Infrared Radiation in the Thermosphere
Near the End of Solar Cycle 24

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Abstract
Observations of thermospheric infrared radiative cooling by carbon dioxide (CO2) and nitric oxide (NO) from 2002 to 2018 are presented. The time span covers more than 6,000 days including most of solar cycle (SC) 23 and the entirety of SC 24 to date. Maxima of infrared cooling rate profiles (nW/m3) are smaller during SC 24 than SC 23, indicating a cooler thermosphere. Rates of global infrared power (W) from CO2 are now at levels observed during the deep solar minimum of 2009. Rates of NO power are still larger than those observed during 2009 and are being maintained at an elevated level by geomagnetic activity. During SC 24 to date, the thermosphere has radiated 70% of the energy of the mean of the past five cycles and would require an additional 1,690 days at current infrared radiation rates to reach that amount.

1. Introduction
The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the National Aeronautics and Space Administration (NASA) Thermosphere, Ionosphere, Mesosphere Energetics and Dynamics (TIMED) satellite has been observing infrared radiation emitted from the terrestrial thermosphere by nitric oxide (NO) and carbon dioxide (CO2) for over 16.5 years, more than 6,000 days, beginning in January 2002 and continuing until the present day. This time span covers most of solar cycle (SC) 23 and all of SC 24 to date. Table 1 lists the start and end dates of SCs 19 to 23 based on the occurrence of consecutive minima in total infrared power radiated from the thermosphere (Mlynczak et al., 2016). From this perspective, SC 24 began in June 2009 and is still ongoing as October 2018. The SABER observations offer unique insight into the effects of solar variability on key terms in the energy budget of the thermosphere over nearly two complete and energetically different SCs. In this paper we examine the SC differences in the global annual infrared radiative cooling rate profiles (W/m3) and in the daily global infrared radiated power (W) for NO and CO2. We also examine the thermosphere climate indexes (TCI), which are the 60-day running mean of the daily global infrared mean power for each parameter. The TCI (Mlynczak et al., 2015, 2016, 2018) are developed from multiple linear regression (MLR) fits of standard (F10.7, Ap, and Dst) indexes to the observed time series of daily infrared radiated power. The TCI are further developed from 1947 to date using extant databases of the three indexes. The TCI enable comparisons of SC 24 with the five complete preceding cycles, SCs 19–23.

The derivation of infrared cooling rate profiles proceeds from the infrared limb radiance emitted by NO and CO2 and measured by the SABER instrument. The details of the derivation of cooling rate profiles and daily power are given by Mlynczak et al. (2003, 2005, 2010). Briefly, the measured vertical profiles of limb radiance (W·m−2·sr−1) are mathematically inverted to yield vertical profiles of radiative cooling in watts per cubic
These profiles are then integrated with respect to altitude to compute the flux (W/m²) of infrared radiation exiting the thermosphere. (Flynn et al., 2018, give a detailed evaluation of the temporal variations of the infrared fluxes from NO emission.) The fluxes are then integrated with respect to area around latitude circles to obtain the emitted infrared power (W), which is then integrated from pole to pole to provide the global radiated power on a daily basis.

In the next section the variability of the vertical profiles of infrared cooling by NO and CO₂ over the past 16 years will be examined. Section 3 will highlight the SC variability of the total global infrared power radiated by CO₂ and NO in the thermosphere over multiple SCs. A discussion and summary in section 4 conclude this letter.

2. Comparisons of Infrared Cooling Rates in SCs 23 and 24

Figure 1a shows vertical profiles of global annual mean radiative cooling (nW/m²) for NO, from 2002 through 2017 (16 years total). The peak cooling near 130-km altitude in 2002 (SC 23) was in excess of 8 nW/m². In 2008–2009, the radiative cooling rate near the peak was just over 1 nW/m², nearly 90% smaller than in 2002. The peak cooling during 2014 (SC 24) is in excess of 5 nW/m², approximately 37% less than in 2002, which is indicative of a cooler thermosphere during the maximum of SC 24. The effects of solar variability on the radiative cooling are also evident in Figure 1b, which depicts the difference in the annual mean cooling rate, by year, from 2002. The sense of the difference is cooling in year X (e.g., 2007) minus cooling in year 2002, and hence, the negative values shown in the contour plot. The prolonged minimum of SC 23 can be clearly seen from 2007 to early 2009 near 130 km in Figure 1b. Solar maximum conditions are evident in 2014 and then the progression to solar minimum begins thereafter in 2015. In 2017, the difference in cooling at 130 km from 2002 is 6 nW/m², and thus SC 24, through 2017, was not yet at the minimum level encountered in 2008–2009 in SC 23.

Table 1
Comparison of Solar Cycles 19–24 Based on the NO and CO₂ Thermosphere Climate Indexes (TCI) and the Measured F10.7 and Ap Indexes

| Solar Cycle | Total days | NO power (10¹⁴ W) | CO₂ power (10¹⁵ W) | Total power (10¹⁵ W) | F10.7 (10⁵ sfu) | Ap (10⁴ nT) |
|-------------|------------|------------------|--------------------|----------------------|-----------------|-------------|
| 19          | 3966       | 7.45             | 3.25               | 4.00                 | 5.42            | 6.08        |
| 20          | 4245       | 5.82             | 3.17               | 3.75                 | 4.70            | 5.36        |
| 21          | 2044       | 6.81             | 3.02               | 3.70                 | 4.97            | 5.67        |
| 22          | 3690       | 6.65             | 3.02               | 3.69                 | 4.85            | 5.66        |
| 23          | 4774       | 6.46             | 3.68               | 4.33                 | 5.54            | 5.58        |
| Mean        | 4047       | 6.64             | 3.23               | 3.89                 | 5.10            | 5.67        |
| Std Dev     | 431        | 5.29             | 2.44               | 2.48                 | 3.25            | 2.33        |
| Std Dev Pct | 10.65%     | 7.96%            | 7.56%              | 6.37%                | 6.37%           | 4.12%       |
| 24 (to date)| 3470       | 3.38             | 2.38               | 2.72                 | 3.38            | 2.86        |
| Percent of Mean | 6/09 to the present | 51%             | 73.8%             | 69.8%               | 66.3%           | 50.5%       |

Note. Total days is the length of the indicated solar cycle from minimum to minimum of Total power; NO power and CO₂ power are the sums of the daily NO and CO₂ power, respectively, from the TCI, and Total power is their sum. F10.7 and Ap are the sums of the daily values of those indexes. Column 2 (Total days) also indicates the start and end dates (month/year) of each solar cycle based on the occurrence of consecutive minima in total radiated infrared power from Mlynczak et al., 2016.

Figure 1. Vertical profiles of global annual mean cooling rates for NO from 2002 to 2017 inclusive (a) and difference from 2002 (b). Units are in nanowatts per cubic meters.
Figure 2a shows the vertical profiles of global annual mean radiative cooling (nW/m^3) for CO\textsubscript{2}, also from 2002 to 2017. The cooling rate profiles are much more uniform in the vertical and over time for CO\textsubscript{2} than they are for NO, likely due to the much stronger temperature dependence of NO infrared emission, the larger variability of NO density with the SC, and the greater uniformity of the CO\textsubscript{2} distribution overall. The CO\textsubscript{2} cooling rate near 105-km altitude in 2002 is 110 nW/m\textsuperscript{3}, while in 2008–2009 the cooling rate is \(\sim\)85 nW/m\textsuperscript{3}, approximately 23% smaller. During 2014 the cooling rate at 105 km rose to about 100 nW/m\textsuperscript{3}, roughly 10% smaller than in 2002. In 2017, the cooling rate at 105 km is just under 90 nW/m\textsuperscript{3}, which is still above the minimum reached in 2008–2009. Figure 2b shows the differences in the cooling rate profiles from 2002, as in Figure 1 (bottom frame). The SC progression is more evident in this difference plot. The peak cooling rate differences from 2002 are \(\sim\)25 nW/m\textsuperscript{3} in the prior solar minimum and are just over 20 nW/m\textsuperscript{3} in 2017. Thus, through 2017, for both NO and CO\textsubscript{2} the radiative cooling rates have not yet decreased to the levels observed in 2008–2009.

Figure 3a shows the 16-plus year record of daily global infrared power exiting the thermosphere that is emitted by NO (green) and CO\textsubscript{2} (red). The time series extends from 22 January 2002 to 13 August 2018, over 6,000 days of data. The blue curves in the NO and CO\textsubscript{2} cooling time series are the 60-day running averages of the data. A 60-day running average is chosen as this is the time required for the TIMED satellite to sample all local times. Figure 3b shows the same data but from 1 January 2010 to 13 August 2018, covering almost all of SC 24. Several features are apparent throughout the entirety of the SABER record. First, large, short-term increases in NO and CO\textsubscript{2} cooling due to geomagnetic storm events are common. The largest storms in the record occurred in the latter stages of SC 23. The semiannual oscillation in CO\textsubscript{2} cooling evidenced in the
60-day running means is also a persistent feature. The peak cooling in SC 24 is less than SC 23. Figure 3b shows that SC 24 actually had a double-peaked maximum, the first peak occurring in late 2011, followed by a slightly larger peak in late 2014. Figures S1 and S2 in the supporting information show the NO and CO\textsubscript{2} cooling from Figure 3 but with the corresponding time series of the F\textsubscript{10.7} and Ap indexes.

### 3. Comparison of SC 24 With SCs 19–23

The TCI (Mlynczak et al., 2015, 2016, 2018) are the 60-day running means of the global daily infrared power emitted from the thermosphere by NO and CO\textsubscript{2}. The TCI are obtained using the standard F\textsubscript{10.7}, Ap, and Dst indexes to construct MLR fits to the SABER 60-day running means obtained from the 16-plus years of data shown in Figure 3a. By employing the F\textsubscript{10.7}, Ap, and Dst indexes, the TCI are developed from 1947, the earliest date for which all three indexes are extant. Mlynczak et al. (2016) showed that, surprisingly, the integrated infrared power for each of the five complete SCs (19–23) covered by the indexes was nearly the same despite apparent differences in SC duration and peak power. This is due to the fact that, over the same time periods, the integrated F\textsubscript{10.7} and Ap indexes (which compose the TCI) are essentially the same over each of the five SCs. The accuracy of the MLR fit to the SABER data, and the generation of the TCI back to 1947, enables a comparison of SC 24 with its five predecessors, with quantitative terrestrial context.

The TCI for SC 23 derived from the MLR fit with that for SC 24 to date for NO and CO\textsubscript{2}, respectively, are shown in Figures 4a and 4b. In both instances, the radiated power in SC 24 is less than in SC 23, and hence, the total (CO\textsubscript{2} plus NO) power radiated is less in SC 24 than in SC 23. Table 1 lists data derived from the TCI and the Ap and F10.7 indexes for SCs 19–23 and SC 24 to date. Specifically, for SC 19–23, measured from minimum to minimum in total (NO plus CO\textsubscript{2}) infrared power, Table 1 lists length (days), integrated NO power, integrated CO\textsubscript{2} power, integrated total power, integrated F10.7 index, and integrated Ap index. The standard deviations
Table 1 also lists these parameters for SC 24, from 19 June 2009 through 16 July 2018. SC 24 is already 3,470 days in length, which is 86% of the mean of the lengths of the five prior cycles, and needs to be about 577 days longer to match the prior five-cycle mean. However, the NO and CO$_2$ power are approximately 51% and 74%, respectively, of their means for the past five SCs. The total power is just under 70% of the mean of the past five cycles. At current radiation levels for NO and CO$_2$ (from the TCI from 1 January to 16 August 2018), SC 24 would require another 1,690 days in order to radiate the same total power as the mean of SC 19–23, making it 3,470 + 1,690 = 5,160 days (14.13 years) in length. This is, however, only 386 days (1.03 years) longer than SC 23, as determined from the TCI in Table 1. Time will tell if the near conservation of infrared energy exhibited in SC 19–23 is maintained throughout what would be one of the longest recorded SCs (https://en.wikipedia.org/wiki/List_of_solar_cycles).

SC 24 to date is clearly energetically weaker than SC 23 by the analyses presented above. However, the infrared power levels for NO are not yet at the low values reached during the last solar minimum in 2009. Figure 5a shows the SABER-measured NO power (60-day running average) for all of calendar year 2009 and compares it with the NO power for calendar year 2018 to date. The NO power in 2018 is clearly larger, by approximately a factor of ~1.34, which is the ratio of the integrated power in 2018 to date versus 2009. The reason for this can be seen in Figure 5b, which shows the 60-day running average of the $Ap$ index for the same time periods. Calendar year 2018 is roughly 1.75 times as geomagnetically active as the solar minimum period in calendar year 2009 by this measure. Figure 5c shows the SABER-measured CO$_2$ power (60-day running average) for calendar year 2009 and for calendar year 2018 to date. The CO$_2$ infrared cooling values in both years are

![Figure 4. Thermosphere climate index for NO (a) and CO$_2$ (b) for solar cycles 23 and 24.](image)
much closer, and as of June 2018, they are equal. This is due in part to the reduction in F10.7 (i.e., solar ultraviolet irradiance) in 2018 but is also due to the simultaneous occurrence of the minimum in CO2 emission associated with the semiannual oscillation evident in the SABER CO2 record shown in Figures 3a and 3b. Figure 5d also shows that the NO cooling is not being kept above the prior solar minimum conditions by solar ultraviolet irradiance as the F10.7 has been at 68 solar flux units (sfu, 1 sfu = 10^{-22} W·m^{-2}·Hz^{-1}), 1 sfu above its minimum value, for a large part of calendar year 2018.

4. Discussion and Summary
Solar variability and its influence on the upper atmosphere of the Earth is a forefront of scientific research. There are few direct, global indicators of the influence of solar variability that have quantitative terrestrial context. Infrared radiation from NO and CO2 are primary components of the energy budget of the atmosphere above 100 km. The SABER instrument on the NASA TIMED satellite has been observing thermospheric infrared radiation from NO and CO2 for well over 16 years. These data and other products derived from them (the TCI) provide direct, quantitative context on the thermal state of the atmosphere (Mlynczak et al., 2018) and enable comparisons of different SCs.

To date, SC 24 is shown to be substantially weaker than its five predecessors from the perspective of infrared radiation escaping the thermosphere. The vertical profiles of global average infrared cooling rates have peak rates that are smaller during SC 24 than SC 23 for both CO2 and NO, indicating an overall cooler thermosphere. The time series of daily power radiated by CO2 and NO have smaller peak power in SC 24 than in SC 23. The thermosphere climate indexes for CO2 and NO are smaller in SC 24 than SC 23. However, in the case of NO, the infrared daily global power radiated from the thermosphere in calendar year 2018 is still larger than the NO power radiated by NO during the deep solar minimum of 2009. The NO power in 2018 is being maintained above the 2009 levels by geomagnetic activity, as indicated by comparisons of the Ap index. The
CO₂ power is much closer in 2018 to the value in 2009 and has, in July–August 2018, become equal to the power levels in 2009.

The prior work of Mlynczak et al. (2016) suggested that infrared power emitted by NO and CO₂ over a SC was a nearly conserved quantity. At current infrared radiation levels, SC 24 will need to be 5,160 days (14 years and 50 days) long, requiring an additional 1,690 days from now for the thermosphere to radiate the same power as the mean of the five prior cycles. This would make SC 24 approximately 386 days (about 1 year) longer than SC 23 and one of the longest SCs on record.

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