Dayside Enhancements of Thermospheric O/N2 Following Magnetic Storm Onset

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Abstract

One frequently observed effect of thermospheric storms is the reduction of atomic oxygen relative to molecular nitrogen at high and middle latitudes. These composition changes lead to a decrease in thermospheric OI 130.4-nm emissions in the sunlit hemisphere. Such decreases have been observed by various satellite-based instruments including the Dynamics Explorer 1 (DE-1) Spin-Scan Auroral Imager. In contrast, this paper focuses on enhancements of the terrestrial 130.4-nm dayglow emission observed with DE 1. Following the onset of a geomagnetic storm at 1610 UT on February 5, 1983, an increase (> 20%) in the OI 130.4-nm emission was observed at middle latitudes in the morning sector of the Southern Hemisphere. The increased OI 130.4-nm emission indicates an increase of atomic oxygen relative to molecular nitrogen. The brightness enhancement coincided with the passage of a large-scale gravity wave that was observed in measurements from a global network of ionosondes. The global FUV images and ionosonde observations are complemented by a TIMEGCM simulation of the February 1–6 period, which provides a framework for combining the ionosonde and DE-1 observations. The primary mechanisms for the FUV variations considered here are increases in the relative abundance of atomic oxygen in the morning sector caused by (1) the large-scale gravity wave launched by the onset of magnetic activity and (2) corotation of previously affected parcels onto the dayside. The investigation leads to a physical interpretation of the observed FUV features in terms of the gravity-wave effects and a transient Hadley circulation cell. This work represents the first detection of a large-scale gravity wave from an orbiting FUV imager.

1. Introduction

It is now well known that geomagnetic storms and substorms cause large-scale changes in thermospheric composition. In-situ observations by orbiting satellites have shown that, at particular altitudes, the abundance of O relative to N_2 can change by a factor of 10 [*Prölss*, 1980]. Large changes have also been seen from the ground [*Christensen et al.*, 1997]. Model simulations have helped to explain these effects. For example, *Crowley et al.* [1989] showed how changes in thermospheric composition develop during storms and how Joule heating leads to upwelling of nitrogen-rich air which is transported to lower latitudes by equatorward winds on the nightside. Corotation then carries the oxygen-depleted air onto the dayside. *Burns et al.* [1995a] described simulation results that revealed upwelling and downwelling neutral winds as the primary mechanism causing the large enhancements of O relative to N_2 on the nightside in the winter hemisphere. Modeling by *Fuller-Rowell et al.* [1996] demonstrated the seasonal dependence of these processes and their effect on ionospheric electron densities.

Decreases in dayside OI 130.4-nm emissions, which can extend from the polar cap to middle latitudes, are a known effect of thermospheric storms [*e.g. Craven et al.*, 1994; *Nicholas et al.*, 1997; *Immel et al.*, 1997, 2000]. These decreases correspond to a reduction of atomic oxygen, O, relative to N_2 throughout the optically active atmospheric column (*i.e.*, above altitudes at which most FUV emissions are attenuated in the Schumann-Runge continuum of O2). The brightness is also affected by the total abundance of N_2 in the same column, because it competes with O for photoelectron excitation to higher energy states [*Parish et al.*, 1994; *Strickland et al.*, 1999].

Strickland et al. [1999] demonstrated through radiative transfer simulations that the response of the DE-1 FUV photometer (using the 123-nm filter) to FUV emissions on the sunlit portion of Earth is directly related to the ratio of the column integrated concentrations of O and N_2 ([O]/[N_2])

in the thermosphere, with an uncertainty on the order of 10%. Recent investigations of thermospheric storms have used global far-ultraviolet (FUV) images from the Dynamics Explorer-1 satellite to study reductions in the 130.4-nm dayglow for analysis of magnetic-storm induced changes in composition [*Meier et al.,* 1995; *Strickland et al.*, 1999; *Drob et al.* 1999; *Immel et al.*, 1997, 2000].

In contrast, this paper focuses on a particularly strong increase in the 130.4-nm OI emissions following the onset of a geomagnetic storm at 1610 UT on February 5, 1983. The increase (> 20%) was observed by DE 1 at middle latitudes in the morning sector of the Southern Hemisphere. *Nicholas et al.* [1997] presented a survey of DE-1 images for different geomagnetic conditions and commented that decreases of FUV brightness on the dayside outnumber increases by 10:1. Brightness enhancements observed by DE 1 have not previously been studied in any detail.

The global images used in this study are complemented by height measurements of the F2 region from ionosondes and a TIMEGCM simulation of the February 1–6 period. The TIMEGCM provides a framework to connect the hmF2 measurements with the DE-1 brightness variations. In particular, changes in the O/N_2 column abundance ratio predicted by the TIMEGCM are compared with the data. The model leads to a physical interpretation of the enhanced airglow feature in terms of a large-scale gravity wave. This is the first time the effect of a large-scale gravity wave has been observed from an orbiting FUV imager.

2. The Magnetic Storm of February 4–5, 1983

The magnetic storm of February 4–5, 1983 (days 35 and 36) is notable for the sudden onset and sustained high levels of activity for two days. Three measures of the magnitude of the magnetic disturbance are shown in Figure 1 for the period of interest. The Dst index (bottom panel) identifies a +50 nT sudden commencement at 1600 UT followed by a main phase decrease that reached

–180 nT at 1800 UT. These data are indicative of a severe compression of the magnetopause followed by a rapid increase in the strength of the magnetospheric ring current. The changes were accompanied by sudden increases in the indices AE (upper panel) and Kp (middle panel), with AE indicating the onset of a substorm at 1610 UT, coincident with the main-phase decrease. The three-hourly Kp index remained at 2o in the 15 hours prior to the storm and then increased to 8- at 1800 UT. This paper is concerned with the thermospheric response to this increase in activity in the several hours shortly after the 1600 UT onset of magnetic activity.

3. Dynamics Explorer-1 Spin-Scan Auroral Imager

The Spin-Scan Auroral Imager (SAI) [*Frank et al.*, 1981] provided global images in the visible and far-ultraviolet (FUV) wavelengths on a routine basis for nearly 10 years, beginning in the fall of 1981. The instrument consisted of three scanning photometer systems each equipped with twelve selectable filters and a stepping mirror, with the pointing range limited to ±15 degrees out of the plane perpendicular to the satellite spin axis, which was also the orbit plane. Full coverage of Earth's disk was provided by the imager from satellite altitudes above ~2.5 earth radii (Re), or for approximately three hours while the satellite was close to its 3.65-Re apogee altitude. The two visible-light photometer systems (designated A and B) were designed for faint-light night-side operations, and were not useful for dayside auroral studies. In contrast, the FUV instrument (designated C) is useful for both nightside auroral and dayside viewing because FUV emissions from the sunlit hemisphere and bright auroral emissions are of the same order of magnitude. The selectable filters allow one to nearly isolate several neutral atomic and molecular emissions, primarily HI at 121.4 nm, OI at 130.4 and 135.6 nm, or the N_2 LBH bands between 127 and 170 nm. In particular, the 123-nm filter yields an instrument response which is due primarily to OI emissions (85–90%), with the remainder attributed to N_2 LBH [*Meier et al.*, 1995]. Images obtained using the 123-nm filter are used in this paper and in all previous studies of thermospheric composition using DE-1 images.

Temporal variations in the FUV brightness can be quantified once changes in brightness with varying solar and satellite zenith angles are removed, and corrections are made for azimuth of observation and time-varying solar EUV and FUV fluxes. For the present study, this was accomplished using the empirical model of DE-1 photometer response to the FUV dayglow [*Immel et al.,* 2000] to represent normal variations in FUV brightness during periods of low magnetic activity. Changes in photometer sensitivity since launch are also accounted for by the model. Comparisons to this empirical model reveal deviations from quiet-time background variations and indicate associated changes in composition.

Dynamics Explorer 2 (DE 2), the low-altitude companion satellite to DE 1, directly measured thermospheric O and N_2 densities throughout its operational lifetime between September, 1981 and February, 1983. The data obtained have proven to be extremely useful in studies of thermospheric composition and dynamics as well as model validation studies [*Burns et al.*, 1995a, 1995b; *McCormac et al.*, 1991; *Roble et al.,* 1988; and *Killeen and Roble*, 1988, and references therein]. Unfortunately, due to the ~30% duty cycle of DE 2, no neutral composition measurements were made during the period of interest for this study. DE-2 data are therefore not included in this report.

3.1 DE-1 FUV Observations on February 4 (day 35), 1983.

The DE-1 imager obtained 123-nm dayglow images in two consecutive 6.83-hour orbits on day 35, 1983. Apogee was reached in the first orbit near 1200 UT (about 4 hours prior to the storm onset at 1610 UT) and again near 1900 UT, three hours after the storm onset. Figure 2a is an average representation of the ten FUV images obtained from the first of these orbits, between 1006 and 1155 UT. Percent differences in the FUV dayglow from the quiet-time model are color coded according to the color bar below the panel. To create this image, percent differences (PD) between DE-1 photometer responses and the corresponding quiet-time empirical model values were calculated for pixels from all ten images and then averaged on a 0.5°x1° geographic grid. These average PD values are mapped to an orthographic projection of geographic coordinates in Figure 2a, centered at 1200 Local Time (LT) and 50°S latitude. Pixels near the limb were not used in this analysis and are not plotted, so these are referred to as disk images.

The pre-storm FUV dayglow is relatively uniform, with only small areas of PD<20% in the polar cap and the morning and evening sectors just equatorward of the auroral oval. There is a small brightening of ~10% in the noon sector near 50°S. This is a typical dayside enhancement similar to that identified in the survey by *Nicholas et al.* [1997]. A detailed analysis of the quiet-time images will not be performed here. Rather, this work concentrates on the much more dramatic morning sector enhancement shown in Figure 2b. This figure shows the average PD values of the ten FUV images obtained from the second orbit, between 1710 and 1859 UT. Processed in the same manner as the images of Figure 2a, the high-latitude portion of the average PD image is now dominated by the bright aurora, and the central polar cap still exhibits a characteristic decrease in brightness [*Immel et al.*, 1997b]. The feature of greatest interest for this report is the unusual ~20% brightening of the dayglow in the midlatitude morning sector (left side of image), which was absent from the quiet-time PD values in Figure 2a. The proximity of this enhancement to the auroral oval and its apparent relation to storm onset set it apart from the quiet-time middle-latitude enhancements noted by *Nicholas et al.* [1997] and suggest an immediate storm effect on dayside composition.

To further analyze this feature, the 10 images used to generate the PD image of Figure 2b were reprocessed and consecutive pairs of images were combined; the resulting PD images are shown in

Figures 3a–3e. To achieve these PD representations, the appropriate quiet-time empirical dayglow value was subtracted from each disk-region pixel of the two individual images to determine the individual percent deviations from quiet times. The resultant PD values were smoothed using a 3x3-pixel moving average and then averaged on a 0.5°x1° geographic grid. This combination of temporal and spatial averaging reduces statistical variations present in the images while still allowing for analysis of temporal variations on the order of 20–30 minutes. Each of the PD images is labeled with the start time (UT) of the first image of each pair and all the measurements included in each PD image were obtained within the following 24 minutes. The heavy dark line delineates the 120°W geographic meridian, which passes through the area of enhanced FUV brightness and is the focus of later sections in this report. The thin dark contour indicates the PD=+10% level in the image, and the thin white contours (which occur mostly in the polar cap) indicate the PD=-20% level.

The OI FUV brightness enhancement in the middle-latitude morning sector is evident from the first image of the series (Figure 3a). There is a clear difference between the morning sector, with enhancements up to 30%, and the rest of the observed Southern Hemisphere, where PD values are closer to 0%. In subsequent images (Figures 3b–3e), the area of the morning-sector brightness enhancement grows, extending to lower latitudes and later local times. These changes in the FUV brightness distribution are reminiscent of a wave launched from the vicinity of the auroral oval and travelling equatorward and eastward. However, additional interpretations of the DE images must be considered including a simple corotation of a pre-existing enhancement in column [O]/[N_2] from the morning into the noon sector. To investigate these possibilities, data from the global ionosonde network were examined for evidence of a coincident atmospheric/ionospheric perturbation, and the NCAR TIMEGCM model was run for the storm period.

4. Ionosonde Data Analysis

Neutral winds and electric fields perturb the ionosphere, causing changes in the F-region electron density profile. At middle and low latitudes the electric field is usually small, and the height of the ionosphere can be used to infer meridional wind speeds if the electric field is ignored [*Miller et al.*, 1986, 1987; *Buonsanto et al.*, 1989]. Ionosondes typically make hourly soundings and report the peak electron density in the E and F regions, together with the base height of the F region (h'F). Large-scale gravity waves launched from the auroral oval during magnetic storms produce large transient changes in the meridional and vertical neutral-wind components, that in turn drive transient changes in the ionospheric heights and peak densities. Transient variations in ionospheric height can also be driven by low-latitude electric fields during geomagnetic storms.

Crowley et al. (1989b) used hourly ionospheric height measurements to determine the propagation characteristics of a large-scale gravity wave, having a period of about 2 hours. We have used the same approach in this paper. The global ionosonde data show that waves were launched from the auroral latitudes of both hemispheres. About 80 ionosondes reported values to the World Data Centers for the February 1983 period. In addition to h'F measured directly by each ionosonde, the peak height of the F-layer (hmF2) was also computed from foF2, foE and M(3000)F2 using the *Bradley and Dudeney* [1973] formula.

Inspection of the ionosonde data for the February storm revealed large transient perturbations in the height of the F region in the 1600 to 2000 UT time frame. For example, the upper panel of Figure 4 (Figure 4a) shows the storm-driven perturbations in hmF2 (solid line) measured at Tahiti on day 35, 1983. For comparison the dashed line indicates the monthly mean values. The storm caused height increases of about 150 km near 2000 UT while Tahiti was in the pre-noon sector, indicating a very strong northward thermospheric wind that forced plasma to higher altitudes along magnetic field lines. The corresponding hmF2 values from the TIMEGCM simulation are shown in Figure 4b and are discussed in the following sections.

Using the times of the peak height perturbation in hmF2 and h'F observed by the 11 available Southern Hemisphere ionosondes, it was possible to trace the wave propagation. The ionosonde stations used to derive the wave location are indicated on a projection of southern geographic coordinates in Figure 5; circles indicate hmF2 data and squares indicate h'F data. Figure 5a displays the phase fronts of the wave at 1700, 1800, 1900 and 2000 UT. In regions of extremely sparse data, the wave front locations are represented by dashed lines, indicating an uncertainty of up to an hour in the arrival time of the wave. Superimposed on the figure is the location of the southern aurora observed by DE 1 at 1823 UT (in gray). The 1823 UT aurora was selected because it is the earliest time after onset that the whole auroral oval was imaged. From the partial coverage of the auroral oval in earlier images, it is inferred that the mean radius of the oval was about 5° smaller at 1700 UT than at 1823 UT. The wavefront at 1700 UT almost exactly matches the location and shape of the aurora, suggesting that the wave was launched by auroral processes. The phase fronts indicate that the phase speed of the wave was about 600 m/s, and the observed hmF2 variations showed the wave period to be about 5 hours.

Also superimposed on Figure 5a is the disk-image field of view of DE 1 (in yellow) from images obtained in the 1700–1900 UT period shown in Figures 2b and 3a–e. Unfortunately, the DE-1 field of view mainly encompasses sparsely populated regions and oceanic areas, so the ionosonde data are sparse in the disk field of view. Regardless of the sparse data, the analysis clearly reveals that the large-scale wave crossed the DE-1 field of view in the 1700–1900 UT time frame and reached the equator shortly after 2000 UT.

To investigate the possible correspondence of the FUV brightening with the propagation of the ionospheric disturbance, Figure 6 compares the progression of the observed peak in hmF2 from Figure 5a with meridional slices from the five PD images of Figure 3. Figures 6a–6c show the PD values of FUV brightness at 110°, 120°, and 130°W longitude, respectively, in the 90°–30°S range for each of the five imaging times of Figure 3, where the images are first smoothed with a 5°x5° filter to bring out larger-scale variations. Three separate meridional slices were included in the figure to demonstrate the consistency of the observations across more than one hour of local time. An example of the statistical uncertainty in the PD values is shown for reference at either 50°S or 60°S. The counting statistics are better at 50°S. The dominant feature in each frame is the signature of the aurora, manifested by the large values of PD in the left-hand portion of each plot. Sub-auroral latitudes are to the right. For comparison with the DE 1 brightness data, the position of the peak hmF2 disturbance inferred from ionosonde measurements (Figure 5a) is indicated in each frame of Figure 6 by a dark vertical bar below the PD values. The uncertainty in this position is also indicated.

The top row of Figure 6 shows PD values and the position of the hmF2 peak at 110°W, beginning at 1710 UT. At this time, the value of the PD is relatively constant and close to zero at latitudes lower than the auroral brightening. At the next imaging time (1734 UT) there is a 10% increase in PD near 65°S. The location of this increase corresponds to the peak in hmF2 at this time in this meridian. At 1759 UT, the enhancement has grown to about 15%, where the maximum has now moved to 60°S. The peak in hmF2 has moved to 54°S, but marks the leading edge of the enhancement in PD. At 1823 UT, the peak in hmF2 is outside of the disk region imaged by DE-1. A comparison with the panel at 1710 UT shows the substantial increase in PD values persisted to 1847 UT.

Forty minutes earlier in local time at the 120°W meridian (Figure 6b), a similar picture emerges: at 1734 UT, a 15% enhancement is evident near 60–65°S, where the hmF2 peak is at 60°S. By 1759 UT the brightness peak has moved to 55°S (peak hmF2 to 50°S), and by 1823UT the enhancement extends from 60°S out to the edge of the DE image, while the hmF2 peak is at 42°S just out of the range of PD values. In the 110°W meridian (Figure 6c), the trend is repeated, with the hmF2 peak coinciding with, then leading the peak in PD values, until the hmF2 peak occurs outside the range of PD value at 1823 UT. It is again clear that the FUV brightness remains higher after passage of the wave through the last imaging time at 1847 UT.

This correspondence between the position of the travelling wave in hmF2 and the changes in PD is remarkable, given the uncertainties in the PD values and in the position of the hmF2 peak. It seems very probable that the enhancement in thermospheric OI 130.4-nm emissions in the morning sector is related to the passage of the wave, and the corresponding disturbance in hmF2. Unfortunately, the effect of the wave on composition or winds was not measured by DE 2 or any ground-based instruments. To obtain some estimate of the composition variations caused by the wave, and other effects which might be influencing the FUV brightness, we turned to global modeling using the NCAR-TIMEGCM.

5. TIMEGCM Simulation of February 4–6, 1983

To assist in the interpretation of the DE-1 airglow features described in Section 3.1, the thermospheric behavior for this period was simulated using the National Center for Atmospheric Research Thermosphere Ionosphere Mesosphere Electrodynamic General Circulation Model (TIMEGCM). This first-principles model was described in detail by *Roble and Ridley* [1994] and is the latest in a series of 3-D models of the upper atmosphere developed at NCAR [*Dickinson et al.,* 1981, 1984; *Roble et al.,* 1988; *Richmond et al.,* 1992]. The model predicts winds, temperatures, major and minor composition, and electrodynamic quantities globally from 30 to about 600 km. The inputs needed by the model include the solar flux at 57 key wavelengths, auroral particle precipitation, high-latitude electric fields, and tides propagating up from below the 30-km lower boundary. Parameterization of the high-latitude inputs used by the TIMEGCM was described in detail by *Roble and Ridley* [1987]. For the present simulation, the solar flux is parameterized in terms of the 10.7-cm solar radio flux index, the particle inputs are parameterized in terms of the hemispheric power index (Hp) obtained from NOAA satellites [*Evans*, 1987; *Fuller-Rowell and Evans*, 1987], the high-latitude electric fields are specified by a Heelis potential pattern driven by Hp and the IMF By component [*Heelis*, 1982], and the tides are specified using a seasonal climatology derived from the GSWM model, [*Hagan et al.*, 1999]. The high-latitude inputs were specified every 10 minutes by interpolating between the hemispheric power values provided by two NOAA satellites. The model was run with a 3-minute time step, interpolating between the 10-minute resolution inputs. Since no IMF data were available for the storm period, the value of By was set to zero in the simulation. The model was run for the entire February 1–6 period. Thus at the time of the sudden onset on February 5, the model had been run with realistic inputs for more than four model days.

Radiative transfer simulations have shown that the response of the DE-1 FUV photometer (using the 123-nm filter) to dayside FUV emissions is well correlated with the ratio of the column densities of O and N_2, with an uncertainty on the order of 10% [*Strickland et al.*, 1999]. It is therefore extremely useful to determine the column-integrated densities of O and N_2 from the TIMEGCM for eventual comparison to FUV brightness. It is important to select a base altitude which is consistent with physical processes affecting the radiative transfer of the OI 130.4-nm emission. *Strickland et al.* calculated the column density ratio of O to N_2 in a fixed N_2 column of

10^{17} molecules/cm2, where the altitude of the column base is adjusted to meet the requirement for N_2. Typically this altitude is around 140 km. For this paper, we integrated the O and N_2 above the TIMEGCM pressure level corresponding to ~7.8×10^{-4} N/m^2, which under most atmospheric conditions is near an altitude of ~135 km. The difference in the O to N_2 column ratios derived using the two methods is insignificant when compared to the normal diurnal and latitudinal variations and the large changes due to magnetic activity. In the course of this study, it was also found that calculations of the column densities using a fixed density of O_2 to determine the column base yield essentially the same results.

Changes in the TIMEGCM output fields induced by the simulated geomagnetic storm were determined by comparing storm-time outputs to those from the same UT on day 33, 1983. The magnetic activity on day 33 was the lowest of the study period (as shown in Figure 1). Therefore the outputs from day 33 are used as the quiet-time reference for all fields for the remainder of this report.

5.1 Neutral Winds

In order to isolate the storm effects from normal quiet-time variations in the TIMEGCM, the difference between quiet and storm fields is calculated. The differences between the quiet- and storm-day values of the vertical wind, meridional wind and column density ratio ([O]/[N_2]) are shown on an hourly basis for 1600–2100 UT in Figures 7–9. A quantitative analysis of the modeled wave effects in the 120°W meridian will be provided in Figure 10. For Figures 7 and 8, neutral winds at a fixed pressure level near 180 km are used. These differences are mapped to the same orthographic projection of geographic latitude and local time as was used for Figures 2 and 3. In this format, the left (right)-hand side of the figure represents the dawn (dusk) sector, with noon at the top. A dark grid is overlain showing 10° increments of latitude and longitude. An indication of the location and intensity of the auroral input to the model is provided by the dark contour surrounding the South Pole, which delineates regions where the TIMEGCM height-integrated Pedersen conductance exceeded 13 mhos. At 1600 UT, this is barely visible because the auroral inputs were very small prior to the storm onset. The approximate disk field of view of the DE-1 imager (excluding observations at the limb) is indicated with a heavier black contour in the 1700–1900 UT panels, corresponding to the PD image shown in Figure 2b. Although there are many interesting features in these figures, we generally restrict our discussion to the dayside pre-noon sector and the DE-1 disk field of view. A dark mark drawn between 0° and −10°S indicates the 120°W meridian.

Changes in vertical wind (at ~180 km altitude) are shown in Figure 7a–f, where areas of pink through red indicate locations where the upward wind component is larger than on the quiet day. Areas where downwelling occurs relative to the quiet time vertical wind are indicated by orange through blue contours. At 1600 UT, the differences are small and confined to upward winds in the auroral region. However, after 1600 UT, the vertical wind field shows clear evidence of the wave on the dayside. The first indication of the wave at 1700 UT was a decrease of 10 m/sec in the dayside vertical wind between 60° and 80°S. By 1800 UT the area of downwelling vertical winds had advanced to the latitude range 40°–70°S in the pre-noon sector. Also at 1800 UT, an upward vertical wind difference (pink) was evident in the noon sector at higher latitudes (between 70° and 80°S). By 1900 UT, the downward vertical winds associated with the dayside surge had propagated beyond the edge of the DE-1 imager's field of view and reached their maximum values near latitudes of 35°S. The region of upward winds had correspondingly expanded to 60°S. By 2000 UT, the region of dayside downward winds was centered at 10° latitude, and the winds were larger than at 1900 UT because the wave from the Northern Hemisphere had reached the same location and constructively interfered with the Southern Hemisphere wave. Meanwhile at higher latitudes, the region of upward winds in the 120°W meridian had propagated to 50°S, and extended all the way to the auroral region, indicating that the wavelength of this wave was about 90° of latitude. At 2100 UT, a complex pattern of vertical winds is evident as the two waves have passed through each other. The wave from the Northern Hemisphere is responsible for the downward winds wrapping around the nightside near 40°S, and splitting the upward winds in the morning sector into high and low-latitude regions.

The corresponding meridional wind changes are shown in Figures 8a–f, for 1600 to 2100 UT. The color bar is similar to the previous plot, but now pink and red contours denote increases in the northward component of the wind. Orange through blue areas indicate regions where the northward wind field has decreased. The figure is dominated on the nightside from 1800–2000 UT by a strong increase in the northward wind, which exited the auroral oval at speeds up to 500 m/sec. On the dayside at 1700 UT, only a slight enhancement (pink) in the northward wind is visible outside the auroral oval. At 1800 UT the noon sector exhibits a northward surge that reaches as far as 40°S in the noon sector, and the differences plotted here attain values of ~100 m/sec along an extended front between 60° and 80°S (Figure 8c). Enhanced northward meridional winds are evident across most of the dayside by 1900 UT, with the greatest perturbation appearing near 65°S in the noon sector. In the 120°W meridian, the positive winds have reached 25°S, and the contour matching zero velocity corresponds exactly to the peak in the downward vertical winds shown in Figure 7c. The picture is similar at 2000 UT, though the maximum dayside winds occur near 55°S in the noon sector and the wind decreases at higher latitudes. At the top of Figure 8e, a region of strong southward winds (yellow) is visible in the Northern Hemisphere, an effect of the encroaching northern-hemisphere wave. By 2100 UT, the winds have started to abate, and the destructive interference of the oppositely directed meridional winds from the two waves makes interpretation of the contours difficult.

The neutral wind perturbation propagates faster at higher altitudes, reaching the equator approximately one hour earlier at the 340-km altitude level than at 180 km. The perturbation travels through a relatively quiet thermosphere, where prior to the encroachment of the wave the meridional winds are on the order of 50 m/sec, as there was no strong magnetic activity prior to the storm onset. In the 120°W meridian, the approximate propagation velocities of ~675 and 575 $m \cdot sec^{-1}$ at the 340 and 180-km altitudes (respectively) are well below the calculated sound velocities of 770 and 670 m/sec, determined from the average TIMEGCM temperature and mean molecular mass along that meridian.

5.2 Changes in O/N2 Ratio

Changes in the TIMEGCM O to N2 column abundance ratio from are shown in Figures 9a–f for the storm simulation between 1600 and 2100 UT, using the same orthographic projection as Figures 7 and 8. Pink and red contours now denote increases in $[O]/[N_2]$ on the storm day, while orange through blue contours depict decreases. Shown below each projection in Figure 9 are the absolute values of $[O]/[N_2]$ for the 120°W meridian from the South Pole to the equator. The solid (dashed) line in each line plot indicates the values of $[O]/[N_2]$ on day 35 (day 33).

At 1600 UT (Figure 9a), before the storm onset, the predominance of orange and yellow indicates that the value of $[O]/[N_2]$ was smaller for day 35 than for day 33 over most of the Southern Hemisphere, especially in the morning sector. This difference is clear in the line plot for the 120°W meridian (plotted below). This was probably due to the moderate increases in magnetic activity occurring earlier on day 35 (see Figure 1), which caused $[O]/[N_2]$ reductions at middle to high latitudes. The values look essentially the same at 1700 UT as those at 1600 UT. After this time, the effect of the gravity wave on [O]/[N_2] becomes evident. At 1800 UT (Figure 9c) an increase in storm-time [O]/[N_2] in the field of view of DE-1 is marked by a change from yellow to orange contours. A local peak in the [O]/[N_2] ratio can be seen in the pre-noon sector between 60° and 75°S, with smaller increases at lower latitudes. The line plot in Figure 9c shows that by 1800 UT the day 35 [O]/[N_2] ratio had increased by about 20% at 65°S, with smaller increases at lower latitudes, nearly returning to quiet day levels. However, the recovery is temporary, and by 1900UT the increase has moved to lower latitudes.

By 1900 UT (Figure 9d), the encroachment of orange and pink contours reveals that the storm-day [O]/[N_2] has increased across most of the dayside. The line plots for the 120°W meridian show that the storm day [O]/[N_2] exceeds the quiet day values for all latitudes equatorward of 50°S. Figure 7d showed that the wave in the vertical wind field had reached latitudes of 30°S but in Figure 9d the wave effect on [O]/[N_2] apparently merges with an overall enhancement at lower latitudes. A similar effect was noted in the global modeling study by *Fesen et al.* [1987] where the convergence of two large-scale waves near the equator was shown. On the nightside at 1900 UT, large decreases (<50%) in [O]/[N_2] are evident as the storm progresses, but the focus of this discussion is the dayside, especially the DE-1 field of view.

At 2000 UT (Figure 9e), [O]/[N_2] for day 35 exceeds that for the quiet day at all latitudes lower than 55°S in the 10–18 LT sector, so that there is an extended region of enhanced [O]/[N_2] at low latitudes. This is particularly clear in the line plot for the 120°W meridian. Figure 7e showed that the two waves had converged at this time, and constructive interference produced large downward winds at low latitudes on the dayside. These downward winds caused increases in [O]/[N_2] for the storm day. On the nightside, the decrease in [O]/[N_2] continues to develop, and corotation is beginning to carry the depletions into the dawn sector.

By 2100 UT (Figure 9f), the values of [O]/[N_2] have started to exhibit reductions below both pre-storm and quiet-time values. In the 120°W meridian, the line plot shows that the storm time [O]/[N_2] only exceeds the quiet time values poleward of 40°S. This appears to be partly a result of corotation of molecularly rich portions of the thermosphere from the dawn sector, and the fact that the upward velocities associated with the wave (Fig 7f) are reducing the O/N_2 at latitudes poleward of 40°S.

5.3 Gravity Wave in TIMEGCM

The sudden onset of magnetic activity in the simulation generated large-scale gravity waves in both hemispheres that affected neutral winds, temperatures, and composition as they propagated from high latitudes to the equator and into the conjugate hemisphere. The wavelength of both waves was about 90° of latitude (~10,000 km) which makes the wave feature difficult to see even in global maps and latitude slices from the model. This wavelength is larger than thermospheric gravity waves previously reported in the literature [Crowley *et al.*, 1989; Trinks and Mayr, 1976, Richmond and Matsushita, 1975]. The behavior of the large-scale wave in the Southern Hemisphere is analyzed in more detail here to determine the time-evolution of its phase-fronts in comparison to the wave observed by the ionosondes, and to investigate its likely effect on the composition and the related FUV emissions detected by DE 1. A closer inspection of the three TIMEGCM output fields discussed above and the simulated hmF2 values clarifies the behavior of the wave, and the relationship between winds and composition.

Figures 10a–10d depict the temporal evolution of the simulated vertical and meridional winds (W and V, respectively) at 180 km altitude, hmF2, and O/N_2 column ratio, respectively, for the 120°W meridian as a function of UT. The three panels of each column show the selected parameter at locations 67.5°, 52.5°, and 37.5°S, for the 120°W meridian. This meridian corresponds to positions in the morning sector in the 1600-2000 UT time frame, and was indicated by a dark line in the DE-1 images of Figures 3a–3e, and the dark mark in Figures 7–9. The quiet-time values (day 33) for each of these parameters are indicated for reference by a dashed line.

Each field exhibits a significant perturbation in the 1600–2000 UT time frame on the active day, and the propagation of the disturbance from high to low latitudes is evident. The vertical winds (W, Figure 10a), for example, show a marked downward deviation from quiet-day values at 67.5°S at 1700 UT, followed by similar deviations at the two lower latitudes at 1800 and 1900 UT. To emphasize the propagation, diagonal lines connect the peaks in the W, V, hmF2 and O/N_2 disturbances. The vertical wind plots clearly show the wave period to be about 5 hours. As expected, the vertical and meridional components of the wave are out of phase, with the vertical wind perturbation preceding the meridional wind changes (V, Figure 10b) at each location. The third field plotted in Figure 10 is hmF2 from the model. Though it is more directly affected by neutral winds at higher altitudes, the magnitude of the change from quiet times is important to this study, as well as it's correspondence to changes in $[O]/[N_2]$ for ionosonde-FUV comparisons.

The final column of Figure 10 shows the $[O]/[N_2]$ perturbation, and again the propagation of the wave is evident. The $[O]/[N_2]$ at each latitude starts to increase as soon as the vertical velocity starts downward, and reaches a maximum when the vertical velocity changes direction to upward, reflecting an integration of the effect of the vertical velocity. Likewise the ratio decreases for upward winds. After a complete wave cycle, when the upward wind has returned to zero, $[O]/[N_2]$ approaches its pre-storm value. This process is clearer at 67.5° and 52.5° than at 37.5°S, where the vertical wind does not clearly exhibit a full wave cycle. This is because of encroachment to 37°S by the northern-hemisphere wave around 2000 UT, as discussed in Figures 7–9.

Together, the panels of Figure 10 reveal that the [O]/[N_2] variation peaks about an hour earlier than the meridional wind, correlates extremely well with the vertical winds, but correlates only fairly with hmF2. The third column shows that the hmF2 values peak at all three latitudes in the same hour of time (1900 UT). This is due mainly to hmF2 being affected more strongly by neutral winds at F2 heights (~300–400 km), where the wind perturbation travels with greater speed. In fact, the hourly peak in meridional winds at a pressure level corresponding to ~340 km (not shown) also occurs at 1900 UT at all three latitudes. It is clear that the winds propagate from the poles to the equator, but with hourly TIMEGCM outputs, it is difficult to discern this propagation.

The model provides us a way to connect the brightness variations from DE 1 with the hmF2 measurements from the ionosonde network: if the brightness variations observed by DE 1 were caused by the wave they should immediately follow a lifting of the ionosphere. Conversely, neutral wind driven enhancements of hmF2 at a particular middle latitude site on the dayside should be followed by enhancements in [O]/[N_2], once the lower altitude perturbation arrives. With this knowledge, it now seems probably that the apparent correspondence between changes in Earth's FUV signature and the advance of the wave in hmF2 shown in Figure 6 is a real effect. The advance of enhanced values of hmF2 should precede the O/N2 enhancement, as is observed.

6. Discussion

The DE-1 image pairs in Figure 3, together with the meridional slices in Figure 6 gave the initial impression of a wave propagating equatorward out of the morning sector. It is tempting to simply interpret the increased dayside FUV brightness purely in terms of the wave, as the wave effects are so clear in the ionosonde data and the TIMEGCM. However, additional interpretations of the DE images must be considered including corotation of an area of enhanced [O]/[N2] from the morning into the noon sector. In this section, evidence for each of the possible mechanisms will be discussed separately.

6.1 Wave

Complimenting the DE image pairs, the global ionosonde network provided evidence for a large-scale wave propagating through the DE-1 field of view. For direct comparison of the ionosonde and TIMEGCM wavefronts, Figure 5b shows the propagation of the simulated wave in the same format as Figure 5a. Figure 5b depicts wavefronts only on the dayside because it was difficult to determine the model wave propagation in the other sectors. The wave was clearly evident in the pre-noon sector of the model, in the vertical and meridional winds and in hmF2. In the afternoon sector, the wave was very weak, while the post-midnight sector was dominated by a surge in the meridional winds (at 180-km altitude) that exited from the auroral oval at speeds of ~500 m/sec.

It is apparent from Figure 5 that the simulated wave in hmF2 developed in a manner similar to the observed wave. The observed wave propagated into the dayside ahead of the simulated wave by about 60 minutes, and in the pre-noon sector the observed wave is approximately 20° closer to the equator than the modeled wave at any given UT. The spacing of the phase fronts indicates that both waves propagated at about 600 m/s, and so the simulated wave must have either been generated about 60 minutes later than the observed wave, about 20° farther poleward, or a combination thereof. The relative energy associated with the observed and simulated gravity waves can be compared by examining the change in hmF2 measured by ionosondes and those derived from the TIMEGCM simulation. Figure 4b showed TIMEGCM predictions of hmF2 for Tahiti on day 35. TIMEGCM predicts changes of only 70 km relative to the day 33 quiet-time hmF2 (shown with a dashed line). In contrast, the observed departure of hmF2 from quiet-time values at Tahiti (Figure

4a) was +150 km, and so the simulation underestimated the hmF2 variations on the dayside by as much as ~50%. This difference is of interest because similar differences might also exist between the modeled and actual O/N2 perturbations that drive the FUV brightness.

The increased O/N_2 ratio in the model (Figure 9) is consistent with an overall brightening of the FUV emissions between 1700–1900 UT, though of a lesser magnitude than that observed by DE 1. For example, the model yielded 15–20% O/N_2 perturbations in the 120°W meridian, but the DE-1 FUV brightness increased by 20–25% in the morning sector. Hence the model appears to underestimate by about 50% the magnitude of both the hmF2 and the $[O]/[N_2]$ perturbations caused by the wave. Assuming that both parameters are affected by the same mechanism (*i.e.* significant changes in neutral winds) and that the magnitude of the changes in hmf2 and $[O]/[N_2]$ are both linearly related to the amplitude of the neutral wind perturbation, a more energetic wave, with greater associated neutral wind amplitudes, would be sufficient to effect changes in modeled $[O]/[N_2]$ and hmF2 consistent with the observations. The input parameters to the TIMEGCM are often tuned such that model outputs better reflect observed conditions, but in this case no adjustments are made and are left for future study. Effects of neutral gas diffusion and the relationship of the relative phase of the wave in different neutral constituents have also been shown to affect $[O]/[N_2]$, and may introduce nonlinear effects as the high-latitude energy input increases.

In addition to the wave amplitudes, the relative timing of the model and observations is also consistent, in that (1) the observed wave in hmF2 propagated across the dayside 60 minutes earlier than the simulated wave, and (2) the FUV brightness was seen to increase at a time beginning an hour prior to the appearance of the large enhancement in the simulated dayside midlatitude O/N_2 (2000 UT). Furthermore, just as the TIMEGCM showed that hmF2 is correlated with the peak change in $[O]/[N_2]$, Figure 6 showed that the observed changes in hmF2 correspond to the advance in the increased FUV PD brightness. This correspondence is remarkable, given the uncertainty both in the PD values and in the location of the wave based on hmF2 measurements. It therefore seems extremely probable that the traveling disturbance in hmF2 and in composition manifested itself as an enhancement of OI 130.4-nm emissions of the thermosphere in the morning sector and accounts for the FUV enhancement observed by DE 1.

In the TIMEGCM simulation, the O/N_2 column abundance ratio in the DE-1 field of view increased from 1600–2000 UT (Figure 8), and then began its decrease to pre-storm values. Correspondingly, the dayside meridional winds increased significantly between 1600–2000 UT (Figure 7) and then diminished toward pre-storm values by 2100 UT. This time scale is consistent with the period of the wave, suggesting that the wave sets up a temporary Hadley circulation cell of the kind that is normally associated with longer-term variations. During storms, high-latitude heating drives a meridional wind circulation with upwelling at high latitudes, and downwelling at middle and low latitudes [*Roble et al.* 1977]. The former leads to a decrease in the high-latitude O/N2 [*e.g. Crowley et al.*, 1989], while the latter leads to an increase in the O/N2 ratio at low and middle latitudes [e.g., *Prölss and Roemer,* 1987; *Burns et al.,* 1995b].

It is most likely that the differences between the modeled and observed waves is caused by the approximate nature of the inputs used to drive the model, and if the inputs could be specified more accurately then the wave would be better simulated. The wave was probably generated at the onset of the storm by a sudden increase in Joule heating and momentum forcing, which depend both on the relative position and overlap of the auroral conductance and electric potential distributions. The location of the aurora in the simulation is remarkably similar to that observed by DE 1 as evident from Figures 5a and 5b, although there are clear differences. The simulated aurora is more uniformly distributed and smaller than that measured by DE 1. The conductance values from the actual aurora are not available for comparison with the model.

One of the major factors in determining high-latitude Joule heating and momentum forcing is the electric field. The Heelis electric field model [*Heelis*, 1982] used by TIMEGCM produces very smooth potential patterns compared with some of the more realistic patterns that could be obtained from assimilative procedures [*Richmond*, 1992; *Crowley et al.*, 2000]. The actual high- latitude electric fields were not measured in February 1983 and large differences are likely between the electric fields used in the model and the fields that actually existed. The size of both the auroral oval and the location of the potential pattern are determined in the model by the hemispheric power index (Hp). The size of the potential pattern in the simulation was probably reasonable, given the good agreement between the simulated and measured aurora shown in Figure 5.

The IMF By component determines the relative sizes of the dawn and dusk convection cells. No IMF measurements were made during days 35 and 36 of 1983, so in the simulation the value of By was simply set to zero. A numerical experiment was performed to test the sensitivity of the model to the By component in which By values of −10, 0, and 10 nT were used. This led to small changes in the vertical winds and the morphology of [O]/[N_2], but the timing of the wave generation and its arrival at the ionosonde sites was nearly unchanged, indicating the lack of By information was not the limiting factor in the simulation.

6.2 Co-rotation

The advance of the FUV brightness enhancement into the afternoon sector between 1700–1900 UT suggested the possibility of a co-rotation effect, but a simple examination of the PD values of Figure 3 reveals that the advance in local time exceeds the co-rotation speed. Co-rotation is clearly involved in moving the observed feature across the DE field of view, but it is not the only factor contributing to the FUV brightness enhancement. The variation in brightness is shown in Figure 6 in fixed geographic coordinates, where the advance of the enhancement is clear.

Examination of the TIMEGCM simulations for this period independently confirms that co-rotation was probably not an important factor in explaining the brightening, and there was no previously existing enhancement in [O]/[N_2] in the dawn sector in the hours before storm onset. For comparison to Figure 2a, which shows the average PD values for ten DE-1 images obtained in a two-hour period prior to the storm, Figure 11 shows the PD values in TIMEGCM [O]/[N_2] at 1100 UT in the same projection of geographic latitude and local time. There is a notably good agreement between the observed FUV brightness distribution and TIMEGCM PD values on the dayside. The simulation apparently accounts for the localized enhancement in FUV brightness in the post-noon sector at middle latitudes, demonstrating a similar localized 10% enhancement in [O]/[N2] in the same area. It also accounts for the moderate decreases in FUV brightness in the morning sector at middle-to-high latitudes. This remarkable correspondence indicates that the TIMEGCM simulation fields were well initialized, and properly simulated neutral concentrations and winds prior to the storm onset. This said, TIMEGCM gives no indication of any significant enhancement in [O]/[N_2] in the dawn sector.

The post-midnight region of the quiet-time simulation shown in Figure 11 rotates into the morning sector six hours later as the storm onset occurs. Hence, the TIMEGCM results indicate that the atmospheric parcels corotating into the mid-latitude morning sector had only been moderately perturbed by auroral inputs, and with no further influences would have caused a slight decrease in FUV brightness in the pre-noon sector. Thus it is certain that the observed OI brightness enhancement developed on the dayside, as predicted by the model.

7. Conclusion

Following the onset of a geomagnetic storm at 1610 UT on February 5, 1983, a 20–25% increase in OI 130.4-nm emissions was observed by the DE-1 SAI at high-to-middle latitudes in the morning sector of the Southern Hemisphere. Such an enhancement is unusual, and previous studies of DE-1 images have shown that decreases in OI FUV brightness are the most common effect of strong auroral activity. An earlier survey of images by *Nicholas et al.* [1997] showed that observations of decreases outnumbered localized enhancements by 10:1 and that enhancements usually occur away from the auroral oval at middle latitudes during periods of low-to-moderate activity. Enhancements in the FUV brightness observed by the DE-1 imager have not previously been studied in detail.

The cause of the enhancement observed here was investigated using data from the global ionosonde network. Variations in the height of the F-region ionosphere were obtained from the ionosondes, which showed that a large-scale gravity wave was launched by the storm onset. The wave had a period of about five hours, and traveled with a horizontal phase velocity of about 600 m/sec in the morning sector of the Southern Hemisphere, propagating across the dayside from the auroral oval to the equator in four hours. The wave detected by the ionosondes traveled through the DE-1 field of view between about 1700 UT and 1930 UT, suggesting the wave may be associated with the DE-1 brightening.

The global FUV images and ionosonde observations were complemented by a TIMEGCM simulation of the February 1–6 period. Changes in the vertical and meridional wind fields were presented, together with calculated values of [O]/[N_2] and hmF2 from the model. The model was used to derive a physical interpretation of the observed FUV features. The primary mechanisms considered were (1) the large-scale gravity wave launched by the onset of magnetic activity, and (2) corotation of previously affected parcels onto the dayside. However, corotation was not found to be the dominant factor.

The simulation reproduced a large-scale gravity wave which affected changes in the model ionosphere similar to those observed with the ionosondes. In particular, the simulated wave in hmF2 also had a period of about 5 hours, and propagated with a horizontal phase speed of about 600 m/s, reaching the equator in 4 hours. The shapes of the phase fronts were similar for the simulated and measured waves. The observed wave crossed the DE-1 field of view ahead of the simulated wave, because the latter was either launched later or from a higher latitude, or both. Differences between the simulated and measured atmospheric response were discussed, and are probably caused by the lack of fidelity in the high-latitude drivers of the TIMEGCM.

The model revealed that the wave causes correlated hmF2 and $[O]/[N_2]$ perturbations. It was therefore possible to use the ionosonde data to predict where the DE-1 brightness perturbations should occur, and how large they should be. The simulated wave resulted in a somewhat weaker perturbation to dayside winds and densities than those of the actual storm. For example, the model indicated only ~70 km increases in the height of the F-region peak at low latitudes on the dayside, compared with ~150 km increases observed by ionosondes. Similarly, the simulated wave resulted in only 15–20% transient increases in the sub-auroral O/N_2 column abundance compared with 20–25% changes in the DE-1 brightness. Since hmF2 was underestimated by the model, it is likely that the model also underestimated the $[O]/[N_2]$ perturbations and the corresponding brightness enhancements. Therefore, the amplitude of the DE-1 brightness enhancement is consistent with the hmF2 amplitude measured by the ionosondes, and the wave effect is able to account completely for the DE-1 brightness enhancement. The measured position of the peak in hmF2 is also well correlated with the traveling enhancement in FUV brightness, as predicted by the model.

Unfortunately there were no DE-2 in-situ composition or wind measurements available for comparison in this interval.

The wave appears to cause a transient Hadley circulation cell on the dayside in response to the high-latitude heating. The Hadley cell seems to last about 5 hours, corresponding to the period of the wave. Increased equatorward winds on the dayside generated by the storm between 16–20 UT lead to downwelling at middle and low latitudes, and result in dayside increases of the column O/N_2 ratio. As the vertical wind reverses to upward, $[O]/[N_2]$ begins to decrease again. By 2100 UT, the simulated winds and $[O]/[N_2]$ at middle to high latitudes had recovered to prestorm values. The maximum perturbation of $[O]/[N_2]$ in the model occurred about an hour later than the maximum DE-1 brightening, consistent with the fact that the simulated wave lagged the observations by 60 minutes. Transient changes in composition have been observed from satellites previously, and explained in terms of transient Hadley cells (see review by *Volland*, [1999]), however, this is the first time the corresponding effect has been observed in both the meridional wind (hmF2) and composition (FUV brightness). It is also the first time the transient has been explicitly associated with a large-scale gravity wave, and has been fully modeled.

This work also represents the first detection and identification of a travelling atmospheric disturbance by an orbiting FUV imager. Further investigation of the effects discussed in this paper will be possible following launch of the NASA TIMED mission later this year. Observations of the Earth's disk by the Global Ultra-Violet Imager (GUVI) will reveal changes in the FUV dayglow, while GUVI limb scans will provide independent height profiles of the neutral species O, N_2 and O_2 [*Christensen et al.*, 1994]. At the same time, the TIDI instrument will measure the thermospheric vector wind profile in the 100–300 km altitude range. Global images of Earth's OI

135.6 emissions obtained by the NASA IMAGE mission should also provide excellent observations of thermospheric effects on FUV brightness.

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