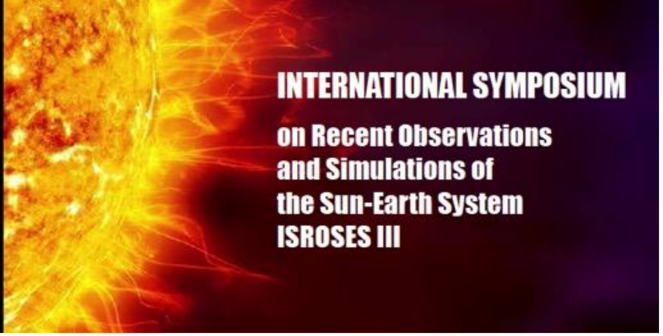


Observations of Space Weather and Space Climate over the Past 15 Years from SABER (And Longer!)

Marty Mlynczak, *NASA Langley*

Linda Hunt, *SSAI*

James M. Russell III, *Hampton University*

The SABER Science *Team*

Outline

- Introduction – "Big Picture" Objectives
- 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

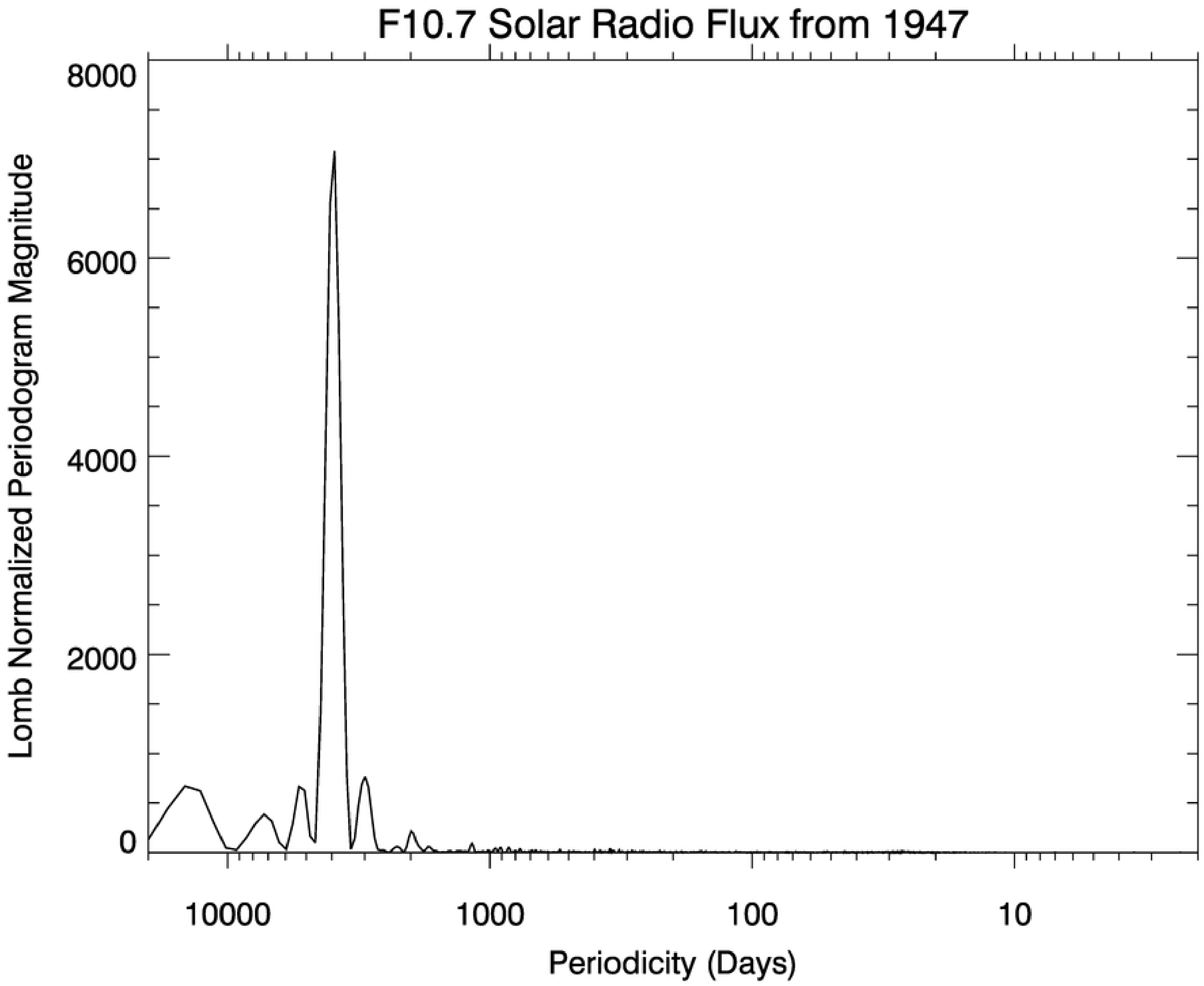
Big Picture Objectives

- To understand the evolution of Earth's thermosphere and mesosphere and the response to human-induced changes
- Region is driven from above (UV, solar wind) and below (ENSO, weather)
- Significant natural variability observed
  - Days – Space weather variability
  - Years – Solar, ENSO
  - Decades – Solar
- Climate change is occurring
  - Carbon dioxide is increasing in M/LT faster than models predict
  - Implications for thermal structure and composition
  - Consequences for space operations
- Understanding human-induced change involves separating natural (solar, weather, ENSO) variability from changes due to human effects
- This presentation looks at the past 15 to 70 years and assesses solar variability over that time

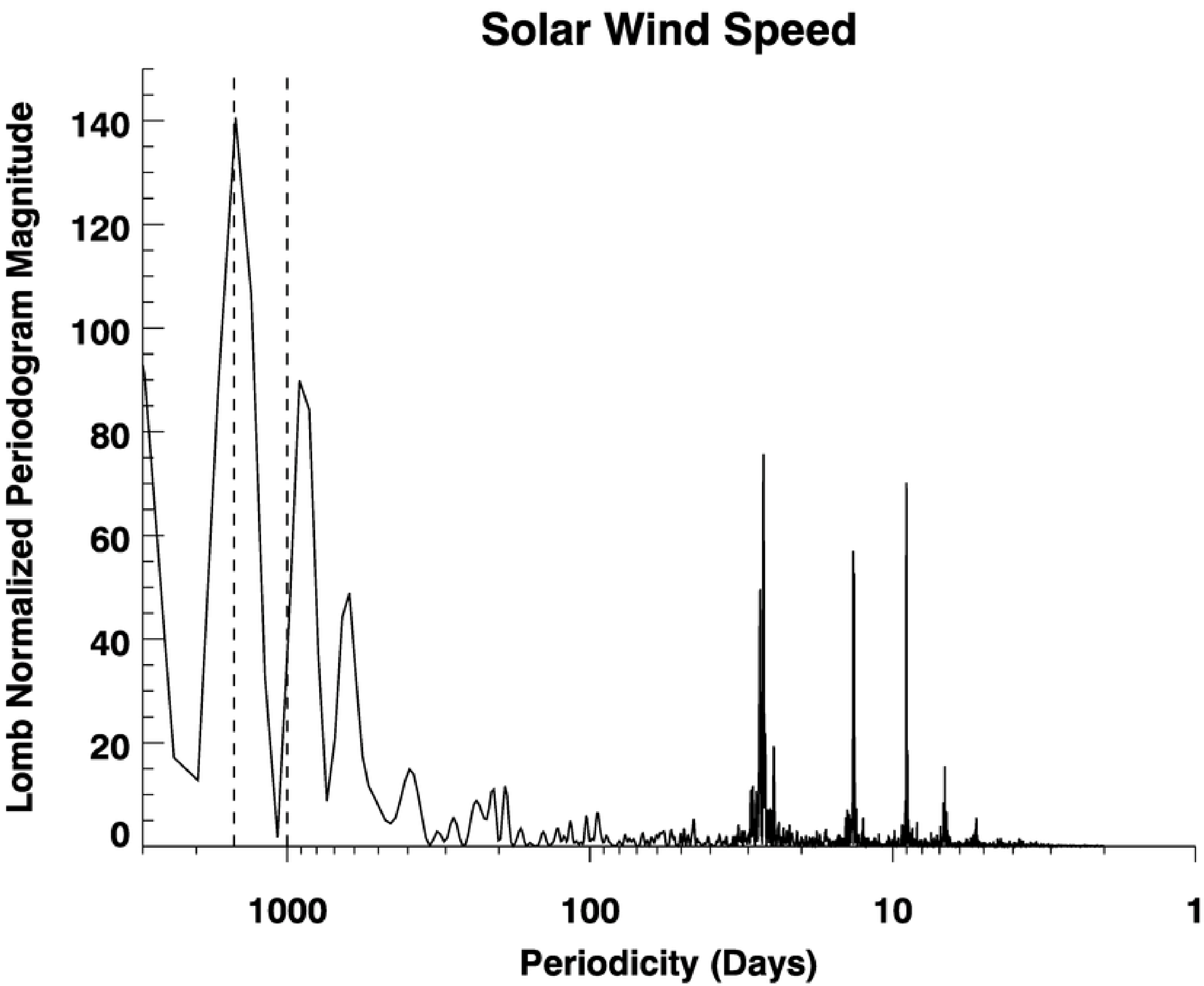
Main Points

- **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**
- **Implication is that, integrated over a solar cycle, "geo-effective" solar energy output is also relatively constant**
- **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**
- ***Critical science remains to do in the "heat sink" region, 110 to 160 km***

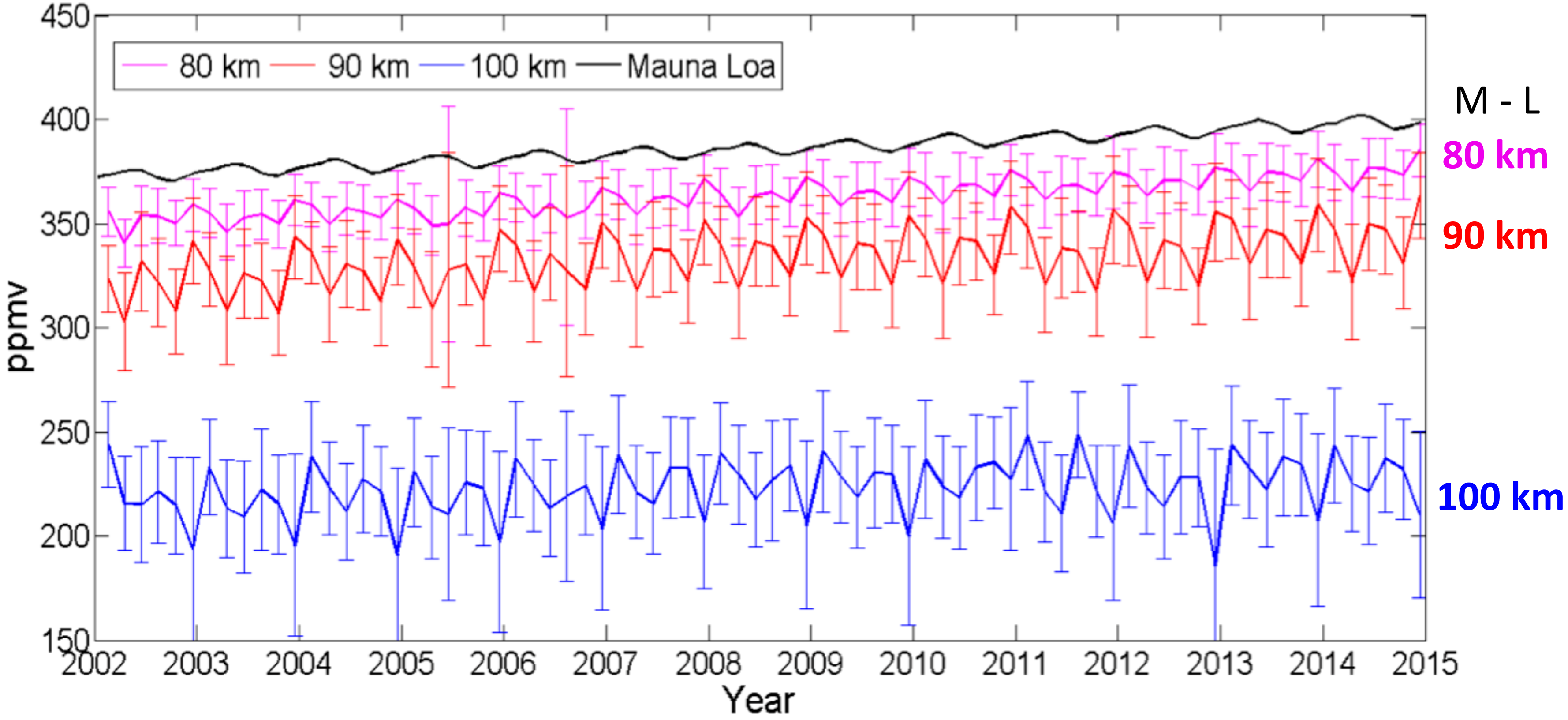
Natural Variability – Solar UV (via F10.7)



Natural Variability – Solar Wind Speed 2002-2015



SABER Mesosphere and Lower Thermosphere CO_2

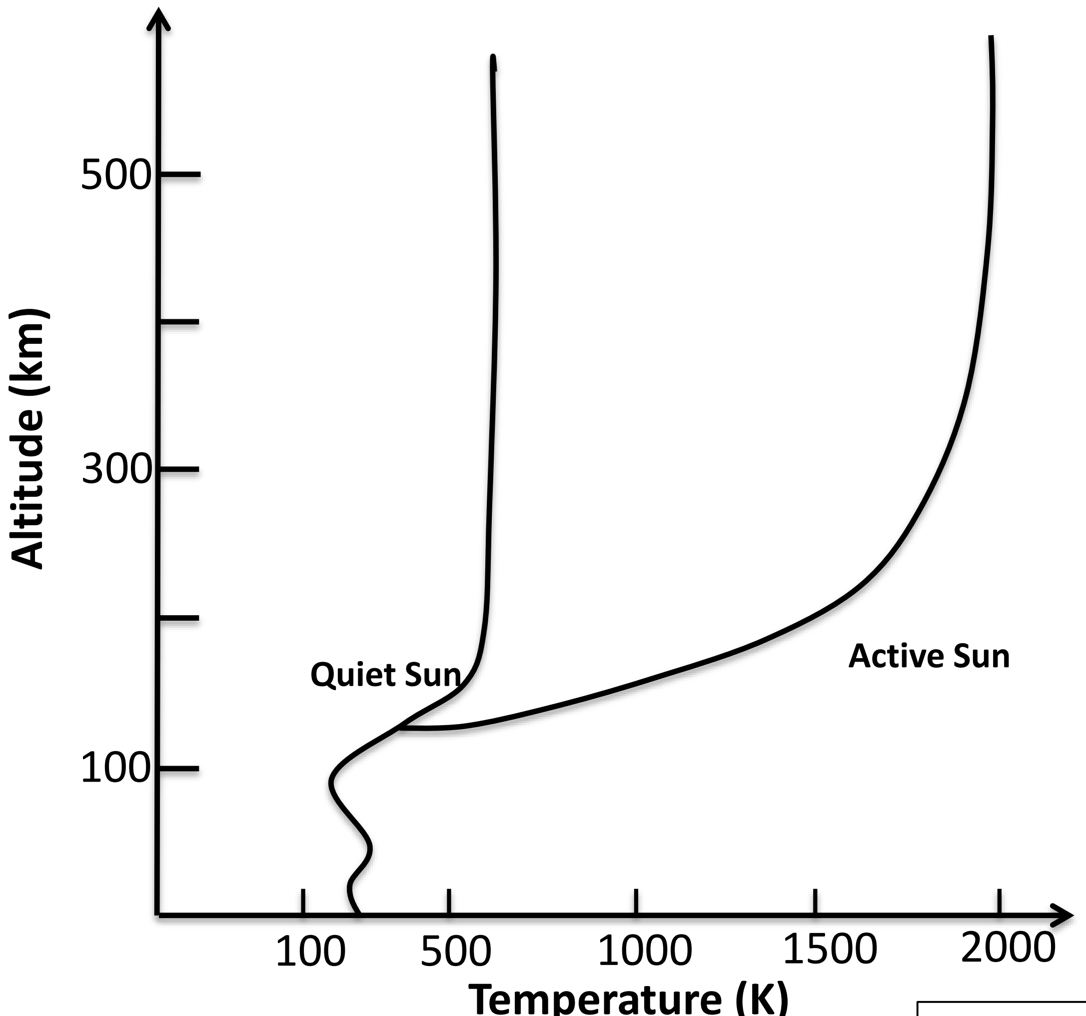


Mesosphere CO_2 trends are not consistent with model predictions

Yue et al., GRL, 2015

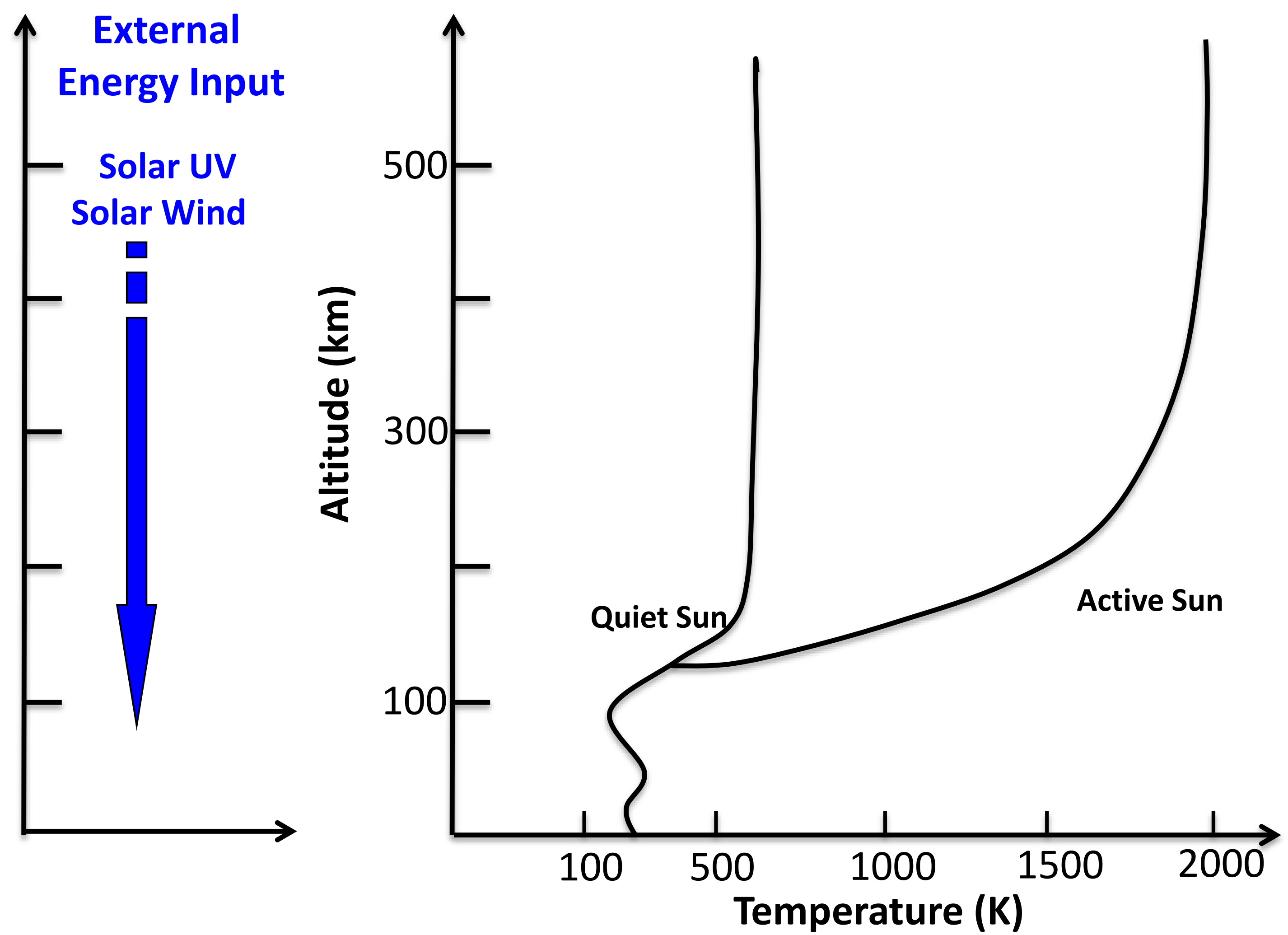
Overview of the Thermosphere Energy Budget

Thermosphere Energy Balance – Thermal Structure

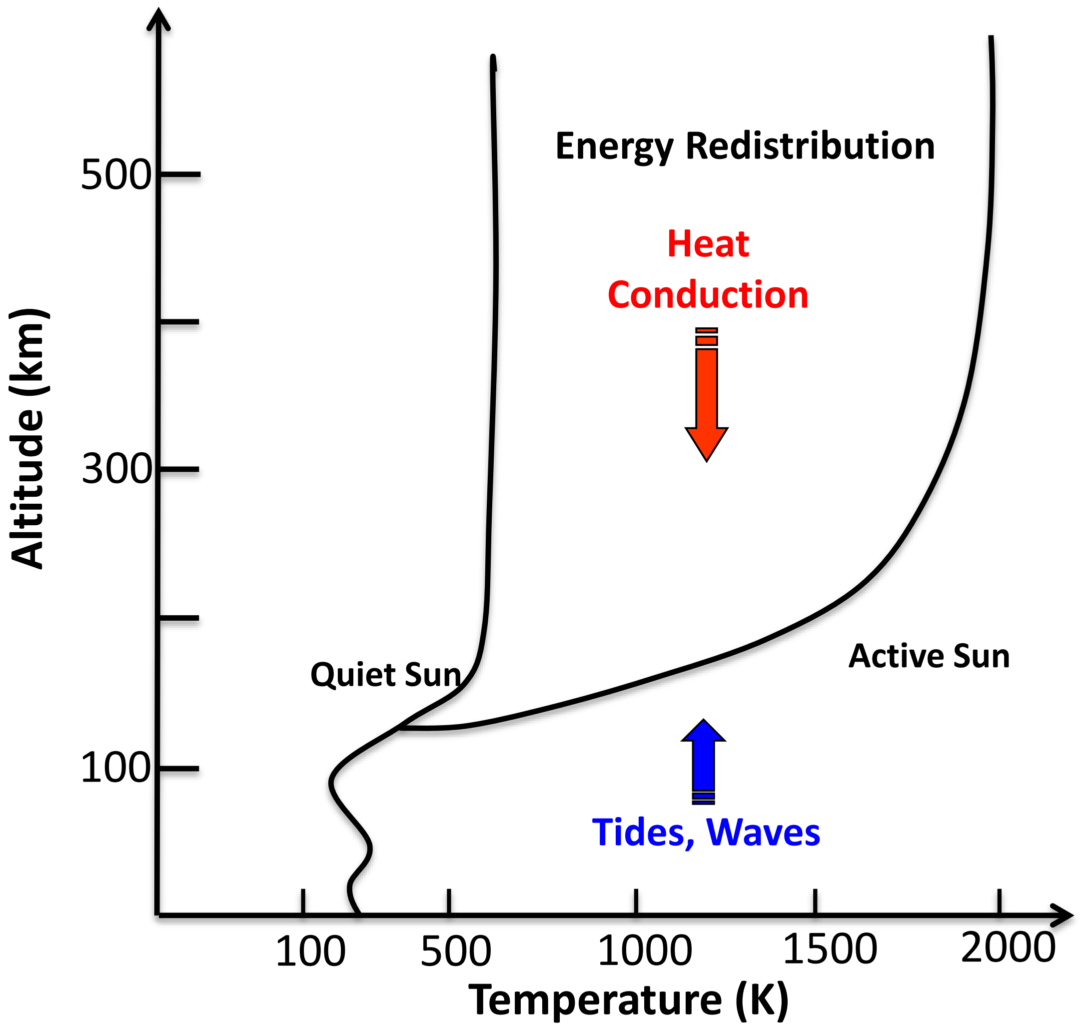


Banks and Kockarts, 1973

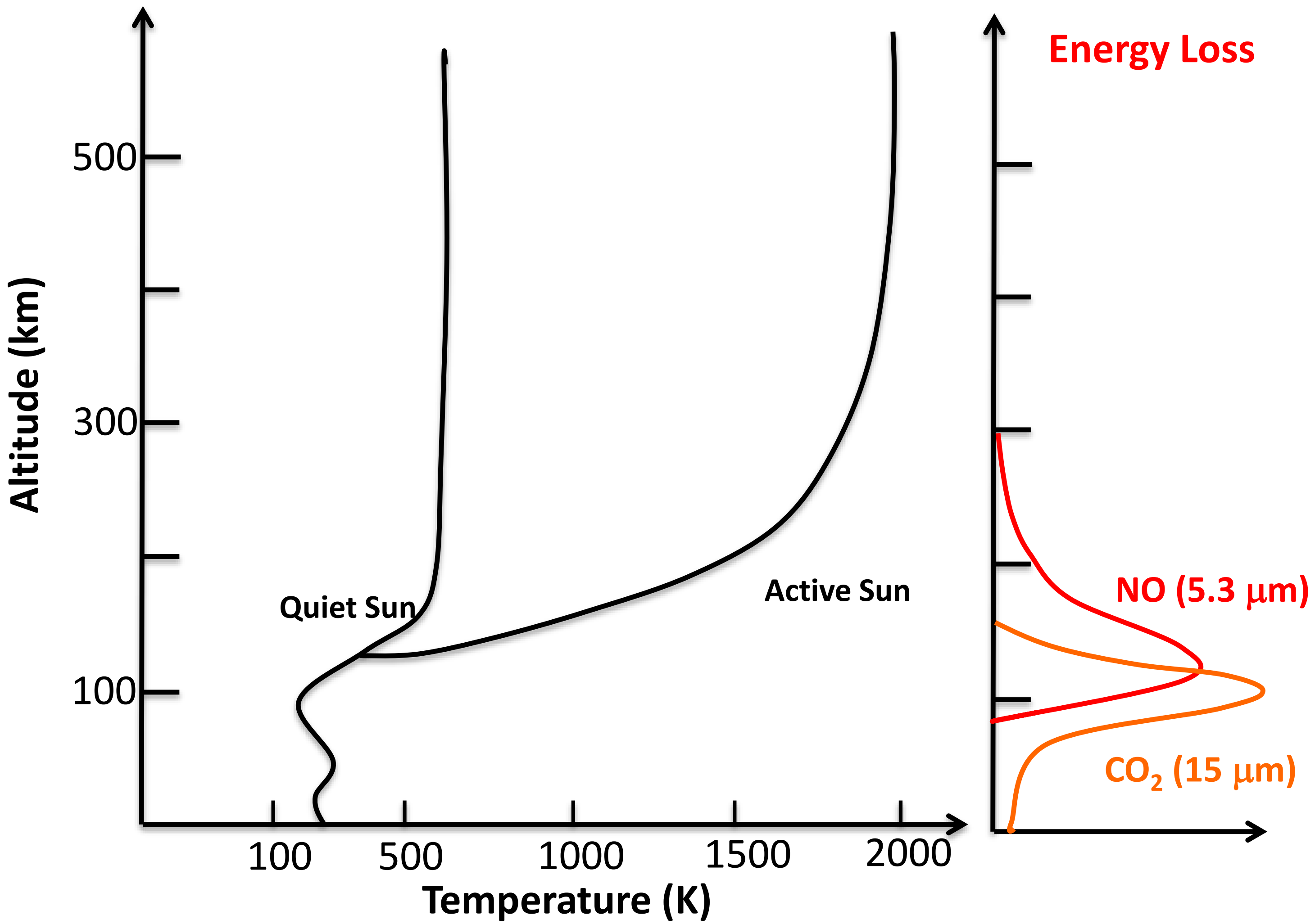
Thermosphere Energy Balance – Energy Inputs



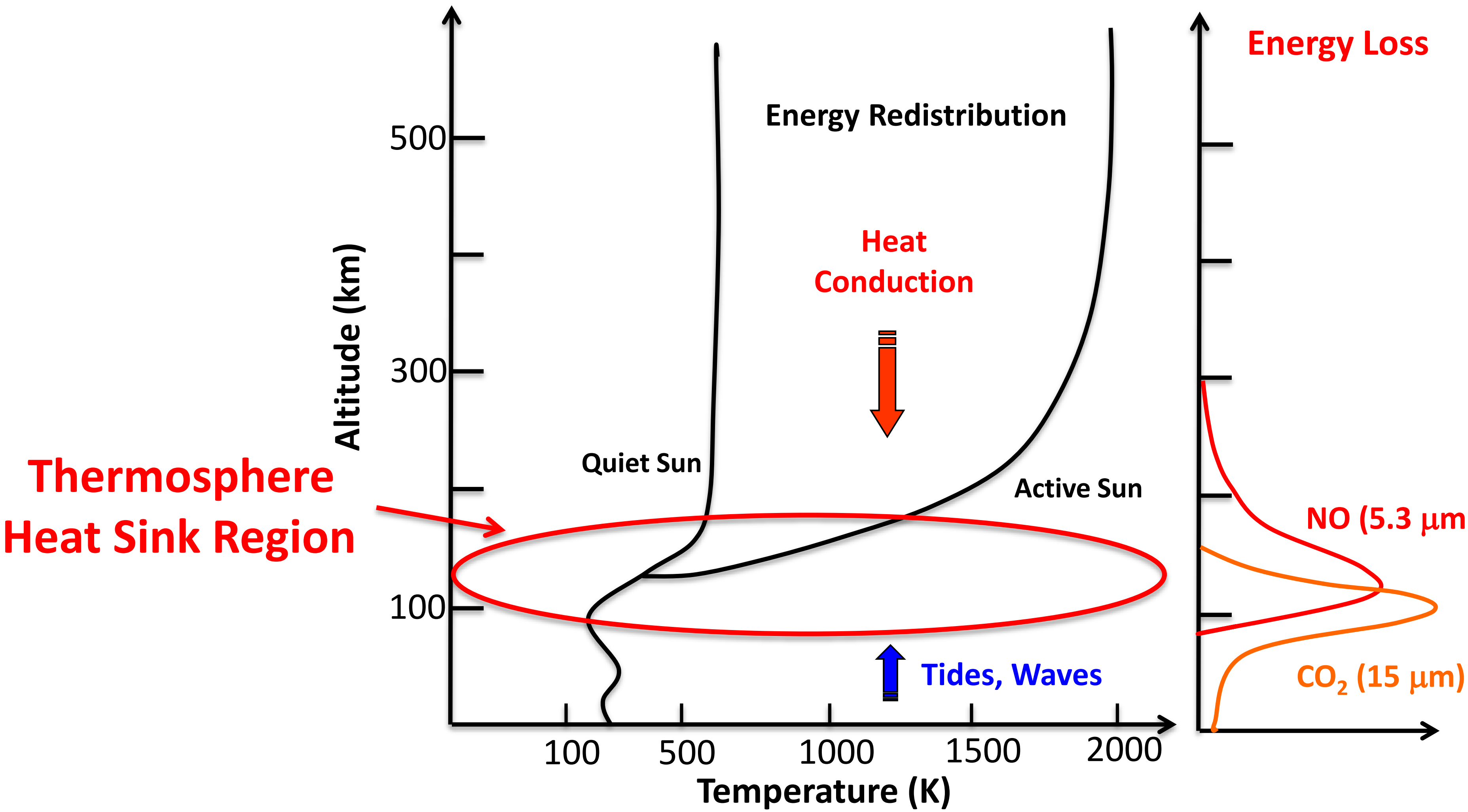
Thermosphere Energy Balance – Energy Redistribution



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:

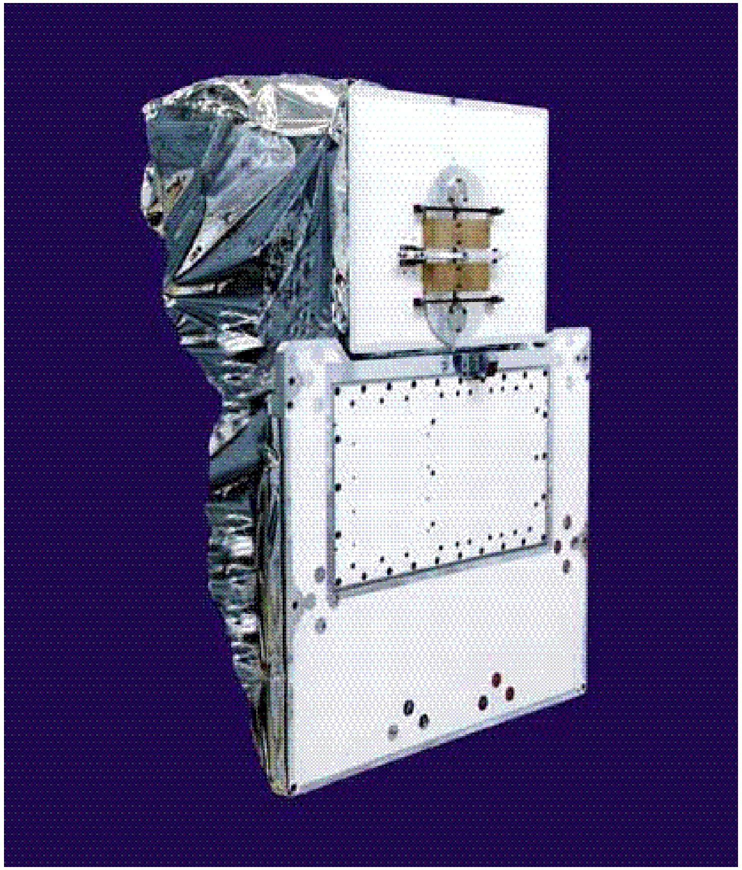
  - NO (υ = 0) + O → NO (υ = 1) + O (Kinetic Energy Removal)
  - NO (υ = 1) → NO (υ = 0) + hν (5.3 μm) (Kinetic Energy Loss)
  - NO (υ = 1) + O → NO (υ = 0) + O (Kinetic Energy Returned)

- 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
- 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
- Approved through September 2017
- Proposing in early 2017 for continued operations through 2019



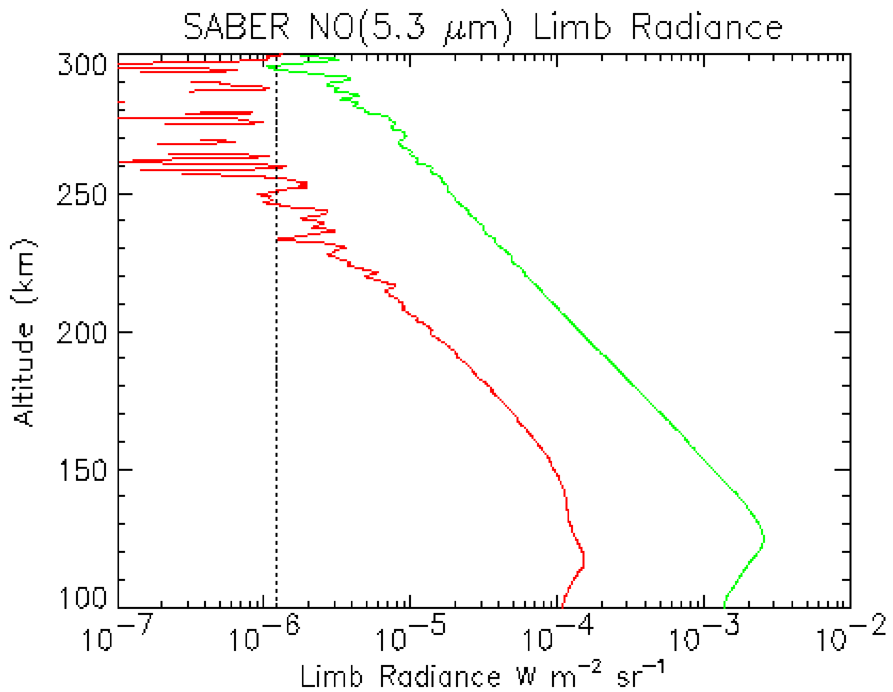
75 kg, 77 watts, 77 x 104 x 63 cm, 4 kbs

SABER Channels and Data Products

Channel	Wavelength	Data Products	Altitude Range
CO_2	15.2 μm	Temperature, pressure, cooling rates	15-100 km
CO_2	15.2 μm	Temperature, pressure, cooling rates	15-100 km
CO_2	14.8 μm	Temperature, pressure, cooling rates	15-100 km
O_3	9.6 μm	Day and Night Ozone, cooling rates	15 - 95 km
H_2O	6.3 μm	Water vapor, cooling rates	15-80 km
CO_2	4.3 μm	Carbon dioxide, dynamical tracer	90-160 km
NO	5.3 μm	Thermospheric cooling	100 - 300 km
$O_2(^1\Delta)$	1.27 μm	Day O_3, solar heating; Night O	50-100 km
OH(υ)	2.0 μm	Chemical Heating, photochemistry	80-100 km
OH(υ)	1.6 μm	Chemical Heating, photochemistry	80-100 km

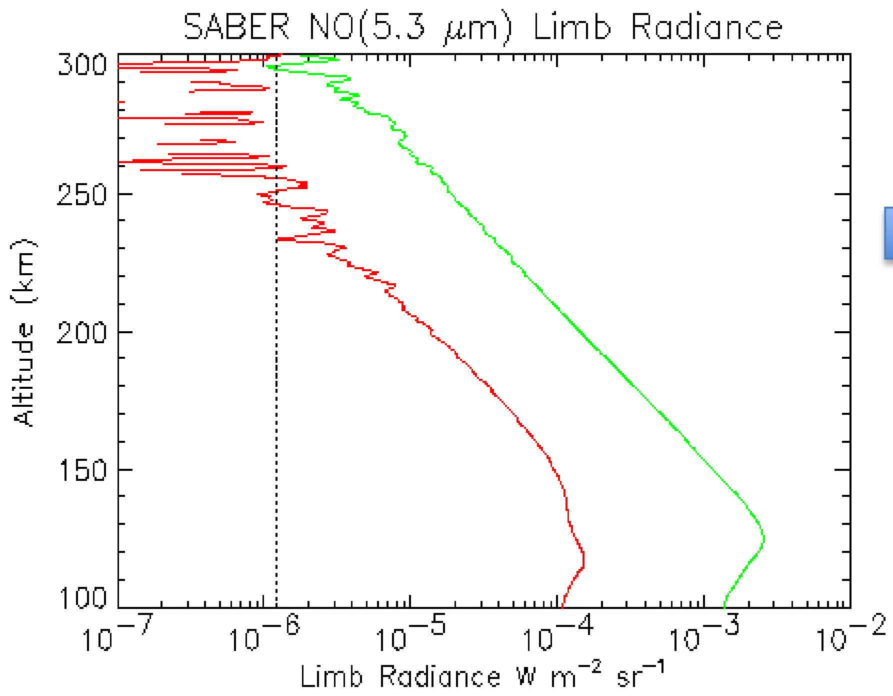
Over 30 data products including T, CO_2, O_3, VER, O, H, $\partial T/ \partial t$

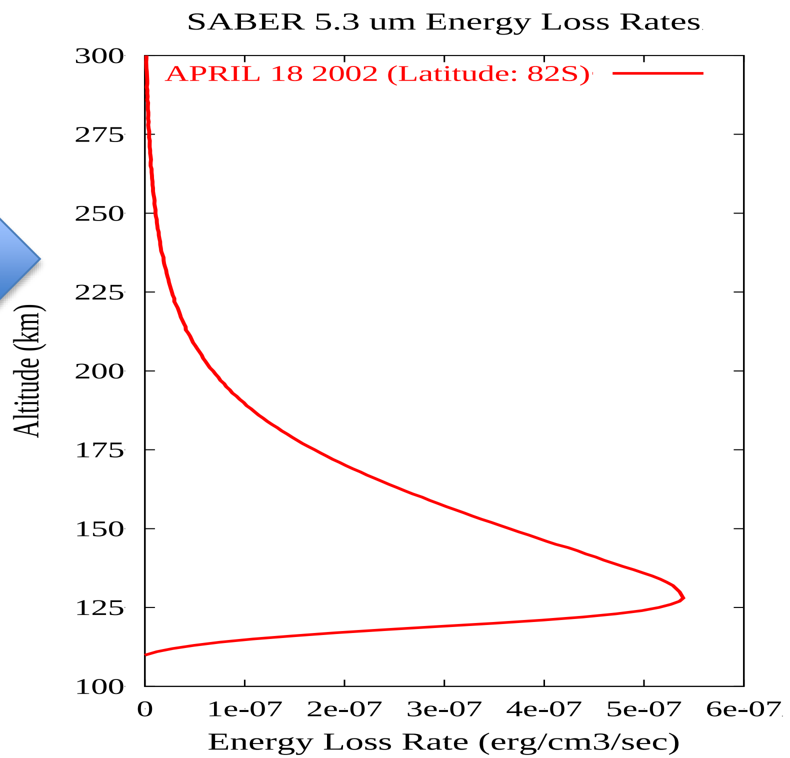
Parameters: Radiances; Cooling Rates; Fluxes; and Power



Infrared Radiance from NO measured by the SABER instrument

Parameters: Radiances and Cooling Rates



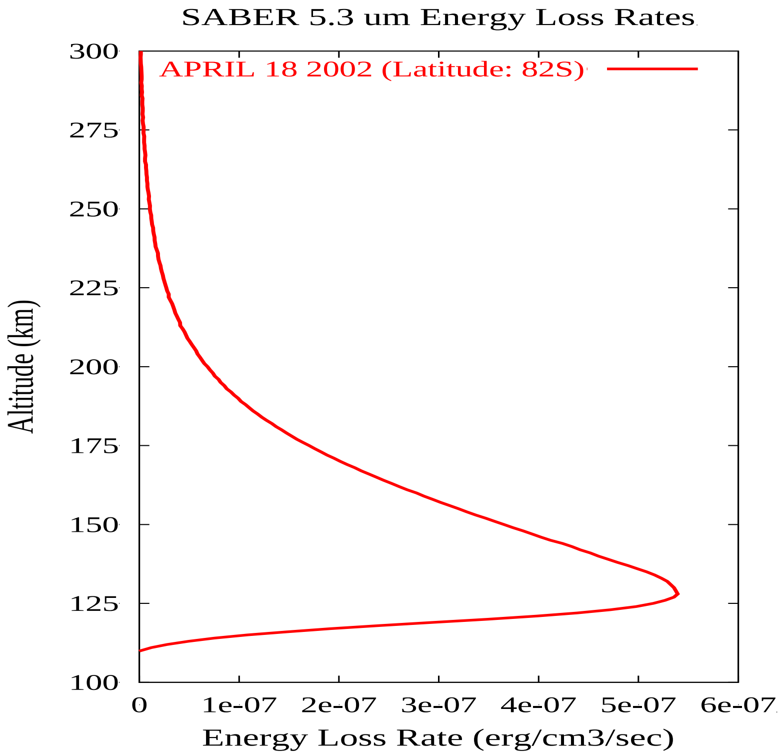


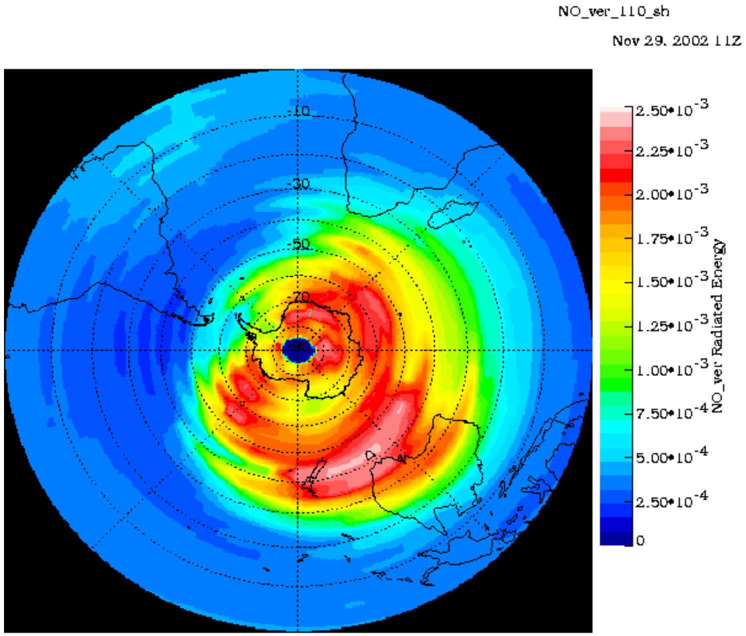
Infrared Radiance from NO
Measured by the SABER instrument

Infrared Cooling Rate
Derived from SABER NO Radiance

Energy/time/volume

Parameters: Cooling Rates to Fluxes





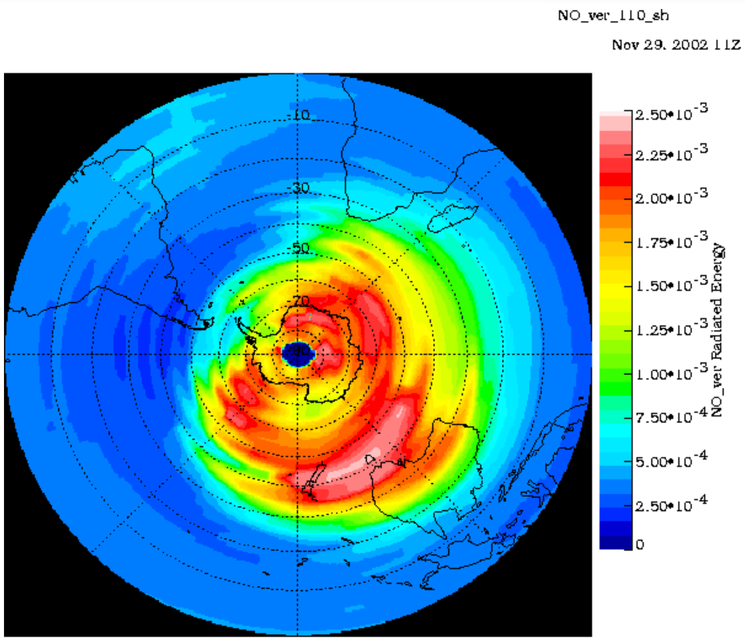
Infrared Cooling Rate
Derived from SABER NO Radiance

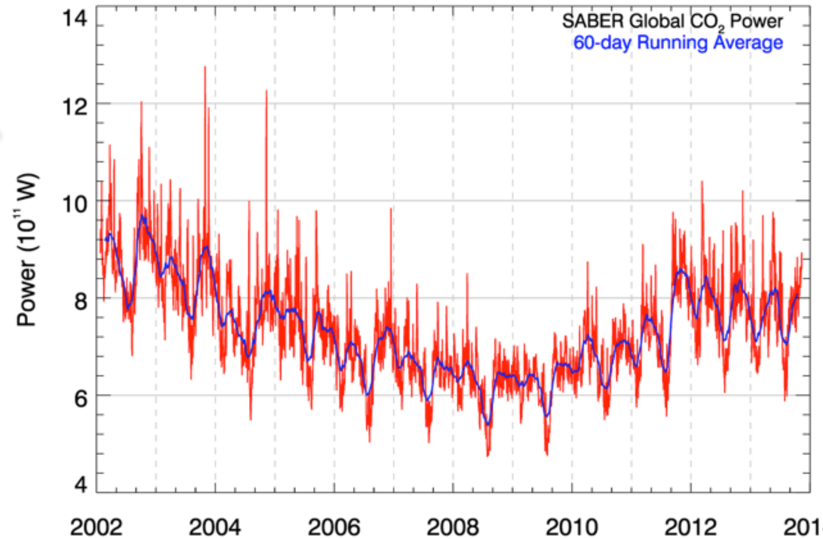
Energy/time/volume

Infrared Radiated Flux from NO

Energy/time/area

Parameters: Cooling Rates to Fluxes





Infrared Radiated Flux from NO

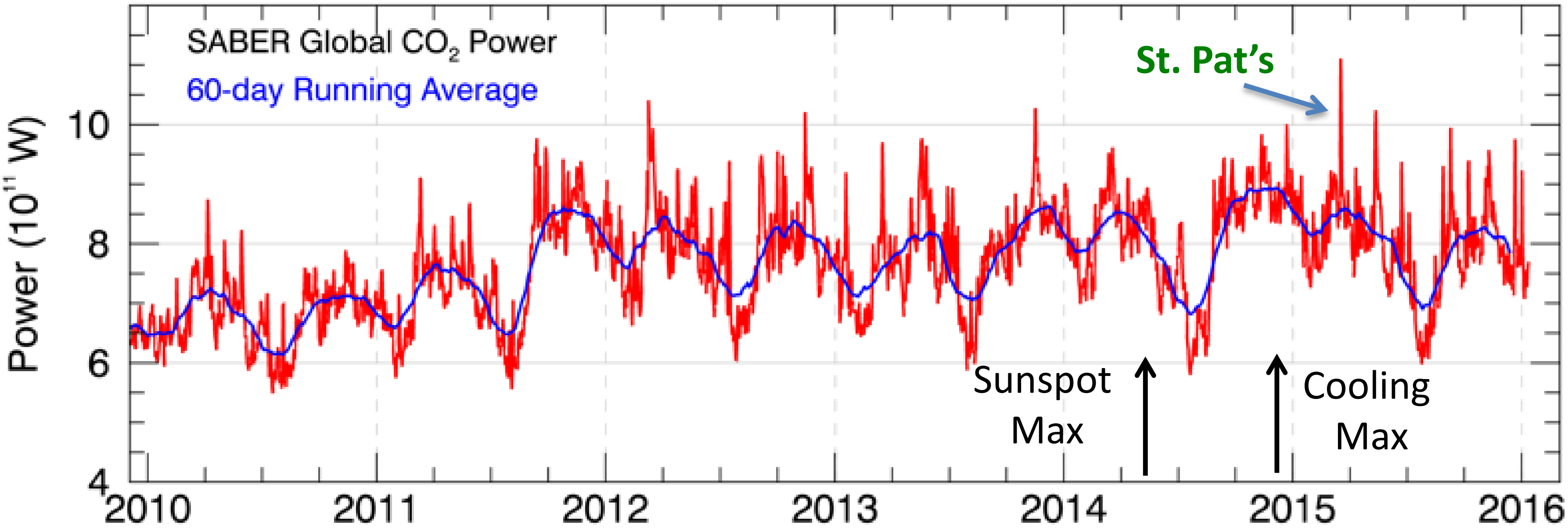
Energy/time/area

Infrared Radiated Power from NO

Energy/time (Watts)

This is the process for Nitric Oxide, which radiates in weak line limit
Carbon Dioxide is much more complex although conceptually similar
See Mlynczak et al., 2010 for details

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

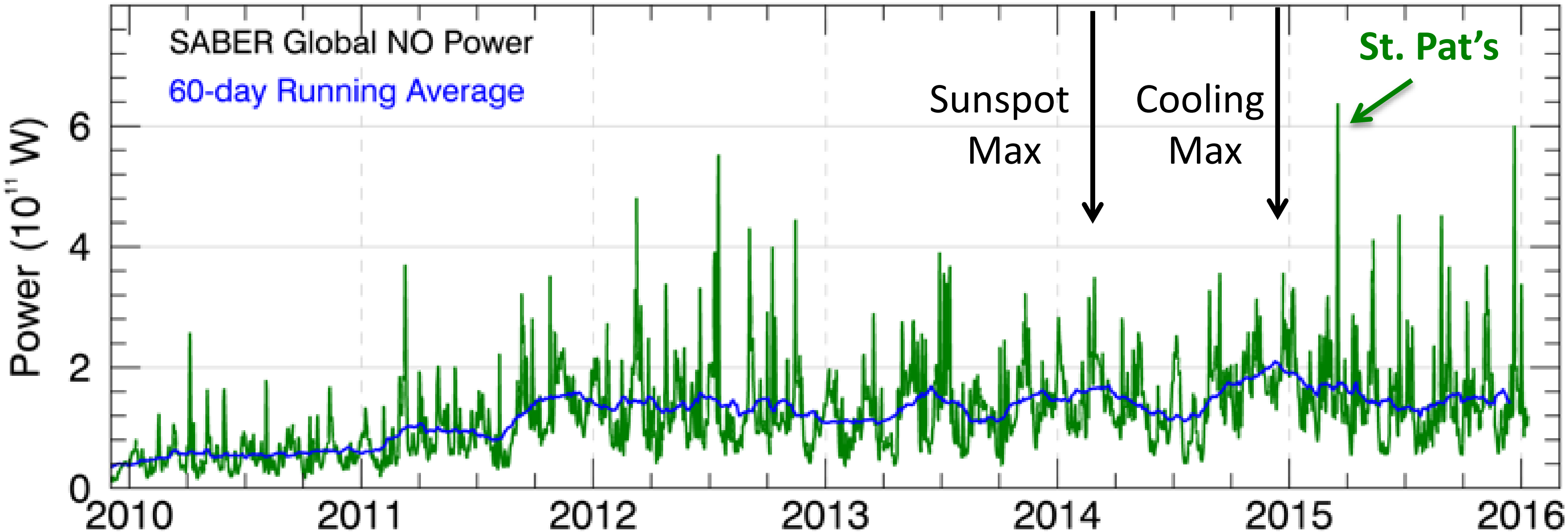


Geomagnetic activity always evident in radiative cooling

Strong semi-annual oscillation evident

Sunspot and cooling maxima are not coincident

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



Sunspot and cooling maxima not coincident

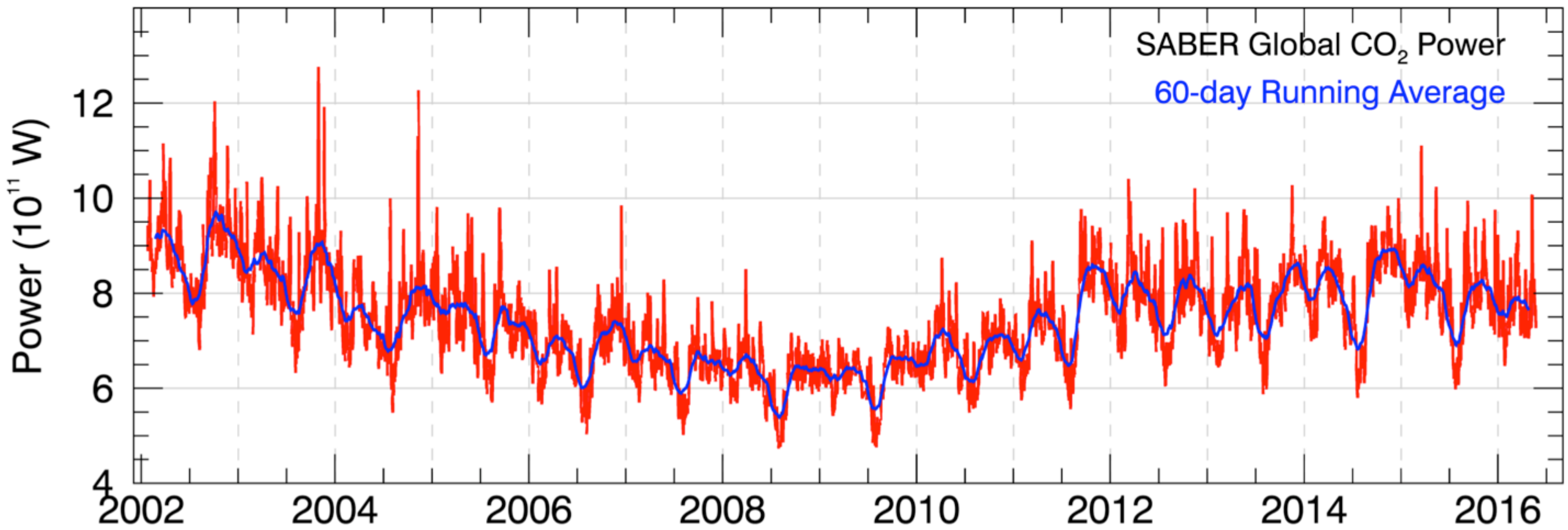
Each "spike" is the response to a geomagnetic event

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

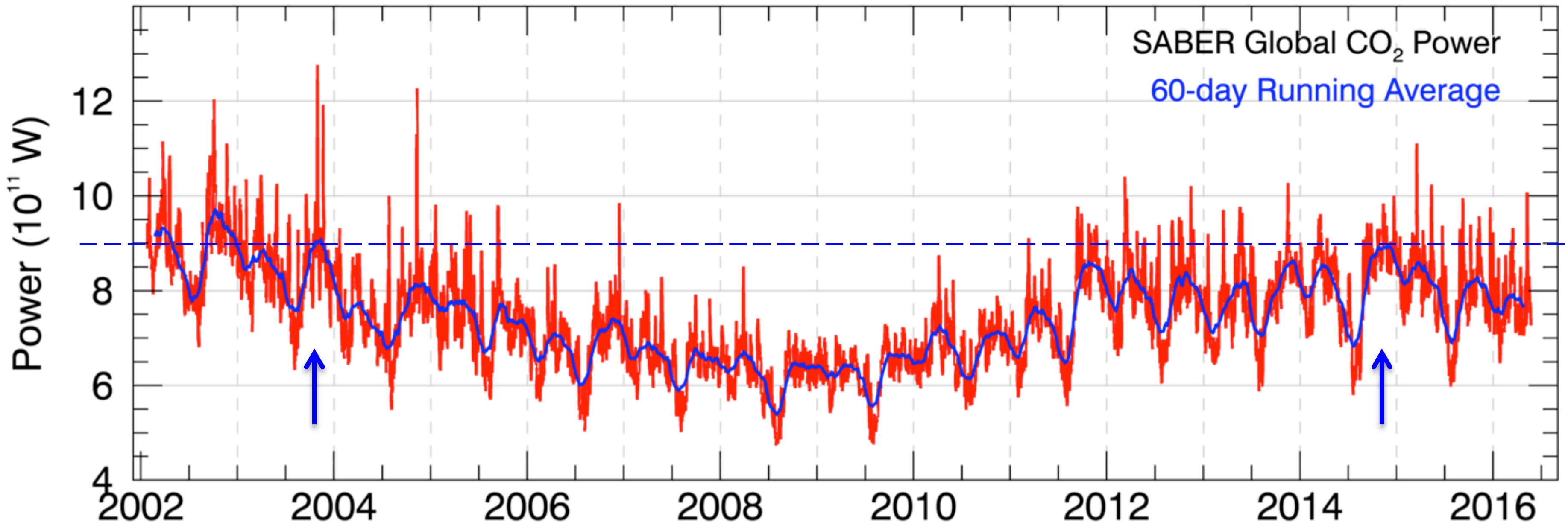
Over 5200 days of data!



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

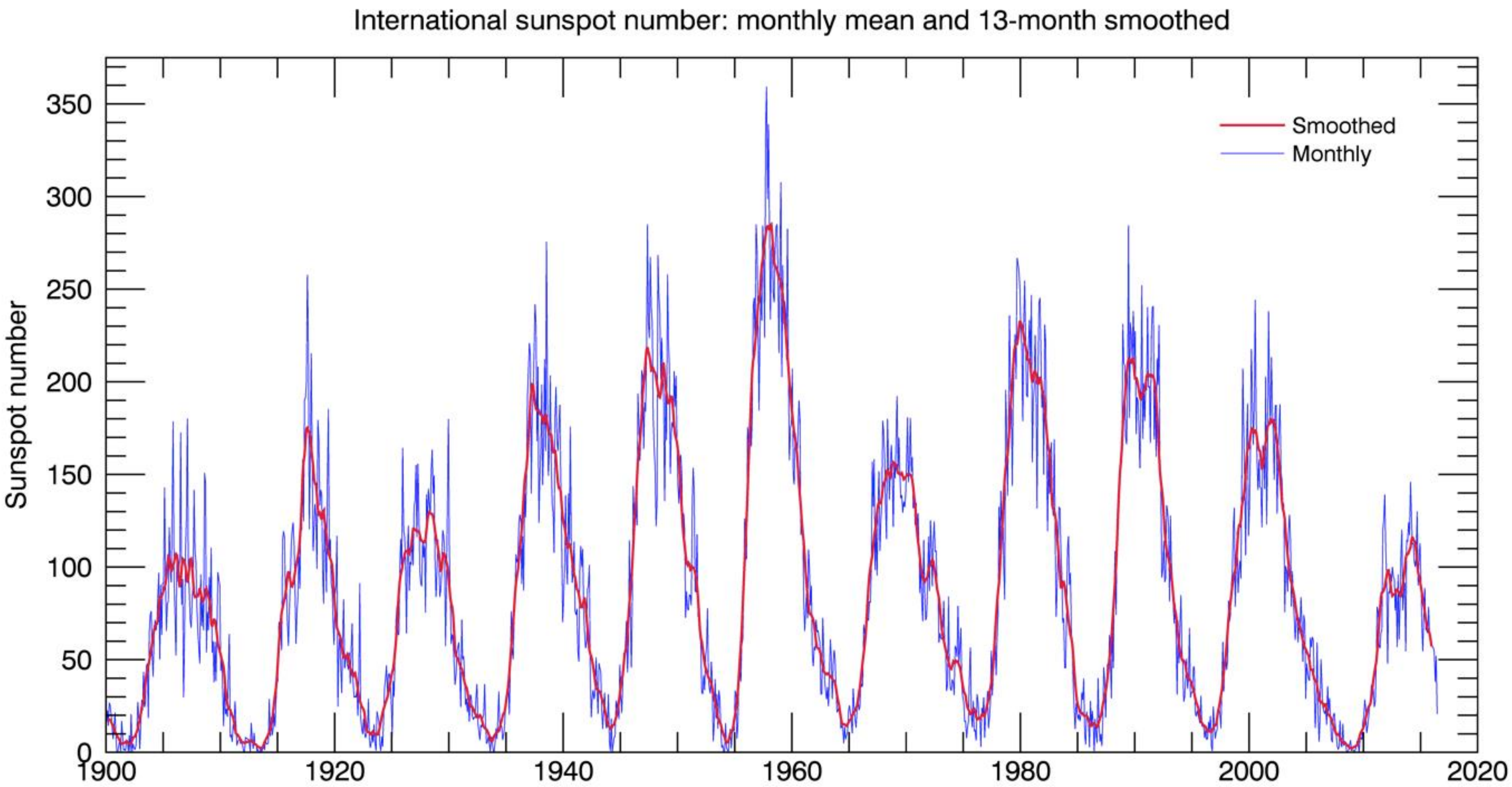
Over 5200 days of data!



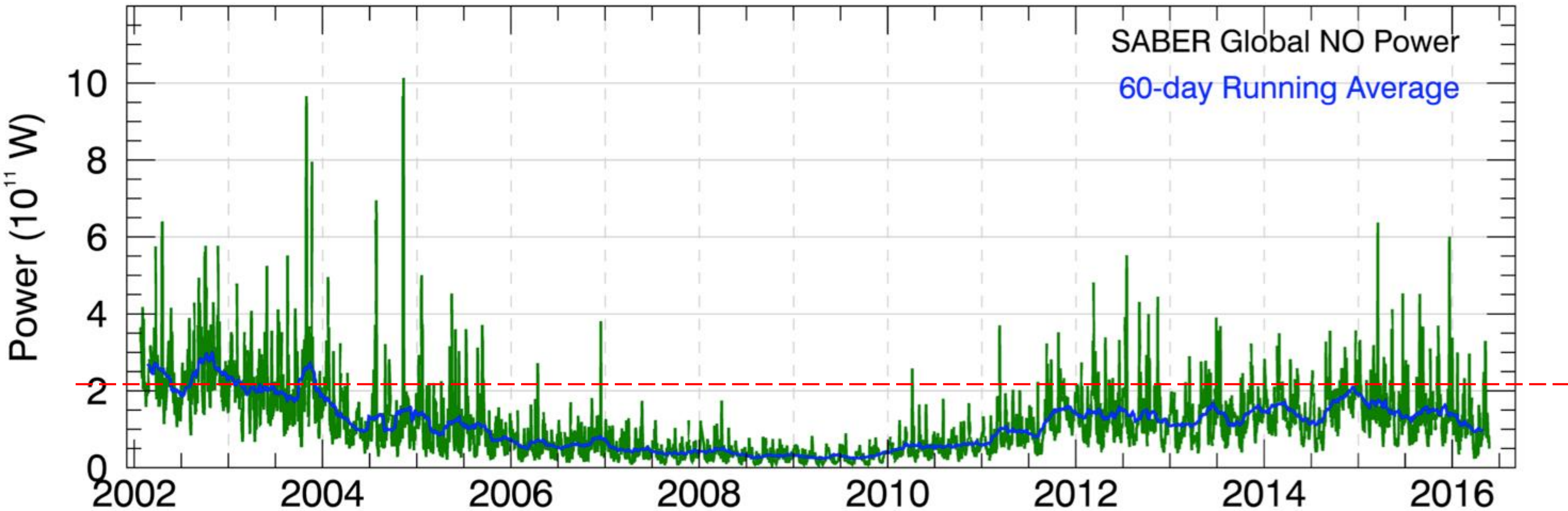
SC 24 solar max (12/2014) as warm as 12/2003 – 11 years prior

But, just how different in total energy are they?

Solar Variability as Indicated by Sunspot Number



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



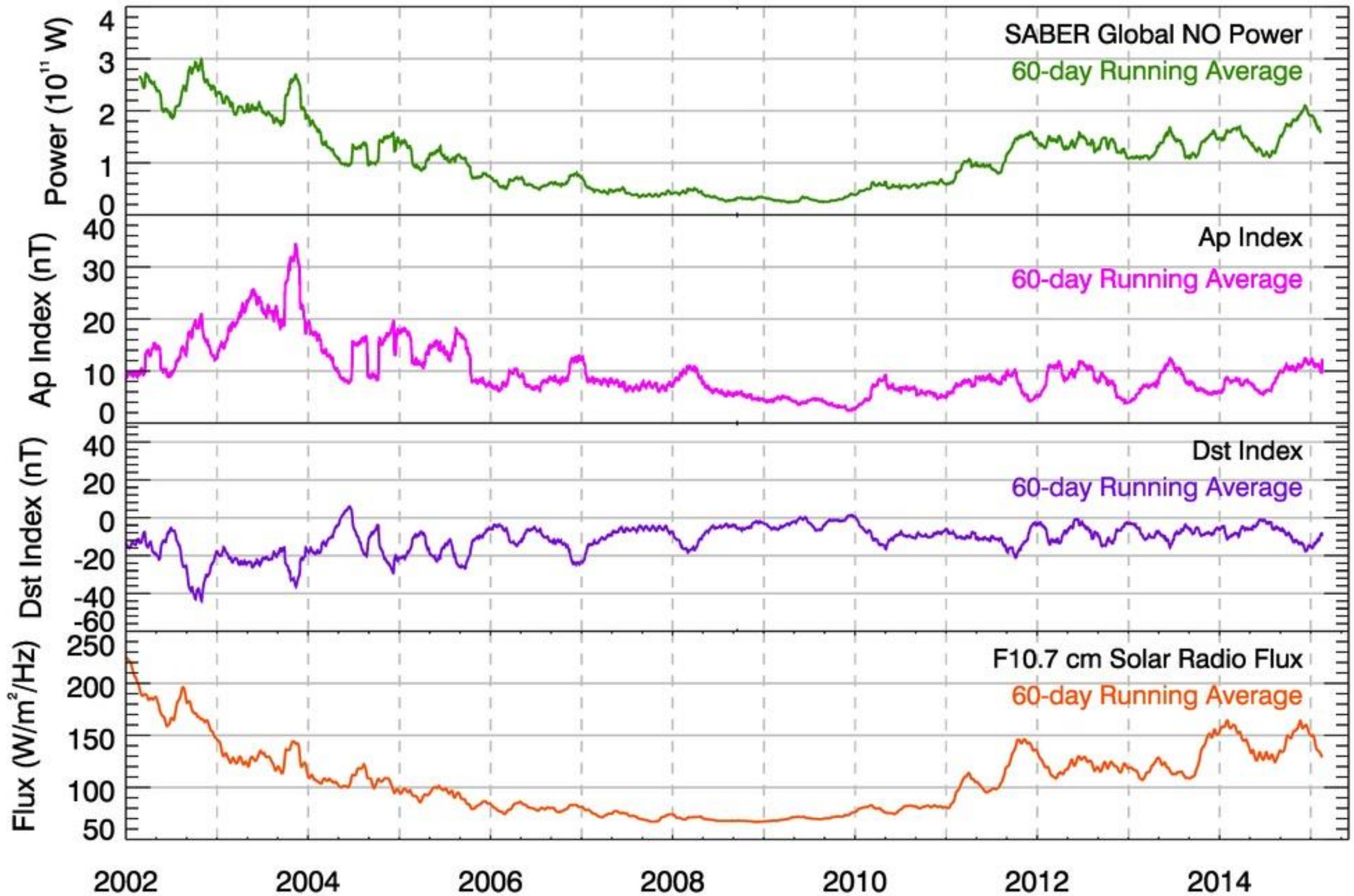
NO Cooling at Peak of SC 24 (12/2014) was highest level since 12/2003

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

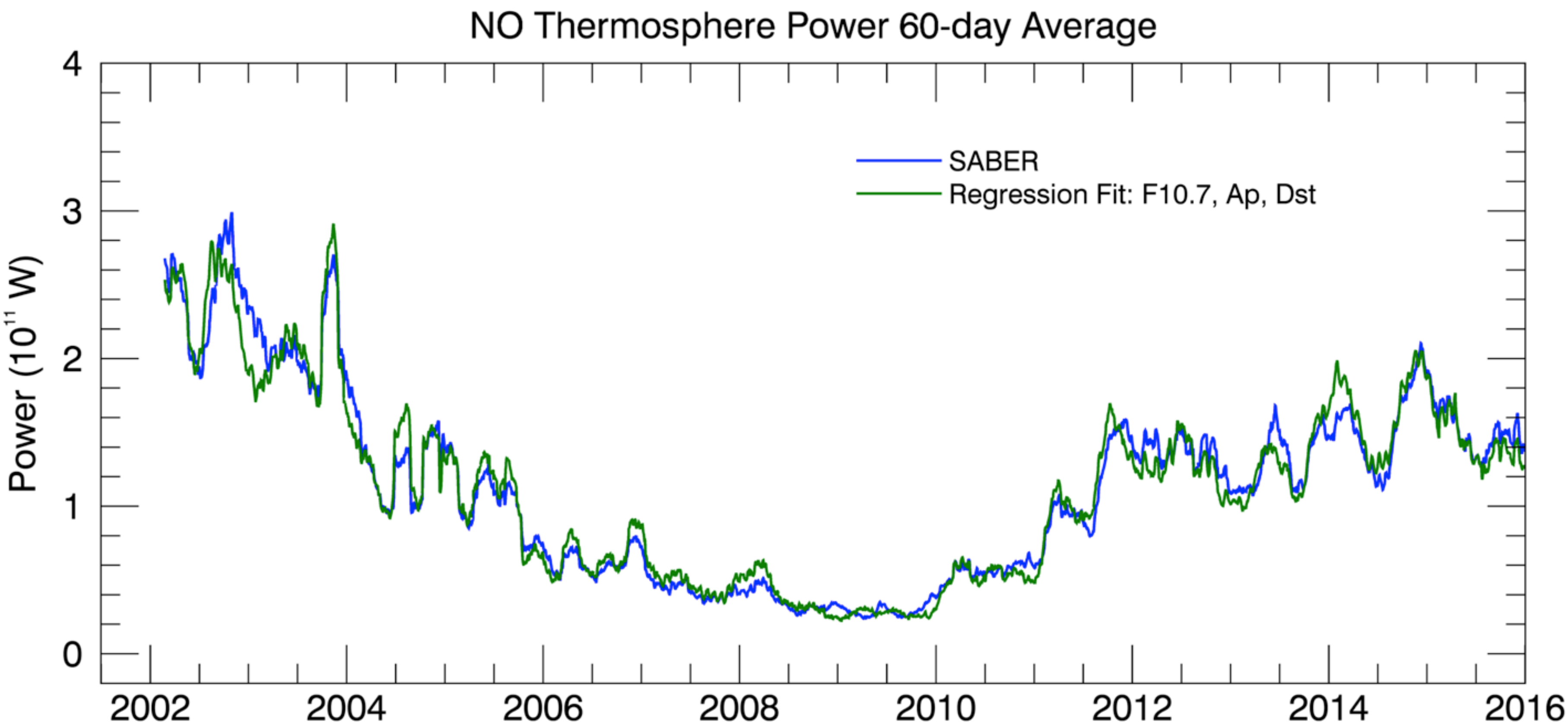
A View to the Past

60-day Running Means – Nitric Oxide Power

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



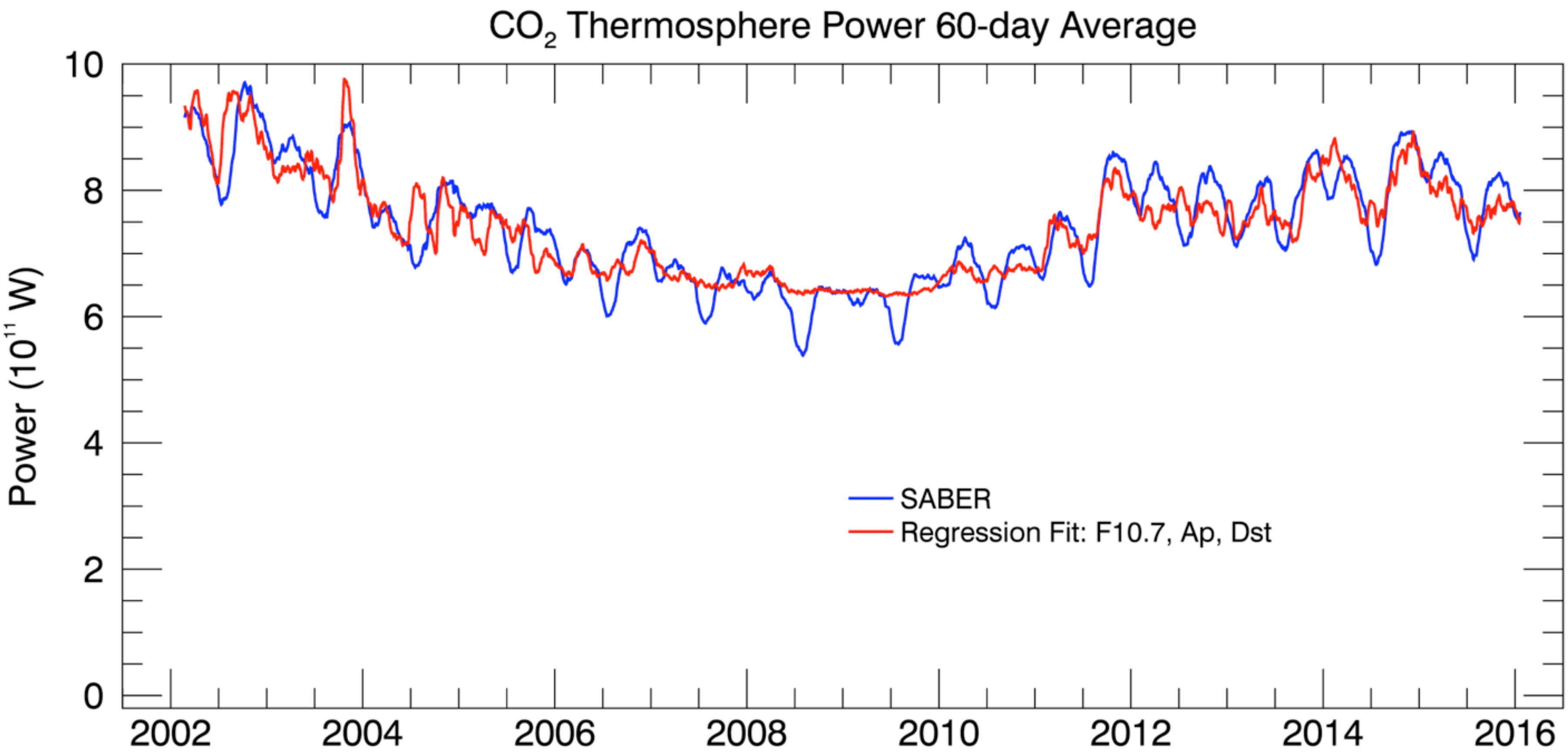
Multiple Linear Regression Fit
SABER NO Power as Function of F10.7, Ap, Dst



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

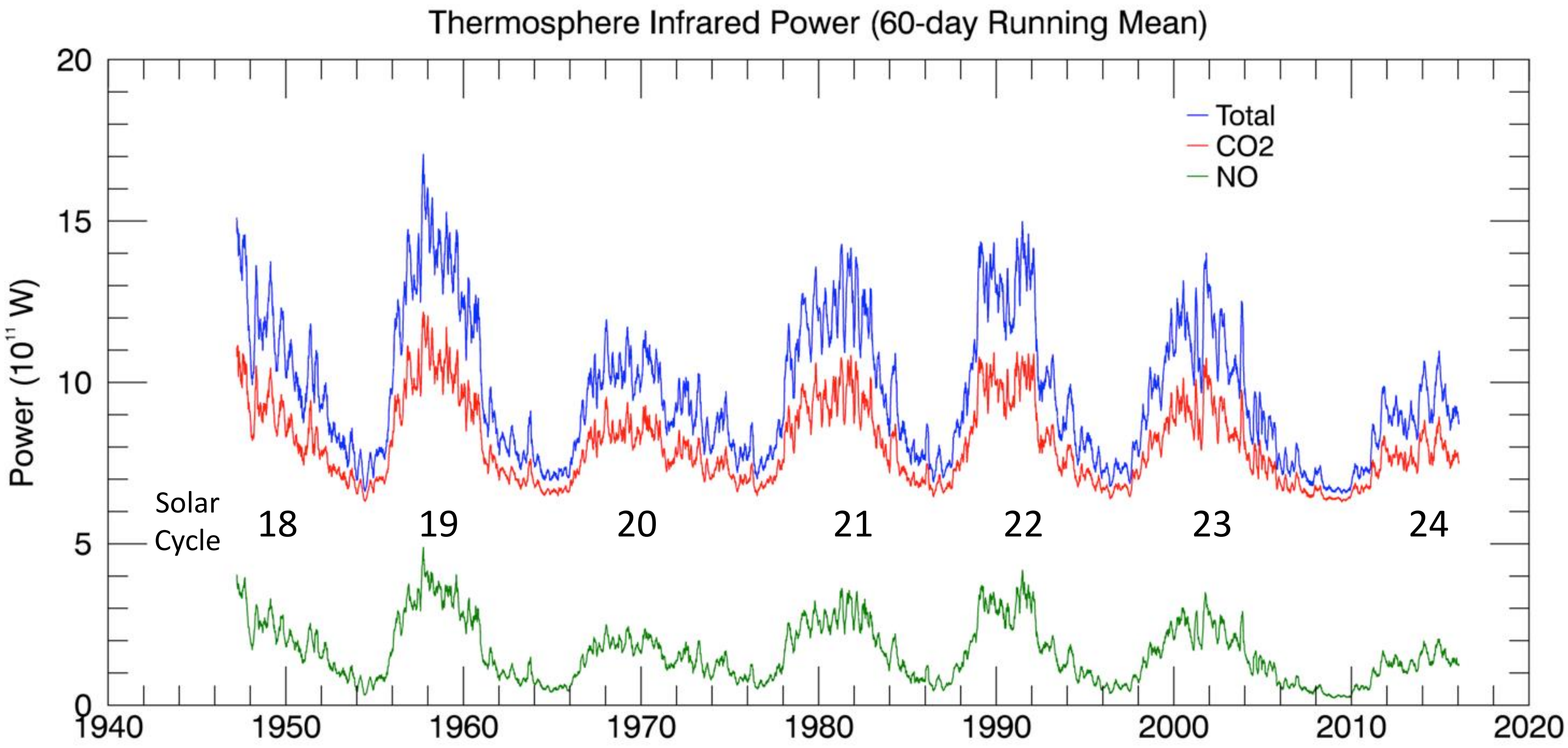
Mlynczak et al., GRL, 2015

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

Reconstruction of Thermosphere Infrared Power



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

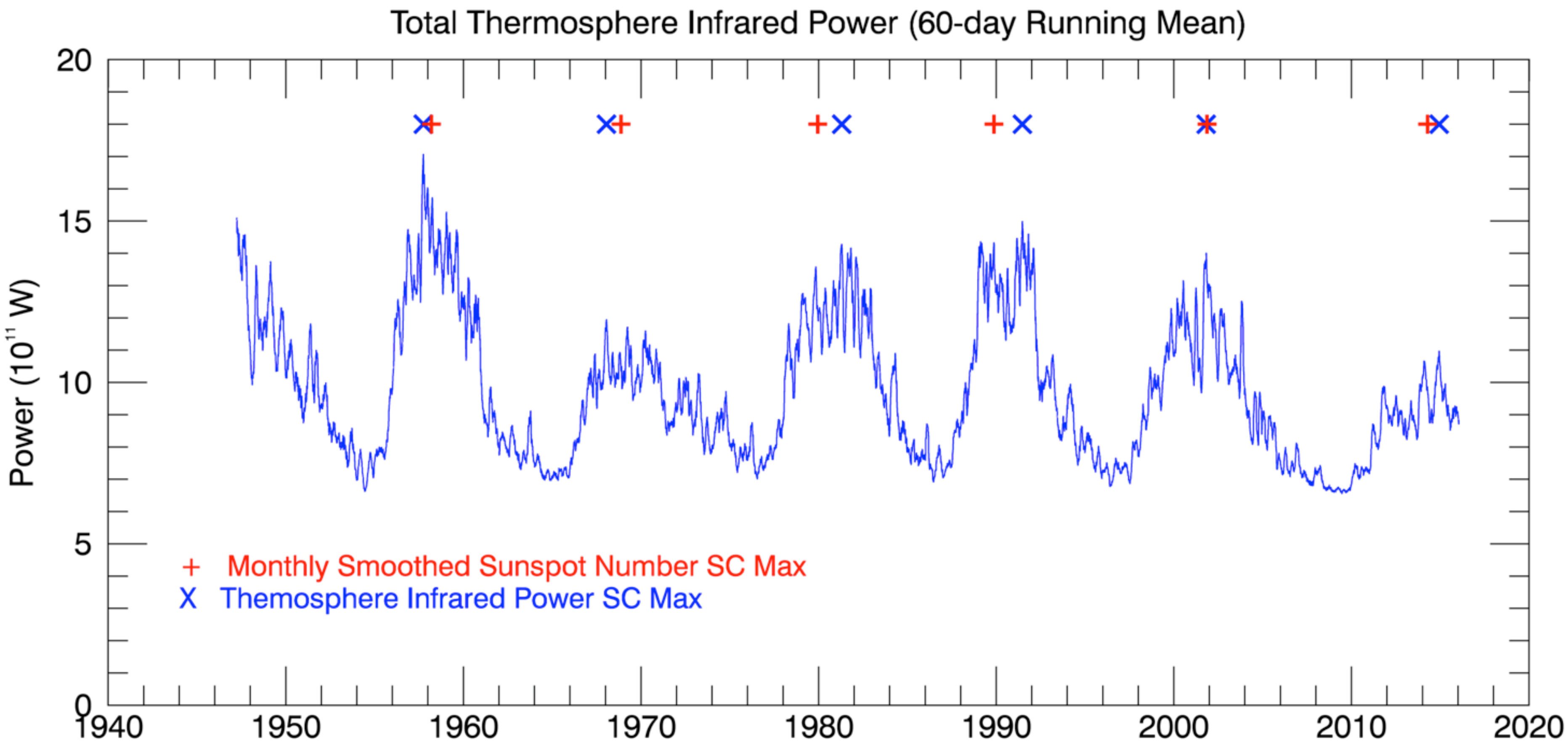
CO_2 is the dominant cooling mechanism above 100 km

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

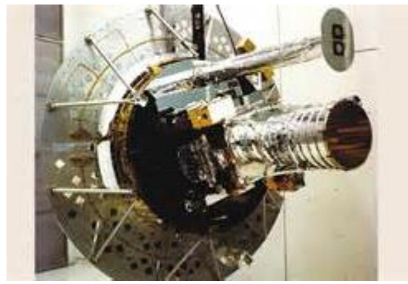


No consistent relationship between sunspot maximum and cooling maximum over six solar cycles

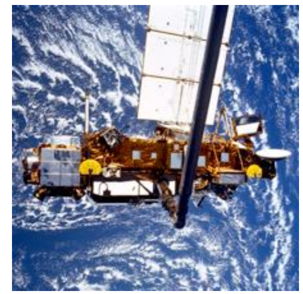
A View to the Future

1975 – 2016
The Golden Age of Upper Atmosphere Science?

Nimbus VII



SME

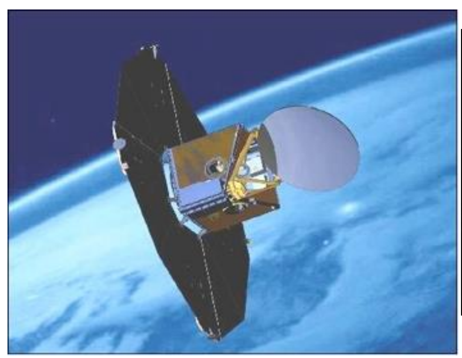


UARS

EnviSat

TIMED

SCISAT



ODIN

Aura

SORCE

The Golden Age of Upper Atmosphere Science

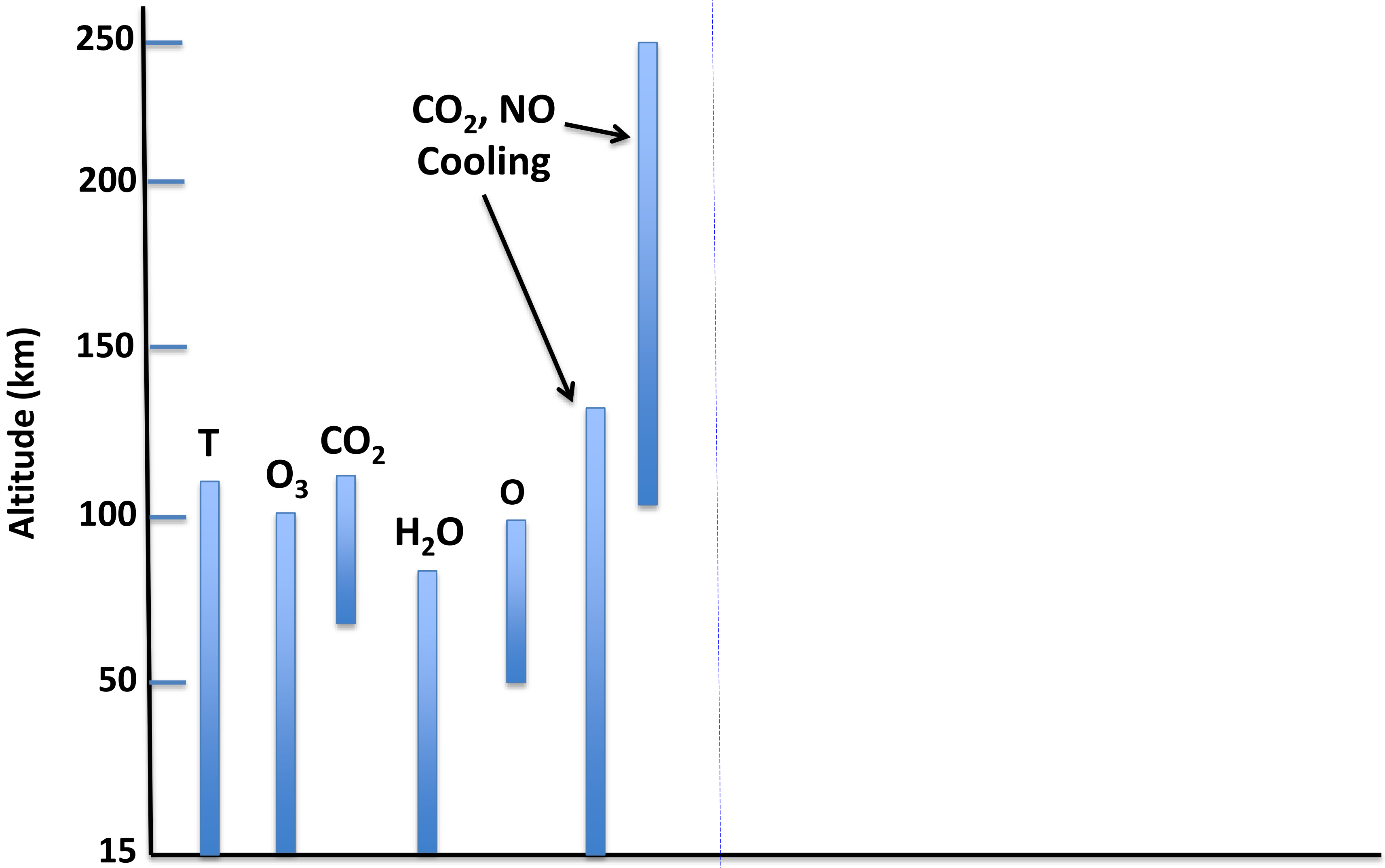
- **1970's -- LRIR, LIMS, AE, SAM**
- **1980's -- DE-1, DE-2, SAGE-II, SME**
- **1990's -- UARS, POAM**
- **2000's -- Aura, TIMED, Envisat, ODIN, SciSat, SAGE-III, SORCE, SMILES, AIM**
- **2010's -- SAGE III (2016); ICON, GOLD, TSIS in 2017**
- **2020's -- ????**
  - **No missions in preparation for observation of the mesosphere and thermosphere – particularly T, O_3, CO_2 and H_2O**

The Golden Age of Middle Atmosphere Science

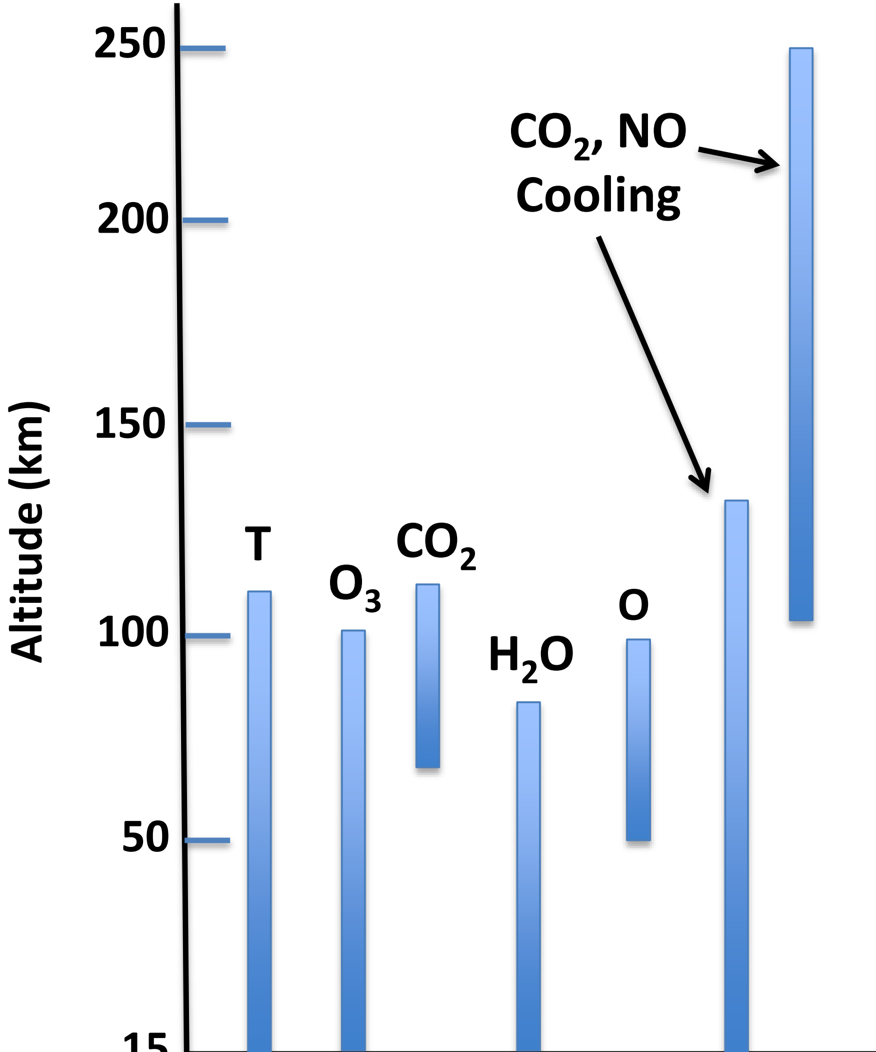
- 1970's -- LRIR, LIMS, AE, SAM
- 1980's -- DE-1, DE-2, SAGE-II, SME
- 1990's -- UARS, POAM
- 2000's -- Aura, TIMED, Envisat, ODIN, SciSat, SAGE-III, SORCE, SMILES, AIM
- 2010's -- SAGE III (2016); ICON; GOLD
- 2020's -- ????
  - No missions in preparation for middle atmosphere science

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

Existing Capability



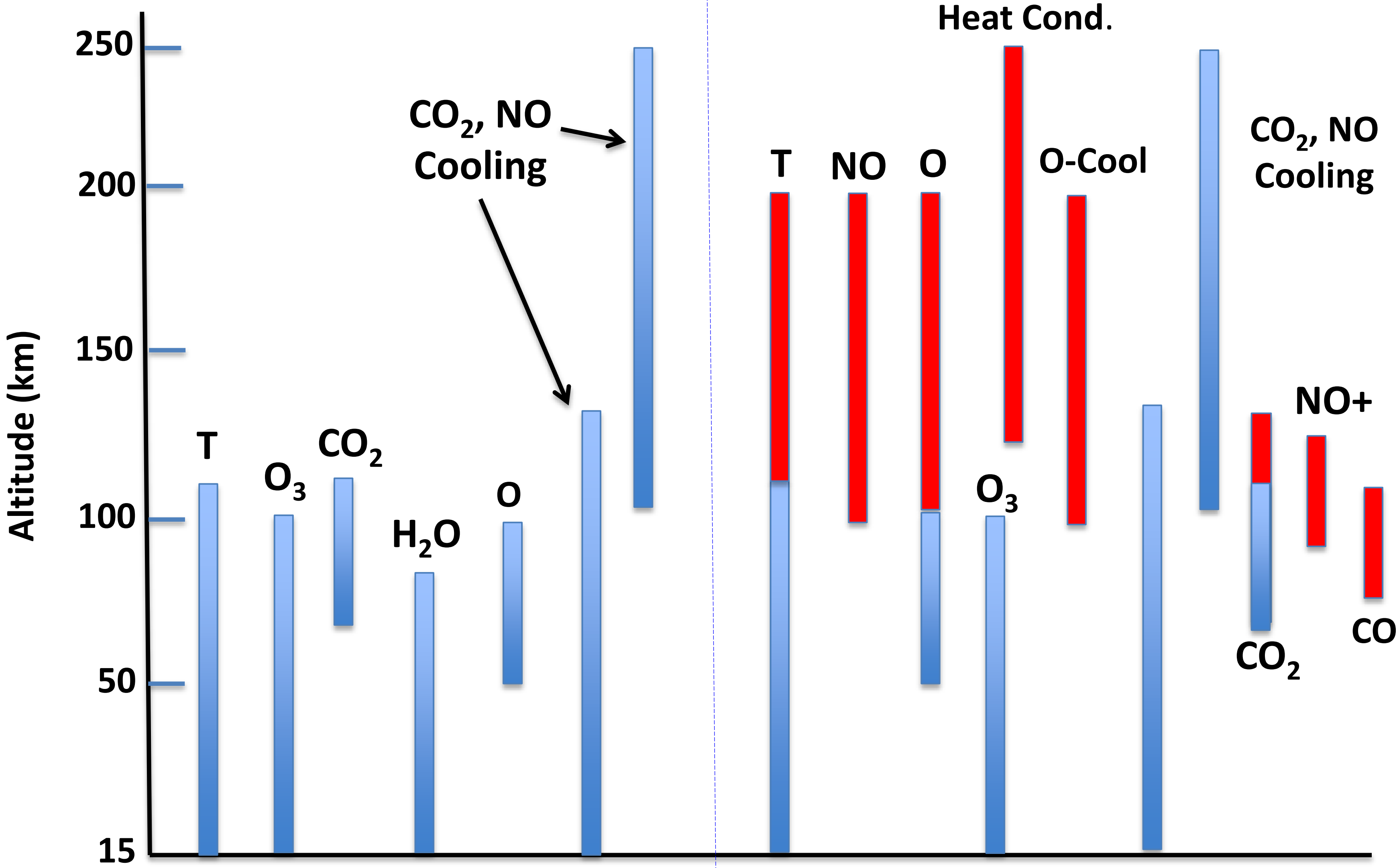
Existing Capability	What's Still Missing?



- Global T profiles 110 – 200 km
- Composition, particularly O, 110-200
- These measurements combined with T, O, etc., below, and NO, CO_2 cooling
- Why?
- Only with these data can we confidently assess models of the "heat sink" region and predict global change above 110 km

Existing Capability

Solar-Terrestrial Energy Explorer Capability



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
- Result implies that solar energy (particles and photons) has similar, small (< 7%) variation from one cycle to next
- From Earth's upper atmosphere perspective, solar cycles are really more similar than different, over their length
- No consistent relationship between peak of IR cooling and sunspot number peak
- Results submitted to GRL 8/2016

Backup Slides