Middle and upper thermospheric odd nitrogen: 2. Measurements of nitric oxide from Ionospheric Spectroscopy and Atmospheric Chemistry (ISAAC) satellite observations of NO γ band emission

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[1] Ultraviolet dayglow observed using the Ionospheric Spectroscopy and Atmospheric Chemistry (ISAAC) satellite instrument is used to determine the concentration of nitric oxide (NO) in the upper mesosphere and thermosphere. ISAAC was launched in February 1999 on board the Advanced Research and Global Observing Satellite (ARGOS). We focus on ISAAC dayside limb observations at tangent altitudes between 80 and 200 km and over the latitude range 40°N-70°S. The data analyzed here were obtained in November and December 1999 during a period of moderate to high solar activity. The NO density retrievals include constraints on instrument sensitivity, in-flight assessments of stray light, and determinations of Rayleigh-scattered background contributions. Residual spectra contain strong dayglow signatures of the NO γ bands which are used for inversion of measured radiances to absolute NO concentrations. Comparison between ISAAC measurements and photochemical calculations indicates improved agreement above 130 km using O_2 and temperatures from the new NRLMSISE-00, as compared to the MS model. In the lower thermosphere, observed daily variations in low-latitude nitric oxide are strongly correlated with variations in the solar soft X-ray flux. INDEX TERMS: 0355 Atmospheric Composition and Structure: Thermosphere-composition and chemistry; 0310 Atmospheric Composition and Structure: Airglow and aurora; 0340 Atmospheric Composition and Structure: Middle atmosphere-composition and chemistry; 0394 Atmospheric Composition and Structure: Instruments and techniques; KEYWORDS: nitric oxide, thermosphere, ISAAC, NRLMSISE, solar soft X rays

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1. Introduction

[2] The distribution of nitric oxide (NO) in the Earth's mesosphere and thermosphere is governed by a number of fundamental radiative, chemical, and dynamical processes involved with space weather, solar forcing, and anthropogenic effects on the upper atmosphere [e.g., *Roble et al.*, 1987]. The importance of NO as a diagnostic tracer of thermospheric transport and energetics has long been recognized [*Barth*, 1964], providing motivation for several rocket and satellite measurements over the past 3 decades [*Rusch*, 1973; *Thomas*, 1978; *McCoy*, 1983a; *Ogawa et al.*, 1984; *Cravens et al.*, 1985; *Siskind et al.*, 1990; *Barth*,

1996; *Gordley et al.*, 1996; *Stevens et al.*, 1997a; *Barth et al.*, 2003]. In general, rocket observations of NO were limited to single vertical profiles, and analysis of previous satellite observations has focused on NO distributions in the lower thermosphere. A rare exception is the study by *Cravens* [1981], which presented measurements of NO in the upper thermosphere near 200 km. These were obtained during a period of low solar activity, using AE-C and AE-D satellite observations.

[3] Difficulties in modeling the distribution of NO in the middle and upper thermosphere were explored by *Siskind and Rusch* [1992]. They found that modeled NO near 200 km was greater than observed by up to a factor of three. Full details of the discrepancy are provided in a companion paper [*Siskind et al.*, 2003] (hereinafter referred to as Paper 1). Here, we present new measurements of NO

up to 200 km using moderate-resolution UV dayglow spectra observed by the Ionospheric Spectroscopy and Atmospheric Chemistry (ISAAC) experiment. These data offer a new view of the nitric oxide distribution in the middle and upper thermosphere during a period of moderate to high solar activity (mean $F_{10.7} = 158$).

2. Data Analysis

2.1. Instrumentation

[4] The ISAAC instrument is a moderate resolution, ultraviolet limb imager designed to observe thermospheric N₂, O, O₂, and NO [*Wolfram et al.*, 1999]. It is based on a heritage of earlier designs from the NRL Space Science Division [*McCoy et al.*, 1994; *Cleary et al.*, 1995]. The instrument package consists of a 1/8 m off-axis telescope, a 1/8 m Ebert-Fastie spectrograph, and an image intensified photodetector.

[5] The spectrograph contains a movable diffraction grating mechanically ruled at 3600 lines/mm. The grating is operated in first order, and in combination with the entrance slit (75 μ m \times 2.52 mm) provides a theoretical spectral resolution of ~2.5 Å. The operational spectral resolution, determined from observations of atomic lines during the flight, is somewhat lower at about 3.8 Å. The overall spectral range of the spectrograph is 1800 to 3300 Å, which is divided into four overlapping passbands using a stepper motor and cam that typically fixes the grating reflection angle in one of four positions. The ISAAC detector system uses an ITT proximity-focused channel intensifier tube to convert ultraviolet photons to visible photons that are detected by a Hamamatsu MOS linear image sensor. This sensor is a linear array of 1024 photodiodes with pixel widths of 20 µm, providing an average dispersion of 0.42 Å per pixel. Further details of the ISAAC intensifier and sensor packages are given in Wolfram et al. [1999].

[6] The instrument is contained within the High Resolution Airglow and Aurora Spectroscopy (HIRAAS) payload that is on board the U.S. Air Force ARGOS (Advanced Research and Global Observing Satellite). ARGOS was launched on 23 February 1999, in a Sun-synchronous, near polar orbit with inclination angle of 98°, an altitude of 833 km, and an ascending node crossing at approximately 1430 LT. The HIRAAS platform performs limb scans in the antivelocity vector direction from 81 to 750 km tangent altitude. The duration of each top-to-bottom limb scan is approximately 100 s, consisting of about 100 spectra sampled about every 7 km.

2.2. Calibration

[7] ISAAC data for individual spectra are collected as photon counts per second per bin (C_{λ}) , which are converted to airglow intensity in photometric units of Raleigh/Å (I_{λ}) :

$$I_{\lambda} = \frac{C_{\lambda} - D}{R_{\lambda}} - S_{\lambda},\tag{1}$$

where *D* is a wavelength-independent offset that arises from the additive effects of stray light within the spectrometer and from a dark count, and S_{λ} is a background signal due to Rayleigh scattered sunlight. The responsivity, R_{λ} , is



Figure 1. Responsivity curve, R_{λ} , for ISAAC over the wavelength range covering passbands 1, 2, and 3. The initial calibration was performed in the laboratory prior to launch, and the curve shown here includes postlaunch adjustments described in the text.

determined from a preflight calibration with minor adjustments discussed below. Figure 1 shows the responsivity over the instrument passbands covering the 1900–2900 Å wavelength range. The calibration employed a NISTtraceable standard FEL lamp with the spectrometer and telescope in flight configuration. Wavelength calibration was accomplished using a platinum hollow cathode lamp and mercury lamp, with small, systematic corrections applied based on in-flight observations of atomic emission lines [*Wolfram et al.*, 1999].

[8] The response curve shown here has been corrected for O_2 absorption and Rayleigh scattering attenuation in the laboratory path length, and for the wavelength-dependent reflectivity of a BaSO₄ screen used in calibration. For O_2 , the laboratory optical path was accurately constrained using strong Schumann-Runge band features observed in passband 1. Cross sections were taken from *Minschwaner et al.* [1992]. A least squares spectral fit to the 4–0 to 1–0 bands yielded the O_2 optical path, which was then used to account for extinction by Rayleigh scattering and O_2 Herzberg continuum absorption in the 2000–2420 Å range. Within passband 2, the maximum correction was about 2% at 2200 Å. Adjustments for the reflecting screen varied from 5% at 2500 Å to 20% at 2200.

[9] The detector system displayed nonlinear behavior and saturation at very high count rates. Threshold levels for saturation were found typically near 24 kcount s⁻¹ (about 2 kRayleigh/Å). Nonlinear effects, where the observed count rate may underestimate the true signal, become evident above 16 kcount s⁻¹. This count rate is observed generally below about 90 km due to increasing brightness of the Rayleigh-scattered background, and at the peaks of the brightest NO γ bands below about 100 km. The nonlinear behavior is likely to be an inherent characteristic of the ITT image intensifier tube and not a condition that developed after launch. However, such high count rates were not anticipated prior to launch because the pointing range of the HIRAAS platform was originally intended to be higher up on the Earth's limb. Therefore the nonlinear response was not completely characterized in the laboratory.

[10] The nonlinear detector behavior is quantified here using peak count rates observed in NO γ band features that dominate the signal at the lowest tangent heights. We examined the relative magnitudes of peak intensities in the NO(0, 2), (0, 1), and (1, 4) γ bands at 81 km tangent altitude (with solar baseline counts subtracted), and compared these intensity ratios to values expected on the basis of calculated emission rate factors [*Stevens*, 1995]. In order to force agreement between the observed and theoretical intensity ratios, the count rate was divided by a scale factor, $f(C_{\lambda})$, given by

$$f(C_{\lambda}) = 0.89 + (3.19 \times 10^{-5})C_{\lambda} - (1.56 \times 10^{-9})C_{\lambda}^{2}, C_{\lambda} > 1.6 \times 10^{4}$$

= 1.0, $C_{\lambda} \le 1.6 \times 10^{4}$, (2)

where C_{λ} is the observed count rate. Values for the polynomial coefficients were found using a least squares fit between observed and theoretical intensity ratios. The method is patterned after dead-time adjustments applied to data obtained with photomultiplier tubes, and results in corrections varying from 0% at $C = 1.6 \times 10^4$ to 25% at $C = 2.4 \times 10^4$. Note that the derivation of $f(C_{\lambda})$ is independent of any assumptions of the absolute magnitude of NO γ band features, and depends only on the calculated, relative peak intensities. Uncertainties in $f(C_{\lambda})$ are estimated to be 5 to 10%, and result primarily from uncertainties in the calculated intensity ratios. The maximum impact on errors in the true count rate is therefore about 2.5% at 81 km.

2.3. Spectral Analysis and Profile Inversion

[11] The ISAAC spectral data were used to quantify NO $A^2\Sigma \rightarrow X^2\Pi \gamma$ band solar fluorescence during an 18 day period of observations in passband 2, between 30 November and 17 December 1999. Individual spectra were binned to a reference altitude grid with 7 km thick layers beginning at 81 km and extending up to 207 km. The tangent altitude for each limb spectrum was determined using pointing angles and satellite coordinates provided in the ARGOS geometry archives. However, there are known systematic offsets as well as possible random errors in these values. Two corrections were applied to better constrain tangent altitudes. First, nightglow emission for this period from the O2 Herzberg bands was used to apply a systematic offset to computed tangent altitudes. It has been well documented that the Herzberg emission is sharply peaked between 95 and 100 km altitude, with a half width of about 8 km [Siskind and Sharp, 1991; Melo et al., 1997]. This constrains the tangent altitude registration with an uncertainty of about ± 6 km. In addition, we applied a latitude-dependent correction for apparent errors in determining spacecraft pitch angle due to climatological variations in CO₂ emission height profiles used for horizon sensing (D. Drob, personal communication, 2002). These variations affect the horizon sensors by up to 5 km from equator to pole. Correcting for the CO₂ latitudinal gradient reduced the standard deviation of the observed Herzberg band intensity peaks by 2 km, so that the final tangent altitude registration has an estimated uncertainty of ±4 km.



Figure 2. (top) ISAAC measured radiances at 81 km tangent altitude (solid line). These have been corrected for stray light, detector nonlinearity, and instrument sensitivity. Arrows indicate two wavelengths used to determine the stray light level. Also shown are SOLSTICE solar irradiances (dotted line), scaled by λ^{-4} and normalized to match ISAAC at 2400 Å. (bottom) Difference between ISAAC and scaled SOLSTICE, along with synthetic spectra of NO (red line), N₂ V-K (green line), and the OII 2470 line (blue line). Most prominent NO γ bands are indicated with upper and lower vibrational levels. The total simulated emission is given by the black dotted curve. Data are a mean of three spectra obtained on 30 November 1990 at a mean latitude and longitude of 10°S, 83°E and a solar zenith angle of 38°.

[12] Figure 2 (top) shows a calibrated spectrum at the lowest tangent altitude along with scaled solar irradiances from SOLSTICE [*Rottman et al.*, 1993]. The solar spectrum has been spectrally degraded at 4 Å to match the effective resolution of ISAAC. In addition, the shape of the SOLSTICE spectrum was adjusted by a factor of λ^{-4} , normalized to 1 at 2400 Å, to account for the wavelength dependence of Rayleigh scattering. The ISAAC spectrum in Figure 2 is a mean of 3 individual measurements within the lowest altitude bin centered at 81 km. It can be seen that many of the spectral features in the ISAAC spectrum may be attributed to Fraunhofer lines in Rayleigh-scattered sunlight, provided that the stray light and sensitivity variations are properly taken into account.

[13] We use the solar Fraunhofer features to quantify the amount of stray light in each spectrum below 120 km. As discussed above, we use a wavelength-independent offset for the stray light magnitude, which can then be grouped together with a dark count correction. Their sum is represented by D in equation (1). The addition of any offset to the spectrum will tend to reduce the contrast (ratio of maximum to minimum intensity) in observed solar Fraunhofer lines. The spectral contrast effect is exploited using two wavelengths at 2286 and 2402 Å where the observed signals represent relative maxima and minima in solar intensity (Figure 2), and where there are no distinctive



Figure 3. Magnitude of stray light and dark count offset (*D*) at each altitude for all ISAAC measurements considered here (points) along with mean values (solid curve). The dashed curve represents the typical intensity from Rayleigh-scattered sunlight near 2400 Å. The dotted curve shows the typical signal counts averaged over the peak of the NO $\gamma(0, 1)$ band between 2360 and 2366 Å.

airglow features. If we let R_S be the ratio of SOLSTICE irradiances at these two wavelengths (scaled by λ^{-4} for scattering efficiency), then

$$R_{S} = \left(\frac{C_{2286} - D}{C_{2402} - D}\right) \left(\frac{R_{2402}}{R_{2286}}\right),\tag{3}$$

where the symbols *C* and *R* have the same meaning as in equation (1). Once *D* is determined using these intensity ratios, then the entire measured spectrum at each altitude is adjusted accordingly and a single scaling factor can be applied to the scaled SOLSTICE irradiances to match ISAAC at 2402 Å, which yields S_{λ} in equation (1).

[14] The magnitude of D is displayed as a function of altitude in Figure 3. This correction increases exponentially below 100 km, as might be expected given the rapid increase in brightness of visible and near-UV radiation at lower altitudes. Also shown in Figure 3 are the mean magnitudes of Rayleigh-scattered sunlight and the average NO $\gamma(0, 1)$ band emission signal at each altitude. As indicated, the stray light offset is typically 20-30% as large as the Rayleigh-scattered intensity at all altitudes below 130 km, but is comparatively much smaller than the peak signal from NO emission. The maximum stray light component of the NO signal is about 12% at 81 km, decreasing to less than 2% above 95 km. The amount of instrument stray light is highly dependent on properties of the diffraction grating and internal baffling of the spectrometer, and it is likely to contain spectral dependencies which cannot be fully characterized by the present analysis. Consequently, we expect that uncertainties in the stray light correction are relatively large, on the order of 50-100%. The maximum error introduced into calibrated radiances is therefore on the order 6-12% at the lowest tangent altitudes, and errors from stray light are negligible above 100 km.

[15] Figure 2 (bottom) displays the difference between the two upper spectra, which is the left-hand side of equation

Table 1. NO γ Band Integrated Emission Rate Factors^a

Temperature,	K (1, 1)	(0, 0)	(0, 1)	(1, 3)	(0, 2)	(1, 4)	(0, 3)
200	1.66	1.86	2.55	0.90	2.08	1.56	1.32
1000	1.62	1.93	2.65	0.88	2.17	1.53	1.38
8 1 1	10-6 1	-1					

^aUnits are 10⁻⁶ photons s⁻¹

(1) and is expected to contain atmospheric dayglow emissions. Also indicated are synthetic spectra for the NO γ bands, N₂ Vergard-Kaplan (V-K) bands, and OII 2470 Å transition. Prominent NO features within this passband are the (1, 1), (0, 0), (0, 1), (0, 2), and (1, 4) γ bands near 2240, 2260, 2360, 2470, and 2550 Å, respectively. These results are typical of all spectra at the lowest tangent altitudes, and they demonstrate that the effects of Rayleigh scattering and atmospheric emission are easily separated, and that the dominant NO γ band features can be used to quantify the line-of-sight column abundance of nitric oxide.

[16] The NO synthetic spectrum was computed using rotational line emission rate factors from Stevens [1995] at tangent altitude temperatures constrained by NRLMSISE-00 [Picone et al., 2002]. Table 1 lists the γ band integrated emission rate factors used for the synthetic spectrum; these are calculated using high-resolution solar irradiances of Hall and Anderson [1991] normalized to an irradiance measurement of SSBUV 5 in April 1993 obtained under relatively quiet solar conditions [Cebula et al., 1994; Stevens, 1997b]. The solar cycle variation at the wavelengths pumping these bands (2150-2260 Å) is only about 5% [Lean, 1991]. Note that normalization to other solar references spectra, such as SOLSTICE, may produce differences in emission rate factors varying from 3-5%. The V-K spectrum shown in Figure 2 is from the AURIC radiance code [Strickland et al., 1999], spectrally degraded to match ISAAC's 4 Å passband.

[17] Figure 4 shows an averaged spectrum obtained at 151 km tangent altitude. Here, effects of Rayleigh solar scattering



Figure 4. Same as Figure 2 but for an altitude of 151 km; solar irradiances are replaced by a linear fit in the top panel. The brightest NO γ band features are indicated along with Vergard-Kaplan bands (V-K) and the OII 2470 Å line.



Figure 5. Magnitude of the Rayleigh-scattered intensity at 2400 Å measured by ISAAC (solid curve) after calibrations described in the text, including a 22% decrease in overall sensitivity. Bars indicate the standard deviation of means at each altitude. The dashed line is a result of a single-scattering radiative transfer calculation using temperatures and densities from NRLMSISE-00.

and instrument stray light are negligible. We adopt a constant dark count offset of 100 counts s⁻¹ above 120 km tangent height. This offset may not completely account for the background intensity, as indicated in Figure 4, and a linear fit to mean intensities at 2330, 2419, and 2522 Å is adopted to remove the background. Comparison of Figures 2 and 4 shows that the effect of N₂ V-K and OII 2470 emissions are more pronounced relative to the NO γ bands, as expected for increasing altitudes [*Cleary et al.*, 1995].

[18] In addition to the calibrations described above, an adjustment has been applied based on strong indications that the sensitivity of ISAAC changed following the preflight calibration. Exposure to high intensity levels observed at the lowest tangent heights resulted in a "burn in" period during which the detector experienced a decrease in sensitivity. This change most likely occurred in the efficiency of the ITT image intensifier tube and not in the linear photodiode array. Preliminary analyses of stellar calibrations [*Budzien et al.*, 1999] indicate that the sensitivity change occurred during the first few months of the mission, and the present analysis shows no evidence of continuing changes in sensitivity during the time period examined here.

[19] The change in ISAAC sensitivity was quantified through comparison between observed and modeled Rayleigh-scattered intensities. A wavelength-independent degradation of 22% in sensitivity provides the optimum, weighted least squares agreement between observed and modeled Rayleigh-scattered intensities. Figure 5 shows the intensity of scattered radiation at 2400 Å for the three lowest altitude bins along with radiative transfer calculations based on SOLSTICE solar irradiances and Rayleigh single scattering. The observed vertical profile of scattering falls off more slowly than expected, an effect that is not well understood but may be related to errors in constraining the stray light. At the lowest altitudes, the inferred Rayleighscattered intensity is more uncertain due to stray light and nonlinear effects; conversely, at 95 km the inferred Rayleigh intensity is sufficiently low to be affected by background noise. Confidence in the 88 km measurement of Rayleigh scattering is highest, and this is precisely where the model and measurements show the best agreement. Given the range of geophysical variability in density-altitude surfaces and temperature, the variation in scattering angles used to construct the observed mean, and the level of uncertainty in tangent altitudes, we conclude that the estimated decrease in sensitivity could range between about 10 and 35%. This level of uncertainty is consistent with the fit and standard deviations indicated in Figure 5.

[20] Slant column abundances of NO are determined using the integrated intensity of the $\gamma(0, 1)$ band, similar to the analysis presented in Paper 1. However, unlike the rocket data discussed in Paper 1, the ISAAC data are of sufficient spectral resolution to allow the (0, 1) band to be completely separated from the neighboring V-K bands. The NO(0, 1) band is virtually unaffected by self-absorption since the lower electronic state involves the $\nu = 1$ level. We restrict the integration over wavelength to the interval 2355-2375 Å in order to avoid interference from the V-K(0, 3) and (1, 4) bands near 2330 and 2380 Å, respectively (see Figure 4). This NO column abundance is used to determine the NO synthetic spectrum over the complete spectral range from 2200 to 2600 Å; the V-K bands and OII atomic lines are then fit to the residual using a least squares method.

[21] The random uncertainty in the NO column is calculated from the error in the spectral fit over the $\gamma(0, 1)$ band, which varies typically between 5 and 10%. The largest source of error arises from the systematic uncertainty in calibration, which is ~30% below 100 km due to the combined errors in stray light, nonlinear behavior, and detector sensitivity. Above 100 km, the calibration error is about 15%. The uncertainty in the adopted emission rate factor is 7%, determined from a root sum square of the uncertainty in oscillator strength, branching ratio, and solar irradiance [*Stevens et al.*, 1997a]. The overall, 1 σ uncertainty in each ISAAC measurement of NO slant column abundance is thus between about 20 and 35%.

[22] The vertical profile of NO density is derived from the set of contiguous slant column abundances measured at each mean tangent height in 7 km steps from 81 to 207 km. Each slant column is assumed to be the integration of spherically symmetric shells of uniform thickness, density, and temperature; retrieval of NO concentrations is a straightforward matter of matrix inversion applied to a set of known geometric elements and emission rate factors [McCoy, 1983a]. The NO slant column amounts are smoothed in altitude using a weighted, 3 pt logarithmic filter prior to inversion. The effect of vertical bin averaging and smoothing of the (0, 1) band radiances leads to an approximate triangular averaging function with a full width at half maximum of 14 km.

3. Results

[23] Three vertical profiles of the nitric oxide density measured by ISAAC are shown in Figure 6. These were obtained on 15 December 1999, within a latitude/longitude



Figure 6. Comparison of ISAAC nitric oxide vertical profiles (triangles) with nearly coincident measurements from HALOE (solid curves) and SNOE (dashed curves) on 15 December 1999 near 22°S latitude [*Gordley et al.*, 1996; *Barth et al.*, 2003]. Error bars for ISAAC NO are the 1σ uncertainties for each measurement. Uncertainties in HALOE average about 20% in the 100–110 km altitude range. Both SNOE and HALOE profiles have been smoothed to match the altitude resolution of ISAAC.

range of 18°-22°S, 53°-100°W, at a local solar zenith angle of 35°. Figure 6 also shows three profiles measured by the Halogen Occultation Experiment (HALOE, version 19) on board the Upper Atmospheric Research Satellite [Russell et al., 1993]. The HALOE profiles were obtained at sunset on the same date, near 22°S and between 12 and 60°W longitude. A set of six NO profiles measured by the Student Nitric Oxide Explorer (SNOE) are also displayed [Barth et al., 2003]. The SNOE data are from the same date, at 20° and 25°S latitude, and between 35° and 60°W longitude. All profiles shown in Figure 6 are therefore within $\pm 4^{\circ}$ in latitude and on the same day. The SNOE data were collected near 1100 LT and ISAAC around 1400 LT; over this 3 hour period NO diurnal variations are expected to be small [McCoy, 1983b] and are not considered in this measurement comparison.

[24] Agreement between ISAAC, HALOE, and SNOE is generally good, and is within the combined measurement uncertainties between 95 and 130 km. The ISAAC profiles indicate slightly less NO (~30%) than HALOE and SNOE at the density maximum near 110 km. Part of the discrepancy with SNOE is likely a result of the smaller (0, 1) band integrated emission rate factor used in the SNOE inversion $(2.25 \times 10^6 \text{ ph s}^{-1} \text{ molecule}^{-1})$ compared to the value implied by the analysis of *Stevens* [1995] which is used in the ISAAC inversion $(2.55-2.65 \times 10^6 \text{ ph s}^{-1} \text{ molecule}^{-1})$ between 200–1000 K). Taken alone, this difference translates to a systematic, 13% smaller NO abundance for ISAAC as compared to SNOE; adjusting for this difference would yield even better agreement between the two data sets above 105 km.

[25] As discussed in Paper 1, current understanding of NO chemistry in the middle and upper thermosphere (140–200 km) involves a relatively small set of reactions. In

particular, at temperatures near 1000K the dominant production and loss reactions for NO both proceed through N(⁴S) such that the steady state concentration of NO is linearly proportional to the density of O₂. Figure 7 shows the mean NO vertical profile for all measurements between 25° and 35°N latitude. Solar zenith angles ranged between 50° to 60°. Also plotted are two calculated profiles using the NOX1DIM photochemical model [Paper 1] for 30°N and mean solar and geomagnetic conditions of the ISAAC observations (F_{10.7} = 158, A_p = 12). The model calculations employed a solar soft X-ray flux (11–50 Å) using a scaling factor of 27 on the *Hinteregger et al.* [1981] solar minimum reference spectrum, which is consistent with the scaling with respect to F_{10.7} of *Bailey et al.* [2000].

[26] The two model profiles in Figure 7 differ only in the input parameters of temperature and neutral atmosphere: one uses the 1990 Mass Spectrometer and Incoherent Scatter (MSIS90) empirical model, and the other uses an updated version of this code, NRLMSISE-00 [Picone et al., 2002]. One of the major revisions in the NRLMSISE-00 model is a reduction, at moderate to high levels of solar activity, in the O₂ density in the middle and upper thermosphere, which leads to lower calculated NO by nearly a factor of two. In agreement with the findings of Paper 1, the comparison in Figure 7 clearly favors the reduced NO densities implied by the updated NRLMSISE-00 model above 130 km. In the lowermost thermosphere, both calculations appear to systematically underestimate the observed NO, although the uncertainty in the data does increase sharply below 100 km. In addition, the increasingly long time constant for NO photochemistry in this region (~days) becomes comparable to timescales for vertical and horizontal transport, which may require a more rigorous treatment than can be provided by a 1-D model.

[27] Figure 8 shows the latitude-altitude NO distribution compiled from 1,115 vertical profiles that were retrieved



Figure 7. Mean of 60 NO profiles measured by ISAAC between 25° and 35° latitude (solid curve). Error bars represent the standard deviation of the mean, indicating the range of geophysical variability in this zonal mean. Also plotted are calculated NO profiles using the NOX1DIM model, constrained by MSIS90 (dashed curve) and NRLMSISE-00 (solid curve) temperatures and neutral densities.

during the 18 day period between 30 November and 17 December 1999. Solar zenith angles of the selected profiles are restricted to values less than 70° in order to avoid twilight effects and changes in NO along the line of sight at the terminator. Latitudes ranged from about 65°S to 40°N. This zonal mean summary of measurements shows a distribution similar to previous climatologies based on SME and HALOE data [e.g., Siskind et al., 1998]. There is a maximum in the high-latitude summer hemisphere near 110 km, with lower peak densities in the winter hemisphere. The sloping of NO isopleths in Figure 8 becomes more pronounced in the middle and upper thermosphere. Near 200 km, the NO density is 60-70% larger at 50°S as compared to 30°N. This difference is consistent with a 30-40% increase in O₂ density and a 90-110 K temperature increase from 50°S to 30°N predicted by NRLMSISE-00. The higher O_2 densities and temperatures at 50°S both contribute to a faster rate for NO production via $N(^{4}S)$ oxidation (e.g., equation (1) of Paper 1).

[28] The ISAAC data also contain evidence for short term variations in lower-thermospheric nitric oxide which are likely related to solar variability, particularly in the flux of solar soft X rays [Barth et al., 1988; Siskind et al., 1995]. The source of NO from photoelectrons produced by soft X rays ($\lambda < 50$ Å) is expected to play a major role in NO production near the equatorial regions [Barth et al., 2003] where the source from auroral electrons is negligible. Figure 9 shows daily mean ISAAC nitric oxide at 95, 109, and 123 km altitude between 20°S and 20°N latitude, as a function of daily mean solar X-ray flux from SNOE [Bailey et al., 2000]. As indicated in Figure 9, we find the best linear correlation and largest slope near the NO peak density at 109 km, consistent with a maximum in the absorption of 20-70 Å solar flux between 105 and 110 km. Computed slopes are 2.93(±0.53), 5.52(±0.54), and 2.66(± 0.32) (10⁷ NO cm⁻³) per (mW m⁻² soft X-ray flux) at 95, 109, and 123 km, respectively. The slope at 109 km is somewhat smaller than the value of 7.2 at 113 km reported by Barth et al. [2003], based on the same X-ray data and SNOE nitric oxide results. However, the SNOE data cover a much larger number of days (384) and



Figure 8. Zonal mean distribution of NO observed between 30 November and 17 December 1999 for solar zenith angles less than 70° . Units are 10^{7} cm⁻³.



Figure 9. Daily mean NO concentrations between $\pm 20^{\circ}$ latitude at altitudes of (top) 123, (middle) 109, and (bottom) 95 km plotted versus daily mean solar soft X-ray flux (20–70 Å) measured by SNOE [*Bailey et al.*, 2000]. Solid lines indicate linear least squares fits, with correlation coefficients of 0.90 at 123 km, 0.93 at 109 km, and 0.80 at 95 km.

a broader range of X-ray flux than applies to the ISAAC data considered in this paper. In addition, more than half of the difference in slopes at 109 km (23% smaller for ISAAC as compared to SNOE) may be attributed to the 13% difference in adopted value for the (0, 1) band emission rate factor discussed above.

4. Conclusion

[29] We have used ultraviolet dayglow spectra from the ISAAC instrument to retrieve the distribution of nitric oxide from the upper mesosphere to the upper thermosphere. This analysis included calibration of the overall instrument sensitivity and corrections for nonlinear effects, stray light, pointing, and Rayleigh scattered background below 110 km. We compared NO vertical profiles from ISAAC, SNOE, and HALOE, and found good agreement to within the expected retrieval errors. The ISAAC NO densities provide tight constraints on the profile of O_2 in the middle to upper thermosphere; our results favor the lower O₂ densities in the updated NRLMSISE-00 model as compared to MSIS90. The observed NO distribution shows latitudinal gradients that reflect variations in thermospheric temperature and O_2 densities. In the equatorial lower thermosphere, the measured NO density appears to respond to daily variations in the flux of solar soft X rays observed by the SNOE instrument. Further work may permit additional NO retrievals from ISAAC during more active solar conditions in 2000, as well as studies of the concurrent observations of N2 V-K and OII 2470 Å emissions.

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