

Large enhancements in the O/N₂ ratio in the evening sector of the winter hemisphere during geomagnetic storms

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Abstract. In this paper, we have looked for enhancements of the O/N₂ ratio in data measured by the Dynamics Explorer 2 (DE 2) satellite in the middle latitudes of the winter hemisphere, based on a prediction that was made by the National Center for Atmospheric Research thermosphere/ionosphere general circulation model (NCAR-TIGCM) that such increases occur. The NCAR-TIGCM predicts that these enhancements should be seen throughout the low latitude region and in many middle latitude locations, but that the enhancements in O/N₂ are particularly strong in the middle-latitude, evening-to-midnight sector of the winter hemisphere. When this prediction was used to look for these effects in DE 2 NACS (neutral atmosphere composition spectrometer) data, large enhancements in the O/N₂ ratio (~50 to 90%) were seen. These enhancements were observed during the main phase of a storm that occurred on November 24, 1982, and were seen in the same region of the winter hemisphere predicted by the NCAR-TIGCM. They are partially the result of the depletion of N₂ and, as electron loss is dependent on dissociative recombination at F₂ altitudes, they have implications for electron densities in this area. Parcel trajectories, which have been followed through the NCAR-TIGCM history file for this event, show that large O/N₂ enhancements occur in this limited region in the winter hemisphere for two reasons. First, these parcels of air are decelerated by the antisunward edge of the ion convection pattern; individual parcels converge and subsidence occurs. Thus molecular-nitrogen-poor air is brought from higher to lower heights. Because neutral parcels that are found a little poleward of the equatorial edge of the eveningside convection pattern are swept inward toward the center of the auroral oval, the enhancements occur only in a very limited range of latitudes. Second, nitrogen-poor air is transported from regions close to the magnetic pole in the winter hemisphere. During geomagnetic storms, enhanced meridional winds are driven by the increased pressure-gradient force that is associated with intensified Joule heating in the auroral oval. These pressure-driven winds decrease rapidly on the dayside beyond the auroral oval where the parcels originate, limiting the region into which the parcels can be transported. Thus these two processes drive values of O/N₂ in a limited region of the winter hemisphere, and reinforce only in the evening sector, causing large changes in this region.

1. Introduction

The idea that negative storm effects (decreases in F₂ electron densities at high and middle latitudes) could be caused by changes in neutral composition was first raised by Seaton [1956]. He postulated that enhancements of O₂ would result in increased electron ion recombination rates and hence decreases in electron density. The first attempt to quantify these changes was made by Duncan [1969], who suggested that the large-scale circulation pattern in the thermosphere may drive composition changes that could explain ionospheric storms. Modeling efforts by Hays *et al.* [1973] showed that the enhancements in N₂ occur when increased Joule heating in the auroral oval results in the upward transport of nitrogen-rich air from below. Mayr and Volland [1973], Mayr and Hedin [1977]

and Mayr and Trinks [1977] showed that the nitrogen-rich air that results from these upwellings could be redistributed by horizontal winds, leading to composition changes beyond the auroral oval. The morphology of these changes has been well described by Prölss and coworkers [Prölss, 1976, 1980, 1981, 1984; Prölss and Fricke, 1976; Prölss *et al.*, 1988] and also by several other investigators [e.g., Jacchia *et al.*, 1967; Taeusch *et al.*, 1971; Allan and Cook, 1974; Chandra and Spencer, 1976; Hedin *et al.*, 1977; Taeusch, 1977; Engebretson and Mauersberger, 1983].

The major advance in theoretical thermospheric physics in the 1980s was the development and testing of thermospheric general circulation models (TGCMs). Two TGCMs, in particular, have contributed greatly to our understanding of the thermosphere: the University College London (UCL) TGCM [Fuller-Rowell and Rees, 1980, 1983; Fuller-Rowell *et al.*, 1987] and the National Center for Atmospheric Research (NCAR) TGCM [Dickinson *et al.*, 1981, 1984] and its more recent versions - the NCAR thermosphere/ionosphere general circulation model (TIGCM) - [Roble *et al.*, 1988] and the latest electrodynamic version of

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the model [Richmond *et al.*, 1992]. The UCL - TGCM was the first GCM used to study thermospheric composition changes during geomagnetic storms [Rishbeth *et al.*, 1985, 1987; Fuller-Rowell *et al.*, 1989]. Recently, it has been shown that both the UCL-TGCM and the NCAR-TIGCM do show realistic changes in neutral composition that can account for negative storm effects [Fuller-Rowell *et al.*, 1991; Burns *et al.*, 1991; 1992].

Not only do GCMs predict negative storm effects in neutral composition (i.e., enhancements of N₂ density relative to O density), but both models also predict large regions where O density should be enhanced relative to the N₂ density [Rishbeth *et al.*, 1987]. Figure 1 shows NCAR-TIGCM predictions of changes in O/N₂ ratio that happened on a constant pressure surface during the large storm that occurred on November 24, 1982. The O/N₂ ratio is used so that the neutral compositional equivalent to negative storm effects is negative. The major feature that is apparent in Figure 1 is that, while negative storm effects in neutral composition occur at high latitudes, the model predicts that increases in the O/N₂ ratio are seen over much of the globe. These increases are seen throughout the low-latitude region and also over much the middle-latitude region in the model, yet such effects have not been confirmed in studies of thermospheric data (but see Prölss, [1987]). These predicted increases are so large that they should be seen easily in the data if they can be isolated from other effects such as the change in neutral density with changes in EUV radiation. The model predicts that these very large enhancements in the O/N₂ ratio should be seen in a 10-15 deg latitude band between local dusk and local midnight at middle latitudes in the winter hemisphere.

One way in which the output from the NCAR-TIGCM differs from the observational data is in the method by which the "altitude" is calculated. Satellite observations are generally measured in situ, so the height used is the distance above an estimated surface of the Earth. However, theoretical calculations are more easily made in pressure coordinates, so pressure heights are used in the NCAR-TIGCM. Normally, the difference between the two does not significantly affect the results that are presented, but, when looking at changes in

composition during geomagnetic storms, large variations do occur. Therefore, for comparison purposes, we plot in Figure 2 the model calculations of the differences in the O/N₂ ratio on a constant height surface at 350 km. A "back-of-the-envelope" estimation of the changes in height of the pressure surface indicates why such large changes can occur between a constant pressure surface and a constant height surface during geomagnetic storms: if the temperature increase is 10% (as it is in the region of interest) and the decrease of mean molecular mass is about 10% (which is reasonable in the region where the O/N₂ ratio increases so greatly) the scale height will increase by approximately 20%. If this increase in scale height is applied over five pressure surfaces the increase in altitude of the pressure surface is about 50 km. This corresponds to one full scale height, enough to change the neutral composition considerably.

In the plot of O/N₂ changes on a constant height surface (Figure 2), as in the pressure surface plot, the predicted increases in the evening in the middle latitudes of the winter hemisphere are large. While they are much smaller than they are when constant pressure surfaces are used (maximum values are now 80% as opposed to 300 %), they are still very significant and should be very apparent in the observational data. Note that the satellite path that is discussed in Figure 5 passes through this feature at about the longitude of the United Kingdom.

Additional support for these theoretical predictions of increases in the O/N₂ ratio comes from work done using the UCL-TGCM. Rishbeth *et al.* [1985] and Fuller-Rowell *et al.* [1989] have suggested that these reductions in mean molecular mass may cause the ionospheric "positive storm effects" (increases in NmF₂) that are often seen in the middle and low-latitude F₂ layer.

Heretofore no observations have supported either modeling effort. In this paper, we provide such support by using the NCAR-TIGCM predictions of the location of this feature during geomagnetic storms to find increases in the O/N₂ ratio in the neutral composition data that was measured by the (NACS) neutral atmosphere composition spectrometer instrument [Carignan *et al.*, 1981] that flew on board the

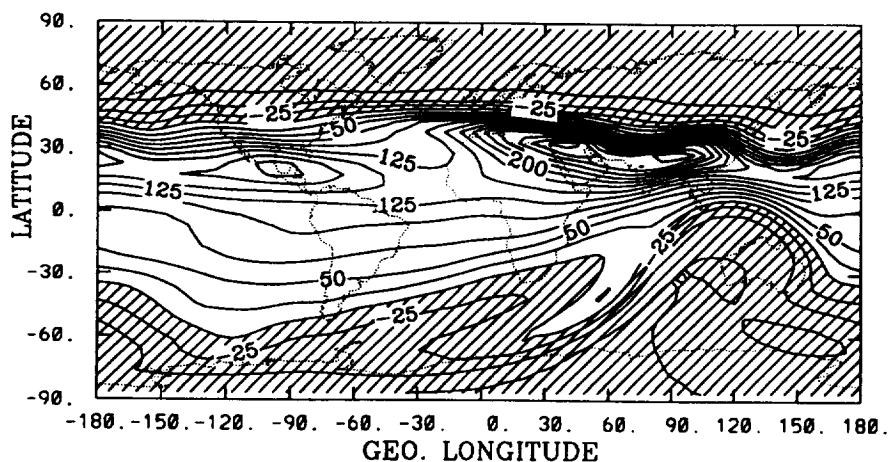


Figure 1. The NCAR-TIGCM predictions of the percentage changes in O/N₂ ratio between storm and quiet time on the $z = 2$ (~350 km) pressure surface. These calculations have been made for 1900 UT, 8 hours after the start of the geomagnetic storm on November 24, 1982. Unless it is explicitly stated otherwise all plots in this paper use geographic coordinates.

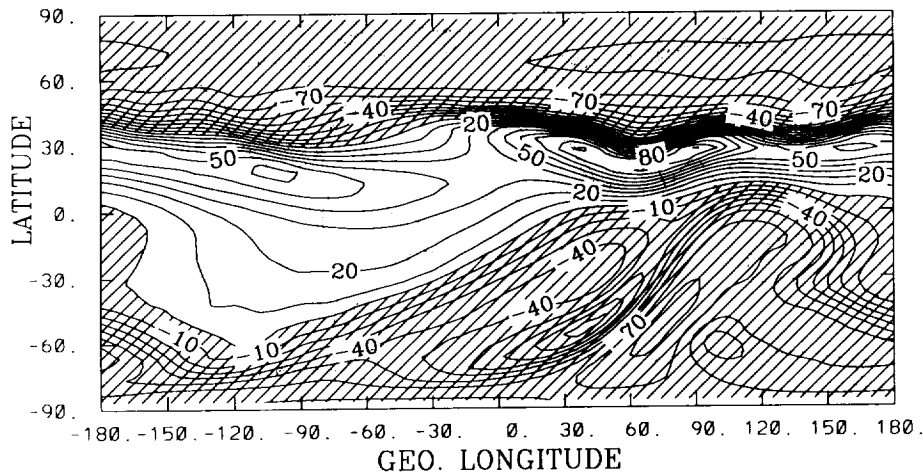


Figure 2. The NCAR-TIGCM predictions of the percentage changes in O/N₂ ratio between storm and quiet time on the 350 km height surface. These calculations are equivalent to those in the previous plot, the only difference being that a constant height surface is now used rather than a constant pressure surface.

Dynamics Explorer 2 (DE 2) satellite [Hoffman *et al.*, 1981]. We have also begun a preliminary investigation of the relationship between these changes in neutral composition and changes in electron density using the Langmuir probe (LANG) [Krehbiel *et al.*, 1981] that flew on board the same spacecraft.

The storm mentioned above was found to be suitable for a case study of these changes in neutral composition and electron density. It is discussed in the next section, and a brief outline of the data analysis techniques, the NCAR-TIGCM and the post processors used are also given there. The observations are discussed in section 3, and an explanation for the large enhancements in O/N₂ that were seen in the winter hemisphere is given in section 4. A discussion of the potential effects of changes in neutral densities on electron density is given in section 5. Section 6 contains a comparison between satellite observations of O/N₂ changes and electron density changes during storms. These observations are discussed in section 7, and the main results from this study are summarized in the last section.

One brief note on nomenclature should be made at this point. The words "positive storm effects" have a long history of being associated with ionospheric, rather than neutral thermospheric, phenomena and may be caused by a number of different processes [e.g., see Prölss *et al.*, 1991]. However, the strong parallel between negative ionospheric storm effects and changes in neutral composition has gradually led to high latitude changes in neutral composition also being labeled as "negative storm effects." With our present knowledge of this region, a similar, correlative statement about "positive storm effects" does not seem appropriate. Instead, when the words "positive storm effects" are used in this paper they are used only to describe ionospheric changes, while the increases in O densities relative to N₂ density in the neutral thermosphere are termed "enhancements in the O/N₂ ratio."

2. Modeling Aspects

The NCAR-TIGCM is a three-dimensional, time-dependent model of the Earth's neutral upper atmosphere that is run on the CRAY-YMP computer at NCAR. The model uses a

finite differencing technique to obtain time-dependent solutions for the coupled, nonlinear equations of hydrodynamics, thermodynamics and continuity of the neutral gas [Dickinson *et al.*, 1981; Roble *et al.*, 1982] and for the coupling between the dynamics and the composition [Dickinson *et al.*, 1984]. A thermosphere/ionosphere general circulation model with a coupled ionosphere and a self-consistent aeronomics scheme has been developed by Roble *et al.* [1988]. More recently the model has been improved by including a self-consistent dynamo model for the low latitudes [Richmond *et al.*, 1992]. Detailed descriptions of the NCAR models, as well as their input parameterizations, have been given previously in papers by Dickinson *et al.* [1981, 1984] and Roble *et al.* [1982, 1987, 1988] and Richmond *et al.* [1992].

The output fields of the NCAR-TIGCM can be treated in much the same way as data insofar as they can be interrogated further to gain a greater understanding of the basic physical processes that cause changes in the model. Killeen and Roble [1984] developed this principle to create a momentum postprocessor for the NCAR-TIGCM. Later [Killeen and Roble, 1985, 1986], they developed the capability of tracing the paths of parcels of air through the output fields, so that only those processes that affect the parcels in a Lagrangian reference frame need be considered. This parcel tracing was extended to three dimensions by Burns *et al.* [1991], and it is used in this paper to study the causes of the enhanced region of O/N₂ in the winter hemisphere during the geomagnetic storm that occurred on November 24, 1982.

DE 2 was a multi-instrumented satellite that flew during the last solar maximum period [Hoffman, 1981]. The measurements that we are most concerned with here are the neutral composition measurements made by the NACS instrument [Carignan *et al.*, 1981]. This instrument measured the densities of molecular nitrogen, helium, argon, atomic nitrogen and oxygen. The NACS instrument could not distinguish between atomic and molecular oxygen due to the nature of the detector. However, this did not cause large problems as the satellite did not orbit at altitudes much lower than 300 km. At these heights molecular oxygen densities are typically of the order of at most a few percent of those of atomic oxygen, so no large uncertainties are introduced into

the atomic oxygen densities. There is also a systematic problem as the molecular nitrogen density measured by the NACS instrument is 20-30% lower than expected (A. Hedin, 1989, private communication). DE 2 O densities are also smaller than MSIS values but the difference is less than that for N₂.

We have compensated for these systematic variations in N₂ and O densities by making statistical comparisons between DE 2 densities and MSIS calculations for quiet periods that last for several days near the time of the orbits used. Mean variations between the DE 2 data and MSIS are calculated, and these means are then used to scale the storm time DE 2 densities, so that they can be compared with the quiet-time MSIS values. The use of MSIS introduces an extra uncertainty into our calculations that is caused by the uncertainty in the semi-empirical model. Killeen *et al.* [1993] used Accelerometer data to estimate this uncertainty in MSIS. Although the Accelerometer measurements were made at a somewhat lower altitude than the measurements made here (in a region where MSIS was probably a little more accurate), the Killeen *et al.* results give an indication of the accuracy of the MSIS model at the latitudes that we are discussing in this paper. These results indicated that the one standard deviation uncertainty for MSIS in this region is about 12%. Given that the probable uncertainty in the DE 2 measurements is at least of the same order, we can only assume significance if the feature that is being discussed varies from its quiet time value by more than about 30 to 40%.

Electron densities were measured by the LANG instrument that has been described by Krehbiel *et al.* [1981]. Where necessary they have been compared with the IRI model [Bilitza, 1986]. The IRI model is used to provide an approximate "quiet time" reference for comparison with the observed storm time electron densities. The uncertainty in these quiet-time reference electron densities are quite large, despite being in the region where the IRI model is most accurate (equatorward of the trough). Dandekar [1985] quotes a one standard deviation uncertainty for the peak electron density in the IRI model of about 30%. Therefore, in looking for regions of increased electron densities, we only looked for increases that were greater than this amount.

A large number of geomagnetic storms occurred during the time that the DE 2 satellite was flying. Most of these storms fell into the category of minor storms, but there were several large storms as well. One of these large storms occurred on November 24, 1982 (day 328) when Kp exceeded 7 for at least 12 hours (Figure 3). Maximum values of the bulk velocity of the solar wind exceeded 800 km/s and the magnitude of the interplanetary magnetic field (IMF) exceeded 30 nT. A large electric field was generated with ion drifts exceeding 2000 m/s at times, and neutral winds in excess of 1200 m/s, the largest seen in the DE 2 period, were driven by these energetic ions. These large winds indicate an enhanced ion convection pattern, and the consequent Joule heating produced neutral temperatures in excess of 2000 K. These winds and temperatures alone would make it an interesting event to study, but the good data coverage available during this event makes it especially interesting. The storm occurred near the end of the DE 2 period, when the satellite was in a nearly circular orbit, with perigee just above 270 km and apogee just below 530 km. The low eccentricity of the satellite path permitted data to be gathered by all the instruments on board the DE 2 satellite over almost the entire orbit, and thus, for

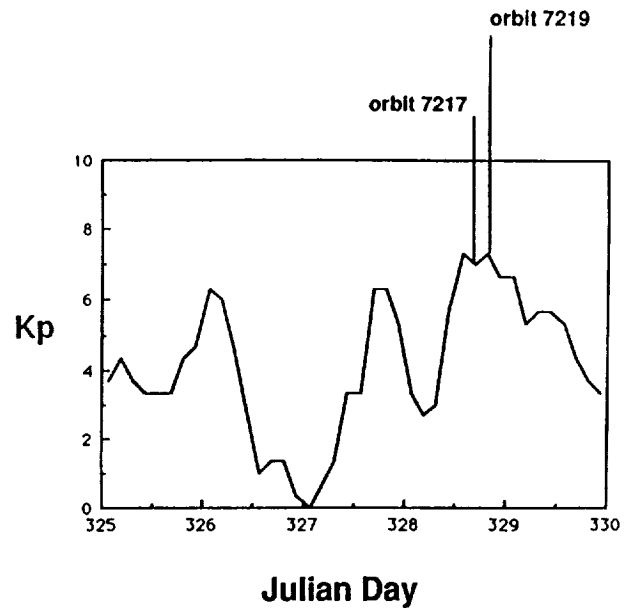


Figure 3. Kp for the period leading up to and including the November 24 (Day 328), 1982 geomagnetic storm.

some orbits during this storm, data were available in both the winter and the summer hemispheres. Of especial interest to this study are the data from the middle latitudes in the evening sector of the winter hemisphere. The satellite altitude was between 320 and 390 km in this region, so the neutral compositional data were reliable, which allows us to determine if the modeled predictions of enhanced O/N₂ ratios are correct.

3. DE 2 Observations of Neutral Composition Changes and MSIS Comparisons

Figure 4 shows the changes in the DE 2 O/N₂ data relative to MSIS-86 [Hedin, 1987] values for orbit 7217 (November 24, 1982). The MSIS values were calculated using the same orbit characteristics, day of the year and EUV flux ($F_{10.7}$ and $F_{10.7}$ average are used as a proxy), for an equivalent quiet-time case. These adjustments were made for constant heights rather than for the constant pressures used in Figure 1. The diagram covers the region between 30° and 60° N, which for this period represents middle latitude, winter hemisphere data. The expected negative storm effects are seen towards the polar cap, with the reductions in O/N₂ ratio of ~60% occurring in this region. These reductions are the result of Joule heating causing the upwelling of nitrogen rich air, which is then redistributed by horizontal winds. The mechanisms responsible for these changes in composition at high latitudes are described in detail by Burns *et al.* [1991], so we will not discuss them further in this paper. The region of interest in this work is the area that is adjacent to the region of "negative storm effects" on the evening side of the auroral oval. The equatorward boundary of these negative storm effects is very sharp in this sector and there is a region equatorward of these effects where the O/N₂ ratio is enhanced by as much as ~80 to 90%. These enhancements occur in a relatively narrow band about 10 deg. of latitude. Equatorward of this region the enhancements in O/N₂ ratio are much smaller and, given the uncertainties that occur in the NACS

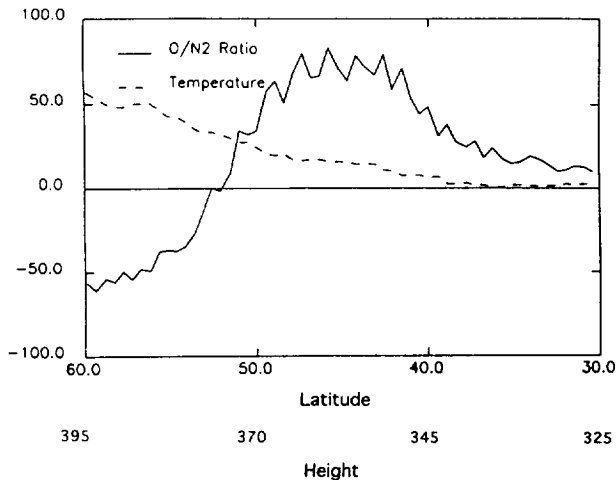


Figure 4. Changes in O/N₂ ratio between storm and quiet times for orbit 7217. This orbit occurred at about 1600 UT, some 5 hours after the storm onset. Storm values, which come from the DE 2 NACS instrument, have been scaled to reflect the differences between quiet time NACS and MSIS densities. Quiet time values come from MSIS, which has been run for the appropriate solar conditions and moderate geomagnetic activity. These changes between storm and quiet values are expressed as a percentage. The local time during this orbit was 18.6 local solar time, so the longitude of the satellite was about 40 E.

data and in the MSIS estimates of density (~15%), they cannot be said to occur with any confidence.

It is expected that a number of transient phenomena will be set up during a geomagnetic storm. In particular, a number of authors including *Richmond* [1979] and *Mayr et al.* [1984] have shown that the large scale waves that are generated by geomagnetic storms can propagate to the equator in about 4-6 hours after the onset of the storm. The storm time at which orbit 7217 occurred (about 5 hours after commencement) is a little long for the initial wave peak that reaches the equator in 4-6 hours [e.g., *Burns and Killeen*, 1992], but it might be argued that a later impulse could have generated a wave that produced the observed enhancements of the O/N₂ ratio. If this is true the effects should not be seen at later times. However, when we look at a later orbit (7219 - the satellite passed the same places about 3 hours later than orbit 7217), we see (Figure 5) that the enhancements occur in the same place as they did for orbit 7217 (at about 45 deg. geographic latitude ~55 deg. geomagnetic latitude), although the magnitude of these effects is diminished. Clearly then, these O/N₂ enhancements are a quasi-permanent feature of this geomagnetic storm, and they cannot be explained in terms of a single large gravity wave that was set up by the dynamical changes that occurred at the start of the storm.

Calculations made using the NCAR-TIGCM also show that these enhancements are a quasi-permanent feature of the thermosphere during geomagnetic storms, and do not represent waves generated in the auroral regions which propagate to lower latitudes. The location of the increases in O/N₂ ratio shown in Figures 4 and 5 is close to the position of the enhancements shown in the model predictions given in Figures 1 and 2, although the enhancements may be a little closer to the pole in the data. This difference is probably due

to difficulties in estimating the radius of the auroral oval in the model during large geomagnetic storms. In both cases the large enhancements are about 10 deg. wide in latitude and occur at similar latitudes. In the modeled data they extend through the region from before 1800 hours to midnight local solar time, so the data presented in Figures 4 and 5 represent the earliest local time at which these major changes occur. Magnitudes are similar in Figures 2 and 5.

Another interesting feature occurred in the data. This feature is the small-scale, wavelike structures that occurred during orbit 7217, but not during orbit 7219. These variations may be short wavelength internal gravity waves that were driven by rapidly changing conditions early in the storm.

From the above mentioned figures we can see that the observed effects occur in roughly the same location and with roughly the same magnitude that the model predicts. This agreement in position, magnitude and structure is sufficient to suggest that the model is calculating the basic physics and chemistry of the situation correctly, allowing us to study the increases more closely using the diagnostic processors described earlier, and thus permitting us to gain a greater understanding of their causal mechanisms. These mechanisms are discussed in the next section.

4. Discussion of O/N₂ Increases

On analyzing the data, as discussed in the previous section, large increases in O/N₂ ratio were observed in the evening sector of the winter hemisphere. Given that these increases were seen in both the modeled results and in the data, it is possible to apply postprocessors to the model output to understand the causes of this increase. The postprocessors used are the momentum postprocessor of *Killeen and Roble* [1984] and the updated version of it given by *Killeen et al.* (unpublished manuscript, 1995), and the trajectory processor described by *Killeen and Roble* [1985, 1986] and *Burns et al.* [1991]. The trajectory processor treats the thermosphere as a set of parcels of air that can be traced through the model output in a Lagrangian sense. The packets can be traced either forward or backward in time.

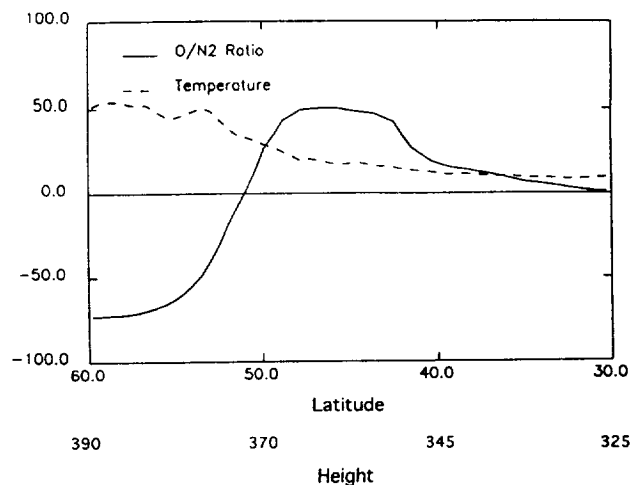


Figure 5. The same as Figure 3, but for orbit 7219 which occurred at 1900 UT, 8 hours after the storm's commencement. The local time is the same as in the previous plot, but due to the change in universal time the longitude of the satellite is about 5° W, corresponding roughly to the longitude of the British Isles.

A parcel of air was traced backward in time in the model run used, from the region of enhancements in the O/N₂ ratio at 1900 hours UT to its position before the storm onset at 1100 hours UT. This storm time parcel was compared with the equivalent parcel of air that arrived at the same location at 1900 hours UT during quiet geomagnetic conditions to gain a greater understanding of the causes of the anomalous enhancement of O/N₂ in this evening sector. The results of this study are shown in Figure 6. Two features related to the starting point of the storm time trajectory are particularly important. First, this parcel of air is found at a latitude that is about 10 deg. higher at 0900 UT than that of the equivalent quiet time trajectory. Second, the starting point of this trajectory occurs at a later local time (about 1 hour later) than the equivalent quiet time trajectory. The two parcels travel similar paths until 1200 UT (insofar as they move through about the same distance in longitude/local solar time, and that they move the same distance poleward). At 1200 UT the path of the storm time trajectory changes noticeably: this parcel moves in an antisunward direction much less rapidly than

previously (i.e., its trajectory does not sweep through local times as rapidly) and, instead of continuing to move inward towards the geomagnetic pole as a result of the day-to-night winds caused by the diurnal tide, and geometrical effects due to the offset of the geomagnetic and geographic poles, this parcel moves away from the geomagnetic pole.

Therefore one cause of the enhancements of the O/N₂ ratio in the evening sector of the winter hemisphere during geomagnetic storms is the transport of nitrogen poor air from a region nearer to the winter pole than the place from which the quiet time trajectories originate (the difference for this storm was about 10 deg. of latitude). In the region from which the storm time parcels come, nitrogen densities are lower than those from which the quiet time parcels originate [e.g., Mayr *et al.*, 1978; Prölss, 1980], thus lower nitrogen densities can occur in the evening sector during storms.

This phenomenon is highly localized in latitude. Parcels of air from latitudes that are 10 deg. lower do not undergo either the same slowing down or the same deceleration in the sunward direction, while parcels from higher latitudes get swept into the region of upwelling associated with the storm and are transported to much higher altitudes.

Another effect of these processes can be seen in Figure 6b. This figure is a comparison between the altitudes of the storm and quiet-time trajectories. The storm time parcel of air follows a similar vertical path to the quiet time trajectory until about 1200 UT, at which time the storm time parcel descends, unlike the quiet time parcel which continues to ascend as a result of the upward winds generated by solar heating. Thus nitrogen-poor air is transported downwards in the region immediately equatorward of the region where the large increases in N₂ density occur, causing enhancements in the O/N₂ ratio in this equatorward region. This is the main reason that the air in the winter sector of the afternoon hemisphere is depleted during geomagnetic storms.

The causes of these changes in motion of the storm time parcel can be understood better if we look at the individual processes causing changes in the parcels' momentum. These forcing terms are given as accelerations in Figure 7. The zonal forces (Figure 7a) relate to the slowing down and speeding up of the parcel in the direction of corotation (i.e., the motion of a point on the Earth's surface in the inertial local time-latitude reference frame). This figure shows that the storm time parcel undergoes a large acceleration in the sunward direction between 1200 and 1300 UT due to ion drag. This is the result of the parcel traveling through the outer edge of the convection pattern. Meanwhile, there is very little acceleration in the zonal direction as a result of the pressure gradient force because large zonal temperature gradients are not established in the storm. The net effect of ion drag on these parcels of air is to cause convergence in the zonal direction and subsequent downwelling.

Pressure gradient forces are important in the meridional direction (Figure 7b). Prior to the storm onset the ion drag force is acting to retard the poleward motion of the parcel of air. At the same time, the pressure gradient force is continuing to push the parcel poleward, away from the region of strongest solar heating on the dayside. The meridional forces pushing a quiet time parcel of air in this region diminish rapidly in the late afternoon (not shown here). This decrease in the pressure gradient force occurs (although it continues to be poleward) because there is less solar heating to force equator-to-pole pressure gradients.

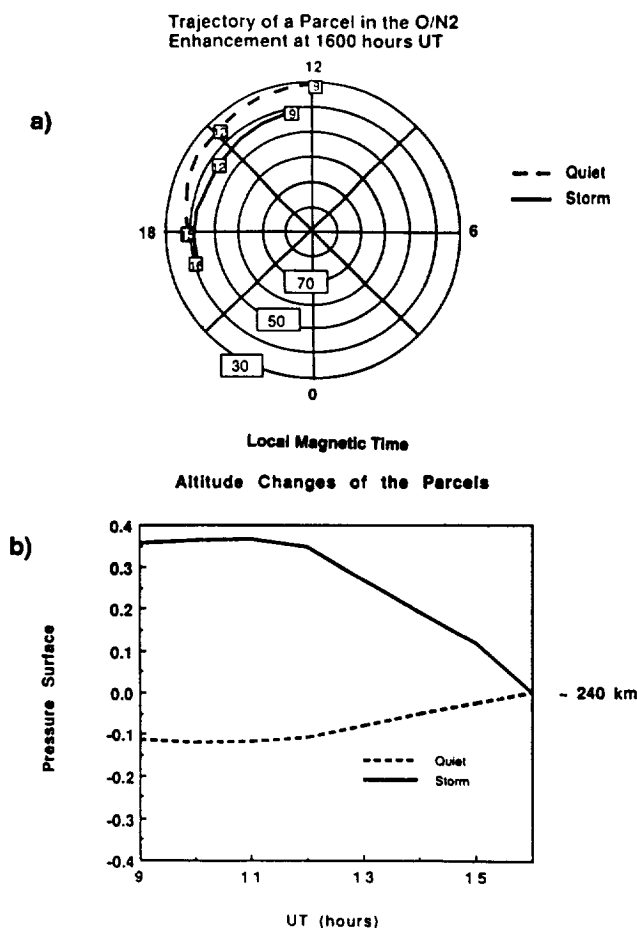


Figure 6. The motion of a parcel of air through the NCAR-TIGCM output file to the region where enhancements in the O/N₂ ratio occur at 1600 UT. The trajectory of the storm time parcel is compared with a quiet time trajectory that arrives in the same location. The (a) horizontal motion of the parcel and (b) the vertical motion. The numbers in the large boxes represent the geomagnetic latitude, while the numbers in the small boxes represent the universal time when the parcel reaches the center of the box.

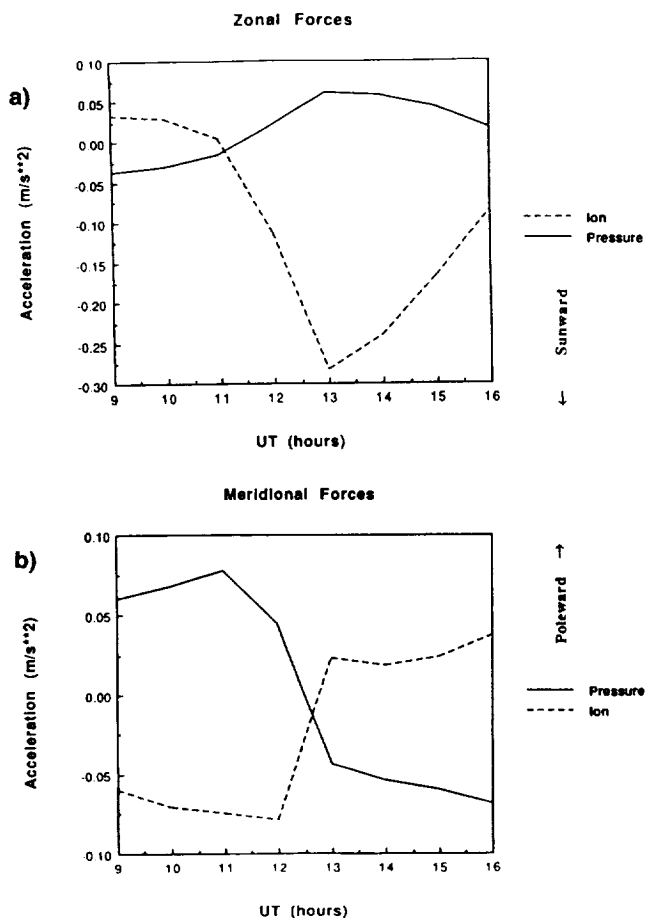


Figure 7. The major forcing terms affecting the trajectory of the parcel of air that was described in Figure 5. The (a) zonal forcing terms and the (b) meridional forcing terms.

The situation is quite different in the storm time case. Soon after the onset of the storm the pressure gradients reverse and start to drive the parcel equatorward. Initially, the equatorward winds are small, so the ion drag that is slowing this equatorward motion is also small. As the equatorward wind speeds increase, ion drag also increases.

Thus two processes come into effect when parcel trajectories are considered. In the first process the zonal motion of the parcel is slowed due to collisions between the neutrals and the ions traveling in the antisunward direction, convergence occurs and the air subsides, bringing nitrogen-poor air down from above. In the second process, air from the high-latitude regions, which is nitrogen poor in the winter hemisphere, is transported into these middle-latitude regions by the pressure gradient forces that result from Joule heating in the auroral zone.

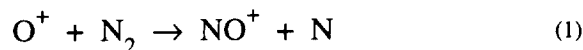
Enhanced O/N₂ ratios in the region discussed here result from changes in the original location of parcels of air that reach the middle-latitude region of the winter hemisphere. In some regions, changes in neutral composition can play an important role in determining the electron content at 300 km. For example, changes in neutral composition are mainly responsible for the negative storm effects discussed in the introduction to this paper. In the next section we discuss the possible relevance of these enhancements in the O/N₂ ratio to electron densities.

5. Relationship Between O/N₂ Changes and Electron Density Variations

It can be seen from the previous discussion that there are strong enhancements in the O/N₂ ratio in the winter middle latitudes during geomagnetic storms. It is not obvious whether these enhancements are a result of an increase in O density or of a decrease in N₂ density or both.

Given that there is an increase in the O/N₂ ratio, there are three possible ways in which it can occur. In the first case O only is enhanced, and the effects on electron density would be expected to be minimal, as the major enhancements in the O/N₂ ratio begin just before dusk and continue until about local midnight. There is very little EUV radiation available at these times to ionize O, so, while there may be a small effect just before dark, the overall impact on F₂ electron densities would be expected to be minimal. In the second case, N₂ densities decrease, but O densities remain constant, while in the third case O densities increase and N₂ densities decrease.

The second and third cases are much more relevant to possible changes in nighttime electron densities than the first one is. At the local times when these changes in neutral composition occur, production is not important and the electron content is dominated both by loss through recombination and by loss and gain through electron transport. O₂ densities are typically small compared with those of the other two major species, so the recombination depends mainly on the reaction:



after which the NO⁺ can recombine rapidly with an electron. Reaction 1 is much slower than the subsequent recombination of NO⁺ with electrons, so the rate at which the electrons and ions recombine is critically dependent on the rate at which O⁺ is converted to NO⁺, which, in turn, is dependent on N₂ density, O⁺ density and temperatures. In most of the region discussed in this paper, temperature changes are not sufficiently large to have a major effect on the O⁺ density, so changes in the density terms dominate (1). Thus, if we ignore transport effects, it can be seen that increasing the N₂ concentration leads to a decrease in the number of electrons relative to quiet time values (the negative storm effects seen at high and middle latitudes), while decreasing the N₂ concentration leads to enhanced electron densities. The reaction involving O₂ may be important, but, as the mechanisms involved in the changing N₂ densities in this region predicate that O₂ behaves in a similar way, the statements made in this section about N₂ also apply to O₂.

6. O/N₂ Enhancements and Electron Density Changes

In the previous section we discussed the way in which changes in neutral composition can affect electron densities. Here we investigate whether these changes in neutral composition possibly have a marked affect on electron densities in the evening sector of the middle latitude winter hemisphere.

Figure 8 shows the changes in N₂ and O densities for orbit 7217 relative to their values for the equivalent quiet time

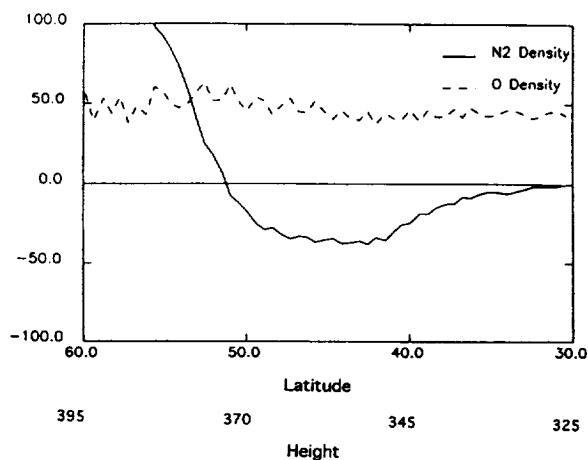


Figure 8. Changes in N₂ and O density between storm and quiet times for orbit 7217. These changes are calculated in a similar fashion to the calculations made in Figure 3.

orbit. There is a great deal of very small scale structure in the O and N₂ densities. However, of more interest to this paper is the more general behavior of the N₂ and O densities at latitudes of about 45 deg. in the winter hemisphere. O densities increase by about 50% while N₂ densities are about 60 to 65% of their quiet time values. The increases in O density across the whole latitude range are a consequence of the increase in temperatures associated with the storm and to a much lesser extent a consequence of the downward winds blowing through the region. Such density increases were first observed in the 1970s [e.g., Mayr *et al.*, 1978; Hedin *et al.*, 1977; and Prölss *et al.*, 1988]. While they are large on a constant height surface, they tend to disappear on a constant pressure surface as the temperature effects are included in the pressure surface calculations.

There is a very noticeable trough in the N₂ densities in Figure 8: it is about 10 deg. wide and is bounded by regions to the poleward, where N₂ densities increase markedly during the storm, and equatorward where N₂ densities are similar to their quiet-time values. O densities are enhanced over the pole in storm time at the satellite's altitude (~370 km). These enhancements are seen to latitudes as low as about 30 degrees in the winter hemisphere at least. The sharp peak in O/N₂ ratio that was discussed earlier coincides very closely with the trough in N₂ density, while no similar structure is seen in O density.

We next calculated the electron loss rate for the storm time conditions that existed during orbit 7217, and compared it with the loss rate for the equivalent quiet-time case calculated using MSIS-86 [Hedin, 1987] and IRI [Bilitza, 1986], assuming that the ion temperature at this middle latitude location was some 50 K higher than the neutral temperature during quiet geomagnetic conditions (Figure 9). A similar comparison was made using quiet time ion temperatures that were the same as the neutral temperatures and the results were almost identical to those shown in Figure 9. As expected, the loss rate during geomagnetic storms is much larger than normal in the region poleward of about 54 deg. in the winter hemisphere, with enhancements in the loss rate of several hundred per cent occurring in this region. In the region of the O/N₂ peak, loss rates decrease to a level that is as little as 55% of their quiet time values, while the return to quiet time values corresponds to the equatorward edge of the O/N₂ peak.

Some of these decreases in the loss rate may result from the uncertainties involved in representing the quiet ionosphere with the IRI model (but these uncertainties could equally well lead to increases in the loss rate), but their major component is due to depletions in N₂ density. Thus these changes in neutral composition produce a relatively narrow region in latitude in which the electron loss rate is decreased by 40 to 50% at a constant altitude.

This change in the loss rate should be reflected in electron density changes. Unfortunately, the orientation of the satellite for this storm was such that it passed through the region of interest just after sunset, when the NCAR-TIGCM predicts that these large enhancements in the O/N₂ ratio were only beginning to occur. Given that changing the loss rate will have an effect on electron densities only in an integrated sense (i.e., it will take some time for changes in neutral composition to manifest themselves as changes in electron density), it is expected that any changes in electron density should be minimal at this time. However, they should be apparent towards midnight, after the ion flux tube has been in this region of depleted N₂ for some time.

The discussion in the previous paragraph indicates that, to find any electron density enhancements that may occur as a result of enhancements in the O/N₂ ratio, we should look at data from orbits at least 2 hours after dusk. Therefore we have looked at electron density data [Krehbiel *et al.*, 1981] from a satellite orbit that passed near local midnight, which is about the time when the large enhancements in O/N₂ ratio begin to decrease. Figure 10 gives the change in N₂ density between the value calculated for orbit 6008 (day 250, September 7, 1982) and the equivalent quiet time value calculated from MSIS [Hedin, 1987]. Differences between electron densities from this orbit and the equivalent quiet-time electron densities calculated using the IRI model are also plotted on this graph. Although this orbit occurred very close to the equinox (16 days away) the pattern of composition change is very similar to the pattern that occurs in the solstices.

Enhancements of N₂ density extend from the north pole to the equator in the midnight sector, while the large enhancements are restricted to within 40 deg. of the pole in the southern hemisphere. Despite the near equinox time of the observations, the northern hemisphere pattern is typical of the summer hemisphere and the southern hemisphere pattern is

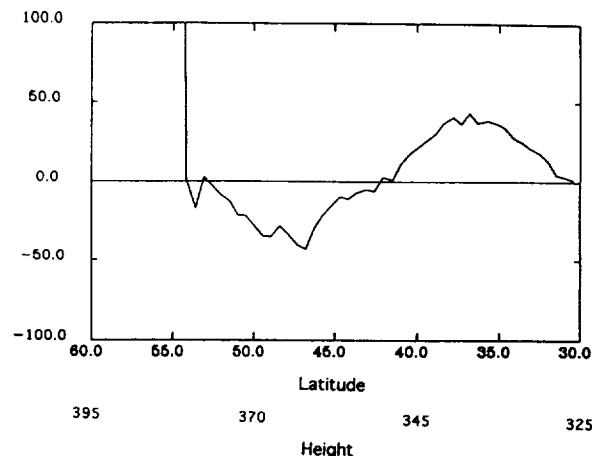


Figure 9. Calculated change in the electron loss rate for orbit 7217. IRI electron densities were used for the quiet time calculations. Losses are expressed as the percentage change in the term between storm and quiet time values.

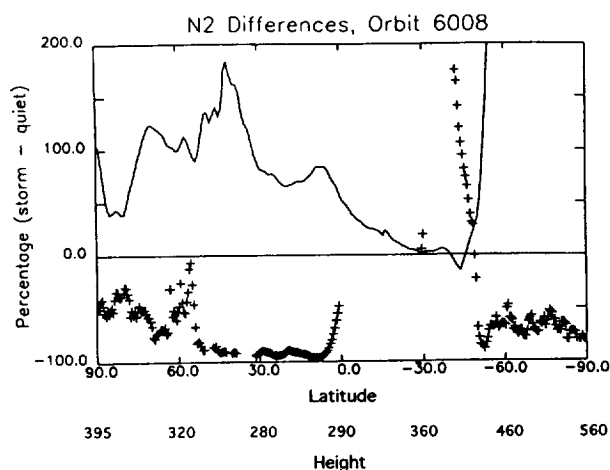


Figure 10. Changes in N₂ density and electron density during the large geomagnetic storm that occurred on September 7, 1982. These changes are expressed as a percentage. Quiet time neutral densities are calculated using MSIS. Quiet time electron densities are estimated using IRI. All latitudes are shown for a satellite trajectory that occurred along the 140 W meridian at about 23.5 local solar time. Note that composition changes are calculated for sets of constant heights rather than constant pressures. The importance of this will be discussed more fully in Burns *et al.* [1995].

typical of the winter hemisphere. Electron densities behave in a similar but opposite fashion to the changes in N₂ densities. Depletions of electron density occur from the north pole to the equator at least, and from the south pole to about 50° S (in the winterlike hemisphere). There is an area near 60° N (summerlike hemisphere) where very little depletion occurs, which is probably associated with a region of electron precipitation. The negative storm effects in electron density that are seen at the equator in these data are probably the result of the satellite moving well below the F₂ peak during the storm, rather than being caused by strong chemical and dynamical changes (perigee is slightly northward of the equator (see Rasmussen and Greenspan [1993 and the references therein] for an explanation of why this is the probable explanation of the diminished electron densities in this equatorial region).

The region of interest to this paper is found around 40° S (40 degrees in the winter-like hemisphere) for this orbit. In this region there are only small decreases in N₂ density. This apparent inconsistency with our earlier results is caused by the large temperature changes that occur in this region. Long-term, storm-induced temperature increases in this region grow larger as the night progresses [e.g., Burns *et al.*, 1992], so the densities of all species tend to increase on sets of constant height surfaces (as we present in Figure 10). In addition, it is shown by Burns *et al.* [1995] that these changes in composition behave differently in pressure coordinates. If composition changes on a constant pressure surface were considered, much larger enhancements in the O/N₂ ratio, and much stronger decreases in N₂ density, would be observed in the data from orbit 6008. As a consequence of the use of constant height surfaces, the decrease in N₂ is rather small at this time (~10–15%). However, it is relevant to this discussion is that the relative nitrogen densities in this region are significantly smaller than in the surrounding regions. At the

same time the peak in relative electron densities occurs in very close coincidence with the nadir in relative N₂ densities. Furthermore, enhanced electron densities are found only in the region of this trough in N₂ densities.

7. Discussion of the Possible Connection Between Electron Density Changes and Enhancements in the O/N₂ Ratio

These results indicate that there is a strong correlation between the region of enhancements in O/N₂ and the region where electron densities are enhanced. Many authors have discussed the regions where positive storm effects are dominant in the ionosphere. Hargreaves and Bagenal [1977] and Tanaka [1979] noted that positive storm effects were concentrated in the evening hemisphere, while Titheridge and Buonsanto [1988], Buonsanto *et al.* [1979] and Jakowski *et al.* [1990] all found that the positive phase was much larger in the winter hemisphere than in the summer hemisphere. Buonsanto *et al.* [1979] found that enhancements in peak density could be as great as 60 to 80% near midnight in the winter and equinoxes. These long-term changes in electron density have been ascribed primarily to changes in circulation during storms [e.g., Prölss *et al.*, 1991], although other possible mechanisms including neutral composition changes [e.g., see Prölss *et al.*, 1991 and references therein], electric fields [e.g., Tanaka and Hirao, 1973] and particle precipitation [e.g., Prölss *et al.*, 1991; Buonsanto *et al.*, 1979] have been proposed. Our work indicates that there is a good correlation between enhancements in the O/N₂ ratio and enhancements in electron density in the evening sector of the winter hemisphere during this geomagnetic storm at least, and it also provides evidence for decreases in the electron loss rate in the evening middle latitude region that are driven by changes in neutral composition. These decreases in the loss rate can be as strong as 30 to 45%.

If temperature effects do not change the recombination rate greatly, and transport effects do not act against the changes in O/N₂ ratio, local electron densities will increase proportionally to the change in the O/N₂ ratio. In this case, a simple "back-of-the-envelope" calculation can estimate the expected electron density changes that could occur as a result of the enhancement in the O/N₂ ratio. When the large electron loss rate change that is shown in Figure 9 is considered and the questionable assumption is made that the electron densities are in equilibrium and that transport rates are the same as they are during quiet times, it can be seen that the expected enhancements in electron density are between 40 and 80%. Figure 9 is consistent with Buonsanto *et al.* [1979] results, suggesting that, at the very least enhancements in the O/N₂ ratio play an important role in producing the large enhancements in electron density seen in the evening sector by Buonsanto *et al.* [1979].

Greater understanding of the role of these neutral composition changes on the observed changes in electron densities and their relative importance compared with changes in electron transport will only come about if their behavior is considered in a quantitative way in concert with changes in circulation in both the thermosphere and ionosphere, and an analytical assessment is made at both storm and quiet times of the various processes that produce the middle-latitude, electron morphology. We intend to address this problem more fully in a future paper that will utilize the new processors that we are developing.

8. Conclusions

We have used DE 2 NACS and LANG data and the NCAR-TIGCM to investigate enhancements in O/N₂ during a geomagnetic storm. The main results that we found in this study were the following:

1. There is a significant enhancement in the O/N₂ ratio at 370 km in the evening sector of the middle latitude, winter hemisphere. Enhancements in O/N₂ can reach 80-90% in a small band some 10 deg. of latitude wide between 40 and 50 deg. in the winter hemisphere. In the modeled storm the largest enhancements were seen from 1800 to midnight local solar time.

2. This enhancement cannot be explained in terms of a large gravity wave that is driven by the strong upwelling at the start of the storm, as enhanced O/N₂ ratios continue to be seen until at least 8 hours after the start of the storm, while the gravity wave would be expected to propagate to the equator in some 4-6 hours. Because of this and because of the causes of the enhancements, we conclude that the region of enhancement is a quasi-permanent feature of geomagnetic storms. The magnitude of the enhancement diminished from 70 to 90%, 5 hours after the storm that we studied commenced, to 50%, 8 hours after the storm's onset.

3. This region of enhanced O/N₂ ratios occurs for two reasons. First, neutral parcels are accelerated in an antisunward direction by the outer edge of the ion convection pattern. Parcels of air converge and the resulting vertical winds transport nitrogen-poor air down from above. Second, pressure gradient forces, that are driven by Joule heating in the polar regions, push nitrogen-poor air from higher latitudes in the winter hemisphere into this middle-latitude region.

4. These changes in the O/N₂ ratio occur both because the O densities are enhanced by as much as 50-60% and because N₂ densities are depleted by as much as 30 to 35% on constant height surfaces. The depletion of the N₂ densities causes reduced electron loss rates and can contribute to the enhanced electron densities that have been observed in this part of the winter hemisphere.

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