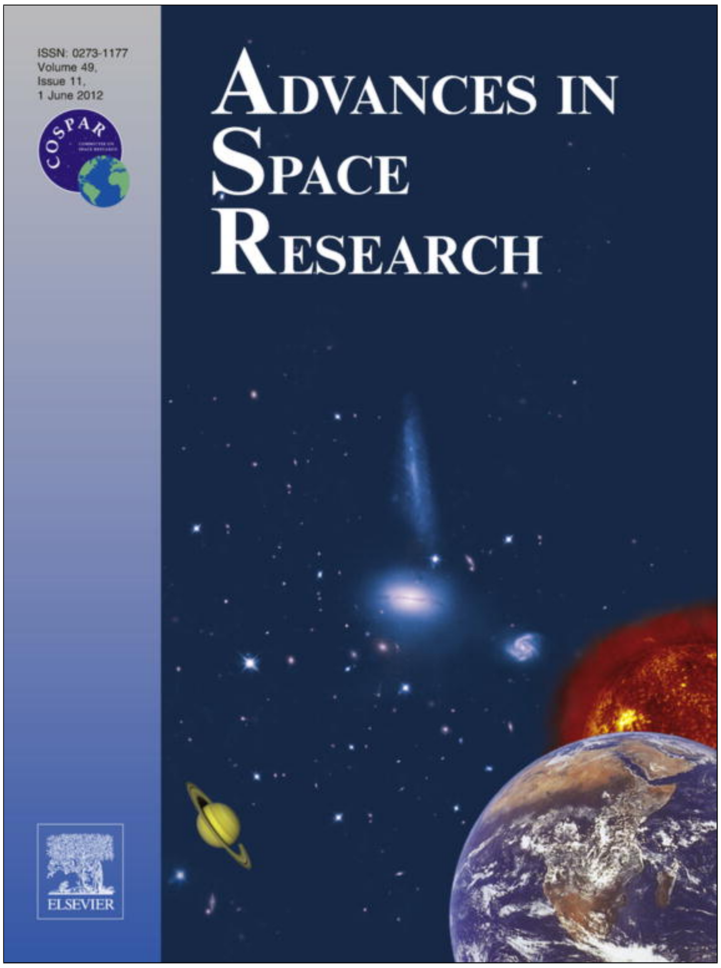
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Thermosphere–ionosphere response to a severe magnetic storm: A case study

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Abstract

This paper reports the response of the ionosphere–thermosphere system to an intense geomagnetic storm. For that, data taken by instruments on board Dynamic Explorer 2 at heights of the F2-layer (molecular nitrogen N_2 and atomic oxygen O compositions, neutral temperature *Tg* and electron density *Ne*) were used. The ionospheric response is characterized by a negative storm effect expanding from mid–high to low latitude. It is observed during this severe geomagnetic storm that negative effects were caused mainly by an increase in molecular nitrogen composition N_2 and almost no changes in atomic oxygen composition O.

Keywords: Geomagnetic storm; Ionosphere; Neutral gas composition

1. Introduction

The response of the ionosphere to intense geomagnetic storms is a principal topic in ionospheric research. A geomagnetic storm is the result of strong enhancement of ring current, which is caused by disturbances in the solar wind and interplanetary magnetic field and their interaction with the magnetosphere. Strong relationship exists between geomagnetic storms and ionospheric disturbances. The ionospheric reaction to such perturbations is the so called ionospheric storm.

It is well known that, at middle latitudes, the ionospheric storms present an initial "positive" phase in which the electron density is greater than normal (median) values and a "negative" phase when the above mentioned quantity is reduced below their normal pre-event values (e.g., Förster and Jakowsky (2000) and references therein for a review on these phenomena). The negative storms occur predominantly during night-time hours while the positive ones at daytime hours (Prölss, 1993). Furthermore, the ionospheric response to a particular geomagnetic storm can vary significantly with latitude, season, local time, etc.

It is generally accepted that negative storms at mid latitudes are associated with an increase in the molecular nitrogen concentration and a simultaneous decrease in the atomic oxygen concentration, that is, an increase in the ratio N_2/O (e.g., Prölss, 1980, 1995; Buonsanto, 1999; Danilov, 2001). However, has been also suggested that increases in the mean molecular mass would be considered as the basic cause of the decreases of the electron density produced during long-lasting main phases and first stage of the recovery phase of intense storms at equatorial and low latitudes (Mansilla, 2006). 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

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positive ionospheric storms observed at different latitudes. 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). Delayed increases of electron density observed at mid latitudes during the recovery phase are associated with the atomic oxygen density increases (Mansilla, 2008). At low latitudes, the maintenance of enhanced electron density during the end of the recovery phase is promoted by an upward plasma drift due to enhanced equatorward winds (Mansilla, 2006).

The aim of this paper is to provide an order of magnitude for the changes produced in the ionosphere-thermosphere system during the intense geomagnetic storm occurred on 13 July 1982. Also, in this work we report the disturbances in the ratio N_2/O and their association with the changes in N_2 and O compositions. For this purpose, data from middle-low latitudes taken at altitudes near to the maximum electron density of F2-layer by instruments onboard Dynamic Explorer 2 (DE-2) spacecraft were used. DE-2 (initial apogee: 1012 km; initial perigee: 309 km; orbital period: 1.63 h; inclination: 90° and eccentricity: 0.03) 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).

The geomagnetic index Dst was used for representing the geomagnetic storm intensity and to describe the different phases of the storm.

2. Observations

In general, during perturbed periods no satellite measurements are often available or they are scant. In spite of these difficulties a reasonable amount of data was found during this severe geomagnetic storm to make a study of the temporal variation of several ionospheric and thermospheric parameters during storm periods. DE 2 measurements took place in a wide range at heights along the satellite track. In this paper were selected data at heights near the peak of the F2-layer. However, there is no guarantee that the selected range of heights correspond to the F layer peak because different satellite orbits can give information above or below the peak. The data between 280 and 300 km were selected for the invariant latitudes 20°, 30°, 40° and 50° and the data between 380 and 400 km for the invariant latitudes 70° and 80° because no data were available at lower altitudes. It is noted that each measurement corresponds to a different place on the globe.

The parameters used in this study are molecular nitrogen N_2 and atomic oxygen O compositions, neutral temperature Tg and electron density Ne. The temporal change of the thermospheric and ionospheric parameters was analyzed in response to the storm at low, middle and high invariant magnetic latitudes. The measurements taken prior to the beginning of the storm are used as a quiet time reference. The storm time measurements and the reference measurements have been selected with the same characteristics both in altitude and in time (15–15.5 solar local 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.

3. Results

The upper atmosphere reaction to the geomagnetic storm was analyzed from five days prior to the storm onset to three days after it. This storm onset was caused by a shock compression of preexisting southward field and the associated solar event was 2/X7.1 (0955 UT 7/12/82) (Tsurutani et al, 1992). Fig. 1 shows a summary of the geomagnetic and solar wind conditions during the period July 8–16, 1982. From top to bottom, the panels are: Dst, AE, the Bz component (in GSM coordinates) and the solar wind velocity. The storm sudden commencement was on July 13 at 1617 UT. During the storm main phase (between about 18 UT and 01–02 UT on July 14), Dst decreased to a minimum (negative) of 325 nT which marked the end of the main phase and the beginning of the relatively rapid recovery phase. AE index indicated a substantial auroral activity since about 12 UT on July 12 reaching values larger than 1500 nT at 01 UT on July 14, when Dst attains the minimum value. After midday on July 13, the north–south component (Bz) of the interplanetary magnetic field exhibited an incursion to the south that lasted several hours. The fast forward shock was identified by the abrupt increase observed in velocity on July 13, from ~500 km/s to ~900 km/s.

The top plot of Fig. 2 presents the temporal evolution of the geomagnetic index Dst and the electron density Ne at 20° of invariant magnetic latitude for the July 8–16, 1982 period. It can be seen that electron density is depressed during the storm recovery phase (~60% change). The middle plot of Fig. 2 presents the behavior of N_2 and O at altitudes 280–300 km. The storm not only affects the ionosphere but also the thermosphere. N_2 increases by about 30–80% during the main phase and the recovery phase while O presents no significant changes during storm period. The ratio N_2/O is also represented in the bottom plot of Fig. 2. At the altitudes of our measurements, an increase is observed during the main phase and first part of the recovery which corroborates a direct relationship between increases in the ratio N_2/O and Ne depletions. Both the increase in molecular gases and the simultaneous decrease in the atomic oxygen density were considered to contribute to a decrease in the electron density (e.g., Prölss, 1995). However, the enhancement in the ratio N_2/O (and therefore the decrease in Ne) is produced by only an increase in N_2.

Fig. 3 is similar to Fig. 2 but for 30° invariant latitude. Similarly that at lower latitude depletion in Ne is observed during the recovery phase. An increase in N_2 (~100%

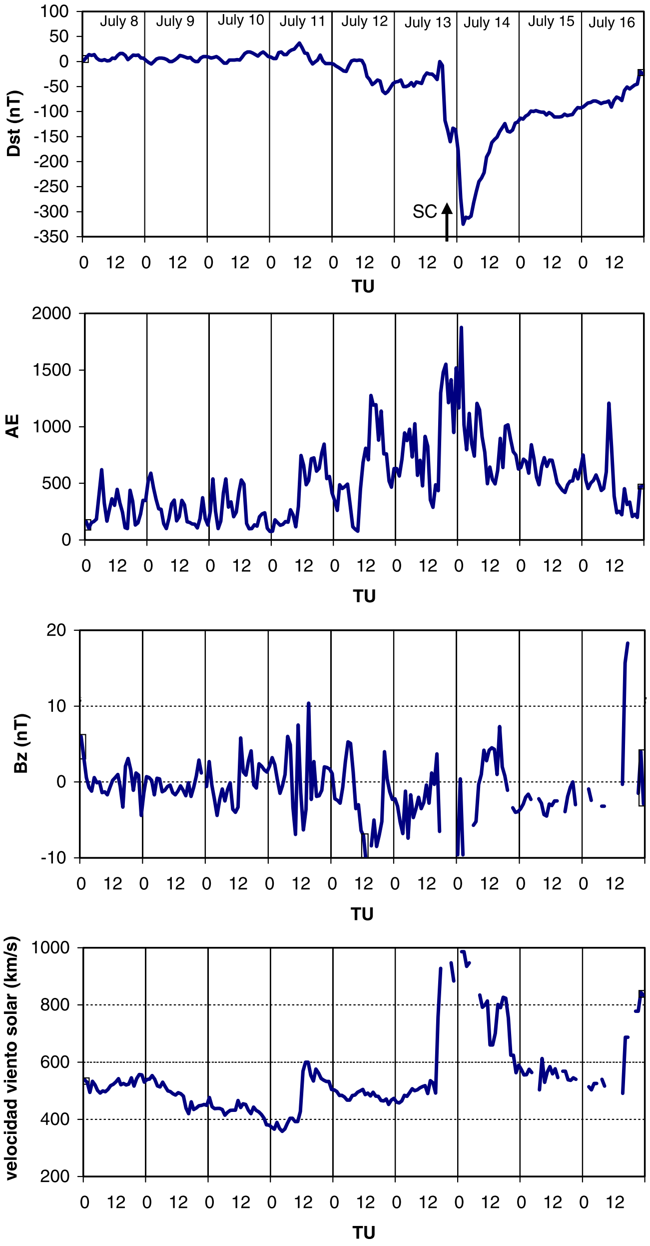

Fig. 1. Variation of index Dst (top panel), index AE and Bz component in GSM coordinates (middle panels) and the solar wind velocity (bottom panel) for the 8–16 July 1982 storm period. The arrow indicates the sudden commencement of the storm at 1617 UT on July 13.

change) is presented during the main phase and first part of the recovery while atomic oxygen practically does not show appreciable changes. Such change gives place to increased values of N_2/O in association with the negative ionospheric storm.

Fig. 4 is similar to Fig. 2 but for 40^0 invariant latitude. A decrease of electron density is observed before that at lower latitudes since the main phase and during recovery phase of the storm. This negative effect suggests that the perturbation started at higher latitudes and propagated to lower latitudes. Although there is a gap of data on 12–13 July, N_2 is enhanced on 14 and 15 July and is followed by a trend to recover undisturbed values, while O density presents almost no change relative to pre-storm values. As it is expected, the ratio N_2/O shows an enhancement with similar duration that the negative storm effect. At 50° invariant latitude (not shown here), depressed values of electron density are observed during the main phase of the storm, which corroborates that the disturbance is initiated at higher latitudes. Similarly that at 40° invariant latitude, N_2 shows an enhancement during the main phase/early stage of the recovery and O practically no change; in accordance with these values, the ratio N_2/O is increased.

The response of ionospheric and thermospheric parameters to the storm at 70° and 80° invariant latitudes is not shown here because the data scarcity. The trend of available data shows decreases of electron density during the storm recovery phase: at 70° the electron density varies from 2.6×10^5 cm^{-3} to 1.6×10^5 cm^{-3} in this stage. In general, it can be seen that the electron density falls to lower values when increasing latitude. N_2 undergoes an important increase (~170% change) while no significant variation is observed in O. Such changes lead to enhanced values of the ratio N_2/O during the main and recovery phases of the storm.

Fig. 5 illustrates the storm time evolution in neutral temperature *Tg* disturbance at several invariant latitudes. There is a gap of data on July 12. Comparing with pre-storm data it can be seen that *Tg* started to increase on July 11; a moderate increase in neutral temperature is observed on the storm day and the following day, during the main phase/recovery phase of the storm. The neutral gas temperature at higher latitudes (not shown here) also presented enhanced values. The increase in temperature at high latitudes leads to an expansion and upwelling of density-rich gases. The neutral winds then redistribute the composition disturbance over much of the high latitude region and the middle to low latitudes 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 F2 region is depleted in the composition disturbance zone. During the recovery phase the increase with respect prior storm values was of about 20% at 20–30° invariant latitude.

4. Discussion and conclusion

This study presents an examination of the storm effects on measurements of ionospheric–thermospheric parameters at several latitudes in a common solar time. The ionospheric response is characterized by negative perturbations in the electron density on 13–14 July corresponding to the main phase and early part of the recovery phase of the geomagnetic storm.

The modern view of negative storm effects still relies primarily on composition changes. In general it was observed that N_2 is increased by a higher percentage than decrease in O in response to the storm. This result differs from the obtained by one Miller et al. (1990). They found that in winter N_2 increased by a higher percentage than O while in

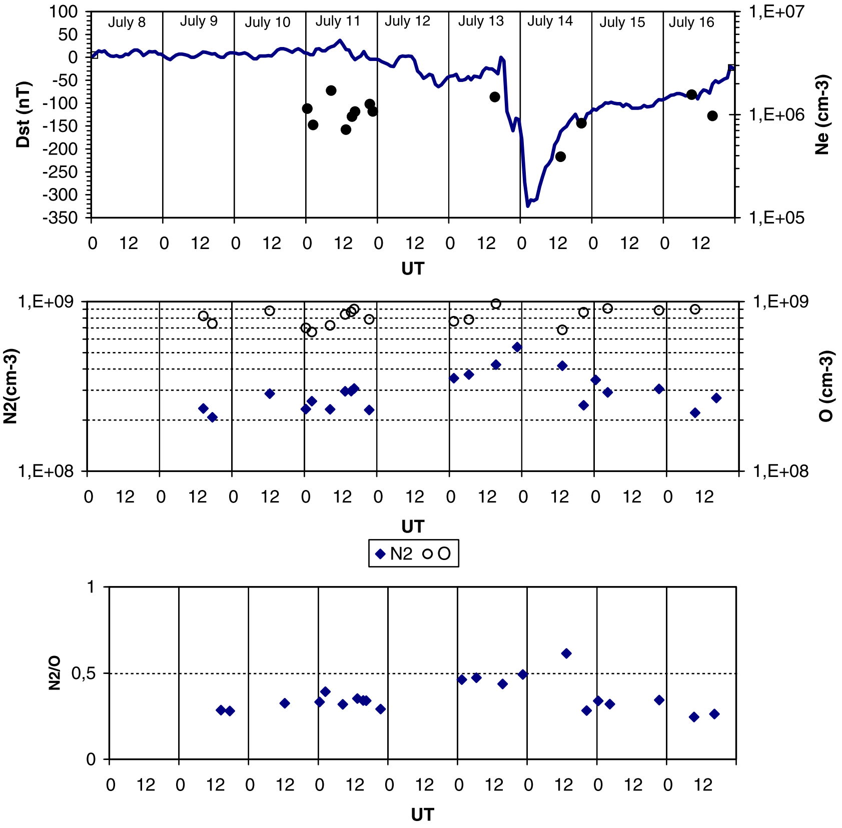

Fig. 2. Variation of index Dst and electron density *Ne* (top panel), gas densities (open circles for O and filled rhombuses for N_2) (middle panel) and the N_2/O ratio (bottom) for the 8–16 July 1982 storm period at the 20° invariant latitude.

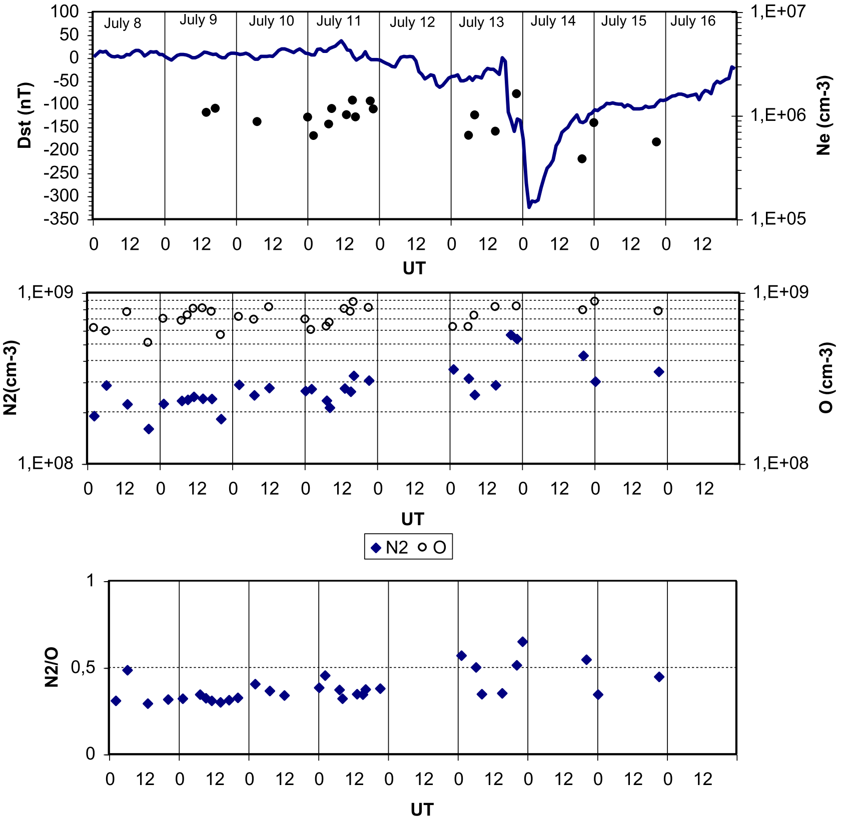

Fig. 3. The same as Fig. 2, but at 30° invariant latitude.

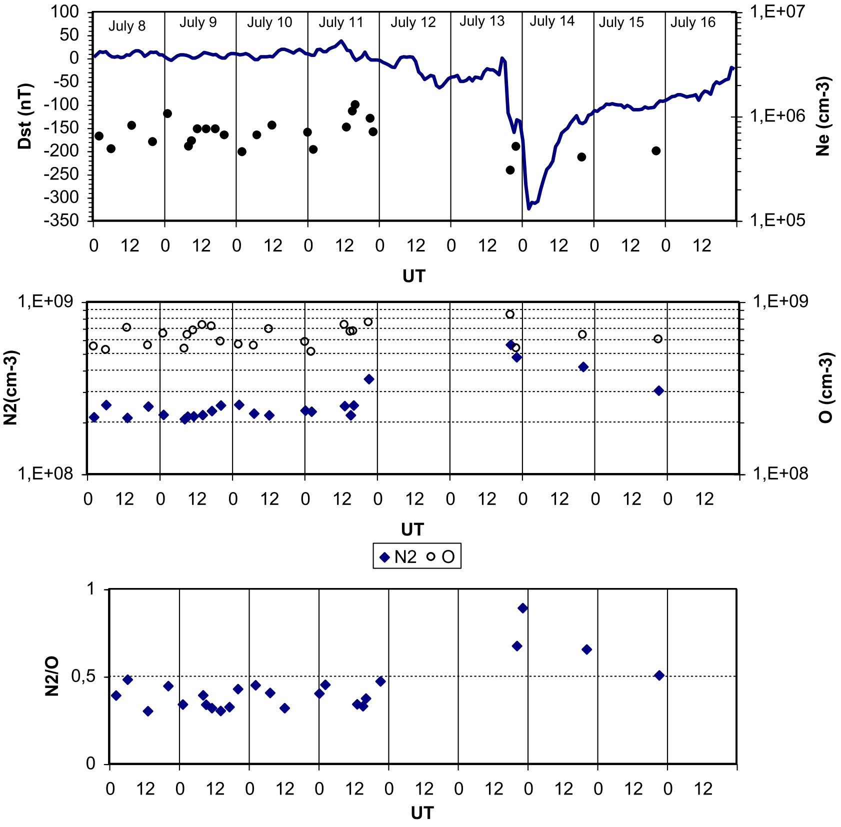

Fig. 4. The same as Fig. 2, but at 40° invariant latitude.

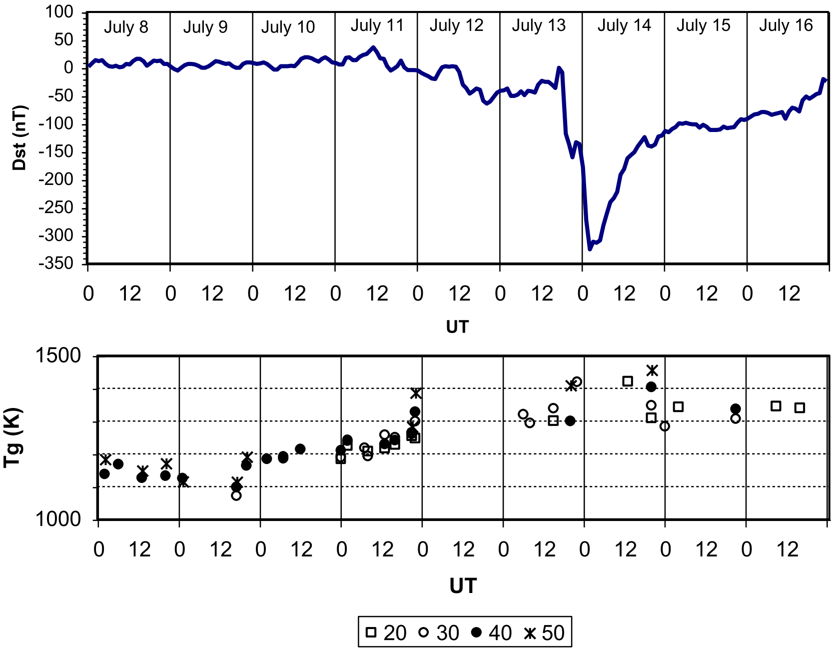

Fig. 5. Variation of Dst index and the neutral temperature Tg at several invariant latitudes (20°, 30°, 40° and 50°) for the 8–16 July 1982 storm period.

summer neither species deviated much from its pre storm values. Prölss (1995) found a simultaneous decrease in the atomic oxygen density and an increase in the molecular nitrogen density at middle latitudes which combine to reduce the ionization density at F-region heights. The original suggestion by Seaton (1956) that the negative storm effects are caused by an increase in the molecular gas O_2 and the suggestion by Chandra and Herman (1969) that negative storm effects are caused by a reduction of the atomic oxygen density are considered incomplete by Prölss (1995). However, we found evidence that negative ionospheric storm effects observed during an intense geomagnetic storm are caused by an increase in N_2 fundamentally and practically no change in O. Since the loss rate of ionization depends on the density of molecular gases (N_2 and O_2) an increase in these gases will increase the loss rate of ionization.

The Figures indicate that the negative storm effect expanded from mid-high latitudes to low latitudes. In summer, the quiet-time and storm-induced circulations coincide (both are equatorward). Both circulations bring the gas with enhanced N_2/O ratio and that tends to reduce the electron density in the F2 peak at lower latitudes. On the contrary, in winter the zone of the increased N_2/O ratio is "locked" at high latitudes because the normal circulation prevents the heated gas penetration to middle latitudes (Danilov, 2001).

The geomagnetic storm 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 low latitudes. So, the negative ionospheric storms will be observed even at relatively low latitudes.

It is well known that the ionospheric parameters at equatorial latitudes show a four-peaked longitudinal structure (e.g., Lin et al, 2007). The four-peaked structure starts to develop at 0800-1000 LT and becomes most prominent at 1200–1600 LT. We investigate a possible longitudinal dependence of the data by comparing the longitude information of our low latitude dataset with the four-peaked structure and found that the depressed values of the electron density lngitudinally coincide with the location of the peaks, that is, in spite of the ionospheric peak there is a depletion of electron density. For that reason we assume negligible the longitudinal variation of the analyzed parameters and consider that the electron density depresses during the main and recovery phases are consequence of the geomagnetic storm.

Summarizing, this paper investigates the changes produced in the ionosphe re-thermosphere system during the very intense geomagnetic storm of 13 July 1982.

Decrease in electron density is the main feature observed in different invariant latitudes. It is already well established the relationship between the negative storm and the increase in the ratio N_2/O during magnetic storms. It is believed that the increase en N_2/O is caused by an increase in N_2 and a simultaneuos decrease of O (e.g., Prölss, 1995).

However the observational results indicate that the negative effects during the considered geomagnetic storm can be produced by a decrease of N_2 and no significant variation in O. Changes in neutral composition observed during less intense geomagnetic storms (Mansilla, 2011) showed similar results, that is, the negative effects are closely related to increases in the ratio N_2/O but mainly produced by the increase in N_2 composition. For that reason more works are needed for the advance current scientific understanding of this question concerning to possible causes of negative storm effects during geomagnetic storms.

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