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Equatorial and low latitude ionosphere during intense geomagnetic storms

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Abstract

An investigation is made in order to analyse the role of neutral gas composition in the equatorial and low latitude ionosphere during intense geomagnetic storms. To this end data taken by the Dynamic Explorer 2 satellite at 280–300 km (molecular nitrogen N_2 and atomic oxygen O concentrations, electron density and vertical plasma drifts) are used. The sudden commencements of the events considered occurred at 11:38 UT on March 1, 1982, 18:41 UT on November 20, 1982 and 16:14 UT on February 4, 1983. Vertical plasma drifts are the most important contributor to the initial storm time response of the equatorial F region. Neutral composition changes (expressed as an increase in the molecular species, mainly N_2) possibly play a predominant role in the equatorial and low latitude (10–20°) decreases of electron density at heights near F2-region maximum during the main and recovery phases of intense geomagnetic storms. Delayed increases of electron density observed at daytime during the recovery phase may be also attributed to increases in atomic oxygen. At low latitudes possibly a combined effect of O increase and upward plasma drift due to enhanced equatorward winds is the responsible mechanism for the maintenance of enhanced electron density values.

Keywords: Geomagnetic storms; Equatorial anomaly; Ionospheric storms

1. Introduction

It is well known that ionospheric F2-region disturbances are produced in association with geomagnetic storms. Such disturbances basically are increases or decreases of the maximum electron density NmF2 from median or quiet time values. These deviations are denoted as positive or negative ionospheric storms, respectively. An ionospheric storm represents an extreme form of space weather, which can have significant adverse effects on increasingly sophisticated ground and space based technological systems of our society (Kumar et al., 2005).

Thermospheric neutral composition changes with molecular nitrogen N_2 to atomic oxygen O (N_2/O) ratio increase are believed to be the responsible for the negative disturbances observed at mid latitudes. This was confirmed by measurements (e.g., Prölss and von Zhan, 1974; Prölss, 1980, 1987) and model

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calculations (e.g., Burns et al., 1991; Fuller-Rowell et al., 1994). The neutral composition changes (mainly N_2/O ratio increases) alter the balance between electron production and loss rates resulting in NmF2 decreases; they are transported to mid latitudes by the storm-time global circulation driven by high-latitude energy inputs (Joule heating and particle precipitation).

It is believed that the positive F2-region storms at middle latitudes are produced by travelling atmospheric disturbances (TADs). Such TADs are originated from the storm-time energy inputs at high latitudes and propagate with high velocity toward equatorial latitudes (Prölss, 1993). An essential feature of these TADs is that they carry along equatorward-directed meridional winds of moderate magnitude. At middle latitudes these winds cause an uplifting of the F2-region to greater heights where fewer molecular species are present, causing the increase in electron density (see Prölss, 1995 and references therein).

It is believed that practically no change of neutral composition occurs at equatorial and low latitudes during storm periods because there are doubts that the storm-induced circulation is able to reach equatorial zone bringing there the heated gas with increased mean molecular mass. The storm-induced circulation is directed equatorward. In winter, it is opposite to the background thermospheric circulation which is directed poleward. That prevents the composition change penetration to middle latitudes. During the night-time the two circulation (the background and the storm-induced ones) coincide (they both are directed equatorward) and so the air with disturbed N_2/O ratio spreads out to lower latitudes than during the daytime. That leads to rather frequent occurrence of the decreases of electron density at middle latitudes at night in winter. In summer the background circulation is all the day through directed equatorward and thus coincides with the storm-time circulation. That is favourable for the penetration of the air with increased N_2/O ratio to middle latitudes, and so decreases of electron density are frequently observed at middle latitudes both during the daytime and at night (see Danilov, 2001 for details). Thus, the effect of the "competition" between the two circulation (the background and storm-induced ones) almost disappears 35–40° magnetic latitude.

The equatorial F2-region disturbances are generally related to $E \times B$ drifts. Negative ionospheric storms observed in the trough of the equatorial anomaly EA during the initial stage of geomagnetic storms are attributed to an enhancement in the eastward electric field, which increase the upward drift of the plasma from this region toward low latitudes. Positive ionospheric storms are attributed to a decrease of eastward (during sunlit hours) electric field as observations suggested (e.g., Fejer, 1981, 1991; Scherliess and Fejer, 1997). Thus, the electric field disturbances play the most important role in the initial storm-time behaviour of the equatorial F2-region.

In this paper, an attempt is made to show that besides vertical drifts due to electric field perturbations, neutral composition changes play a prominent role in the equatorial and low latitude (10–20°) electron density Ne disturbances at heights near F2-region maximum during the main and recovery phases of geomagnetic storms.

To this end, simultaneous measurements of electron density, neutral gas composition (molecular nitrogen and atomic oxygen) and vertical ion velocity taken by the Dynamic Explorer 2 (DE 2) satellite at heights between 280 and 300 km at equatorial and low geomagnetic latitudes during three intense geomagnetic storms were considered.

2. Results

The Dst geomagnetic index was used to specify the different phases of the storms. The sudden commencements (SC) of the events considered in this study occurred on March 1, 1982 at 11:38 UT (storm 1), November 20, 1982 at 18:41 UT and February 4, 1983 at 16:14 UT (storm 3).

DE 2 measurements took place in a wide range of heights along the satellite track however studied data were all measured at altitudes between 280 and 300 km. There are available just limited amount of data in the selected latitudinal region during geomagnetic disturbances at heights of F2-region for the period of measurements of DE 2 satellite. The data collected were analysed during the main and recovery phases of the storms. Measurements used as reference (quiet time conditions) were selected with the same characteristics that perturbed ones both in altitude and in local time.

Since neutral species composition changes exponentially with altitude and a relatively small change in altitude results in a potentially large change in composition, a small altitude difference (20 km) was considered to assume negligible possible heights variation effects.

The longitudinal variation of data is also neglected since it is assumed that the latitude dependence is stronger than the longitude dependence.

In order to determine the perturbation degree of neutral composition data during storm period relative deviations of disturbed values from their respective quiet time values, in percentage, were calculated.

Fig. 1a shows the Dst geomagnetic index variation for the March 1–3, 1982 storm period (storm 1). The main phase remained until about 3–4 UT on March 2, followed by a gradual recover toward prestorm values (recovery phase).

Fig. 1b presents latitudinal variation of electron density Ne at heights between 280 and 300 km in response to storm 1 for three consecutive satellite passes at 12:28–12:34 UT (March 1), 18:46–18:53 UT (March 2) and 4:21–4:27 UT (March 3) and also the values considered as reference which were taken prior to the storm onset (6:05–6:11 UT on March 1). All the measurements correspond at

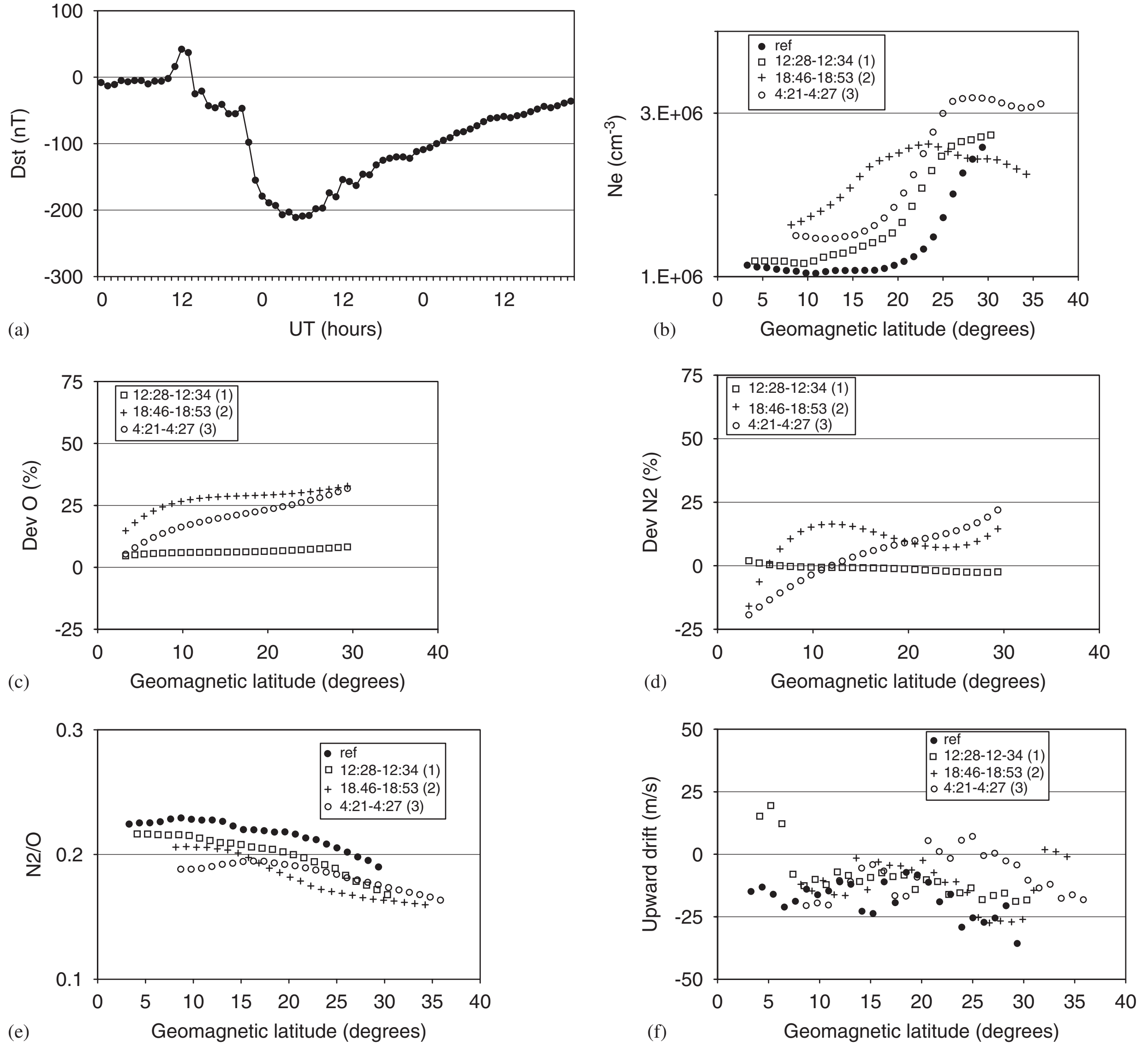

Fig. 1. (a) Hourly variation of Dst geomagnetic index on March 1–3, 1982; Latitudinal variation between 280 and 300 km of; (b) electron density during quiet and perturbed conditions; (c) relative deviation of atomic oxygen O; (d) relative deviation of molecular nitrogen N_2; (e) N_2/O ratio, and (f) vertical ion drifts. Measurements taken on 6:05–6:11 UT on March 1 were used as a quiet-time reference. Both quiet and disturbed period measurements correspond at the same solar local time: 11.9 h.

the same solar local time: 11.9 h. A few after SC there is a Ne increase at low and low-middle latitudes while practically no change is observed at the trough of EA. During the first stage of recovery a significant and extended enhancement of electron density can be observed, with relative increases of the order of 40% and 120% occurring at equatorial and low latitudes respectively. During the end of the recovery phase Ne is slightly increased in the equatorial region while the increase is larger above the crest and higher latitudes. This long-lasting enhancement in the equatorial anomaly region suggests that the structure is very different from quiet time periods.

Relative changes in atomic oxygen O and molecular nitrogen N_2 concentrations between storm and quiet times at the height of satellite (280–300 km) for the satellite passes are presented in Fig. 1c and d respectively. In situ measurements simultaneously taken with electron density are used as reference. It can be seen that during the initial stage O and N_2 practically remain unchanged and nearly constant with latitude at F2-region heights. During the early stage of the recovery (18:46–18:53 UT on March 2) atomic oxygen shows an increase (~25%) at low latitudes which is larger than molecular nitrogen. Then both neutral gas concentrations are reduced.

Fig. 1e presents N_2/O ratio in the same format as Fig. 1b. No considerable change from undisturbed conditions is observed during the storm period. The larger relative deviations from the reference are of the order of about 16% at latitudes between 20° and 30°.

The latitudinal structure of vertical ion drift presented in Fig. 1f shows upward drift afterwards SC above the magnetic equator and no significant variation from reference values at low latitudes (10–20°).

Then, storm time values are close to undisturbed ones. During the last stage of the recovery phase small downward drifts at subequatorial latitudes and upward drifts at higher latitudes (25–30°) can be observed.

The initial increase in the upward drift would produce a displacement of ionization from the equatorial region toward low latitudes. Since no Ne decrease is produced at the trough of the EA a speculative and non verifiable explanation would be that possibly this effect occurred at daytime when the ionization production is still occurring.

It is unlikely that enhanced electron density observed during the early stage of the recovery was associated to vertical plasma drifts because the storm-time values remained close to reference ones in this stage of the storm. A possibility is that Ne increase may be due to an atomic oxygen concentration increase at low latitudes associated to a downwelling motion resulting from storm-induced equatorward thermospheric wind.

Possibly a combined effect of the upward plasma drift (due to enhanced equatorward thermospheric winds carried by TADs) as well as the atomic oxygen concentration variation may be considered as responsible processes for the maintenance of the enhanced electron density observed at low latitudes during the end of the recovery phase. Above the equator, where the magnetic field is horizontal, thermospheric meridional winds do no rise the plasma and therefore they cannot be responsible for the increases of electron density as occur at middle latitudes.

Fig. 2a shows the behaviour of Dst for the period November 20–22, 1982 (storm 2). The main phase lasted until around 2–3 UT on November 22 after which a nearly regular recovery is observed.

Four satellite passes during the storm period are considered: 01:30–01:36, 06:08–06:11, 23:05–23:10 UT on November 21 (main phase), and 17:35–17:40 UT on November 22 (recovery phase). The satellite orbit prior to the storm onset (13:10–13:18 UT on November 20) is used as the quiet time reference. Solar local time for the observations is approximately 19 h.

Fig. 2b shows the corresponding latitude dependence of electron density in the height interval 280–300 km. A significant decrease of Ne (~90% change) in the south crest region and an increase near the equator are initially observed as reaction to the storm onset. In the next pass there is a trend toward prestorm values. When Dst reaches its minimum values Ne is again decreased in the south crest region and increased in the vicinity of the equator. During the last stage of the recovery a limited recovery exists because an increase remains at subequatorial latitudes.

Relative deviations for atomic oxygen and molecular nitrogen are presented in Fig. 2c and d respectively. No data are available for the first satellite pass during the considered storm period. Relative increases which do not exceed 25% at heights of the satellite are seen before decaying Dst index. During the end of the main phase

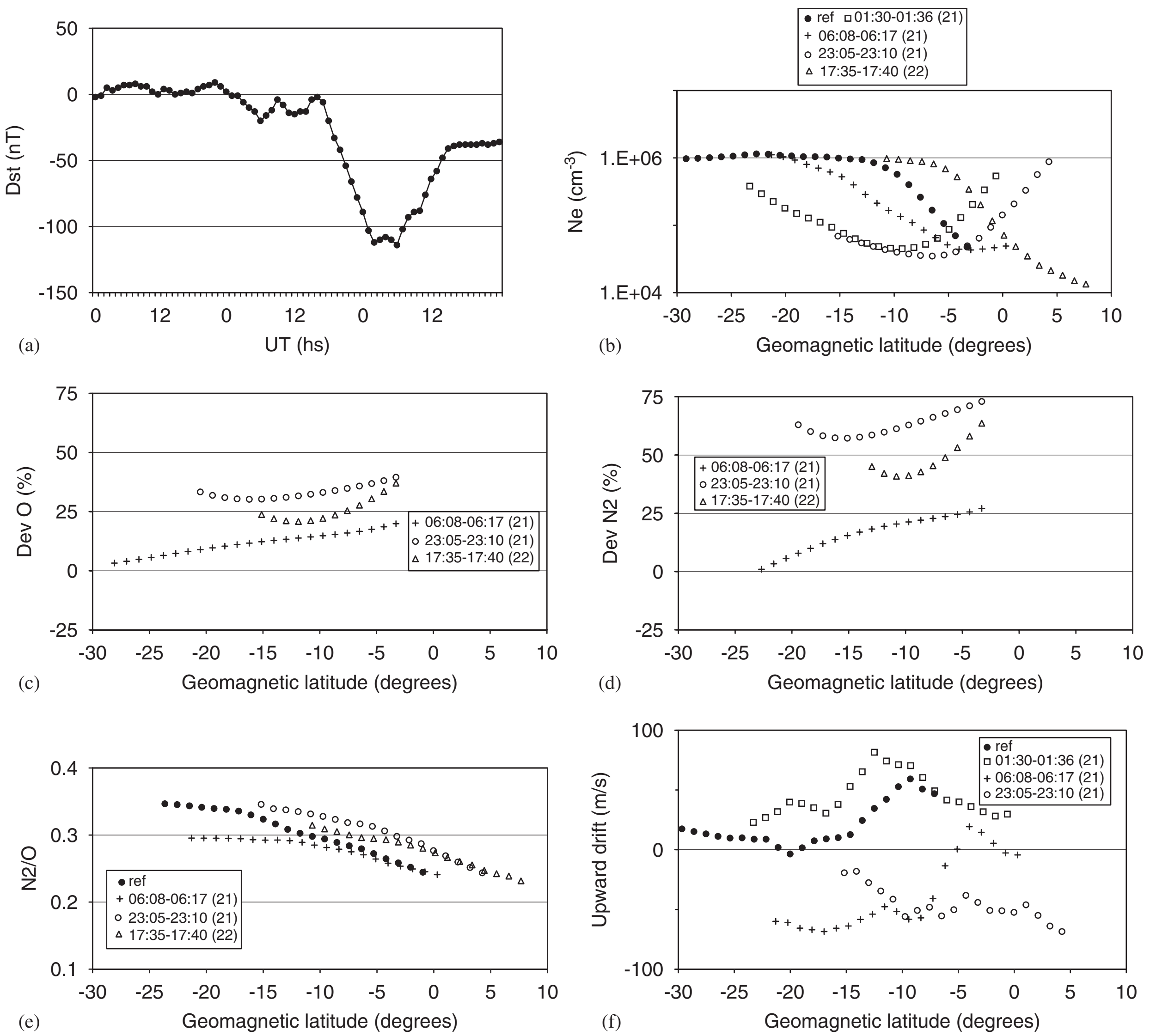

Fig. 2. (a) Hourly variation of Dst geomagnetic index on November 20–22, 1982; latitudinal variation between 280 and 300 km of; (b) electron density during quiet and perturbed conditions; (c) relative deviation of atomic oxygen O; (d) relative deviation of molecular nitrogen N_2; (e) N_2/O ratio, and (f) vertical ion drifts. Measurements taken on 13:10–13:18 UT on November 20 were used as a quiet-time reference. Both quiet and disturbed period measurements correspond at the same solar local time: 19 h.

molecular nitrogen presents a considerable increase (~55–70%) throughout the anomaly region which is larger than atomic oxygen (30–40%). Both the neutral gas compositions are less increased during the end of the recovery phase being the relative deviation for N_2 larger than for O.

Fig. 2e presents the latitude variation of the N_2/O concentration ratio in the same format as Fig. 2b. In spite of larger increase of N_2 during the end of main phase and the recovery phase of the storm N_2/O ratio practically stays unchanged during storm period. Thus, the maximum relative variation is of about 13% and it is observed at low latitudes (~−20°).

Fig. 2f shows the latitudinal profile of vertical ion drifts. Measurements above the equator during quiet time conditions and during the recovery phase are not available. An upward drift is seen a few after sc at low latitudes, which may be responsible for the initial decrease of Ne. During the development of the main phase (06:08–06:11 UT) a significant downward ion drift is observed at low latitudes and a weak upward drift at equatorial latitudes. During the end of this stage, vertical drifts remain

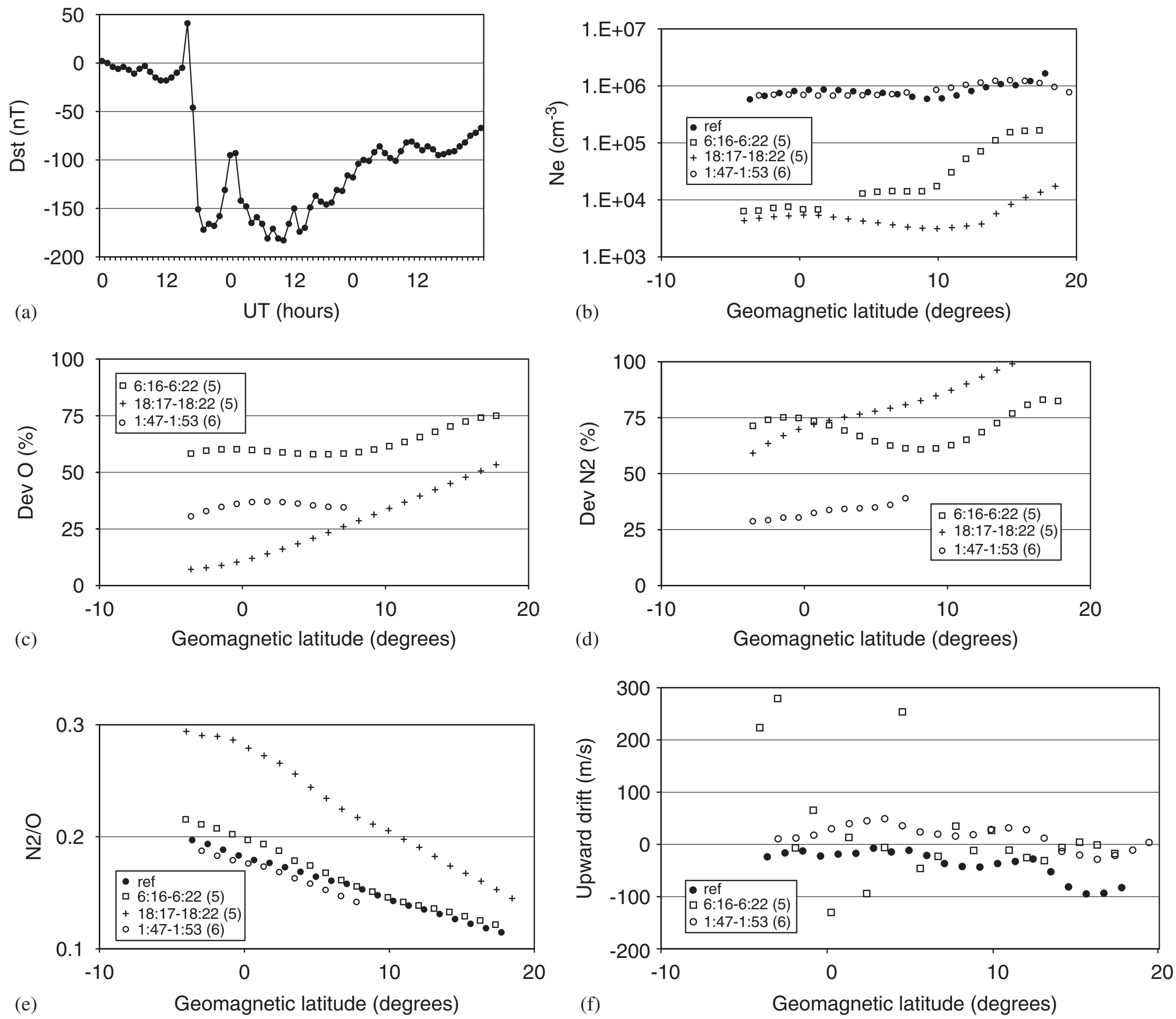

Fig. 3. (a) Hourly variation of Dst geomagnetic index on February 4–6, 1983; latitudinal variation between 280 and 300 km of; (b) electron density during quiet and perturbed conditions; (c) relative deviation of atomic oxygen O; (d) relative deviation of molecular nitrogen N_2; (e) N_2/O ratio, and (f) vertical ion drifts. Measurements taken on 1:44–1:49 UT on February 4 were used as a quiet-time reference. Both quiet and disturbed period measurements correspond at the same solar local time: 1.2 h.

downward at low (at a time when there is a decrease in Ne) and also at equatorial latitudes.

The depressed Ne values observed at low latitudes during the last stage of main phase possibly are due to the increase of N_2 concentration. It is quite unlikely that they are caused by an electrodynamic mechanism because one expects to observe increased electron density values in association with a downward plasma drift.

However, the neutral gas composition changes seem do not affect above the equator because there exists an increase of N_2 and prevails an increase of electron density which may be due to the downward drift. In fact, according to Mikhailov (2000) moderate downward drifts carrying plasma from the topside to the F2-layer maximum result in Ne increases above quiet-time levels but the lack of drift data in this stage prevents corroborate the assumption.

Fig. 3a shows the Dst geomagnetic index during February 4–6, 1983 storm period (storm 3). This storm was characterized by a short duration main phase followed by a long-lasting and irregular recovery. Solar local time of observation during both disturbed and quiet conditions is approximately 1.2 h. Three satellite passes are considered during the recovery phase of the storm: 0616–0622 UT, 1817–1822 UT on February 5 and 0145–0153 UT on February 6. Data during the main phase of the storm are not available. Values taken at 1:44–1:49 UT on February 4 are used as the quiet time reference.

Fig. 3b presents the latitudinal variation of electron density in the range 280–300 km during the recovery of the storm and during undisturbed conditions. A prominent reduction in Ne throughout the equatorial anomaly region (~100% change above the equator) can be seen during the first stage of the recovery phase. At low latitudes the drop in Ne increases in the next pass of the satellite (18:17–18:22 UT on February 5). On February 6, electron density returns to reference levels.

Atomic oxygen and molecular nitrogen concentrations present definitely increases (~60–75%) during the first stage of the recovery as documented in Fig. 3c and d, respectively. In the next pass of satellite (18:17–18:22 UT on February 5) the relative increase from undisturbed conditions at low latitudes is reduced for O while is larger than before for N_2 (80–100% change). During the last stage of the storm, relative deviations for both the neutral constituents are decreased when compared to the relative deviations during the first stage of the recovery which are of the order of 25–40%.

The molecular nitrogen to atomic oxygen ratio N_2/O is presented in Fig. 3e. A significant increase from quiet time conditions in the equatorial region (~50%) is observed at 18:17–18:22 UT on February 5 in association with the significant drop in the electron density. On the contrary, during the first satellite pass (6:16–6:22 UT on February 5) negligible changes in the N_2/O ratio occur at the same time that Ne decrease. Finally, storm time values return to quiet levels to the onset of the storm.

Fig. 3f shows the latitudinal distribution of ion vertical drifts during storm recovery period and quiet conditions. No data are available for the satellite pass occurred at 18:17–18:22 UT on February 5. Pronounced upward drifts at subequatorial latitudes occur during the first part of recovery. That suggests that possibly a combined effect of vertical drifts and changes in neutral gas composition contribute to the decreases of electron density observed in this stage of the storm. During the recovery phase similar values than prestorm ones are observed.

At low latitudes one should expect to observe increases of electron density as consequence of the plasma uplifting at subequatorial latitudes. However, the observed electron deviation is negative. Therefore, the composition changes possibly play a more predominant role than the vertical movement.

3. Discussion and conclusions

In this paper an attempt is made to show that ionospheric disturbances occurred at equatorial and low latitudes during the development of the main phase and the recovery phase of geomagnetic storms would be linked with changes in neutral gas composition. That physical mechanism possibly competes with vertical drifts associated to electric fields during these phases of storms.

In general ionospheric storm effects during the initial phase of the storm are not analysed because no satellite data were available in these stages.

To this end a sequence of in situ measurements between 280 and 300 km by the DE2 satellite in the equatorial and low latitude region during three geomagnetic storms have been considered.

There is no doubt that electric field disturbance is the most important contributor to the initial storm time response of the equatorial F region. This is because the formation of the quiet equatorial F2-layer is strongly controlled by ExB drifts and many morphological features are related to zonal electric field variations.

The storm time modifications in equatorial zonal electric fields fall into two broad groups (e.g., Prölss, 1995; Buonsanto, 1999; Sastri et al., 2000). The first group is the rapid and short-lived (2–3 h) changes associated with changes in interplanetary magnetic field Bz, polar cap potential drop, auroral electrojets, and symmetric/asymmetric ring current activities, all of which are intricately related to each other (Sastri et al., 2000). These are due to direct (prompt) penetration of magnetospheric convection electric fields and field-aligned current systems (e.g., Senior and Blanc, 1984; Fejer et al., 1990).

Smoothly varying and longer-lived (several hours duration) dynamo electric fields from the disturbance neutral winds and storm-related changes in ionospheric conductivity that follow the magnetic activity with a delay >6 h constitute the other group (e.g., Fejer, 1997; Abdu et al., 1997 and references therein).

Many of the equatorial and low latitude ionospheric variations begin to occur an hour or so after of the storm onset and thus a fairly rapid mechanism is required (such as electrodynamic mechanism).

Data for one DE 2 satellite orbit obtained during the initial stage of storm 1 confirm the aforementioned ionospheric response. The upward drift initially observed along equatorial latitudes during storm 1 may be caused by a temporary enhancement of the eastward-directed zonal electric field. This increase of vertical drift could be generating an increase of diffusion toward low latitudes.

On the contrary, storm time winds require some hours to propagate from auroral to mid and low latitudes, by this reason the wind effects may play an important role in delayed ionospheric disturbances.

The effects observed at 1:30–1:36 UT on November 21 may be explained in terms of electric field perturbations due to a modification of the dynamo winds (Blanc and Richmond, 1980). According to this mechanism the storm winds blow in such a way that the quiet-time electric dynamo field is reduced, which weakens the fountain effect. That lead to daytime increases of electron density at equatorial latitudes and decreases at low latitudes which is occurring at latitudes higher than 25° during storm 1.

The results obtained here suggest that composition changes (expressed as increases in molecular species, mainly N_2) seem to be responsible of the decreases of electron density observed during the end of long-lasting main phase and recovery phase of the storms. This is evidenced by the significant drop of electron density observed at low latitudes (23:05–23:10 UT on November 21; 18:17–18:22 UT on February 5) during the end of main phase or early stage of the recovery phase which occur in close temporal association with a relative increase of N_2 over O (the loss of ionization produced by N_2 would be greater than the production of ionization by O reducing the electron density). During storm 2 (summer hemisphere) the storm-time circulation and the background (quiet) circulation are both directed equatorward which is favourable for the arrival of composition changes at low latitudes. It is, therefore, quite unlikely that these effects are consequence of a downward vertical movement as occurs throughout the equatorial region. Unfortunately, lack of vertical drift data during storm 3 prevents to examine their effect on electron density. A speculative and non verifiable explanation is that the global circulation from summer hemisphere (nighttime) may penetrate into the opposite hemisphere (Fuller-Rowell et al, 1994) and produce the decreases in Ne.

Increases in atomic oxygen concentration possibly contribute to delayed increases of electron density at heights of F-region as observed at low latitudes (10°–20°). The enhanced O concentration on March 2 at 18:46–18:53 UT (storm 1) in association with Ne increases seems to support this assumption. As the electron density is proportional to O^n with $n = 0.7-0.85$ (Mikhailov et al., 1995) simultaneous variation of O and N_2 with the N_2/O ratio remaining constant still leads to an increase of Ne. It is quite apparent that this is the dominant mechanism underlying the behaviour of equatorial anomaly because as can be seen from Fig. 1f a weak downward vertical drift (similar to the reference) is observed at this time (sunset period).

The constancy of the N_2/O ratio at the heights of the F2-region in the equatorial and low latitude region during storms periods has been already observed (e.g., Prölss, 1980; Skoblin and Mikhailov, 1996; Mikhailov et al, 1997). However, it is of interest to mention the abnormal increase of the order of 50% in the N_2/O ratio at equatorial and subequatorial latitudes during the early stage of recovery of storm 3, which is mainly produced by the N_2 enhancement. Possibly further studies are required to establish any correlation between N_2/O changes and strong decreases of electron density as at mid latitudes.

In the simplest approximation, the above mentioned composition changes are generated in the high-latitude region due to the large amount of energy injected in the upper polar atmosphere during magnetic storms. Heating at high latitudes causes the rapid expansion of the neutral atmosphere which causes upwelling, i.e., the motion of air through constant pressure surfaces, resulting in departures from diffusive equilibrium and increases in the mean molecular mass (increases in the ratio of molecular nitrogen N_2 to atomic oxygen O concentration). The expansion also results in pressure gradients which modify the global thermospheric circulation. Enhanced equatorward winds transport the composition changes to lower latitudes, so that one sees a "composition disturbance zone" of increased mean molecular mass from high to low latitudes. The equatorward winds are usually stronger at night because the storm-induced winds add the back-ground circulation. They often take the form of equatorward surges or travelling atmospheric disturbances (TADs). (see Mayr et al, 1978; Prölss, 1980, 1995; Buonsanto, 1999; Danilov, 2001 and references therein for details).

During intense geomagnetic storms as considered in this analysis they possibly carry such composition changes to low latitudes or even penetrate to the opposite hemisphere. This may be the reason for the decreases in Ne during the main phase and first stage of the recovery.

The relative increases of Tn (not showed) are lower than 18% during the considered storm periods. This increase of Tn leads to an increase in the linear recombination coefficient and so to further decreases in the electron density (Mikhailov et al., 1995). Thus, actually the depletions in Ne are due to factors: the increase in N_2 by a higher percentage than O and the elevated temperature (Danilov, 2001).

Summarizing, in this paper it is suggested that neutral composition changes (increases in the mean molecular mass) would be considered as the basic cause of the decreases of electron density produced during long-lasting main phases and first stage of the recovery phases of intense storms at equatorial and low latitudes. Delayed increases of electron density at equatorial latitudes may be caused mainly by increases of O concentration relative to N_2. Possibly the maintenance of enhanced electron density at low latitudes during the end of the recovery phase is promoted by an upward plasma drift (due to enhanced equatorward winds). Thus, different mechanisms seem to be operative at different times, and often simultaneously.

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