Solar induced variability in the thermosphere over the last 70 years

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Outline

- The Big Picture
- Overview of Thermosphere Energy Budget
- Radiative Cooling in the Thermosphere 2002 - present
- A View to the Past
  - Are solar cycles more similar than different?
- Summary

The Big Picture….

- **Major objective is to understand the climate and energy balance of the thermosphere**

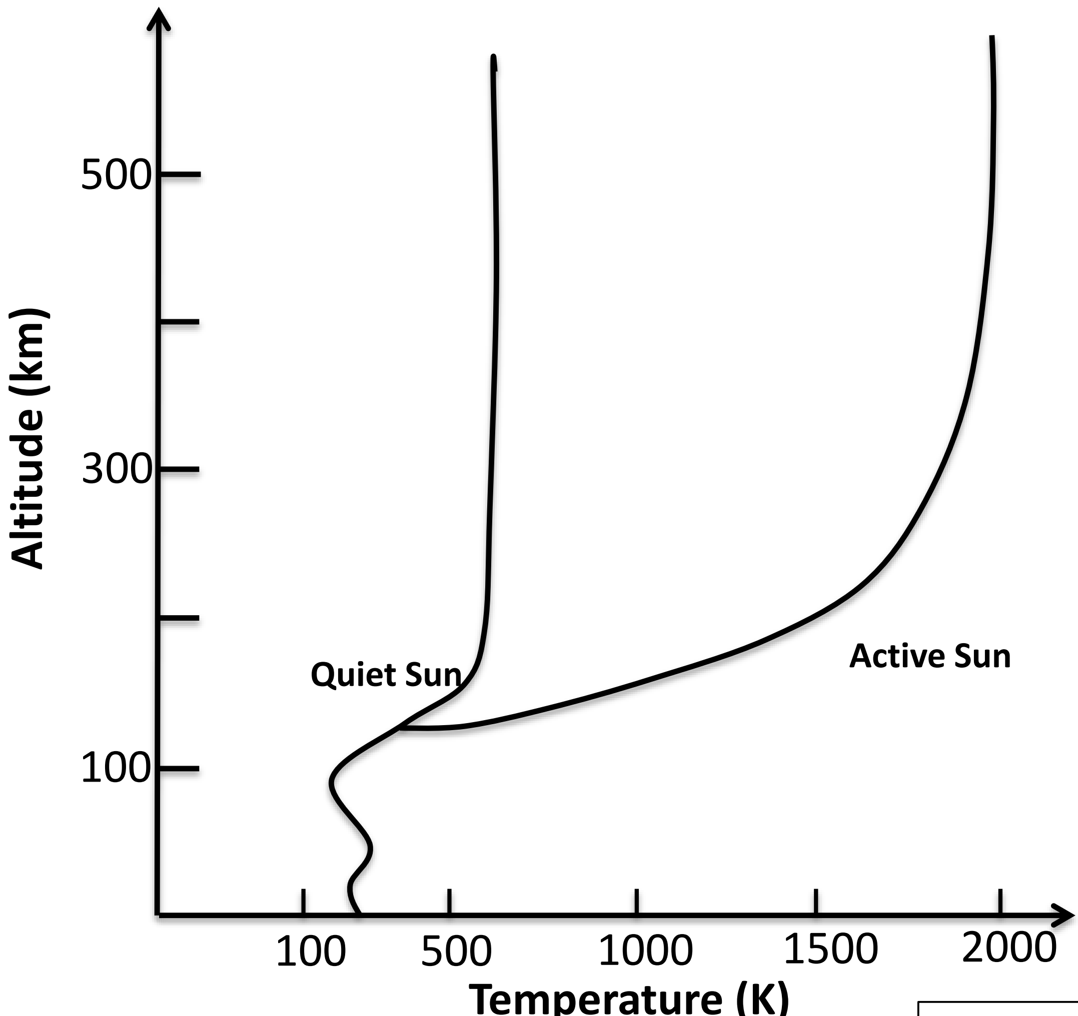
- **This is a very complex interaction of radiative transfer, chemical/gas kinetics, energy storage, energy conversion, and solar physics**

- **We have learned over the past 14 years of observations from the TIMED satellite that the energy budget varies on time scales from a *few days* to *decades***

- **This presentation summarizes some of the major results to date**

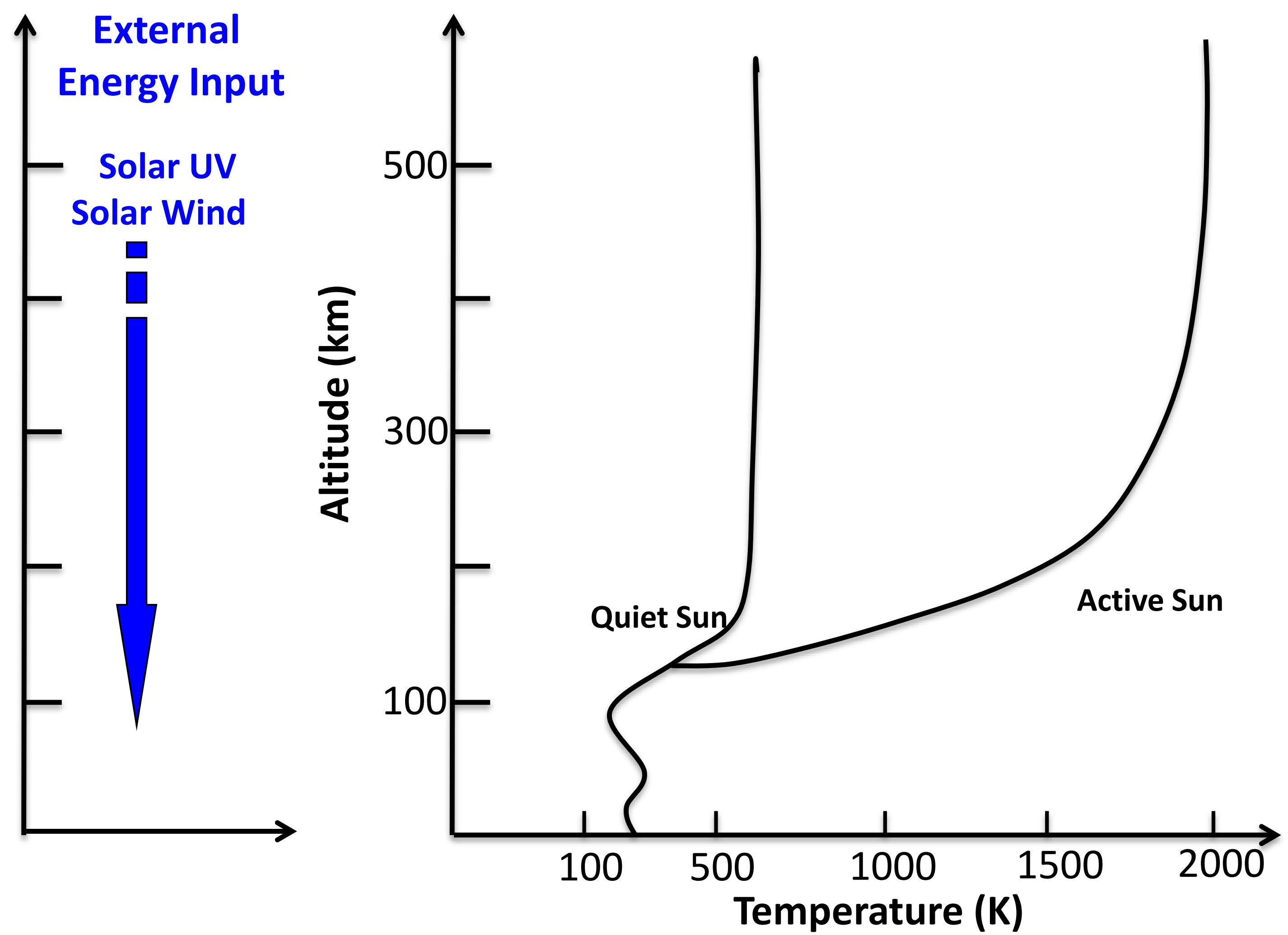
Overview of the Thermosphere Energy Budget

Thermosphere Energy Balance – Thermal Structure

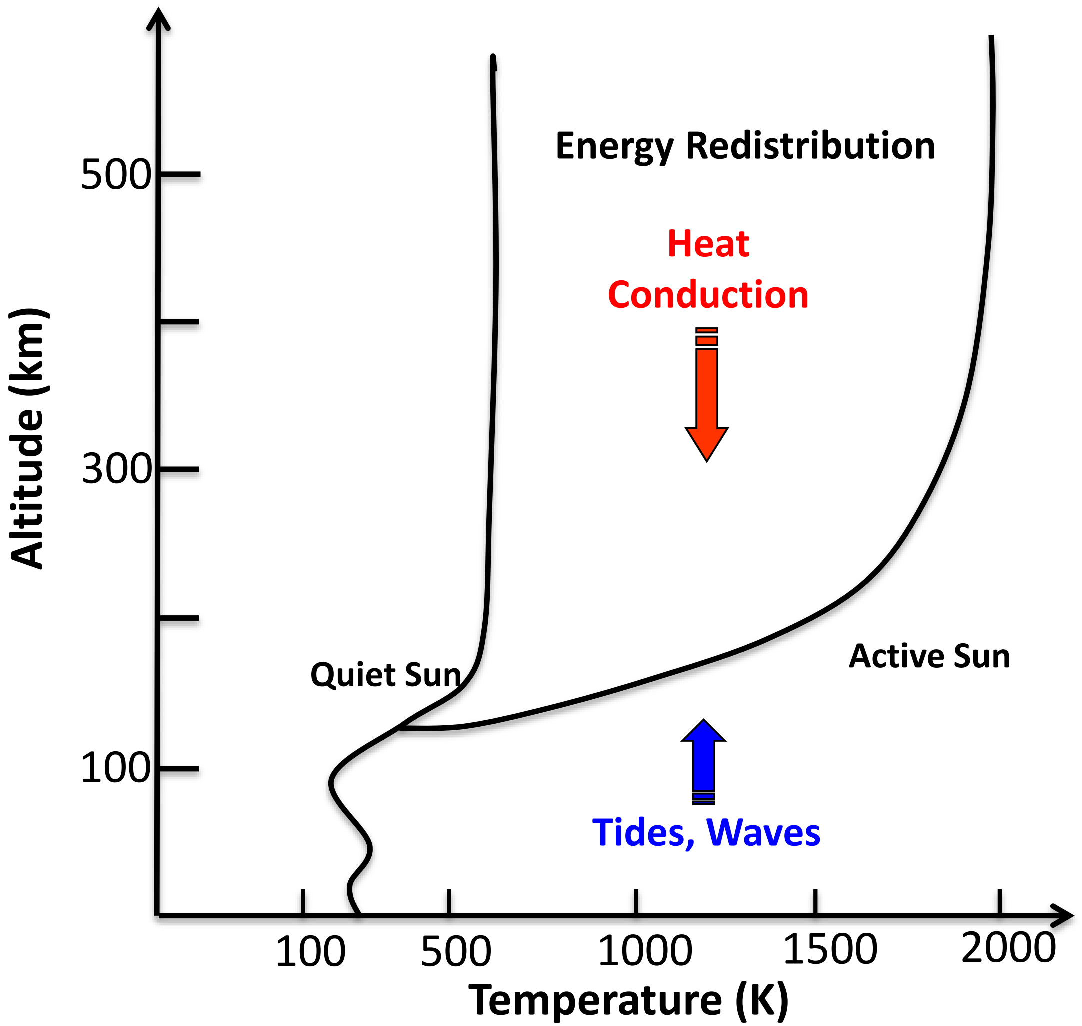


Banks and Kockarts, 1973

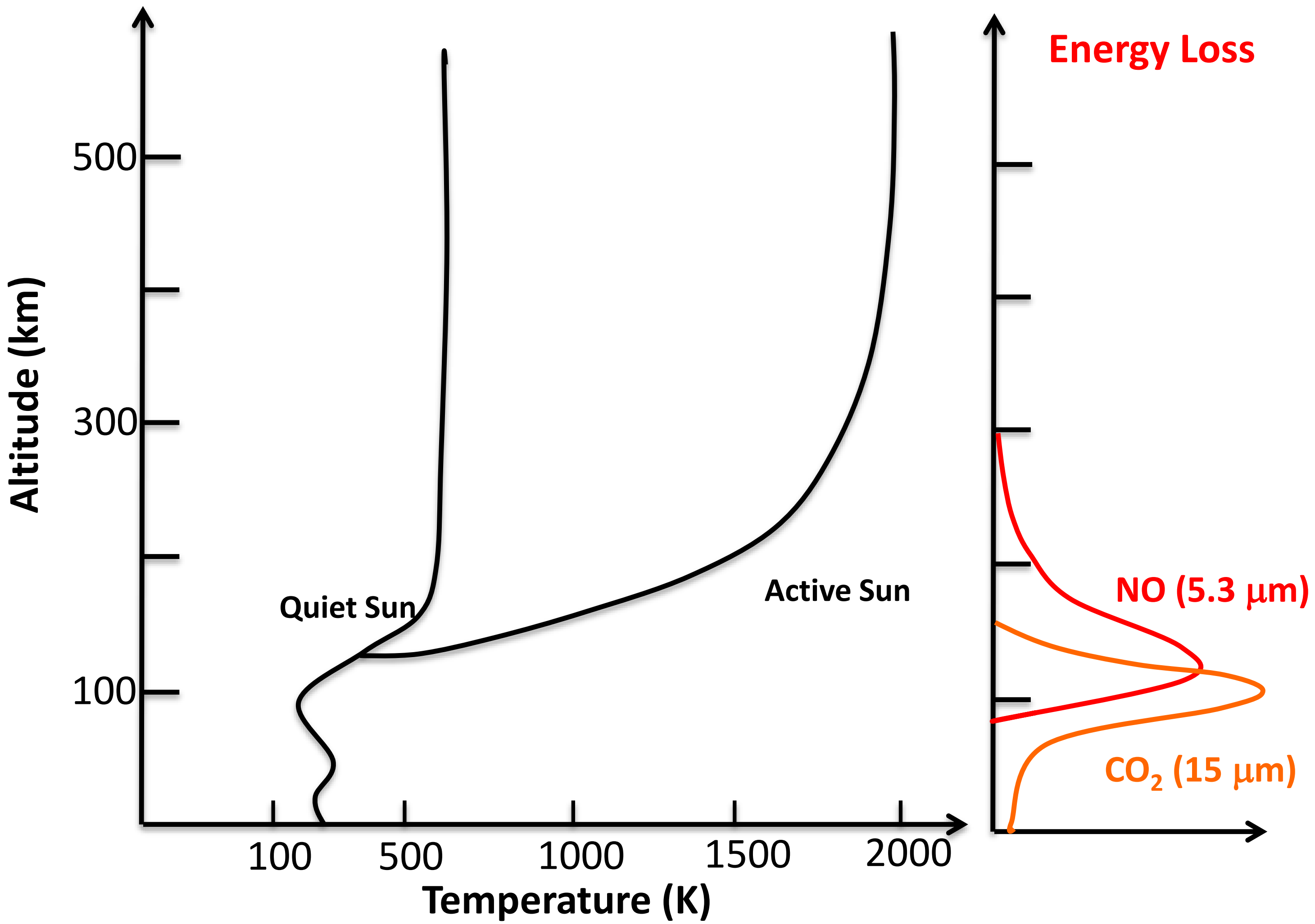
Thermosphere Energy Balance – Energy Inputs



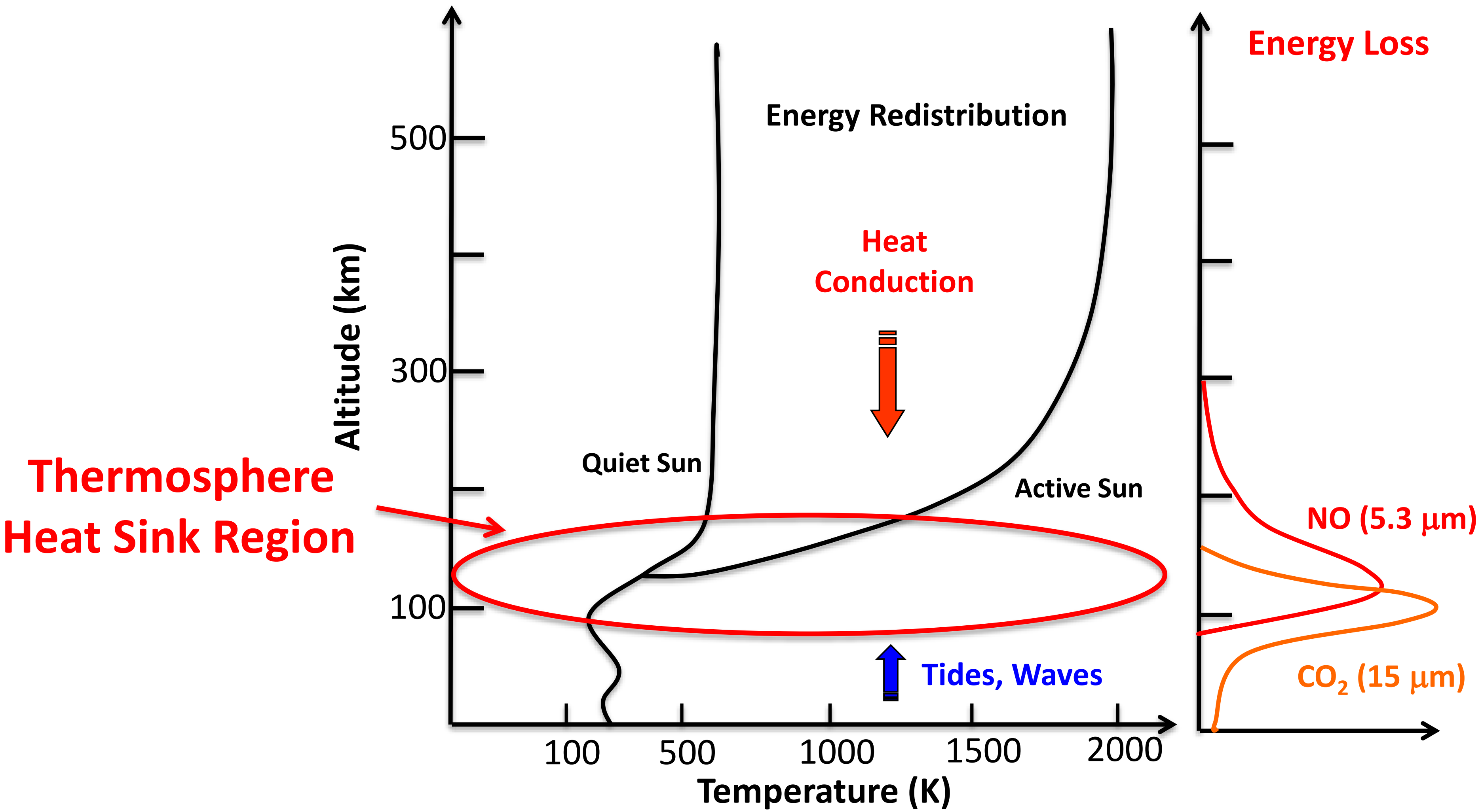
Thermosphere Energy Balance – Energy Redistribution



Thermosphere Energy Balance – Energy Outputs



Thermospheric Heat Sink



Radiative Cooling in the Thermosphere

Radiative Cooling in the Thermosphere

- Radiative cooling is the action of infrared radiation to reduce the kinetic temperature of the neutral atmosphere

- It is accomplished almost entirely by two species:
  - Carbon Dioxide (CO_2, 15 μm)
  - Nitric Oxide (NO, 5.3 μm)

- Collisions between atomic oxygen (O) and CO_2 and NO initiate the cooling process:

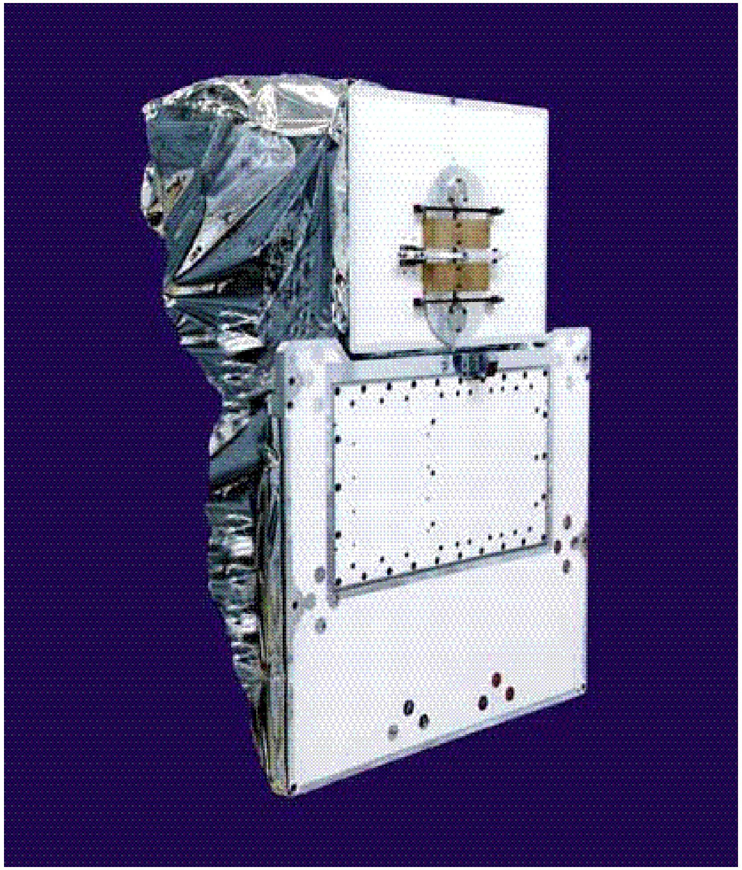
  - NO ($\upsilon = 0$) + O → NO ($\upsilon = 1$) + O (Kinetic Energy Removal)
  - NO ($\upsilon = 1$) → NO ($\upsilon = 0$) + $h\nu$ (5.3 μm) (Kinetic Energy Loss)
  - NO ($\upsilon = 1$) + O → NO ($\upsilon = 0$) + O (Kinetic Energy Returned)

- Collisional process are highly temperature dependent

Sounding of the Atmosphere using Broadband Emission Radiometry
-- SABER --

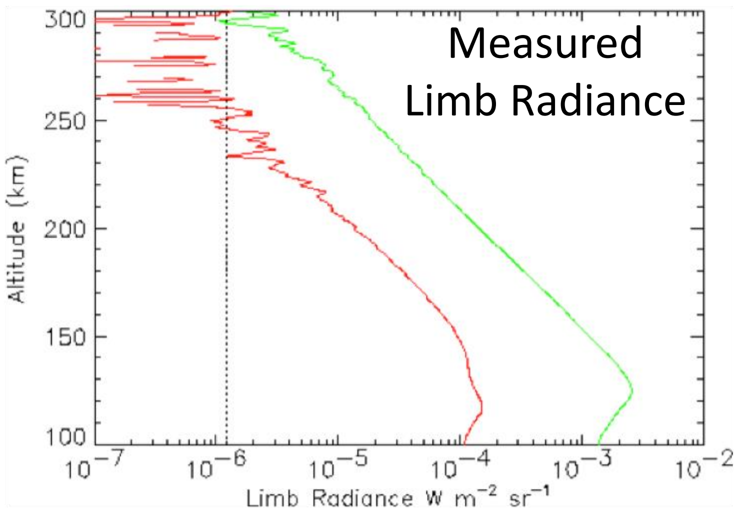
SABER Experiment

- Limb viewing, 400 km to Earth surface
- Ten channels 1.27 to 16 μm
- Over 30 routine data products including energetics parameters
- 8.3 million radiance profiles – per channel!
- Cryo-cooler operating excellently at 77 K
- Noise levels at or better than measured on ground
- Now in 15th year of on-orbit operation
- **Over 1200 refereed journal articles!**

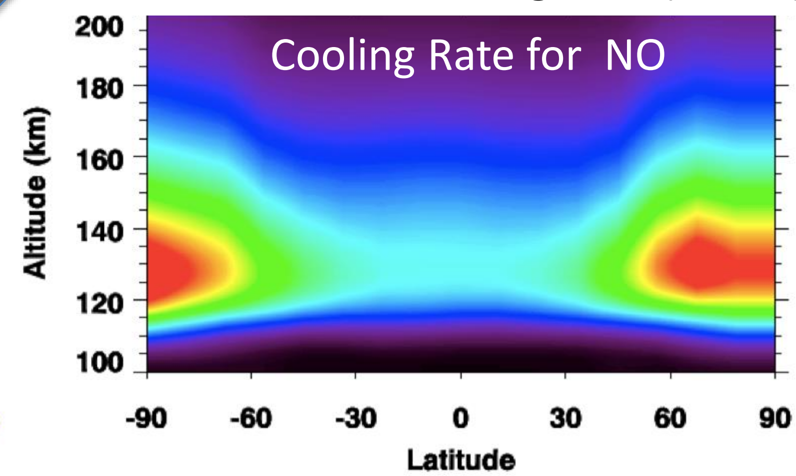


75 kg, 77 watts, 77 x 104 x 63 cm, 4 kbs

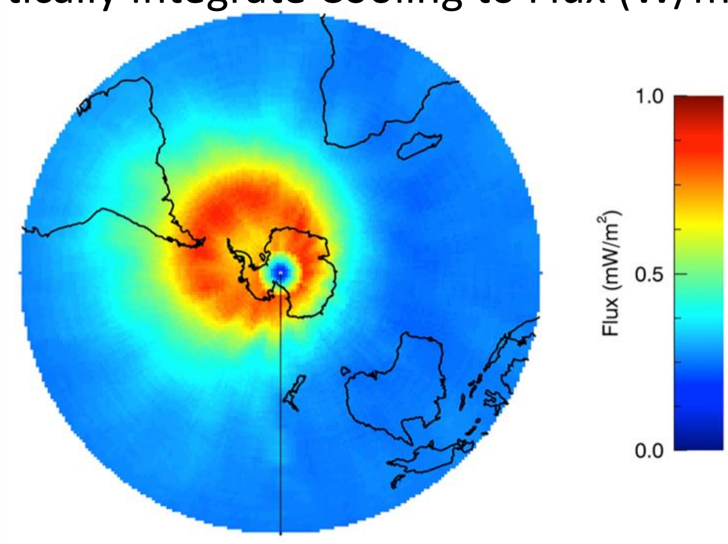
NO and CO_2 Cooling Parameter Derivations by SABER



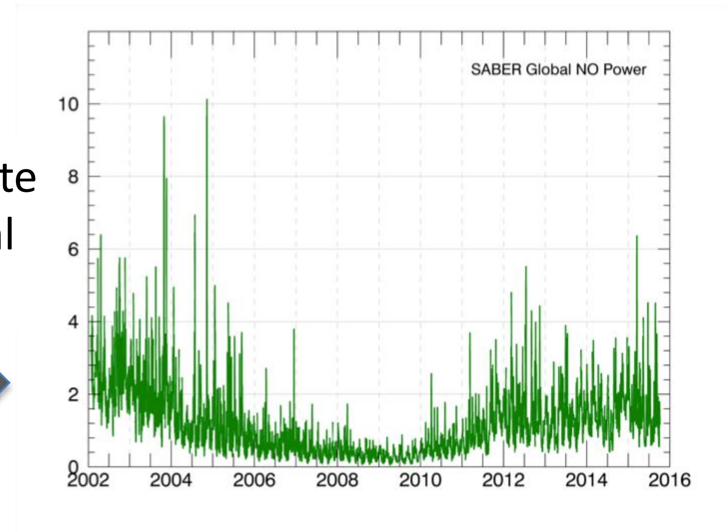
Abel Inversion to Cooling Rate (W/m³)



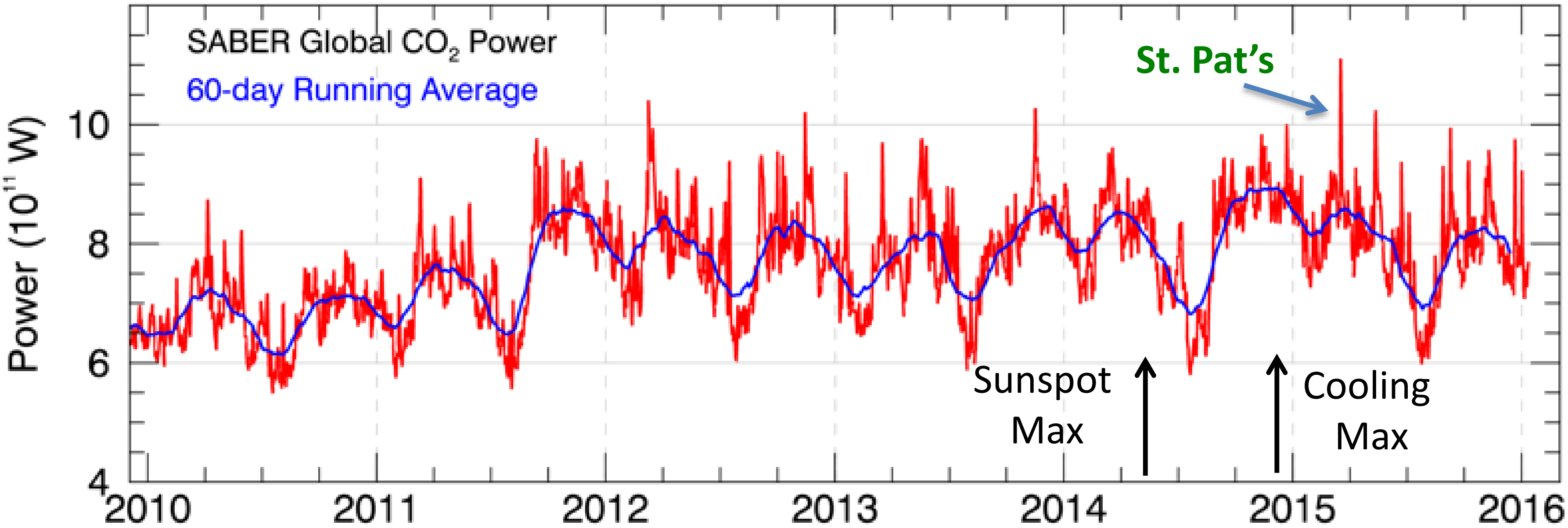
Vertically Integrate Cooling to Flux (W/m²)



Area integrate to get global power (W)



SABER Global Power from CO_2 in SC 24
Jan 2010 – Dec 2015; 100 – 140 km

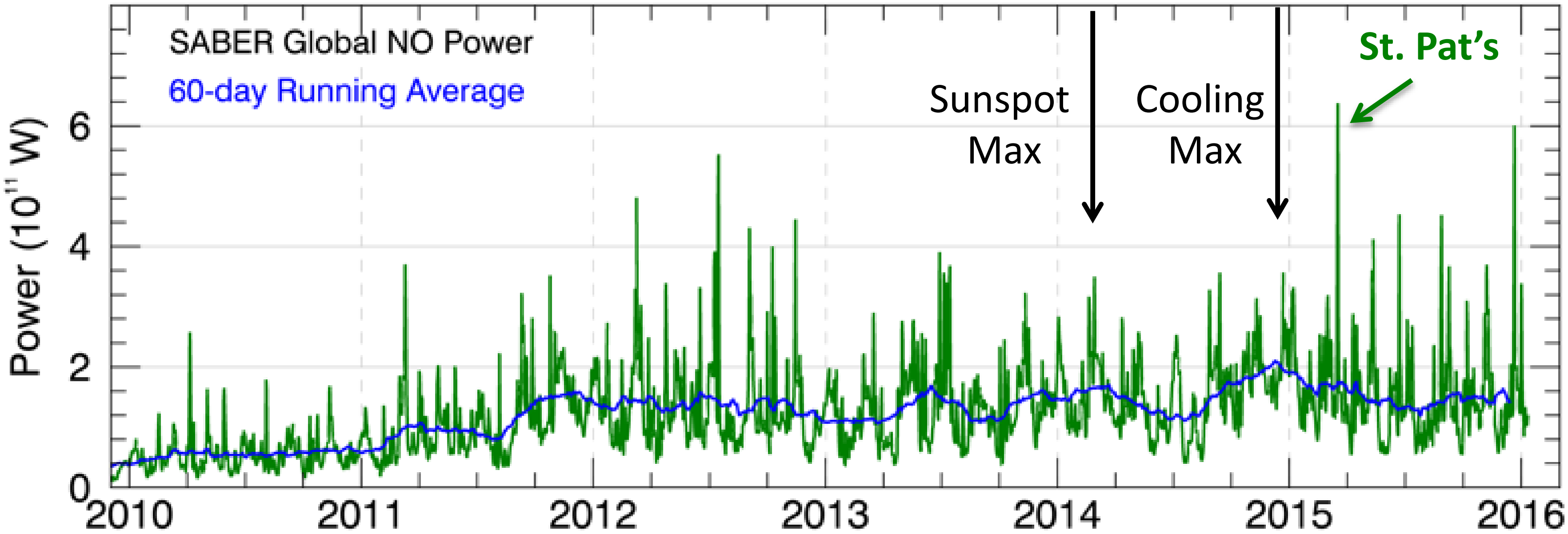


Sunspot and cooling maxima are not coincident

Strong semi-annual oscillation evident

Geomagnetic activity always evident in radiative cooling

SABER Global Power from NO in SC 24
Jan 2010 – Dec 2015; 100 – 250 km



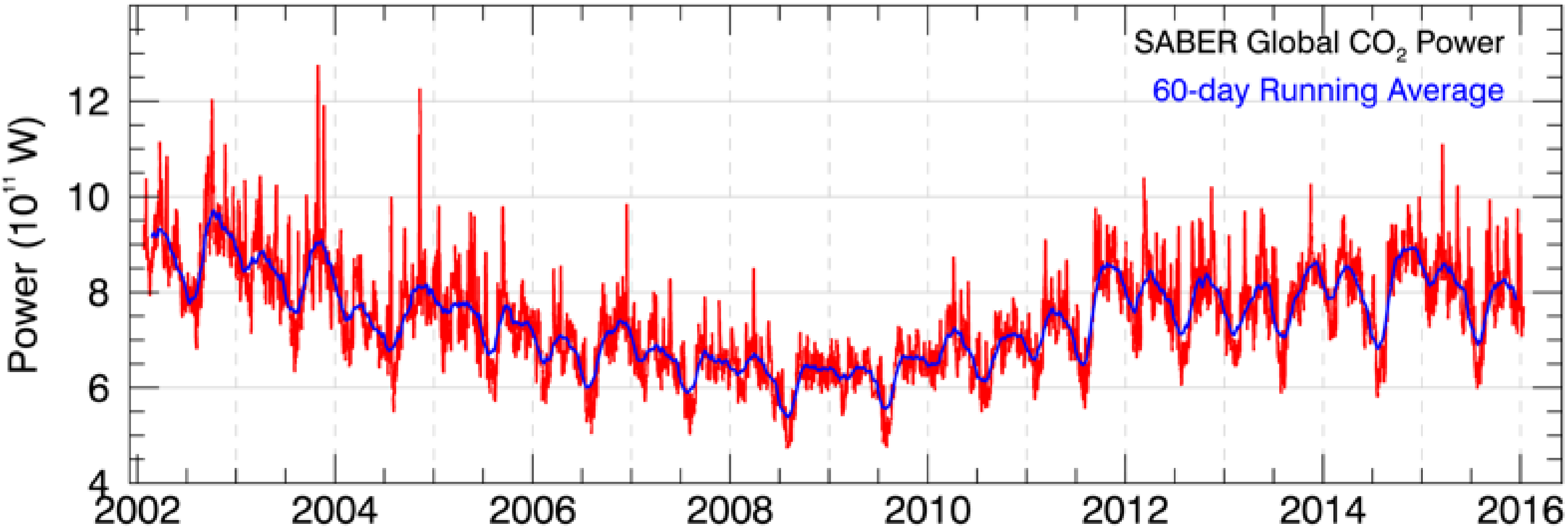
Sunspot and cooling maxima not coincident

Each "spike" is the response to a geomagnetic event

St. Patrick's Day Storm is largest event since 2010

SABER Global Power from CO_2
Jan 2002 – Dec 2015; 100 – 140 km

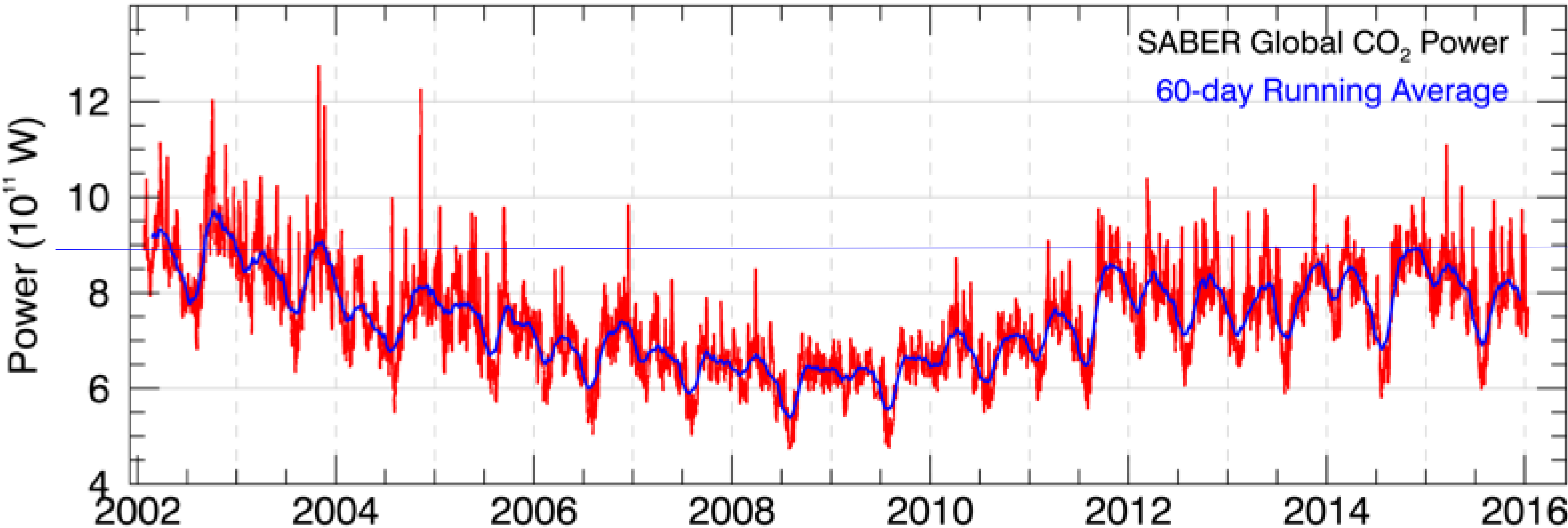
<u>Over 5200 days of data!</u>



Strong semi-annual cycle evident in global cooling
Evidence of response to geomagnetic activity in each "spike"

SABER Global Power from CO_2
Jan 2002 – Dec 2015; 100 – 140 km

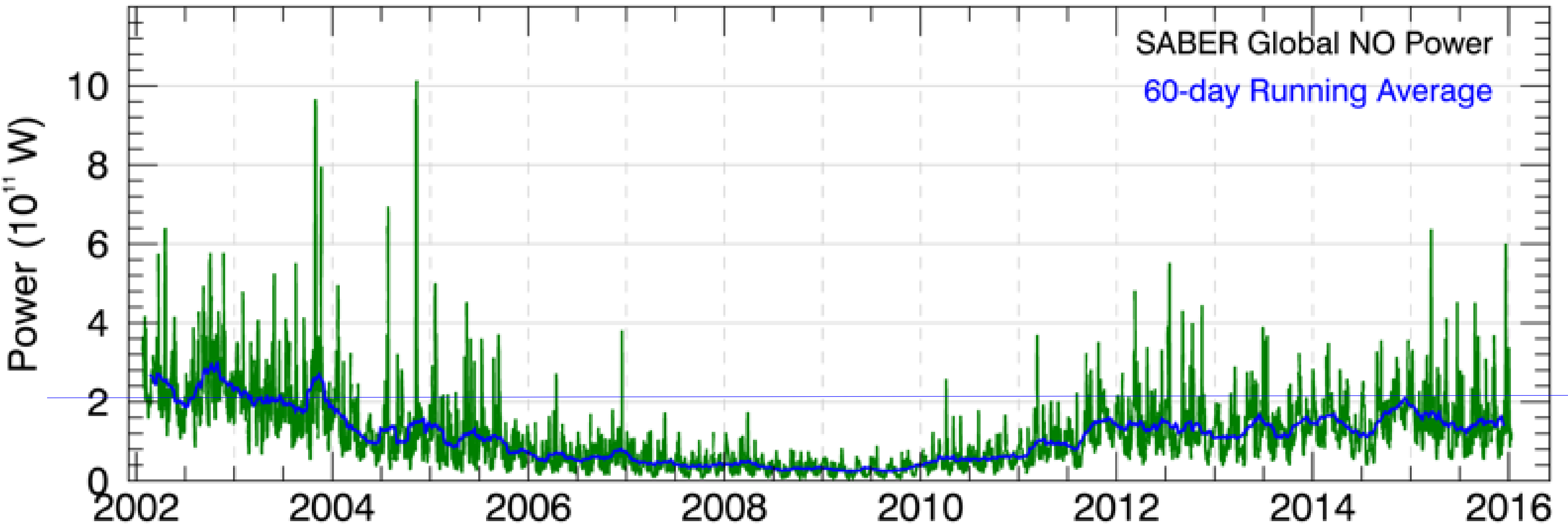
<u>Over 5200 days of data!</u>



SC 24 solar max (12/2014) as warm as 12/2003 – 11 years
SC 24 peak clearly weaker than SC 23

But, just how different in total energy are they?

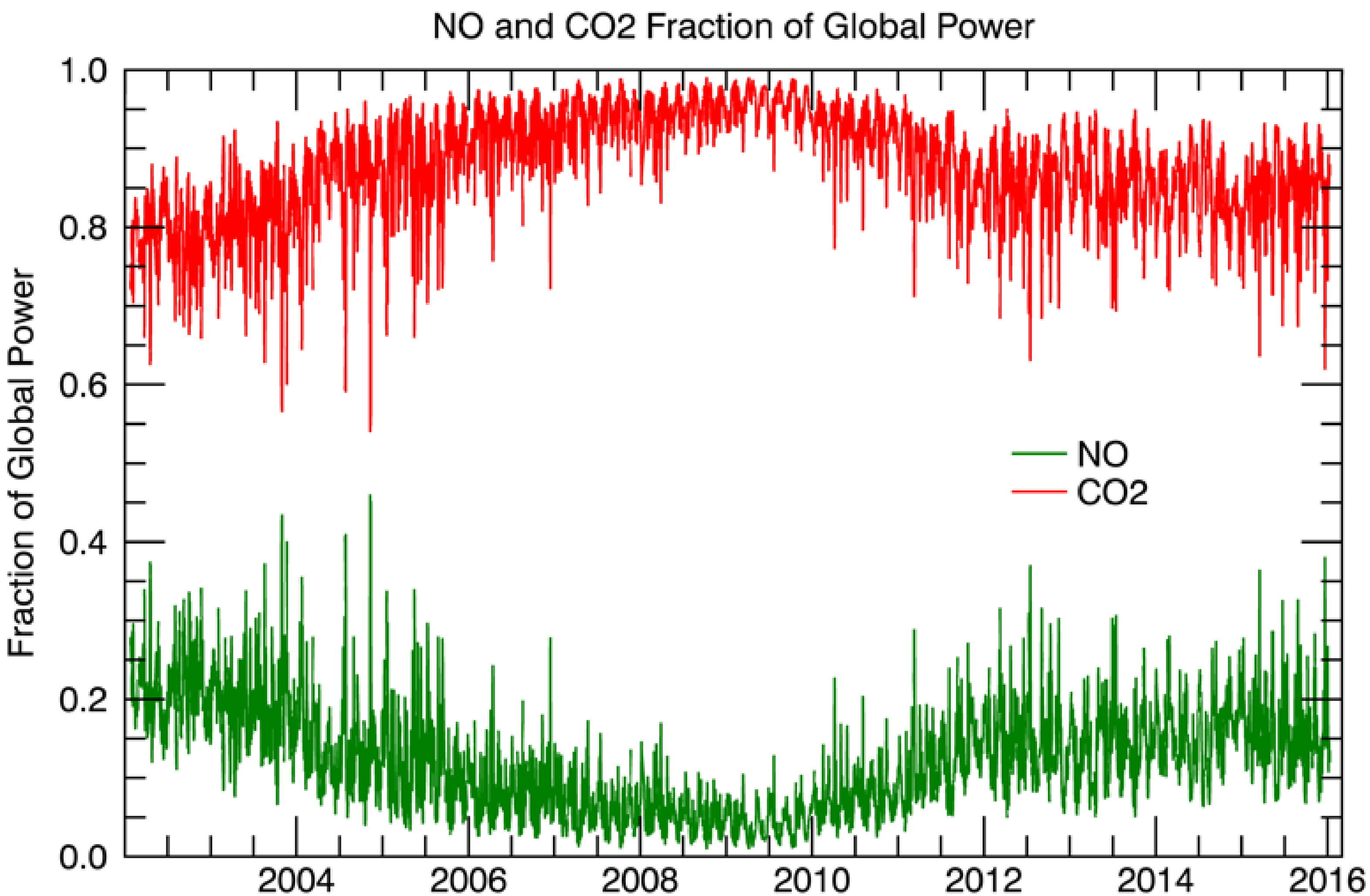
SABER Global Power From NO
Jan 2002 – Dec 2015: 100 – 250 km



NO Cooling at Peak of SC 24 (12/2014) was highest level since 12/2003

From the perspective of integrated energy,
just how different is one solar cycle from another?

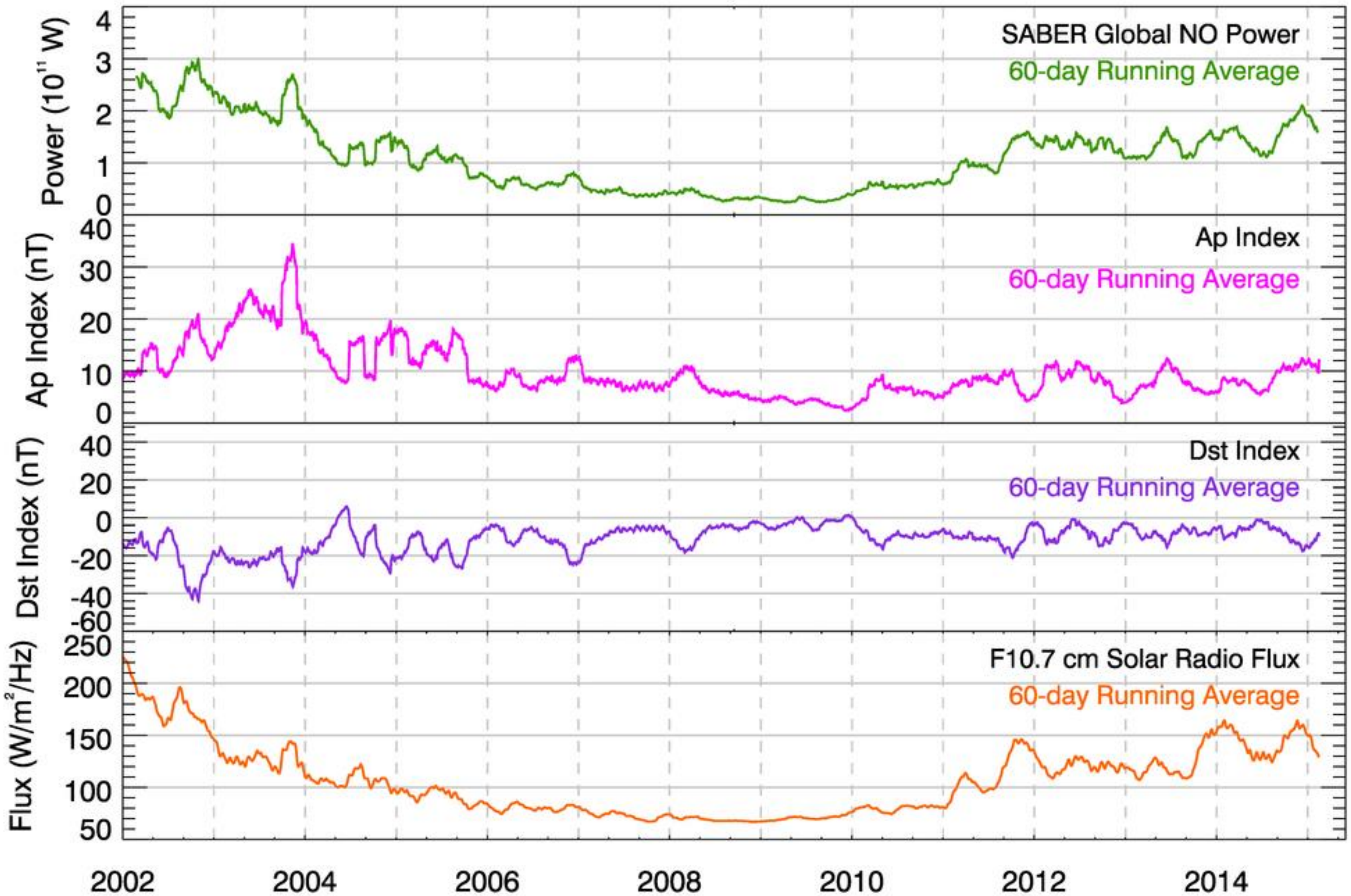
Fraction of Thermosphere Global Infrared Power
CO_2 and NO



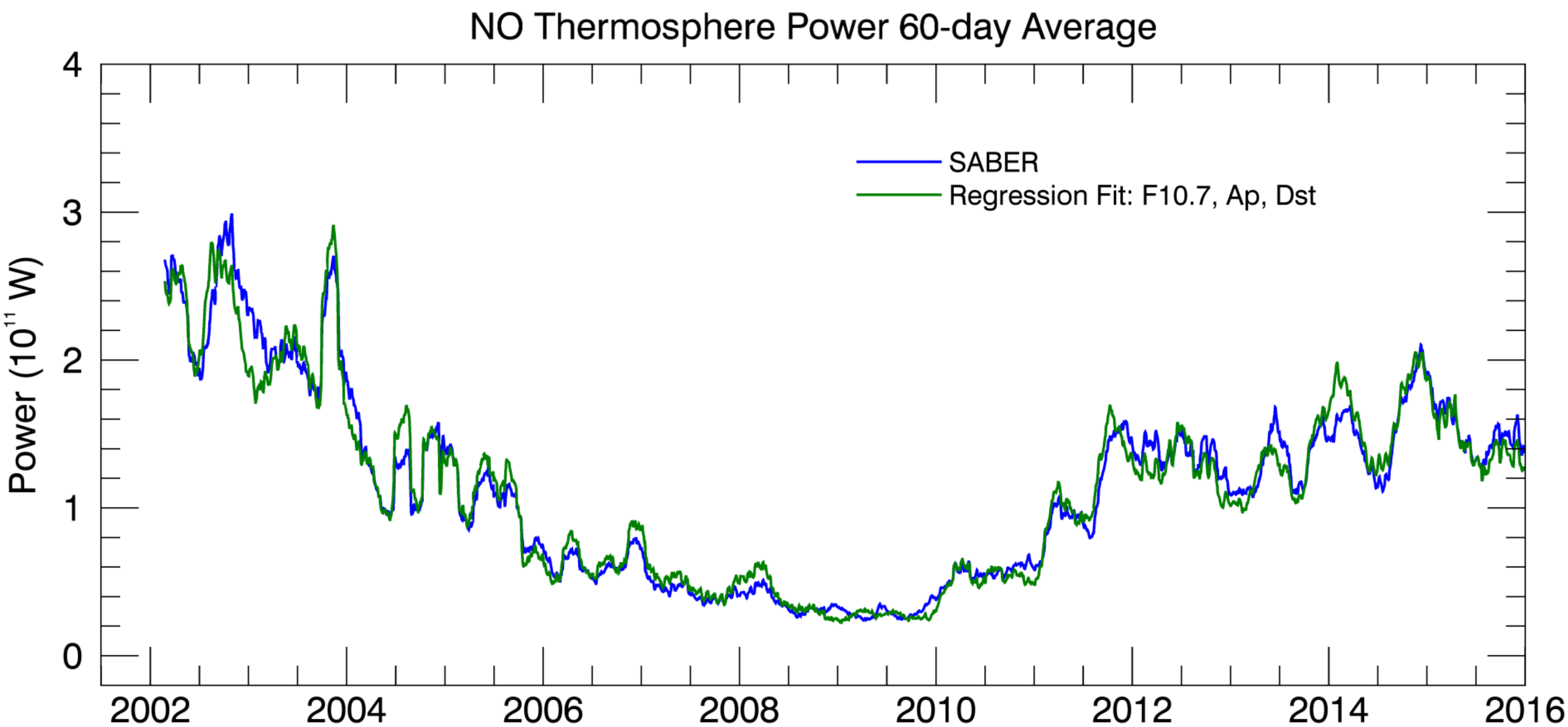
A View to the Past

60-day Running Means – Nitric Oxide Power

Strong Visual Correlation in NO, Ap, Dst, F10.7

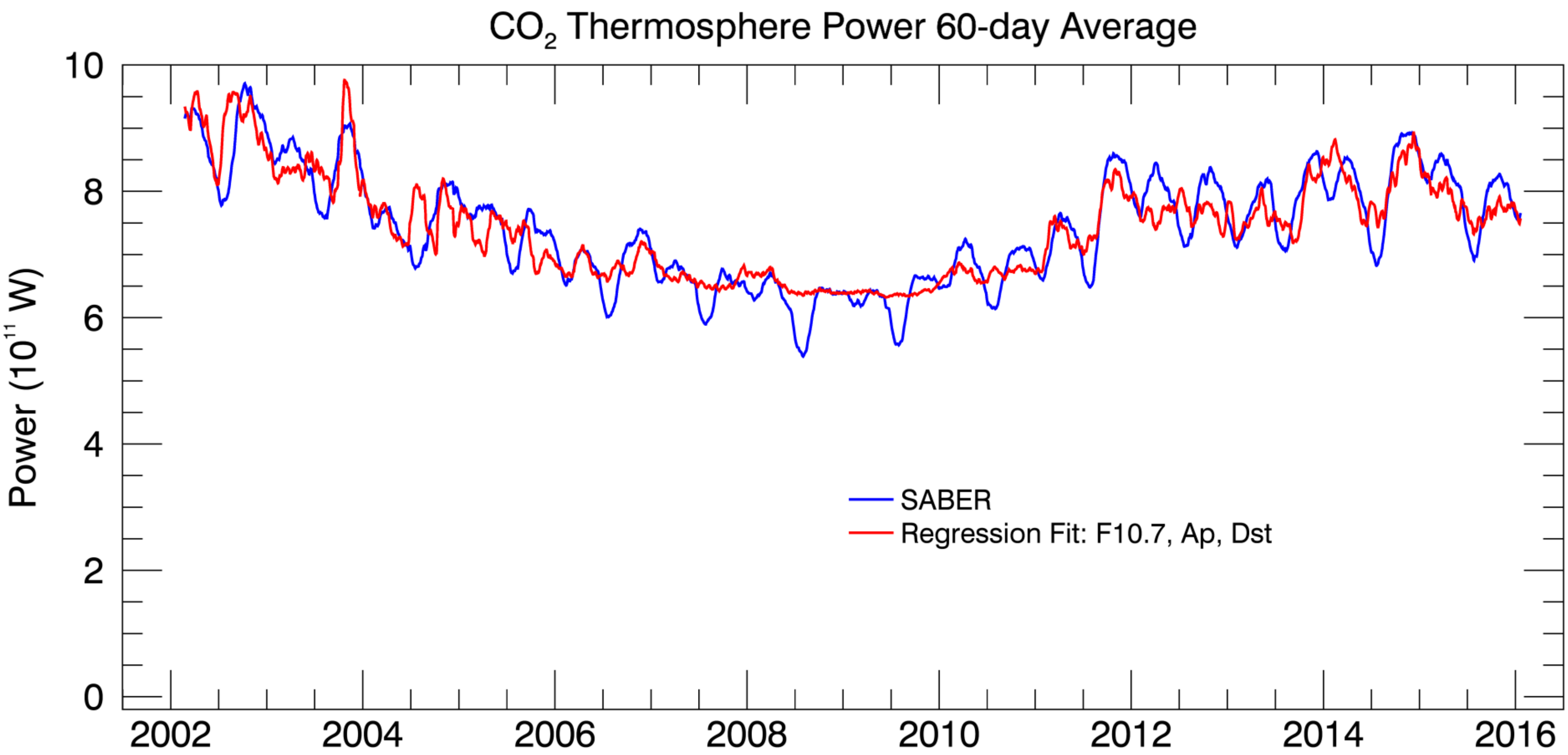


Multiple Linear Regression Fit
NO Power as Function of F10.7, Ap, Dst



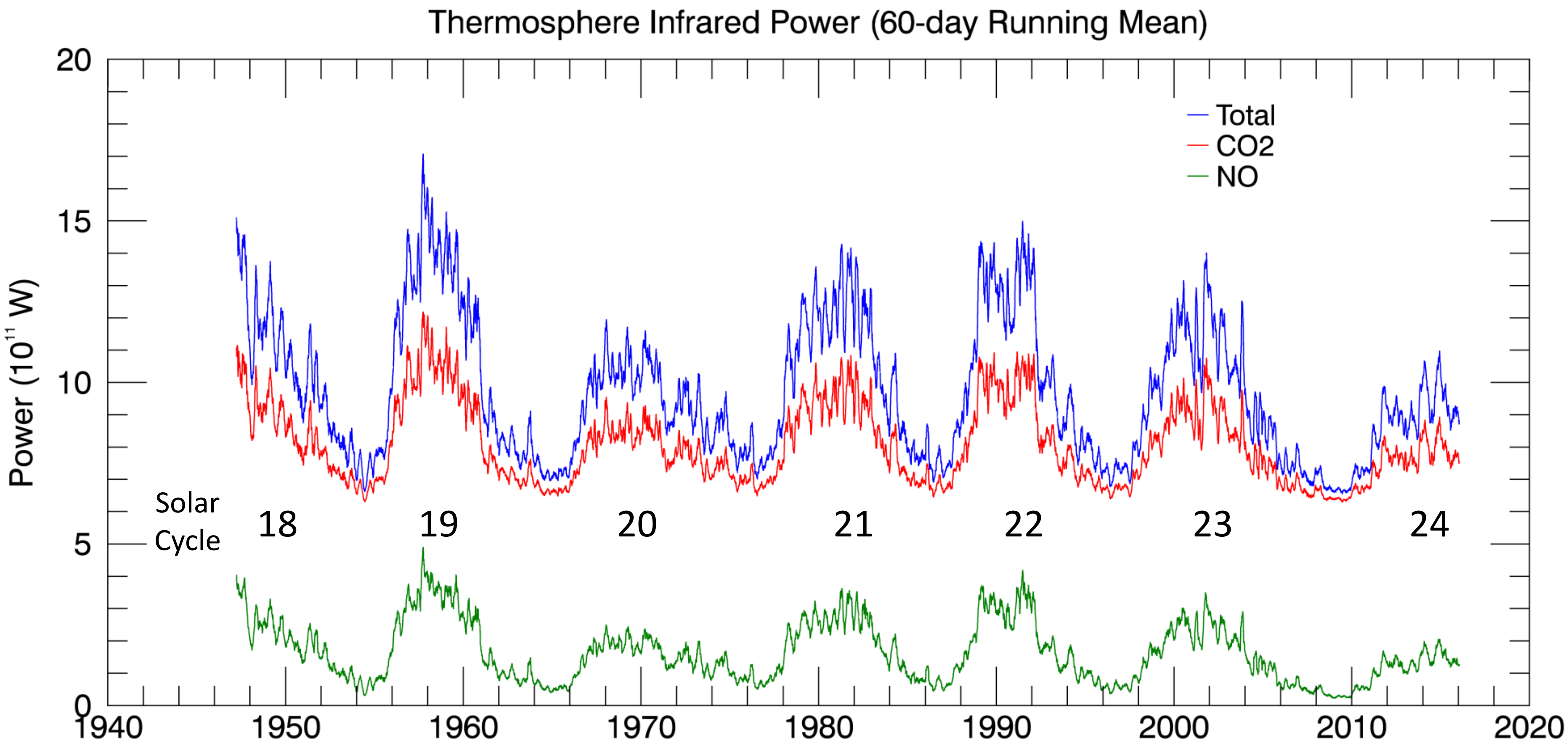
Correlation Coefficient: 0.983
Integrated area ratio - SABER NO to Fit: 0.999999

Multiple Linear Regression Fit
CO_2 Power as Function of F10.7, Ap, Dst



Correlation Coefficient: 0.898
Integrated area ratio - SABER CO_2 to Fit: 0.999998

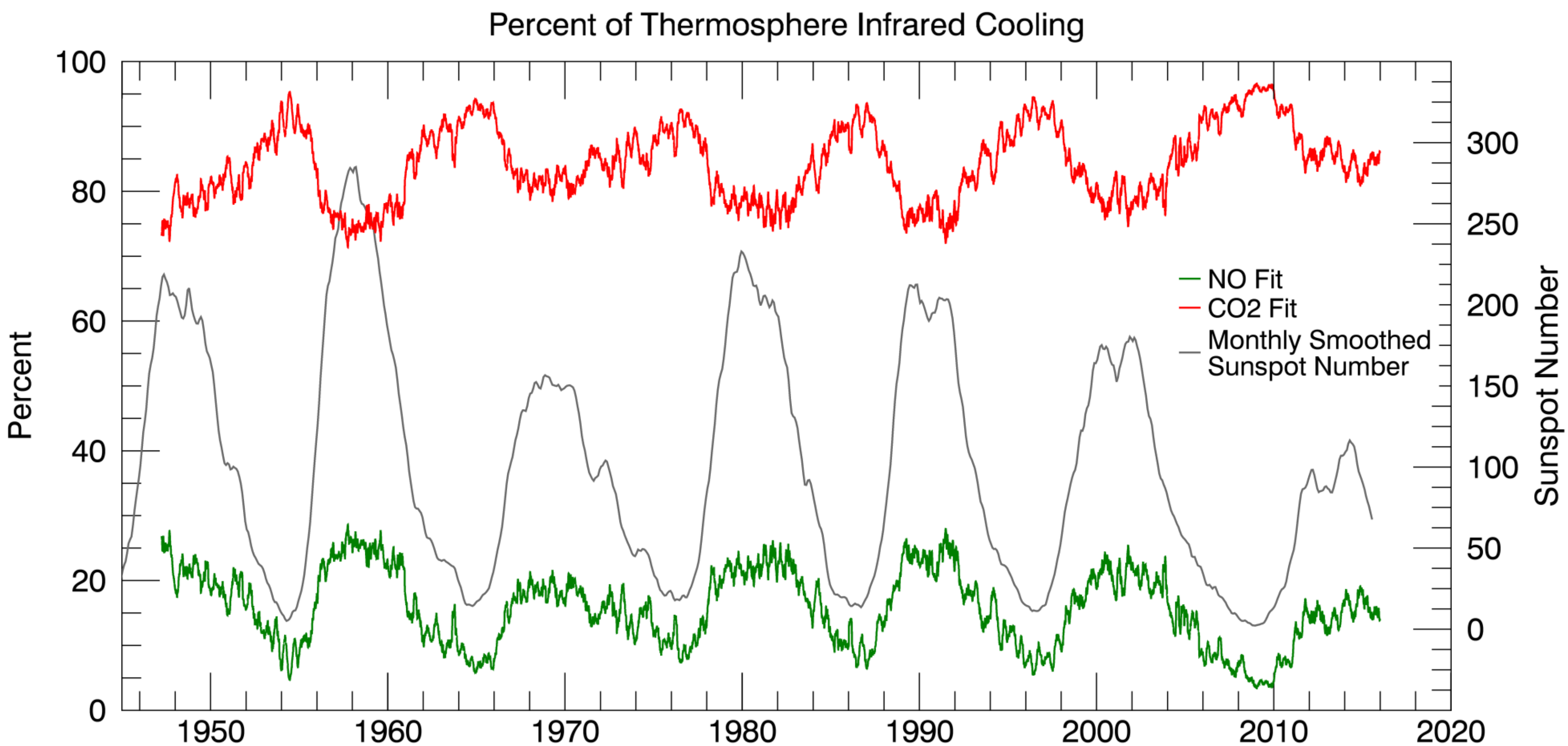
Thermosphere Infrared Power
as Function of F10.7, Ap, Dst



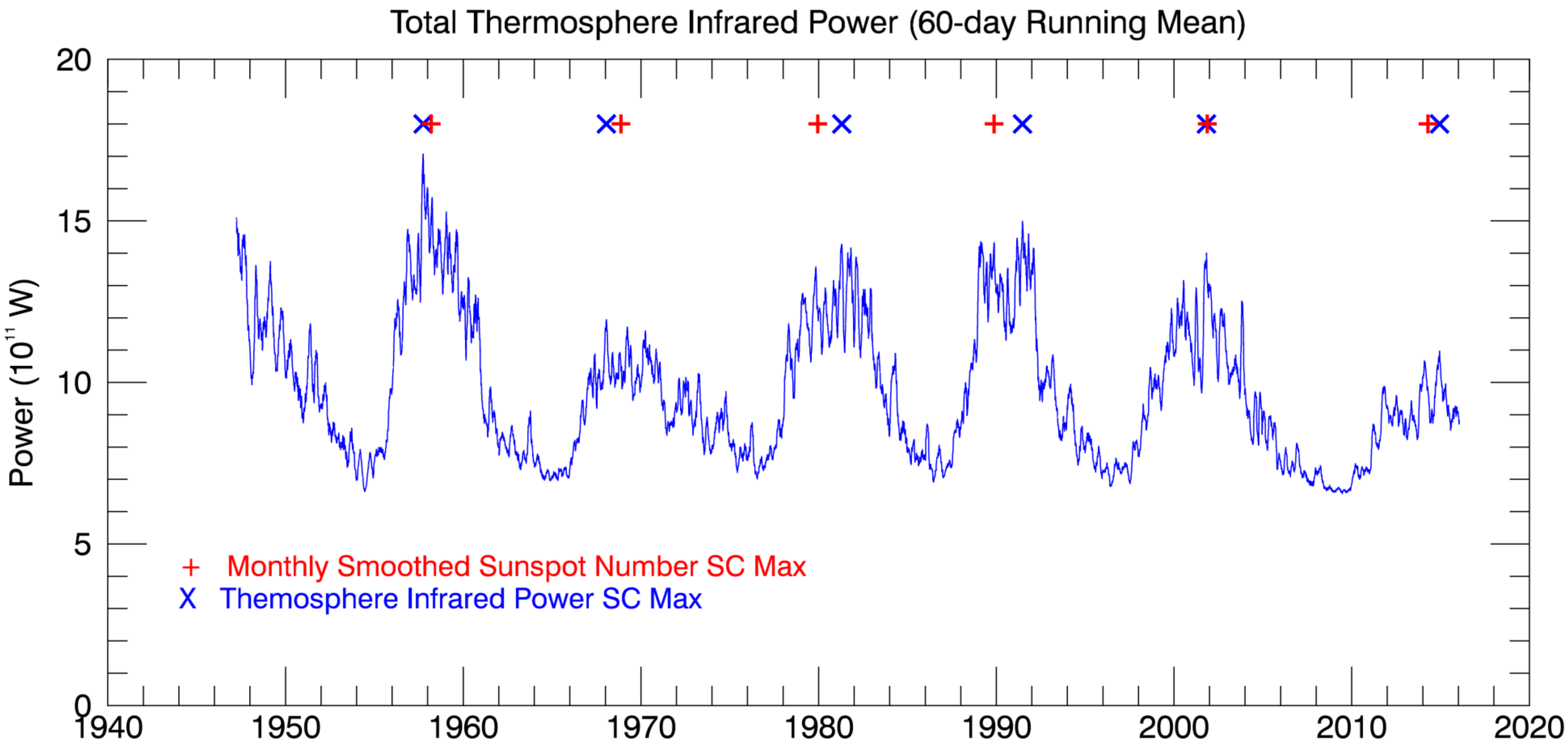
Reconstruct cooling time series back to 1947 using extant F10.7, Ap, Dst

CO2 is the dominant cooling mechanism above 100 km

Percent of Thermosphere Infrared Cooling
CO_2 and NO

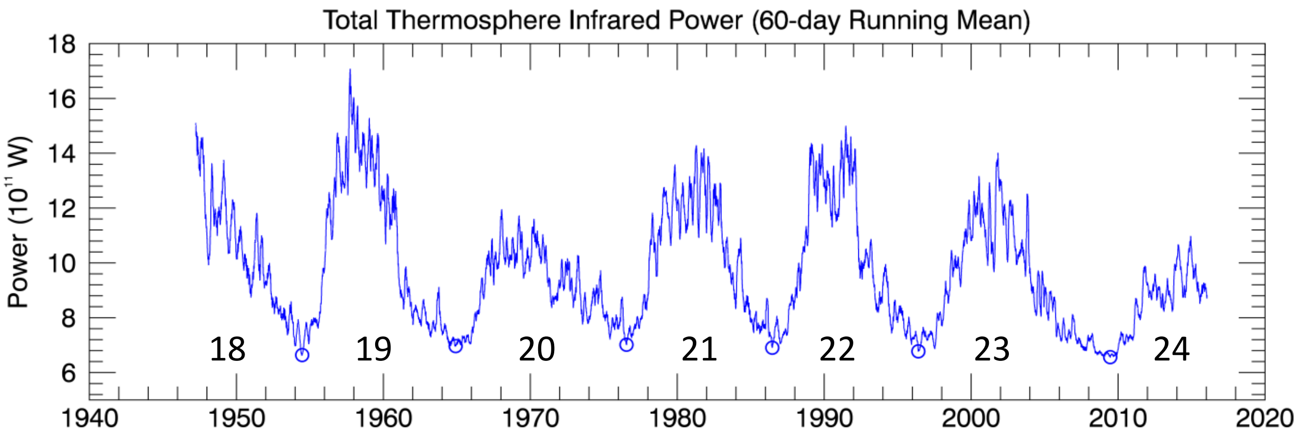


Thermosphere Infrared Power
as Function of F10.7, Ap, Dst



No consistent relationship between sunspot max and cooling max over six solar cycles.

Thermosphere Infrared Power
as Function of F10.7, Ap, Dst



Solar Cycle	Total Power (W)
19	3.904E+15
20	3.867E+15
21	3.720E+15
22	3.685E+15
23	4.344E+15

Mean: 3.904e+15 Std Dev: 2.631e+14

There is only a 6.7 % standard deviation about the mean, so the solar cycles are not that different from a total energy perspective.

Summary

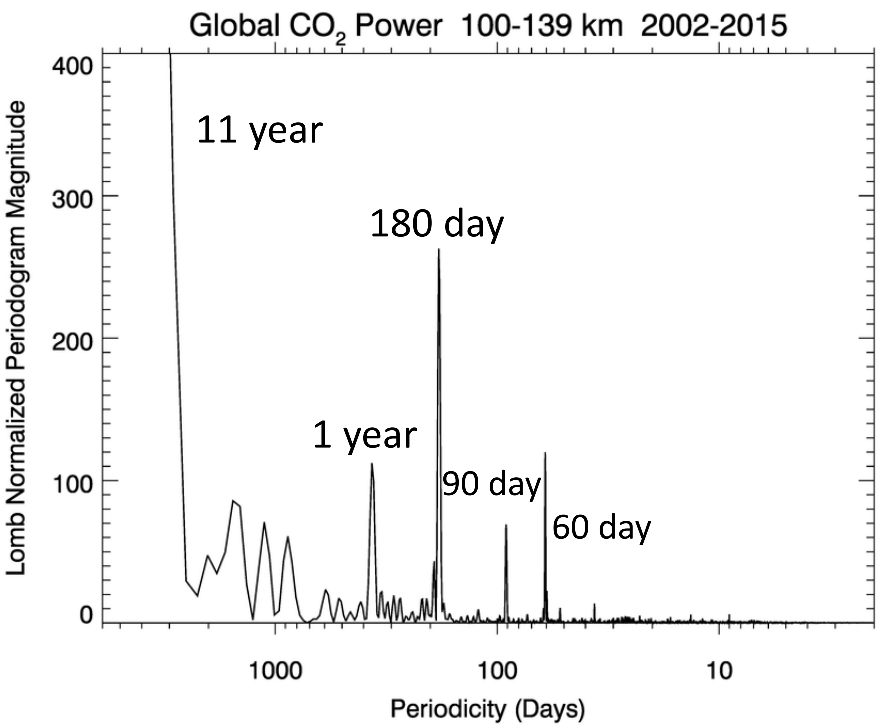
- **SABER data illustrate a very complex and interesting thermosphere that responds to solar variability on timescales from days to decades**

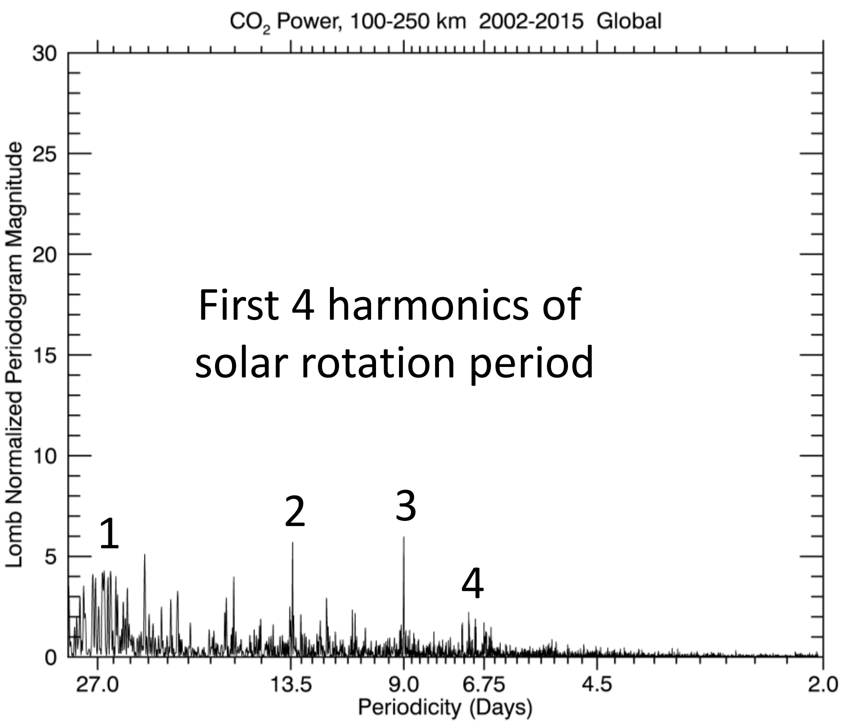
- **Past 5 solar cycles show IR emission from atmosphere varies by at most 17% from min to max, with a standard deviation of less than 7% about the mean**
  - ***Thermosphere's IR response is surprisingly consistent from one solar cycle to the next.***
  - ***Implies solar energy inputs are consistent when integrated over the solar cycle.***
  - ***Solar cycles appear more similar than different.***
  - ***Are new metrics for solar max/min for atmosphere response needed?***

Acknowledgement

- **Today we have looked at data from the NASA TIMED satellite and the SABER instrument that was launched over *14 years* ago on 7 December 2001.**
- **This is possible only because in the late 1990's, numerous engineers, project managers, resource analysts, and technicians did an excellent job of building and testing the TIMED instruments and satellite**
- **This talk is dedicated to them, for the outstanding job they did, which provides all of us the privilege of doing science with the data**

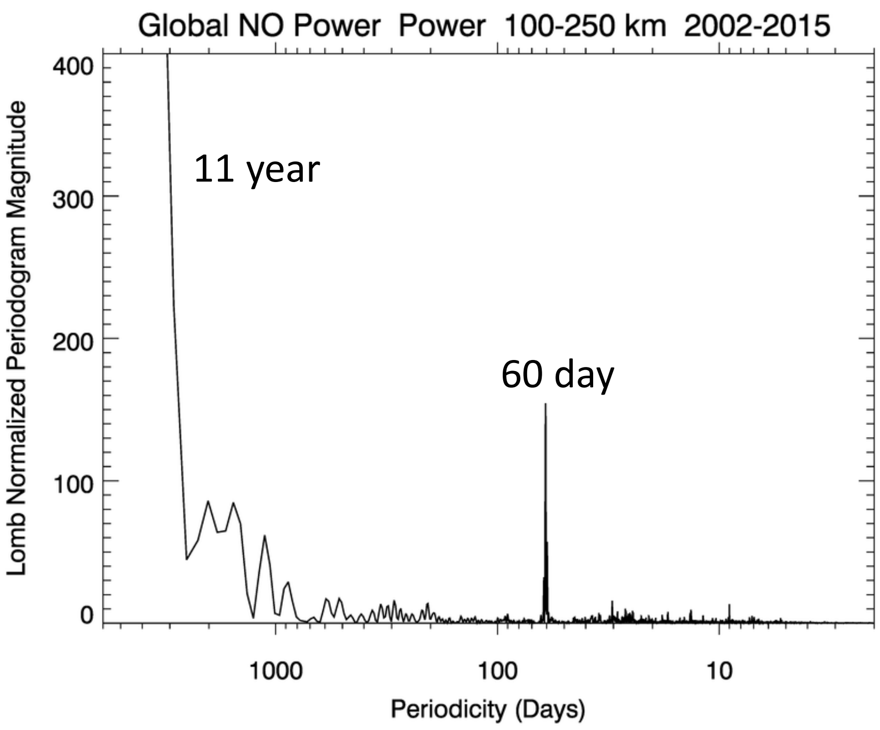
CO_2 Global Power 2002 - 2015 Lomb Normalized Periodogram

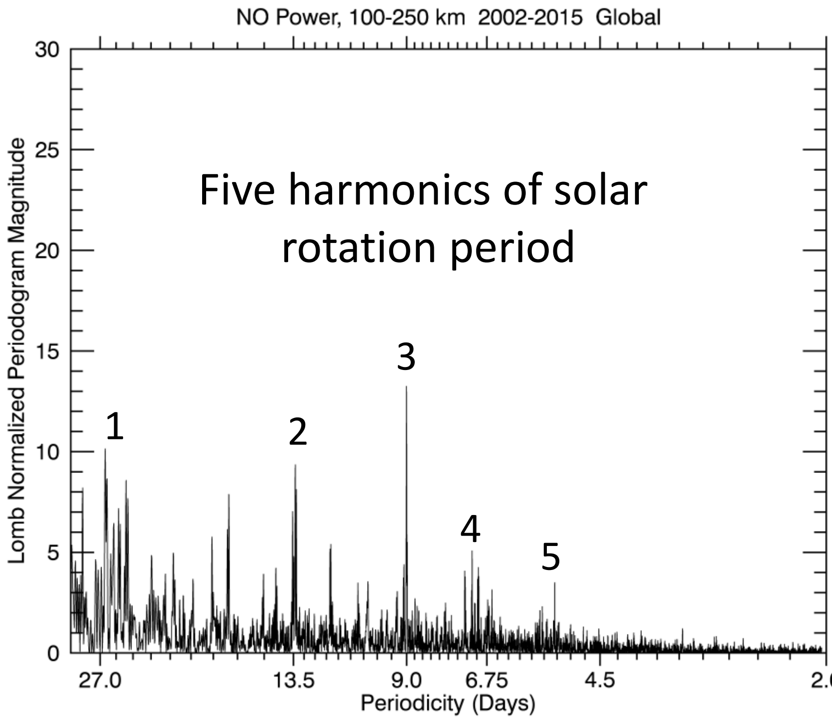




Short term periods associated with high speed streams emanating from coronal holes

NO Global Power 2002 - 2015
Lomb Normalized Periodogram





Short term periods associated with high speed streams emanating from coronal holes