AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL064038

Key Points:

- $F_{10.7}$, *Ap*, and *Dst* replicate time series of radiative cooling by nitric oxide
- Quantified relative roles of solar irradiance, geomagnetism in radiative cooling
- Establish a new index and extend record of thermospheric cooling back 70 years

Correspondence to:
M. G. Mlynczak,
m.g.mlynczak@nasa.gov

Citation:
Mlynczak, M. G., L. A. Hunt, B. T. Marshall, J. M. Russell III, C. J. Mertens, R. E. Thompson, and L. L. Gordley (2015), A combined solar and geomagnetic index for thermospheric climate, *Geophys. Res. Lett.*, *42*, doi:10.1002/2015GL064038.

Received 31 MAR 2015
Accepted 27 APR 2015
Accepted article online 29 APR 2015

A combined solar and geomagnetic index for thermospheric climate

Martin G. Mlynczak[1], Linda A. Hunt[2], B. Thomas Marshall[3], James M. Russell III[4], Christopher J. Mertens[1], R. Earl Thompson[3], and Larry L. Gordley[3]

[1]NASA Langley Research Center, Hampton, Virginia, USA, [2]SSAI, Hampton, Virginia, USA, [3]GATS, Newport News, Virginia, USA, [4]Center of Atmospheric Science, Hampton University, Hampton, Virginia, USA

Abstract Infrared radiation from nitric oxide (NO) at 5.3 µm is a primary mechanism by which the thermosphere cools to space. The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite has been measuring thermospheric cooling by NO for over 13 years. In this letter we show that the SABER time series of globally integrated infrared power (watts) radiated by NO can be replicated accurately by a multiple linear regression fit using the $F_{10.7}$, *Ap*, and *Dst* indices. This allows reconstruction of the NO power time series back nearly 70 years with extant databases of these indices. The relative roles of solar ultraviolet and geomagnetic processes in determining the NO cooling are derived and shown to vary significantly over the solar cycle. The NO power is a fundamental integral constraint on the thermospheric climate, and the time series presented here can be used to test upper atmosphere models over seven different solar cycles.

1. Introduction

The climate of the thermosphere is controlled in part by cooling to space driven by infrared radiation from carbon dioxide (CO_2, 15 µm), nitric oxide (NO, 5.3 µm), and atomic oxygen (O, 63 µm). The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument [*Russell et al.*, 1999] on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite has been measuring infrared cooling from CO_2 and NO in the thermosphere since January 2002 [*Mlynczak et al.*, 2014]. These data provide integral constraints on the energy budget and climate of the atmosphere above 100 km.

In this paper we examine the causes of variability of the infrared cooling by nitric oxide. Physically, changes in NO emission are due to changes in temperature, atomic oxygen, and the NO density. These physical changes, however, are driven by changes in solar irradiance and changes in geomagnetic conditions. We will show that the 13 year time series of NO cooling derived from SABER can be accurately fit with a multiple linear regression using standard solar and geomagnetic indices. This fit enables several fundamental properties of the NO cooling to be determined, including the relative importance of solar ultraviolet irradiance and geomagnetic conditions and their variability with time. In addition, the time series of solar and geomagnetic indices extends back to 1947, allowing a reconstruction of thermospheric cooling by NO back in time nearly 70 years. This reconstruction then provides a long-term time series of an integral radiative constraint on thermospheric climate that can be used to test climate models. The test can be done in two ways: First, validating the overall NO radiative cooling time series, and second, validating the relative roles of solar and geomagnetic effects in determining the total cooling over time over seven very different solar cycles. Previously, *Lu et al.* [2010] showed a high correlation coefficient (0.89) between $F_{10.7}$, the *Kp* index, and the daily global NO power for 7 years of SABER data. This paper extends that work to short- and long-term climate timescales at much higher accuracy (0.985 correlation coefficient) with simpler mathematical expressions for the linear regression fits.

The results presented below show that solar and geomagnetic effects jointly determine the radiative cooling by NO. The relative roles vary significantly over the course of a solar cycle. We therefore propose a new index, the Thermosphere Climate Index (TCI), based on the results herein. The TCI can be used to assess the general state of the thermosphere because it reflects the main processes that control a key radiative cooling element of thermospheric climate.

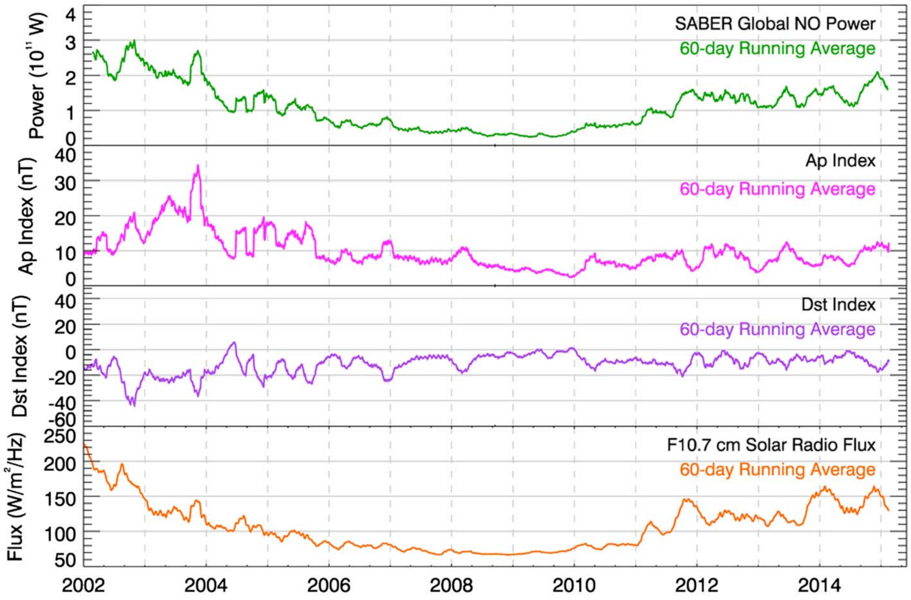

Figure 1. Sixty day running means of NO power, *Ap* index, *Dst* index, and $F_{10.7}$ index from January 2002 to March 2015.

2. Methodology

The time series of radiative cooling in the thermosphere as measured by the SABER instrument on the NASA TIMED satellite has previously been described in detail [*Mlynczak et al.*, 2014, and references therein]. We specifically look here at the daily global infrared power (W) radiated by the NO molecule. This parameter is the total amount of energy radiated on a daily, global basis due to infrared emission from the NO molecule at 5.3 μm. The NO power is derived by integrating with respect to altitude each vertical profile of radiative cooling (W/m^3) due to NO and then integrating this with respect to latitude (area) and longitude. The integral is taken from 100 to 250 km in altitude. Approximately 1500 vertical profiles of radiative cooling per day go into the global calculation. At this time over 4750 days of data comprise the time series of NO infrared power and radiative cooling. The data are observed to exhibit large day-to-day variability associated with geomagnetic effects and long-term variability associated with changes in the UV output over the 11 year solar cycle.

As this paper focuses on thermospheric climate, we use the daily global power radiated by NO and construct a time series of the 60 day running mean of the NO power. Sixty days is chosen as this is the time required for the TIMED satellite to sample all local times. There is a strong 60 day period in the NO power [*Mlynczak et al.*, 2008], implying a strong dependence of the NO power on local time that is very repetitive. The local time variation is due to tidal effects in the NO cooling [*Oberheide et al.*, 2013] and to photochemical effects that vary diurnally. The 60 day running mean gives a consistent average of the NO power over all local times for each reported point in the time series. By doing so, we avoid potential biases in the NO power time series due to improper sampling of local time variability. For purposes of the multiple linear regression fits, we also compute the 60 day running means of the $F_{10.7}$, *Ap*, and *Dst* indices. $F_{10.7}$ is a commonly used proxy for solar UV and EUV irradiance and its variation. The 60 day running means of these four parameters are shown in Figure 1.

Visual correlations between the *Ap*, $F_{10.7}$, and *Dst* indices and the NO power are evident upon examination of Figure 1. These strongly suggest that the NO power time series can be fit with a multiple linear regression involving these three standard solar and geomagnetic indices. Figure 2 shows the results of this fit. The multiple correlation coefficient of the regression fit to the observed power is 0.985. The integrated power (area under each curve) from January 2002 to January 2015 agrees to better than 2 ppm. The inclusion of *Dst* in addition to *Ap* and $F_{10.7}$ was found to slightly improve the agreement in regions where there is a marked peak in the NO power. Without *Dst* the correlation coefficient is 0.982.

The fit shown in Figure 2 is remarkable in the sense that the complex photochemical and geomagnetic energetic processes that ultimately lead to thermospheric infrared cooling can be represented so accurately by three standard solar and geomagnetic indices. This allows extension of the fit back in time

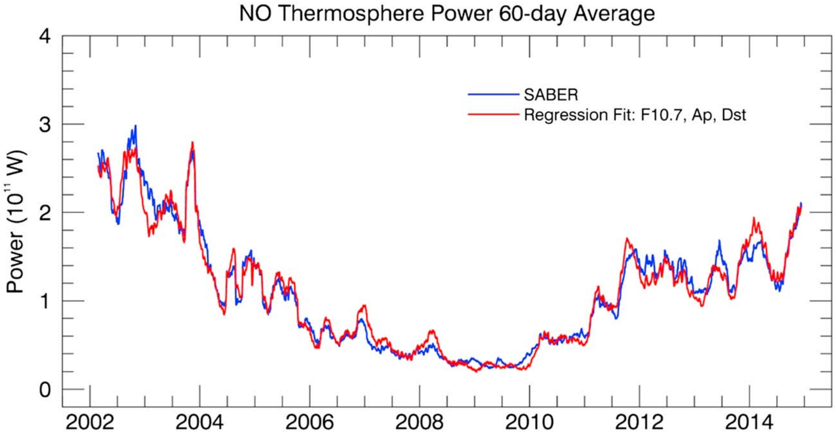

Figure 2. Sixty day running mean of the daily global radiated power from nitric oxide observed by SABER (blue curve) and the multiple linear regression fit using the 60 day running means of $F_{10.7}$, *Ap*, and *Dst*. The multiple correlation coefficient is 0.985.

with the extant databases of the three standard indices. Both $F_{10.7}$ and *Ap* are available back to 1947, and *Dst* is available back to 1957. From these we can construct a time history of NO cooling back nearly 70 years and covering almost seven solar cycles, from the peak of solar cycle (SC) 18 to the peak of SC 24 today.

Figure 3 (top) shows the reconstruction of the thermospheric NO power, which will be referred to as the Thermosphere Climate Index (TCI), as discussed in the next section. The blue curve is the reconstruction back to 1957 using *Ap*, $F_{10.7}$, and *Dst*. The red curve is the reconstruction going back to 1947 using *Ap* and $F_{10.7}$. Figures 3 (middle) and 3 (bottom) are the 60 day running means of *Ap* and $F_{10.7}$ (respectively) used in the reconstruction back to 1947. From this figure, we can see several interesting features about the time evolution of radiative cooling by NO. First, the largest radiative cooling occurred back in the late 1950s during SC 19. The peak NO emission briefly exceeded 4×10^{11} W, a level that was reached only one other time in the early 1990s near the peak of SC 22. The large NO power associated with SC 19 was followed by a much weaker SC 20 in which the peak NO power was roughly half that of its predecessor. The minimum in NO power during the prolonged minimum of SC 23 in 2008–2009 is the lowest power value in the time series. In addition, although SC 24 is yet to complete, the NO power during the peak of SC 24 is the smallest of any prior peak in the reconstructed time series. Given the fundamental role NO plays in the energy budget of the thermosphere, the time series shown in Figure 3 provides a long-term record of an integral constraint on the energy budget of the atmosphere above 100 km. As such, the time series can be used to test upper atmosphere climate models over a variety of solar and geomagnetic conditions of the past ~ 70 years.

The long-term time series shown in Figure 3 can be separated into its solar UV and geomagnetic components by using the coefficients derived for the fit shown in Figure 2. The expression for the fit shown in Figure 2 is

$$\mathrm{NO} = a_0 + a_1 \times F10.7 + a_2 \times Ap + a_3 \times Dst \tag{1}$$

Each term is the 60 day running mean of that parameter. The NO power is in units of 10^{11}W, *Ap* and *Dst* are in nanotesla, and $F_{10.7}$ is in solar flux units (sfu, 1 sfu = 1×10^{-22} W m^{-2} Hz^{-1}). The coefficients a_0, a_1, a_2, and a_3 are, respectively, -1.0271, 1.5553×10^{-2}, 4.0665×10^{-2}, and -8.2360×10^{-3}. The fraction of NO cooling due to deposition of solar irradiance is $(a_1 \times F_{10.7})/(a_1 \times F_{10.7} + a_2 \times Ap + a_3 \times Dst)$, and the fraction due to geomagnetic effects is $(a_2 \times Ap + a_3 \times Dst)/(a_1 \times F_{10.7} + a_2 \times Ap + a_3 \times Dst)$. This immediately provides an assessment of the relative roles of solar and geomagnetic processes that ultimately lead to radiative cooling by NO. Figure 4 shows the percentage of the radiative cooling in Figure 3 due to solar irradiance (red curve) and geomagnetism (blue curve), obtained from these expressions. Over the nearly 70 year record, about 70% of the radiative cooling is due to energy deposition of solar UV radiation and about 30% is due to geomagnetic processes. However, the relative contributions show a strong variability with the solar cycle. Overlaid in Figure 4 in grey is the 60 day running mean of the daily sunspot number. From this we can see that during solar maximum conditions (as indicated by the peak in sunspots) solar irradiance is responsible for up to 90% of the radiative cooling by NO. However, during solar minimum conditions, geomagnetic processes account for more than 40% of the cooling and, briefly on several occasions, are essentially comparable to solar UV.

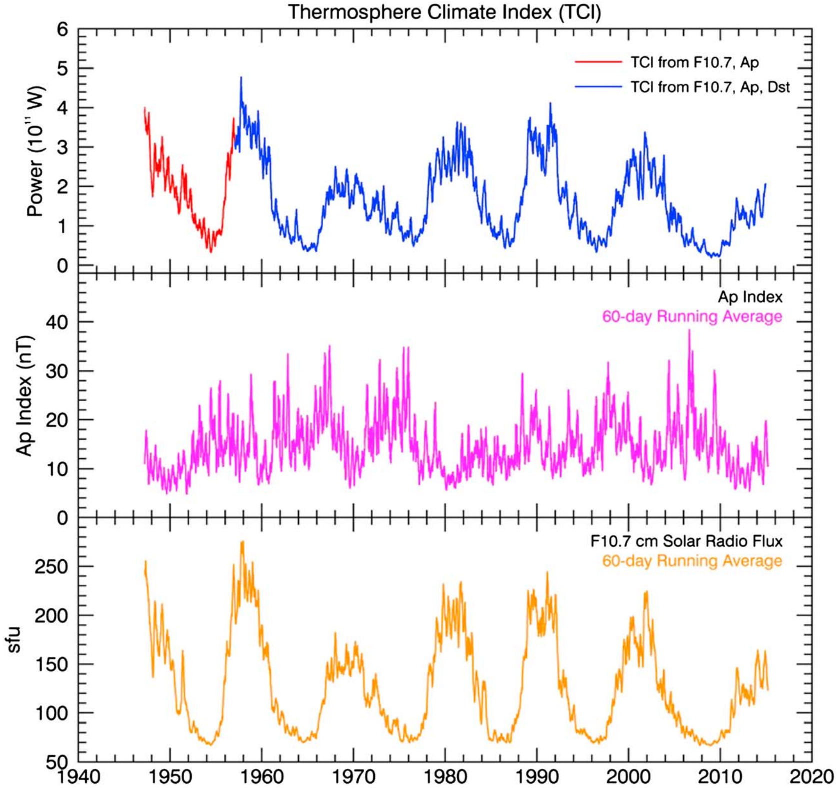

Figure 3. (top) Time series of the 60 day running mean of the NO power extended back to 1947, which we now refer to as the Thermosphere Climate Index (TCI). The TCI is constructed from 1957 to the present day using extant databases of $F_{10.7}$, *Ap*, and *Dst*. From 1947 to 1957 the TCI is constructed with $F_{10.7}$ and *Ap*. Corresponding 60 day averages of (middle) *Ap* and (bottom) $F_{10.7}$ used to construct the index. The TCI represents a fundamental integral constraint on the climate system of the thermosphere and provides a time series for testing upper atmosphere climate models over nearly seven complete solar cycles.

3. A Proposed TCI

Solar and geomagnetic indices are individually very useful for gauging levels of solar and geomagnetic variability and activity. However, they do not individually provide information on the state of the atmosphere in response to that variability and activity. We therefore propose a new index, the

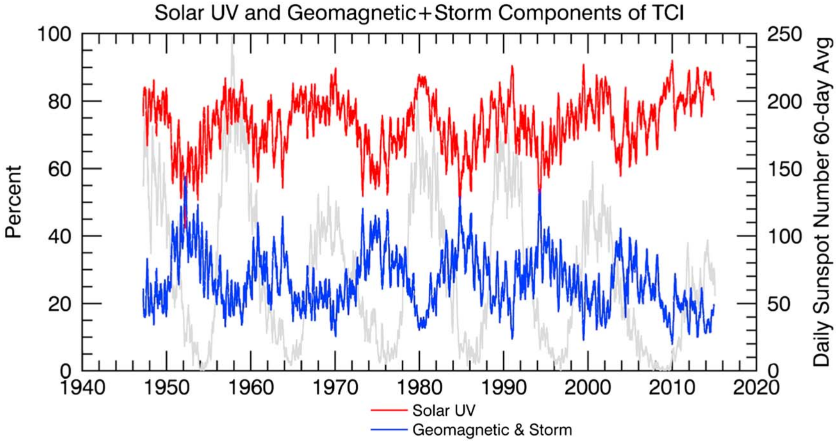

Figure 4. Relative contributions of solar irradiance (red) and geomagnetic processes (blue) to the variability of the NO cooling. The grey curve is the 60 day running mean of the daily sunspot number. Solar irradiance is the dominant mechanism for energy deposition resulting in NO cooling at solar maximum, while geomagnetic processes are much more important during solar minimum.

Thermosphere Climate Index (TCI) that provides a quantitative measure of the state of the thermosphere. The TCI would be the 60 day running mean of the NO power computed from the fit of the 60 day running means of $F_{10.7}$, *Ap*, and *Dst* to the SABER-observed NO power as given in equation (1). We suggest that the new index is critical because the thermosphere response in radiative cooling due to NO and to carbon dioxide (CO_2) has been shown to occur well after the maximum in sunspot number during solar cycle 24, as we will document in a forthcoming publication. The proposed TCI combines both solar irradiance and geomagnetism into one index to replicate accurately a key parameter of thermospheric climate. We further suggest that upon further modeling, the TCI could be given adjectival descriptors to describe the thermal state of the thermosphere, such as those applied to the *Kp* index and geomagnetic storms.

4. The Role of CO_2 Increases and NO Cooling

The multiple linear regression fit of $F_{10.7}$, *Ap*, and *Dst* to the observed SABER NO power tacitly assumes that these parameters adequately capture the processes associated with solar UV and geomagnetic effects that ultimately result in infrared cooling to space by NO. These drivers ultimately originate with the Sun as UV photons and solar wind particles. However, we point out that there is a slow, long-term driver internal to the Earth system associated with the continual buildup of CO_2. *Roble and Dickinson* [1989] predicted that the continued buildup of CO_2 would lead to a long-term cooling of the thermosphere. Thus, it is to be expected that over time, there would be a slow decrease in the NO emission as the temperature of the lower thermosphere decreases. Roble and Dickinson predict decreases in lower thermospheric temperature ranging from 5 K near 100 km to 35 K near 200 km for a doubling of the CO_2 concentration. At 130 km, the peak altitude of NO emission, a decrease of ~15 K is predicted. For a nominal temperature of 525 K at 130 km, a 15 K cooling would result in a reduction of NO emission of about 15% for doubled CO_2 amounts. We estimate that since 1947 the CO_2 in the atmosphere has increased by approximately 100 ppmv (annual rate of 1.5 ppmv), which is roughly one third the amount expected for CO_2 doubling since preindustrial times. Thus, the decrease in NO emission since 1947 due to CO_2 increase would be about 5%, assuming all other temperature-dependent processes related to NO chemistry (of which there are several) are essentially constant. The long-term effects of thermospheric cooling due to carbon dioxide increase on NO cooling merit further investigation.

5. Summary and Conclusion

A key time series of the global infrared power radiated by NO from the thermosphere can be fit quite accurately with a multiple linear regression of three solar and geomagnetic indices. This has enabled reconstruction of the NO power time series back to 1947 using extant databases of the $F_{10.7}$ solar radio flux, the *Ap* index, and the *Dst* index. The NO power is an integral constraint on the climate of the thermosphere. The reconstructed time series enables tests of upper atmosphere climate models over the last six solar cycles. The multiple regression fit has also enabled the relative roles of solar irradiance and geomagnetic processes in driving the NO cooling to be determined. In general, solar UV irradiance is the primary factor that determines the NO cooling, particularly at solar maximum. During solar minimum conditions, geomagnetic processes may rival the solar irradiance in driving the radiative cooling by NO. The proposed thermosphere climate index is a new metric that accurately replicates the state of the thermosphere. Its main advantage is that it provides a key measure of the state of the thermosphere that is not captured by other individual metrics. This is an important point as individual metrics such as sunspot number do not adequately reflect all of the processes which cause the atmosphere to respond to solar variability.

Acknowledgments

The authors acknowledge support from the NASA Heliophysics Division Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics mission. The *Ap* and $F_{10.7}$ solar flux are obtained from the daily geomagnetic and daily solar data sets prepared by the NOAA Space Weather Prediction Center. The *Dst* data are obtained from the Data Analysis Center for geomagnetism and Space Magnetism at the World Data Center for Geomagnetism in Kyoto, Japan. The daily sunspot data are downloaded from the WDC-SILSO (World Data Center for Sunspot Index and Long-term Solar Observations) at the Royal Observatory of Belgium, Brussels. The NO power data are available by contacting the first author of this article.

The Editor thanks Jiuhou Lei and Liying Qian for their assistance in evaluating this paper.

References

Lu, G., M. G. Mlynczak, L. A. Hunt, T. N. Woods, and R. G. Roble (2010), On the relationship of Joule heating and nitric oxide radiative cooling in the thermosphere, *J. Geophys. Res.*, *115*, A05306, doi:10.1029/2009JA014662.

Mlynczak, M. G., F. J. Martin-Torres, C. J. Mertens, B. T. Marshall, R. E. Thompson, J. U. Kozyra, E. E. Remsberg, L. L. Gordley, J. M. Russell III, and T. Woods (2008), Solar-terrestrial coupling evidenced by periodic behavior in geomagnetic indexes and the infrared energy budget of the thermosphere, *Geophys. Res. Lett.*, *35*, L05808, doi:10.1029/2007GL032620.

Mlynczak, M. G., L. A. Hunt, C. J. Mertens, B. T. Marshall, J. M. Russell III, T. Woods, R. E. Thompson, and L. L. Gordley (2014), Influence of solar variability on the infrared radiative cooling of the thermosphere from 2002 to 2014, *Geophys. Res. Lett.*, *41*, 2508–2513, doi:10.1002/2014GL059556.

Oberheide, J., M. G. Mlynczak, C. N. Mosso, B. M. Schroeder, B. Funke, and A. Maute (2013), Impact of tropospheric tides on the nitric oxide 5.3 μm infrared cooling of the low-latitude thermosphere during solar minimum conditions, *J. Geophys. Res. Space Physics*, *118*, 7283–7293, doi:10.1002/2013JA019278.

Roble, R. G., and R. E. Dickinson (1989), How will changes in carbon dioxide and methane modify the mean structure of the mesosphere and thermosphere, *Geophys. Res. Lett.*, *16*, 1441–1444, doi:10.1029/GL016i012p01441.

Russell, J. M., M. G. Mlynczak, L. L. Gordley, J. Tansock, and R. Esplin (1999), An overview of the SABER experiment and preliminary calibration results, in *Proceedings of the 44th Annual Meeting, Denver, Colorado, July 18–23*, vol. 3756, pp. 277–288, SPIE, Bellingham, Wash.