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ANALYSIS OF SELECTED NITRIC OXIDE OBSERVATIONS IN THE LOWER THERMOSPHERE BY HALOE ON UARS

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Abstract. Measurements of nitric oxide mixing ratios have been made by the Halogen Occultation Experiment on the Upper Atmosphere Research Satellite over an altitude range extending from 15 to 130 km on every spacecraft sunrise and sunset event with the exception of about 8% downtime. Selected NO profiles from the first few months of observations were examined with emphasis on the relation between geomagnetic disturbances and enhanced NO in the lower thermosphere. During a large geomagnetic storm on November 8-9, 1991, HALOE obtained 15 NO sunrise profiles along the ~50^0N latitude circle. A factor of 3 increase in NO mixing ratio above ~115 km at this latitude and a one to two day decay time were observed. The measured NO longitude/altitude cross section on this day shows a longitudinal asymmetry in the NO distribution with a maximum near the geomagnetic pole. From approximately one month's data, a latitude/altitude cross section of zonal mean NO mixing ratio was calculated. An example of such cross sections demonstrates a strong positive correlation between geomagnetic activity and thermospheric NO globally. This auroral forcing has a larger effect on increasing NO at high latitude than at low latitude.

Introduction

Thermospheric nitric oxide is formed by rapid reactions between excited or ground state atomic nitrogen [$N(^2D)$ or $N(^4S)$] and molecular oxygen. Atomic nitrogen is generated by dissociation of N_2 either through the effects of solar radiation or energetic particles [Banks and Kockarts, 1973; Barth, 1992]. Therefore, the distributions of nitric oxide in different latitudinal regions reflect the combined effect of solar and auroral energies on the upper atmosphere and the responding motion of the atmosphere to these energy inputs. The Halogen Occultation Experiment (HALOE), one of the nine instruments aboard the Upper Atmospheric Research Satellite (UARS) launched September 1991, is able to measure NO mixing ratio profiles between 15 and 130 km. In brief, the occultation experiment measures the absorption of solar energy by atmospheric gases during satellite sunrise and sunset events. The NO channel is one of the four gas filter radiometer channels in the HALOE instrument. A more detailed description of the HALOE can be found in the paper by Russell et al. (1993).

The response of thermospheric nitric oxide to solar and geomagnetic activity has been studied by using theoretical models [Solomon et al., 1982; Cravens and Killeen, 1988, Siskind et al., 1989; Roble, 1992]. These simulations suggest that, based on our current understanding of the NO chemistry in the lower thermosphere, the NO concentration in this region has strong positive correlations with the solar and auroral energy inputs. A significant amount of NO will be generated in the lower thermosphere in the auroral oval during disturbed geomagnetic conditions and the combined effects of auroral forcing and solar radiative forcing need to be considered to explain the resulting NO concentration at any latitude and time. A time-dependent model calculation for an isolated storm event conducted by Roble (1992) shows in the lower thermosphere, a decay time of order one day for globally averaged NO density profiles following the geomagnetic disturbances.

Prior to HALOE on UARS, satellite measurements of thermospheric nitric oxide had been made by the Atmospheric Explorer satellites (AE - C and -D) during 1974 and 1975 [Barth et al., 1973; Cravens et al., 1985] and the Solar Mesosphere Explorer (SME) satellite between January 1982 and August 1986 [Barth et al., 1988; Siskind et al., 1989; Barth, 1992]. The NO density observed by these two satellites is inferred from the measurement of the fluorescent scattering of the (1,0) gamma band with ultraviolet spectrometers. These studies showed that there is always more NO observed at higher latitude than at lower latitudes, which indicated the existence of an auroral source for NO. Long term NO measurements by SME showed a strong correlation between low latitude NO and solar cycle [Barth et al., 1988; Barth, 1992]. From AE-C measurements Cravens et al. found a longitudinal dependence of NO with greater abundances existing near the magnetic poles and they presented a model calculation to demonstrate that NO can be transported away from the auroral regions in a longitudinally asymmetric manner [Cravens and Stewart, 1978; Cravens and Killeen, 1988]. The model simulation by Roble (1992) showed that the low latitude enhancements of NO during geomagnetic storms are more likely caused by enhancement in solar soft X-rays as proposed by Barth [Barth et al., 1988; Siskind et al., 1990].

A qualitative analysis of selected HALOE measured NO mixing ratios during its early few months in orbit will be presented in this paper. Following a brief description of HALOE observations, we will present NO results from November 8-9, 1991 during the occurrence of a large geomagnetic storm and then we will discuss the NO monthly latitude/altitude cross sections. A good agreement in general behavior of NO in the lower thermosphere was found between theoretical predictions and HALOE measurements.

HALOE Observations

Detailed description of the HALOE experiment is given in a paper by Russell et al. (1993). The measurement of ni-

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tric oxide is made using one of the four gas filter radiometer channels. During satellite sunrise or sunset events, HALOE measures solar radiation absorbed by atmospheric gases in the Earth limb. For the NO channel, after passing a wide band filter centered at 5.26 μm, the sun light is split into the NO gas cell path and the vacuum path. The absorption of NO in the gas cell acts as a high spectral resolution filter. The signal difference between the two paths is used to retrieve nitric oxide volume mixing ratios in the atmosphere.

HALOE provides NO mixing ratio vertical profiles at approximately 15 sunrise and 15 sunset points each day. The two sets of 15 events are distributed at two narrow latitude bands with width of +/- 5 deg. HALOE therefore provides two longitude versus height NO mixing ratio cross sections at two latitude positions for the sunrise and sunset event respectively. The geometry of the solar occultation experiment provides limited latitude coverage on a daily basis. In order to obtain latitude versus height cross sections for the mixing ratios of measured species, a data spanning approximately one month is needed.

An extensive effort is underway to validate HALOE results which includes internal consistency checks, comparisons with past observations, evaluation of vertical profile shapes and seasonal changes, and comparison with correlative underflight or other satellite data. some of these steps have been taken for NO, but the validation is not yet complete. The nitric oxide measurements show good internal consistency. Above the 0.5 mb level for example, sunrise/sunset differences are small. Below this level, the sunrise mixing ratio is less than for sunset as expected. The vertical profile minimum and maximum regions occur at the expected levels, i.e. stratospheric maximum, mesospheric minimum, and rising levels into the lower thermosphere. The measurements confirm the expected seasonal mesospheric characteristics including the deep summer minimum, overall smaller mixing ratios in summer, and larger values in winter. Another qualitative evaluation we have done is comparison with 1985 ATMOS measurements in the stratosphere and lower mesosphere [Farmer et al., 1987; Russell et al., 1988]. The peak mixing ratio occurs at the same altitude in both experiments, the maximum mixing ratios agree to within 15%, and the profile slopes are very similar.

Quantitative comparisons will be made with ATMOS and Grille Spectrometer measurements made during the Space shuttle ATLAS mission launched in March 1992 as soon as these results become available. These experiments also use the occultation approach and thus the results will be well suited for validation studies. Signal sensitivity calculations were done using observed instrument noise levels in orbit to estimate signal-to-noise (S/N). Our results show that the NO S/N ratio for a daily averaged profile is of order 60 at 80 KM, 300 at 95 KM, 30 at 110 KM, and 9 at 130 KM. These S/N values allow good retrievals to be made up to the limit of the data.

Lower Thermospheric NO on Nov. 8-9, 1991

We noted earlier that the HALOE observations extended over an altitude range from about 15 km to 130 km. We concentrate here however on the lower thermosphere from 80 km to 120 km where effects of charged particles on NO density will be greatest.

A large geomagnetic storm occurred on November 8-9, 1991 and visible aurora were observed by a number of ground-based instruments at middle latitudes [Peterson et al., 1992; Smith et al., 1992]. During this time period, HALOE measured sunrise nitric oxide mixing ratio profiles at approximately 51^0N latitude. Figure 1 shows those daily averaged profiles for Nov. 6, 8, 9, 10 and 11. The daily averaged profile is calculated by averaging 15 sunrise profiles along the latitude circle. The daily Ap magnetic index [Mayaud, 1980] started from 18 on Nov. 6, reached a maximum of 119 on Nov. 9 and went down to 20 on Nov. 11 [Coffey, 1992]. The variations of the Kp three-hourly indices [Coffey, 1992] show that the auroral storm started between 1200 and 1500 UT on Nov. 8 (Kp jumped from 4 to 7-) and lasted for about one day. We observe during the storm day, at least a factor of 3 increase in HALOE measured sunrise NO mixing ratio above ~115 km at 51^0N, which indicates that the auroral event did indeed enhance the nitric oxide density in the lower thermosphere. The latitude range for HALOE sunset measurements during the geomagnetic disturbance period is between 47^0S and 27^0S. The sunset profiles also showed a great enhancement of NO on Nov. 9, 1991 and about a factor of 3 increase in thermospheric NO mixing ratio was also observed.

A one to two day decay time for lower thermospheric NO concentration following the geomagnetic storm is estimated from Figure 1. This value agrees with the result from a model simulation by Roble (1992). According to Roble, with the production rate of NO due to auroral secondary electrons decreasing to the pre-storm value, the loss of globally averaged NO due to solar photodissociation through NO + hv -> $N(^4S)$ and $N(^4S) + NO \rightarrow N_2 + O$ in the lower thermosphere is on the order of a day. The downward transport of NO from the lower thermosphere to the mesosphere could also attribute to its decay. One needs to note that the decay time estimated for the NO profiles following the auroral storm mentioned above is at the latitude band near 51^0N.

The daily longitude versus height NO mixing ratio cross section obtained by HALOE at 51^0N on November 9, 1991 allow us to study the longitudinal dependence of NO in response to geomagnetic disturbances (Figure 2). The calculated geomagnetic latitudes corresponding to the 51^0N geo-

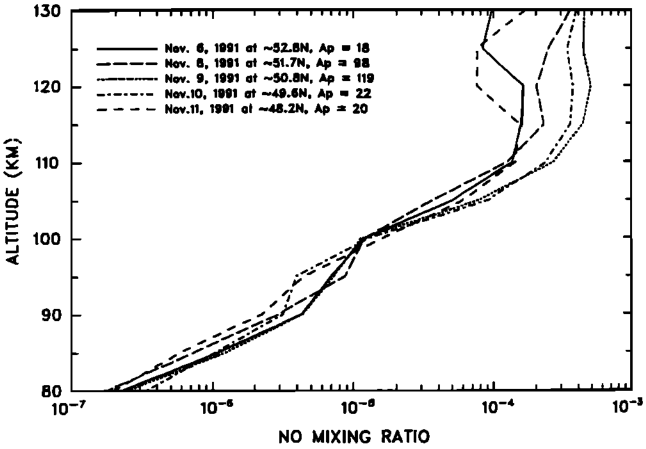

Fig. 1. HALOE vertical profiles of daily averaged sunrise NO volume mixing ratio during a large geomagnetic storm on November 8-9, 1991. Each profile is calculated by averaging 15 sunrise profiles along the latitude circle. Data version 5 is used.

graphic latitude circle are also plotted in Figure 2. We found the enhanced NO mixing ratio in the lower thermosphere due to the large geomagnetic storm to be non uniformly distributed along the ~51^{0}N latitude circle. Obviously, the variation in the geomagnetic latitudes is the main reason. Figure 2 implies that the enhancement of NO strongly depends on geomagnetic latitudes. The relatively large NO increase between 200 E and 330 E longitude in Figure 2 corresponds to the northernmost geomagnetic latitudes in this particular day's measurements. It also appears that in the vicinity of the geomagnetic pole, along with very effective downward transport of NO, a large amount of energetic particles could penetrate deeper into the upper mesosphere and produce nitric oxide there. In addition to the HALOE observations, the fact that low latitude auroral activity on Nov. 8-9 was observed by ground-based instruments [Peterson et al., 1992; Smith et al., 1992] indicates the NO enhancement in the low latitudes during this geomagnetic storm is mainly due to energetic particles penetrating to the mid-latitudes. Another interesting feature shown in Figure 2 is a less pronounced NO maximum below ~95 km near the 120 E which corresponds to the southernmost geomagnetic latitude along the geographic 51^{0}N latitude circle. To determine whether this enhancement is caused by particles, the measurements on distributions of charged particles injected into the Earth's atmosphere over this time period are needed. This information could be provided by the Particle Environment Monitor (PEM) instrument on UARS.

The Thermospheric NO Altitude Versus Latitude Zonal Mean Cross Section

Several phenomena need to be considered in analyzing the latitudinal dependence of thermospheric nitric oxide profiles, including the enhancement of NO due to auroral activity, the variation of daily solar activity and the seasonal effect which determines daily sunlit time at different latitudes. As HALOE and other observations show, geomagnetic disturbances have a great influence on global thermospheric NO.

Figure 3 is a HALOE measured latitude versus height cross section (zonal monthly mean NO mixing ratios) in February 1992. Because the occultation measurement provides zonal mean NO vertical profiles at only two latitudes each day, we used a whole month's set of profiles to get latitude coverage between 75^{0}S and 57^{0}N. An averaging process was used to the data block, that is the profiles are binned using Gaussian weighting and a grid spacing of 3 degrees latitude. The width of the bin is 20 degrees and the width of the normalized Gaussian function applied to each profile inside the bin is 10 degrees. The Ap index corresponding to each date in February was mapped versus the latitude of HALOE observations on that date with similar binning as the NO vertical profiles; Ap index values are plotted on Figure 3. The emphasis is to qualitatively exam the global NO behaviors resulting from relatively active and quiet geomagnetic conditions. We note a very strong positive correlation between thermospheric NO mixing ratios and geomagnetic activities above ~95 km which is clearly displayed by for example, the $10^{-4.25}$ contour line. The enhancement of NO amount following large geomagnetic activities (high Ap index) not only showed at high latitudes but also showed at low latitudes. As expected, the effect of geomagnetic distur-

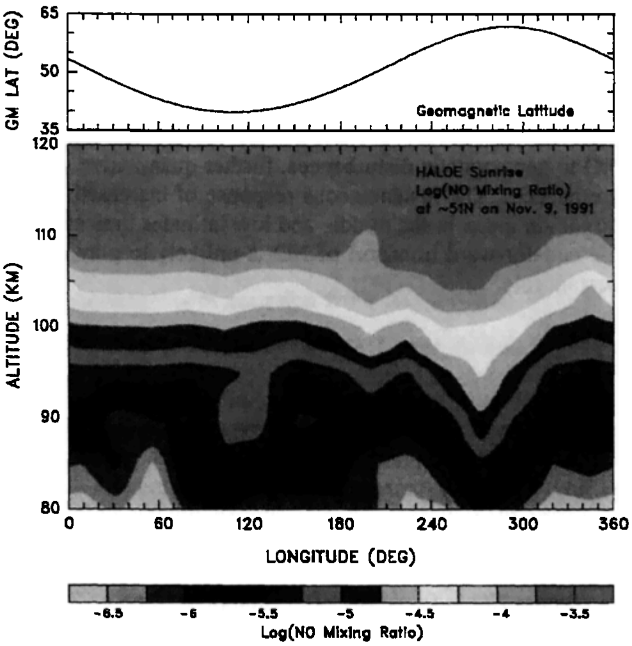

Fig. 2. HALOE sunrise NO mixing ratio at ~51^{0}N on November 9, 1991 (data version 5). The horizontal axis is geographic longitude. Contours are labeled with the base 10 log of the mixing ratio. The top plot is calculated geomagnetic latitudes corresponding to 51^{0}N geographic latitude circle. The north geomagnetic pole is at geographic location of 79^{0}N, 70^{0}W. In the lower thermosphere, a maximum enhancement of NO is found near the longitude band with the northernmost geomagnetic latitudes.

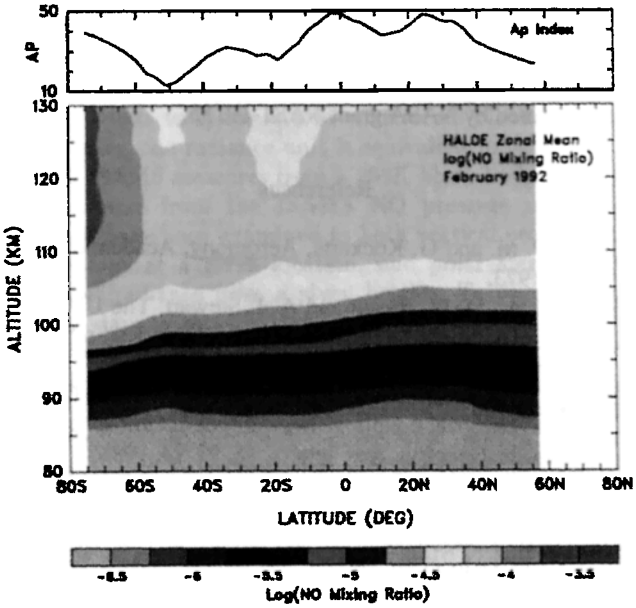

Fig. 3. HALOE zonal mean NO mixing ratio altitude versus latitude cross section for February 1992 (data version 5). Contours are labeled with the base 10 log of the mixing ratio. HALOE provides two daily averaged NO vertical profiles at two latitudes each day. This graph is obtained by accumulating one month of profiles. The corresponding daily Ap index is plotted to show the correlation between geomagnetic activities and thermospheric NO.

bances on thermospheric NO has a large latitudinal gradient with its maximum in the polar region. This behavior has also been observed by other satellite measurements and predicted by theory [Cravens and Stewart, 1978; Siskind et al., 1989; Roble, 1992]. To explain the response of low latitude NO to geomagnetic disturbances, further quantitative studies are needed. The instantaneous response of increased NO to larger Ap index in the middle and low latitudes indicates that the equator-ward transport of NO is unlikely to play an important role.

Summary

A qualitative analysis is given of selected nitric oxide data in the lower thermosphere obtained by HALOE on UARS. NO mixing ratio profiles showed great enhancement during the large geomagnetic storm on November 8-9, 1991. A factor of 3 increase in NO sunrise mixing ratio above ~115 km was observed by HALOE at ~51^{0}N latitude. A longitudinal asymmetry of enhanced NO is observed and the maximum NO is found near the geomagnetic pole. The decay time of NO enhancement following the storm is estimated to be one to two days which agrees with the model simulation by Roble (1992).

The February 1992 zonal mean NO mixing ratio altitude versus latitude cross section demonstrates the strong positive correlation between thermospheric nitric oxide and geomagnetic disturbances. Compared to high latitudes, the auroral effect on NO at low latitudes is relatively small. For the enhancement of low latitude NO during geomagnetic storms, more studies are needed to identify the importance of equator-ward transport, solar soft X-rays and low latitude auroral particle precipitation.

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