The natural thermostat of nitric oxide emission at 5.3 μm in the thermosphere observed during the solar storms of April 2002

Marty Mlynczak,[1] F. Javier Martin-Torres,[2] James Russell,[3] Ken Beaumont,[4] Steven Jacobson,[4] Janet Kozyra,[5] Manuel Lopez-Puertas,[6] Bernd Funke,[6] Christopher Mertens,[1] Larry Gordley,[4] Richard Picard,[7] Jeremy Winick,[7] Peter Wintersteiner,[8] and Larry Paxton[9]

Received 6 May 2003; revised 19 July 2003; accepted 3 October 2003; published 7 November 2003.

[1] The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) experiment on the Thermosphere-Ionosphere Mesosphere Energetics and Dynamics (TIMED) satellite observed the infrared radiative response of the thermosphere to the solar storm events of April 2002. Large radiance enhancements were observed at 5.3 μm, which are due to emission from the vibration-rotation bands of nitric oxide (NO). The emission by NO is indicative of the conversion of solar energy to infrared radiation within the atmosphere and represents a "natural thermostat" by which heat and energy are efficiently lost from the thermosphere to space and to the lower atmosphere. We describe the SABER observations at 5.3 μm and their interpretation in terms of energy loss. The infrared enhancements remain only for a few days, indicating that such perturbations to the thermospheric state, while dramatic, are short-lived. *INDEX TERMS:* 0310 Atmospheric Composition and Structure: Airglow and aurora; 0358 Atmospheric Composition and Structure: Thermosphere—energy deposition; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3369 Meteorology and Atmospheric Dynamics: Thermospheric dynamics (0358). **Citation:** Mlynczak, M., et al., The natural thermostat of nitric oxide emission at 5.3 μm in the thermosphere observed during the solar storms of April 2002, *Geophys. Res. Lett.*, *30*(21), 2100, doi:10.1029/2003GL017693, 2003.

1. Introduction

[2] The TIMED satellite was launched on December 7 2001 into a 74 degree inclined orbit carrying four instruments designed to study the relatively unobserved atmosphere between 60 and 180 km in altitude. The SABER instrument [*Russell et al.*, 1999] on the TIMED satellite is a broadband radiometer that measures spectrally integrated infrared radiance in 10 bands between 1.27 and 15 μm as it scans the limb from the surface of the Earth to approximately 350 km. These measurements will be used to derive the radiative and chemical components of the energy budget of the mesosphere and thermosphere [*Mlynczak*, 1995; 1997].

[3] In mid-April 2002 a series of coronal mass ejections and solar flares occurred. From April 15–21 2002, an active solar region underwent three eruptions as it traversed the solar disk. The first two of these eruptions on April 15 and April 17 created fast coronal mass ejections (CMEs) driving shocks toward the Earth along with energetic solar particles accelerated at the shocks. When the CME perturbations arrived on April 17, 2002, and April 19, 2002, they drove moderate double-peaked magnetic storms, the first peak in each case due to the impact of the shock/sheath preceding the CME and the second peak due to the passage of the CME itself. The energetic solar particles entered the polar cap on April 17 and 19 as the shocks impacted the magnetosphere. The magnetic storm activity reached its maximum severity on April 20 between 06:00–07:00 UT. The third eruption of the solar active region on April 21 was closely associated with a large flare observed by the GOES satellite and began at 00:43 UT, reached a maximum by 01:51 UT, and ended at 02:38 UT. The CME from this eruption was traveling at very high velocity but not directed at the Earth. A long-duration solar particle event also observed by GOES began at Earth shortly after the flare at 01:55 UT, reached a maximum at 10:25 UT and ended at 23:34 UT on April 22. The flare and solar particle event occurred during a period of relatively low magnetic activity. This implies that the impacts of the magnetic storms and of the solar particle event on the NO emission may be separable due to their spacing in time.

[4] The energy from these solar events arrived at the Earth and was deposited into the upper atmosphere, causing large changes in temperature, density, and composition. These events perturbed the neutral thermosphere and upper mesosphere, the ionosphere, and the magnetosphere. SABER observed enhancements in infrared limb emission in a number of its channels. Figure 1 shows the zonal mean limb radiance profile in a 5-degree latitude bin centered at 82 S observed by SABER at 5.3 μm on April 15 before the onset of the storm and on April 18 during the storm. Thirty radiance profiles are used to generate each zonal mean profile. The radiance noise limit of the instrument (1.2×10^{-6} W m^{-2} sr^{-1}), divided by $\sqrt{30}$, is also indicated. Two features stand out. First, the 5.3 μm limb radiance increases by a factor of 5 to 7 during the storm time, and second, the altitude range over which radiance is recorded increases by nearly 45 km. NO

[1]NASA Langley Research Center, Hampton, Virginia, USA.
[2]Analytical Services and Materials Inc., Hampton, Virginia, USA.
[3]Hampton University, Hampton, Virginia, USA.
[4]G and A Technical Software, Newport News, Virginia, USA.
[5]University of Michigan, Ann Arbor, Michigan, USA.
[6]Instituto de Astrofisica de Andalucia, Granada, Spain.
[7]Air Force Research Laboratory, Hanscom AFB, Massachusetts, USA.
[8]ARCON Corporation, Waltham, Massachusetts, USA.
[9]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.

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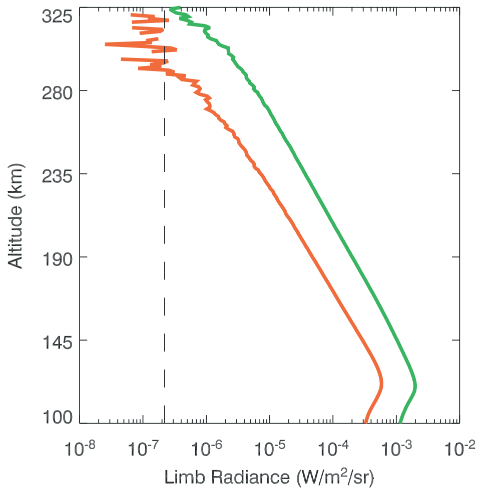

Figure 1. SABER zonal mean limb radiance profiles near 82 S on April 15 (red line) and April 18 2002 (green line), before and during the solar storm, respectively. The vertical dashed line represents the zonal mean noise level.

emission at 5.3 μm is one of the two primary emissions responsible for cooling the thermosphere [*Kockarts*, 1980], the other being emission from the fine structure lines of atomic oxygen at 63 μm. The large increase in limb radiance at 5.3 μm observed by SABER implies a comparable increase in energy loss by the atmosphere during this time, which we will now evaluate.

2. Analysis of the NO 5.3 μm Emission

2.1. Generation of 5.3 μm Radiation by NO

[5] NO is a diatomic molecule that possesses a fundamental vibration frequency of 1876 cm^{-1} (0.233 eV). Its binding energy is approximately 6.56 eV (52840 cm^{-1}) implying over 28 bound vibrational levels in the ground electronic state. The primary excitation mechanism of NO vibrations under quiescent conditions is via inelastic collisions with atomic oxygen [O]. These collisions rapidly facilitate the conversion of particle kinetic energy into internal vibrational energy of the NO molecule. This internal energy generated by collisions is either radiated by spontaneous emission from NO, resulting in a cooling of the atmosphere, or it is physically quenched back into the thermal field, resulting in no net change in kinetic temperature. Nitric oxide vibrations may also be excited through impact of particles other than O (such as electrons) but collisions with N_2 and O_2 are not efficient at populating NO vibrational levels.

[6] Nitric oxide is formed in the thermosphere by the exothermic reactions [*Sharma et al.*, 1998]:

$$N(^4S) + O_2 \rightarrow NO + O \quad \text{(R1)}$$

$$N(^2D) + O_2 \rightarrow NO + O \quad \text{(R2)}$$

Reaction (1) is exothermic by 1.4 eV, potentially populating as many as 6 vibrational quanta, and reaction (2) is exothermic by 3.76 eV, potentially populating up to $\upsilon = 16$. None of the bound electronic states of the NO molecule are accessible via these reactions, implying that only vibrational and rotational excitation within the ground electronic state of NO may occur.

[7] All of these processes mentioned above may be present during the solar storm period, in addition to sharply increased atmospheric heating [e.g., J. Thayer and J. Semeter, The convergence of magnetic energy flux in the polar atmosphere, submitted to *Journal of Atmospheric and Solar-Terrestrial Physics*, 2003]. We may summarize the processes that give rise to a change in the amount of radiation emitted by the NO molecule: 1) An increase in the NO abundance, leading to more vibrationally excited NO via collisions with O; 2) An increase in the kinetic temperature, which governs the rate of collisional excitation of NO via detailed balance with collisional quenching. A higher kinetic temperature means more excited NO molecules all else being equal; 3) Exothermic production of vibrational levels of NO, which almost certainly is occurring during the solar storm event; and 4) increase in the atomic oxygen abundance. As is discussed below, the interpretation of the SABER limb radiances in terms of energy loss from the thermosphere is largely independent of the process by which the radiation is generated. We use SABER as a "trap" in which to capture photons emitted from the atmosphere so that we may interpret the results in terms of the energetics of the atmosphere.

2.2. Description and Analysis of the Saber 5.3 μm Observations

[8] At the time of the solar storm the SABER instrument was observing local times roughly 2 hours past local sunset. The time required for SABER to record an individual limb scan is about 52 seconds, implying that each radiance profile is recorded as the satellite travels a distance of about 350 km, or ~3 deg of latitude. The instrument records about 2000 radiance profiles per day as it continuously scans the limb. The 5% relative transmission bandpass points of the SABER 5.3 μm channel are 1865 cm^{-1} to 1945 cm^{-1} (5.362 μm to 5.141 μm). Based on the HITRAN 2000 spectroscopic database [*Rothman et al.*, 2003] SABER observes radiation from the 1-0 fundamental vibration-rotation band of NO, the 2-1 first hot band, and the 3-2 second hot band. At the HITRAN reference temperature of 296 K approximately 60%, 48%, and 15% of the 1-0, 2-1, and 3-2 bands respectively are within the SABER bandpass. As will be discussed in detail below the fraction of the bands within the SABER bandpass changes significantly with altitude in the thermosphere. The effect is that the relative amount that each band contributes to the SABER radiance varies with altitude because of the large change in kinetic temperature with altitude in the thermosphere.

[9] In order to interpret the SABER radiance data in terms of energy loss we must first derive the vertical profile of energy loss rate per unit volume from the limb radiance, accounting for the radiation emitted by NO both inside and outside of the spectral bandpass of the instrument. The full details of this procedure will be given in a future publication and are summarized here briefly. The major assumption in the analysis is that the atmospheric emission in the limb view is in the weak line radiative transfer limit, allowing us to apply an Abel inversion [e.g., *Hays and Roble*, 1973] to the measured radiance profiles. This process yields a

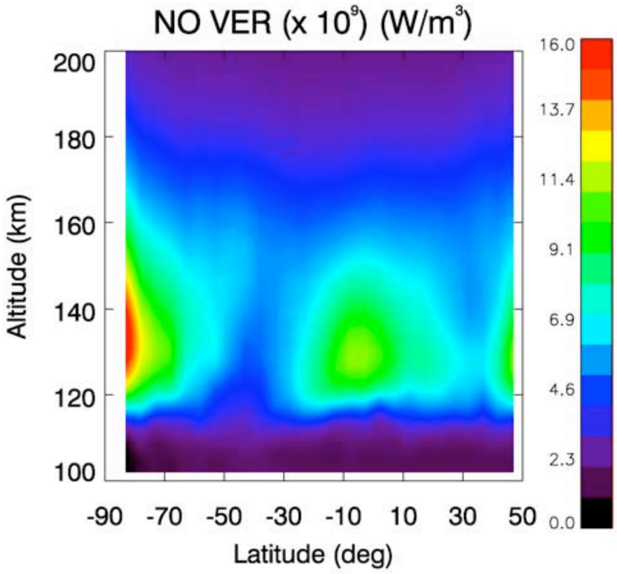

Figure 2. The zonal mean volume emission rate (VER, W/m^3) at 5.3 μm from NO on April 15 prior to the onset of the solar storm.

vertical emission rate profile, i.e., the rate of emission of energy per unit volume per unit time per unit solid angle, as weighted by the spectral bandpass of the instrument. The volume emission rate (VER) over all solid angles is then obtained by multiplying by 4π. To account for the limited spectral bandpass, we multiply the retrieved VER profile by an ''unfilter'' factor U(z) that is the ratio of total energy radiated by the NO molecule to the energy radiated by the NO molecule weighted by the SABER spectral response function. The factor U(z) is pre-calculated over a range of geophysical conditions and altitudes z and ranges in value from 2.5 near 120 km to 3.9 at 200 km during storm conditions. The factors increase with altitude (implying increasingly more energy outside of the SABER 5.3 μm bandpass with altitude) due to the increase in kinetic temperature with altitude throughout the thermosphere, which results in the population of higher rotational states of NO that lay outside of the SABER bandpass. The vibrational temperature model of *Funke and Lopez-Puertas* [2000] is used in the computation of U(z). Our approach in analyzing the data during the solar storm period is to compute the unfilter factor U(z) based on an MSISE reference atmosphere for high solar activity which is reflected by high thermospheric temperatures.

[10] The complex nature of the thermospheric emission of radiation by NO has been studied in detail by *Dothe et al.* [2002], *Sharma et al.*, [1998], and *Sharma and Duff* [1997]. The results presented in these papers indicate the existence of significant vibrational and rotational excitation of the high-lying hot bands of NO and of the occurrence of sub-thermal rotational temperatures in the fundamental band of NO. As the emission from NO occurs primarily from the v = 1, 2, and 3 states, we do not include at this time emission from higher-lying states which constitute a small fraction of the total radiance below 200 km. The assumption that the rotational states are thermalized will likely result in an overestimate of the total band energy loss profiles and integrated fluxes, which will compensate to some extent for the neglect of the high-lying hot bands. We conservatively estimate that the energy loss rates and the fluxes shown below are accurate to ~20%. The illustrated temporal and spatial variability of the NO emission is not affected by these issues, which will be addressed in more detail in subsequent papers.

2.3. Energy Loss from the Thermosphere due to Radiative Emission at 5.3 μm

[11] The process of inverting and unfiltering the measured SABER limb radiance profiles as described above yields vertical profiles of energy loss per unit time per unit volume. During the period of the solar storms of April 2002 the SABER instrument was observing in its ''southward'' mode due to its position on the TIMED spacecraft. It observes the latitude range from 54°N to 83°S. The days of interest span from approximately 3 days before the commencement of the storm at the Earth (April 15) to April 26 when the thermosphere was particularly quiet at 5.3 μm and the storm effects had dissipated. Figures 2 and 3 show the zonally averaged energy loss rates (W m^{-3}) from 80°S to 50°N between 100 and 200 km, for April 15 and April 18 2003. Note the change in scale between the two figures. The large increases in the radiative emission rate are evident in these figures as is the dynamical response of the thermosphere. In particular, strong downwelling in the tropical middle thermosphere is suggested in Figure 3, as would be expected from continuity, in response to the large heating and vertical expansion of the polar thermosphere from the storm.

[12] We will now compute the flux (W m^{-2}) of 5.3 μm radiation out of the thermosphere. To obtain the radiated flux of energy we vertically integrate the profiles of energy loss derived as described above. All 5.3 μm radiation emitted by NO exits the thermosphere [*Mlynczak*, 2002]. Figures 4 and 5 show the radiated fluxes of energy (W m^{-2}) over the southern and northern hemispheres,

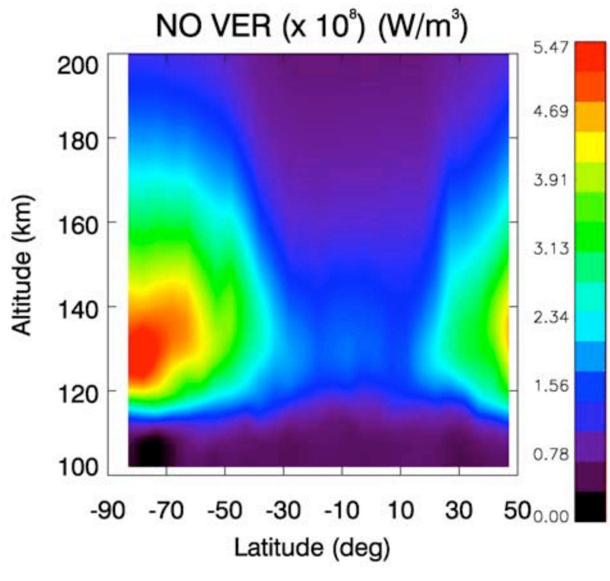

Figure 3. The zonal mean volume emission rate (VER, W/m^3) at 5.3 μm from NO on April 18 during the solar storm. Note the change of scale from Figure 2.

respectively, from April 16 through April 24 obtained by integrating the energy loss profiles from 100 km to 275 km. The dark circle poleward of 54 N indicates the absence of SABER data at these latitudes owing to its view direction during this time period. The fluxes range in value from 0 to 2.5 $\times$ 10^{-3} W m^{-2}. These data clearly show the global extent of the storm effects in the thermosphere. The maximum fluxes are radiated on April 20 (Day 110 of 2002) with local maxima over the Tasman Sea between Australia and New Zealand and in the tropical Pacific between the continental United States and Hawaii. The peak in radiated fluxes corresponds to the maximum in magnetic storm activity rather than the maximum in the solar particle event that follows the magnetic activity by more than a day. The pattern of radiative flux is shifted off from the geographic pole in the southern hemisphere because of the displacement of the geomagnetic pole from the geographic pole. In both hemispheres radiative enhancements during the storm are observed to occur all the way to the Equator.

3. Discussion and Summary

[13] We have shown that the terrestrial thermosphere shows an exceptional response in terms of greatly enhanced emission of radiation at 5.3 μm during the solar storms of April 2002. The storm energy is input to the upper atmosphere in the form of particle kinetic energy and radiative fluxes from the Sun. This energy is converted to heat and also changes the distribution of chemical potential energy within the thermosphere. In turn, these processes alter the distribution of nitric oxide and its radiative properties. The radiation from NO either cools the atmosphere if it originated as kinetic energy of atmospheric species or lowers the amount of energy available for heat if it originates as chemical potential energy. As seen in Figures 4 and 5, the perturbations in NO radiative fluxes die out after 3 days from the time of maximum emission (which occurs near the maximum in magnetic storm activity). This process is a "natural thermostat" allowing large perturbations of energy to damp out by infrared radiation in a relatively short time period. Future studies with these data will include global radiated power calculations that require consideration of the variation of NO emission over the course of the day, estimation of radiation emitted by high-lying hot bands of NO not sensed by the SABER instrument, and comparison with energy inputs from the Sun by which the efficiency of the radiation at damping out the storm effects can be assessed. These and other studies are underway to assess energy balance in the Sun-Earth system during the solar storms of April 2002 and will be reported in much greater detail in subsequent publications.

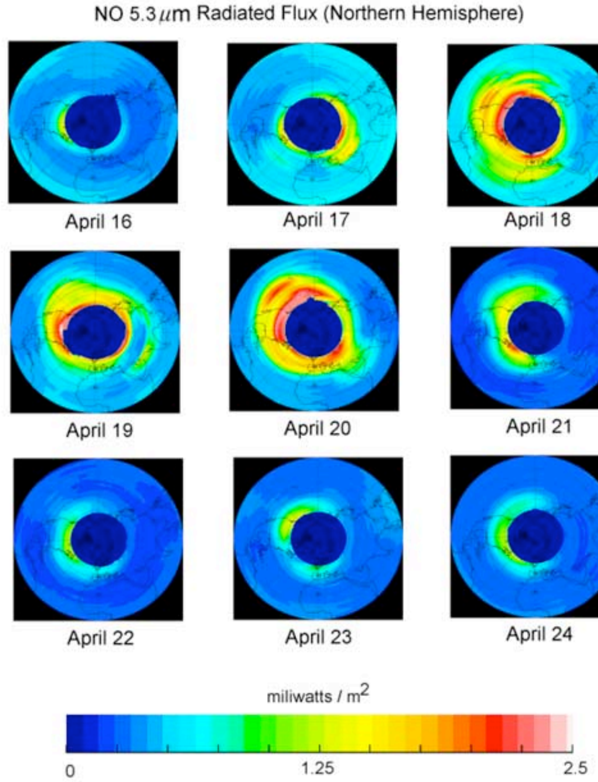

Figure 5. NO radiative fluxes (W/m^2), northern hemisphere, 16–24 April 2002.

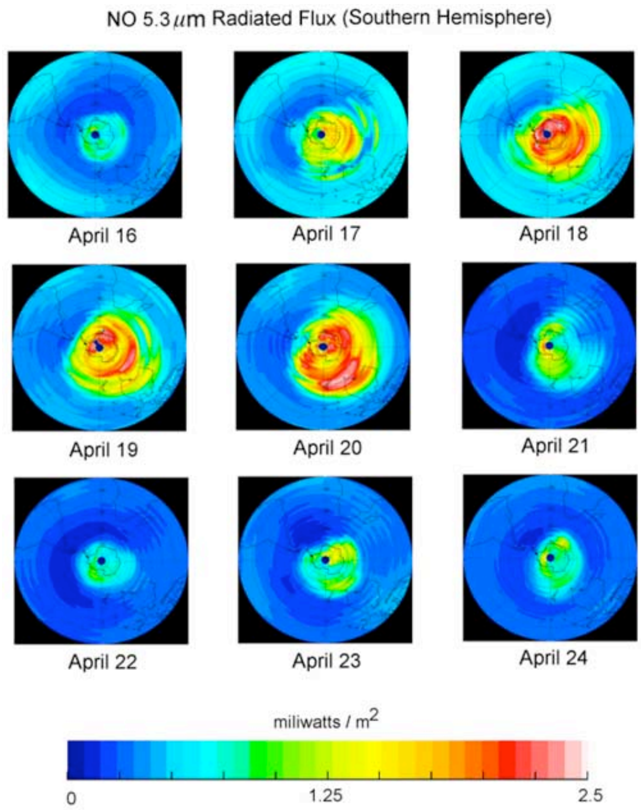

Figure 4. NO radiative fluxes (W/m^2), southern hemisphere, 16–24 April 2002.

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M. G. Mlynczak and C. Mertens, NASA Langley Research Center, Mail Stop 420, Hampton, VA 23681-2199, USA. (m.g.mlynczak@nasa.gov)
F. J. Martin-Torres, Analytical Services and Materials Inc., Hampton, VA, USA.
J. Russell, Hampton University, Hampton, VA, USA.
K. Beaumont, S. Jacobson, and L. Gordley, G and A Technical Software, Newport News, VA, USA.
J. Kozyra, University of Michigan, Ann Arbor, MI, USA.
M. Lopez-Puertas and B. Funke, Instituto de Astrofisica de Andalucia, Granada, Spain.
R. Picard and J. Winick, Air Force Research Laboratory, Hanscom AFB, MA, USA.
P. Wintersteiner, ARCON Corporation, Waltham, MA, USA.
L. Paxton, Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA.