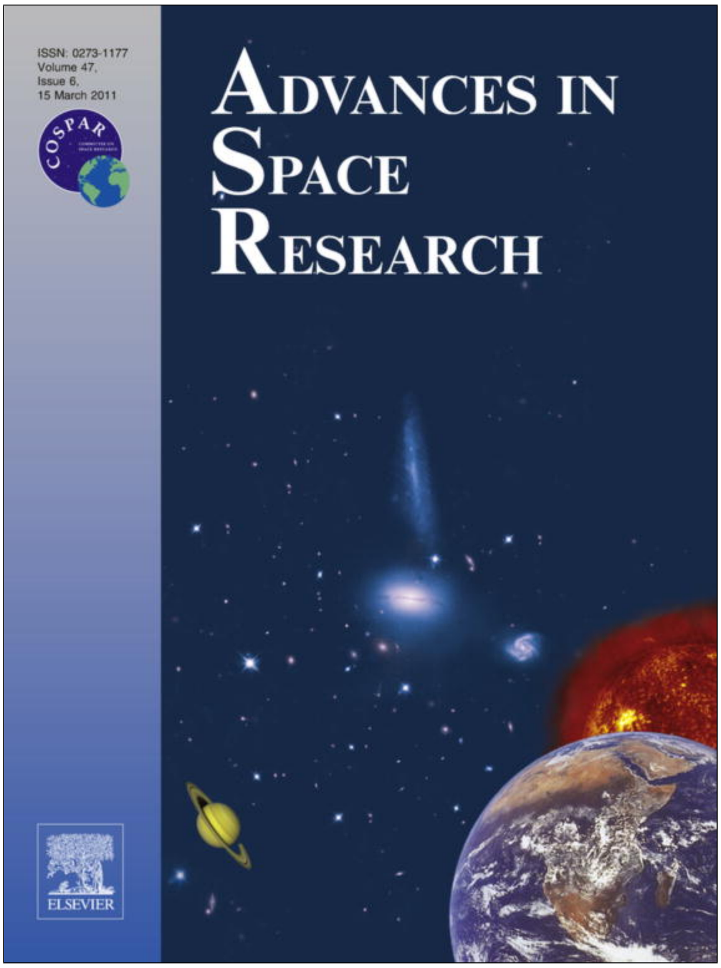
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Some effects in the upper atmosphere during geomagnetic storms

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Abstract

This paper examines the response of the high latitude ionosphere–thermosphere system during two intense geomagnetic storms. For that, data taken by instruments on board Dynamic Explorer 2 taken at heights of the F2-layer are used. These results represent a comparison of simultaneous measurements of storm disturbances in gas composition, electron density and temperature in common local time sectors. Documented are an increase in electron temperature and a decrease in electron density; increases both in electron temperature and electron density; and the correlation between electron density decreases and increases in the ratio N_2/O. It is noticed that the decrease in electron density is sometimes due to an increase in the molecular nitrogen density N_2 and not always is attributed both to the increase in N_2 density and the simultaneous decrease in the atomic oxygen density.

Keywords: Geomagnetic storms; Ionosphere; Thermosphere

1. Introduction

Significant disturbances are produced in the upper atmosphere during geomagnetic storms. Although they have been intensively studied for many decades using several techniques such as ionosondes and satellite in situ measurements, neither the morphology nor the physics of the changes is completely known, testifying to the complexity of this phenomenon.

The study of such perturbations is of great practical importance because intense storms disturb transionospheric radio communications, shorten lifespans of satellites and degrade satellite ephemeris predictions (Richards et al., 1994; Prölss, 1998).

During storm periods a transient large amount of energy is deposited in the auroral region, which leads to the development of a disturbance zone in the neutral composition and to a change of the meridional pressure gradient driving a global circulation in which neutral winds flow from high to low latitudes.

The neutral winds transport the neutral composition changes up from much lower altitude in the thermosphere into the ionospheric F region, which are then advected away from the auroral zone as part of the global circulation that is set up by the auroral heating.

The upward and equatorial flow of oxygen atoms (O) collisionally forces the ionospheric plasma upward along equatorward geomagnetic field lines, thus causing enhanced electron densities (positive ionospheric storms).

The storm time circulation also transports molecular nitrogen (N_2), which causes accelerated ion-atom charge transfer reaction between O^+ and N_2, leading to depressed electron densities (negative ionospheric storms).

The objective of this paper is to provide an order of magnitude of the changes in neutral gas composition at high latitudes during disturbed periods. To do this, we analyze data taken during two geomagnetic storms occurred in 1982, by the scientific instruments on board the Dynamic Explorer 2 (DE-2) spacecraft (initial apogee: 1012 km; initial perigee:

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309 km; orbital period: 1.63 h; inclination: 90° and eccentricity: 0.03), which probed the upper atmosphere between Fall 1981 and Spring 1983. A detailed description of the satellite mission can be found in Hoffman and Schmerling (1981). In general, the global numerical modelling presents serious limitations (e.g., Fuller-Rowell et al., 1994) and their results may be affected by systematic errors. For that reason the measurement in situ is a good diagnostic tool to investigate magnetosphere–ionosphere–thermosphere processes.

Two events were found with a considerable amount of data at high and mid-high latitudes. The events considered in this study occurred on August 6, 1982 with peak Dst = −155 nT (storm 1) and September 21, 1982 with peak Dst = −210 nT (storm 2).

The atmospheric data are molecular nitrogen (N_2) and atomic oxygen (O) composition measurements; the ionospheric ones are electron density and electron temperature. They are presented for different invariant magnetic latitudes.

2. Results

The geomagnetic index Dst was used to describe the level of magnetic activity. Measurements from the Northern hemisphere taken at heights between 300 and 320 km for storm 1, and between 280 and 300 km for storm 2 were selected from the satellite data. The measurements were taken at 13.6 and 22.9 h solar local time for storm 1 and storm 2, respectively. It is noted that each point corresponds to a different place on the globe. Measurements taken prior to the beginning of the storms are used as a quiet-time control. Reference values have been selected with the same characteristics both in altitude and in time that storm time values. Although neutral species composition changes exponentially with altitude and relatively small change in altitude results in a potentially large change in composition, small ranges of altitudes were adopted to make negligible possible height variation effects.

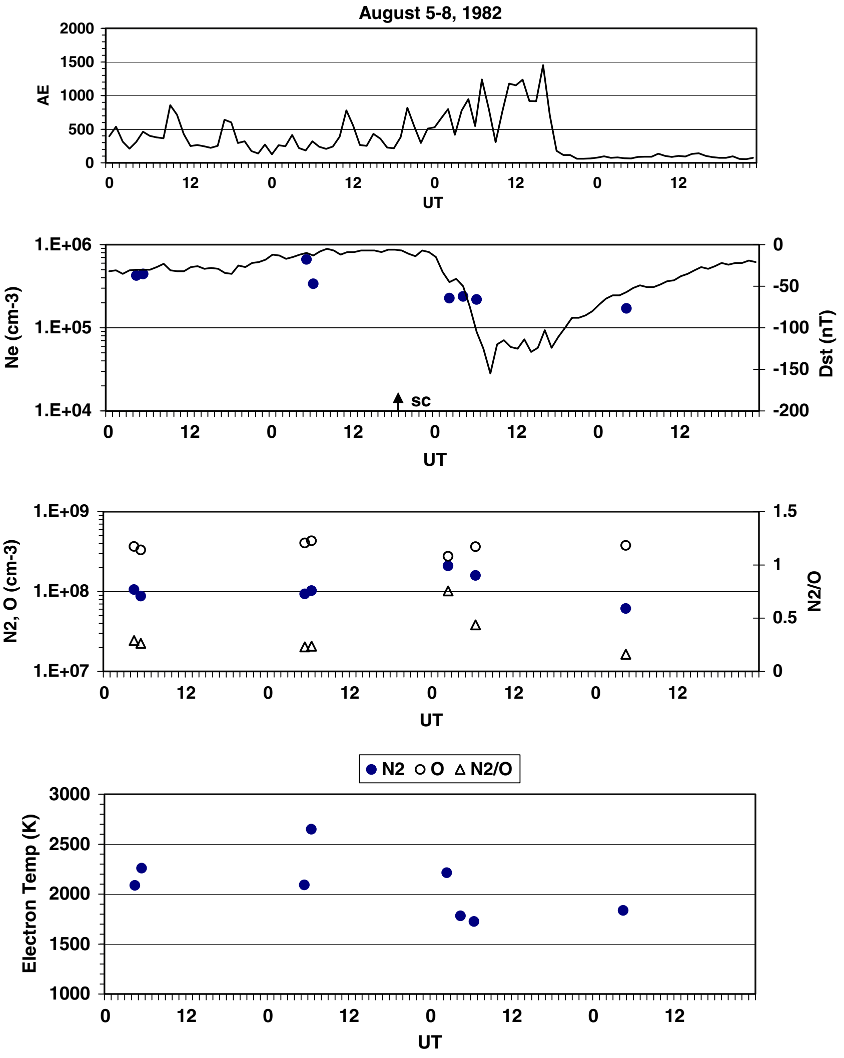

Fig. 1. Variation of index AE, index Dst and electron density Ne (top panels), gas densities (N_2 and O) and ratio N_2/O (middle panel) and electron temperature Te (bottom panel) for the 5–8 August 1982 storm period at the 80° invariant latitude. The arrow indicates the storm sudden commencement (1836 UT on August 6).

The top plots of Fig. 1 show the temporal evolution of the index AE and the index Dst together with electron density Ne at 80° of invariant magnetic latitude for the August 5–8, 1982 storm period. The sudden commencement (SC) of the storm 1 was at 1836 UT on August 6. The main phase onset (MPO) was at 22 UT on August 6 while the main phase end (MPE) was at around 8 UT on August 7. The recovery towards prestorm levels (recovery phase of the storm) lasted for more than 24 h. The electron density presented depressed values (negative storm) before the SC, during the main phase and the recovery phase. The middle plot of Fig. 1 shows the behaviour of N_2 and O at 300–320 km and the ratio N_2/O. The storm not only affects the ionosphere but also the thermosphere. In association with the negative storm of the main phase, N_2 increased by a higher percentage (~97% change) than O decrease (~16% change). At the altitudes of our measurements, an increase in N_2/O is observed during the storm main phase, corroborating the direct relationship between N_2/O increases and Ne depletions. That disturbance feature may be considered typical since both the increase in molecular gases and the simultaneous decrease in the atomic oxygen density are considered to contribute to a decrease in the electron density (e.g., Prölss, 1995). However such a relationship is not noticed during the recovery phase because N_2/O recovers pre-storm values but Ne does not. The electron temperature T_e is also represented in the bottom plot of Fig. 1. An electron temperature increase can be noticed associated to the drop in electron density, followed by a trend to recover pre-storm values during the recovery phase of the storm.

Fig. 2 presents the same format of Fig. 1 but for 70° invariant latitude. A clear and easily identified Ne depletion started before the SC, which remained during the main

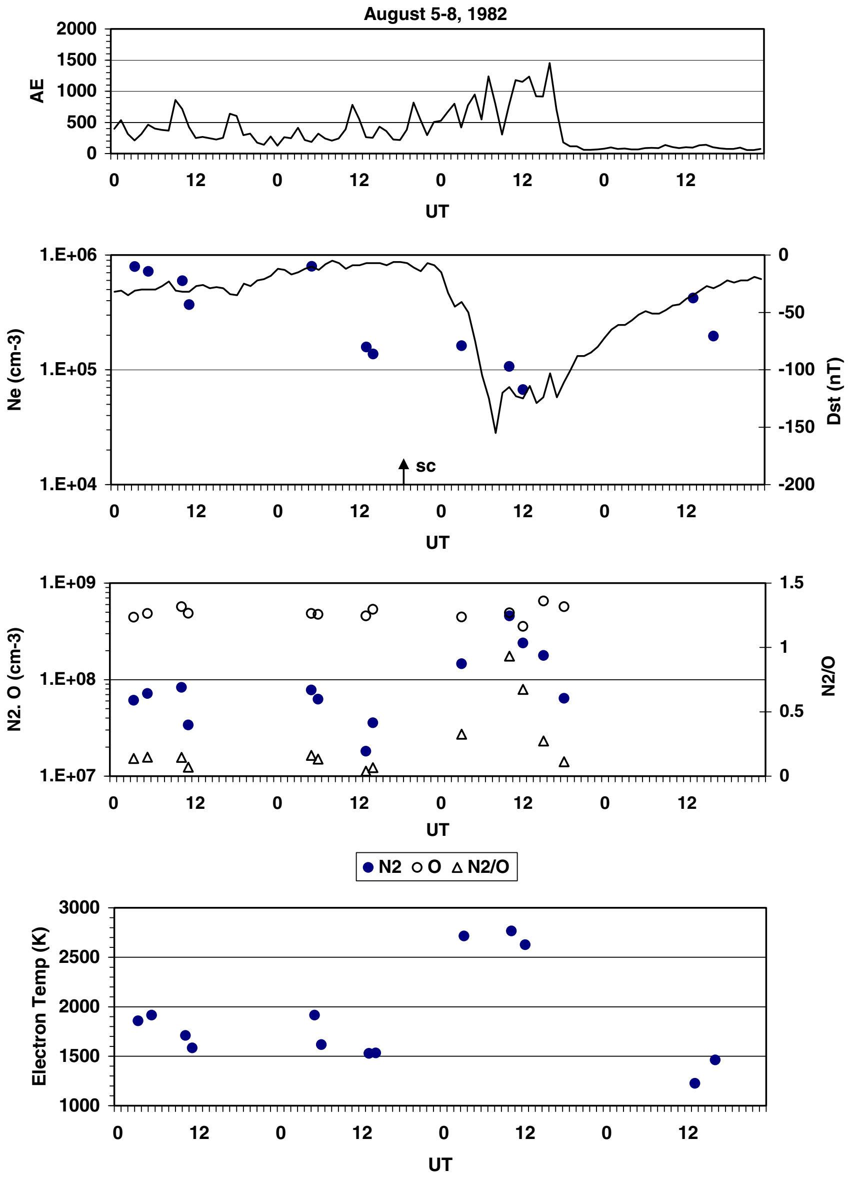

Fig. 2. The same as Fig. 1, but at 70° invariant latitude.

phase and first part of the recovery. Herein N_2 increased by a factor of 4 in correlation with the Ne depletion observed during the main phase, while O values during the storm period were comparable to pre-storm values. The significant increase in the ratio N_2/O in association with the Ne depletion was caused by the increase in N_2 fundamentally. The increase in N_2/O stops many hours before the electron concentration approaches its pre-storm level. Moreover an enhancement in T_e is observed after SC, being the increase greater than 1000 K.

Fig. 3 is also similar to Fig. 1 but for 65° invariant latitude. A negative storm less intense than at 70° occurred before the SC, which remained until the first part of the recovery. The N_2 and O variations were smaller than at 70° invariant latitude; the increase in the N_2/O ratio was also of about 24 h of duration and it was produced by an increase in N_2 by a factor 4. In correlation with the negative storm T_e presented an increase by about 800 K during the first part of the recovery.

The top plots of Fig. 4 present the behaviour of the index AE and the geomagnetic index Dst together with the electron density Ne at 80° invariant magnetic latitude for the September 19–23, 1982 storm period. The geomagnetic storm started with an SC at 0339 UT on September 21. The MPO was at about 18 UT while MPE occurred at 08 UT on the following day, followed by a relatively steady recovery. A long lasting drop in Ne was observed after the SC, which lasted during the recovery phase. As shown in the middle panel of Fig. 4, this negative storm seems to be related mainly with the increase in N_2 density (~80% change) because O density just presented a small decrease (~20% change) during the development of the

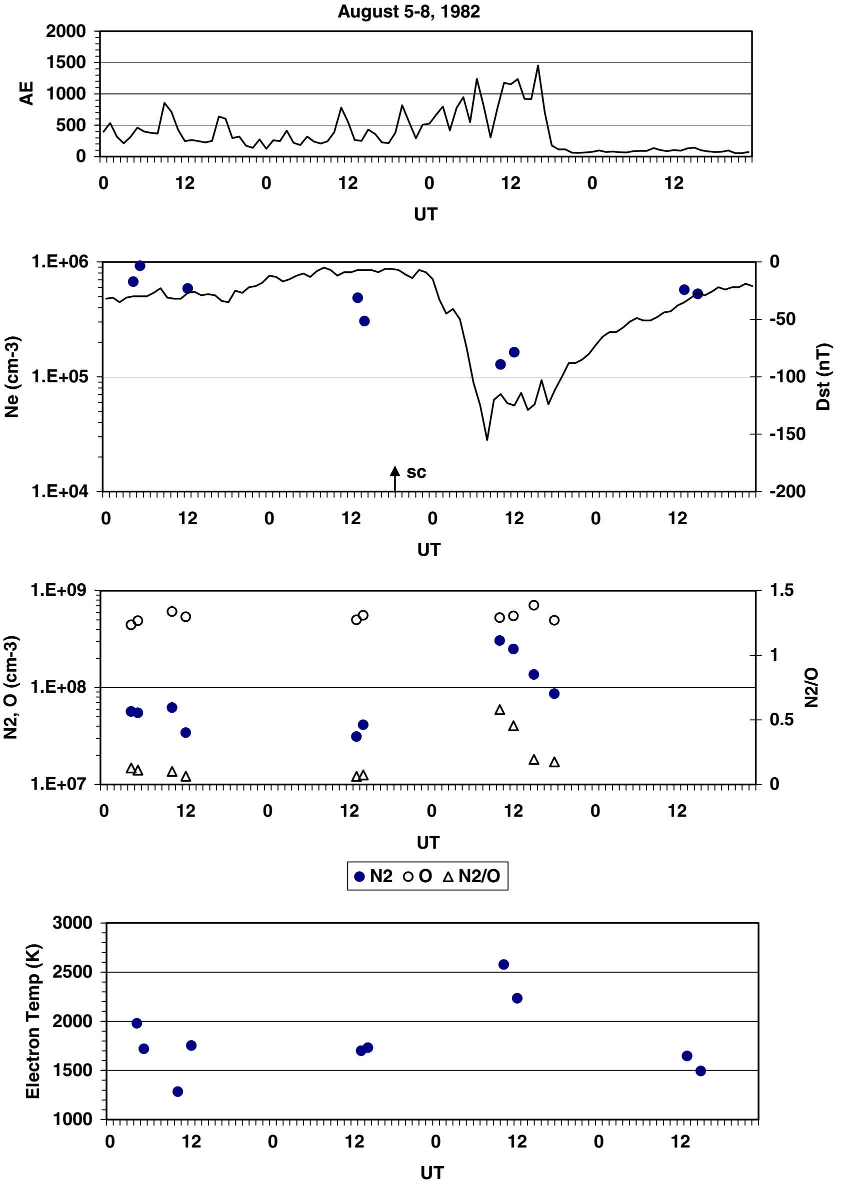

Fig. 3. The same as Fig. 1, but at 65° invariant latitude.

main phase. These changes give place to a significant increase in the N_2/O density ratio by almost a factor 2, which presents similar duration than the drop in Ne. The electron temperature (bottom plot of Fig. 4) exhibits an irregular behaviour with storm-time values.

Fig. 5 presents the variations of the indexes AE, Dst, electron density Ne, N_2 and O densities, ratio N_2/O and the electron temperature T_e for September 19–23, 1982 storm period in the same format as Fig. 4 but at 70° invariant latitude. The electron density Ne presented a drop until the end of the recovery phase. Similarly that at 70°, the plot for N_2 and O densities presents an increase in N_2 and a simultaneous decrease in O, while the ratio N_2/O shows a significant increase in correlation with the drop in Ne. The electron temperature T_e in this region also presented an irregular behaviour during the storm period.

Fig. 6 is similar to Fig. 4, but for 60° invariant latitude. The increase in the electron density observed after the SC till about the first part of the recovery demonstrates a typical positive phase. The O density undergoes a small decrease after the onset of positive storm (~30% change) where N_2 density was almost with no variation during storm period. The ratio N_2/O has a pronounced peak at the end of the main phase caused by the O decrease. A

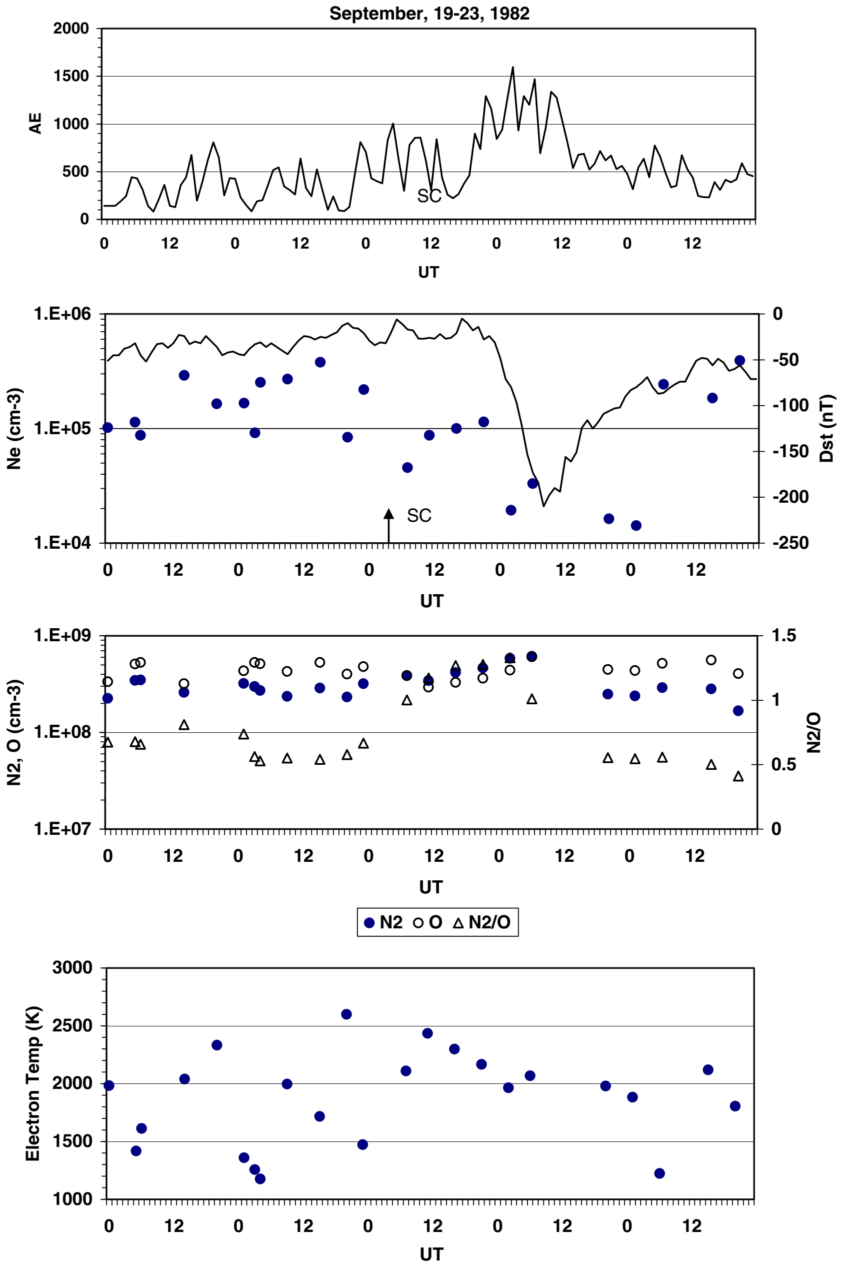

Fig. 4. Variation of index AE, index Dst and electron density Ne (top panels), gas densities (N_2 and O) and ratio N_2/O (middle panel) and electron temperature T_e (bottom panel) for the 19–23 September 1982 storm period at the 80° invariant latitude. The arrow indicates the storm sudden commencement (0339 UT on September 21).

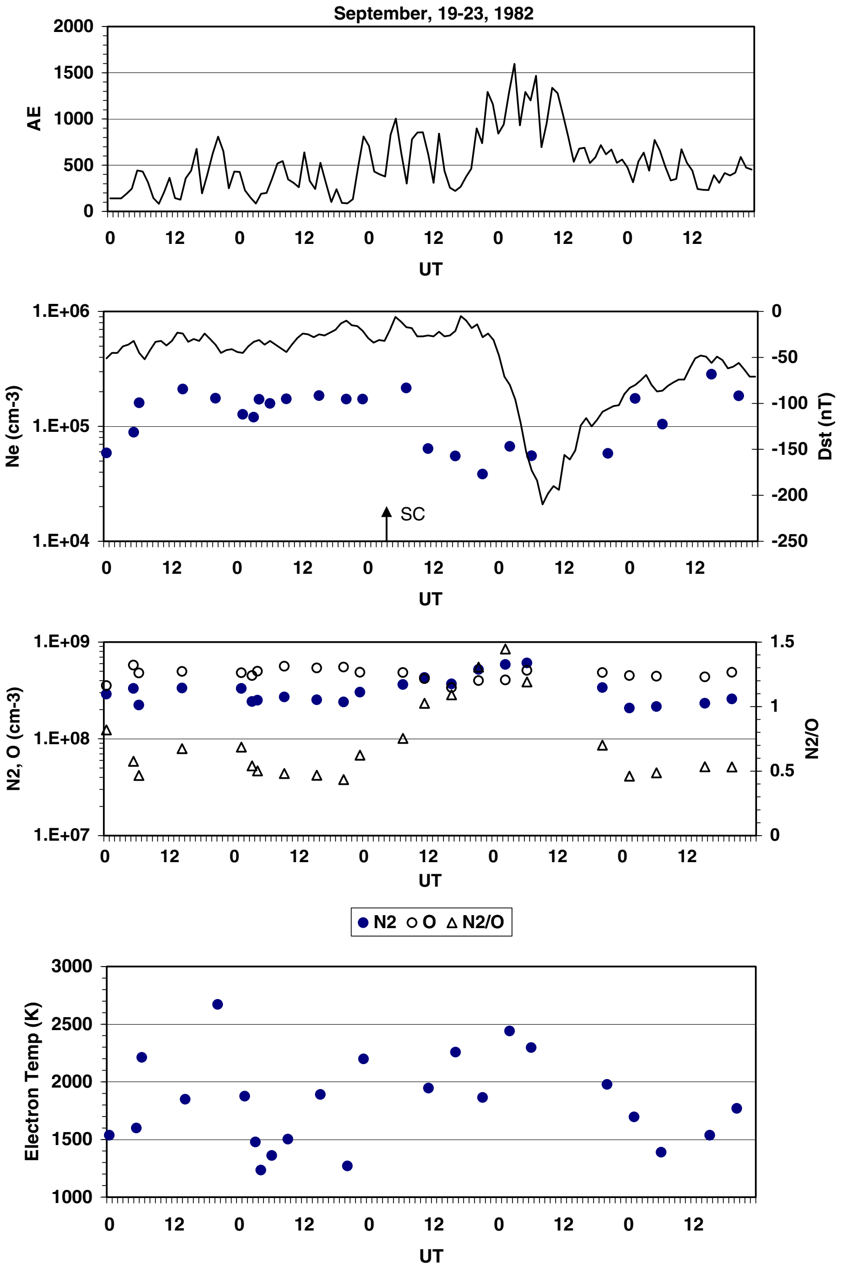

Fig. 5. The same as Fig. 4, but at 70° invariant latitude.

considerable increase by more than 500 K was observed in the electron temperature simultaneously with the increase in Ne.

3. Conclusions and discussion

In response to the storm the main observational results in the electron density can be summarized as follows:

At high latitudes (70° and 80° invariant latitude) long-term decreases in Ne were observed (~80–110% maximum change) which remained during the main phase and the first part of the recovery. The magnitude of the decreases seems to depend of the intensity of the storm.

At mid-high latitudes, increases (110% maximum change) or decreases in the electron density were noticed after the SC. In storm 2 data taken at night-time hours show an increase in electron density. This is similar to the so called "dusk" effect, a mid latitude phenomenon, in which are sometimes observed enhancements in electron density and total electron content in the evening hours. Forbes et al. (2000) and Rishbeth and Mendillo (2001) consider that variations in electron density during quiet periods usually do not exceed 10–20%; so, the greater perturbations observed herein are indicative of the storm time disturbances.

Decreases in electron density which occur from before the sudden onset (storm 1) have been already observed

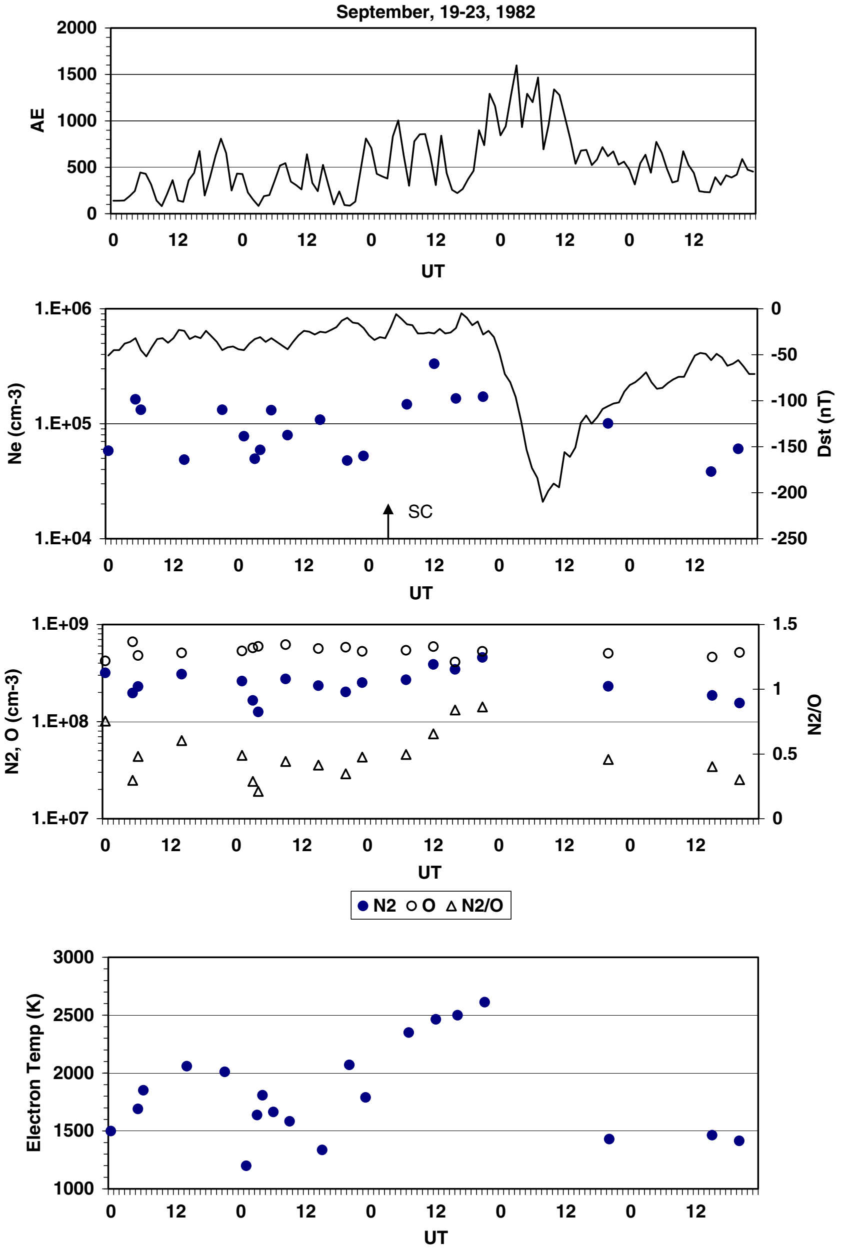

Fig. 6. The same as Fig. 4, but at 60° invariant latitude. Note the increase in the ratio N_2/O.

(e.g. Mansilla, 2007). These decreases were not caused by a perturbation in neutral composition change because neither N_2 density nor O density showed almost variations. Another causal mechanism would be responsible to produce the electron density decrease from before the beginning of the storm. The decrease in Ne in the absence of Dst decrease is possibly an effect of the auroral heating (e.g., Sobral et al., 2006).

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).

At 70° and 80° invariant latitude (storm 2), decreases in electron density were maintained while remained disturbed the neutral composition. The ratio N_2/O was also enhanced while the negative effect persisted. This does not come as a surprise because such a correlation between decreases in electron density and increases in the ratio N_2/O has been already observed. The increase in N_2/O (and decrease in Ne) is attributed both to an increase in N_2 density and a simultaneous decrease in the atomic oxygen density and the earlier suggestion that the negative storm effect is caused by a reduction of the atomic oxygen density was considered incomplete (e.g., Prölss, 1995, 1998). The increases in the ratio N_2/O seem to be not always caused by both changes in neutral constituents, because that may be also produced by the increase in N_2 and no variation in the O density (see storm 1).

Storm 1 is a summer disturbance so that the background and the storm induced circulation are directed in the same direction. Possibly for that reason the disturbance in neutral composition reaches lower latitudes than winter disturbance. So, the negative phase of the ionospheric storm will be observed even at relatively low latitudes. However, the magnitude of the increase of the ratio N_2/O is greater during storm 2, which could be related with the intensity of the storm.

At 80° invariant latitude an increase in the electron temperature and a decrease in the electron density were observed; less clearly this effect was also seen at 70° invariant latitude. Prölss (2008) considered that at least part of the electron temperature enhancement is caused by the drop in electron density, not by increased particle precipitation. Because the recombination coefficient is proportional to gas temperature at thermal energies and it increases rapidly with increasing electron temperature (Rishbeth and Garriott, 1969) that leads to a further decrease of the electron concentration. Thus, it is suggested that possibly the drop in electron density is due to two factors: the increased N_2/O and the increased recombination due to increased temperature. The enhancement in electron temperature is not produced only during electron density decreases. During storm 2, at 60° invariant latitude there is remarkable correlation between electron temperature and electron density, that is, electron temperature increases with the increase in electron density. Clearly, that further investigations including particle precipitation data are needed to establish a pattern of electron temperature variations during magnetic disturbances.

It is interesting to note the electron density enhancement at 60° invariant latitude during storm 2. Simultaneously with that enhancement an increase in the ratio N_2/O as at higher latitude (associated with a negative effect) is observed. In fact, the data do not show a clear relationship between N_2/O and Ne. The parameter N_2/O would be not a reliable indicator to study the evolution of negative disturbances at high latitudes during storms. Because that decrease of the oxygen density will decrease the production of ionization other competitive mechanism possibly controls the F2 region plasma density. In winter the two circulations (background and storm-induced) could be oppositely directed. In this case the gas with enhanced N_2/O would not go far down the latitudes and the storm-induced circulation would lift the F2 layer up into the region of lower recombination, forming a positive phase. That is what, evidently, occurred at 60° during the second storm.

Summarizing, the features of these storms may not generalize well to other storms because geomagnetic storms and the response of Earth's upper atmosphere to them are so varied, but provide a real order of magnitude of the changes in neutral gas composition during disturbed periods. The positive and negative variations in the electron temperature during storms are a feature that should be emphasized, as also the not clear relationship between N_2/O and Ne at high latitudes.

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