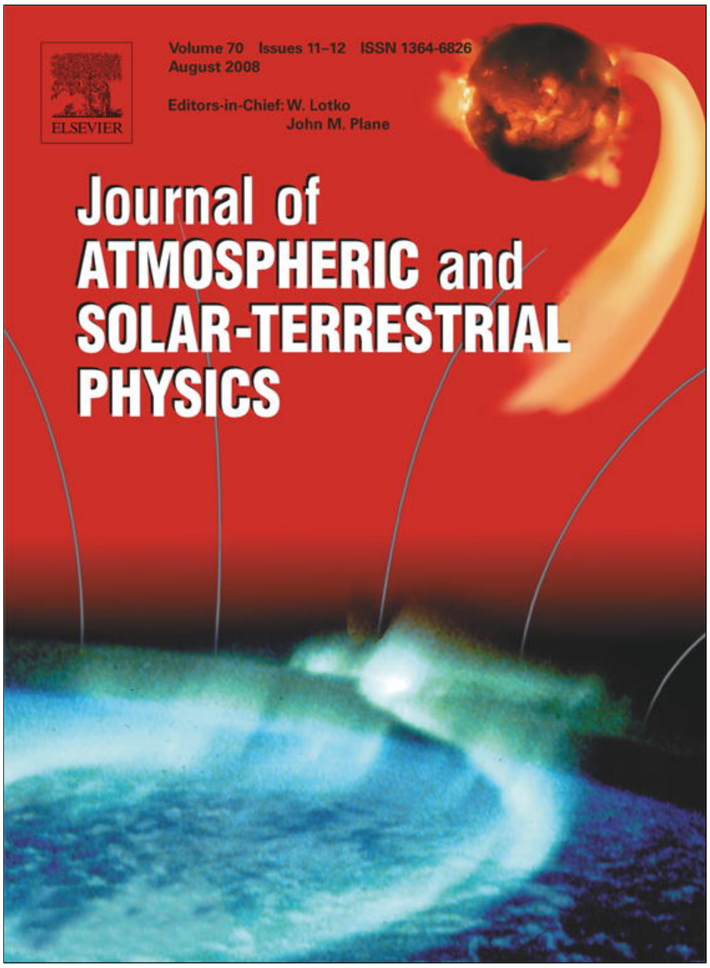
ELSEVIER
Volume 70 Issues 11–12 ISSN 1364-6826
August 2008
Editors-in-Chief: W. Lotko
John M. Plane
Journal of
ATMOSPHERIC and
SOLAR-TERRESTRIAL
PHYSICS

Journal of Atmospheric and Solar-Terrestrial Physics 70 (2008) 1448–1454

Contents lists available at ScienceDirect

Journal of
Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Thermosphere–ionosphere response at middle and high latitudes during perturbed conditions: A case study

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ARTICLE INFO

Article history:
Received 23 August 2007
Received in revised form
5 February 2008
Accepted 17 April 2008
Available online 26 April 2008

Keywords:
Geomagnetic storm
Electron density
Neutral gases
Ion drifts

ABSTRACT

Neutral gas composition and ionospheric measurements taken by the Dynamic Explorer 2 satellite at F2-region heights (280–300 km) during an intense geomagnetic storm (peak $Dst = -187$ nT) were used to analyze the role of some possible physical mechanisms responsible for the changes of electron density at high and middle latitudes. The storm considered in this study occurred on 26 September 1982. The main features observed were increases of electron density during the initial stages of the storm at middle latitudes; followed by decreases of electron density at high and mid-high latitudes during the main phase of the storm and the first phase of the recovery. Delayed increases of electron density during the recovery phase have also been observed at mid-high latitudes (50–60°). Several mechanisms were discussed in explaining the features observed for the electron density variations.

1. Introduction

The F2-region response to a geomagnetic storm is known as an ionospheric storm. Ionospheric storms represent an extreme form of space weather, which have significant, adverse effects on increasingly sophisticated ground- and space-based technological systems of our society (Buonsanto, 1999).

The ionospheric behaviour during storm periods associated with changes in neutral composition and thermospheric winds has been the subject of study for several decades. It is generally accepted that the decrease in the electron density of the ionospheric F2-region relative to a background level (negative phase of the storm) observed at mid- and mid-high latitudes is associated with an increase in the molecular nitrogen concentration to atomic oxygen concentration ratio N_2/O (e.g., Prölss, 1980, 1995; Buonsanto, 1999; Danilov, 2001, and references therein). In addition to that mechanism, some authors (see for example, Pavlov, 1994; Pavlov et al., 1999; Pavlov and Foster, 2001; Prölss and Werner, 2002) believe that vibrationally excited molecular nitrogen and oxygen are important for the decreases of electron density, which occurred in summer during periods of high solar activity. Several physical mechanisms have been considered as the causes for the increase of the electron density also observed at different latitudes (positive phase of the storm). They include the F2-layer uplifting 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, and remain as subject of debate until the present day (e.g., Burns et al, 2007).

There are many works that deal with the ionospheric response to geomagnetic storms at high, middle and low latitudes. However, due to their complexity, the ionospheric storms and the underlying physical processes are still not full understood. For example, Danilov (2001)

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doi:10.1016/j.jastp.2008.04.011

considers that for region responses to geomagnetic disturbances, there are still several unsolved problems which include the appearance of positive phases before the beginning of the magnetic storms, the occurrence of strong negative phases at the equator, the role of vibrationally excited nitrogen in forming the negative phase of the storm, and the relation of positive phases to the dayside cusp.

The objective of this paper is to examine the thermosphere–ionosphere interaction at middle and also at high latitudes during the different phases of an intense geomagnetic storm, by using simultaneous measurements of atmospheric and ionospheric parameters taken at heights of the F2-layer by the Dynamic Explorer 2 (DE 2) satellite. Satellite data have the advantage over ground-based data that they are in situ measurements of different upper atmosphere parameters, which permit them to examine simultaneous storm effects.

From the several physical mechanisms mentioned above for the positive phase, this paper presents additional evidence in supporting the neutral composition change as the possible cause for the positive phase observed at mid-latitudes during the recovery phase of the geomagnetic storm.

2. Results

In the storm period considered, two sudden commencements occurred: 1703 UT (SC1) and 2030 UT (SC2), both on 25 September 1982 (peak Dst = −187 nT).

The upper atmosphere reaction to the geomagnetic storm was analyzed on the storm onset day and the 2 following days.

DE 2 measurements took place in a wide range of heights along the satellite track. However, data at heights between 280 and 300 km near the peak of the electron density of the F2-region were selected. The parameters that were measured are electron density Ne, molecular nitrogen N_2 and atomic oxygen O concentrations, and plasma drifts. Measurements taken prior to the beginning of the storm period were used as a quiet time reference. All the measurements considered in this study were taken at 10.5 h solar local time. The storm period measurements and the reference measurements have been selected with the same characteristics both in altitude (280–300 km) and in time. Since neutral species composition changes exponentially with altitude and relatively small changes in altitude results in a potentially large change in composition, a small range of altitudes was adopted to make negligible possible height variation effects.

Neutral composition models use constant pressure surfaces, whereas the data are measured at a set of constant heights along satellite orbits. Prölss (1987) compared data for constant height surfaces with data for constant pressure surfaces, and he concluded that the molecular nitrogen to atomic oxygen ratio N_2/O is only moderately affected by the coordinate transformation. Burns et al. (1995) showed that neutral composition changes in the winter hemisphere during geomagnetic storms are very different, depending on whether constant pressure surfaces or constant height surfaces are considered. In this paper only constant height (280–300 km) is considered due to the difficulty involved in reducing the data to a set of constant surfaces.

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

25 September (Reference): 1409–1416 UT
26 September: 0238–0245 UT; 0852–0900 UT;
1506–1514 UT; 1946–1955 UT
27 September: 0334–0343 UT

Fig. 1 shows the Dst and AE indices for the 25–27 September 1982 storm period and also lists storm times for the DE-2 passes when data were taken (arrows). The main phase of the storm began at about 02 UT on 26 September. Dst decreased to −187 nT at 18 UT on that day. Thereafter, the storm activity subsided during the recovery phase. An enhancement of the AE index was observed between SC1 and SC2. After SC2, AE declined to 70 nT at 22–23 UT; immediately, AE began to increase (at 01 UT on 26 September) and at 13 UT on 26 September reached a value of about 1500 nT. The $F_{10.7}$ solar activity index was changed from 170.3 to 191.4 during 25–27 September 1982, and the monthly median was equal to 167.1 for September 1982.

Fig. 2 shows the latitudinal variation of the electron density Ne between 280 and 300 km in response to the geomagnetic storm. The solid line represents the reference values, corresponding to 1409–1416 UT on 25 September. At high and mid-high latitudes (65–90°), the electron density decreased during the main-phase development and during the first part of the recovery phase. At high latitudes the decrease was between 40% and 65% during the main phase. At latitudes lower than 60°, an enhancement in Ne by over 40% near 60° was seen during the main phase, which significantly increased during the recovery phase. The Ne data between 1850 and 1856 UT on 25 September (no showed here) over the polar cap and around the auroral oval did not show any increase as is observed sometimes when the AE index is enhanced. This enhancement is generally attributed to particle precipitation.

Fig. 3 presents the associated variation for molecular nitrogen concentration during the storm as well as the reference values (solid line). In general, N_2 concentration was enhanced at the heights 280–300 km during the entire storm period. During the end of the main phase and first part of the recovery (1506–1514 and 1946–1955 UT on 26 September) N_2 increased by 200% or more at latitudes between 55° and 90°. During the recovery phase (0334–0343 UT on 27 September), a significant drop occurred at lower latitudes (50–60°), simultaneously with the mentioned increase in Ne.

Fig. 4 shows the latitudinal variation for the atomic oxygen during the storm. The pattern of O changes was more complex than the N_2 changes. At high latitudes a decrease in O concentration of about 50% was initially observed (0238–0245 UT on 26 September), while during the main phase a modest increase of the order of only 30%

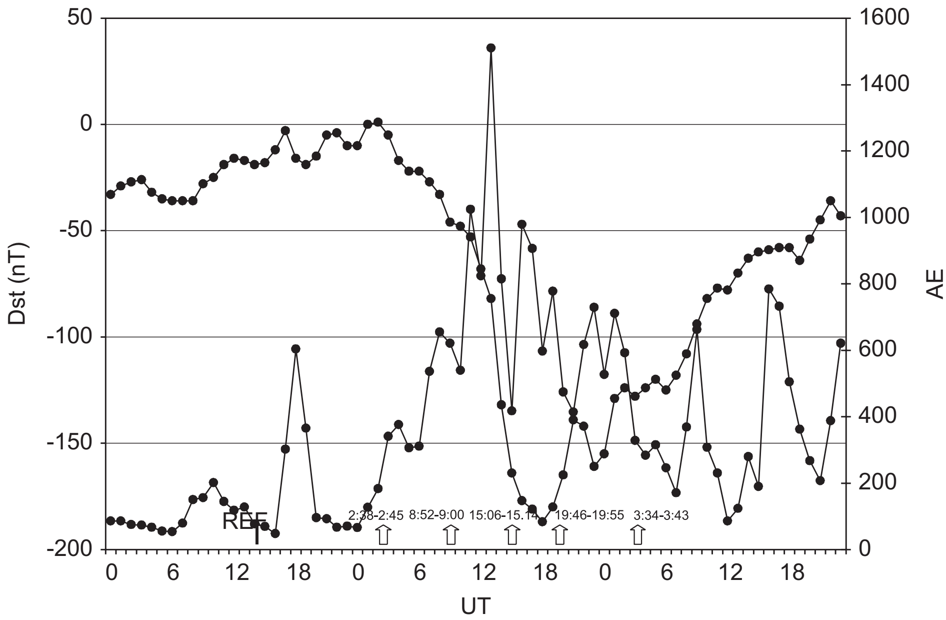

Fig. 1. Hourly variations of Dst and AE indices for the 25–27 geomagnetic storm period. The arrows indicate the storm times for the satellite passes when data were taken.

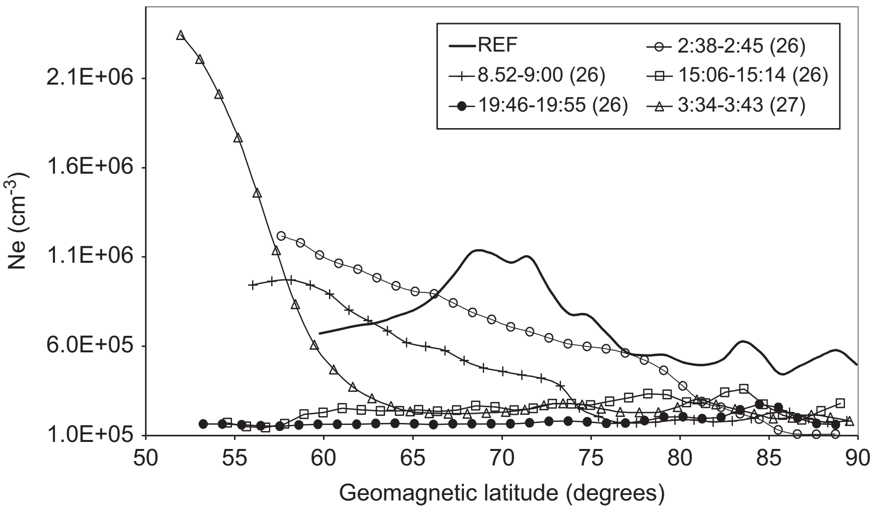

Fig. 2. Latitudinal variation of the electron density between 280 and 300 km during six satellite passes on 25–27 September 1982. Solid line represents reference values.

at latitudes between 60° and 80° was observed. This picture confirms previous observations that at high latitudes O concentration decreases at low altitudes (below 300 km) and increases at higher altitudes; at low latitudes increases in O concentration occur at all heights (e. g., Mayr et al., 1978; Prölss, 1980). This behaviour at high latitudes is related to the upwelling of parcels of air in this region associated with induced winds (Mayr et al., 1978). During the first part of the recovery (1946–1955 UT on 26 September), O concentration was decreased compared with reference values at all the latitudes considered. After that, there was a trend toward the reference values at latitudes higher than 70°. In this last stage of the storm there was a significant enhancement at latitudes lower than 60°. It is noted that this enhancement occurred simultaneously with the increase in Ne.

Fig. 5 presents the variations of the N_2/O ratio for the storm period. The initial feature observed was an increase at high latitudes and no appreciable change at lower latitudes. During the main-phase development until the first part of the recovery, the N_2/O ratio continuously increased at all the latitudes. At lower latitudes (~60°) the increases at 1506–1514 UT and 1946–1955 UT on 26 September were of the order of 170% and 450%, respectively. During the recovery phase (0334–0343 UT on 27 September), at latitudes lower than 60° a significant reduction to values close to those before the storm period was observed, which was produced by a simultaneous decrease in N_2 and increase in O; meanwhile, the electron density is enhanced there (see Fig. 2).

Fig. 6 shows the storm time evolution of disturbances in the eastward ion drifts. The striking feature observed

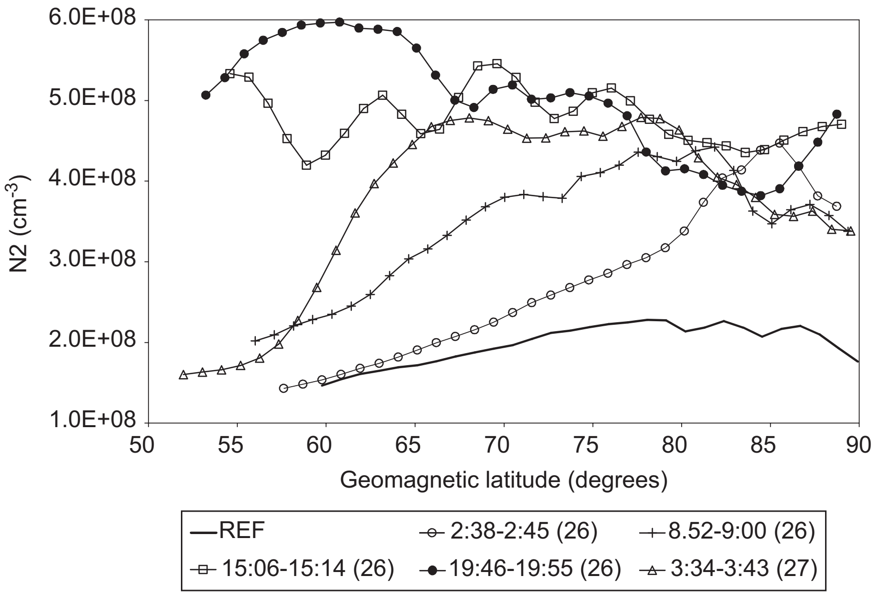

Fig. 3. The same as Fig. 2, but for molecular nitrogen.

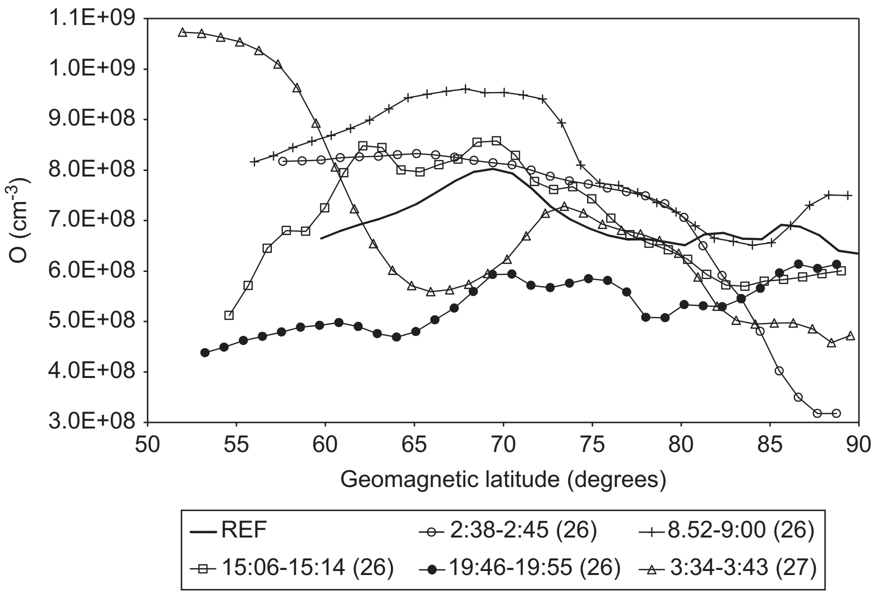

Fig. 4. The same as Fig. 2, but for atomic oxygen.

was a perturbation propagating equatorward, which is registered over a wide range of latitudes. If the times at which the eastward drift reaches its minimum are selected as references, a propagation velocity of the order of about 83 m/s is obtained. This velocity is within the range of typical values of travelling ionospheric disturbances TIDs (e. g., Rishbeth and Garriott, 1969). This may possibly only represent the sampling of the high-latitude convection pattern at different latitudes at different UTs with some changes in the auroral oval size added in.

Fig. 7 shows the corresponding upward ion drifts. The variations during the storm were quite irregular. However, ion drifts of about 110–130 m/s during the main phase of the storm (0852–0900 and 1506–1514 UT on 26 September) can be seen, which seemed to propagate equatorward producing an initial uplift of the plasma.

3. Discussion and conclusions

In this paper, a sequence of in situ measurements taken at heights between 280 and 300 km in the middle and high latitude region by the Dynamic Explorer 2 (DE 2) satellite is used to examine the response of the thermosphere–ionosphere system during an intense geomagnetic storm.

The results during the main phase and first part of the recovery at mid- and mid-high latitudes exhibit a close relation between the decreases observed in the electron

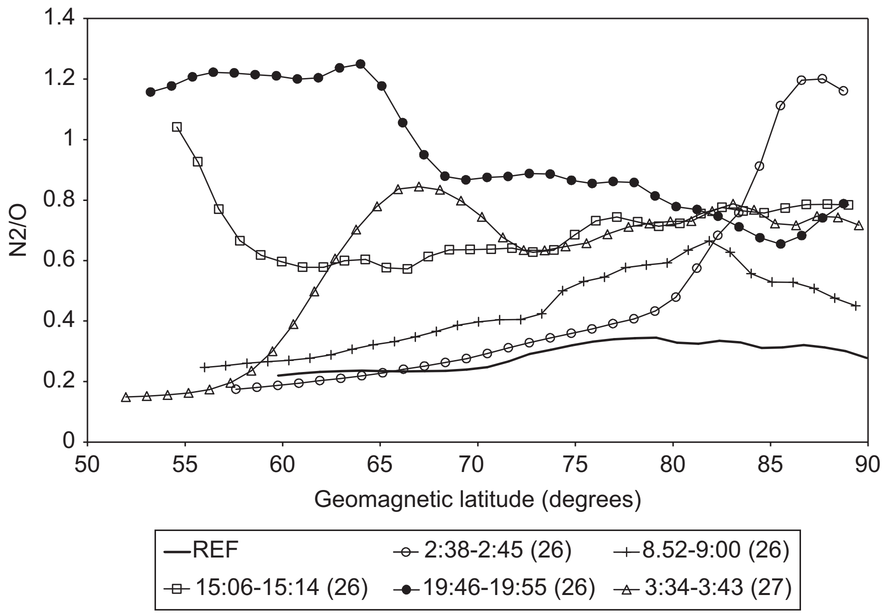

Fig. 5. The same as Fig. 2, but for the N_2/O ratio.

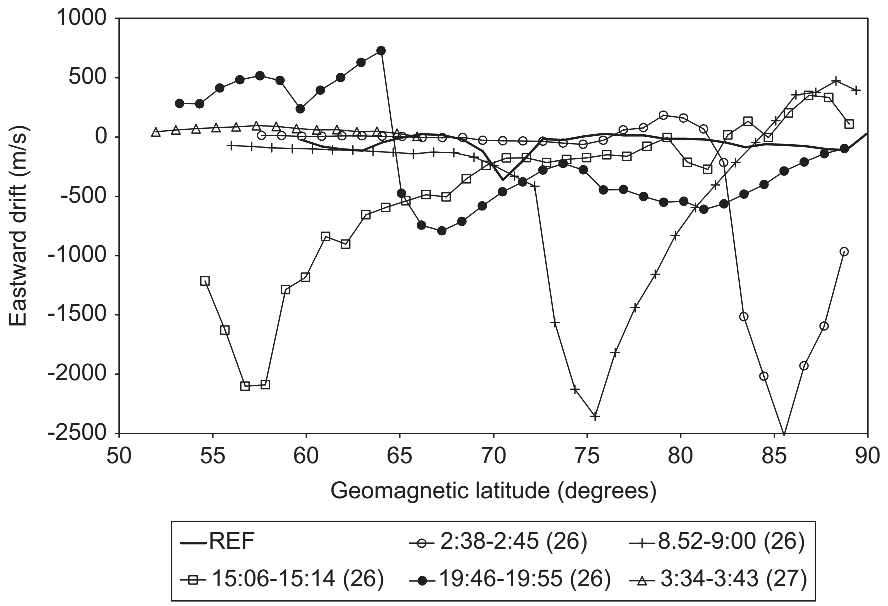

Fig. 6. The same as Fig. 2, but for the eastward ion drift.

density and the increases in the N_2/O ratio, which confirms previous observations (e.g., Prölss and von Zahn, 1974; Prölss, 1980). Moreover, there were increases in the neutral temperature T_n (not shown here) by about 40–50% at geomagnetic latitudes between 60° and 70° during the end of the main phase and early stage of the recovery. This increase of temperature leads to an increase of the linear recombination coefficient and thus to a further decrease of the electron density at the F2-region heights. Thus, actually, the negative phase of the storm is formed due to two factors, the increased N_2/O and the increased recombination due to increased temperature (see, Danilov and Lastovicka, 2001, and the references therein).

Some authors (e. g., Pavlov, 1994; Pavlov et al., 1999; Prölss and Werner, 2002) believe that vibrationally excited molecular nitrogen and oxygen play a significant role in negative phase formation. The matter is that due to several factors, including the neutral temperature increase, there may occur increases of the vibrational temperatures T_v (N_2) and T_v (O_2) of N_2 and O_2 at F2-region heights. The temperature increase should lead to strong intensification of the O^++N_2 reaction and so to a significant reduction in the electron density (Danilov, 2001). The mentioned strong changes in T_n in geomagnetic latitude should be a source of the corresponding strong change of vibrational temperatures in geomagnetic latitude. It means that, in addition to variations in latitude of neutral composition and variations in latitude of the plasma drift caused by neutral winds and electric fields, changes in latitude could also be produced by changes in

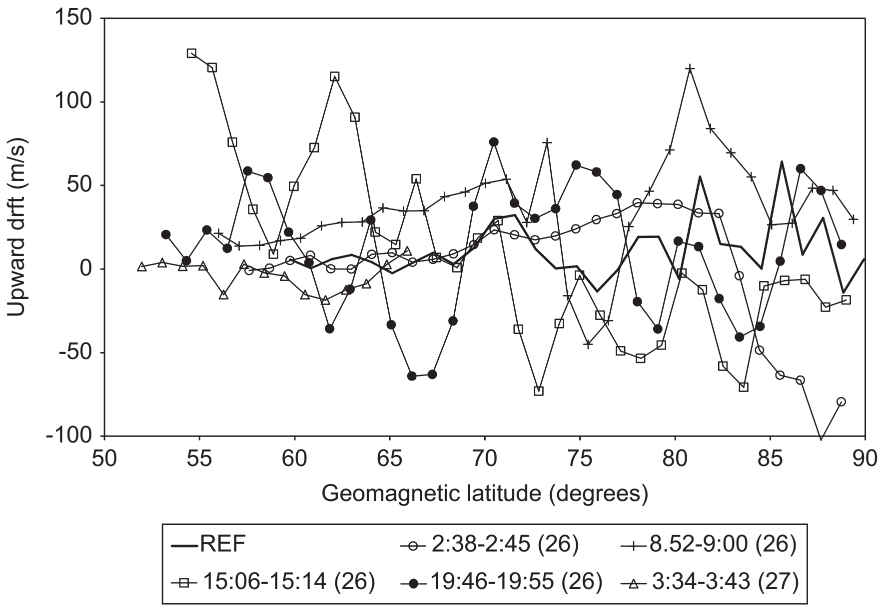

Fig. 7. The same as Fig. 2, but for the vertical ion drift.

latitude of effects of vibrationally excited N_2 and O_2 on Ne. The values of Ne and electron temperature T_e determine the values of T_v (N_2)–T_n and T_v (O_2)–T_n. The strong change of Ne in geomagnetic latitude, which is observed, could strengthen changes of T_v (N_2)–T_n and T_v (O_2)–T_n in geomagnetic latitude, and, as a result, this could strengthen a change of Ne in geomagnetic latitude. Only with numerical calculations the relative role of this physical process in forming the negative phase could be clarified. However, Danilov and Lastovicka (2001) concluded that in many case studies (Mikhailov and Foster, 1997; Mikhailov and Schlegel, 1998; Mikhailov et al., 1994, 1995) the principal features of many storms (including prominent ones) were successfully explained without any assumption on the T_v increase.

At latitudes lower than 60°, the delayed increase in Ne observed during the recovery phase (0334–0343 UT on 27 September) could be associated with a composition change. In this satellite pass, a significant increase of O concentration can be observed, while N_2 concentration was close to reference values. This enhanced oxygen density affects both the ionization production and diffusion, leading to an increase in the electron density. In this stage of the storm no significant increases of T_n were observed. The increase of T_n from their respective quiet values at heights near the peak of the F2-layer does no exceed 13%. Since the correlation between temperature and O composition change is poor, other factors apart from thermal expansion also affected neutral composition. This could be winds blowing through constant pressure surfaces as is suggested by Burns et al. (1995).

It is unlikely that the delayed increase of electron density at mid-latitudes was produced by an uplifting of the F2 layer due to thermospheric winds, because neither eastward nor upward significant ion drifts occurred as is observed in Fig. 7. Thus, this scheme did not work. Another mechanism is necessarily responsible for the increases in Ne. Possibly the composition changes sometimes predominate over the recombination by uplifting at higher altitudes during the recovery phase, producing the enhancement in the electron density. Supporting this explanation, Mayr et al. (1978) suggested that storm-induced winds effectively deplete O in the auroral zones and accumulate it at lower latitudes increasing the ionization there. However, more cases studies need to be done to confirm this mechanism. That will permit a better understanding of the causes of the increases of electron density (positive storm effects), which at present are not fully understood (Burns et al., 2007).

In a simple way, the perturbation in thermospheric parameters is generated in the high-latitude region due to a large amount of energy deposited during the geomagnetic storm. The strong Joule heating causes strong upward winds, which transport molecular-species-rich air from much lower in the thermosphere into the F region. This leads to a substantial increase in the ratio of the neutral molecular species compared with the neutral atomic species. The neutral winds then redistribute the composition disturbance over much of the high-latitude region and the mid-latitude region (e.g., Prölss, 1980). The increases in neutral molecular species (N_2) result in the increased recombination of O^+, so that electron density of the F2 region is depleted in the composition disturbance zone.

Summarizing, the observations lead to the conclusion that delayed increases of the electron density observed at mid-latitudes during the recovery phase are likely associated with atomic oxygen density increases. Obviously, although no definite conclusion can be established by considering one case, this mechanism seems to increase the electron density when the uplift of the F2 layer due to vertical drifts is not operative. More in situ satellite observations are needed in order to conclude that changes in neutral gas composition may be responsible for the increase in electron density. Knowledge of the physical mechanisms that produce the increases of electron density will permit the development and/or the improvement of predictive models of the ionosphere. Moreover, in this paper it is confirmed that decreases of electron density occur in association with increases in the N_2/O ratio. They are produced by both the increase in N_2 concentration and the simultaneous decrease in O concentration (or also by a moderate increase in O compared with the N_2 increase). The data of electron density between SC1 and SC2 from the high-latitude region do not show enhanced values in association with the enhancement of the AE index as sometimes is observed, which are attributed to the precipitation of energetic electrons that ionize the neutral gas.

Acknowledgement

The author thanks the two anonymous referees for their constructive comments.

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