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Ionospheric storm effects at the equatorial anomaly

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Abstract. Ionospheric disturbances produced at the equatorial anomaly (EA) region during some geomagnetic storms were investigated using hourly N_mF2 peak electron density of $F2$-layer values from stations located at equatorial and low geomagnetic latitudes. In general, increases (positive storm effects) or decreases (negative storm effects) of N_mF2 (proportional to square of f_oF2 ionospheric critical frequency) in the nighttime hours were observed at equatorial latitudes in response to storms started during sunset hours. For the storm onset occurring during morning hours an intensification of the fountain effect was produced. For the storms starting in the nighttime hours, no significant disturbances appeared at the crest regions in association with the initial positive or negative effects observed at the trough in the daytime. During the recovery phase in general, significant delayed positive storm effects occurred mainly at low latitudes and a minor degree at equatorial latitudes. Possible physical mechanisms for controlling the morphology of the ionosphere during these events are considered.

1. Introduction

A feature of the ionospheric $F2$ region in the vicinity of the magnetic equator is the so-called Appleton or equatorial anomaly (EA). This is characterized by a depression in the electron density or "trough" centered about the geomagnetic equator, and two peaks (crests) on both sides of the equator at about magnetic latitude $\pm 10 - 20^\circ$.

The EA is due to a "fountain effect" caused by the $\mathbf{E} \times \mathbf{B}$ upward electrodynamic drift of the plasma over the equator during daytime. The plasma then diffuses downward along magnetic field lines under the influence of gravity and pressure gradient forces to subequatorial latitudes.

Most studies of the response of the $F2$ region to geomagnetic storms at the EA region have been performed with measurements from one particular ionospheric station. However, many studies of the equatorial anomaly region have been carried out using modeling techniques, and there are a few studies of the ionospheric reaction simultaneously observed in several stations with experimental data. During geomagnetic storms, both increases and decreases of ionization (the so-called positive and negative ionospheric storm effects, respectively) are observed.

Electric fields, thermospheric meridional winds and changes in the neutral gas composition have been suggested as probable physical mechanisms to explain the $F2$-region reaction to geomagnetic disturbances [see, e.g., *Buonsanto*, 1999; *Danilov*, 2001, and references therein; *Prölss*, 1995].

Positive ionospheric storm effects are primarily observed above the magnetic equator during the main phase of the storms and during the daytime [e.g., *Adeniyi*, 1986; *Mikhailov et al.*, 1994]. However, negative ionospheric storm effects may be observed during severe geomagnetic storms [e.g., *Adeniyi*, 1986; *Batista et al.*, 1991; *Turunen and Rao*, 1980].

At low latitudes (crests), negative ionospheric storm effects in association with the positive effects at the minimum of EA have been observed [*King et al.,* 1967]. Delayed positive storm effects have been also observed at low latitudes [e.g., *Mayr et al.*, 1978; *Rishbeth*, 1991].

In this paper an attempt is made to illustrate some features of the response of the ionospheric peak electron density N_mF2 of the $F2$ layer at the EA region during geomagnetic

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Table 1. Magnetic Storms Used in the Study

Date	Sudden Commencement, UT	Minimum Dst, nT
15 March 1960	0818	−148
4 June 1960	0242	−97
6 Oct. 1960	0236	−287
24 Oct. 1960	1448	−136
10 May 1964	0036	−72
17 April 1965	1312	−158

storms. For this, simultaneous N_mF2 values (calculated as N_mF2 [m^{-3}] $= 1.24 \times 10^8\, f_oF2^2$, where f_oF2 is the critical frequency in Hz) from a chain of ionospheric stations located in the range of 278°E–295°E geographic longitude at equatorial and low geomagnetic latitudes were used. In addition, some possible physical mechanisms of the observed features are briefly considered.

In Table 1 the considered geomagnetic storms are listed. These storms were selected because no more recent simultaneous f_oF2 measurements from a chain of stations with similar longitude located below the EA have been found. Although the available data are rather old, the additional information obtained from this study is useful for the knowledge of the global morphology of the upper atmosphere and the physical interpretation of the ionospheric effects of geomagnetic storms. The ground-based hourly f_oF2 data were collected from the Space Physics Interactive Data Resource (SPIDR) of the NGDC NOAA for the stations listed in Table 2. The Dst geomagnetic index was used to specify the different phases of the storms. For the six events considered in this study, four had the sudden commencement (SC) during nighttime hours (local sunset to local predawn) and two during the daytime hours (2–3 hours before local noon).

In general, the ionospheric reaction to geomagnetic storms was analyzed on the storm day and the two following days. In order to see the disturbance degree during the storm, N_mF2 values from perturbed periods were compared with those obtained on undisturbed control days of the month of the storms (solid circles in the figures).

2. Results

Figure 1 shows the ionospheric storm effects (in logarithmic scale) observed during the period covering the storm on 15 March 1960. The development of Dst index during the storm is shown at the top, followed by the time variations of the peak electron density N_mF2. The SC occurred in the nighttime hours. The main phase remained about 24 hours until around 0700–0800 UT on 16 March followed by a long-duration recovery phase.

At equatorial latitudes (Talara, Huancayo and La Paz), irregular negative storm effects were observed in response to SC ($\sim$ 70% maximum change occurring during the first stage of main phase). These effects remained until around 0000 UT on 16 March after which, at Talara and Huancayo a trend to recover undisturbed values was observed. La Paz exhibited a delayed enhancement in N_mF2 of about 100–120% between 0300 and 1000 UT on 16 March in the nighttime hours, during the end of main phase and beginning of recovery, suggesting a regional phenomenon. At the south crest of EA, although the measurements are scant, it can be seen that no significant reaction to the storm was initially produced. During the recovery phase a fluctuating positive effect in the daytime hours was observed, followed by an irregular behavior, which includes a conspicuous depression on 17 March.

The structure observed during the main phase of the storm seems to indicate that the equatorial anomaly in the daytime hours was less developed than during a quiet day; that is, there is an inhibition of the fountain mechanism.

In Figure 2 the variations for the geomagnetic storm that occurred on 4 June 1960 are presented. The development of the main phase corresponds to the evening hours of the local time (until about 0800 UT on 4 June), and it was followed by a fluctuating recovery phase.

Similar positive storm effects arose shortly after SC at equatorial stations Talara, Huancayo, and La Paz (up to 400% change) which remained until 1100 UT on 4 June; these effects were followed by smaller enhanced values that do not exceeded 70–80% during the recovery. Significant delayed increases of ionization were observed at all these stations from after midnight to predawn local (0700–1200 UT on 5 June). At the south crest of EA, no noticeable reaction to the storm was presented during the main phase and

Table 2. Ionospheric Stations and Their Coordinates

Station	Code	Geographic Latitude	Geographic Longitude E	Geomagnetic Latitude	Geomagnetic Longitude
Bogota	BG	4.5	285.8	15.9	4.9 W
Talara	TA	−4.6	278.6	6.6	11.9 W
Huancayo	HU	−12.0	284.6	−0.6	5.7 W
La Paz	LP	−16.5	292.8	−5.0	1.3 E
Tucuman	TU	−26.9	294.6	−15.5	3.8 E

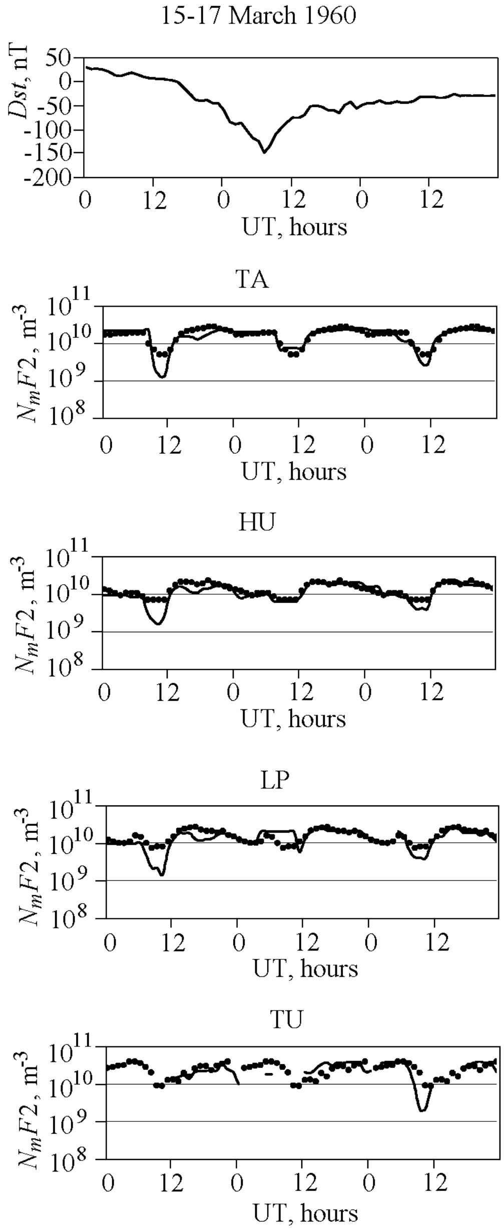

Figure 1. *Dst* index and N_mF2 variations during the 15–17 March 1960 disturbance event (solid line). Solid circles indicate N_mF2 values for a control day: 9 March.

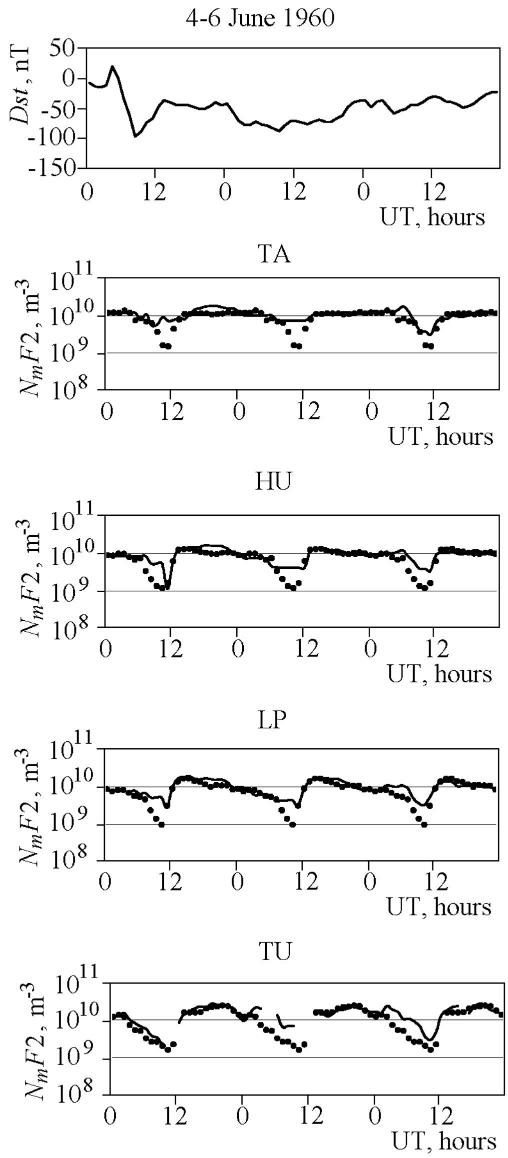

Figure 2. Same as Figure 1, but for the 4–6 June 1960 disturbance event. Control day: 12 June.

first stage of the recovery. Although there is a gap of data during the recovery phase, a strong delayed positive disturbance (higher than 300%) appeared there from nearly dusk to predawn local (0000 to 1200 UT on 5 June).

The classical ionospheric disturbance in response to geomagnetic storms was partially seen since increases of ionization at the equatorial region were observed during daytime hours (early part of the recovery phase). The difference was that no appreciable disturbances are seen at low latitudes.

Figure 3 shows the variations of *Dst* index and N_mF2 values for the geomagnetic storm on 6 October 1960. As for the previous storm, the SC occurred in the nighttime hours. The end of the main phase was during sunset hours (0100 UT on 7 October). No data for Tucuman were available.

No similar f_oF2 disturbances than preceding storm were initially seen in response to SC. Decreases arose nearly 2 hours after SC at Talara and Huancayo. The gap of control data at La Paz does not allow us to trace the variation of N_mF2 during the first stage of the main phase, but the available data evidence a decrease. The negative storm effects abruptly changed to positives (higher than 90%) in the daytime hours from around 1400 UT to 1–2 hours before the minimum *Dst*. During the recovery phase, oscillating behaviors with negative effects followed by significant positive effects were observed.

In Figure 4 the variations of *Dst* index and N_mF2 val-

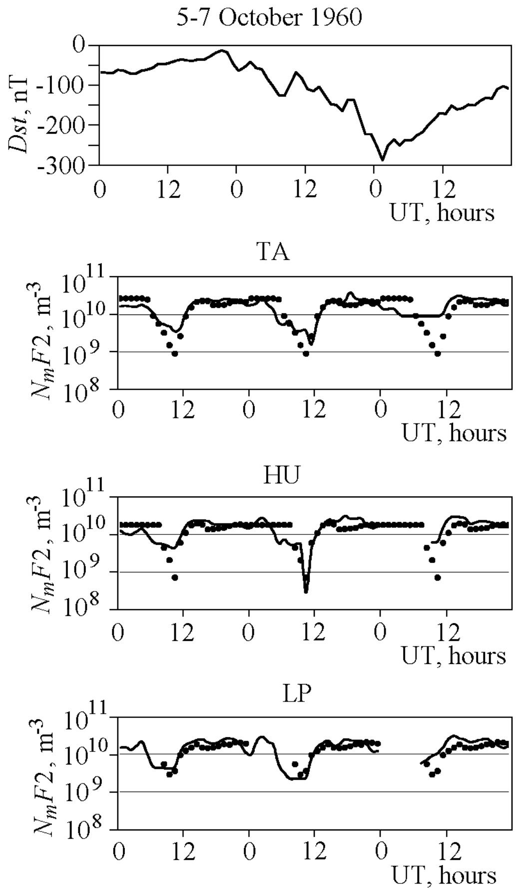

Figure 3. Same as Figure 1, but for the 5–7 October 1960 disturbance event. Control day: 23 October.

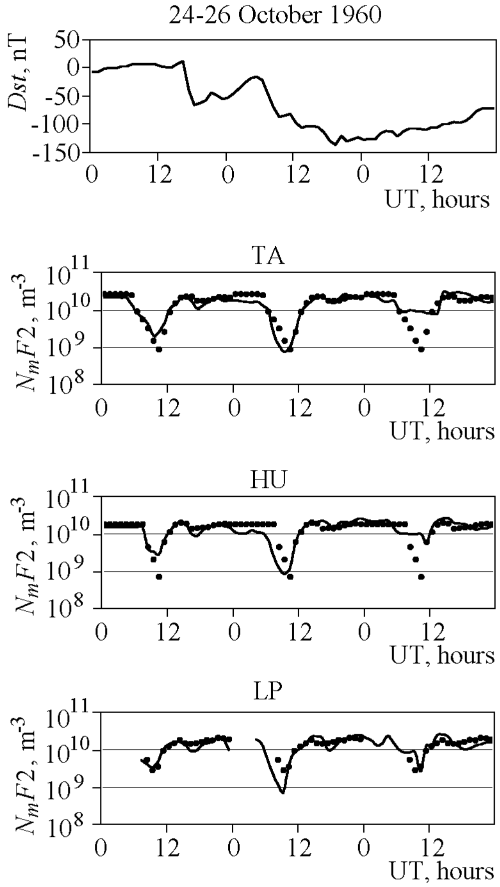

Figure 4. Same as Figure 1, but for the 24–26 October 1960 disturbance event. Control day: 23 October.

ues taken during the storm on 24 October 1960 are shown. No measurements for low latitudes (Tucuman) are available. The storm sudden commencement occurred in this longitudinal sector in the morning hours. The storm exhibited a fluctuating main phase and no recovery to prestorm conditions during the considered period. The minimum Dst was produced near local noon at about 1900 UT on 26 October.

Increasing negative storm effects appeared in response to SC at the equatorial region, followed by no apparent storm effects at around the end of the main phase. During the recovery, significant short-duration positive storm effects arose in the first hours of the day at Talara and Huancayo (higher than 400% increase) and a minor degree at La Paz.

The variations for Dst and N_mF2 data along equatorial and low-latitude stations for the storm occurred on 10 May 1964 are shown in Figure 5. The storm started in sunset hours. A long-lasting main phase (of about 24 hours) until around 0100–0200 UT on 11 May was followed by a slow recovery.

A localized small positive effect ($\sim$ 100% change) at Talara and minor disturbances at the remaining stations were the features observed during the growth of the main phase at the equatorial region. At both the crest's irregular increases of ionization in the night hours accompanied the positive effect observed at the equator. During the recovery phase, substantial positive effects arose at the crests (note the asymmetry in magnitude of the crests), in a more minor degree at Tucuman than at Talara, while negative effects are observed at La Paz and there was no significant storm effect at Huancayo.

Figure 6 presents the variations of Dst index and the ionospheric storm effects during the storm that began on 17 April 1965. The sudden commencement occurred in the morning hours. The main phase remained until 0900 UT on 17 April followed by a long-duration recovery with values that not return to levels prior to the onset of the storm.

No f_oF2 measurements for Tucuman were available. Irregular negative storm effects occurred at Huancayo and La Paz ($\sim$ 50% change) from around local noon and delayed at Talara. These effects continued until nearly the local dawn on 18 April (around 1200 UT); they were replaced by small positive effects in the daytime hours during the recovery of the storm. At the north crest of EA an increasing positive effect was produced in response to SC abruptly terminating in the afternoon hours, followed by no significant disturbances. The behavior observed at equatorial and low latitudes indicates an intensification of the fountain effect mechanism in the daytime hours during the main phase of the storm.

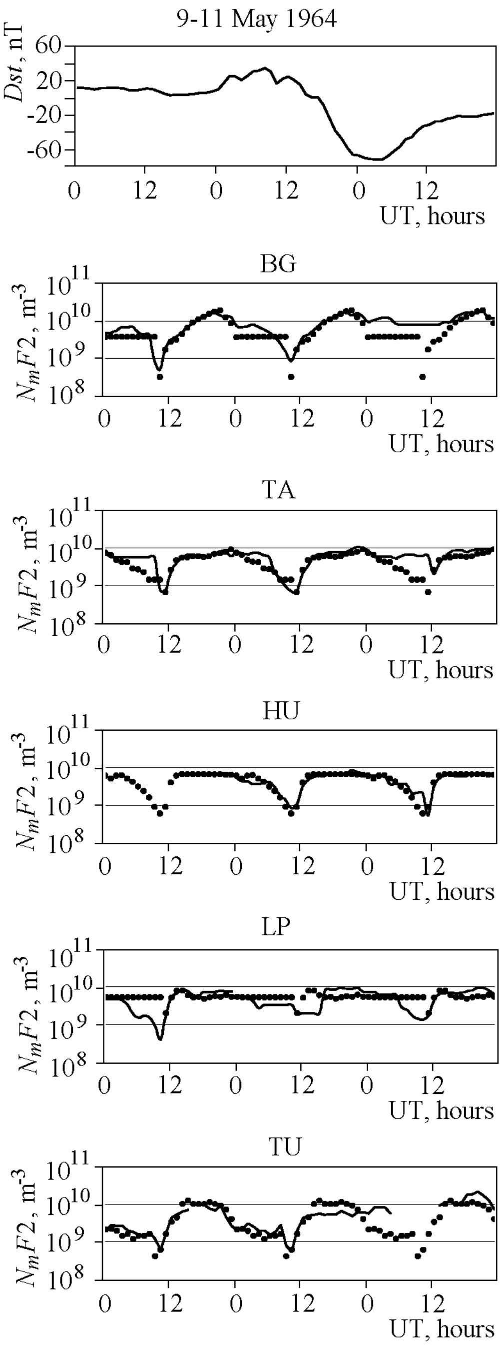

Figure 5. Same as Figure 1, but for the 9–11 May 1964 disturbance event. Control day: 8 May.

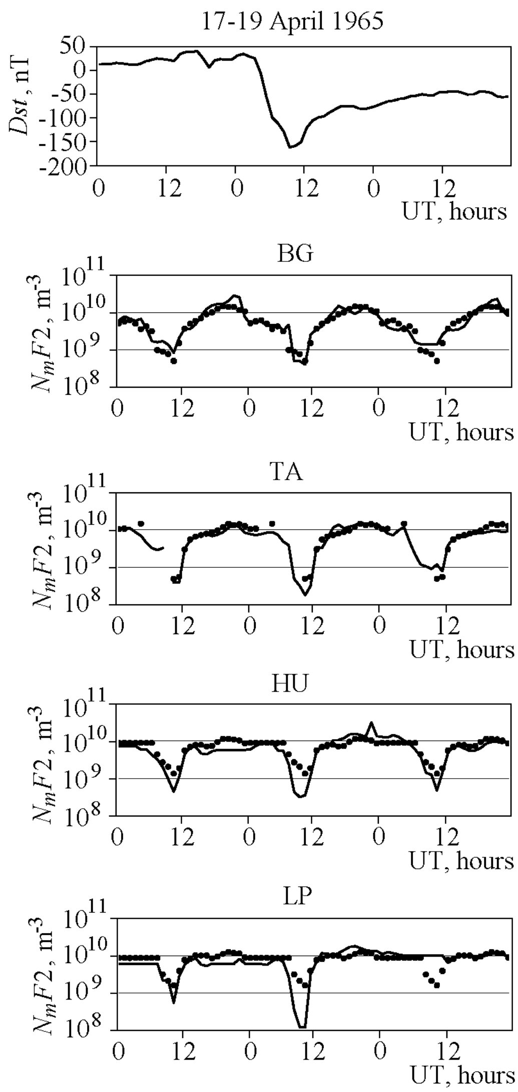

Figure 6. Same as Figure 1, but for the 17–19 April 1965 disturbance event. Control day: 12 April.

3. Discussion and Conclusions

Some features of the ionospheric disturbances at the equatorial anomaly in association with geomagnetic storms have been considered. The behavior of the peak electron density was quite different from one storm to other. The main observational results can be summarized as follows:

For similar local time of SC occurrence, the ionospheric responses in the same longitudinal sector differed appreciably.

Both positive and negative effects in the nighttime hours at equatorial latitudes were observed in response to storms started during sunset hours.

During the recovery phase of storms, significant delayed positive storm effects occurred mainly at low latitudes and a minor degree at equatorial latitudes.

No correlation between the intensity of the geomagnetic storm and the amplitude of the initial disturbances was observed.

For the storm onset during morning hours an intensification of the fountain effect is produced.

In general, for the storms started in the nighttime, no significant disturbances appeared at the crest regions in association with the initial positive or negative effects observed at the through in the daytime hours. That seems to indicate a smoothing of the EA, when the crests are less tall than a quiet day.

Although this paper does not seek to discuss in detail the responsible physical mechanisms that produce the ionospheric disturbances, the various accepted mechanisms operating in the equatorial $F2$ region during perturbed conditions are briefly considered.

As mentioned in section 1, the formation of the EA can be explained by a $\mathbf{E} \times \mathbf{B}$ upward drift of ionization. Tidal motions of the thermosphere primarily cause the electric fields responsible for the "fountain effect" formation. The magnetospheric electric field is relatively weak in the equatorial region due to the shielding effects by space charge, which builds up at the Alfvén layer. However, the shielding layer cannot respond to changes in the magnetospheric electric field in short time scales (shorter than 20 min). Thus through this mechanism a large electric field can penetrate to the $F2$-region height during magnetically disturbed periods and to cause the equatorial $F2$-layer perturbations.

Negative storm effects initially produced at the valley of EA are usually attributed to an enhancement in the eastward electric field, resulting in an increase of the upward plasma drift and a subsequent drainage of ionization from the equatorial region toward low latitudes [e.g., *Batista et al.*, 1991; *Rasmussen and Greenspan*, 1993]. This could be the cause of these initial effects observed in the ionospheric stations since a fairly rapid mechanism is required to produce a response with a slight time lag.

However, decreases of the electric field are also observed during disturbed periods [e.g., *Fejer*, 1981, 1991], which would produce decreases of the upward plasma drift and subsequent positive N_mF2 storm effects at the trough of EA as occurred during the growth of main phase and early stage of the recovery.

It is believed that equatorward storm time circulation also plays an important role at equatorial $F2$ layer. These winds are opposed to the poleward transport of ionization along the magnetic field lines so hinder the formation of the EA [e.g., *Burge et al.*, 1973], generating negative storm effects in the anomaly crest region and positive storm effects near the equator. These effects are expected to be produced with a time delay with respect the storm onset since a few hours are required for the generation and propagation of the storm winds toward low latitudes.

Although a very few events were considered, this mechanism seems to be partially operative during the recovery phase of the storm started on 4 June 1960 since while positive storm effects were observed at the trough, no storm disturbances occurred at the crest regions, suggesting the possible validity of this concept.

Winds possibly play a dominant role also during the recovery phase of the storm. As was suggested [e.g., *Prölss*, 1995, and references therein], the storm induced large-scale thermospheric circulation transports air rich in atomic oxygen toward low latitudes. This enhanced oxygen density will affect both the ionization production and diffusion, leading to positive storm effects.

Significant increases of atomic oxygen during the recovery phase of intense geomagnetic storms in association with increases of electron density have been observed from satellite measurements, suggesting that this might be the major cause of the enhancements of ionization [*Mansilla*, 2003].

Increases in electronic and neutral temperatures observed during the main phase of intense geomagnetic storms [*Mansilla*, 2003] may contribute to the maintenance of the long-duration decreases in N_mF2. An increase of neutral temperature leads to an increase in the recombination coefficient, which leads to an increase in the loss rate.

In brief, several physical mechanisms appear to leave their signatures in the equatorial and low-latitude ionosphere during geomagnetic storms. The degree of importance seems to depend of the different stages of the storms.

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