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# Thermosphere climate indexes: Percentile ranges and adjectival descriptors

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A B S T R A C T

Thermosphere Climate Indexes (TCI) represent the 60-day running average of the global infrared cooling power radiated from the thermosphere by nitric oxide and by carbon dioxide. The TCI are accurately expressed as linear combinations of the 60-day running averages of the F10.7, Ap, and Dst indexes, thus providing terrestrial context to the long record of solar and geomagnetic indexes. We examine the percentile distribution in quintiles of the TCI generated using solar and geomagnetic indexes covering five complete solar cycles. We further assign adjectival descriptors (Cold, Cool, Neutral, Warm, or Hot) to these quintiles as the TCI largely indicate the global thermal state of the thermosphere. We suggest that the TCI are valuable new solar-terrestrial indexes due to the information they contain about the global thermosphere and due to their ease of calculation from standard indexes. Specifically, given dynamic range of the TCI associated with NO cooling, and its significant dependence on both solar irradiance and geomagnetic processes, we recommend that it be included henceforth as a new, standard solar-terrestrial Index. The NO TCI data show that the thermosphere was "Warm" only for a brief period of time at the maximum of solar cycle 24 and thus experienced the coolest solar maximum of the past seven solar cycles. As of February, 2018, the thermosphere power is in the lowest quintile of values, to which we assign the level of 'Cold.'

## 1. Introduction

Indexes are widely used in aeronomy to express the current state and variability of the Sun, geospace, and the Earth's magnetic field. These indexes include the widely used solar radio flux at 10.7 cm wavelength (F10.7) and the Ap and Kp indexes which gauge the degree of perturbations to the Earth's magnetic field during disturbances arising from the solar wind, solar coronal mass ejections, and other solar ejecta. A description of geomagnetic indexes is given by Mayaud (1980). However, none of the standard solar and geomagnetic indexes, by themselves, give direct terrestrial context in terms of a key property of the atmosphere.

Mlynczak et al. (2015, hereafter, M1) presented a combined solar and geomagnetic index using the F10.7, Ap, and Dst indexes to accurately represent the observed 15-year record of global infrared power (W) at 5.3 μm wavelength radiated from Earth's thermosphere by the nitric oxide (NO) molecule. The observations were made by the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite. Mlynczak et al. (2016, hereafter, M2) extended this concept to the global infrared power at 15 μm wavelength radiated from Earth's thermosphere by the $CO_2$ molecule. In addition, M2 used the extant record of solar and geomagnetic indexes to extend the record of infrared cooling by NO and $CO_2$ back over 70 years to 1947, covering five complete solar cycles (SC, 19 through 23), and part of SC 18. M2 found that the infrared radiated energy from the thermosphere, integrated over a solar cycle, was nearly constant for the five complete solar cycles examined. Recently, Varotsos and Efstathiou (2018) examined both the observed NO and $CO_2$ infrared power and the empirically derived NO and $CO_2$ power extending back to 1947. They found no evidence of power-law behavior in either the observed or derived infrared radiation time series, implying they have the same intrinsic properties, and thus, the empirically derived time series is statistically consistent with the observed time series.

In the next section, we evaluate the distribution of the ranges of the empirically-derived NO and $CO_2$ infrared power, henceforth referred to as Thermosphere Climate Indexes (TCIs) over the five complete solar cycles covered in the empirically derived time series. These NO and $CO_2$ TCI time series, covering just over 20,000 days, are analyzed in terms of percentiles based on frequency of occurrence of observed power levels radiated by each molecule. The NO TCI is then shown from 1947 to 2018. Given its larger dynamic range relative to the $CO_2$ TCI, the NO TCI is recommended as a new solar-terrestrial index. As the NO TCI largely reflects the thermal state of the thermosphere, the adjectival descriptors of "Cold, Cool, Neutral, Warm, and Hot" are applied from the lowest to highest quintiles of the NO TCI. The new Index will be updated regularly

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and will be publicly available for download at the SABER project web site. A Summary concludes the paper.

## 2. Results

Shown in Fig. 1 are the empirically-derived time series of NO and $CO_2$ infrared power radiated by the thermosphere above 100 km, from M2. These cover SC 19 through 23, beginning on June 24, 1954 and running through June 19, 2009, 55 years in total. The $CO_2$ power is larger overall than the NO power because it primarily originates below the NO emission where the atmosphere is more dense and hence there is more thermal energy to radiate. The peak altitude of the $CO_2$ emission is

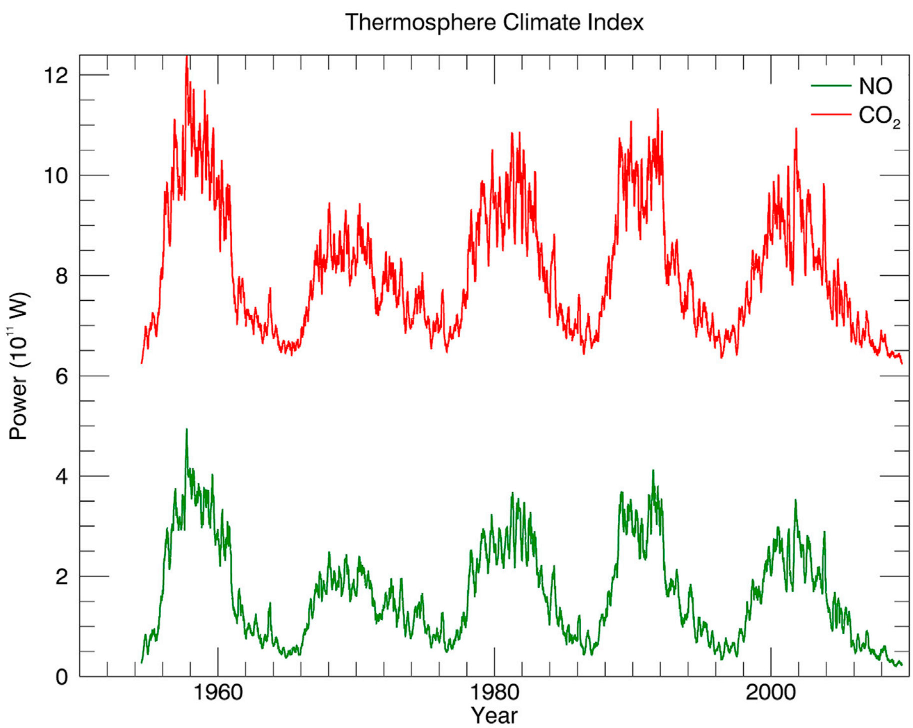


**Fig. 1.** Time series of NO and $CO_2$ Thermosphere Climate Indexes from 1955 to 2009 covering 5 complete solar cycles.

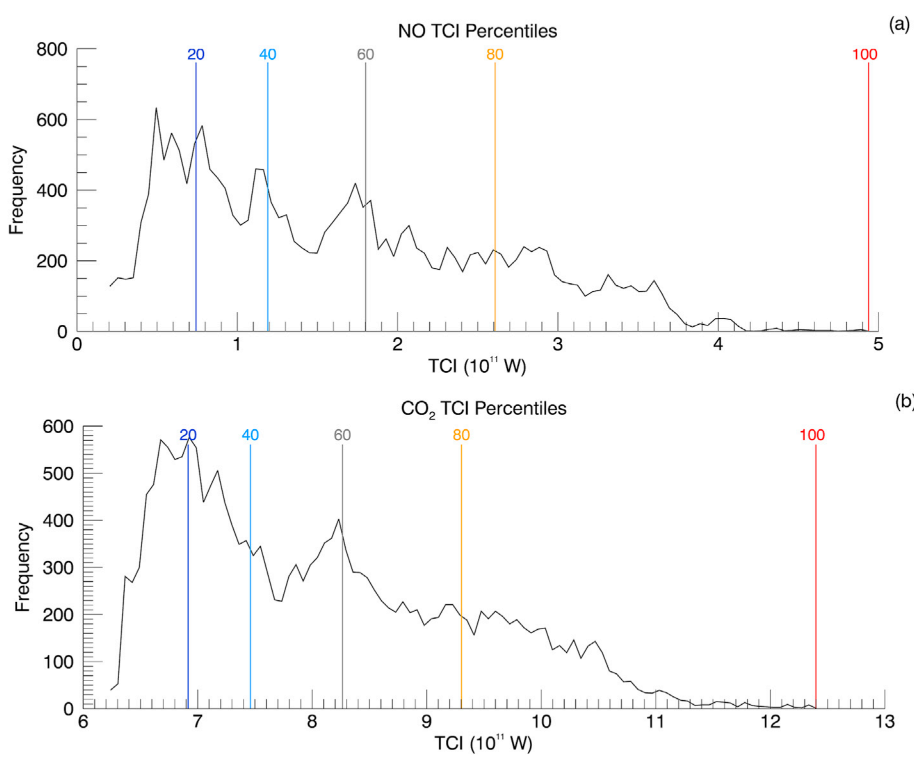


**Fig. 2.** Histograms of frequency of occurrence of power for NO (top) and $CO_2$ (bottom) over the 55 years of the time series shown in Fig. 1. The quintiles of each distribution are indicated by vertical lines.

approximately 105 km while the NO emission peak is approximately at 130 km (Mlynczak et al., 2010, 2014). The five solar cycles are clearly visible in each time series, and each appears different in its peak intensity. There are over 20,000 data points (i.e., days of data) corresponding to the 60 day running means of the thermospheric infrared power each for NO and $CO_2$.

The NO TCI exhibits a much larger dynamic range than the $CO_2$ TCI. This is a consequence of three factors: (1) NO infrared emission is substantially more temperature dependent than the $CO_2$ emission, by a factor of exp(2700/T) vs. exp (960/T), where T is the neutral kinetic temperature; (2) NO is chemically active and its abundance is greater at times of higher solar activity; (3) The NO chemical abundance increases substantially at times of elevated and high geomagnetic activity.

**Table 1**
Ranges of NO power and $CO_2$ power within each quintile based on the 55-year time series of each shown in Fig. 1. The associated adjectival descriptors for the NO power (NO TCI) are shown in the right-most column.

| Percentile Range (%) | Range NO Power ($10^{11}$ W) | Range $CO_2$ Power ($10^{11}$ W) | Adjectival Descriptor |
|---|---|---|---|
| 0–20% | 0.0–0.743 | 0.0–6.917 | COLD |
| 20 - 40% | 0.743–1.190 | 6.917–7.460 | COOL |
| 40–60% | 1.190–1.801 | 7.460–8.265 | NEUTRAL |
| 60–80% | 1.801–2.608 | 8.265–9.303 | WARM |
| 80–100% | 2.608–4.937 | 9.303–12.398 | HOT |

Fig. 2 shows the frequency of occurrence of power values for the NO TCI (top frame) and $CO_2$ TCI (bottom frame). The shape of the frequency distribution is similar both NO and $CO_2$ in that the highest frequencies of power occurrence are near the lowest levels of radiated power. Also shown in each figure of the locations of the 20th, $40^{th}$. $60^{th}$, and $80^{th}$ percentiles of the range of radiated power, indicated by an enumerated vertical line. These lines define the five quintiles of the distribution of radiated power for NO and $CO_2$. There are just over 5000 days in each quintile. Table 1 lists the ranges of NO and $CO_2$ power corresponding to each quintile and provides adjectival descriptors (Cold, Cool, Neutral, Warm, Hot) for these. An interesting result of this analysis is that the dates of occurrence of the quintile distributions for NO and $CO_2$ are essentially coincident, as shown in Fig. 3. The different colors correspond to the different quintiles of data shown in Fig. 2. From Fig. 3 we conclude that there is no material temporal difference in the occurrence of NO and $CO_2$ TCIs.

We choose NO TCI as the preferred index because of its larger dynamic range and its greater sensitivity to geomagnetic effects [see Fig. 4, M1], thus more accurately reflecting the response of the thermosphere to variability in solar irradiance and geomagnetic conditions. Fig. 4 shows the complete NO TCI from 1947 to 2018. The percentile ranges are given

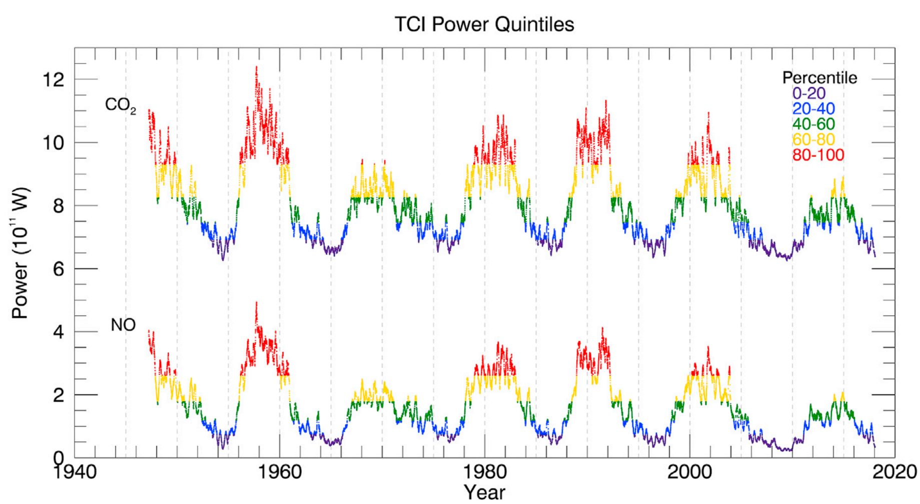


**Fig. 3.** NO and $CO_2$ TCI from 1947 to 2018, color coded according to the five quintiles of each parameter. The NO and $CO_2$ TCI quintiles are observed to be nearly coincident in time.

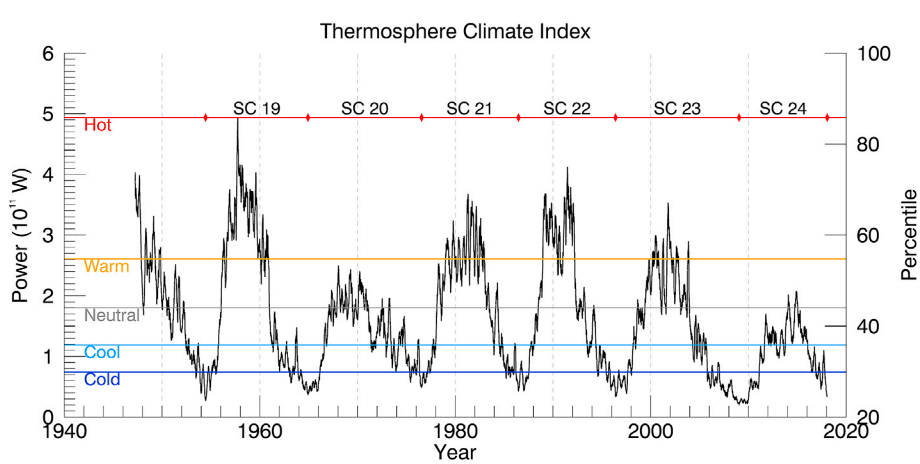


**Fig. 4.** The TCI empirically derived from 1947 to 2018. Quintile ranges based on the frequency of occurrence of power over SC 19–23 are provided on the right ordinate. Color-coded adjectival descriptors of the thermal state of the thermosphere are indicated along the left ordinate, and colored horizontal lines across the figure help visualize the ranges during the different solar cycles.

in the plot and shown on the right ordinate and the adjectival descriptors from Table 1 are shown along the left ordinate. In early 2018, the thermosphere is observed to be in a "Cold" state based on the current value of the NO TCI. Fig. 4 also shows that the thermosphere during solar cycle 24 was in a "Warm" condition for only a brief period of time between 2014 and 2015, and by this measure, was the coolest solar maximum of the last seven solar cycles.

## 3. Summary

We have evaluated the time series of infrared power radiated from the thermosphere by NO and by $CO_2$ based on the empirically-derived relations between these and the F10.7, Ap, and Dst indexes described in M1 and M2. These NO and $CO_2$ thermosphere climate indexes are shown to be temporally coincident in terms of occurrence of the quintile ranges. Dividing the time series into quintiles based on ranges over 5 complete solar cycles, we classify each range with an adjectival descriptor indicative of the thermal state of the global thermosphere. The NO TCI is recommended as a new solar-terrestrial Index representative of the thermal conditions in the global mean thermosphere. Future work will involve relating the NO TCI to the global exosphere temperature or other state variables in the thermosphere. Weimer et al. (2015) have already demonstrated strong correlations between the NO and $CO_2$ power and the exosphere temperature. Thus, the possibility exists to develop an index similar to the NO and $CO_2$ TCIs that relate combined solar and geomagnetic indexes to the exosphere temperature.

The ongoing NO TCI time series will incorporate the SABER-derived NO TCI for as long as the instrument continues to operate. However, the index can be carried on indefinitely after the SABER era, using the ongoing measurements of F10.7, Ap, and Dst. In the long-term the TCI can be used to diagnose changes in solar irradiance output over different solar cycles, as done in M2. The TCI data are available at https://saber.gats-inc.com.

## Acknowledgement

This work was supported under the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics satellite project. The data used in this study are available on the SABER project website, https://saber.gats-inc.com. The NO TCI data are also available at the same website and will be updated on a routine basis.

## Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jastp.2018.04.004.

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