

Solar-terrestrial coupling: Solar soft x-rays and thermospheric nitric oxide

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Abstract. Simultaneous measurements were made of the solar soft x-ray irradiances and the thermospheric nitric oxide density in the tropics from the Student Nitric Oxide Explorer (SNOE) satellite. The analysis of these observations for 44 days of low geomagnetic activity in the spring of 1998 show that there is a correlation between the solar soft x-ray irradiances and thermospheric nitric oxide densities in the tropics. Photochemical model calculations that used the measured solar soft x-ray irradiances as input parameters adequately reproduce the magnitude of the time-varying component of the thermospheric nitric oxide in the tropics. An additional amount of nitric oxide is present in the tropics that does not vary with the time period of the solar rotation. The conclusion of this analysis is that solar soft x-rays are the primary cause of the variation in the thermospheric nitric oxide densities in the tropics during times of low geomagnetic activity.

Introduction

Nitric oxide is an important minor constituent of the lower thermosphere because of its chemical and radiative properties. Satellite measurements have shown that the maximum density which occurs near 110 km is highly variable [Barth, 1992] and that the variability is connected with solar activity. In 1988, a hypothesis was proposed that the cause of the variability in the thermospheric nitric oxide was the variability in the flux of solar soft x-rays in the 2-10 nm wavelength range [Barth *et al.*, 1988]. The reasoning was that solar x-rays in this wavelength region are absorbed in the altitude region where the maximum nitric oxide occurs and that the variability in the solar soft x-ray flux is greater than the variability of the solar extreme ultraviolet radiation. In the proposed mechanism for producing nitric oxide, the solar soft x-rays ionize the major constituents of the lower thermosphere, molecular nitrogen and atomic oxygen, producing energetic photoelectrons. These photoelectrons produce additional ionization and additional energetic photoelectrons. These energetic photoelectrons produce excited atomic nitrogen atoms from the dissociative excitation of molecular nitrogen and the additional ionization leads to the production of excited nitrogen atoms through the dissociative recombination of ionized nitric oxide. The excited nitrogen atoms then react with molecular oxygen to produce nitric oxide.

Siskind *et al.* [1990] did a model calculation to determine the flux of solar soft x-rays that would be needed to produce the thermospheric nitric oxide densities that had been measured in rocket experiments. The result of the calculation was a solar

soft x-ray flux that was larger than the fluxes that had been measured during the 1960s and 1970s. No solar x-ray measurements had been made at the time of the rocket experiment nor during the time of the satellite observations that had measured the variability of the nitric oxide density [Barth *et al.*, 1988]. A subsequent model calculation by Siskind *et al.* [1995] which included a more detailed calculation of the photoelectron flux showed that the solar soft x-ray mechanism was more efficient at producing nitric oxide than the initial calculation had indicated. The question of how large is the variability in the magnitude of the flux of solar soft x-rays remained unanswered.

Clearly, what is needed to confirm the hypothesis is a simultaneous measurement of the solar soft x-ray flux and the thermospheric nitric oxide density under conditions of varying solar activity. A satellite experiment was proposed, built, and flown to make these measurements. This paper is a report on the results of these simultaneous measurements.

Observations

Nitric oxide densities between 90 and 170 km and solar radiation between 2 and 20 nm have been measured simultaneously from the Student Nitric Oxide Explorer (SNOE) satellite starting in March, 1998. This satellite is in a near-circular orbit at an altitude of 556 km. The nitric oxide density is determined from the measurement of the resonance scattering of the (1,0) gamma band of nitric oxide at 215 nm with an ultraviolet spectrometer similar to that used on the Solar Mesosphere Explorer (SME) satellite [Barth, 1992]. The telescope on the spectrometer scans the limb five times a minute using the spinning motion of the satellite. The observations from several contiguous spins are summed into five-degree latitude bins. The Rayleigh scattering contribution to the observed ultraviolet radiance is subtracted from the measured signal and the resulting column emission rate is inverted to produce a volume density of nitric oxide with an altitude sampling interval of 3.3 km between 90 and 170 km. The SNOE satellite, which is in a sun-synchronous orbit at an inclination of 97.75 degrees, provides global coverage with its 15 orbits a day.

The solar soft x-ray irradiance in the wavelength range 2 to 20 nm is measured with three photodiodes which have different thin film coatings [Bailey *et al.*, 1999]. In this analysis, daily averages of the solar soft x-ray irradiance in the 2-10 nm region are used for comparison with the nitric oxide observations.

Altitude profiles of the nitric oxide density measured on two days that had very different solar activity are shown in Figure 1. These observations were made in the tropics between latitudes 20°S and 20°N where the solar radiation dominates the production of nitric oxide and the effect of geomagnetic activity is at a minimum. On April 1, 1998, solar activity was low as indicated by a value of 0.22 ergs cm⁻² s⁻¹ for the solar soft x-rays and on April 5, the activity was higher with a solar soft x-ray irradiance of 0.38 erg cm⁻² s⁻¹. Geomagnetic activity was low as indicated by Ap index of 3 on both days. In both profiles, the maximum density occurs near 110 km. There is a

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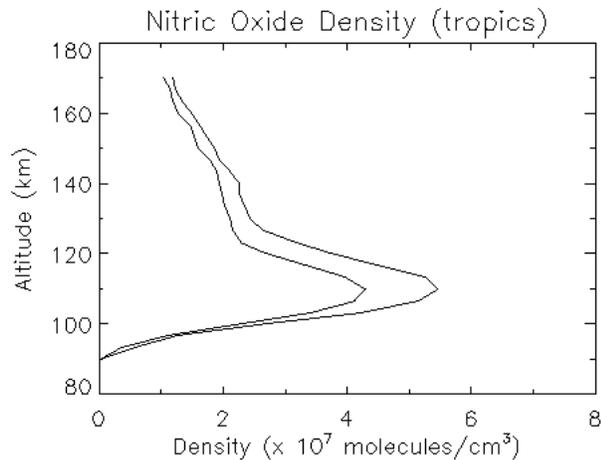


Figure 1. Altitude profiles of nitric oxide density in the tropics for a day with low solar soft x-ray flux and for a day with high solar soft x-ray flux. The low nitric oxide density profile was measured on April 1, 1998 when the soft x-ray irradiance was $0.22 \text{ ergs cm}^{-2} \text{ s}^{-1}$. The high nitric oxide density profile was measured on April 5, 1998 when the x-ray irradiance was $0.38 \text{ ergs cm}^{-2} \text{ s}^{-1}$.

clear-cut change of slope in the profile above 120 km. The maximum density changes by a factor of 1.3 between these two days. The altitude region between 100 and 120 km is where the solar soft x-rays in the 2-10 nm region are absorbed.

The density of nitric oxide at 110 km in the tropics is plotted in Figure 2 for the 131 day period between March 11, 1998 and July 19, 1998. This figure shows that there is a variation in the nitric oxide density of over a factor of 1.3 with a period that is approximately the period of the solar rotation. The solar soft x-ray irradiance in the 2-10 nm region shows a similar variation during this period [Bailey *et al.*, 1999]. These solar observations are plotted in Figure 3.

Data Analysis

Nitric oxide is produced in the auroral region by precipitating auroral electrons. In fact, there is always more

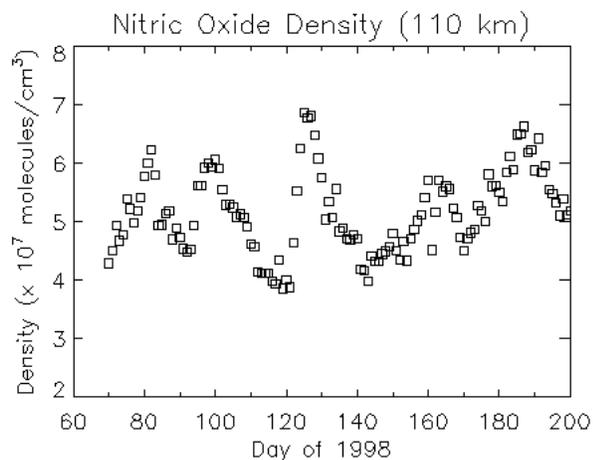


Figure 2. Variation of thermospheric nitric oxide at 110 km in the tropics as a function of time between March 11, 1998 and July 19, 1998.

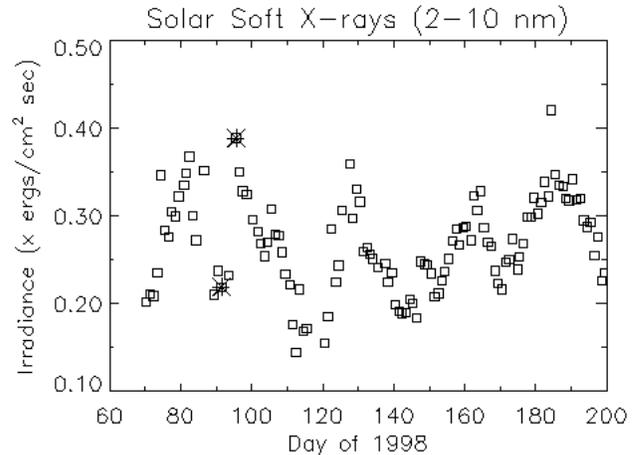


Figure 3. Variation of solar soft x-ray irradiance (2-10 nm) for the time period March 11, 1998 to July 19, 1998. The asterisks indicate the days that were used in Figure 1 when plotting the nitric oxide density.

nitric oxide in the auroral zone than there is in the tropics [Barth, 1992]. During geomagnetic storms, the increase in nitric oxide extends equatorward and affects the amount of nitric oxide in the tropics. For this reason, in the analysis of the effect of solar soft x-rays on the nitric oxide density in the tropics, care was taken to exclude any geomagnetic influence from the analysis by considering only those days when the geomagnetic Ap index was less than 10 on both the day of the nitric oxide observation and the previous day. Out of the 131 days of the period being analyzed, 44 days met this criteria. For this data set, a linear regression was performed to determine the correlation between the nitric oxide densities in the tropics and the solar soft x-ray irradiances in the 2-10 nm wavelength range. The results are shown in Figure 4. The calculated correlation coefficient is 0.88. This result is interpreted as evidence that the variation in the nitric oxide density in the tropics is primarily the result of the variation in the solar soft x-ray irradiance.

Model Calculations

A photochemical model was used to calculate the nitric oxide densities in the lower thermosphere for the solar and geomagnetic conditions that occurred during the time period of the SNOE observations. The most important input to the model calculations is the measured solar soft x-ray irradiances measured by the SNOE solar soft x-ray photometer [Bailey *et al.*, 1999]. This model is a one-dimensional, time-dependent calculation that includes vertical transport processes for nitric oxide and atomic nitrogen [Cleary, 1982; Barth, 1992]. The neutral atmosphere is calculated from the MSISE-90 model [Hedin, 1991]. The glow model which takes into account Auger ionization is used to calculate the photoelectron flux [Solomon *et al.*, 1988; 1989]. In the photochemical model, the rate coefficients and branching ratios that are used are those listed in Barth [1992] with the following changes: the branching ratio for the production of excited nitrogen atoms from the electron impact dissociative excitation of molecular nitrogen is 0.54 [Zipf *et al.*, 1980], the branching ratio for the production of excited nitrogen atoms from the dissociative recombination of ionized nitric oxide is 0.85 [Vejby-Christensen *et al.*, 1998] and the rate coefficient for the deactivation of excited nitrogen atoms by atomic oxygen is $5 \times 10^{-13} \text{ cm}^3/\text{sec}$ [Cf: Fell and Steinfeld, 1990]. These values may

be compared to those used in a detailed and up-to-date photochemical model [Swaminathan *et al.*, 1998].

The results of these model calculations for the low geomagnetic activity days between March 11, 1998 and July 19, 1998 are shown in Figure 5. The measured nitric oxide density at 110 km is plotted as a function of the calculated nitric oxide density. An inspection of the figure shows that there is a linear relationship between the measurements and the model calculations. This result is interpreted as meaning that the model adequately describes the major physical and chemical processes that produce the variation in the density of nitric oxide in the lower thermosphere and that the major cause of the time variation is the varying solar soft x-ray irradiance. There is a significant uncertainty in the magnitude of the nitric oxide density calculated by the model because of the uncertainties of the rate coefficients and branching ratios of the many physical and chemical processes that are included in the model.

Further inspection of Figure 5 shows that while the model does describe the time variation of the nitric oxide density, there is an additional component of the measured nitric oxide density in the tropics that is not accounted for in the model. The component of the tropical nitric oxide that does not vary with time may be seen directly from the observations. In Figure 4, the measured nitric oxide density is plotted as a function of the measured solar soft x-ray irradiance. A straight line fit through this observational data gives an intercept of 2.6×10^7 molecules/cm³ for zero solar soft x-ray irradiance. The most likely source of this background density of nitric oxide in the tropics is transport of nitric oxide from the auroral regions where the density of nitric oxide is always greater than in the tropics. The one-dimensional model used in this analysis does not include horizontal transport. Multi-dimensional models are needed to take into account horizontal transport.

Summary

The primary cause of the variability of the nitric oxide density in the lower thermosphere in the tropics is the variability in the flux of the solar soft x-rays. The evidence for this conclusion are: (1) simultaneous measurements of the solar soft x-ray flux in the 2-10 nm region and the thermospheric

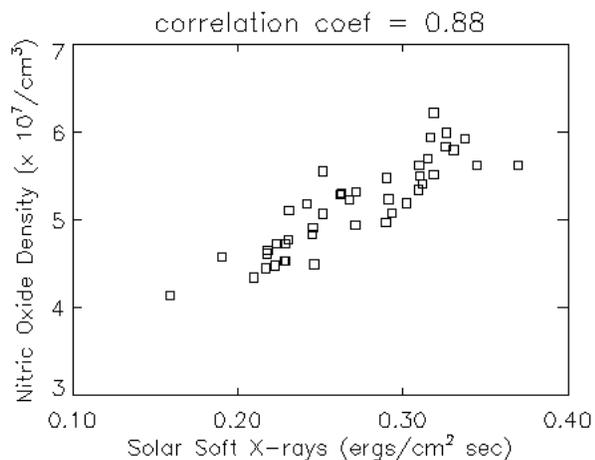


Figure 4. Correlation of the thermospheric nitric oxide density (110 km) with the solar soft x-ray irradiance (2-10 nm). The influence of geomagnetic activity was minimized by using only observations when the Ap index was less than 10 on the day of the measurement and the preceding day.

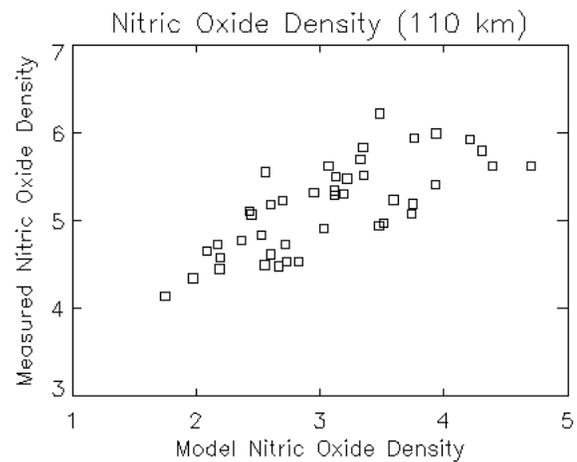


Figure 5. Comparison of the measured nitric oxide density (110 km) with the nitric oxide density calculated with a photochemical model that used the measured solar soft x-ray irradiance (2-10 nm) as an input parameter.

nitric oxide density in the tropics show a high degree of correlation, and (2) calculations of the thermospheric nitric oxide density with a photochemical model that uses the measured solar soft x-ray fluxes as input parameters adequately reproduce the measured variability in the thermospheric nitric oxide density.

An additional result of the analysis of the SNOE observations is that there is an additional amount of thermospheric nitric oxide in the tropics that does not vary with the time scale of a solar rotation. The most likely source of this nitric oxide is horizontal transport of nitric oxide from the auroral regions. During the time of the observations reported on here (Spring, 1998), the magnitude of this non-varying component was about equal to the magnitude of the nitric oxide produced from the solar soft x-rays.

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