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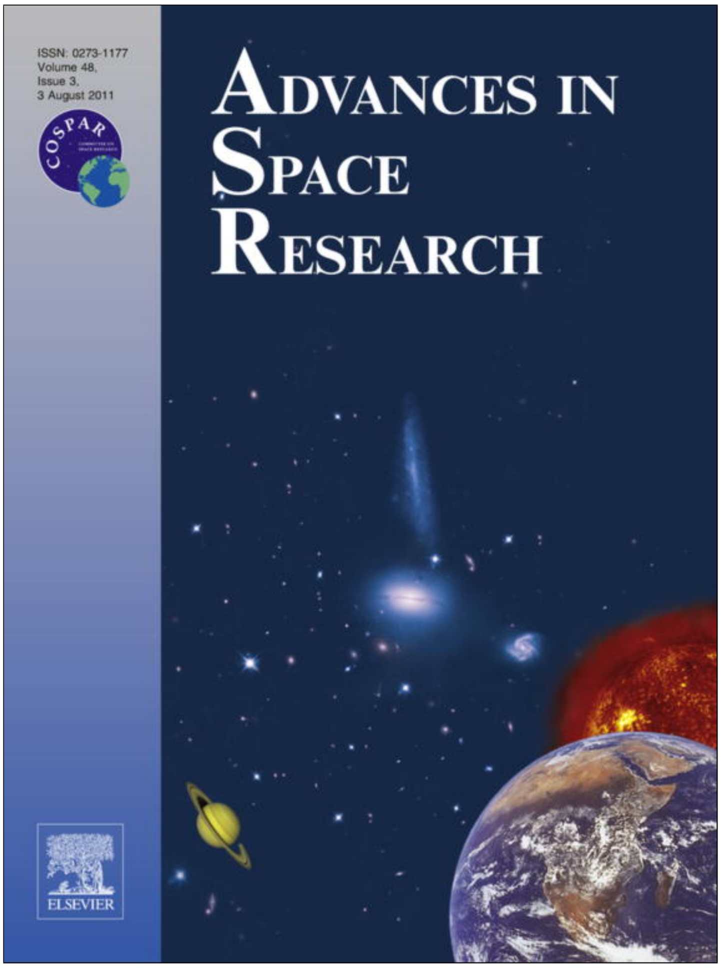

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Moderate geomagnetic storms and their ionospheric effects at middle and low latitudes

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Abstract

This paper reports the global response of the mid high and low latitude ionosphere in four longitudinal sectors to two moderate geomagnetic storms that occurred during 2007 (the more intense storms occurred that year). The results obtained during these storms show that the ionospheric effects in general are not moderate in magnitude, showing an important degree of complexity as during intense storms. The outstanding features produced during the storms are 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 negatives effects at middle latitudes and delayed positive effects during the night-time hours in the trough of the equatorial anomaly ("dusk" effect). Possible physical mechanisms for controlling the morphology of the ionosphere during these events are considered.
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Keywords: Geomagnetic storm; Ionosphere; Physical mechanisms

1. Introduction

It is well known that significant changes in the F2-layer are produced in response to geomagnetic storms (the so called ionospheric storms). Basically, during storm periods the peak electron density of the F2-layer NmF2 (proportional to the square of the critical frequency foF2) may be greatly increased or decreased relative to a background level, which are termed positive or negative ionospheric storms respectively. However, many studies have revealed that the storm-time ionosphere changes in complex ways.

A large number of papers reported case studies and statistical studies of the ionospheric effects caused by to intense geomagnetic storms, but due the complexity of ionospheric storms many aspects of their underlying physical processes are still far beyond being fully understood. So, case studies are still important for the understanding of various physical processes during ionospheric storms.

Electric fields, thermospheric meridional winds, a "composition bulge", high latitude particle precipitation have been suggested as possible physical mechanisms to explain the ionospheric response to geomagnetic storms observed at different latitudes (see for example Fuller-Rowell et al., 1994; Prölss, 1995; Bounsanto, 1999; Danilov, 2001, and references therein).

Most studies performed to analyze the ionospheric storm effects are based on the variations of foF2 alone or together with the virtual height h'F2, for which is considered one particular location or several stations of one particular region. However, some papers use both foF2 and hmF2 to study the ionospheric storm effects globally or in confined longitudinal sectors (e.g., Szuszczewicz et al., 1998; Blagoveshchensky et al., 2003; Liu et al., 2004).

The aim of this paper is to report the ionospheric response to two moderate magnetic storms that occurred

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during 2007 (low solar activity year) by considering two ionospheric parameters, foF2 and hmF2 (peak height of the F2 layer). For that, simultaneous observations from chains of high, middle and middle-low latitude stations distributed in four different longitudinal sectors are considered. The storms occurred on March 23, 2007 and November 19, 2007 (solar-geophysical data prompt reports). Furthermore, the ionospheric disturbances recorded in different longitudinal sectors are discussed in terms of the current physical mechanisms.

Ground-based hourly foF2 and hmF2 data provided by the Space Physics Interactive Data Resource (SPIDR) of NOAA (http://spidr.ngdc.noaa.gov/spidr/index.html) have been used for two storm periods: March 22–25, 2007 (March 22: $\sum kp = 6-$, $Ap = 3$; March 23: $\sum kp = 19$, $Ap = 20$; March 24: $\sum kp = 24$, $Ap = 18$; March 25: $\sum kp = 17$, $Ap = 11$) and November 19–21, 2007 (November 19: $\sum kp = 5+$, $Ap = 10$, November 20: $\sum kp = 28+$, $Ap = 24$; November 21: $\sum kp = 23+$, $Ap = 16$). On the total, the data of 30 ionospheric stations were analyzed. The station names and their geographic latitudes and longitudes are listed in Table 1.

Table 1
Stations used in this study.

	Geographic latitude	Geographic longitude (E)	Geomagnetic latitude
15°W–25°E			
Tromso	69.7	19.0	67.1
Pruhonice	50.0	14.6	49.9
Tortosa	40.4	0.3	43.6
Rome	41.8	12.5	42.3
El Arenosillo	37.1	353.3	40.8
Athens	38.0	23.8	36.5
Ascension Is	−7.9	345.6	6.6
130°E–175°E			
Macquarie Is.	−54.5	159.0	−61.0
Hobart	−42.9	147.2	−51.6
Christchurch	−43.6	172.8	−47.7
Canberra	−35.3	149.0	−43.9
Camden	−34.0	150.7	−42.0
Norfolk	−29.0	167.9	−34.7
Brisbane	−27.5	152.9	−35.4
Townsville	−19.3	146.8	−28.4
Darwin	−12.4	130.9	−22.9
Kwajalein	9.0	167.2	3.6
200°E–260°E			
College	64.9	212.2	64.8
Gakona	62.4	215.0	63.6
King Salmon	58.4	203.6	63.5
Boulder	40.0	254.7	48.9
Dyess	32.5	260.3	42.2
Point Arguello	34.6	239.4	42.3
280°E–315°E			
Thule/Qaanaaq	77.5	290.8	88.8
Sondrestrom	67.0	309.1	77.1
Narssarssuaq	61.2	314.6	71.1
Goose bay	53.3	299.2	64.6
Millstone Hill	42.6	288.5	53.9
Wallops Is.	37.8	284.5	49.3
Puerto Rico	18.5	292.8	29.8

The geomagnetic index Dst was chosen as diagnostic tool of the geomagnetic activity. Hourly values of Dst were obtained from the World Data Center at the University of Kyoto database: http://swdc.kugi.kyoto-u.ac.jp/dstdir.

The four longitudinal sectors considered are: 15°W–25°E, 130°E–175°E, 200°E–260°E and 280°E–315°E. Such a division is convenient for the investigation of the global positive and negative ionospheric storm effects characteristics (longitudinal dependence). A similar distribution of ionospheric stations located on different meridians during storm periods has been already done (e.g., Szuszczewicz et al., 1998; Blagoveshchensky et al., 2003).

2. Results

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

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

where foF2 is the hourly perturbed critical frequency and foF2(q) represents the reference level (the average value of quiet days of the month). So, positive and negative DfoF2 values correspond to positive and negative ionospheric storm effects. A similar relation was considered for the relative deviation of hmF2, DhmF2. Neither foF2 and hmF2 data for the 15°W–25°E longitude sector during the first storm event nor hmF2 data for the 130°E–175°E sector during the second storm event were available.

2.1. First storm event: 22–25 March 2007

Fig. 1a presents the variation of the index DfoF2 between 130°E and 175°E geographic latitudes together with the index Dst during the 22–25 March 2007 disturbance period. The sudden commencement (SC) occurred at 0900 UT on 23 March (Solar-Geophysical Data prompt reports, March 2007, p. 103). The average values of foF2 and hmF2 between 17 March and 20 March serve as reference level. For this sector, the storm started in the afternoon–dusk hours. A positive ionospheric storm effect (~50% increase) is observed in response to SC at mid-high latitude (Macquarie Is.) which remains until 18 UT on the storm day, followed by an irregular negative storm effect. At middle latitudes (Hobart, Christchurch, Canberra, Camden and Brisbane) positive storm effect are observed which propagate toward lower latitudes (~50% change) since about 12–13 UT on the storm day in the evening hours. At low latitudes (Townsville and Darwin – not shown here), positive phases are immediately noticed in response to the storm onset (see Townsville) which remain during the main and recovery phases. At equatorial latitudes on the Northern hemisphere (Kwajalein) no storm

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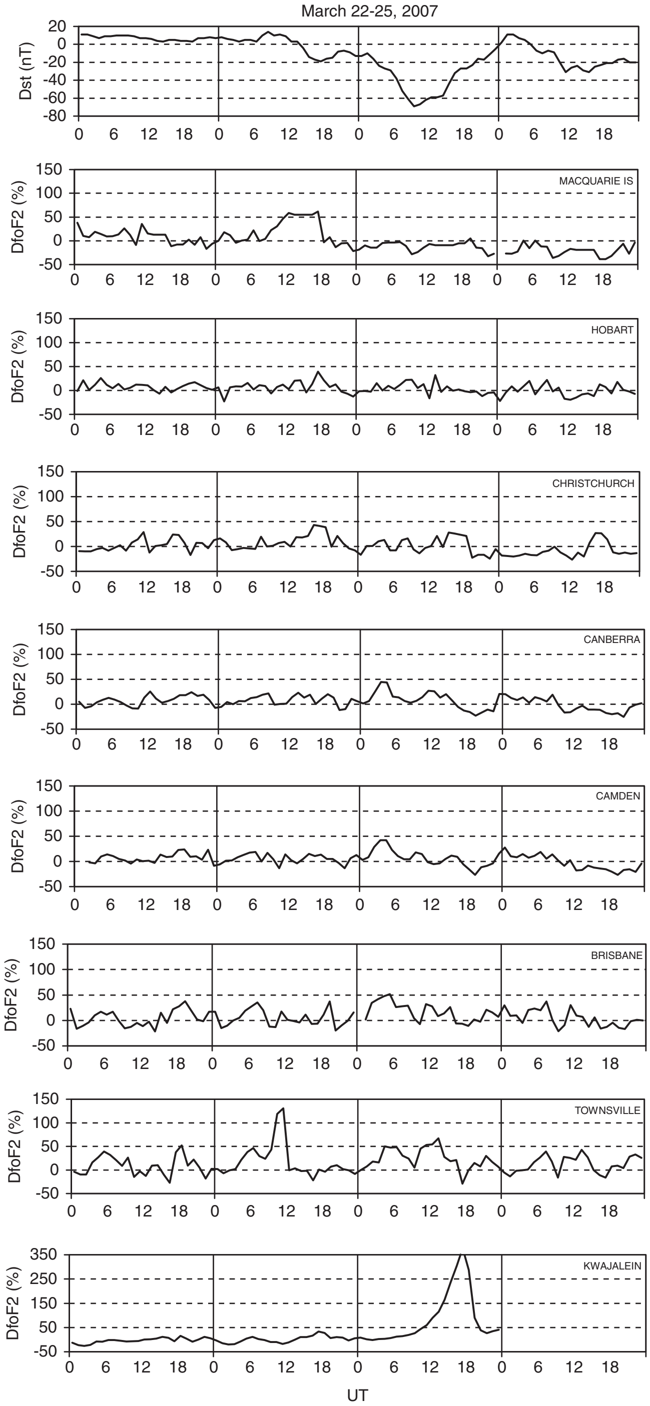

Fig. 1a. Temporal behavior of Dst index (top) and DfoF2 at ionospheric stations located in the 130°E–175°E longitudinal sector on March 22–25, 2007.

effect is observed neither near the time of the SC nor during the storm main phase; during the recovery phase (in the nighttime hours) a positive effect of short duration with amplitude higher than 350% is noticed.

Fig. 1b shows the variations of DfoF2 in the 200°E–260°E sector. In this sector, the SC occurred at around local midnight. At College a positive storm effect is observed before the magnetic storm onset increases after the SC until 18 UT. After SC, at Gakona a positive effect and at King Salmon almost no storm effect is observed. During the end of the main phase and early recovery phase, the positive effect at College changes to negative whereas at Gakona is observed a second enhancement of longer duration (∼12 h), with amplitude of up to 350% (between afternoon and past midnight). The middle latitude stations (Boulder, Dyess and Point Arguello) do not present reaction to the storm initially; between about 18 UT and 07 UT on 24 March (in the morning to around midnight hours) positive storm effects with amplitude increasing with time and decreasing with latitude (from about 90% to 60%) are observed, which gradually turn to negative during the storm recovery phase.

Fig. 1c shows the variation of DfoF2 in the 280°E–315°E sector. In this sector, the SC occurred in the pre-dawn hours. In general, no significant response to the storm onset is initially observed, only a small positive disturbance at high latitudes (Sondrestrom) which does not exceed 30%. An outstanding feature is the significant increase in foF2 over Narssarssuaq (∼150% change) before the beginning of the storm. During the main and recovery phases of the storm, at mid-high latitudes are noticed positive storm effects weaker at lower latitudes (at Narssarssuaq reached 250% and at Wallops Is. 30%), increasing again at Puerto Rico (up to 50%). They are followed by irregular negative phases whose amplitude decrease with latitude.

Fig. 2a presents the variations of DhmF2 in the 200°E–260°E longitude sector. At College and Gakona no considerable height decreases accompanied the positive effects in foF2 which possibly indicates particle precipitation and/or horizontal drifts of ionization from higher latitudes. During the main phase and early recovery phase, at College is noticed an increase in hmF2 which is associated to the negative deviation in DfoF2, and at Gakona a decrease in hmF2 during the second positive storm effect. The mid latitude stations present minor increases throughout storm period (less than 20%). The closeness of the stations does not allow determine whether these increases occured later at decreasing latitudes.

Fig. 2b presents the relative deviations DhmF2 for the chain of stations located in the 280°E–315°E longitude sector. At Sondrestrom, an irregular increase in the height hmF2 is associated to the weak positive phase, while at Narssarssuaq a moderated decrease in hmF2 accompanied the significant positive storm effect observed during the end of the main phase. At the remaining stations, slightly increased hmF2 values are observed since the main phase until the first part of the recovery but is not possible to determine any definite latitudinal dependence.

2.2. Second storm event: 19–21 November 2007

Fig. 3a shows the geomagnetic index Dst during the 19–21 November 2007 storm period together with the variation of DfoF2 at the longitudes 15°W–25°E. The sudden storm commencement (SC) was at 18 UT on 19 November. In this sector, the storm started in the afternoon hours. The average

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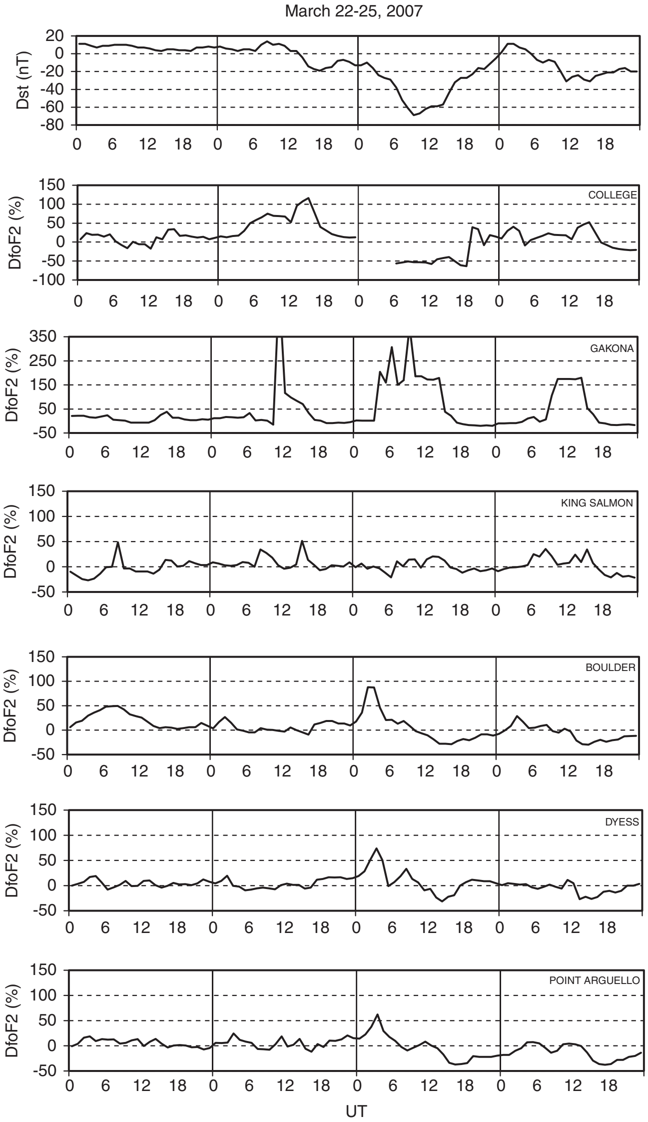

Fig. 1b. The same as Fig. 1a, but for 200°E–260°E longitudinal sector.

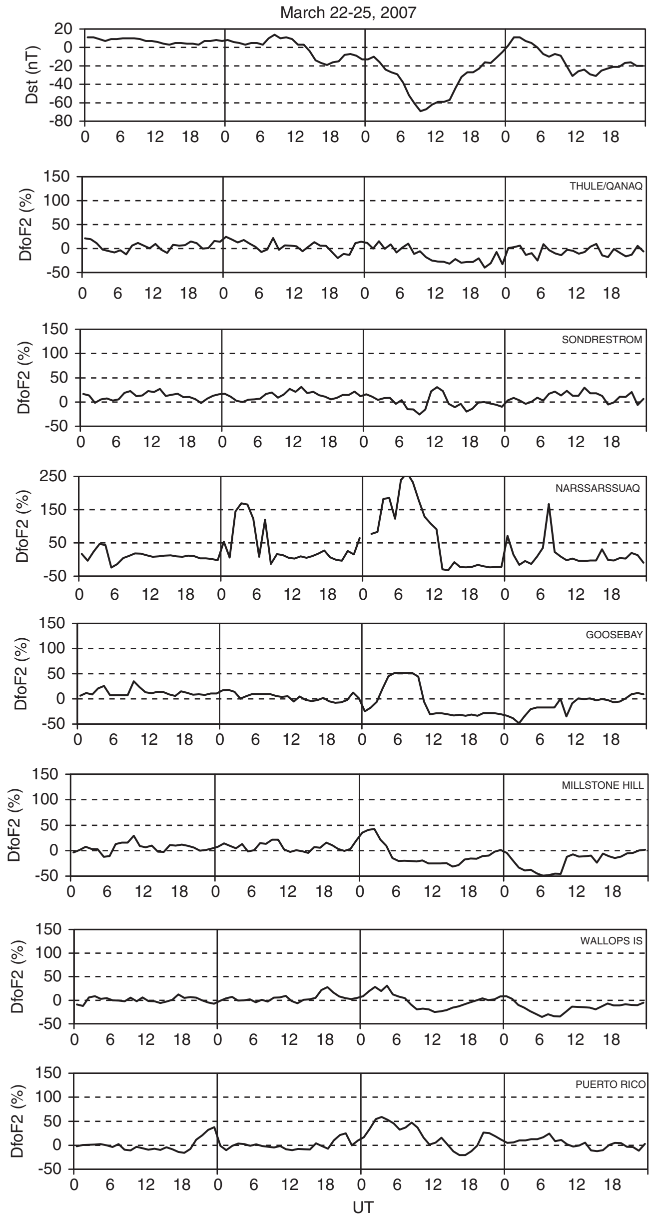

Fig. 1c. The same as Fig. 1a, but for 280°E–315°E longitudinal sector.

values of foF2 and hmF2 between 4 November and 7 November were used as reference level. At mid-high latitudes (Tromso) a positive storm effect appears two times: the first positive storm is observed a few hours following SC till about 05 UT on 20 November; the second enhancement of larger amplitude than before is produced between about 12 UT and 18 UT (from before noon to afternoon hours). In general, the lower latitude stations exhibit initially minor negative DfoF2 (~15–20% change), possibly no statistically significant. At middle latitudes (Pruhonice, Tortosa, Rome, Athens and El Arenosillo) irregular long-lasting positive storm effects are observed from the growth of the main phase till the first stage of the recovery, between about 12 UT on 20 November and 02–06 UT in the next day. In general, the positive disturbances increase with time and progress of the storm. At low latitude (Ascension Is.), a positive storm effect is noticed since the initial phase till about 03 UT on 20 November (between afternoon and night-time hours), followed by an oscillating behavior.

Fig. 3b presents the variation of DfoF2 in the 130°E–175°E sector. For this sector, the storm started in the night-time to pre-dawn hours. During the initial phase, irregular long-lasting positive storm effects whose amplitude increased with time (up to 50%) start at mid and mid-high latitude stations (Hobart, Christchurch, Canberra, Camden, Norfolk and Brisbane – not shown here) from about 22–23 UT on 19 November till 12–13 UT in the next day (between daytime and pre-midnight hours), followed by negative storm effects, which occurred delayed with decreasing latitude. The higher latitude station (Macquarie Is.) presents a significant increase in foF2 (up to near 200%) from about 08 UT to 23 UT on 20 November, which is followed by a minor negative storm effect (~30% change). The changes at Kwajalein (Northern hemisphere) are relatively modest: a weak positive disturbance a few

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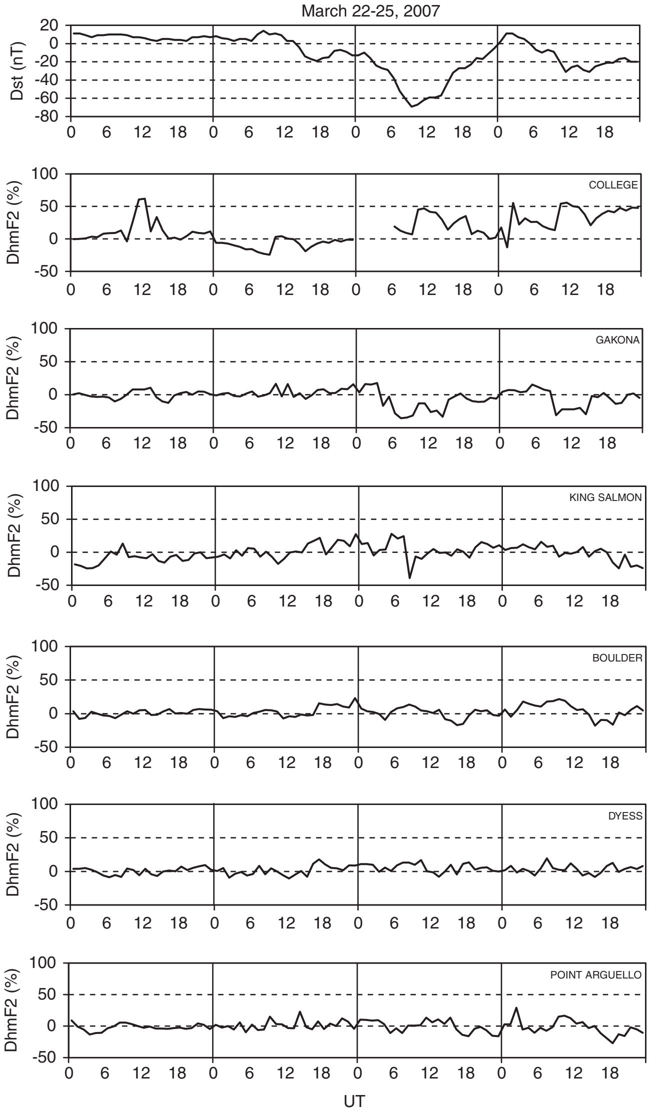

Fig. 2a. Temporal behavior of Dst index (top) and DhmF2 at ionospheric stations located in the 200°E–260°E longitudinal sector on March 22–25, 2007.

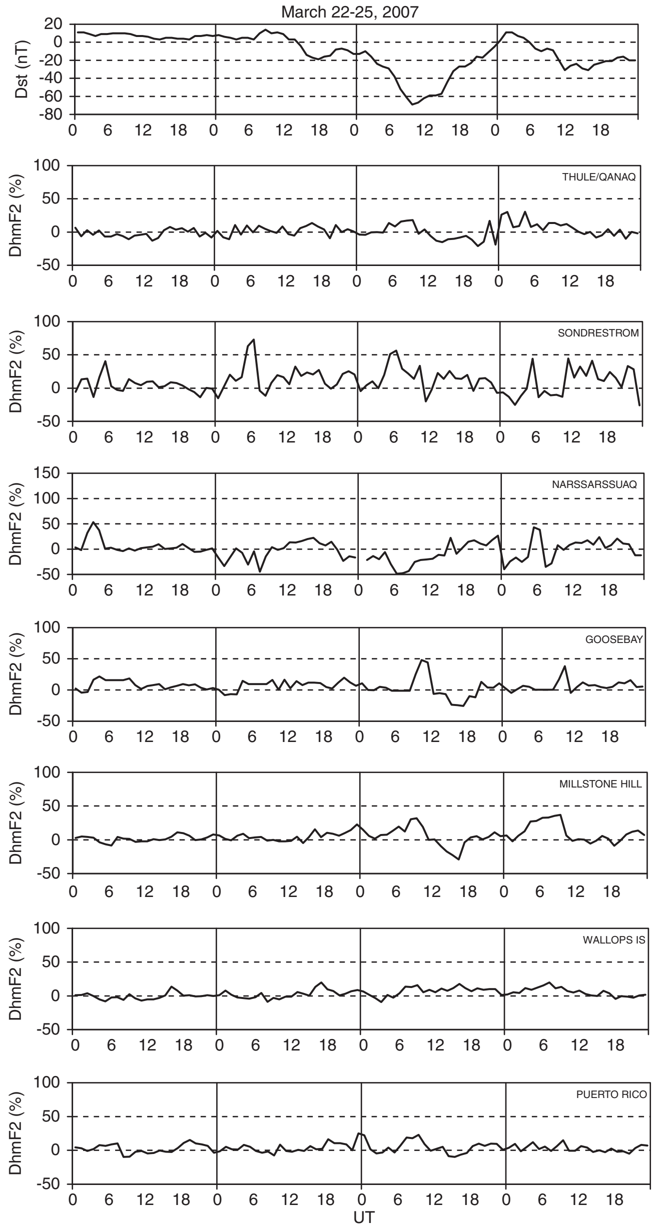

Fig. 2b. The same as Fig. 2a, but for 280°E–315°E longitudinal sector.

after SC (∼ 30% change) which changes to negative during the growth of the main phase (up to 35%), and positive again during the recovery phase.

Fig. 3c shows the variation of DfoF2 for the chain of stations located at the longitudes 200°E–260°E. The storm started during day-time and the maximum of Dst occurred around local noon. Minor disturbances initially prevail at all stations of the chain. A significant positive disturbance of foF2 (∼250% maximum change) is noticed at Gakona and in minor degree at the higher latitude station College (∼50% maximum change) between 06 UT and 18 UT on 20 November (in the evening hours to dawn in the next day). These disturbances change to negative in the daytime hours near to the end of the main phase till the first part of the recovery, when they change to positive again. At Boulder is produced a negative storm effect time displaced of the significant positive disturbance at Gakona, while at Point Arguello afterwards a minor negative disturbance, a positive phase with amplitude higher than 80% during the recovery phase is observed. The data gap at Dyess from 00 UT to 12 UT on November 20 do not allow know the ionospheric disturbance in this stage of the storm, but the trend of the subsequent data indicate an irregular positive storm effect whose amplitude reaches 50%.

Fig. 3d presents the relative deviations DfoF2 for the stations in the 280°E–315°E sector. The SC occurred in the afternoon hours. An irregular latitudinal behavior can be noticed during the storm period. At the high latitude stations (Thule and Sondrestrom) weak positive storm effects are observed during the first stage of the main phase, followed by no significant disturbance (Thule) or an oscillating behavior (Sondrestrom), while the Narssarssuaq data show two abnormal positive phases whose amplitude exceed 150%. At Goose Bay the data gap does not permit

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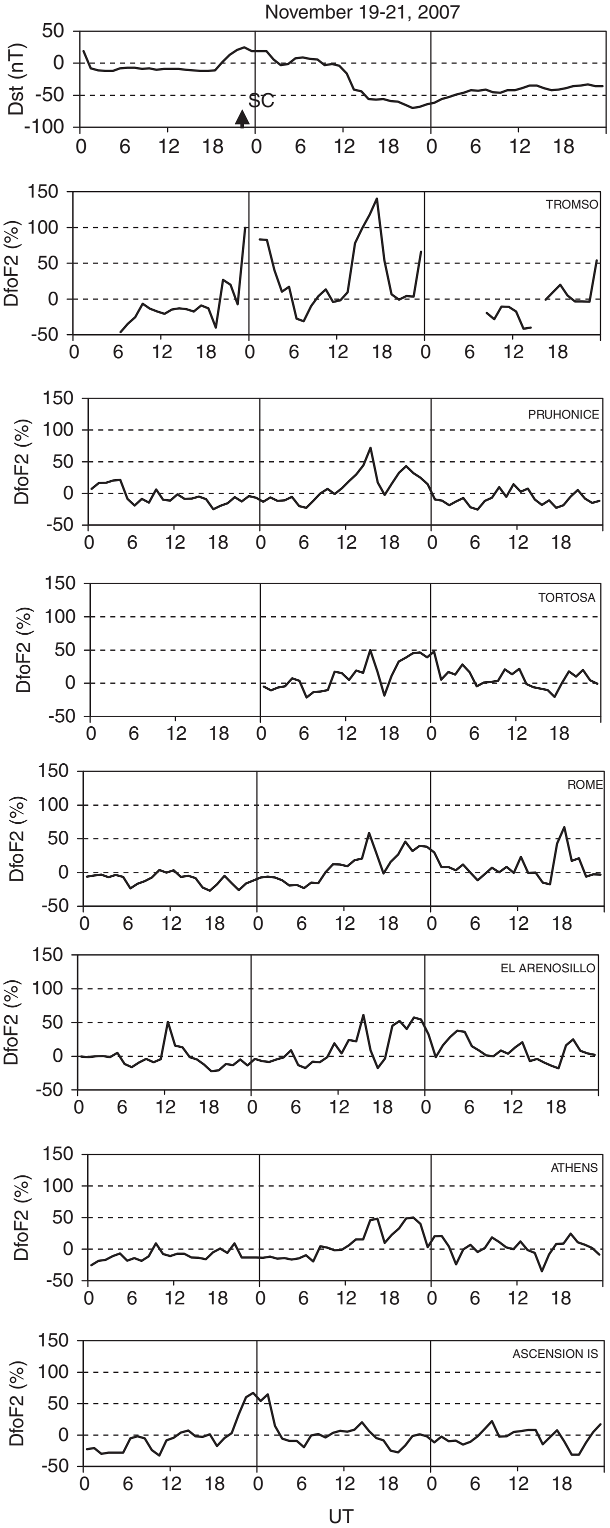

Fig. 3a. Temporal behavior of Dst index (top) and DfoF2 at ionospheric stations located in the 15°W–25°E longitudinal sector on November 19–21, 2007.

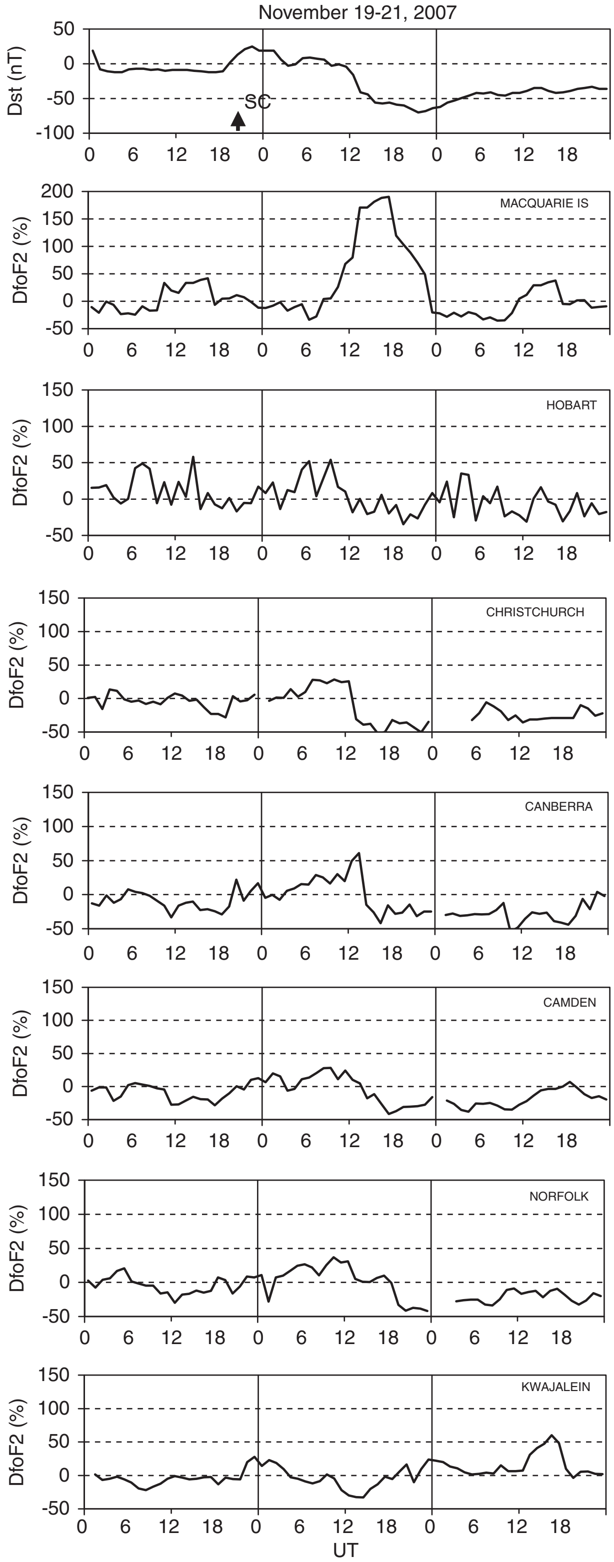

Fig. 3b. The same as Fig. 3a, but for 130°E–175°E longitudinal sector.

determine the initial ionospheric response to the storm, but subsequent data show almost no storm effect. At Millstone Hill, a minor negative effect which do not exceed 25% during the main phase is followed by a no significant positive storm effect during the end of the main phase and the first stage of recovery of the magnetic storm (from around noon to midnight).

Fig. 4a shows the variations of DhmF2 for the 15°W–25°E sector. At the high latitude stations (Tromso

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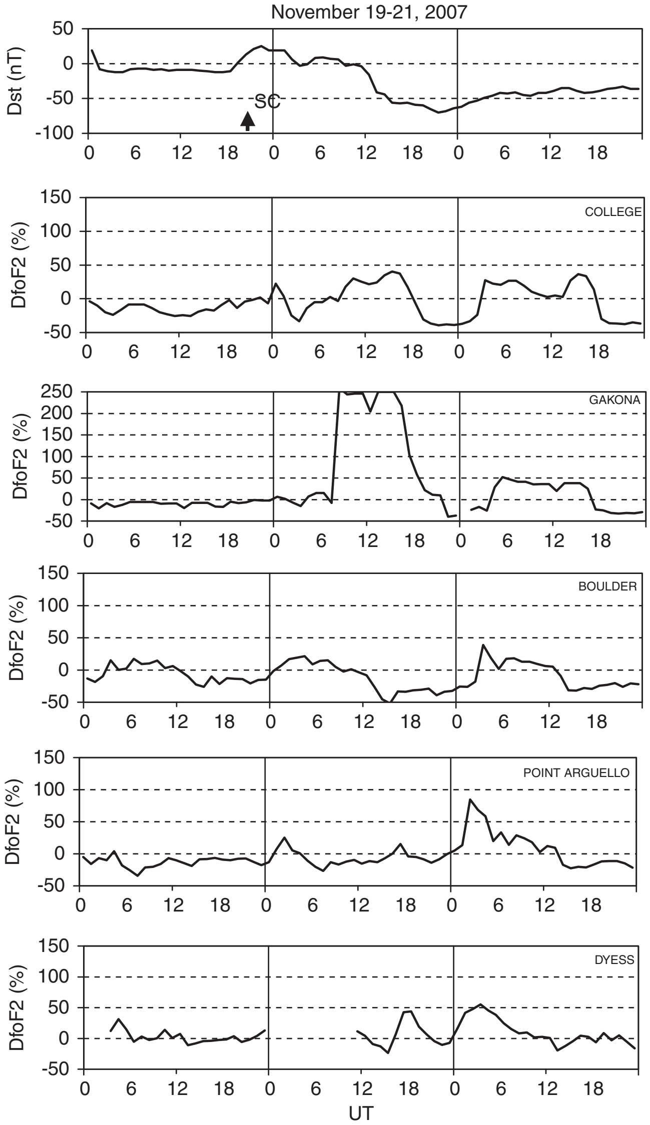

Fig. 3c. The same as Fig. 3a, but for 200°E–260°E longitudinal sector.

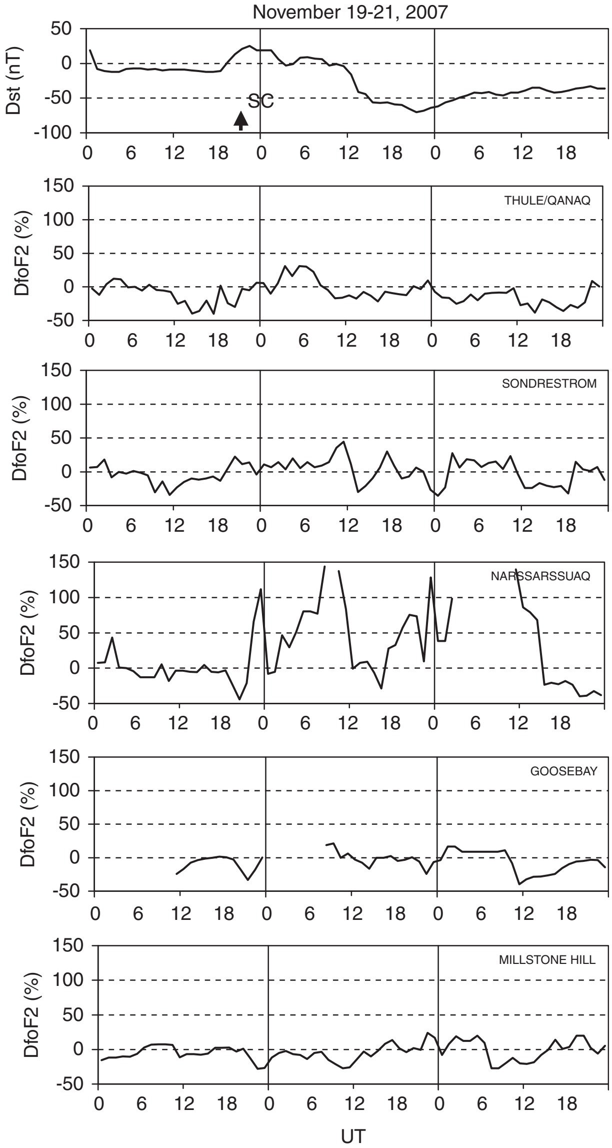

Fig. 3d. The same as Fig. 3a, but for 280°E–315°E longitudinal sector.

and Pruhonice) simultaneous short-duration decreases can be noticed after SC. A moderate increase in hmF2 (∼25–30% change) starts at Tromso since about 06 UT on 20 November and 11–12 UT at the remaining stations, which are associated to the positive storm effects. The increases in hmF2 show a weak dependence with latitude (see Pruhonice, Athens and El Arenosillo) which last till a few hours before of the end of the positive phases in foF2. At Ascension Is., the increased hmF2 values are associated to the positive storm effect started during the initial phase.

Fig. 4b presents the variation of DhmF2 for the stations of the chain 200°E–260°E. The observations show that hmF2 is not immediately responsive, because near to the storm onset hmF2 values are generally close to the reference conditions. At the high latitude station College, the disturbed hmF2 values are in general depressed relative to the quiet time values (by 35%) in association with the positive storm effect. On the contrary, at Gakona no substantial height variation is observed in correlation with the prominent positive storm effect. At the lower latitude stations, in general hmF2 increases (20–30%) during the negative and positive storm effects.

Fig. 4c shows the variation of DhmF2 at the stations located in the sector 280°E–315°E. Irregular spatial and temporal variations are observed. At Thule and Sondrestrom can be noticed oscillating behaviors with increasingly values of hmF2 during the development of the storm. At Narssarssuaq hmF2 is increased in association to the first enhancement in foF2, and also raised but delayed from the second enhancement, while at Millstone Hill and Wallops Is. hmF2 is increased during the main and recovery phases of the storm.

3. Discussion and conclusions

The global ionospheric response to two moderate/weak geomagnetic activity is reported in terms of the ionospheric

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parameters foF2 and hmF2. Severe long-lasting decreases of ionization at mid and mid-high latitudes which constitute the typical ionospheric response to intense geomag-

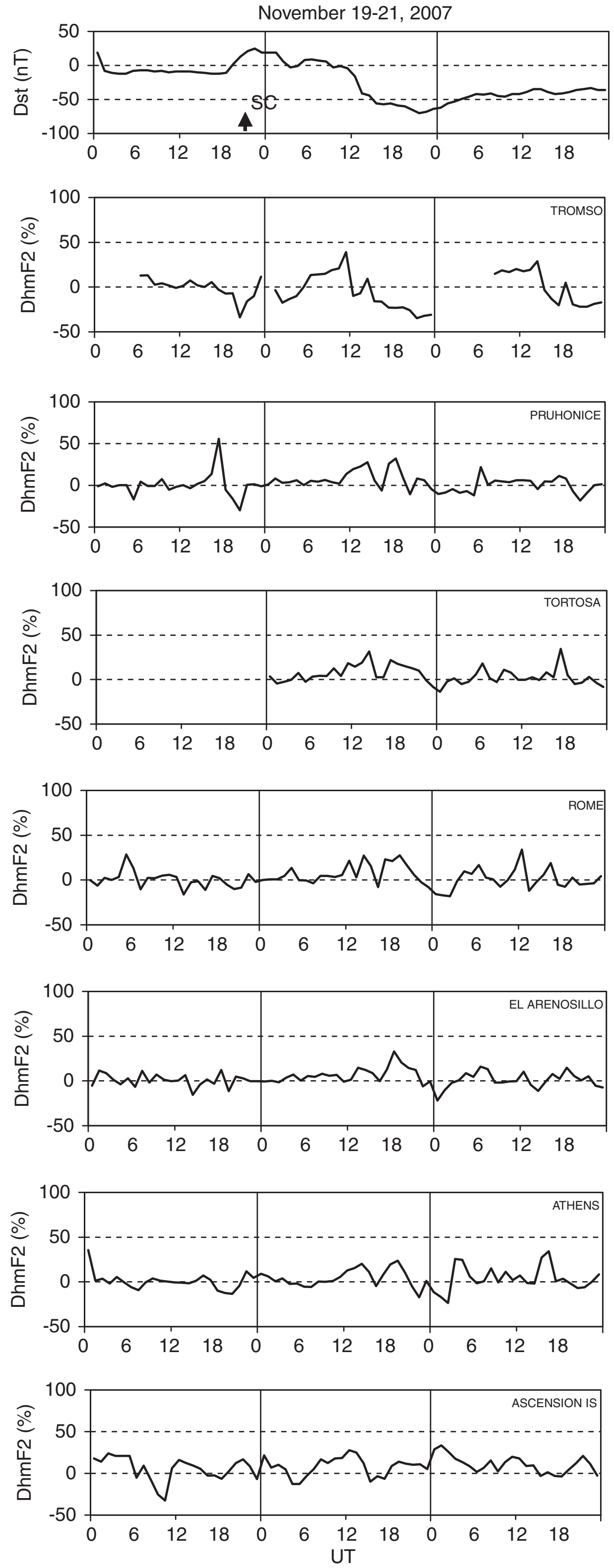

Fig. 4a. Temporal behavior of Dst index (top) and DhmF2 at ionospheric stations located in the 15°W–25°E longitudinal sector on November 19–21, 2007.

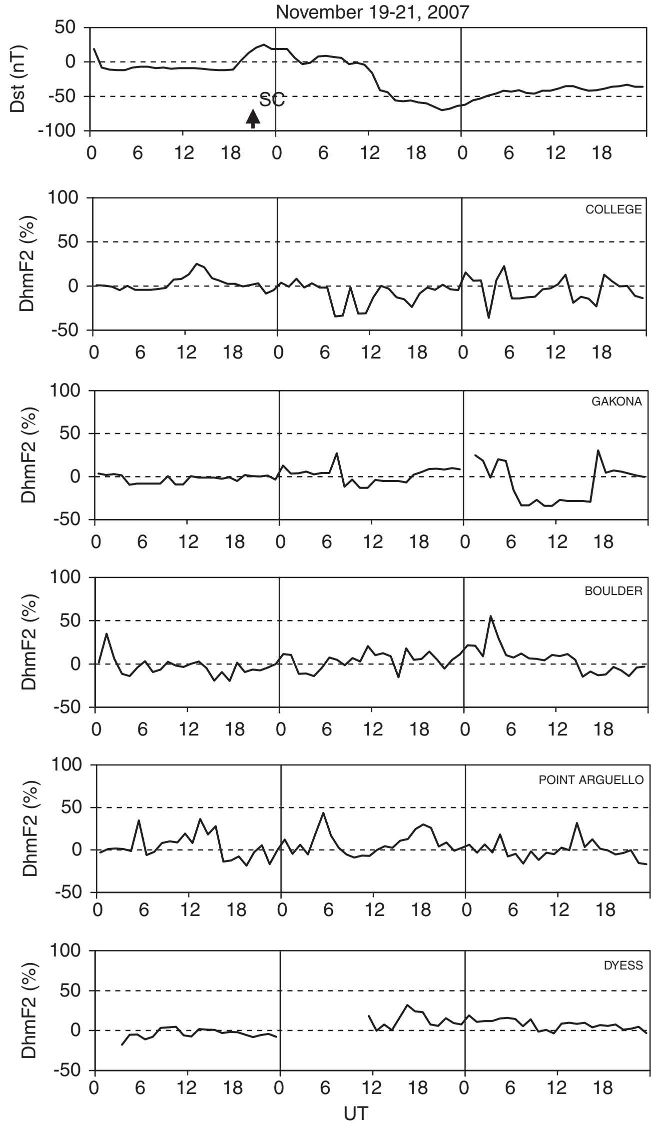

Fig. 4b. The same as Fig. 4a, but for 200°E–260°E longitudinal sector.

netic storms are not observed; however, many interesting features as during in intense storms can be observed during these case studies.

For the first storm event, in response to the SC, at mid-high latitudes there is no correspondence between positive effects in foF2 and the hmF2 behavior. Moreover, pre-storm enhancements can be noticed before the geomagnetic storm commencement in the evening hours. At middle latitudes positive storm effects are observed during the main phase development, which do not present a definite onset but, in general, they are of long duration. The amplitude of these disturbances decreases with latitude. The middle latitude positive storm effects are followed by irregular negative storm effects (in the night-time hours) in the Northern hemisphere or they remain positive in the southern hemisphere. An interesting feature of this storm is the significant positive storm effect (accompanied by a decrease in hmF2) at mid-high latitudes (Gakona, Narssarssuaq) during the end of the main phase and first part of the recovery in

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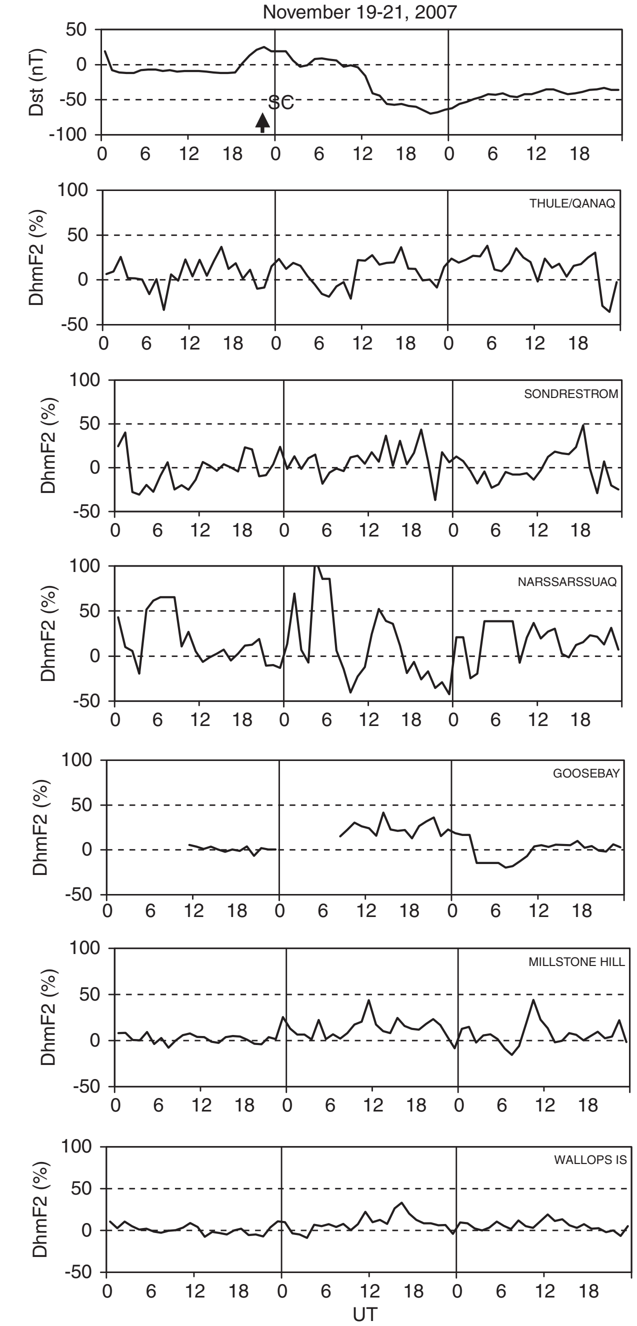

Fig. 4c. The same as Fig. 4a, but for 280°E–315°E longitudinal sector.

the afternoon and evening hours. Finally, in the trough of the equatorial anomaly a significant increase of ionization is observed during the first stage of the recovery phase in the night-time hours.

The second storm event (with similar intensity that the first one) presents a quite different longitudinal response to the storm. During the storm main phase, at mid-high latitudes (from afternoon hours to around noon in the next day) significant positive disturbances associated to moderate decreases or increases in hmF2 can be noticed. At middle latitudes, also positive phases are noticed from the initial phase (in the day-time sectors) till the first part of the recovery (in the evening and following daytime hours). These positive effects are accompanied by increases in hmF2. In the southern hemisphere, the initial positive disturbances change to negative (in the night-time hours) before the end of the main phase, which appear delayed with decreasing latitude. Also at middle latitudes, after minor disturbances during the main phase, positive storm effects are observed during the early recovery phase (in the afternoon hours to around midnight), which are accompanied by no significant increases in hmF2. At low latitudes a positive storm effect observed during the initial phase of the storm (from afternoon/predusk to night-time hours) is accompanied by a weak enhancement in hmF2.

The disturbances observed seem to indicate that several physical processes were operative during both storms.

Although there is no simple explanation for the ionospheric positive disturbances occurring at stations located within the range of the auroral oval zone (College, Narssarssuaq) a probable mechanism is a particle precipitation in the high latitude region, as already was considered by Kane (2005). Supporting this explanation is the earlier (before SC) enhancement of AE index (not shown here), indicative of high energy input to the high latitude region. That implies that energetic particles might precipitate to that region leading to the ionization enhancement. The pre-storm enhancements are accompanied by no significant depressed hmF2 values which supports that explanation.

Because there is still neither storm-induced circulation nor composition changes (discussed below) particle precipitations could be the more important mechanism for the initial positive storm effects observed at some high and mid-high latitude stations since before the SC.

Some significant increases in foF2 produced at high and mid-high latitudes (e.g., Tromso, Gakona, Narssarssuaq) during the end of main phase/first part of the recovery are accompanied by depressed hmF2 values relative to quiet time values. A possible but nonverifiable explanation of this behavior would be cessation of the meridional storm-induced circulation or reversal in wind direction (enhanced poleward winds). However, further experimental evidence is needed to confirm if the mechanism is plausible.

The positive storm effect observed at mid and low latitudes during the initial phase of the magnetic storms requires a fairly rapid mechanism since it begins to occur about one hour or so after SC. Some recent papers (Lei et al., 2008; Wang et al., 2010) have demonstrated that changes in the daytime eastward electric fields play a dominant role in generating the ionospheric positive storm effect at low and middle latitudes during the initial phase as well as the negative response around the geomagnetic equator in the daytime. The eastward electric field enhancements are caused by the penetration of high latitude electric fields to low latitudes during southward interplanetary magnetic field (IMF) periods. As consequence of the eastward electric field enhancements the ionosphere is lifted up at low and middle latitudes to

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heights where recombination is weak allowing the plasma to exist for a long period resulting in higher densities.

Traveling atmospheric disturbances TADs possibly promote or substitute the initial effect of penetration electric fields to the maintenance of the long duration positive storm effects at middle latitudes. These TADs are generated during substorm activity and propagate with high velocity from polar to equatorial latitudes. They cause a lift of the F2 layer, which in turns leads to positive disturbances (Prölss, 1993, 1997). The dissipation of these TADs leads to that positive disturbances decrease with latitude.

With respect to the negative storm effects it is widely believed that they are caused by changes in the thermospheric composition generated during geomagnetic storms at auroral latitudes (increase in the ratio of the molecular nitrogen N_2 compared with the atomic oxygen O, N_2/O), which are then transported to lower latitudes by the disturbed thermospheric wind circulation produced by Joule heating and particle precipitation in the auroral region. At mid latitudes the negative storm effects in the night-time hours produced following the positive disturbances can be explained in terms of composition changes. During the night-time the storm-time circulation and the background (quiet) circulation are both equatorward which is favorable for the arrival of composition changes at mid latitudes and also at low latitudes. The delayed negative storm effects with decreasing latitude and their associated uplifting of F2-layer due possibly to storm-time meridional winds seem to corroborate the mechanism.

Summarizing, the outstanding features of two moderate magnetic storms occurred during low solar activity are significant positive storm effects at mid-high latitudes during the main phase and first part of the recovery, positive storm effects after the onset of the storm, followed by negatives effects at middle latitudes, and delayed positive storm effect during night-time hours in the trough of the equatorial anomaly ("dusk" effect). Some deviations were erratic, which suggests considerable local effects. The observations show that the F2 region behavior during moderate geomagnetic storms presents an important degree of complexity. Since most studies of ionospheric responses have been performed during intense geomagnetic storms it is obvious that additional studies are also required during moderate storms to gain a better knowledge of the ionospheric response and to obtain possible patterns of behavior in these conditions.

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