Infrared radiation in the thermosphere near the end of solar cycle 24

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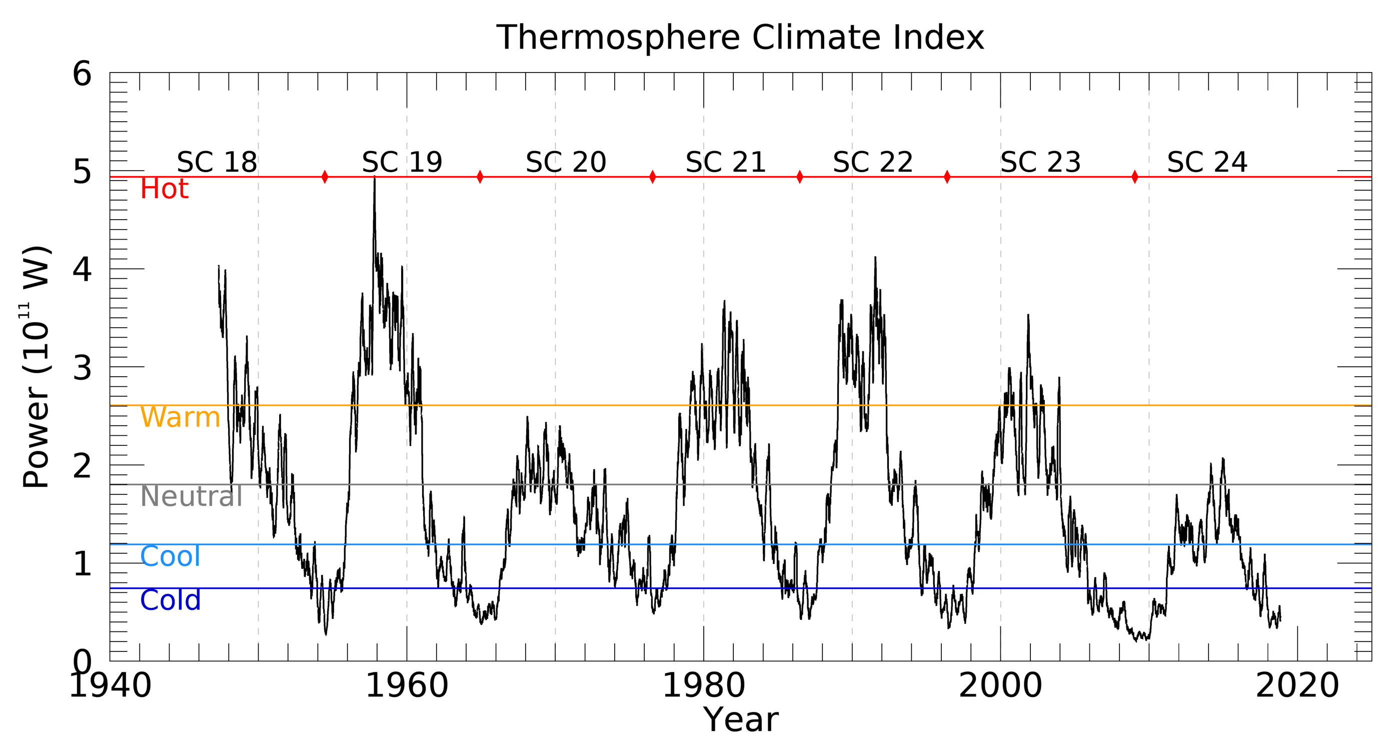
Introduction

- Thermosphere climate is controlled in part by cooling to space driven by infrared radiation, primarily from nitric oxide (NO, 5.3µm) and carbon dioxide (CO_2, 15µm).
- The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite has been measuring the vertical distribution of infrared radiation emitted by these species (and others) for nearly 17 years-–more than 6000 days. This data set spans much of Solar Cycle (SC) 23 and all of SC 24 to date.
- A thermosphere climate index (TCI) has been derived by noting the correlation between 60-day running averages of NO cooling power and three long-term solar and geomagnetic indexes: F10.7 cm solar radio flux, the Ap index of geoeffective solar activity, and the disturbance storm time (Dst) index.
- A multiple linear regression (MLR) fit of these three parameters to the NO cooling rate over the SABER mission has a better than 0.98 correlation.
- Applying the MLR constant and coefficients from that fit provides a good estimate of thermospheric cooling back to 1947, the extent of the data available for all three indexes. [Ref. 2]
- We examined the percentile distribution of the TCI in quintiles over the five complete solar cycles, and assigned adjectival descriptors to those quintiles as shown in the plot below. [Ref. 4]



Solar Cycle Comparison – SC 19-23 with SC 24

- SABER observations give us insight into the effects of solar variability over two energetically different solar cycles.
- The TCI allows us to compare the current solar cycle, SC 24 with the complete cycles from SC 19-23.

The table below provides a comparison of solar cycles 19-24 based on the NO and CO2 thermosphere climate indexes (TCI) and the measured F10.7 and Ap indexes.

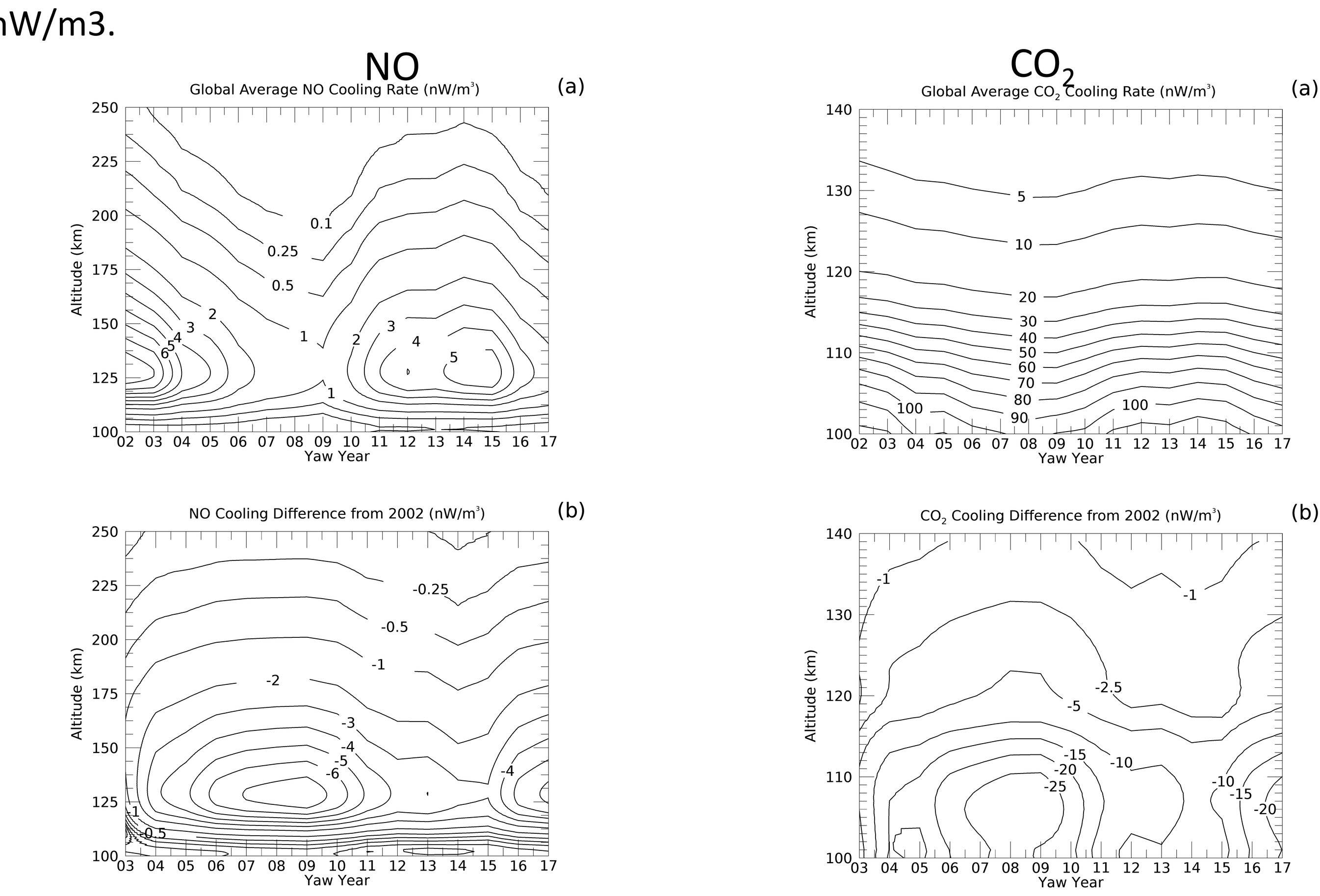
- Total Days is the length of the indicated solar cycle from minimum to minimum of Total Power.
- NO Power and CO2 Power are the sums of the daily NO and CO2 power respectively, from the TCI. Total Power is their sum.
- F10.7 and Ap are the sums of the daily values of those indexes.

Solar Cycle	Total Days	NO Power (10^{14} W)	CO_2 Power (10^{15} W)	Total Power (10^{15} W)	F10.7 (10^5 sfu)	Ap (10^4 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	3622	6.81	3.02	3.70	4.97	5.67
22	3630	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	85.7%	51%	73.8%	69.8%	66.3%	50.5%

- SC 19-23 are very similar in terms of the integrated power over each cycle despite their different durations and distributions. [Ref. 3]
- To date SC 24 is decidedly weaker than its predecessors. [Ref. 5] The table shows SC 24 through July 2018.
  - Its length of 3470 days is 86% of the mean duration of SC 19-23, so in 577 days it would reach the mean length of those solar cycles.
  - Total power for SC 24 is less than 70% of the mean for SC 19-23, and it would take nearly 1700 more days to reach the mean power of those solar cycles. That would make SC 24 5160 days or 14.13 years long, which is 386 days or just over a year longer than SC 23.

Solar Cycle Comparison – SC 23 with SC 24

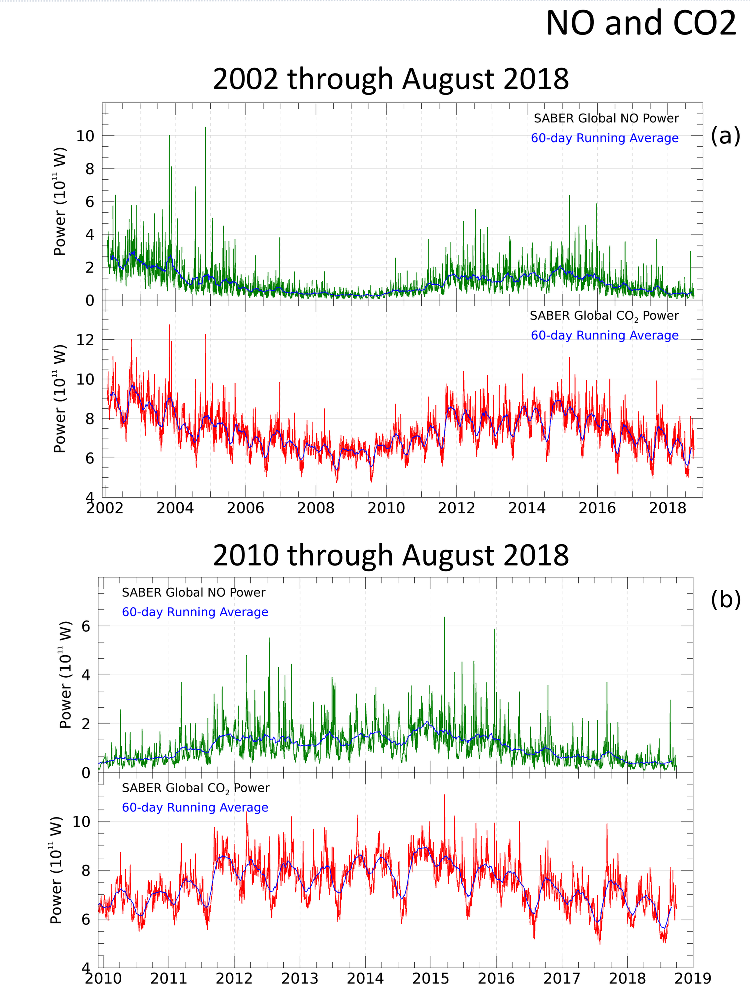
Vertical profiles of global annual mean cooling rates from 2002 to 2017 (16 years total) and difference from 2002 for NO (left top and bottom) and for CO_2 (right top and bottom). Units are nW/m3.



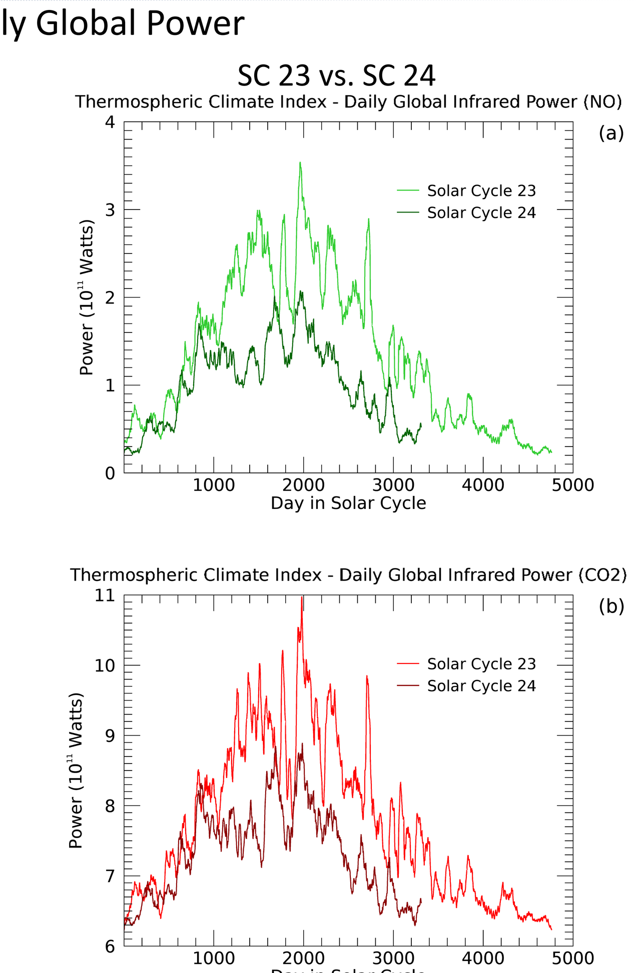
- Peak cooling near 130-km altitude in 2002 (SC 23) was > 8 nW/m3.
- In 2008– 2009 (solar min), it was just over 1 nW/m3, nearly 90% smaller than in 2002.
- During 2014 (SC 24) peak cooling is in excess of 5 nW/m3, ~ 37% less than in 2002, so thermosphere is cooler during the maximum of SC 24.
- The time difference plot (b) illustrates the prolonged solar min, the 2014 solar max, and that so far SC 24 has not reached the minimum seen in 2008-2009.

- The CO2 cooling rate near 105-km altitude in 2002 is 110 nW/m3
- In 2008–2009 the cooling rate is ~85 nW/m3, approximately 23% smaller.
- During 2014 the it rose to about 100 nW/m3, roughly 10% smaller than in 2002.
- In 2017, it is just under 90 nW/m3, which is still above the minimum reached in 2008–2009.
- The peak cooling rate differences from 2002 are ~25 nW/m3 in the prior solar minimum and are just over 20 nW/m3 in 2017.

NO and CO2 Daily Global Power



Time series of daily global infrared power (W) exiting the thermosphere from January, 2002 to August, 2018 (a), and from January, 2010 to August 2018 (b).



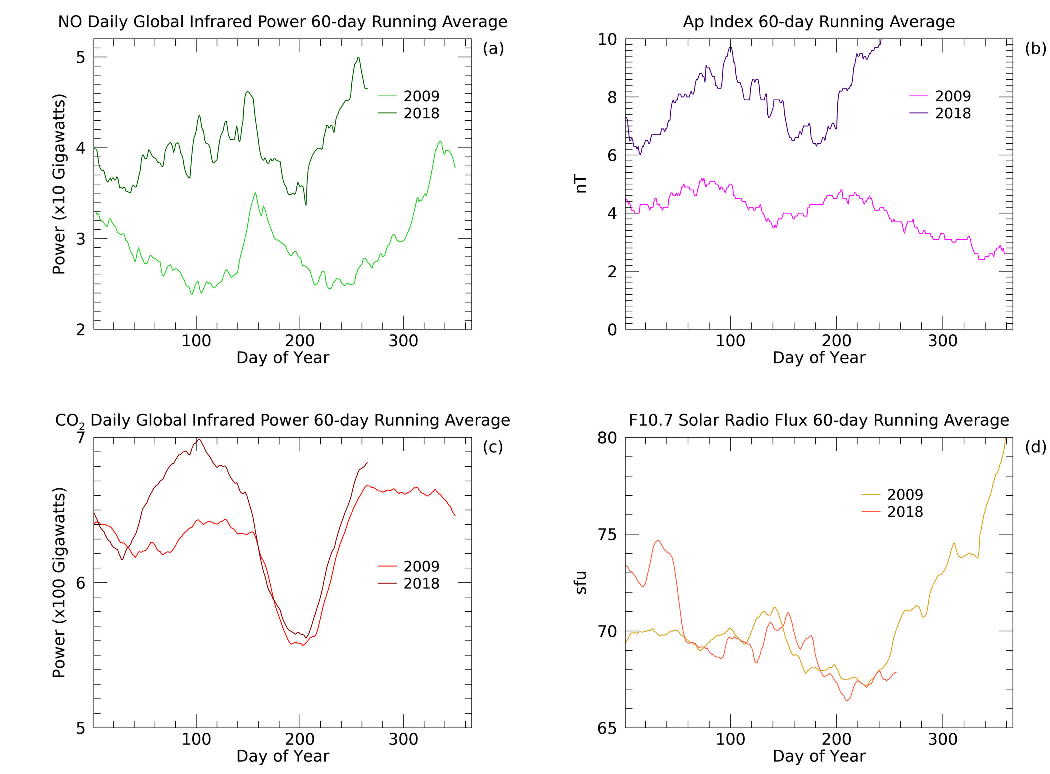
Thermosphere Climate index for NO (a) and CO_2 (b) for solar cycles 23 and 24.

Several features are apparent in the 2002-2018 SABER daily global power record (above left):

- Large, short-term increases in NO and CO_2 cooling due to geomagnetic storm events are common.
- The largest storms occurred in the latter stages of SC 23.
- The semiannual oscillation in CO_2 cooling seen in the 60-day running means is also a persistent feature.
- Peak cooling in SC 24 is less than SC 23.

The TCI (above right) are derived from an MLR fit to the SABER NO and CO2 daily global power using F10.7, Ap, and Dst. The plots of TCI (above right) compare the values for SCs 23 & 24.

- For both NO and CO_2, the radiated power in SC 24 is less than in SC 23, and hence, the total (CO2 plus NO) power radiated is less in SC 24 than in SC 23.
- However, the infrared power levels for NO has not yet reached the low values of the last solar minimum in 2009.



Sixty day running averages for 2009 (solar min) vs 2018 for (a) SABER NO power, (b) Ap Index, (c) SABER CO_2, and (d) F10.7 cm Solar Radio Flux.

- NO power in 2018 (a) is clearly larger, by approximately a factor of ~1.34, which is the ratio of the integrated power in 2018 to date versus 2009.
- Calendar year 2018 is roughly 1.75 times as geomagnetically active as the solar minimum period in calendar year 2009 (Ap plot b).
- CO2 infrared cooling values (c) in both years are much closer, and as of June 2018, they are equal. This is due in part to the semiannual oscillation seen in the CO2 record.
- F10.7 (d) , a proxy for solar ultraviolet irradiance is lower in 2018 provides additional explanation for the CO2 result.
- Figure (d) also shows that NO cooling is not being kept above the prior solar minimum conditions by solar ultraviolet irradiance as the F10.7 has barely above its minimum value for a large part of 2018.

Discussion and Summary

Solar variability and its influence on the upper atmosphere of the Earth are 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 and have been measured by SABER on TIMED for nearly 17 years. These data and products derived from them (the TCI) provide direct, quantitative context on the thermal state of the atmosphere and enable comparisons across SCs:

- To date, SC 24 is shown to be substantially weaker than its five predecessors.
- 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, and correspondingly, the thermosphere climate indexes for CO2 and NO are smaller in SC 24 than SC 23.
- NO infrared daily global power in 2018 is still larger than the NO power radiated 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.
- Our prior work [Ref. 3] 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, more than 1,600 days from now, 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.

References

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Acknowledgments

SABER NO and CO2 cooling rate profiles, vertically integrated fluxes, and daily global power are publicly available from **ftp://saber.gats-inc.com/Version2_0/SABER_cooling**.
The Ap and F10.7 data are from the geomagnetic and solar databases at the NOAA Space Weather Prediction Center. The Dst data are from the University of Oulu, Finland, http://dcx.oulu.fi.

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