A reconstruction of infrared radiative cooling of the thermosphere over the past 70 years: *Implications for long-term solar variability*

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The SABER Science Team

Acknowledgement

- **Today we will look at data from the NASA TIMED satellite and the SABER instrument that was launched over *14 years* ago on 7 December 2001.**

- **This talk 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**

Outline

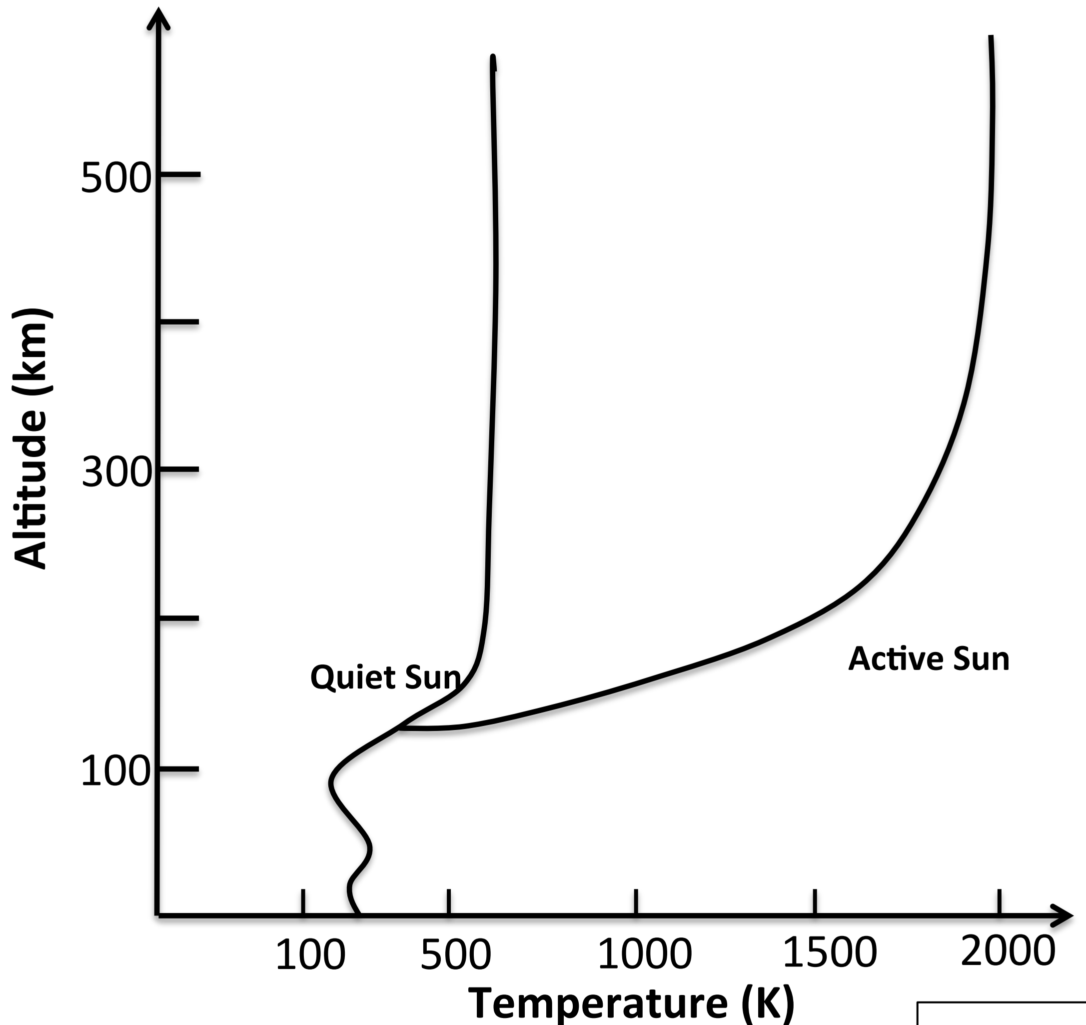
- **Main Points**
- **Overview of Thermosphere Energy Budget**
- **Observed Radiative Cooling in the Thermosphere 2002 - present**
- **A View to the Past**
  - **Reconstructing the IR energy budget back 70 years**
  - **Implications for "geo-effective" solar variability**
- **A View to the Future**
- **Summary**

Main Points

- **The global infrared (IR) energy budget of the thermosphere has been reconstructed back 70 years (to 1947)**
  - **Data provide an integral constraint on the climate above 100 km**
- **IR cooling, integrated over a solar cycle, is relatively constant over the 5 complete cycles (19 – 23) studied**
- **Solar Cycle 23 was the strongest in terms of IR cooling**
- **No consistent relationship between peak of IR cooling and sunspot number peak**
- **The community faces a gap in measurements above 50 km (T, O_3, CO_2, energetics) after ~ 2020**

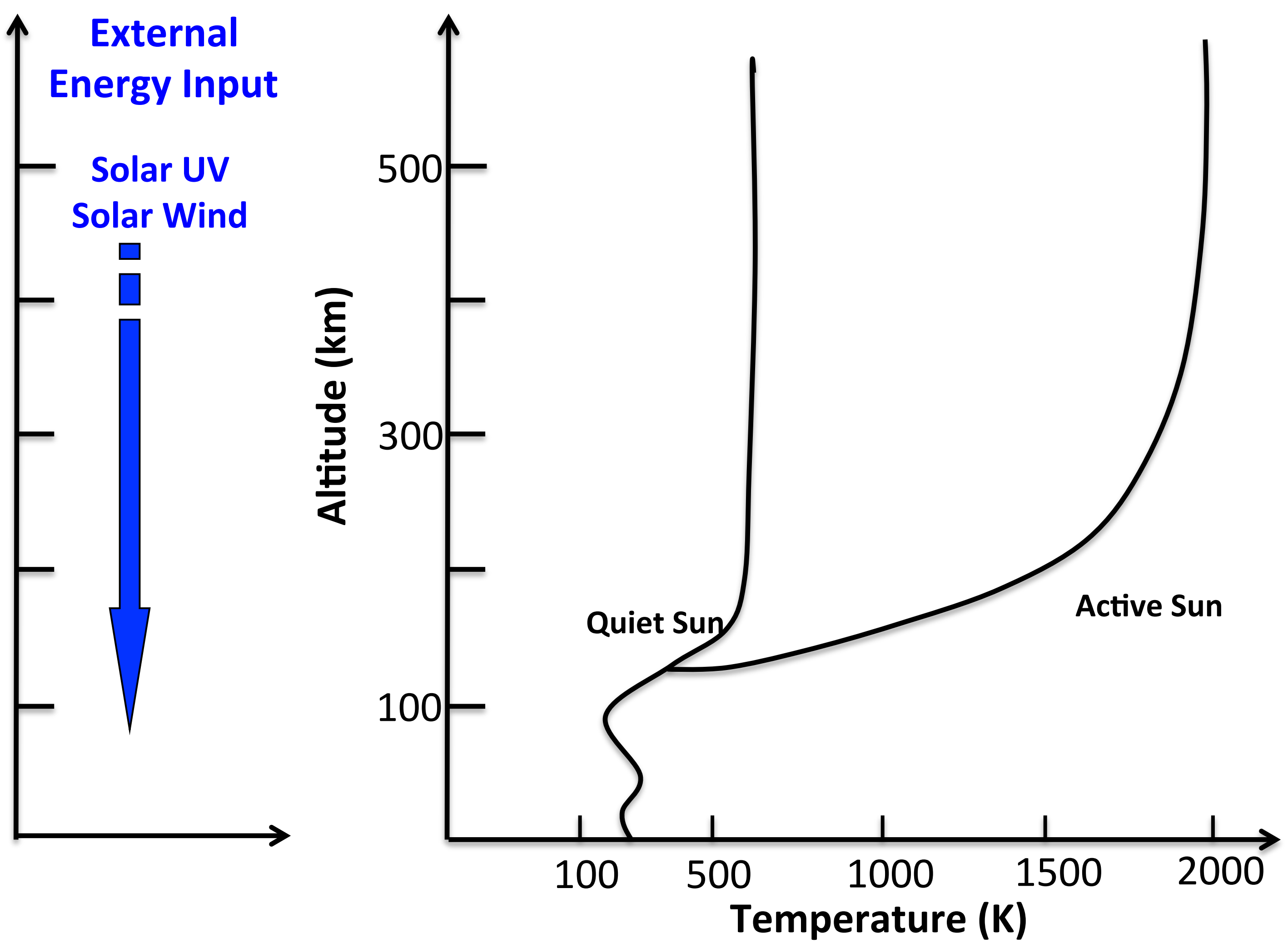
Overview of the Thermosphere Energy Budget

Thermosphere Energy Balance – Thermal Structure

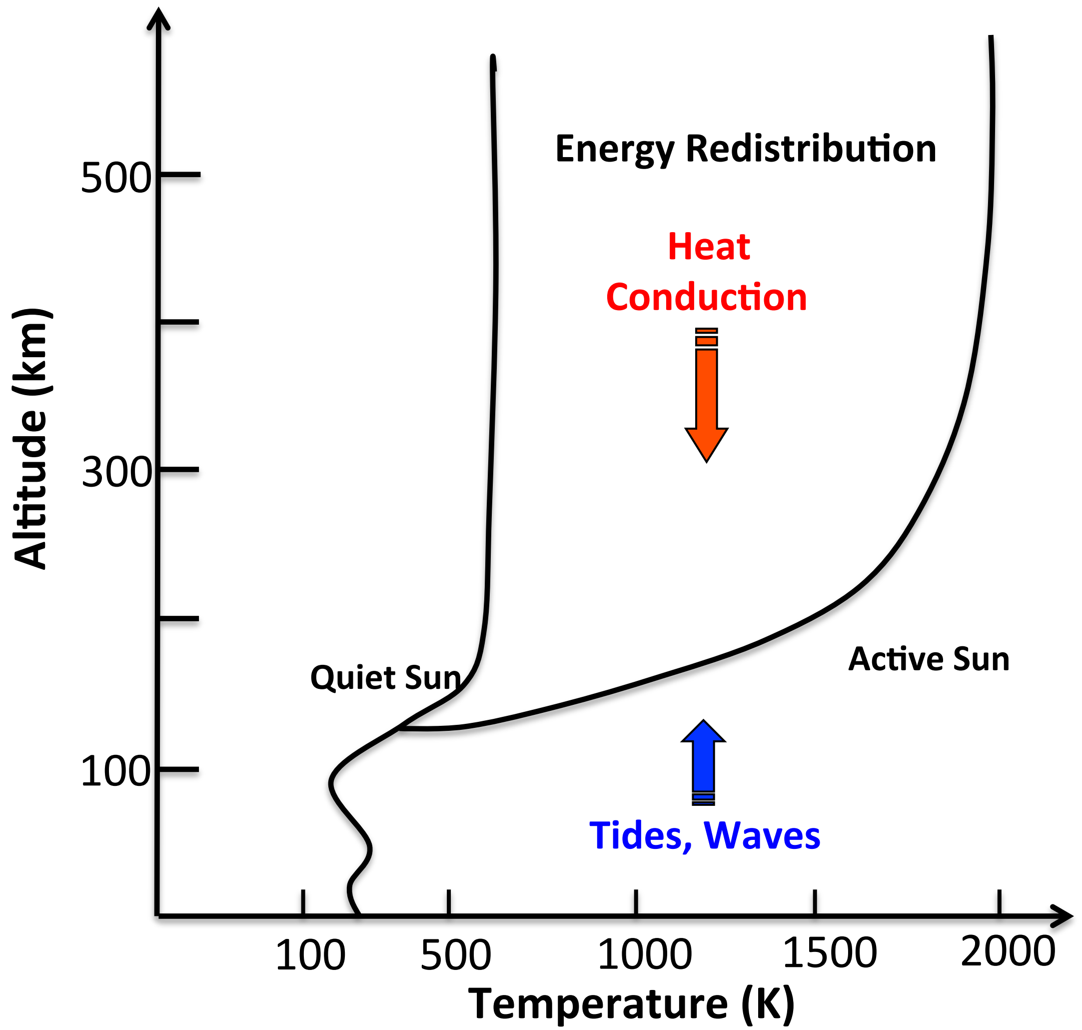


Banks and Kockarts, 1973

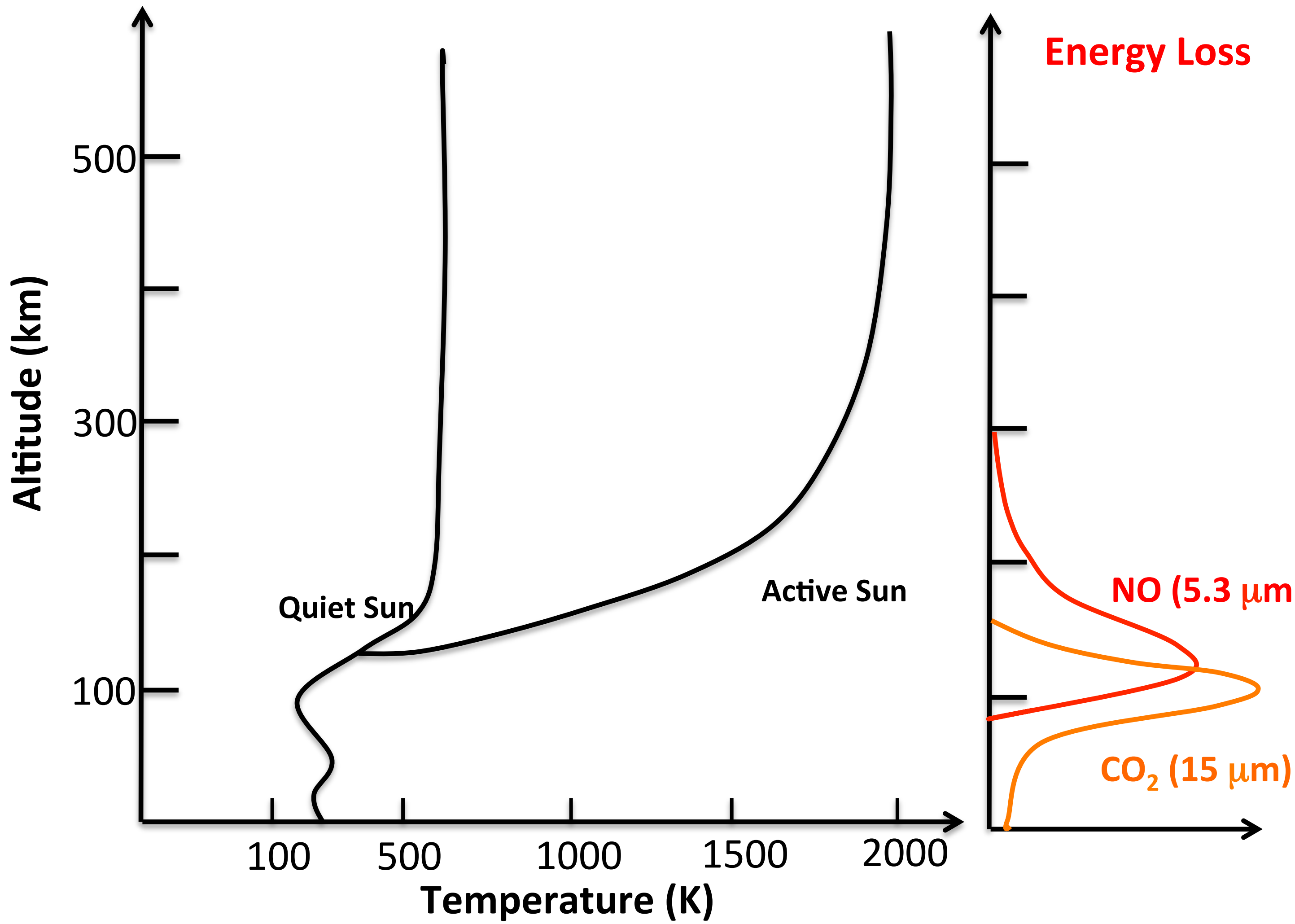
Thermosphere Energy Balance – Energy Inputs



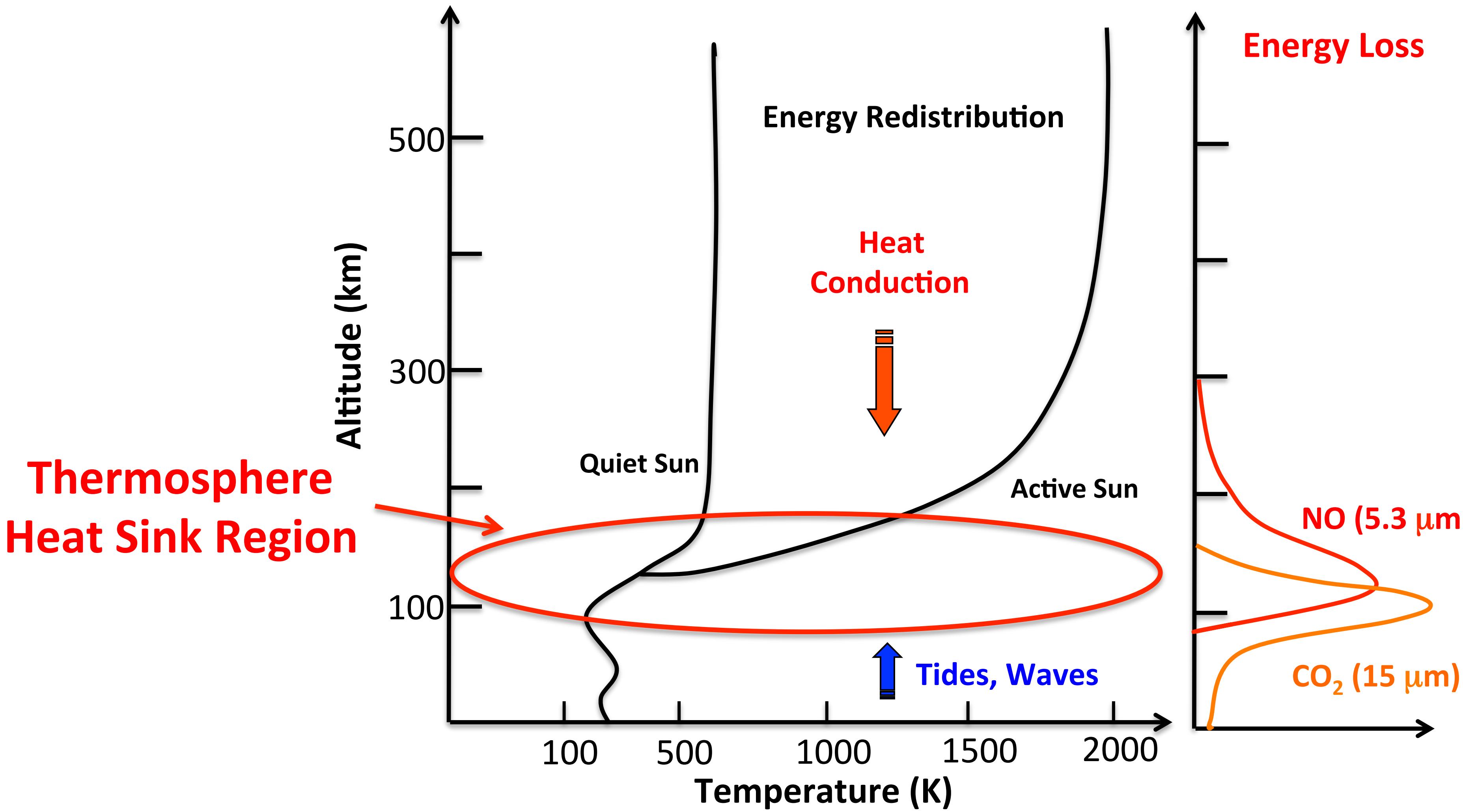
Thermosphere Energy Balance – Energy Redistribution



Thermosphere Energy Balance – Energy Outputs



The Thermospheric Heat Sink



Infrared 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:**

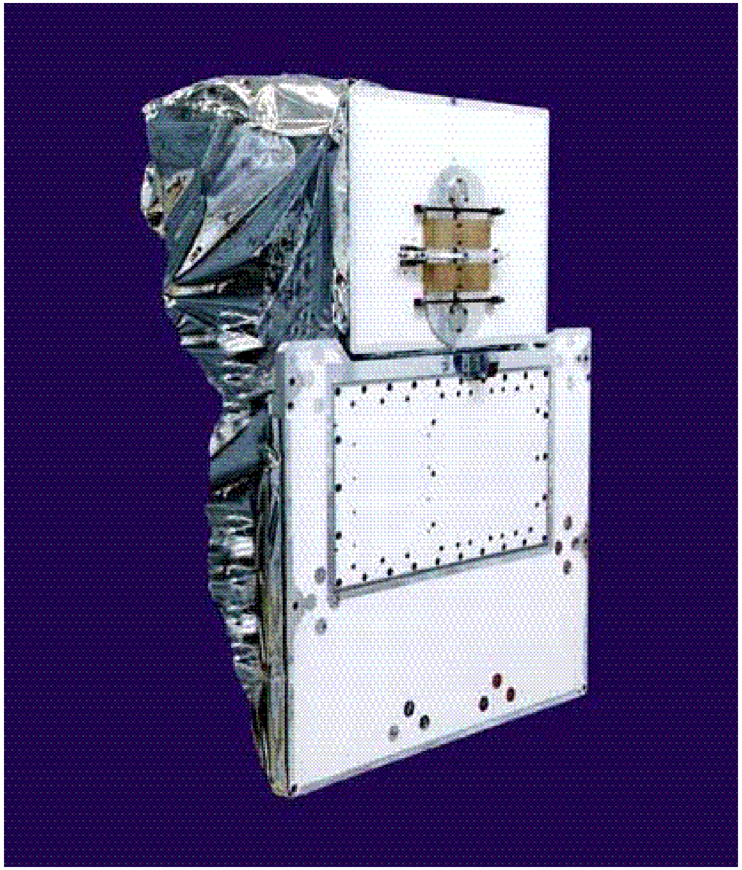
  - **NO (υ = 0) + O → NO (υ = 1) + O** **(Kinetic Energy Removal)**
  - **NO (υ = 1) → NO (υ = 0) + hν (5.3 μm)** **(Kinetic Energy Loss)**
  - **NO (υ = 1) + O → NO (υ = 0) + O** **(Kinetic Energy Returned)**

- **Collisional processes are highly temperature dependent**

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

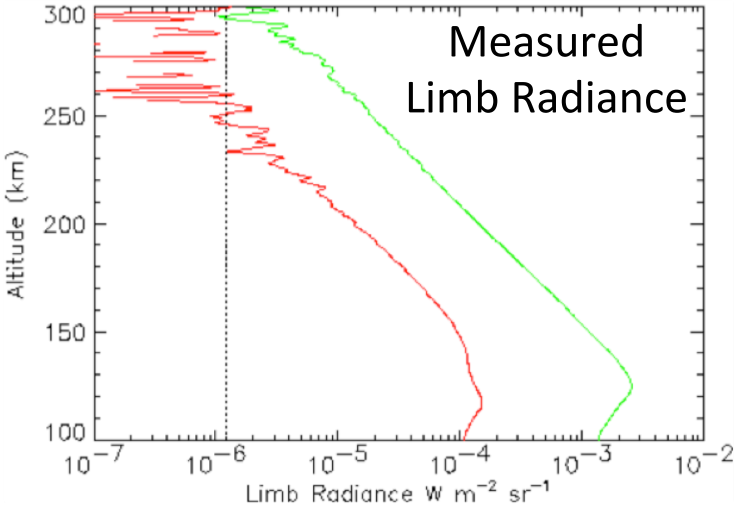
SABER Experiment

- 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!

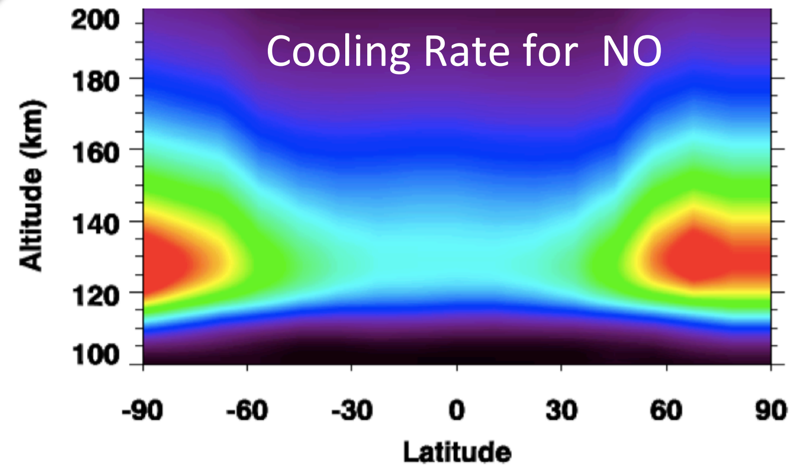


75 kg, 77 watts, 77 x 104 x 63 cm, 4 kbs

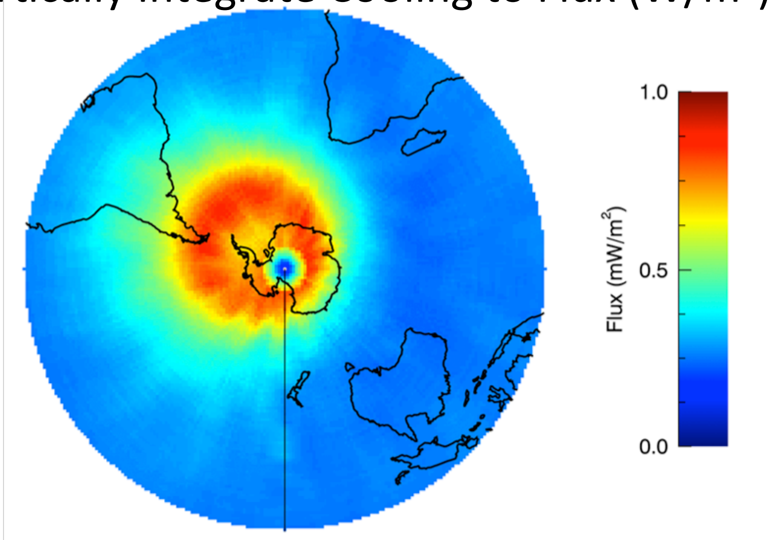
NO and CO_2 Cooling Parameter Derivations by SABER



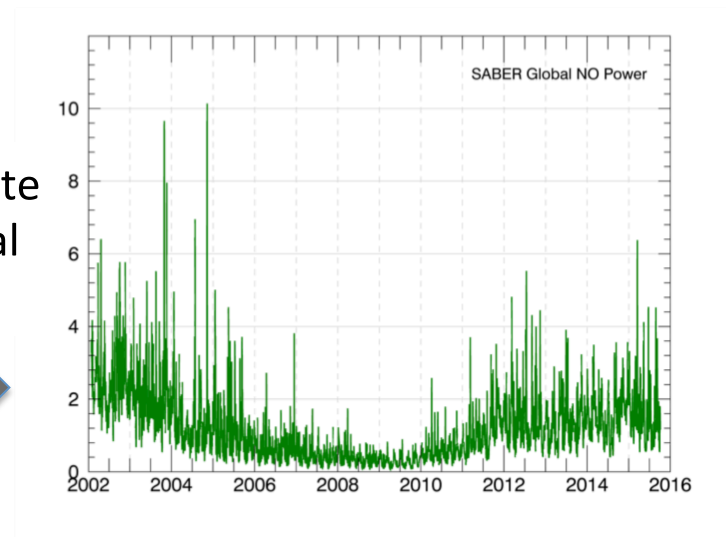
Abel Inversion to Cooling Rate (W/m^3)



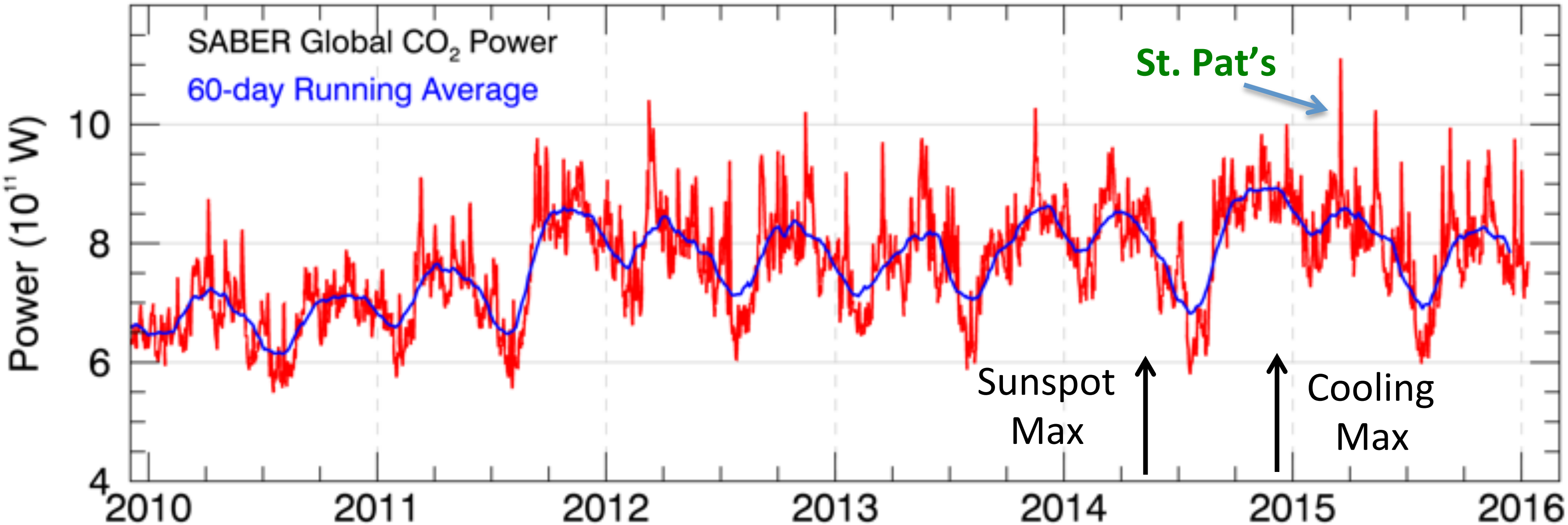
Vertically Integrate Cooling to Flux (W/m^2)



Area integrate to get global power (W)



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

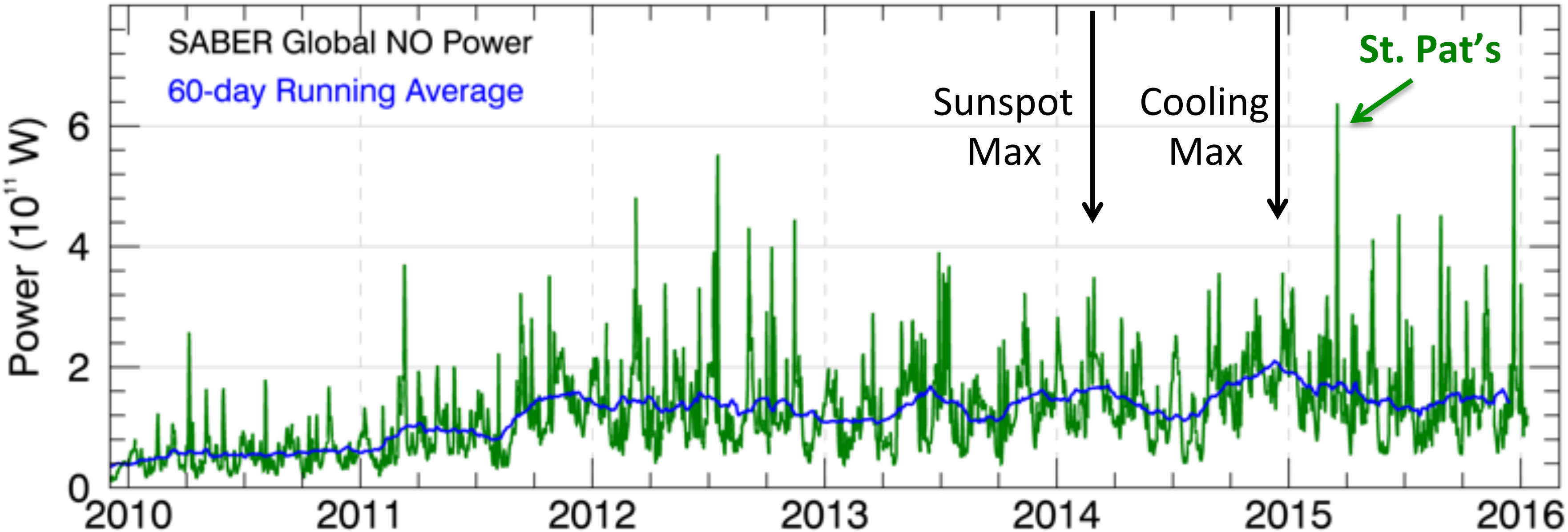


Geomagnetic activity always evident in radiative cooling

Strong semi-annual oscillation evident

Sunspot and cooling maxima are not coincident

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



Sunspot and cooling maxima not coincident

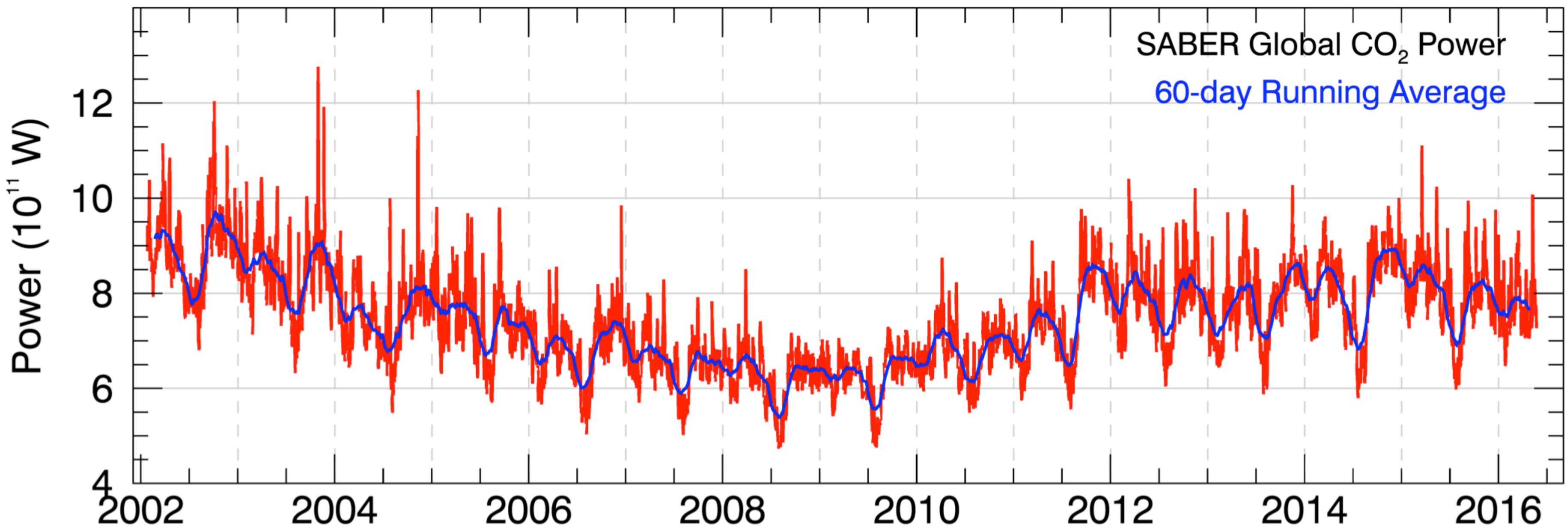
Each "spike" is the response to a geomagnetic event

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

No evidence of annual, semi-annual oscillations

SABER **Daily** Global Power from CO_2
January 2002 – May 2016; 100 – 140 km

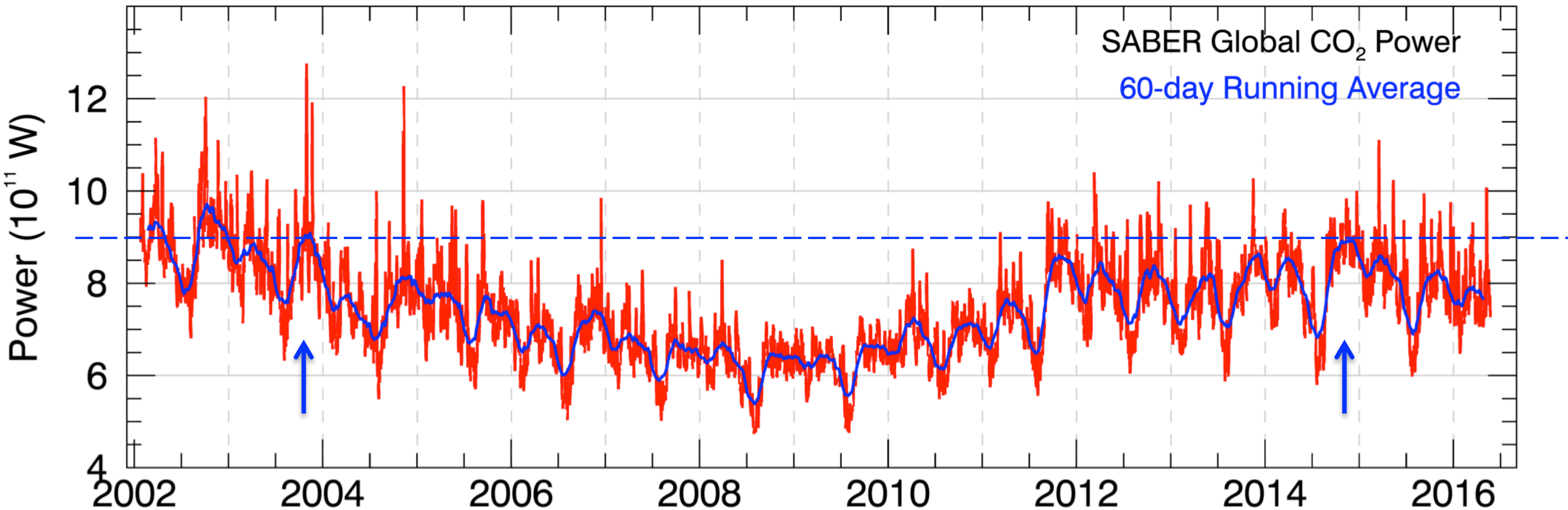
Over 5200 days of data!



11-year Solar Cycle Evident in the 14+ Year SABER Record

SABER Daily Global Power from CO_2
January 2002 – May 2016; 100 – 140 km

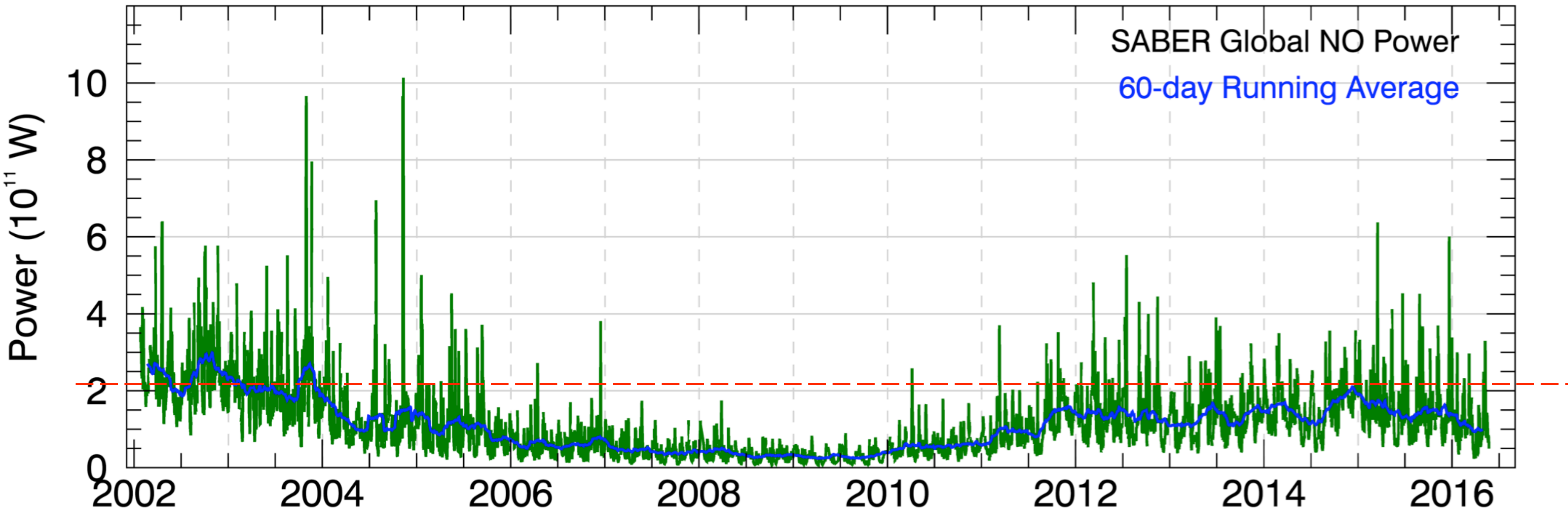
Over 5200 days of data!



SC 24 solar max (12/2014) as warm as 12/2003 – 11 years prior

But, just how different in total energy are they?

SABER Daily Global Power From NO
Jan 2002 – May 2016: 100 – 250 km



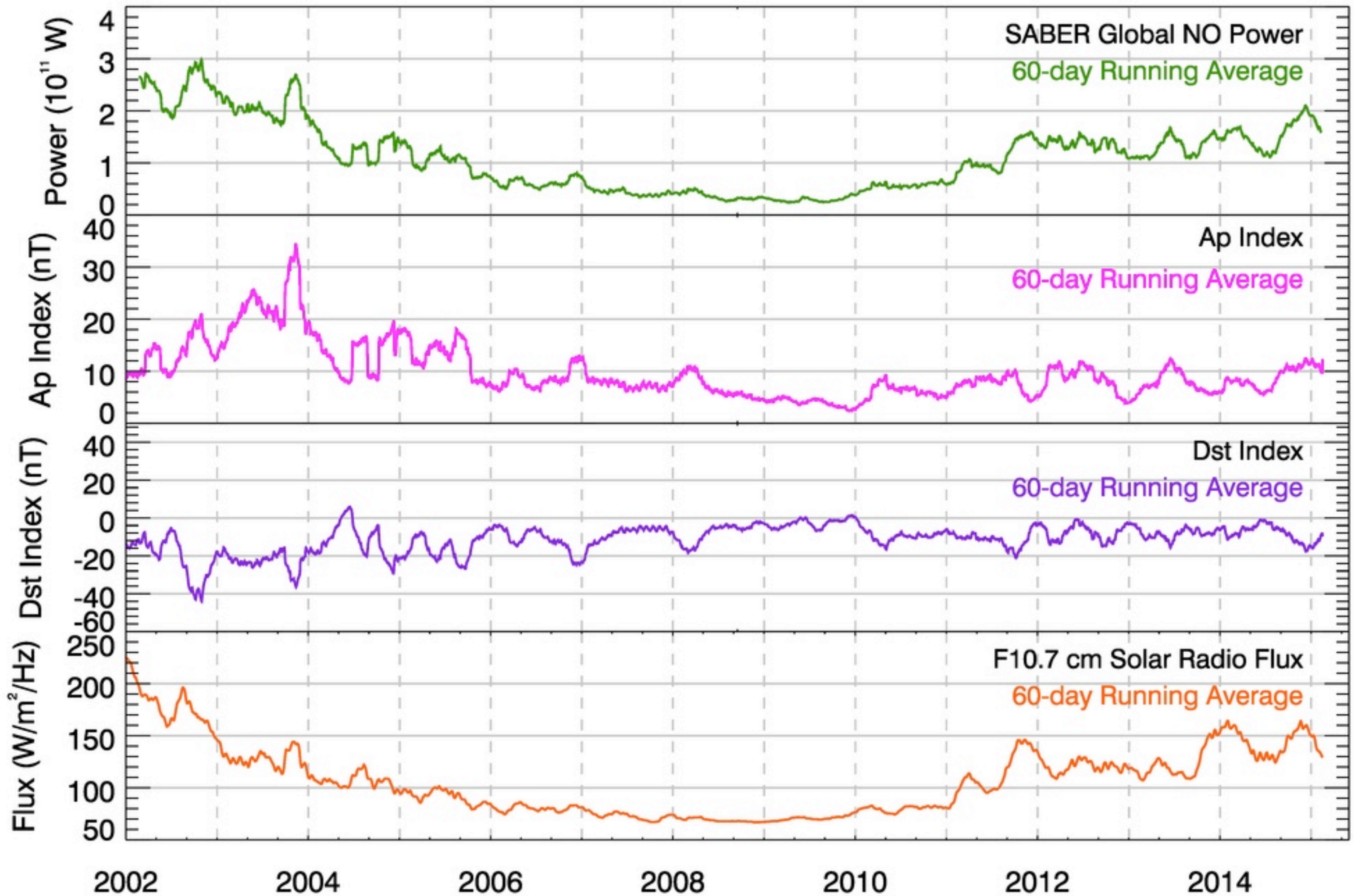
NO Cooling at Peak of SC 24 (12/2014) was highest level since 12/2003

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

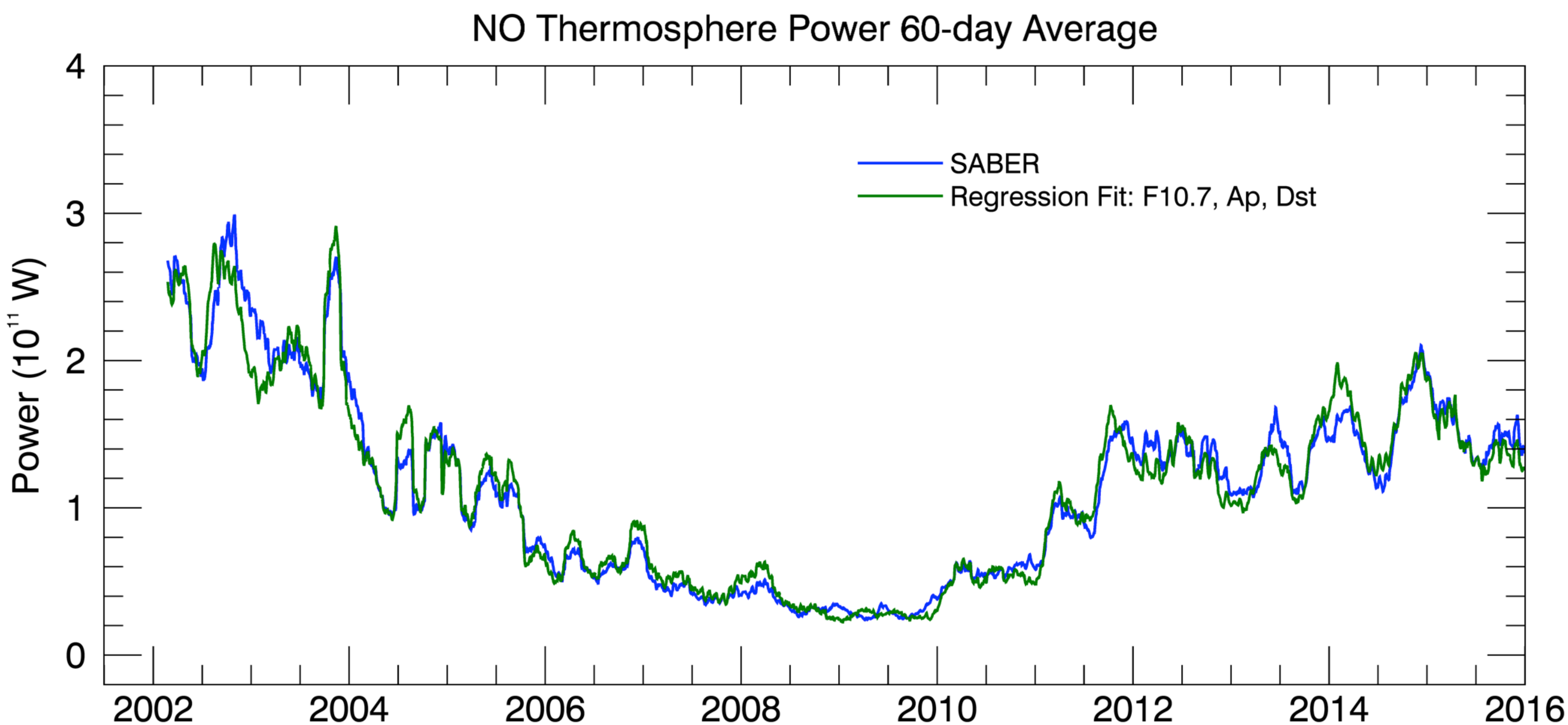
A View to the Past

60-day Running Means – Nitric Oxide Power

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



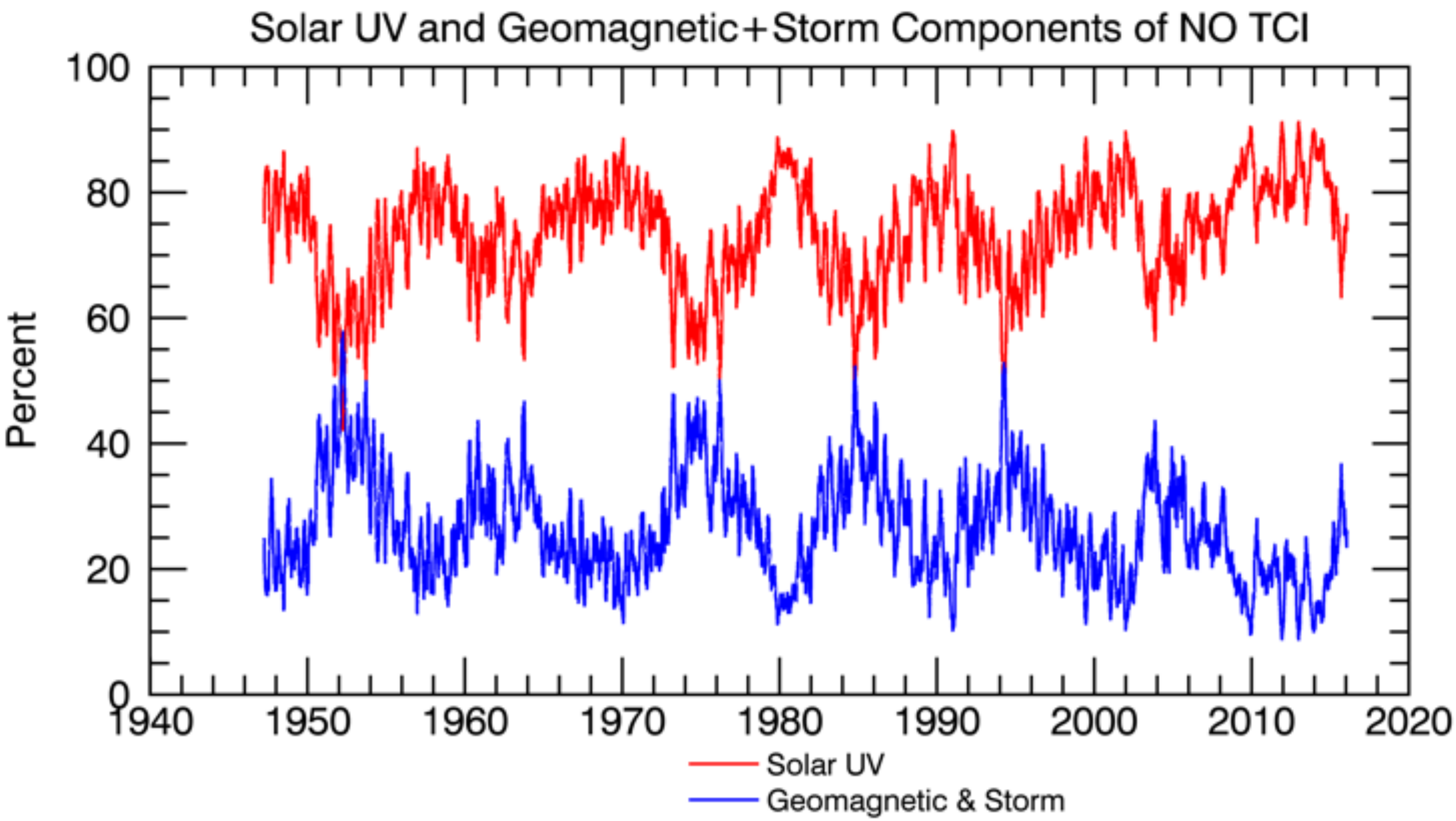
Multiple Linear Regression Fit
SABER NO Power as Function of F10.7, Ap, Dst



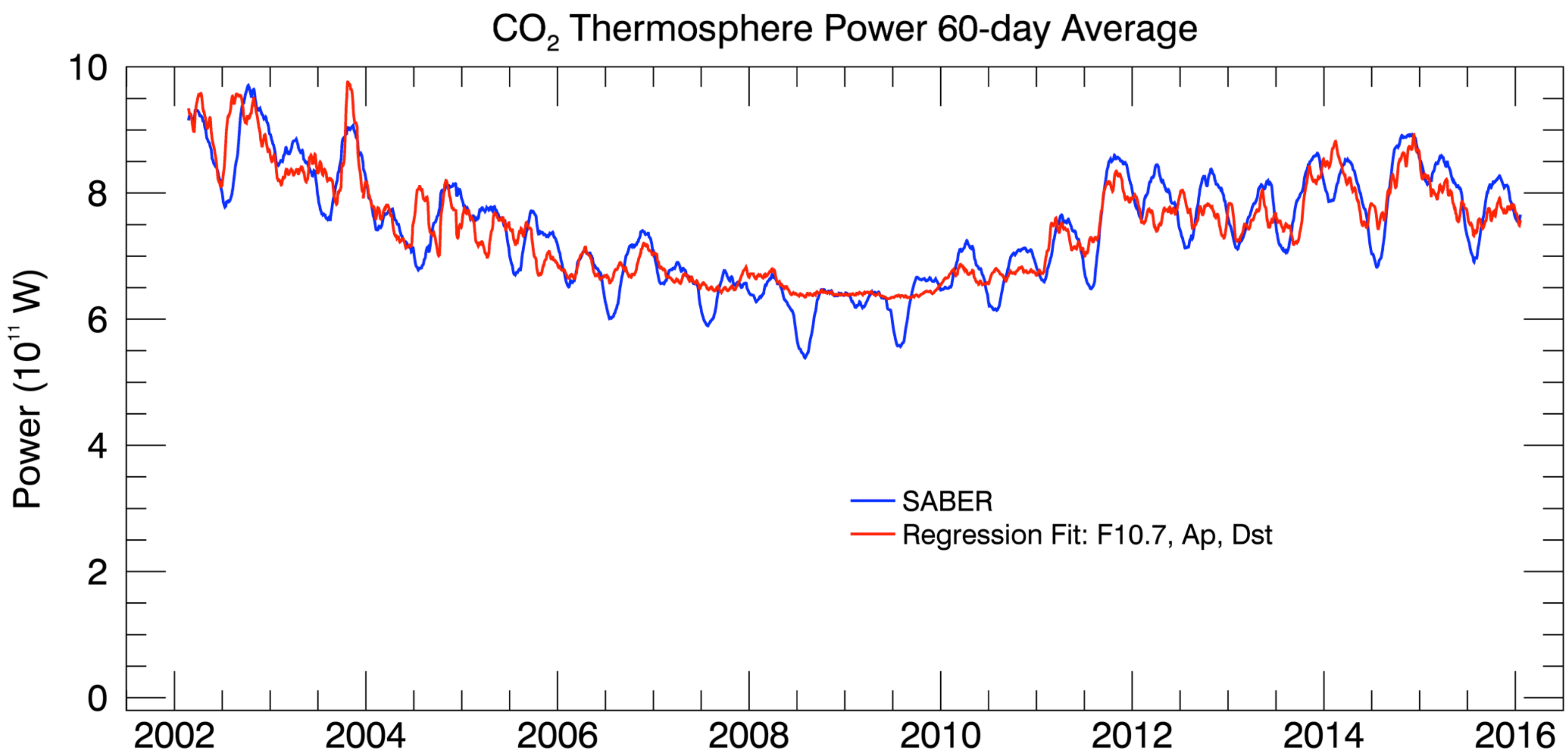
Correlation Coefficient: 0.983
Integrated area ratio - SABER NO to Fit: 0.999

Mlynczak et al., GRL, 2015

Relative Contributions of Solar and Geomagnetic Activity to NO Cooling

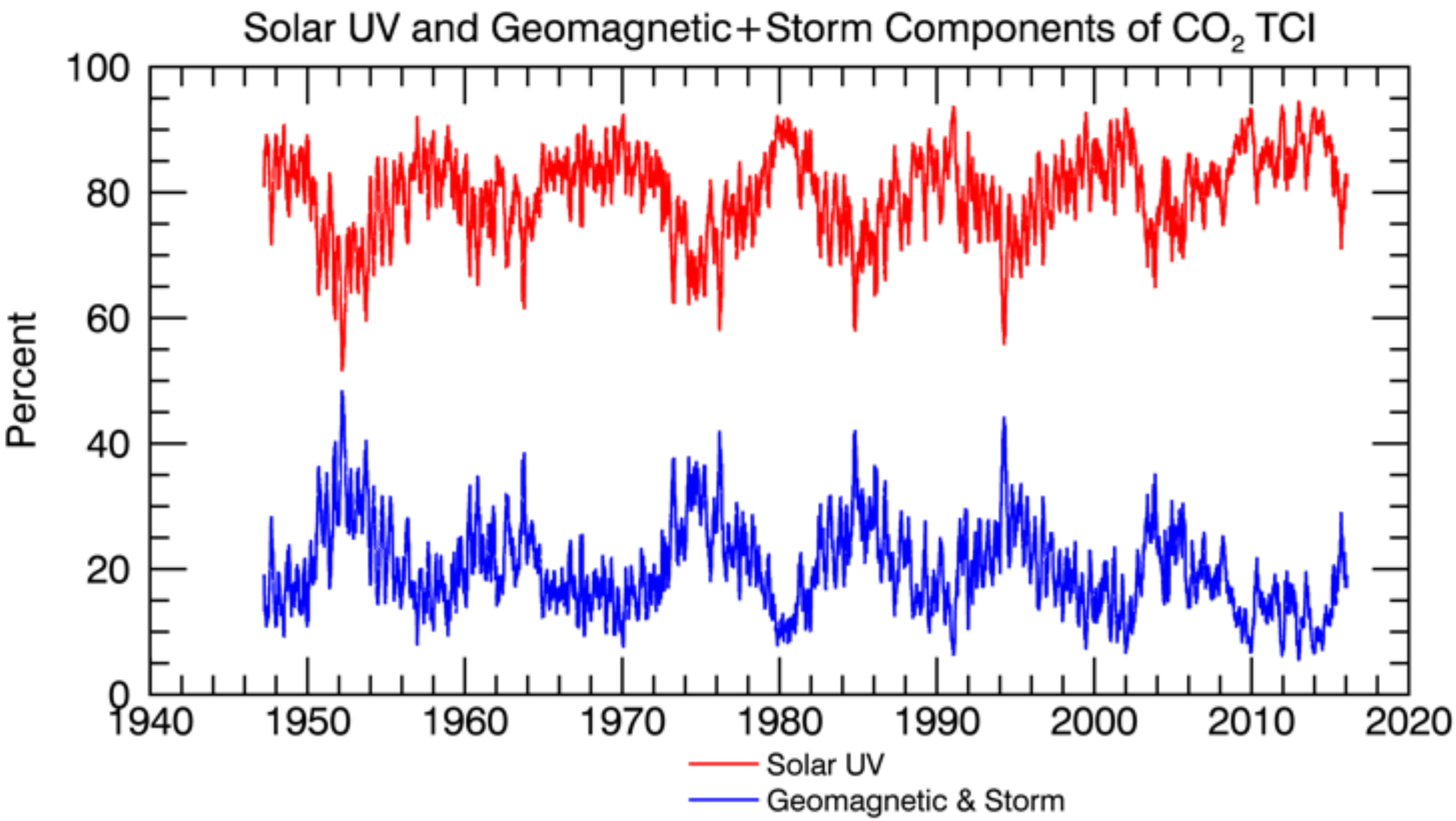


Multiple Linear Regression Fit
SABER CO_2 Power as Function of F10.7, Ap, Dst

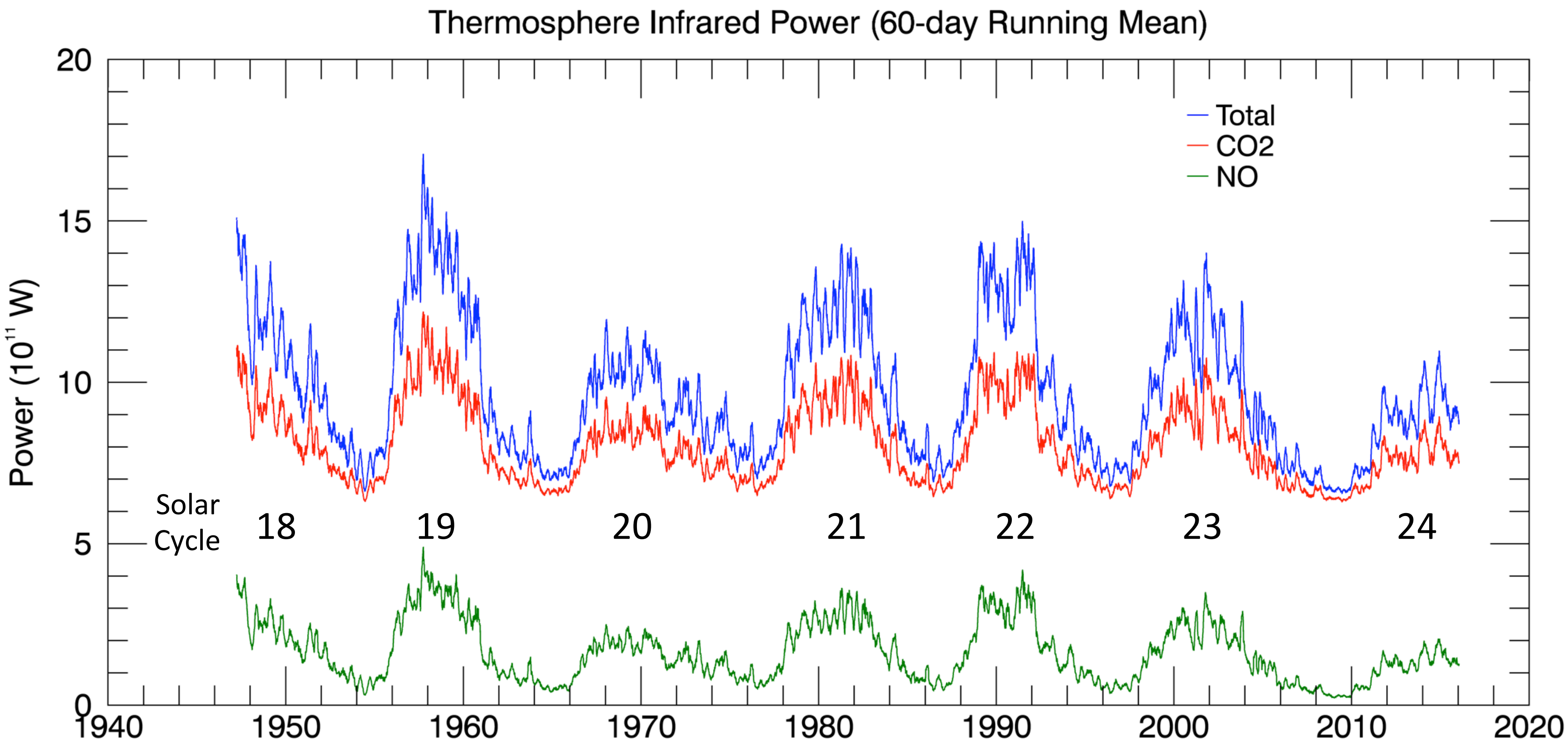


Correlation Coefficient: 0.898
Integrated area ratio - SABER CO_2 to Fit: 0.999

Relative Contributions of Solar and Geomagnetic Activity to CO_2 Cooling



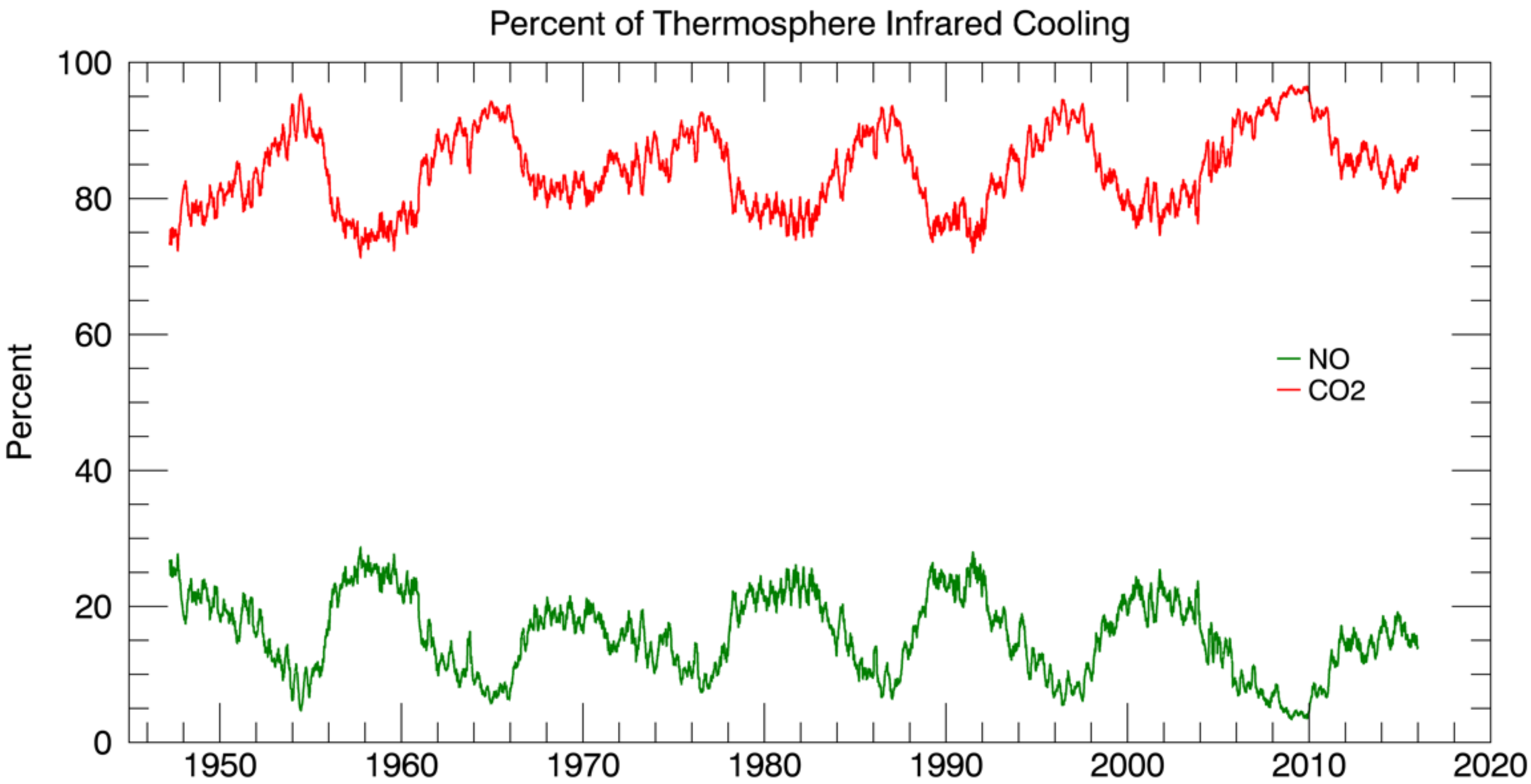
Reconstruction of Thermosphere Infrared Power



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

CO_2 is the dominant cooling mechanism above 100 km

Percent of Thermosphere Infrared Cooling
Due to CO_2 and NO

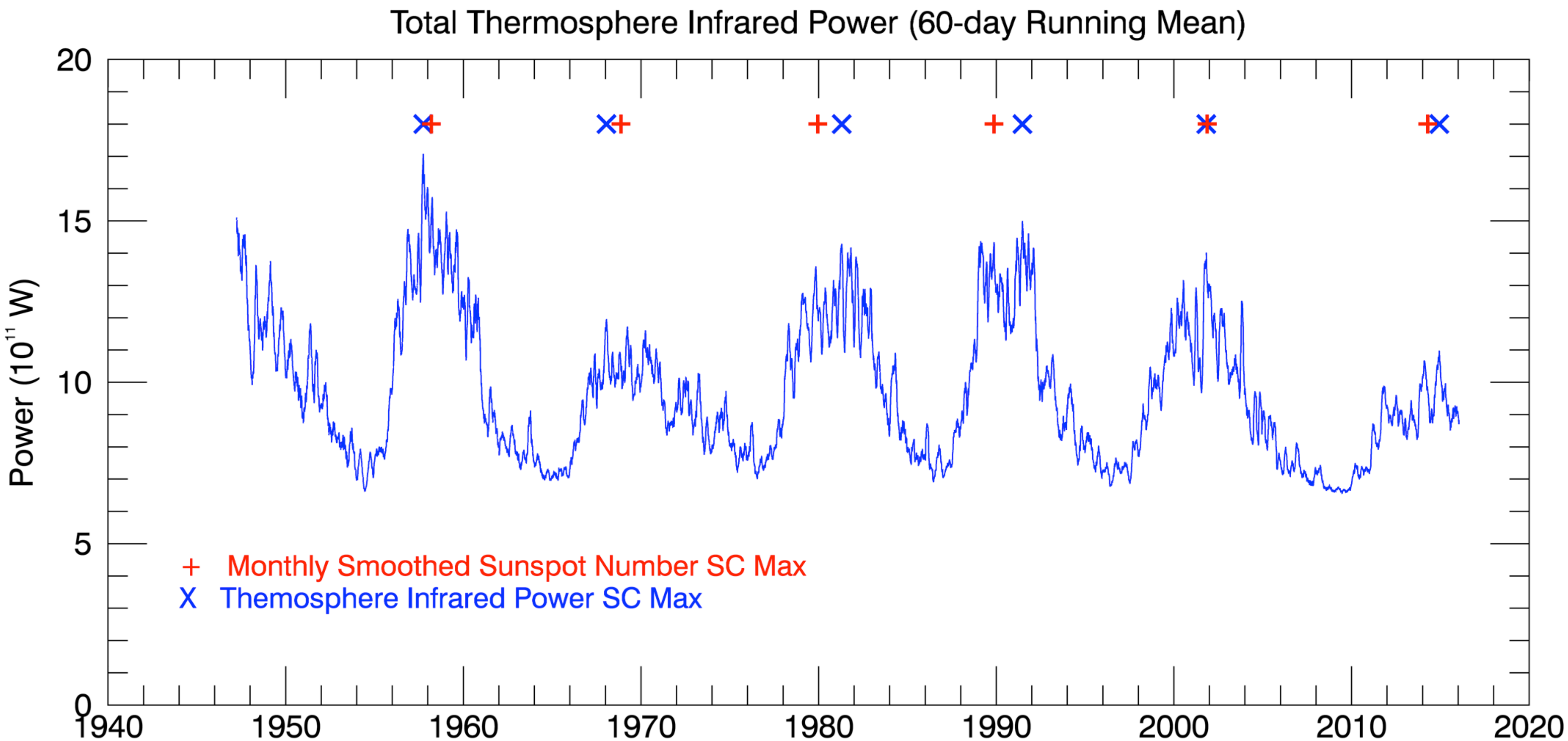


Variability of NO, CO_2 Power and F10.7 Over 5 Solar Cycles

Sunspot Cycle	Length (Days)	Sum NO Power (10^{14} W)	Sum CO_2 Power (10^{15} W)	Total Power (10^{15}W)	Sum F10.7 (10^5)	Mean Sunspot Number
19	3692	7.48	3.16	3.91	5.30	129.5
20	4242	5.88	3.28	3.87	4.81	85.4
21	3623	6.86	3.03	3.72	4.97	116.2
22	3629	6.69	3.02	3.69	4.85	105.6
23	4761	6.55	3.69	4.35	5.54	77.6
	Mean	6.69	3.23	3.90	5.09	
	Std. Dev.	8.6%	8.5%	6.7%	6.1%	

Total IR Power Radiated over a SC is relatively constant for 5 SC!
Consistent with Variability of F10.7 – Proxy for Solar UV

Cooling Maxima in Relation to Sunspot Maxima

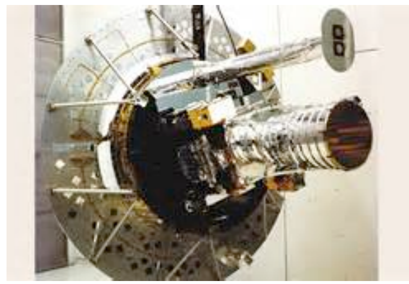


No consistent relationship between sunspot maximum and cooling maximum over six solar cycles

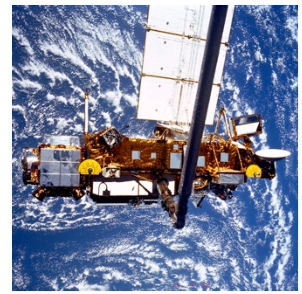
A View to the Future

1975 – 2016
The Golden Age of Upper Atmosphere Science?

Nimbus VII

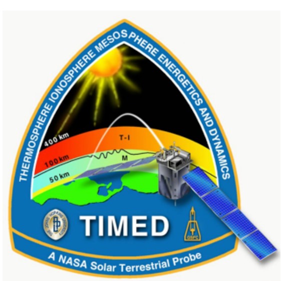


SME

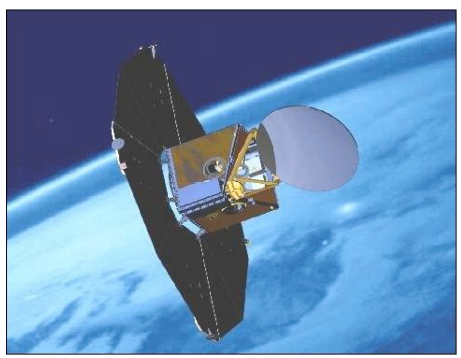


UARS

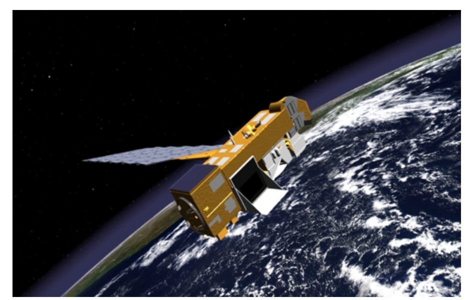
EnviSat



TIMED



ODIN



Aura

SORCE

The Golden Age of Upper Atmosphere Science

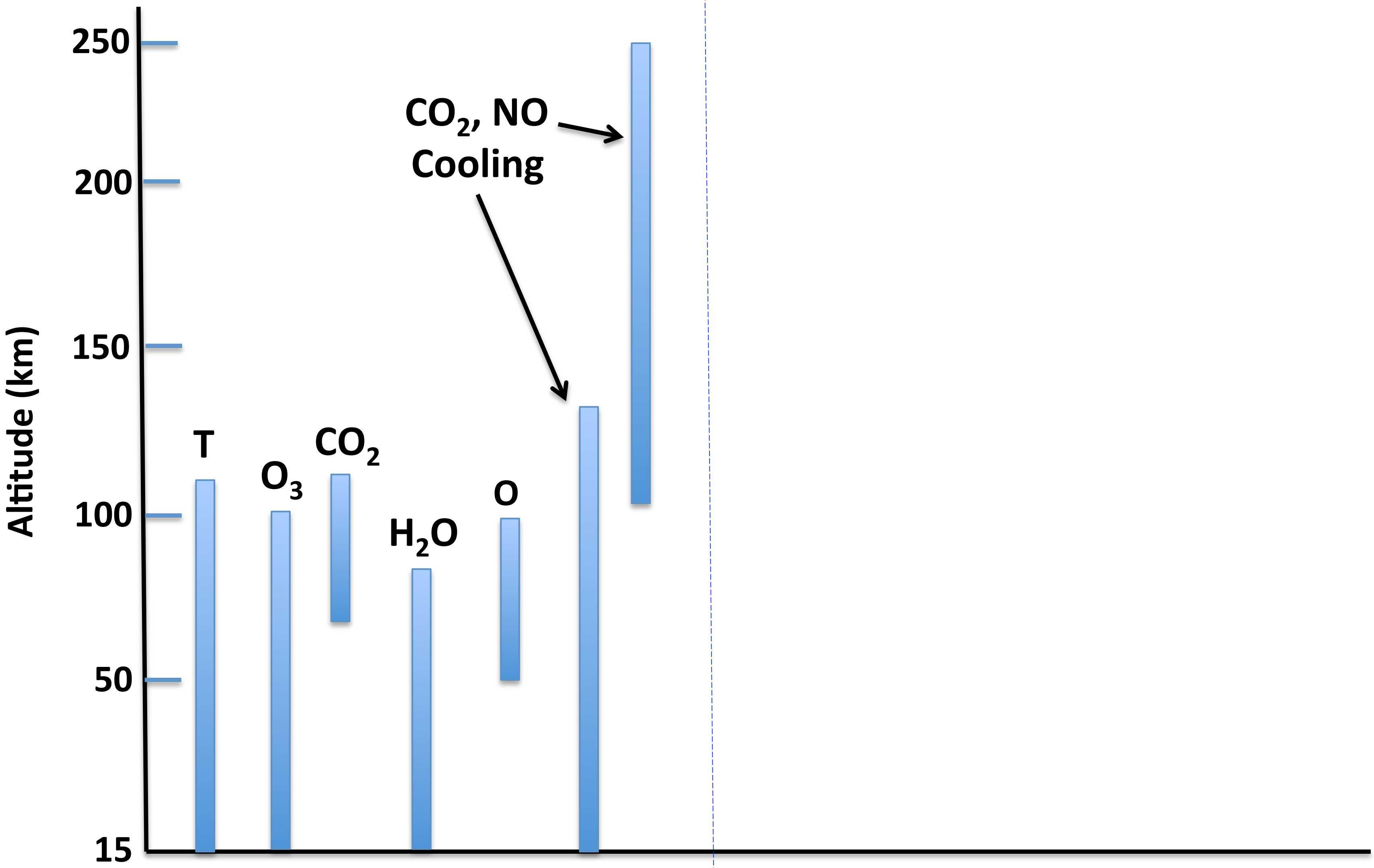
- **1970's -- LRIR, LIMS, AE, SAM**
- **1980's -- DE-1, DE-2, SAGE-II, SME**
- **1990's -- UARS, POAM**
- **2000's -- Aura, TIMED, Envisat, ODIN, SciSat, SAGE-III, SORCE, SMILES, AIM**
- **2010's -- SAGE III (2016); ICON; GOLD; TSIS**
- **2020's -- ????**
  - **No missions in preparation for observation of the mesosphere and thermosphere**

The Golden Age of Middle Atmosphere Science

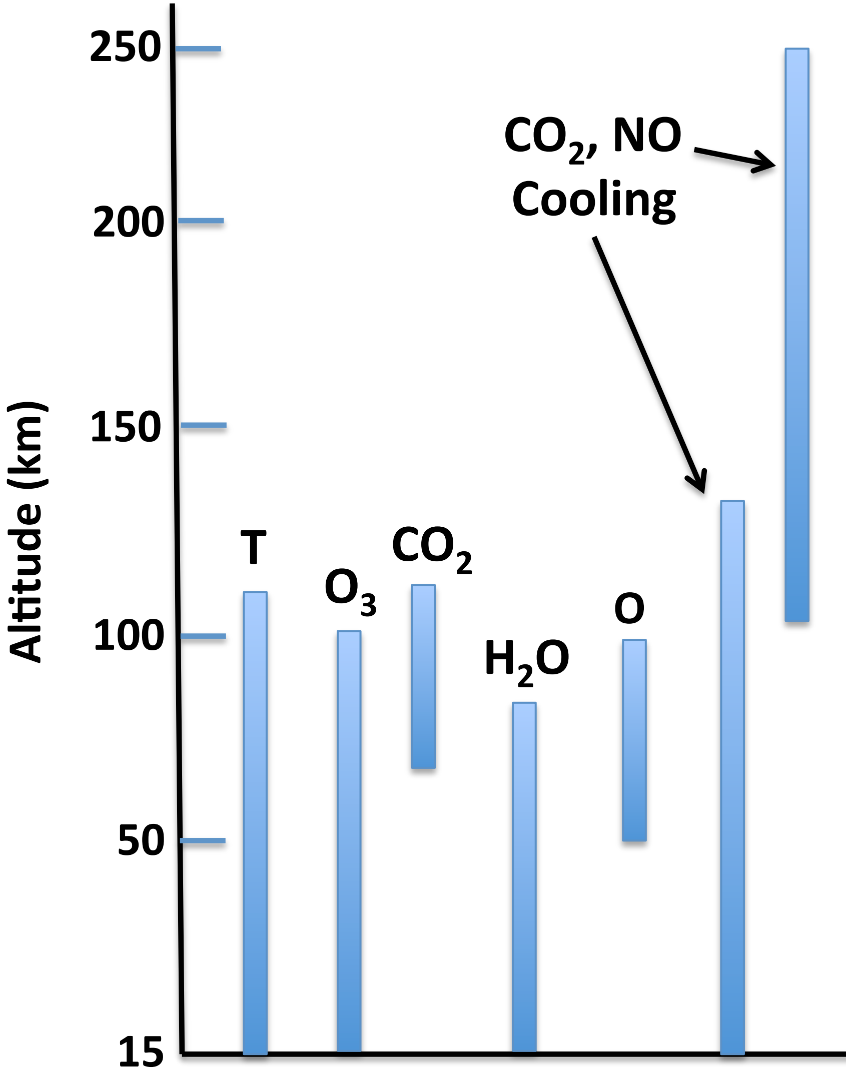
- 1970's -- LRIR, LIMS, AE, SAM
- 1980's -- DE-1, DE-2, SAGE-II, SME
- 1990's -- UARS, POAM
- 2000's -- Aura, TIMED, Envisat, ODIN, SciSat, SAGE-III, SORCE, SMILES, AIM
- 2010's -- SAGE III (2016); ICON; GOLD
- 2020's -- ????
  - No missions in preparation for middle atmosphere science

A gap in thermal structure, chemical composition, and energetics measurements after 2020 seems inevitable

Existing Capability



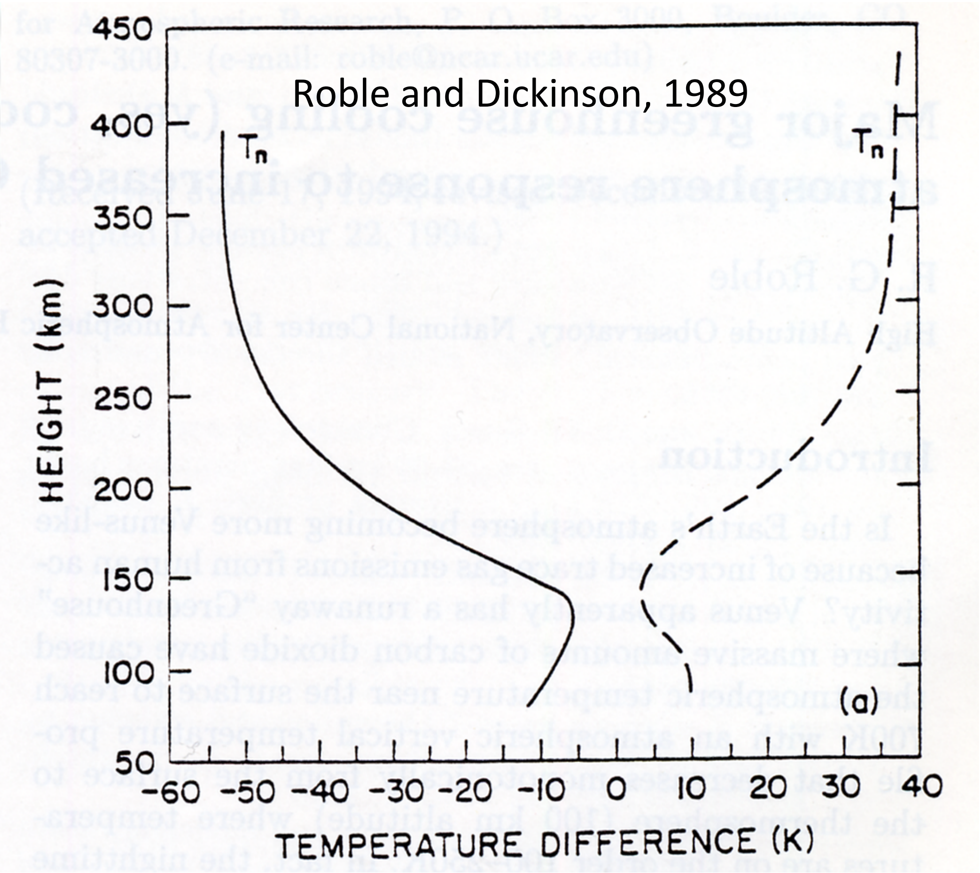
Existing Capability



What's Still Missing?

- Global Temperature 110 – 200 km
- Composition, particularly O, 110-200
- These measurements combined with T, O, etc., below, and NO, CO2 cooling
- Why?
- Only with these data can we confidently assess models of the "heat sink" region and predict global change above 110 km

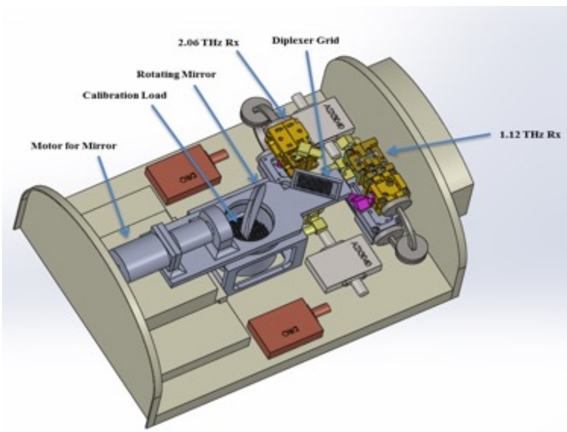
Global Cooling due to Increasing CO_2



Understanding the future of the atmosphere above 200 km implies detailed understanding of the atmosphere 100-160 km

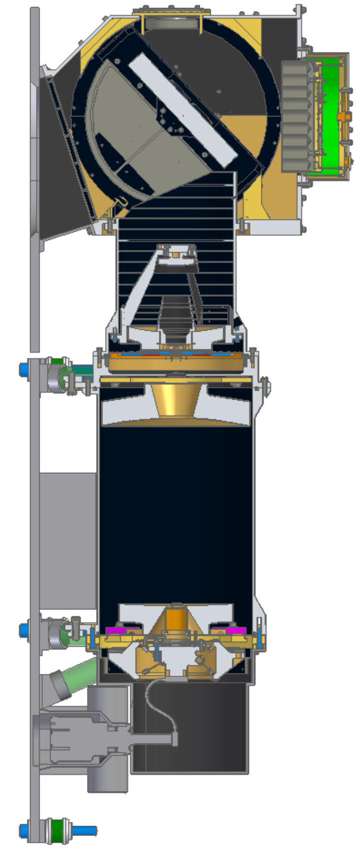
Solar-Terrestrial Energy Explorer

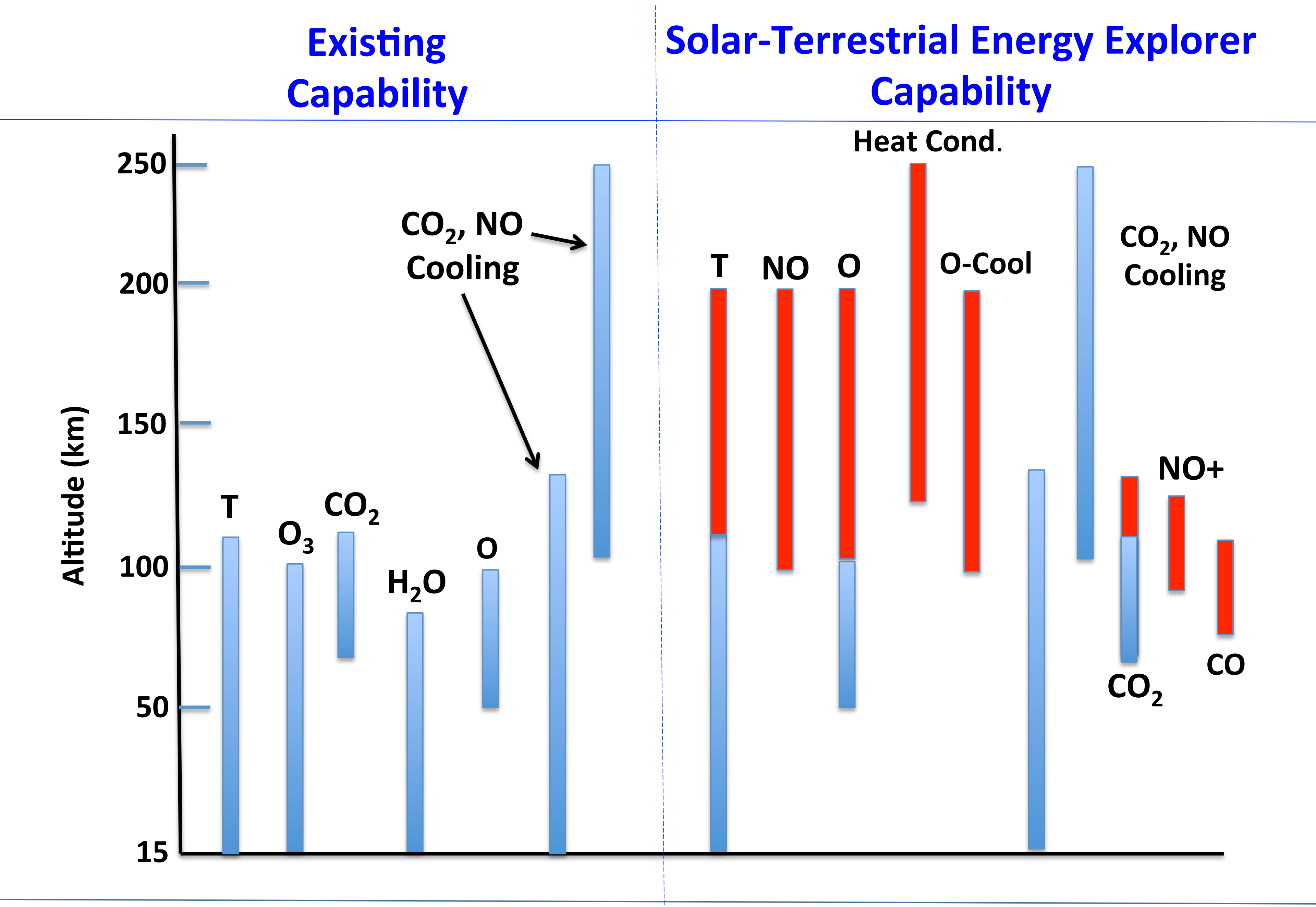
- **A mission to explore the thermosphere above 100 km**
- **Mission will continue legacy measurements from SABER**



TLS Instrument (S. Yee, APL)
T, O, winds – 100 to 160 km
15 kg
25 W

SABER-II Instrument
35 kg, 35 W
100% SABER Heritage
½ mass, ½ power, 1/3 volume
Identical radiometric performance

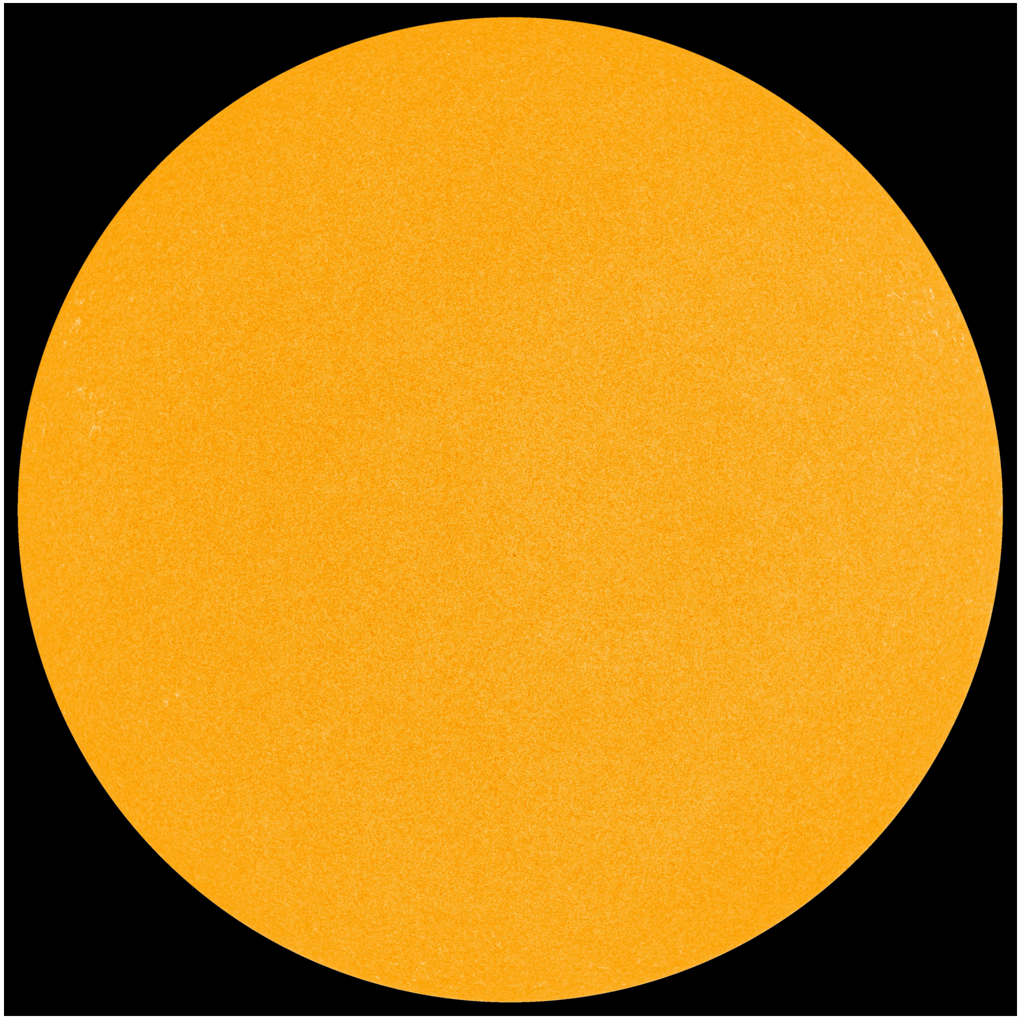



Existing Capability
Solar-Terrestrial Energy Explorer Capability
Altitude (km)
250
200
150
100
50
15
T
O_3
CO_2
H_2O
O
CO_2, NO Cooling
Heat Cond.
T
NO
O
O-Cool
CO_2, NO Cooling
NO+
CO_2
CO

Summary

- **The global infrared (IR) energy budget of the thermosphere has been reconstructed back 70 years (to 1947)**
- **IR cooling, integrated over a solar cycle, is relatively constant over the 5 complete cycles (19 – 23) studied**
  - **Consistent with observed variability of solar input (F10.7)**
- **Solar Cycle 23 was the strongest in terms of IR cooling**
  - **Largely due to its length (4761 days)**
- **No consistent relationship between peak of IR cooling and sunspot number peak**
- **The community faces a gap in measurements above 50 km (T, O_3, CO_2, energetics) after ~ 2020**

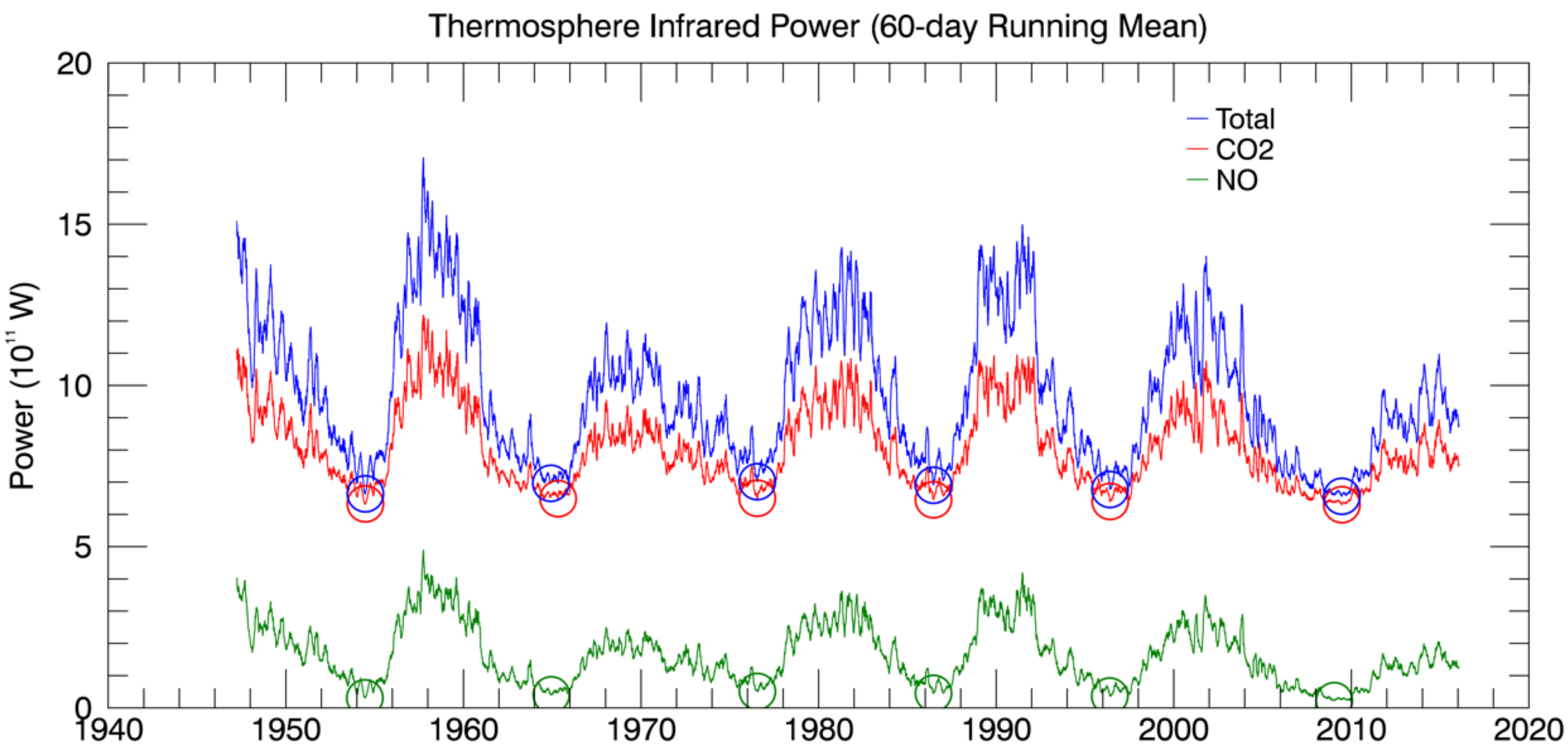
June 6, 2016
Spotless Sun – 3 days running



Backup Slides

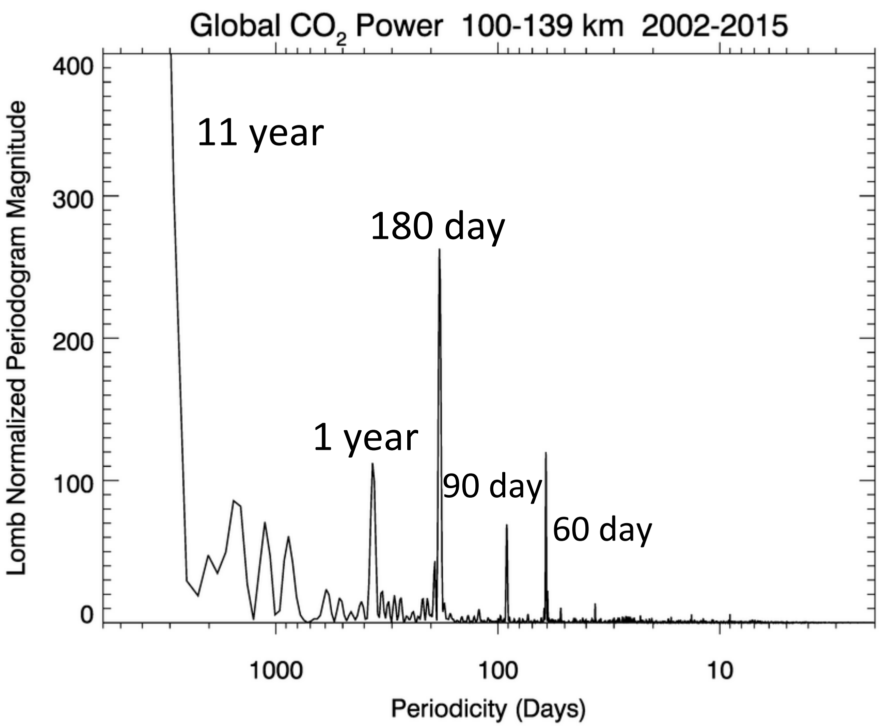
Summary

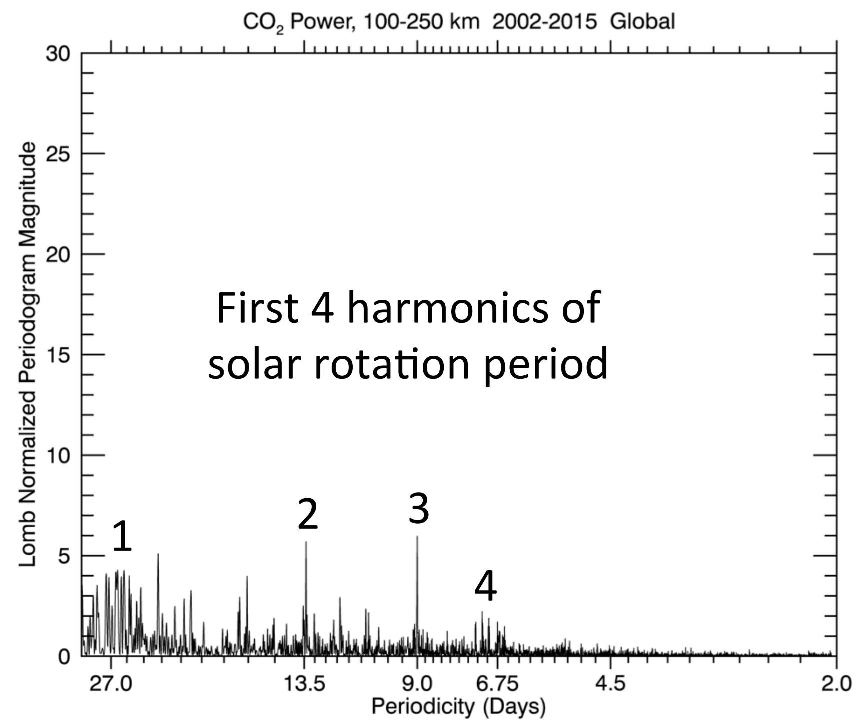
- **SABER data illustrate a very complex and interesting thermosphere that responds to solar variability on timescales from days to decades**
- **Solar maximum, from the atmosphere's perspective, does not have a consistent relationship to the sunspot number**
  - ***Are new metrics for solar max/min for atmosphere response needed?***
- **Past 5 solar cycles vary 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.***



Thermosphere Infrared Power (60-day Running Mean)
Total
CO2
NO
Power (10^{11} W)
20
15
10
5
0
1940
1950
1960
1970
1980
1990
2000
2010
2020

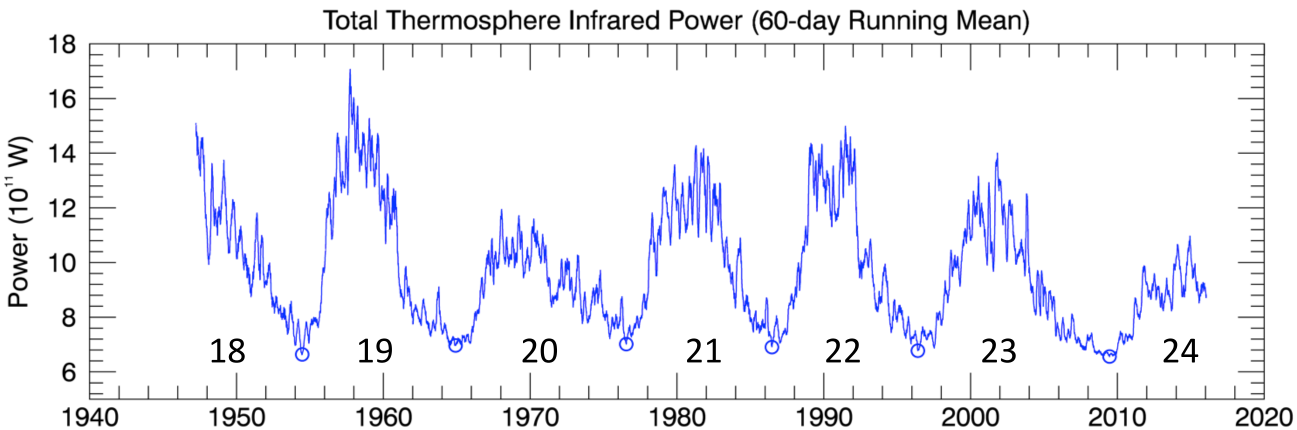
CO_2 Global Power 2002 - 2015
Lomb Normalized Periodogram





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

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

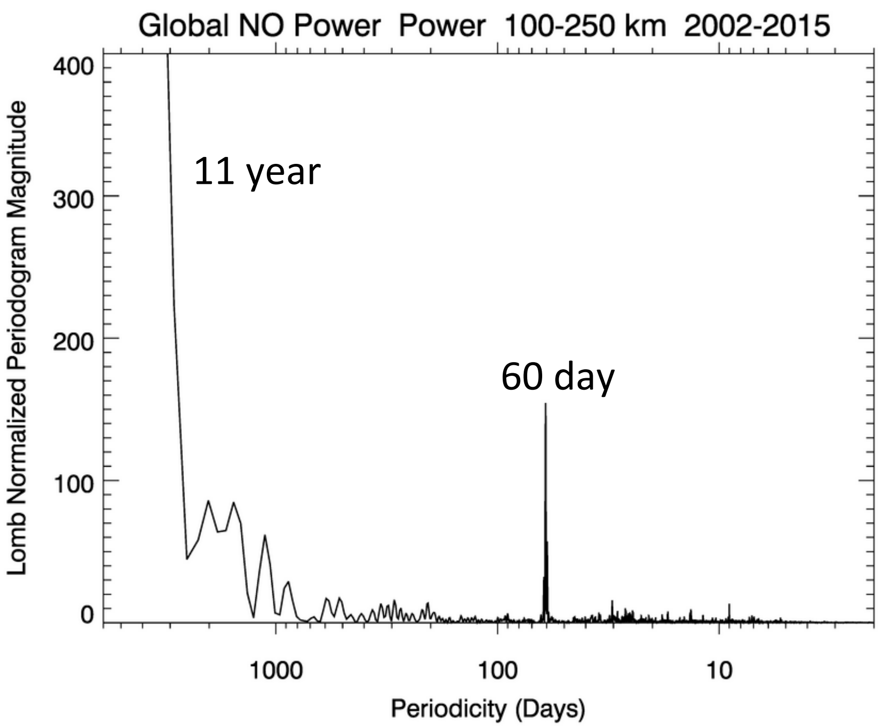


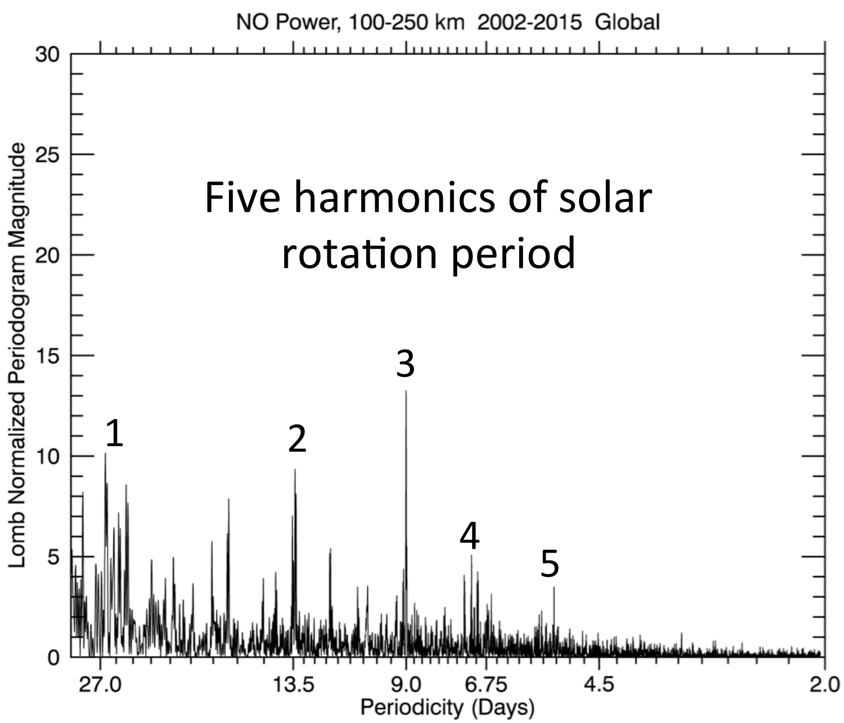
Solar Cycle	Total Power (W)
19	3.904E+15
20	3.867E+15
21	3.720E+15
22	3.685E+15
23	4.344E+15

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

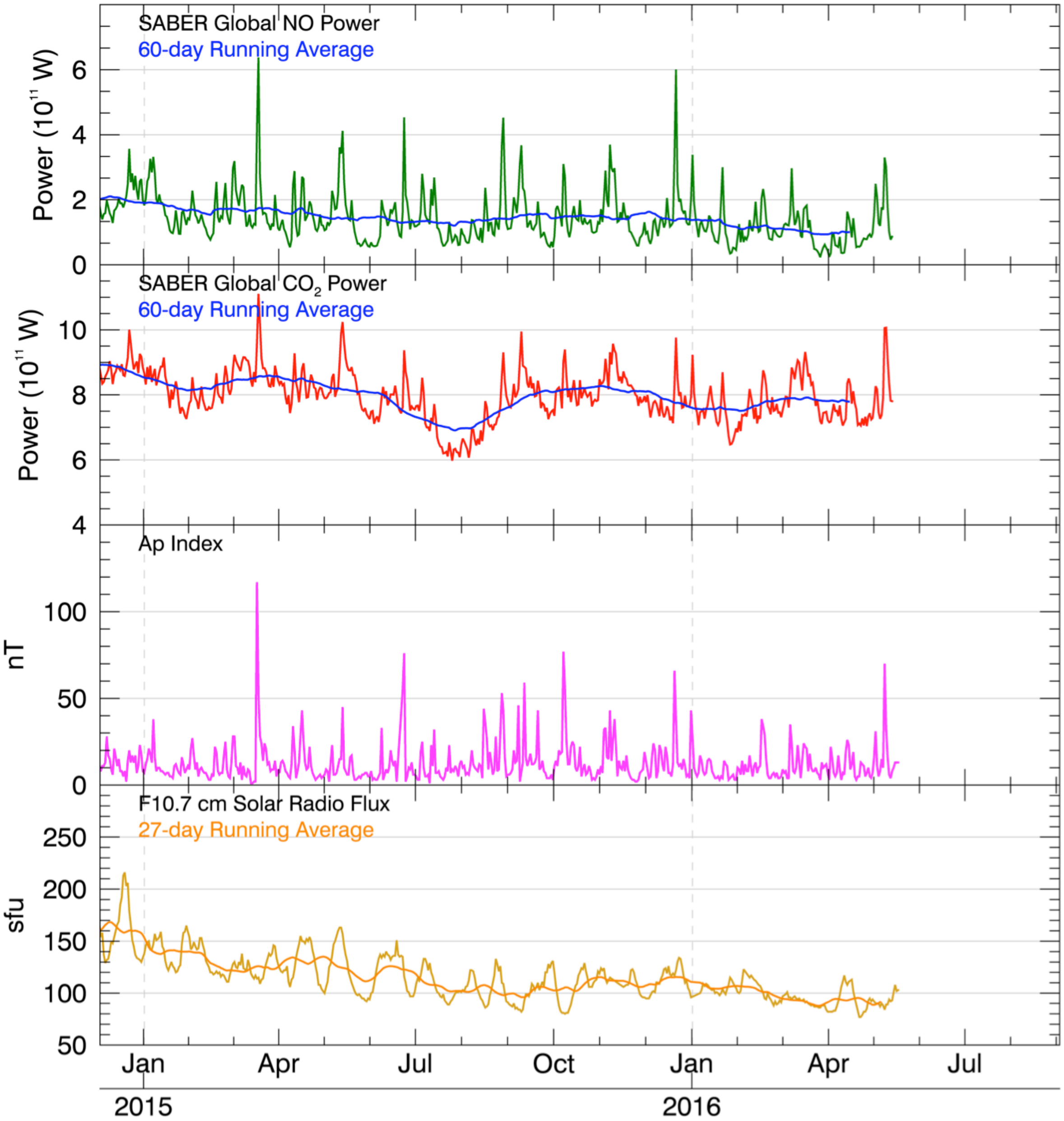
There is only a 6.7 % standard deviation about the mean, so the solar cycles are not that different from a total energy perspective.

NO Global Power 2002 - 2015
Lomb Normalized Periodogram





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


SABER Global NO Power
60-day Running Average
Power (10^{11} W)
SABER Global CO_2 Power
60-day Running Average
Power (10^{11} W)
Ap Index
nT
F10.7 cm Solar Radio Flux
27-day Running Average
sfu
Jan
Apr
Jul
Oct
Jan
Apr
Jul
2015
2016

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**

Fraction of Thermosphere Global Infrared Power CO_2 and NO