fig. 7 but for the European-SouthAfrican sector.

for the first time at the end of the 1980s, the existence of the phenomenon has been discussed in several publications with opposite views. For example, analyzing 65 strong geomagnetic storms observed over the period 1995–2005, Buresova and Lastovicka (2007) observed that the prestorm enhancements do not exhibit a systematic latitudinal dependence and are not accompanied by a corresponding change of hmF2. The results of this paper are one more argument in favor of the reality of the event. Coinciding with Kane (2005), these prestorm disturbances could have very important implications, namely, these could be considered as precursors of geomagnetic disturbances.

The change in neutral composition, especially the increase in molecular oxygen or nitrogen to atomic oxygen ratio, is believed to be responsible for the reduction in electron density. This composition change is transported to lower latitudes by the disturbed thermospheric wind circulation produced by Joule heating and particle precipitation in the auroral region. Analyzing intense geomagnetic storms Mansilla and Zossi (2012) observed that the increases in the ratio $[N_2]/[O]$ were caused mainly by an increase in molecular nitrogen composition N_2 and almost no changes in atomic oxygen composition O.

As it was mentioned, in the Australian sector negative storm effects were observed at mid high latitudes during the last stage of the recovery. According to a simple scheme this effect can be explained as follows: the storm-induced circulation is directed equatorward; in winter it is opposite to the background thermospheric circulation which is directed poleward. That leads to the effect of "stopping" of the negative phase equatorward drift, the region of the negative phase development thus being confined to high and mid-high latitudes (Danilov, 2001). On the contrary, in summer the storm-time circulation and the background circulation are both equatorward which is favorable for the arrival of composition changes at mid latitudes and also at low latitudes as in the European sector.

Summarizing, the observations show that the F2 region behavior during a moderate geomagnetic storm presents an important degree of complexity. Some disturbances were erratic, which suggests considerable local effects. The majority of the studies of ionospheric responses have been performed during intense geomagnetic storms. It is evident that for a better understanding of the physical processes responsible for positive and negative ionospheric effects, it is also convenient to consider moderate geomagnetic disturbances. Also, it can be noted that different mechanisms are necessary to explain the effects observed still in the same longitude sector because in general there is a hemispheric asymmetry of the ionospheric response to a magnetic storm. There are many unclear points about the details of various processes of ionospheric storms. As an example, Danilov (2001) concludes that there are still problems unsolved. The most acute ones are: the appearance of positive effects before the beginning of a geomagnetic disturbance, the occurrence of strong negative effects at the equator, the role of vibrationally excited nitrogen in forming the negative effect, and the relation of positive effects to the dayside cusp.

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