A combined solar and geomagnetic index for thermospheric climate

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Introduction

The climate of the thermosphere is controlled in part by cooling to space driven by infrared radiation from carbon dioxide (CO2, 15µm), nitric oxide (NO, 5.3µm), and atomic oxygen (O, 63µm). The Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) instrument on the NASA Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite has been measuring infrared cooling from CO2 and NO in the thermosphere since January 2002. These data provide integral constraints on the energy budget and climate of the atmosphere above 100 km.

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.

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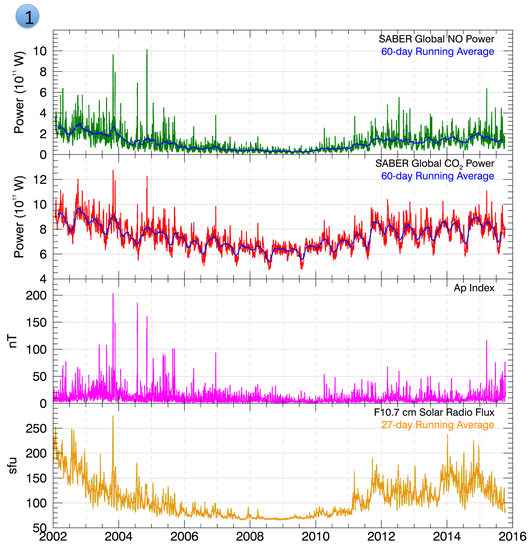

Methodology

We start by looking at the daily global infrared power (W) radiated by the NO molecule at 5.3 µm. The NO power is derived by integrating with respect to altitude (from 100 to 250 km) each vertical profile of NO radiative cooling (W/m3) and then integrating this with respect to latitude and longitude (area).

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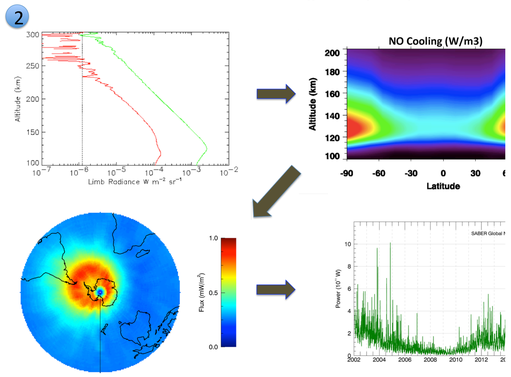

Methodology (cont.)

Approximately 1500 vertical profiles of radiative cooling per day go into the global calculation, and more than 5000 days of data have been obtained over nearly 14 years. 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 approximately 11-year solar cycle.

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We then construct a 60-day running mean, which gives a consistent average of NO power over all local times for each point in the time series. For purposes of the multiple linear regression fit, we also compute the 60-day running means of the F10.7, Ap, and Dst indices. F10.7 is a commonly used proxy for solar UV and EUV irradiance and its variation. The 60-day running means of these parameters are shown in Figure 3.

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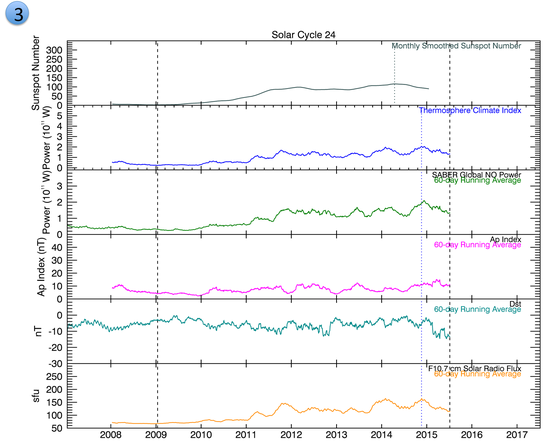

Visual correlations between the Ap, F10.7, and Dst indices and the NO power are evident upon examination of Figure 3. These strongly suggest that the NO power time series can be fit with a multiple linear regression involving these three standard solar and geomagnetic indices. Figure 4 shows the results of this fit. The multiple correlation coefficient of the regression fit to the observed power is 0.983. 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 F10.7 was found to slightly improve the agreement in regions where there is a marked peak in the NO power.

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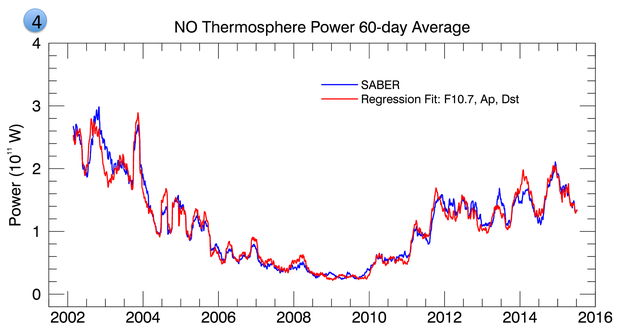

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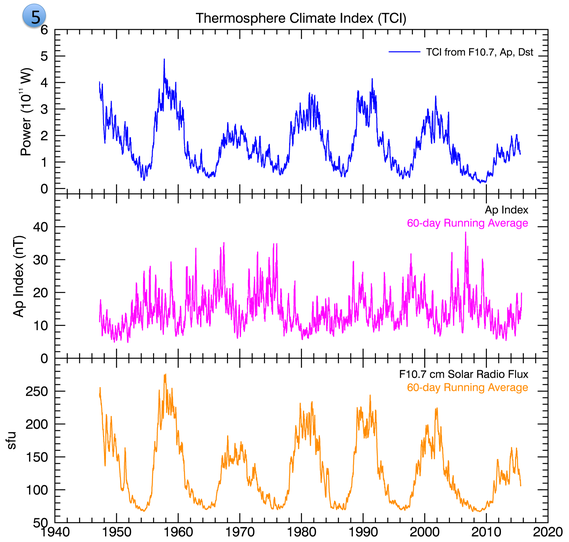

The fit shown in Figure 4 is remarkable in the sense that the complex photochemical and geomagnetic energetic processes that ultimately lead to thermospheric infrared cooling can be represented so accurately by three standard solar and geomagnetic indices. This allows extension of the fit back in time with existing databases of the three standard indices. F10.7 data are available back to 1947, and both Ap and Dst extend back even further. From these we can construct a time history of NO cooling over nearly 70 years and covering almost seven solar cycles, from the peak of solar cycle (SC) 18 to the peak of SC 24 today. Given the fundamental role NO plays in the energy budget of the thermosphere, the time series shown in Figures 5 and 6 provides a long-term record of an integral constraint on the energy budget of the atmosphere above 100km.

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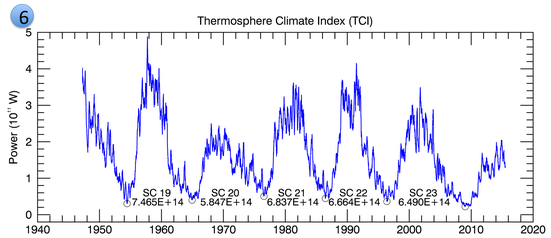

Discussion

Figure 6 also lists below each of the five complete solar cycles the integrated power (W) radiated during each solar cycle. Despite the maximum power varying by a factor of 2, the integrated power varies only by 25% due to the varying duration of each solar cycle.

We have also investigated the relationship of the peak in the solar cycle as given by the occurrence of sunspot maxima with the peak in radiative cooling by NO. We find no definitive relationship between the occurrence of sunspot maximum and radiative cooling maximum. In solar cycles 19, 20, and 23, the sunspot maximum occurs after the maximum in NO cooling. In cycles 21, 22, and 24, the NO cooling maximum occurs after the sunspot maximum. The sunspot number is strongly correlated with F10.7 (and hence solar ultraviolet irradiance), but not with Ap (i.e., geomagnetic processes). The NO cooling is driven by both solar ultraviolet irradiance and geomagnetic processes.

The long-term time series shown in Figure 5 can be separated into its solar UV and geomagnetic components using the coefficients derived for the fit shown in Figure 4. The expression for the fit shown in Figure 2 is

$$NO = a0 + a1 * F10.7 + a2 * Ap + a3 * Dst$$

where each term is the 60 day running mean of that parameter. This expression can be used to determine the relative roles of solar and geomagnetic processes, which over the 70 year record works out to approximately 70% due to solar energy deposition and about 30% due to geomagnetic processes, on average. Figure 7 shows these processes and their varying relationship over the solar cycle (illustrated by the monthly smoothed sunspot number in light grey).

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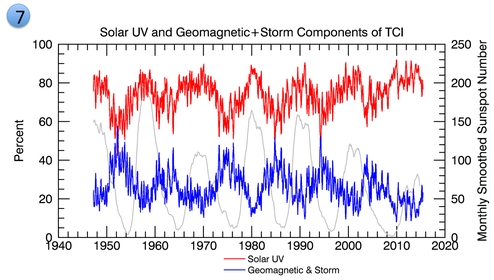

Conclusion

Infrared radiation from nitric oxide (NO) at 5.3 µm is a primary mechanism by which the thermosphere cools to space. The 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 readily available databases of the F10.7 solar radio flux, the Ap index, and the Dst index.

This reconstructed time series enables tests of upper atmosphere climate models over the last six solar cycles. The multiple regression fit has also enabled determination of the relative roles of solar irradiance and geomagnetic processes in driving the NO cooling.

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.

Reference

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.

Acknowledgments

F10.7 Solar Radio Flux and Ap Index data obtained from the NOAA Space Weather Prediction Center, http://www.swpc.noaa.gov
Dst data downloaded from the University of Oulu Dsx server, http://dcx.oulu.fi
International sunspot number data source WDC-SILSO, Royal Observatory of Belgium, Brussels, version Nb. 2.0; http://sidc.be/silso
The SABER NO and CO2 power datasets can be obtained by contacting Linda.A.Hunt@nasa.gov.