Joule heating and nitric oxide in the thermosphere, 2

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[1]   During geomagnetic storms, gravity waves propagate from the polar regions toward the equator heating the thermosphere at 140 km and higher. These gravity waves are produced by Joule heating that occurs at latitudes of 60° and higher. The heating leads to an increase in the density of nitric oxide at 140 km in the thermosphere. On some occasions, the increased nitric oxide diffuses downward to the 110 km level causing the nitric oxide density at that level to increase substantially. Two and a half years (11 March 1998–30 September 2000) of Student Nitric Oxide Explorer (SNOE) observations of nitric oxide were examined to look for occurrences of increased nitric oxide produced by Joule heating initiated gravity waves and to determine how often downflow of nitric oxide occurs. The results of this study show that gravity wave heating occurs frequently, about 12–14% of the time at 40° latitude. For about 50% of these events, downflow of nitric oxide from 140 km to 110–120 km occurs the following day. About 2–3% of the time, gravity waves propagate all the way to the 20°N and S latitude band around the equator. On special occasions, downflow of nitric oxide occurs at the equator as the result of Joule heating occurring in the polar regions. This happened on five occasions during the two and a half year period in 1998–2000.

1.   Introduction

[2]   The effect of low- and midlatitude heating initiated by Joule heating on the nitric oxide density in the thermosphere during the 25 September 1998 geomagnetic storm was studied in detail using the National Center for Atmospheric Research Thermosphere Ionosphere Electrodynamics General Circulation Model (NCAR TIEGCM) [*Barth et al.*, 2009]. The Joule heating event occurred at 0600 UTC on day 268 (25 September 1998) heating the 140 km region of the thermosphere. The meridional wind was 200–300 m/s between 0600 and 0800 UTC. A gravity wave propagated from 60°N to 30°N in one hour raising the temperature at 140 km from 700 K to 850 K. This increase in temperature moved at an effective velocity of approximately 600 m/s. The gravity wave continued to the equator. The increased temperature led to an increase in the nitric oxide density. The rapid increase in nitric oxide density propagating to low latitudes is the signature of a Joule heating initiated event. The meridional wind may have transported nitric oxide from 60°N to 50°N, but the wind was not strong enough to transport nitric oxide to low latitudes as the observations showed. Only the gravity wave created by the Joule heating event moved at a large enough velocity to agree with the observations.

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[3]   The plan of the present study is to examine all 935 days of the SNOE primary mission, 11 March 1998–30 September 2000, to look for occurrences of nitric oxide increases initiated by Joule heating. The objectives are to determine the frequency and equatorward extent of these Joule heating initiated events. Another objective is to determine how often downflow of nitric oxide from the 140–150 km region to the 110–120 km region occurs following a Joule heating event. Of particular interest, is how often does Joule heating at polar latitudes lead to increases in nitric oxide density at 110 km at the equator.

[4]   One of the reasons for studying the nitric oxide density increase during Joule heating events is that there is an accompanying increase in energy loss from low- and midlatitudes from the NO 5.3 micron emission. During the Joule heating event, both the nitric oxide density and the temperature increase. The result is a large increase in energy loss off-setting, in part, the energy input from thermospheric heating. This natural thermostat effect has been measured by the SABER experiment on the TIMED satellite [*Mlynczak et al.*, 2003] and has been analyzed in detail for the April, 2002 solar storm [*Mlynczak et al.*, 2005]. Observations of the infrared radiative cooling in the thermosphere for the seven year period 2002–2008 have been published by *Mlynczak et al.* [2010]. This data set shows hundreds of occurrences where increased radiative cooling occurs as a result of Joule heating. Using the TIMED/SABER data set, *Lu et al.* [2010] have compared NO radiative cooling power with global Joule heating power which they obtained by using the Assimilative Mapping of Ionospheric Electrody-
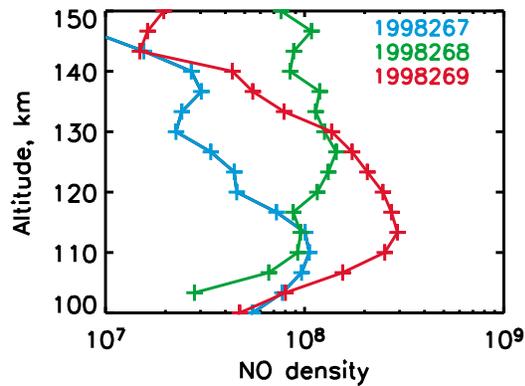
Figure 1. NO density-altitude plot for the1998268 event. A semi-log plot of NO density versus altitude for the day before, 1998267 (blue), the day of the event, 1998268 (green), and the day after, 1998269 (red). On day 1998268 (green) the density at 140 km has increased because of heating initiated by Joule heating in the polar region. On day 1998269 (red), the density at 110 km has increased as a result of downflow from 140 km. The latitude is 30°N and the longitude is 314°E.

namics (AMIE) algorithm with data inputs from DMSP and NOAA satellites, the SuperDARN radar network, and ground magnetometers. They found a close correlation of global Joule heating power and global NO cooling power with a time lag of about 10 h.

[5] Another effect of Joule heating is that the atmospheric density increases in the upper thermosphere at altitudes of low earth orbit satellites (400–600 km). A study of accelerometer data from the CHAMP satellite showed density enhancements of 200–300% at 400 km during times of geomagnetic storms [*Sutton et al.*, 2005]. Further studies of density measurements from the CHAMP satellite were performed using the NCAR TIEGCM to determine the response of the thermosphere to coronal mass ejections [*Forbes et al.*, 2005].

2. Nitric Oxide Database

[6] Global observations of nitric oxide were made from the limb scanning ultraviolet spectrometer on the Student Nitric Oxide Explorer (SNOE) spacecraft [*Barth et al.*, 2003]. The SNOE database contains nitric oxide densities at altitudes between 100 and 150 km, latitudes between 82°S and 82°N, and 15 longitudes spaced 24° apart from 15 orbits a day. All of the measurements of nitric oxide were made at a solar local time of approximately 11:00 A.M. The altitude resolution is 3.3 km; the latitude resolution 5°. The primary mission extends from 11 March 1998 (1998070) to 30 September 2000 (2000274), a period of 935 days.

3. Nitric Oxide Photochemistry

[7] The photochemistry of nitric oxide in the thermosphere is described by *Bailey et al.* [2002] Very briefly, nitric oxide is formed from the reaction of nitrogen atoms with molecular oxygen. The largest source is the reaction of excited $N(^2D)$ atoms with molecular oxygen. These excited atoms are produced by photoelectrons which in turn are

produced by the action of solar soft X-rays principally on atomic oxygen and molecular nitrogen in the thermosphere. Excited nitrogen atoms are produced in the auroral region by the action of precipitating electrons on atomic oxygen and molecular nitrogen. In general, more nitric oxide is produced in the auroral region than at low latitudes. Nitric oxide is also produced throughout the thermosphere by the reaction of ground state $N(^4S)$ atoms with molecular oxygen. This source is very temperature dependent and is usually much smaller than the $N(^2D)$ atom source. However, when the thermosphere is heated following a Joule heating event, the rate of the N(4S) reaction increases and when the heated thermosphere is illuminated by solar soft X-radiation, the density of nitric oxide increases reaching a maximum at noon solar local time [*Siskind et al.*, 1989]. Using the Field Line Interhemispheric Plasma (FLIP) model, *Richards* [2004] showed that nitric oxide at midlatitudes increased at 110 km as a result of vertical diffusion from higher altitudes following a magnetic storm.

4. Joule Heating and SNOE data

[8] Joule heating occurs in the thermosphere as a result of electric currents that flow during geomagnetic storms [e.g., see *Richmond and Lu*, 2000]. These currents heat the atmosphere as the ions collide with the neutral molecules in the auroral region. Joule heating produces gravity waves that propagate equatorward to lower latitudes [*Richmond*, 1978]. The gravity waves generated by Joule heating heat the low and midlatitude thermosphere by conduction, collisions of neutral molecules with neutral molecules. The relationship between the thermospheric heating initiated by Joule heating and increased nitric oxide has been studied using the TIEGCM for the September 25, 1998 geomagnetic storm [*Barth et al.*, 2009]. The increased nitric oxide density
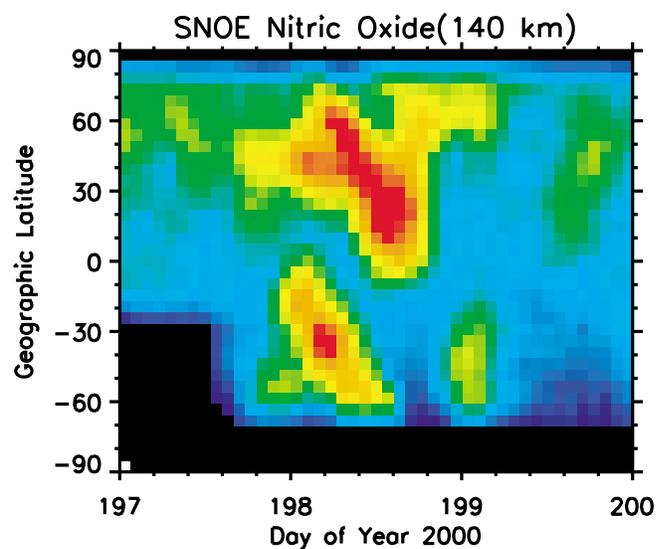

Figure 2. Time-latitude plot of NO density at 140 km for the 2000198 event. A gravity wave initiated by Joule heating moves southward at the beginning of day 198 reaching the equator by the middle of the day. Increased nitric oxide occurs from latitude 50°N to 5°S.
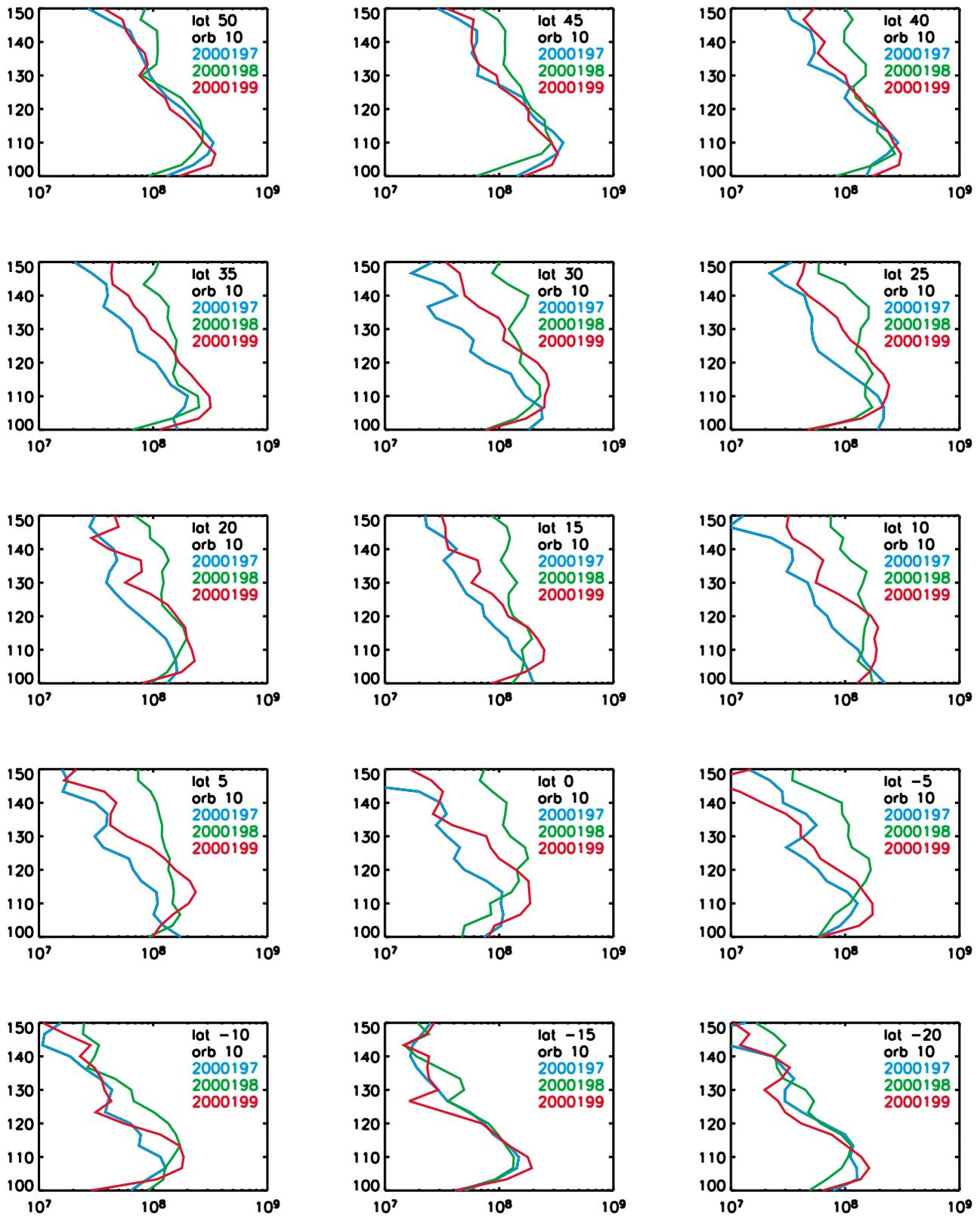
Figure 3. NO density-altitude plots for 15 latitudes for the 2000198 event. See Figure 1 for the description of these plots. Increased nitric oxide occurs at 140 km for latitudes 50°N to 5°S and not at latitudes 10°S − 20°S. Downflow of nitric oxide to 110 km occurs from 35°N to 10°S and at latitudes 15°S and 20°S. The longitude at the equator is 267°E.
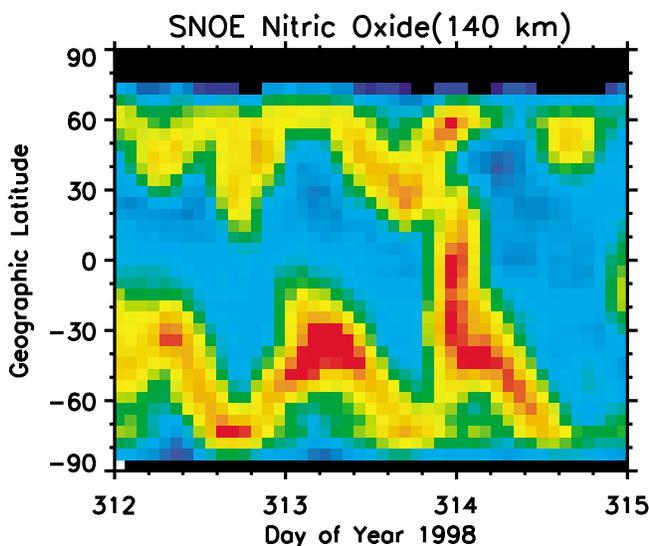
Figure 4. Time-latitude plot of NO density at 140 km for the 1998313 event. At the end of day 313 and the beginning of day 314, a gravity wave initiated by Joule heating moves northward reaching the equator and beyond. Increased nitric oxide occurs from latitude 60°S to 20°N.

at 140–150 km diffused downward during the 24 hours following the Joule heating event. This downflow produced an increase in the nitric oxide density of about a factor of 2 in the 110–120 km altitude region. This behavior is shown in Figure 1 which shows SNOE observations for the three day period, September 24, 25, and 26, 1998 (days 1998267, 1998268, 1998269). The log of the nitric oxide density is plotted versus altitude at latitude 30°N for the three day period. The density distribution on day 1998267, the day before the Joule heating event is plotted in blue. The maximum density occurs near 110 km and falls off logarithmically with increasing altitude decreasing by a factor of five by 140 km. At 1100 UT on day 1998268 the nitric oxide density which is plotted in green has increased dramatically at altitudes higher than 120 km. At 140 km, the increase is about a factor of three larger than on day 1998267. On day 1998269, the day after the Joule heating event, the density above 120 km has decreased and the density at 110 km has increased by about a factor of two and a half compared to day 1998267. This increase is the result of downward flow of nitric oxide from high to low altitudes as a result of eddy and molecular diffusion. The TIEGCM results show the same behavior, increased densities at 140 km on day 268 followed by downward diffusion to 110 km on day 269 [*Barth et al.*, 2009] The model calculations show that the physical mechanisms that produces the downflow are eddy and molecular diffusion.

[9] All 935 days of the SNOE mission were examined for similar increases in nitric oxide density at 140 km initiated by Joule heating events. Twenty-seven were found that showed increased nitric oxide that extended from 60°N or S latitude equatorward to mid and low latitudes. In all of these cases, the apparent movement of the nitric oxide was rapid, within 1–3 h. Two examples from this group are described in the next few paragraphs.

[10] A Joule heating event occurred on 16 July 2000, day 2000198 near 0000 UT. The equatorward propagation of low latitude heating initiated by Joule heating is shown in Figure 2 which is a time-latitude plot of nitric oxide at 140 km for days 197, 198, and 199 of 2000. Fifteen orbits of density data are plotted for each of the three days. For each orbit, the UT increases by 96 min and the longitudes change by 24°. The solar local time of each orbit remains the same, 1100 SLT. The Joule heating event starts toward the end of day 197. The increase in nitric oxide density starts to move equatorward at the beginning of day 198 reaching the equator by the middle of the day. Joule heating occurs at latitudes 60° and higher. Gravity wave heating occurs at latitudes 40° and lower. The downward flow of nitric oxide is evident in Figure 3 which shows a series of density-altitude plots on day 2000198 for fifteen latitudes from 50°N to 20°S showing the propagation of the thermospheric heating from the northern polar region toward the equator. Increased nitric oxide occurs at 140 km at latitudes from 50°N to 5°S and is not present at latitudes southward of 10°S. Downward flow of nitric oxide to 110 km is present at latitudes 35°N to 10°S and downflow does not occur at 15° and 20°S.

[11] Another example of Joule heating and gravity wave heating is shown in the time-latitude plot in Figure 4 for days 312, 313, and 314 of 1998. A Joule heating event occurs during day 313. Near the end of the day and continuing into day 314, a gravity wave propagates northward from 60°S to the equator and beyond heating the thermosphere and causing the nitric oxide density to increase. The behavior of the nitric oxide density as a function of altitude and latitude is shown in the density-altitude plots in Figure 5 for the last orbit of day 1998313. At all latitudes from 20°N southward to 50°S heating occurs as demonstrated by the increase in density at 140 km on day 1998313 (green line) as compared to day 1998312 (blue line). There is a dramatic increase in the nitric oxide density at 110–120 km on day 1998314 (red line) as compared to day 1998312 (blue line) including at the equator (0°).

5. Number of Occurrences

[12] The systematic search for occurrences of nitric oxide density increases caused by gravity wave heating initiated by Joule heating was conducted in the following way. For each of the 935 days, the nitric oxide density in the altitude band 137 to 143 km was calculated and compared to the density the preceding day. This calculation was performed every 10° of latitude between 40°N and 40°S for each of the 15 orbits. The number of days was calculated with the requirement that the nitric oxide density on the day of the Joule heating event was three times the density on the day before the event. When these conditions were met for any of the 15 orbits during a day, it was counted as having a Joule heating initiated event that caused an increase in the low- and mid- latitude nitric oxide density.

[13] An additional search of the complete data set was made to determine how many of the gravity wave heating events also have downflow of nitric oxide from the 140 km altitude region to the 110–120 km region. The following additional requirement was added to the search criteria. The density of nitric oxide at 110–120 km needs to be 1.5 times
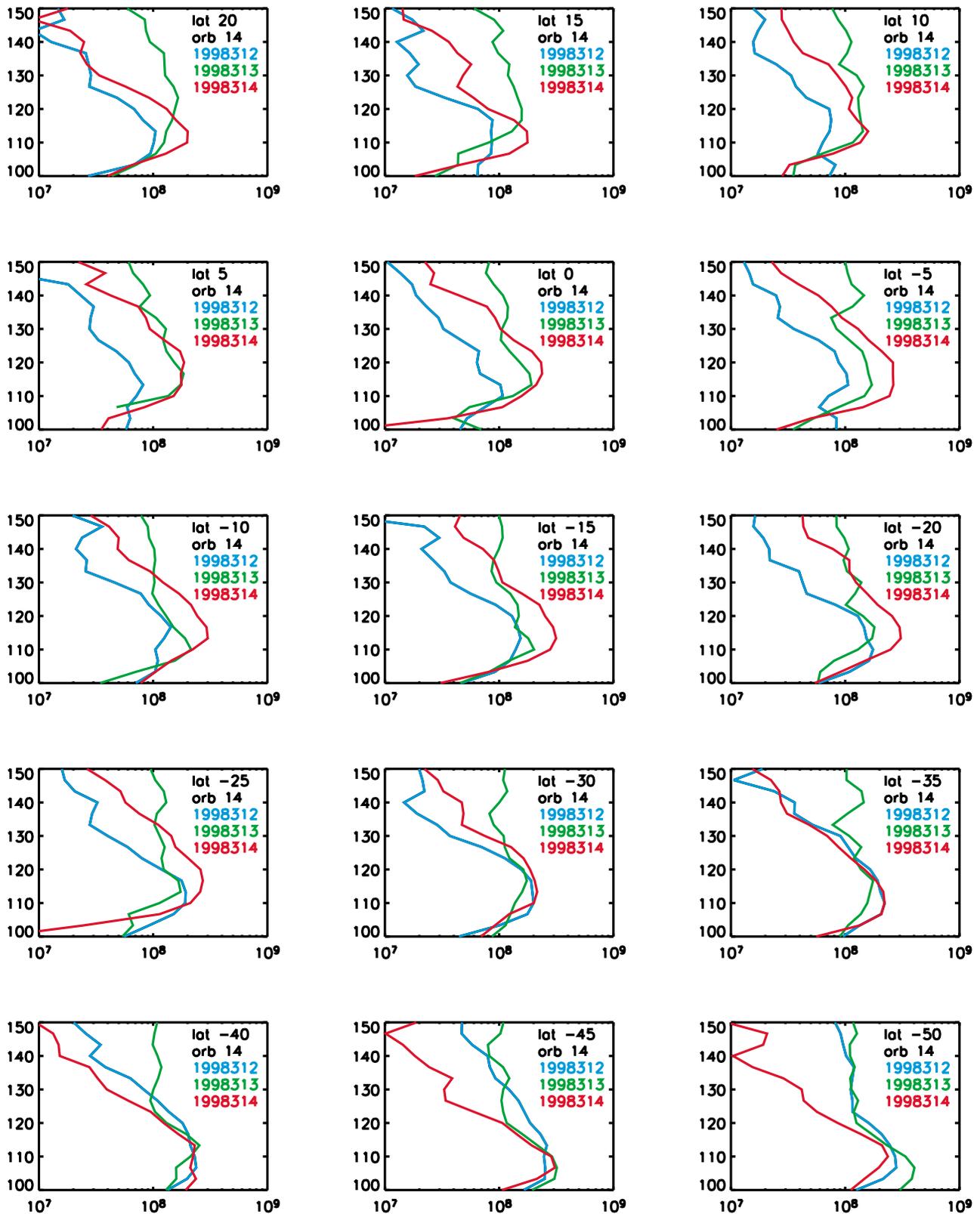
Figure 5. NO density-altitude plots for 15 latitudes for the 1998313 event. See Figure 1 for a description of these plots. Increased nitric oxide occurs at 140 km for all latitudes from 20°N to 50°S. Downflow of nitric oxide to 110 km occurs at latitudes 20°N to 25°S including at the equator. The longitude at the equator is 165°E.

Table 1. Occurrences of Nitric Oxide Density Increases Caused by Gravity Wave Heating as a Function of Latitude[a]

Latitude	Number of Days With Gravity Wave Heating	Percent Gravity Wave Heating Days/ Total Days	Number of Days With Nitric Oxide Downflow	Percent Downflow Days/ Gravity Wave Heating Days
40°N	130	14%	64	49%
30°N	72	8%	25	35%
20°N	28	3%	14	50%
10°N	20	2%	9	45%
Equator	11	1%	5	45%
10°S	11	1%	5	45%
20°S	24	3%	13	54%
30°S	69	7%	28	41%
40°S	114	12%	47	41%

[a]Column 2 shows number of days with gravity wave heating. Column 3 shows ratio of gravity wave heating days to the 935 days in the data set expressed as percent. Column 4 shows number of days with nitric oxide downflow. Column 5 shows fraction of the gravity wave heating days that have nitric oxide downflow expressed as percent.

greater on the day after the Joule heating event as on the day before the event.

[14] The results of the search for occurrences of Joule heating induced gravity waves and nitric oxide downflow as a function of latitude are shown in Table 1. The first column lists the latitude in ten degree increments from 40°N to 40°S. The second column lists the number of days that gravity wave heating initiated by Joule heating occurred on one or more orbits. At 40°N and 40°S the number of occurrences is 130 and 114 days out of the 935 days that were examined. At the equator, the number of occurrences is 11 days. The third column lists the fraction of gravity wave heating days in percent, 14% for 40°N, 12% for 40°S, and 1% for the equator. The fourth column lists the number of days that nitric oxide downflow from 140 km to 110–120 km occurs, 64 for 40°N, 47 for 40°S, and 5 for the equator. The last column lists the fraction of gravity wave heating days in percent that also had downflow, 49% for 40°N, 41% for 40°S, and 45% for the equator. In going from high latitudes to the equator, the number of gravity wave heating induced events decreases, but the fraction of events that lead to downflow of nitric oxide remains about the same at an overall average of 45%.

6. Downflow at the Equator

[15] To further explore the characteristics of the occurrences of downflow at or near the equator, fourteen events were studied. The events chosen are those where downflow occurred between 20°N and 20°S. They are listed in Table 2. The first two columns list the calendar date and the day of the year. The third column gives the latitude closest to the equator where downflow occurred. For the events considered in this Table, there are five days where downflow occurred at the equator, 27 August 1998, 25 September 1998, 09 November 1998, 19 February 1999, and 16 July 2000. These were all times when large geomagnetic storms occurred. For four of these events the maximum nitric oxide density at 140 km that occurred in the 20°N–20°S latitude band was greater than 10×10^7 molecules/cm^3. (The average nitric oxide density at 140 km for days with quiet geomagnetic activity is less than 2×10^7 molecules/cm^3.)

The 16 July 2000 storm was one of the largest during 1998–2000. The details of this event are shown in Figures 2 and 3. A comparison of the data in Figures 2 and 3 and Table 2 helps to understand the table. Similarly, the data displayed in Figures 4 and 5 of the 09 November 1998 events may also be compared to the data in Table 2. For these five days, downflow occurred for 85% of the Joule heating initiated occurrences for all latitudes between 20°N and 20°S. There were six additional days when major geomagnetic storms occurred, 04 May 1998, 19 October 1998, 14 November 1998, 23 September 1999, 07 April 2000, and 11 August 2000. For these six days the maximum nitric oxide density that occurred at latitudes between 20°N and 20°S was greater than 10×10^7 molecules/cm^3 and 70% of the gravity wave heating events resulted in downflow.

7. Discussion and Conclusions

[16] The largest production of nitric oxide in the thermosphere occurs in the auroral region at 110 km as the result of electron precipitation during geomagnetic storms . When Joule heating also occurs during a geomagnetic storm, there may also be a gravity wave propagating equatorward at the 140 km level to produce increased nitric oxide which then diffuses downward to the 110 km altitude level. A time-latitude plot of nitric oxide density at 110 km during such a storm gives the appearance of the nitric oxide being produced in the auroral region and being transported equatorward at the 110 km level [*Barth et al.*, 2003]. This study shows that it is heat that is transported equatorward at 140 km that produces increased nitric oxide at 110 km as result of downward diffusion to the 110 km region.

[17] This study of two and a half years of SNOE observations of nitric oxide density shows that midlatitude heating produced by gravity waves generated by Joule heating in the polar regions occurs frequently, 12 to 14% of the time at 40°N and S latitude. Following these events, downflow of nitric oxide from 140 km to 110–120 km the following day occurs about 50% of the time. About 2–3% of the time, Joule heating initiated gravity waves propagate all the

Table 2. Days When Downflow of Nitric Oxide Occurred in the Latitude Range 20°N–20°S[a]

Date	Day of Year	Min Latitude	Max NO Density, 10^7 cm^{-3}
04 May 1998	124	15	13
27 Aug 1998	239	0	12
25 Sep 1998	268	0	12
19 Oct 1998	292	−10	11
09 Nov 1998	313	0	15
14 Nov 1998	318	−20	10
14 Jan 1999	014	−15	9
18 Feb 1999	049	15	8
19 Feb 1999	050	0	8
17 Apr 1999	107	20	8
23 Sep 1999	266	−15	12
07 Apr 2000	098	15	10
16 Jul 2000	198	0	12
11 Aug 2000	225	10	15

[a]Column 1 shows the calendar date, column 2 the day of the year. Column 3 shows the minimum latitude where downflow of nitric oxide occurred. There were five days when nitric oxide downflow occurred at the equator. Column 4 shows the maximum density of nitric oxide at 140 km in the 20°N–20°S latitude band in units of 10e7 molecule/cm^3.

way to the 20°N–20°S latitude band around the equator. Increased nitric oxide at 110 km at the equator that is produced as a result of Joule heating occurring in the polar region at 140 km does take place, but it is a special event when it does. There were five occasions during the two and a half year period during 1998–2000.

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