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# Disturbances at F2-region heights of equatorial anomaly during geomagnetic storms

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**Abstract**

Neutral gas composition and ionospheric measurements taken by the Dynamic Explorer 2 satellite at F2-region heights during two geomagnetic storms are used to analyze the role of some possible physical mechanisms responsible for the changes of electron density at equatorial and low geomagnetic latitudes. The storms considered occurred on October 2, 1981 (storm 1) and July 13, 1982 (storm 2). During storm 1 (weak), vertical plasma drifts and equatorward storm-time winds operated increasing of the electron density at the trough of equatorial anomaly and the decreases at the crest region. During storm 2 (intense) changes of composition (increase of molecular nitrogen and atomic oxygen) played a fundamental role for the changes of electron density observed at low latitudes in summer hemisphere. It is concluded that different physical processes seem to have varying degrees of importance depending on the intensity of the storm.

*Keywords:* Geomagnetic storm; Equatorial anomaly; Electron density; Gas composition

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## 1. Introduction

A feature of the ionospheric F-region at low latitudes is the so-called equatorial anomaly (EA), which is the latitude variation of electron density with a depression or "trough" centred about the geomagnetic equator and two peaks (crests) at about magnetic latitude ±10–20°.

The EA is due to a "fountain effect" caused by the EẋB upward electrodynamic drift of the plasma over the equator which then diffuses downward along magnetic field lines under the influence of gravity and pressure gradient forces to subtropical latitudes.

The structure of EA is different during geomagnetic storms. Electric fields, thermospheric meridional winds and changes in the neutral gas composition have been suggested as probable physical mechanisms to explain the F2-region reactions to geomagnetic disturbances (see for example Prölss, 1995; Buonsanto, 1999; Danilov, 2001, and references therein).

Above the geomagnetic equator, increases of ionization (the so-called positive ionospheric storms or positive ionospheric effects) are frequently observed during the main phase of the storms and during the daytime (e.g., King et al., 1967; Adeniyi, 1986; Mikhailov et al., 1994). Electric field measurements during geomagnetic storms (Fejer, 1981, 1991; Fejer and Scherliess, 1997; Scherliess and Fejer, 1997) show a decrease at the equatorial zone of the eastward electric field (during sunlit hours) which leads to a reduction of the upward drift and so to the positive storm effects.

However, decreases of ionization (the so-called negative ionospheric storms or negative ionospheric effects) may be observed during severe geomagnetic storms (e.g., Turunen and Rao, 1980; Adeniyi, 1986; Batista et al., 1991).

These negative ionospheric storm effects are usually attributed to an enhancement in the eastward electric field, resulting in an increase of the upward plasma drift and a

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subsequent drainage of ionization from the equatorial region (e.g., Batista et al., 1991; Rasmussen and Greenspan, 1993).

Equatorward storm-time circulation also plays an important role at equatorial F2-region. These winds are opposed to the poleward transport of ionization along the magnetic field lines, so hinder the formation of the EA, and lead to negative storm effects at peaks and positive ones at the trough.

These winds blow in such a way that they may reduce the quiet-time electric dynamo field and also produce similar effects (Blanc and Richmond, 1980).

However, these effects are expected to be produced with a time delay with respect to the storm onset since a few hours are required for the generation and propagation of these storm winds toward low latitudes.

Delayed positive storm effects observed at low latitudes have also been attributed to changes in the neutral gas composition (e.g., Mayr et al., 1978; Rishbeth, 1991). According to this mechanism, it is believed that the storm-induced circulation transports air rich in atomic oxygen toward lower latitudes. That leads to an increase of the ionization production and subsequent positive effects.

In this paper, an attempt is made to analyze the effects of the above mentioned physical mechanisms during the different phases of two geomagnetic storms, by using simultaneous atmospheric and ionospheric measurements taken by the Dynamic Explorer 2 satellite at F2-region heights at equatorial and low geomagnetic latitudes. The events considered in this study occurred on October 2, 1981 (weak storm) with peak $D_{st} = -50$ nT and July 13, 1982 (intense storm) with peak $D_{st} = -325$ nT (provided by solar—geophysical data prompt reports).

During geomagnetic perturbed periods, no satellite measurements are often available or they are scant. In spite of these difficulties, during these two geomagnetic storms, a considerable amount of data was found at equatorial and low latitudes.

The atmospheric data are molecular nitrogen ($N_2$) and atomic oxygen (O) composition measurements; the ionospheric ones are electron density and vertical ion velocity.

## 2. Results

The $D_{st}$ geomagnetic index was used to specify the different phases of the storms. Fig. 1 shows the development of $D_{st}$ during October 2–4, 1981 (storm 1) and July 13–15, 1982 (storm 2). The sudden commencements of storms 1 and 2 were at 2022 UT on October 2 (SC1 in Fig. 1) and 1617 UT on July 13 (SC2 in Fig. 1), respectively. The main phase onset (MPO) was at 22 UT on October 2 and 17 UT on July 13 while the main phase end (MPE) was at around 19 UT on October 3 and 02 UT on July 14. The recovery toward prestorm levels (recovery phase of the storm) lasted for more than 24 h in both storms.

The upper atmosphere reaction to geomagnetic storms was analyzed on the storm day and the two following days.

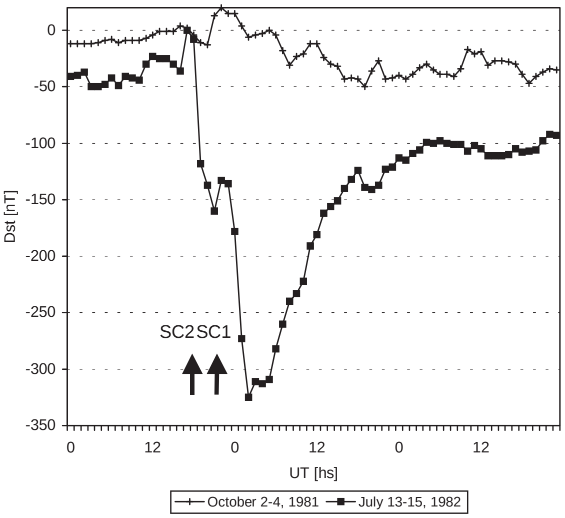

Fig. 1. Hourly Dst geomagnetic index on October 2–4, 1981 (storm 1) and July 13–15, 1982 (storm 2). The arrows indicate the sudden commencements of the storms.

For this, the relative deviations of the measured parameters from their respective reference values, in percentage, were calculated. For storm 1, measurements taken prior to the beginning of the storm were used as a quie-time reference since the storm was preceded by quiet conditions while for storm 2, measurements were taken a few days before storm commencement (July 9, $\Sigma k_p = 18$; Ap=10).

Data at heights between 300 and 320 km for storm 1, and between 280 and 300 km for storm 2 were selected from the satellite measurements; they were taken at approximately 10.2 and 15 h solar local time. Respective reference values have been selected with the same characteristics both in altitude and in time. Although neutral species composition changes exponentially with altitude and relatively small change in altitude results in a potentially large change in composition, a small range of altitudes was adopted to make negligible possible height variation effects.

The different UT of observation (satellite passes) during storm 1 are as follows:

October 2 (reference): 0145–0154 UT (122°E),

October 3: 0519–0528 UT (69°E); 1955–2003 UT (210°E),

October 4: 0853–0901 UT (13°E); 1347–1353 UT (30°E).

The corresponding UT of observation for storm 2 are

July 9 (reference): 2029–3035 UT (284°E),

July 13: 2028–2036 UT (281°E),

July 14: 1342–1353 UT (21°E); 2000–2011 UT (207°E),

July 15:0048–0054 UT (215°E).

Fig. 2 shows the equatorial and low-latitude variation of the relative deviation of electron density $N_e$ between 300 and 320 km in response to geomagnetic storm 1. In the figure, solid line represents the reference $N_e$ values. It can be

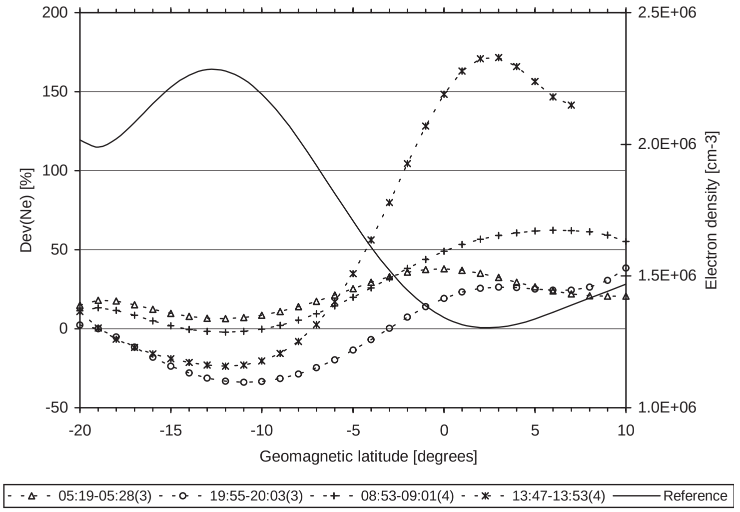

Fig. 2. Equatorial and low-latitude variation of the relative deviation of electron density between 300 and 320 km during five satellite passes on October 3–4, 1981 (left-hand scale). Solid line represents reference values (right-hand scale).

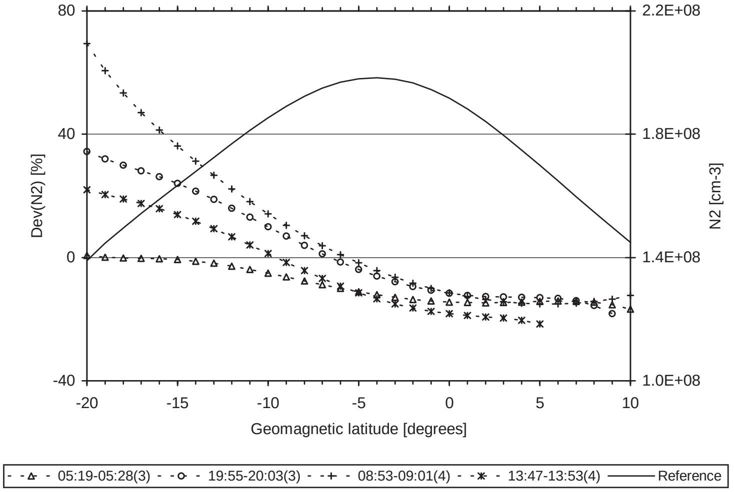

Fig. 3. The same as Fig. 2, but for molecular nitrogen.

seen that the electron density is enhanced in the equatorial trough during the different phases of the storm. The relative deviation increases during storm evolution; values of about 40% and 150% during the main and recovery phases, respectively, are observed. At the crest region, an oscillating behavior with small increases of about 15% during the main phase development and decreases of about 30–40% during the end of the main phase and recovery phase are produced.

Fig. 3 presents the associated relative variation for molecular nitrogen concentration during storm 1 as well as the reference values (solid line). Above the magnetic equator, $N_2$ is below reference values during the entire storm period. The maximum negative relative deviation does not exceed 20% and it is observed during the recovery phase. At the crest region, no change is initially seen during the main phase development, while during the end of this stage and recovery phase, enhanced values increasing with latitude are observed. For instance, during the recovery phase the relative deviations are 35% at $-15°$, and 70% at $-20°$. A trend to prestorm levels (relative deviation tending to zero) is observed during the last stage of the storm.

Fig. 4 shows the relative deviations for atomic oxygen composition. O latitudinal reaction to the storm is similar to the $N_2$ reaction. At equatorial latitudes, a decrease that does not exceed 10% is observed, the greater deviation occurring during the main phase, while at low latitudes positive

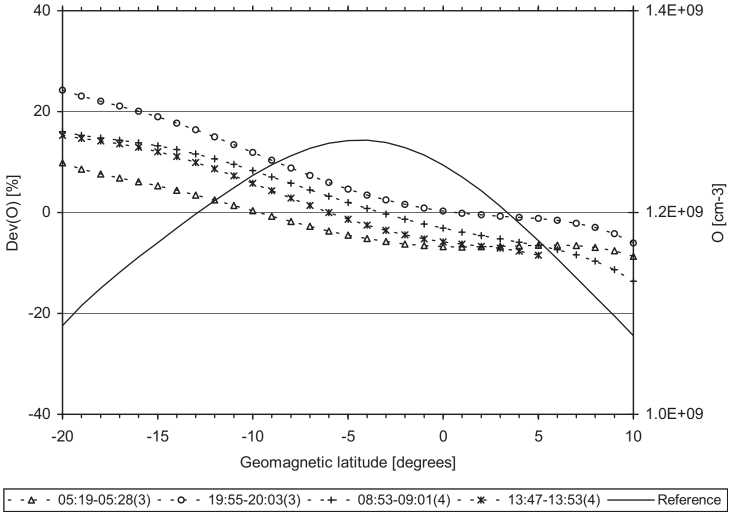

Fig. 4. The same as Fig. 2, but for atomic oxygen.

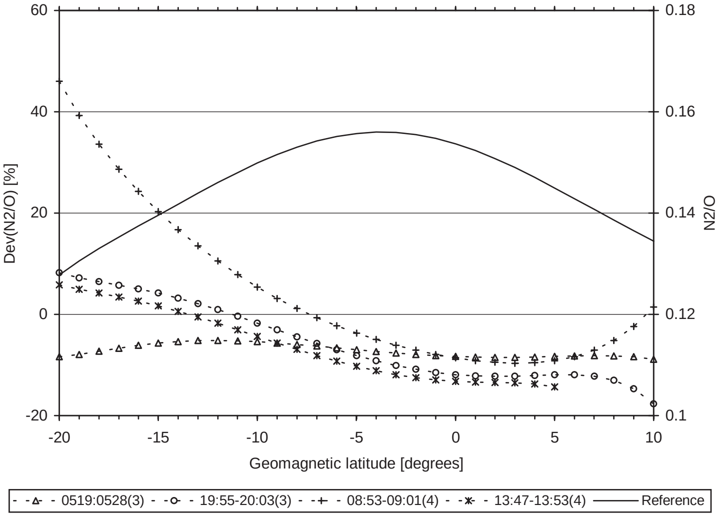

Fig. 5. The same as Fig. 2, but for the $N_2/O$ ratio.

variations increasing with latitude are observed which are in general below 20%.

According to these observations, the delayed strong positive variation on $N_e$ at equatorial latitudes during recovery phase cannot be explained in terms of atomic oxygen increase as was suggested, at least during this weak storm.

Fig. 5 presents the corresponding relative deviations of the $N_2/O$ ratio. The initial changes in $N_e$ at low latitudes would not be related to neutral composition changes, since they seem to be insufficient to produce considerable $N_e$ disturbances because negative deviations in the $N_2/O$ ratio smaller than 15% have been observed. Moreover, at low latitudes, a decrease in $N_e$ is not observed in association with the significant increase in $N_2/O$.

Relative deviations of the neutral temperature $T_n$ from their respective quiet values (not shown) do not exceed 2–3% during the weak storm. This suggests that no appreciable increase in the recombination coefficient, which leads to decreases in $N_e$, is produced. Other different mechanisms may essentially contribute to produce $N_e$ disturbances.

Fig. 6 shows the changes of relative deviations of vertical ion drift. At equatorial region (although there is an $N_e$ enhancement), practically no change occurs during the main phase evolution. During the end of the main phase and early

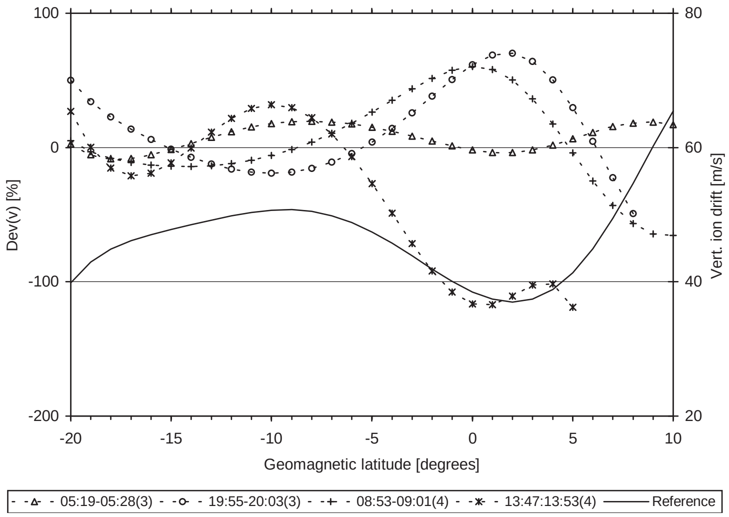

Fig. 6. The same as Fig. 2, but for vertical ion drift.

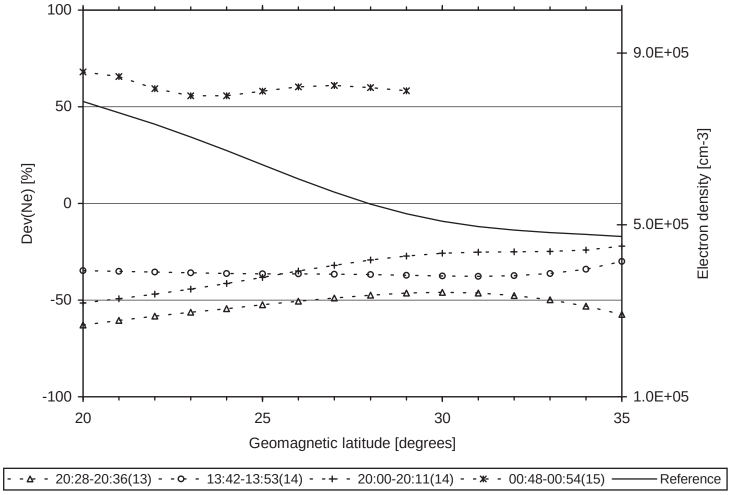

Fig. 7. Low-latitude variation of the relative deviation of electron density between 280 and 300 km during four satellite passes on July 13–15, 1982 (left-hand scale). Solid line represents reference values (right-hand scale).

part of the recovery phase increase of about 60% in association with $N_e$ enhancements are presented in this region. During the recovery phase, the vertical drift falls by about 120% suggesting that the significant increase in the electron density is strongly related to the vertical drift of ionization (see below). At low latitudes the storm-time behavior shows a very complicated pattern, and seems not be statistically significant. Consequently, it shall not be discussed here.

Fig. 7 shows the relative deviation of $N_e$ between 280 and 300 km for storm 2 at the crest region and at low latitudes (solid line represents reference values). At the crest region and outside the crest, depressed and nearly constant relative deviations (negative storm effects) are observed during the main phase and early part of the recovery phase of the storm. Subsequently, above the crest region an increase of about 60% is observed during the end of the recovery phase.

Fig. 8 presents the $N_2$ reaction to geomagnetic storm 2. During the main phase, unlike storm 1 when no variations are seen, significant relative increases at the crest region (200–220%) and also at low latitudes (120–180%) are observed. These deviations decrease during the recovery phase of the storm. However, they remain considerably above the reference values mainly near the crest with increase of the order of 80% or more.

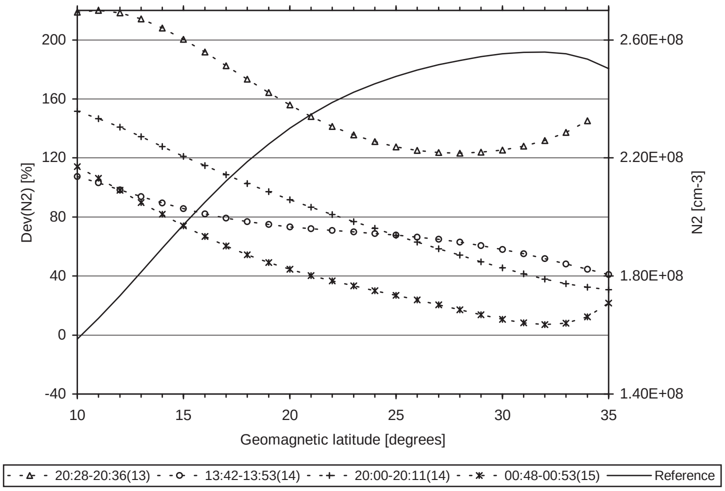

Fig. 8. The same as Fig. 7, but for molecular nitrogen.

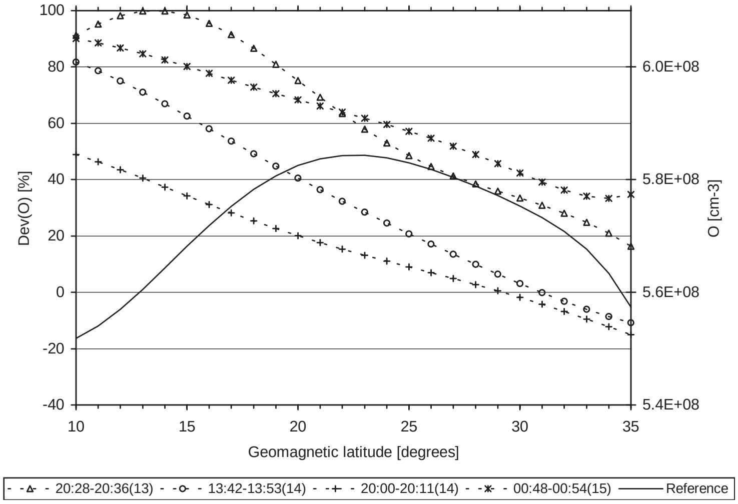

Fig. 9. The same as Fig. 7, but for atomic oxygen.

Fig. 9 shows the relative deviation of O composition. As in $N_2$ reaction to the storm, during the main phase of the storm significant increases are observed to occur at the crest region (∼ 90–100%) and a minor degree at latitudes between 20° and 30° (∼ 40–80%). During the recovery phase, an initial decrease in the magnitude of the relative deviation followed by an important increase (up to values near to the main phase) during the end of the recovery is observed. At latitudes higher than 25°, increase larger than during the main phase occurred.

The fact that considerable variations in $N_2$ and O are observed suggests that these might be the major cause of the $N_e$ changes during the storm.

Fig. 10 presents the relative deviations of the $N_2/O$ ratio for the storm period. At the crest a pronounced increase of about 50–60% in the $N_2/O$ ratio is observed during the main phase of this storm (in accordance with $N_e$ depletion) which would indicate a close relationship between $N_2/O$ increase and negative storm effects as in middle latitudes. Confirming this cause–effect relationship, during the first part of the recovery phase increased values of $N_2/O$ are obtained as before. At the end of recovery, the relative deviation near equator does not exceed 10% while at low latitudes it is negative and of the order of only 10–20%. A speculative explanation of the $N_e$ increase observed at this stage would be that it is caused by the large increase of O composition.

Relative increases of $T_n$ (not shown here) as high as 20–25% during the main phase and first stage of the recovery occurred. The increase of $T_n$ leads to an increase in the recombination coefficient. Thus, the increase in $N_2$ by a

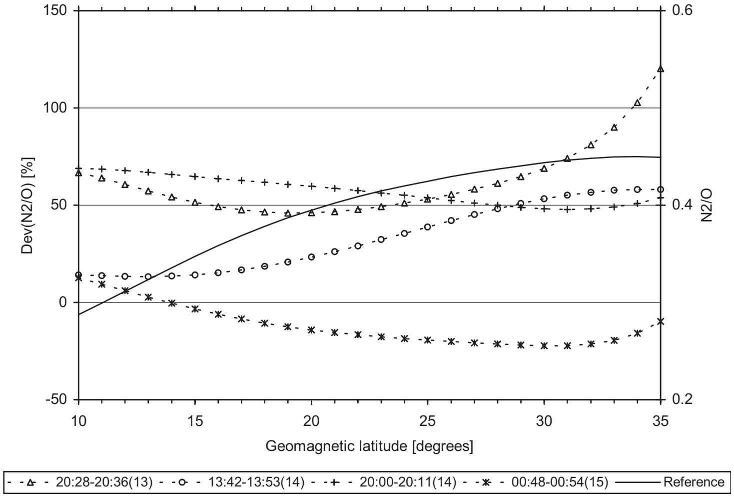

Fig. 10. The same as Fig. 7, but for the $N_2/O$ ratio.

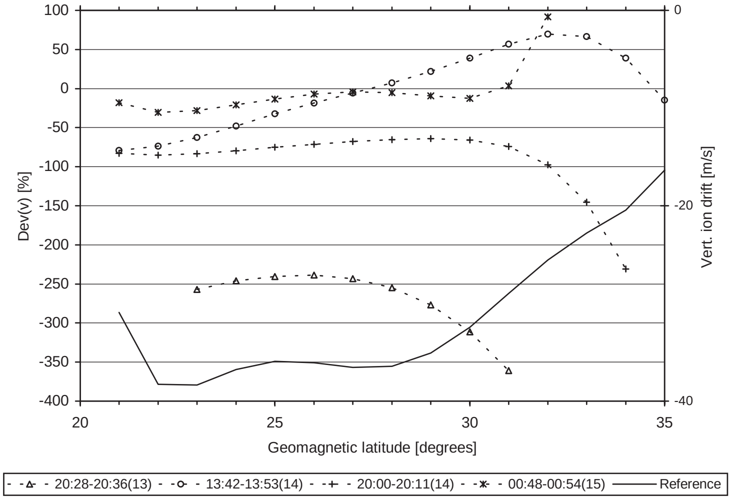

Fig. 11. The same as Fig. 7, but for vertical ion drift.

higher percentage than O and the elevated $T_n$ may be the reason for the $N_e$ decrease in the high- and middle-latitude ionosphere (e.g., Danilov, 2001).

Fig. 11 shows the vertical ion drift relative deviations. During the main phase, significant falls at low latitudes are produced as a consequence of a great upward ion velocity (note that reference values are negative). However, no considerably different $N_e$ values from those obtained during the recovery phase are observed, when the ion drift relative deviation is reduced. Note also that the smaller deviations at the crest region occur during the last stage of the recovery. These results suggest that upward drifts are not responsible for the $N_e$ variations produced in this intense storm and possibly, as was mentioned, the electron density variations are primarily caused by changes in the neutral gas composition.

## 3. Discussion and conclusions

As mentioned in the introduction, several physical mechanisms appear to leave their signatures in the equatorial and low-latitude ionosphere during geomagnetic storms.

In the weak storm, around the trough of EA the $N_2/O$ ratio practically does not change. Besides, no increase of atomic oxygen composition is seen during the recovery phase which seems to indicate that the delayed increases of electron density at equatorial latitudes cannot be attributed to this effect. Therefore, it is likely that the observed positive storm effects are a consequence of the vertical plasma drift. Thus, the strong increase of $N_e$ during recovery phase would be attributed to a decrease in the eastward component of the electric field, resulting in a reduction of the upward drift and so to the positive storm effects, as was suggested (see for example Mikhailov, 2000 and references therein).

However, the increase of ionization at the trough of EA during the end of the main phase and the early part of the recovery phase cannot be explained in terms of a drift mechanism because there is a contradiction between the ionospheric storm effects observed and the upward vertical drifts.

According to the electrodynamic mechanism, one expects to observe depressed electron density values at equatorial latitudes in association with the increased plasma uplift. However, positive storm effects were seen. A speculative and non-verifiable explanation is that possibly the equatorward storm-induced circulation hinders the formation of the equatorial anomaly generating negative storm effects near the crest and positive storm effects at equatorial latitudes, as was initially pointed out by Burge et al. (1973). However, the explanation is not entirely consistent with the observations since there is no deviation above the crest during the early part of the recovery phase.

The changes in $N_2$ and O composition during the intense geomagnetic storm have a profound effect on the $N_2/O$ ratio. The increase of the $N_2/O$ ratio at the crest region during the main phase and first part of the recovery (caused by the increase in atomic oxygen and primarily by the increase in molecular nitrogen) are closely related to the long-duration negative effects at high and mid latitudes (Prölss, 1980, 1987). As was mentioned, the increase of the neutral temperature also may contribute to decreases in electron density.

The composition change is generated in the auroral region due to a large amount of energy deposited during geomagnetic storms. It is transported to mid-latitude regions through a circulation cell created by heating of the high-latitude atmosphere (e.g., Mayr et al., 1978; Prölss, 1980). The intense storms can carry such composition changes to low and even equatorial latitudes (see Prölss, 1995 and references therein).

It is known that the equatorward storm-induced and background circulation coincide in summer hemisphere, which is favorable for the arrival of the air with increased $N_2/O$ to lower latitudes, and so the negative storm effects are produced. Thus, the neutral composition changes seem to be the main mechanism to explain the depletion in the electron density at the crest and low latitudes as was suggested (e.g., Prölss, 1998).

However, the upward vertical drift during the main phase cannot be excluded since the uplifting of the plasma possibly also contributes to the negative storm effects.

With regard to the probable cause for the delayed increase in electron density, it is consistent with results obtained from a global theoretical model (Fuller-Rowell et al., 1994) which considers that composition changes are the primary cause of positive ionospheric effects during the later stages of the storm.

Summarizing, the observations and the previous discussion lead to the conclusion that different physical mechanisms with varying degrees of importance which seem to depend on the intensity of geomagnetic storm are working at equatorial and low latitudes.

During the weak geomagnetic storm, vertical plasma drifts and equatorward winds play an important role in the equatorial ionosphere. Neutral composition changes seem to be insufficient to produce the decrease in the electron density.

No experimental evidence is found for this storm that delayed positive ionospheric storm effect at the trough of EA is attributed to an increase in the atomic oxygen density.

During the intense storm, the composition changes seem to be essentially responsible for low-latitude negative ionospheric storm effects. Increase in the neutral gas temperature would also play an important role in decreasing the electron density.

These composition changes are extended to low and even equatorial latitudes because in summer hemisphere, seasonal and storm-induced winds transporting neutral gas perturbations support each other.

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