IONOSPHERIC EFFETCS OF AN INTENSE GEOMAGNETIC STORM

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ABSTRACT

An investigation of the response of the mid-high, mid and low latitude critical frequency foF2 to the geomagnetic storm of 15 July 2000 is made. Ground-based hourly foF2 values (proportional to square root of peak electron density of F2-layer) from four chains of ionospheric stations located in the geographic longitude ranges 10°W–35°E, 60°E–120°E, 130°E–170°E, 250°E–295°E are used. Relative deviations of foF2 are considered. The main ionospheric effects for the considered storm are: long-duration negative disturbances at mid-high latitudes in summer hemisphere in sectors where the storm onset occurred in the afternoon/night-time hours; short-duration positive disturbances in the summer hemisphere at mid-high latitudes in the pre-sunset hours during the end of main phase-first stage of the recovery; small and irregular negative disturbances in the low latitude winter hemisphere which predominate during the main phase and first part of the recovery, and positive disturbances in both hemispheres at mid-high and mid latitudes prior to the storm onset irrespective of the local time. In addition, the validity of some physical mechanisms proposed to explain the F2 region behaviour during disturbed conditions is considered.

Key words: geomagnetic storm, ionospheric disturbances

1. INTRODUCTION

The ionospheric electron density changes in complex ways during geomagnetic storms. Basically, the maximum electron density of F2-layer *NmF2* (proportional to the square of the critical frequency *foF2*) may increase (the so-called positive ionospheric storm) or decrease (the so-called negative ionospheric storm). A large number of papers reported case studies but due the complexity of ionospheric storms many aspects of the storms still need to be investigated and confirmed. Case studies which consider several stations of different longitudinal regions are important for a view of space weather and for the understanding of the role of various physical mechanisms during ionospheric storms. So, perturbations of the ionosphere associated to geomagnetic storms remain one of the most challeging topics of the space weather.

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The global total electron content TEC was used to investigate the ionospheric response to the geomagnetic storm of July 15, 2000 (*Kil et al., 2003*; *Liu et al., 2004*). The global TEC showed seasonal effects characterized by a dominance of decreases in plasma density in the summer (northern) hemisphere and pronounced increases in plasma density in the winter (southern) hemisphere. The northern decreases of plasma density expanded to the equator at midnight and even penetrated to the opposite hemisphere during the storm main phase while in the southern hemisphere decreases in plasma density began in the morning sector but were confined to narrow latitudes.

Global simulations, solar and atmospheric studies have been already published for this event (*Burns et al., 2004*; *Dymond et al., 2004*; *Huba et al., 2005*; *Tsurutani et al., 2006*), however no study based on using the *foF2* data from different chains of ionospheric stations has been made. Studies by considering the *foF2* response only in some confined sectors have been made (e.g., *Liu et al., 2002*). The *foF2* data of this storm period have been used to validate the empirical storm-time ionospheric model STORM (*Araujo-Pradere and Fuller-Rowell, 2001*) which was included in the latest version of the International Reference Ionosphere IRI (*Bilitza, 2001*).

The aim of this paper is to analyze the features of the ionospheric effects using the *foF2* parameter during the 15 July 2000 geomagnetic storm at different latitudes and in different longitudinal sectors. In addition, the role of some physical mechanisms during all stages of the storm is considered.

The data used in this analysis, obtained from the Space Physics Interactive Data Resource (SPIDR) of NOAA (*http://spidr.ngdc.noaa.gov/spidr/index.html*), are hourly *foF2* values from twenty-two ground-based ionosospheric stations for the period 14 − 17 July 2000. The stations and their locations are listed in Table 1.

Four longitudinal sectors are considered: 10°W–35°E, 60°E–120°E, 130°E–170°E, 250°E–295°E. Such a division is convenient for showing longitudinal dependence of storm effects. However, due to this strongly disturbed storm period some ionospheric stations present data gaps.

2. OBSERVATIONS

Fig. 1 shows the *Dst* geomagnetic index for the 14–17 July 2000 storm period. This magnetic storm undergoes two sudden commencements (SC). The first one occurred at 1533 UT on 14 July ($\Sigma k_p = 36$, $A_p = 51$). A gradual and irregular decrease is observed until about 14 UT on 15 July ($\Sigma k_p = 50$, $A_p = 164$) when *Dst* increases ocurring the second sudden commencement at 1438 UT. Thereafter, *Dst* sharply decreases and begin the main phase of the storm. At 2200 UT *Dst* reaches its minimum of −300 nT and after that starts a relatively rapid recovery.

As an index of the ionospheric disturbance relative deviation of the critical frequency from the quiet level is calculated. This deviation is given by the expression

$$DfoF2(\%) = \left[\frac{foF2 - foF2(q)}{foF2}\right] \times 100 ,$$

Table 1. Stations, used in this study.

Station	G Lat	G Long	M Lat	M Long
Salekhard	66.5°N	066.5°E	57.4°N	149.7°E
Podkamennaya	61.6°N	090.0°E	50.8°N	165.4°E
Leningrad	60.0°N	030.7°E	56.1°N	118.3°E
Magadan	60.0°N	151.0°E	50.9°N	211.6°E
Juliusruh/Rugen	54.6°N	013.4°E	54.3°N	099.7°E
Novosibirsk	54.6°N	083.2°E	44.2°N	158.9°E
Petropavlovsk	53.0°N	158.7°E	44.9°N	219.9°E
Chilton	51.6°N	358.7°E	54.1°N	083.2°W
Sofia	42.7°N	023.4°E	41.0°N	103.9°E
Rome	41.8°N	012.5°E	42.3°N	093.2°E
Tashkent	41.3°N	069.6°E	32.3°N	145.2°E
Tortosa	40.4°N	000.3°E	43.6°N	080.9°E
Boulder	40.0°N	254.7°E	48.9°N	318.7°E
Wallops Is	37.8°N	284.5°E	49.2°N	353.9°E
Anyang	37.4°N	126.9°E	27.3°N	195.9°E
Eglin Afb	30.4°N	273.3°E	41.1°N	341.2°E
Hobart	42.9°S	147.2°E	51.4°S	225.9°E
Canberra	35.3°S	149.0°E	43.7°S	225.7°E
Norfolk Is	29.0°S	168.0°E	34.5°S	244.6°E
Townsville	19.3°S	146.7°E	28.5°S	220.4°E
Darwin	12.4°S	130.9°E	22.9°S	202.7°E
Vanimo	02.7°S	141.3°E	12.3°S	212.5°E

where *foF2* is the hourly perturbed critical frequency and *foF2*(*q*) represents the quiet level (mean value of five quiet days of the month).

Fig. 2 shows the temporal behaviour of *DfoF2* for the 14−17 July 2000 storm period at ionospheric stations located in the sector 10°W−35°E. For this sector, the first SC occurred in the afternoon hours. Long-duration negative storm effects are observed in response to the first SC at mid-high and mid latitudes. The disturbance amplitudes increase after the second SC. In general, the negative storm variations remain until 12 UT on 17 July. The greater deviations are observed in the evening hours during the end of the main phase and first stage of the recovery. The amplitude of the negative effects seems to be greater at the high latitude stations of the chain. At Juliusruh and Chilton the relative deviations reach about 70–80% while at Rome and Sofia they are lower than 60% (01 UT on 16 July).

Fig. 3 presents the variation of *DfoF2* in the 60 E−120°E sector. For this sector, the SC occurred in pre-dusk hours. Although there is a gap of the data, the trend of available data indicate negative storm effects since first SC at mid-high latitudes (Podkamenaya and Novosibirsk), which seem increase after the second SC. At Tashkent (mid-low latitude station) a positive effect (up to 40%) is observed in response to first SC. The data gap do not allow to trace the variation of *foF2* during the main and recovery phases of the storm.

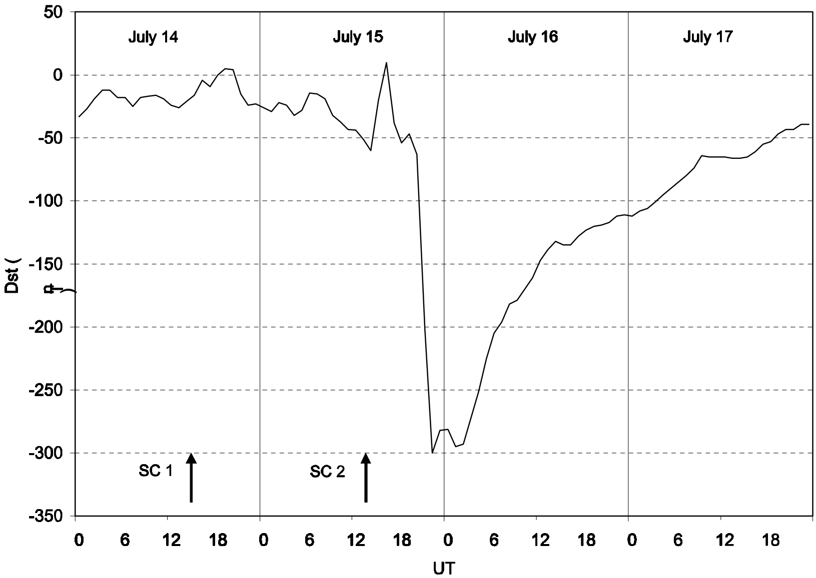

Fig. 1. Hourly *Dst* geomagnetic index on 14–17 July, 2000.

In general the storm effects in this region remain until around 10–12 UT on 17 July (during afternoon hours).

Fig. 4 shows the variations of *DfoF2* in the 130°E–170°E longitude sector (Southern hemisphere, winter). The SC occurs in this sector around local midnight. At mid-high and mid latitudes positive disturbances are observed from before the onset of magnetic storm. At higher latitude stations (Hobart and Canberra) these storm effects change to negative after the second SC, which remain about 24 h. At Canberra relative deviations with amplitude of up to 60% are observed during day-time hours on 16 July. The positive disturbances with initial amplitude of up to 110% at Norkolk Is. and Townsville remain in general during the main and recovery phases of the storm. At Darwin a negative disturbance is observed in response to first SSC (~40% change), followed by a short-duration positive disturbance during the main phase and a negative disturbance during the recovery phase. At low latitudes (Vanimo) in general negative low amplitude deviations of *DfoF2*, which do not exceeded 30% are observed until around 14 UT on 16 July in the local midnight.

Fig. 5 presents the variations of *DfoF2* at the longitudes 125°E–160°E (Northern hemisphere, summer). The trend of available data suggests negative disturbances at mid-high latitudes (Magadan and Petropavlovsk) from before storm onset until around 0 UT on 17 July. A negative disturbance is also observed at a low latitude station (Anyang) during the main and recovery phases of the storm. During the recovery the disturbance amplitude decreases with decreasing latitude: at mid-high latitude stations reaches 50% and at low latitude station do not exceeded 30% (10–12 UT on 16 July).

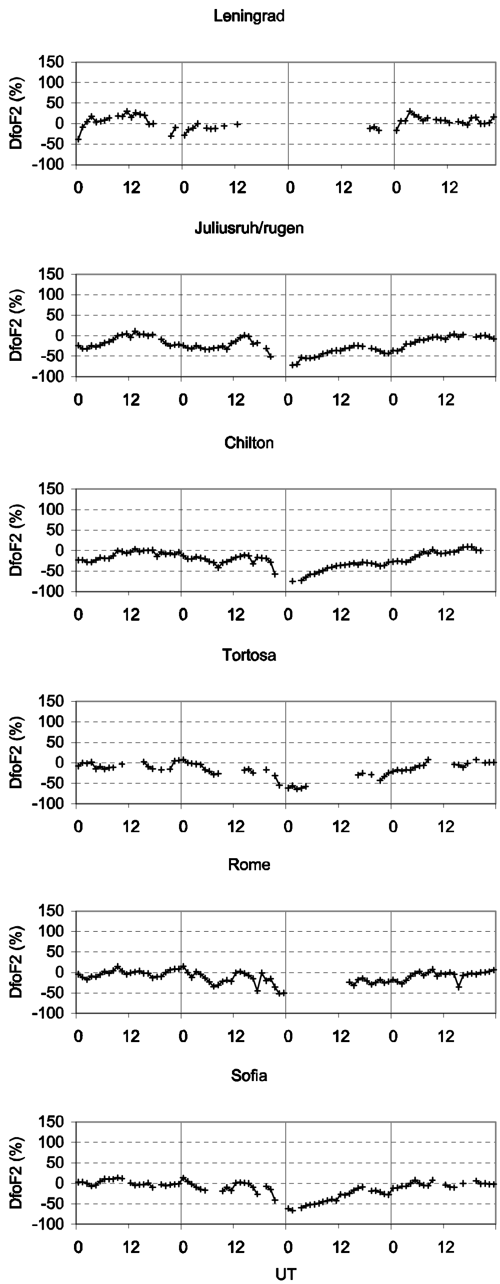

Fig. 2. Variations of the relative deviation *DfoF2* as a function of UT in the 10°W−35°E (summer) longitudinal sector during the period of 14−17 July, 2000.

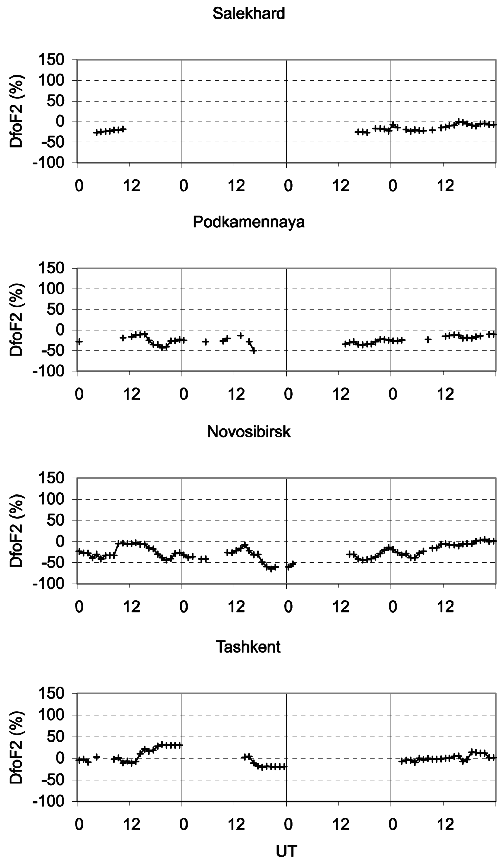

Fig. 3. The same as in Fig. 2, but for 60°E–120°E (summer) longitudinal sector.

Fig. 6 shows the variations of the index of ionospheric disturbance at longitudes between 250°E and 295°E. In this region the storm starts during day-time. Positive deviations are observed at Wallops Is. before the first SC, which changed to negative near the minimum *Dst* index till 10–12 UT on 17 July. At Boulder a small negative disturbance after the first SC (~20–25% change) while at Eglin no appreciable effect are observed until around 20–22 UT on 15 July when rapid increases (up to 90% at Eglin) of short-duration (3–4 h) are observed in the later afternoon hours at these stations. The positive disturbances are presented delayed with decreasing latitude. These effects change to negative with amplitude of up to 50% during the early stage of the recovery in pre-dusk hours.

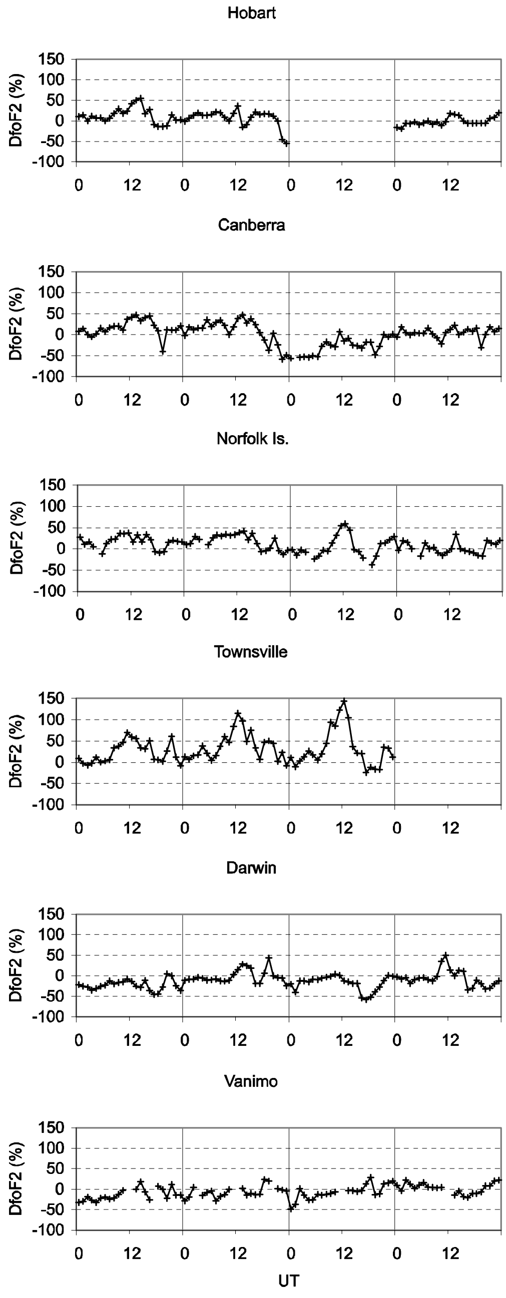

Fig. 4. The same as in Fig. 2, but for 130°E−170°E (Southern hemisphere, winter) longitudinal sector.

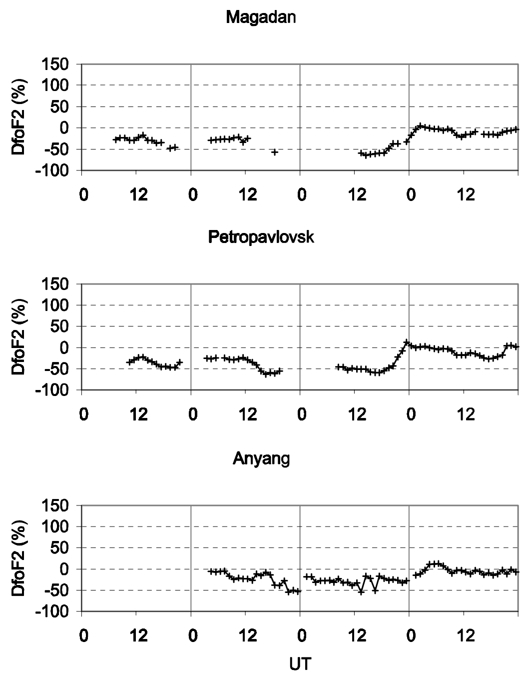

Fig. 5. The same as in Fig. 2, but for 125°E−160°E (Northern hemisphere, summer) longitudinal sector.

3. DISCUSSION AND CONCLUSIONS

The analysis performed contains a description of the *DfoF2* time behaviour in four longitudinal sectors during the 15 July 2000 storm. The behaviour observed is different for different intervals, this fact confirming the known regularity that the *DfoF2* behaviour depends on the local time of the magnetic storm beginning in the particular sector.

According to the current morphology (e.g., *Prölss, 1980,1995*; *Buonsanto, 1999*; *Danilov, 2001* and references therein), it is believed that the negative storm disturbances 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.

In summer hemisphere the negative disturbances are better developed than in the winter hemisphere. Long-lasting negative storm disturbances observed in the summer hemisphere may be reasonabily explained in terms of composition changes. The equatorward storm-induced circulation (bringing the heated gas with high N_2/O ratio),

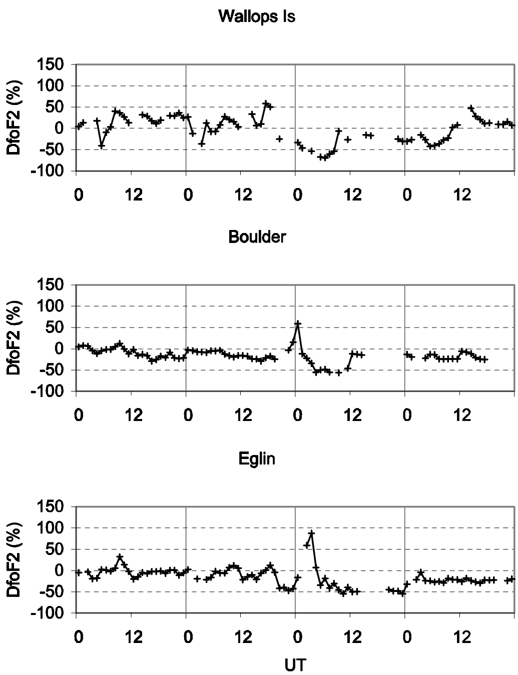

Fig. 6. The same as in Fig. 2, but for 250°E−295°E (summer) longitudinal sector.

which requires a few hours for the generation and propagation to mid-high latitudes, coincides with the nighttime and daytime background (quiet) circulation. This is favourable for the arrival of composition changes to mid and low latitudes. In winter, the background and the storm induced circulation are not directed in the same direction throughout the day. During the geomagnetic storm, the storm circulation (intensified during the main phase of the storm) is possibly so strong that even at day-time the background circulation (poleward) is not able to stop it. For this reason, the zone of the depleted atom-to-molecule ratio can to arrive to mid-high latitudes producing the negative storm disturbances as is observed in the region 130°E−170°E. Moreover, the decrease of the amplitude with decreasing latitude observed at the longitudes 10°W−35°E may be explained by considering the latitudinal structure of the composition disturbance (see *Prölss, 1980*).

The maintenance of the irregular negative storm effect at low latitude in winter hemisphere is possibly due to the combined effect of an electric field (discussed below) followed by the weak penetration of the composition changes from the summer hemisphere during the storm main phase. Satellite measurements show composition changes (increases in the mean molecular mass) at low latitudes in association with decreases of electron density at heights near F2 region maximum during the main phase and first stage of the recovery phase of storms (e.g., *Mansilla, 2006*), which possibly are due to the penetration of the composition bulge from the opposite hemisphere.

Several mechanisms have been considered as causes of the positive storm disturbances, which remain as subject of debate until the present day. They are: uplifting of F2-layer due to vertical drifts (caused by equatorward neutral winds or increases of electric fields of magnetospheric origin), plasma fluxes from the plasmasphere and neutral composition changes.

The onset of the delayed positive storm disturbances observed during the development of the main phase (in the pre dusk hours) at mid-high latitude ionosondes in the 250°E–295°E sector occur delayed with decreasing latitude. Possibly they are produced by travelling atmospheric disturbances (TADs), which carried along equatorward-directed meridional winds of moderate magnitude (*Prölss, 1993*). According to *Prölss (1993)* TADs are launched during magnetospheric substorms (described by an increase of *AE* index). During the main phase and first part of the recovery of the 15 July 2000 storm *AE* index considerably increased (up to 2500 γ), which indicates that energy is being injected into the high latitude atmosphere. Moreover, these positive effects occur with time delay of about 3–4 hours after the onset of the main phase. If the times at which the enhancements of *foF2* reached their peaks are selected as reference points, a propagation velocity of about 110 m/s is obtained. This velocity falls within of typical values for meridional winds of moderate intensity. According to this mechanism, the meridional winds of the TADs cause an uplifting of the F2 layer, which in turns leads to positive disturbances. Since the ionization losses (which are proportional to the N_2 and O_2 densities) decrease much faster with the height than the ionization production (which is proportional to the O density), this lead to the increase in electron density, i. e. to positive storm effects (*Prölss et al., 1991*). In this sector (with the storm period started during daytime hours) only after passage of TADs the storm circulation carrying the composition changes (increased N_2/O ratio) arrive to middle latitudes. That may be indicative of a preference of occurrence of this mechanism in the day-time ionosphere of the summer hemisphere. However, more experimental evidences are needed.

The negative storm effects observed at near-equatorial latitudes in winter hemisphere (Darwin and Vanimo) are possibly due to a short-lived enhancement of the eastward electric field. Observations in the Indian (midnight) sector show vertical plasma drifts in the F region from the magnetic equator to low latitudes between 19 and 21 UT on 15 July 2000 (*Sastri et al., 2002*) during the development of the main phase. It is likely that a super equatorial fountain occurred during this storm period producing an anomalous extension in the crest regions because positive disturbances are observed at mid-low latitudes in winter hemisphere (Norfolk and Townsville) and in summer hemisphere (Tashkent). The initial negative storm disturbance at low latitude in the winter hemisphere is possibly promoted and/or substituted by the equatorward-directed wind carrying composition changes from the summer hemisphere.

At mid-high latitude stations in the winter hemisphere (Hobart and Canberra) and in the summer hemisphere (Lenningrad and Wallops Is.) positive disturbances with amplitude of up to 50% are observed from a few hours prior to SC of the magnetic storm irrespective of the local time. The ionospheric positive disturbances occurring sometimes before the beginning of the magnetic storm can not be explained in terms of above mentioned physical mechanisms because there are still neither storm induced circulation nor composition changes. Analyzing 65 strong geomagnetic storms observed over the period 1995−2005, *Burešová and Laštovička (2007)* observed that the pre-storm enhancements do not exhibit a systematic latitudinal dependence and are not accompanied by a corresponding change of *hmF2*. It is assumed that they could be the effect of a particle precipitation in the high latitude region as already was suggested by *Kane (2005)*. Supporting this explanation is the earlier (before SSC) enhancement of *AE* index (not shown here), indicative of high energy input to the high latitude region. That implicates that energetic particles might precipitate to this region leading to the ionization enhancement.

The long-duration positive storm disturbances could be caused by an uplifting of the F layer due to winds. As was mentioned, in winter the zone with increased N_2/O ratio is confined at high and mid-high latitudes in the daytime ionosphere because the background and the storm-induced circulation are opposed. The increased heating at F layer heights in the high latitude region by the prolonged injection of energy into the thermosphere results in an intensification of the storm-induced circulation. Since during daytime the region of composition change is "stopped" in the middle-high latitude region (see the negative disturbance at Hobart and Canberra), the intensified storm-time circulation arrives to middle latitudes because it is stronger than background (quiet) circulation. Thus the mid-low latitude region is possibly exposed to only equatorward winds which lift the ionization to greater heights at a time when the production is still occurring. That possibly explains the long-duration positive disturbances under these conditions. However, it seems to be a local effect.

Summarizing, the results of the analysis of the variations of the critical frequency *foF2* at four chains of ionospheric stations located at different meridian sectors during the storm on July 15, 2000 are useful to validate the effectiveness of some physical mechanisms during geomagnetic storms. However, further case studies are needed to confirm the relative importance of particles precipitation and large-scale changes in the thermospheric circulation to cause the positive disturbances. Also, if the small and irregular negative disturbances observed at low latitudes in winter hemisphere are primarily caused by the penetration of composition bulge from the summer hemisphere as proposed some numerical predictions (e.g, *Fuller-Rowell et al. 1994*).

The main features observed may be summarized as follows:

- Long-duration negative disturbances at mid-high latitudes (40−55 degrees of geomagnetic latitude) in summer hemisphere in sectors where the storm onset occurred in the afternoon/night-time hours. These storm effects intensified during the main phase and first part of the recovery of the storm.
- Positive disturbances in both hemispheres at mid-high and mid latitudes prior to the storm onset irrespective of the local time. At mid-high latitudes in both hemispheres these effects change to negative around the second SSC.
- Delayed short-duration positive disturbances in the summer hemisphere effects at mid-high latitudes in the pre-sunset hours during the end of the main phase-first stage of the recovery.
- Small and irregular negative disturbances in the low latitude winter hemisphere, which predominate during the main phase and first part of the recovery.

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