Infrared Radiation in the Thermosphere from ~~2002~~ 1947 to 2019

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The SABER Science Team

Acknowledgments

- We would like to recognize the excellent engineers, technicians, project managers, contract specialists, program executives who from 1996 – 1999 built the SABER instrument and TIMED satellite project – they have given the world new knowledge and provided careers to scores of scientists world wide

- And we thank the organizers of this meeting for the invitation and opportunity to present our work.

Main Points

- SABER radiative cooling rate record now more than 17 years
- Apparently quite different solar cycles seen in CO_2 and NO cooling – *but are they really*?
- Variability evident on time scales from ~ half century to a few days
- Storm type greatly influences magnetosphere-atmosphere interaction of Earth response to geomagnetic events
- Many questions still remain

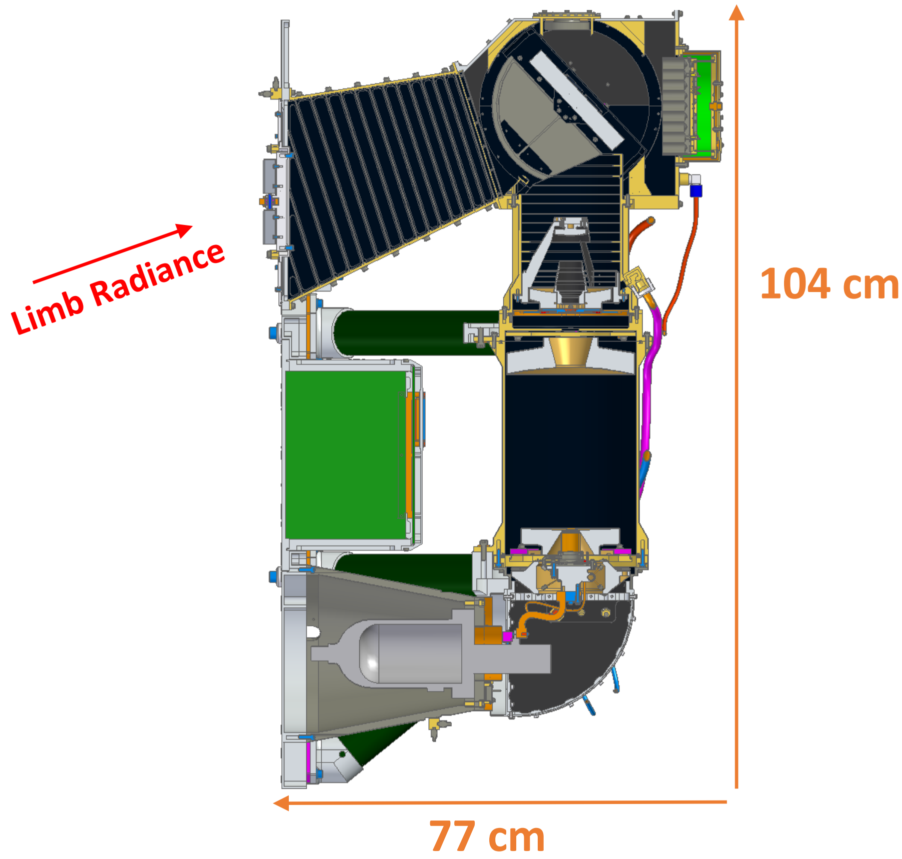
Sounding of the Atmosphere using Broadband Emission Radiometry

SABER Experiment

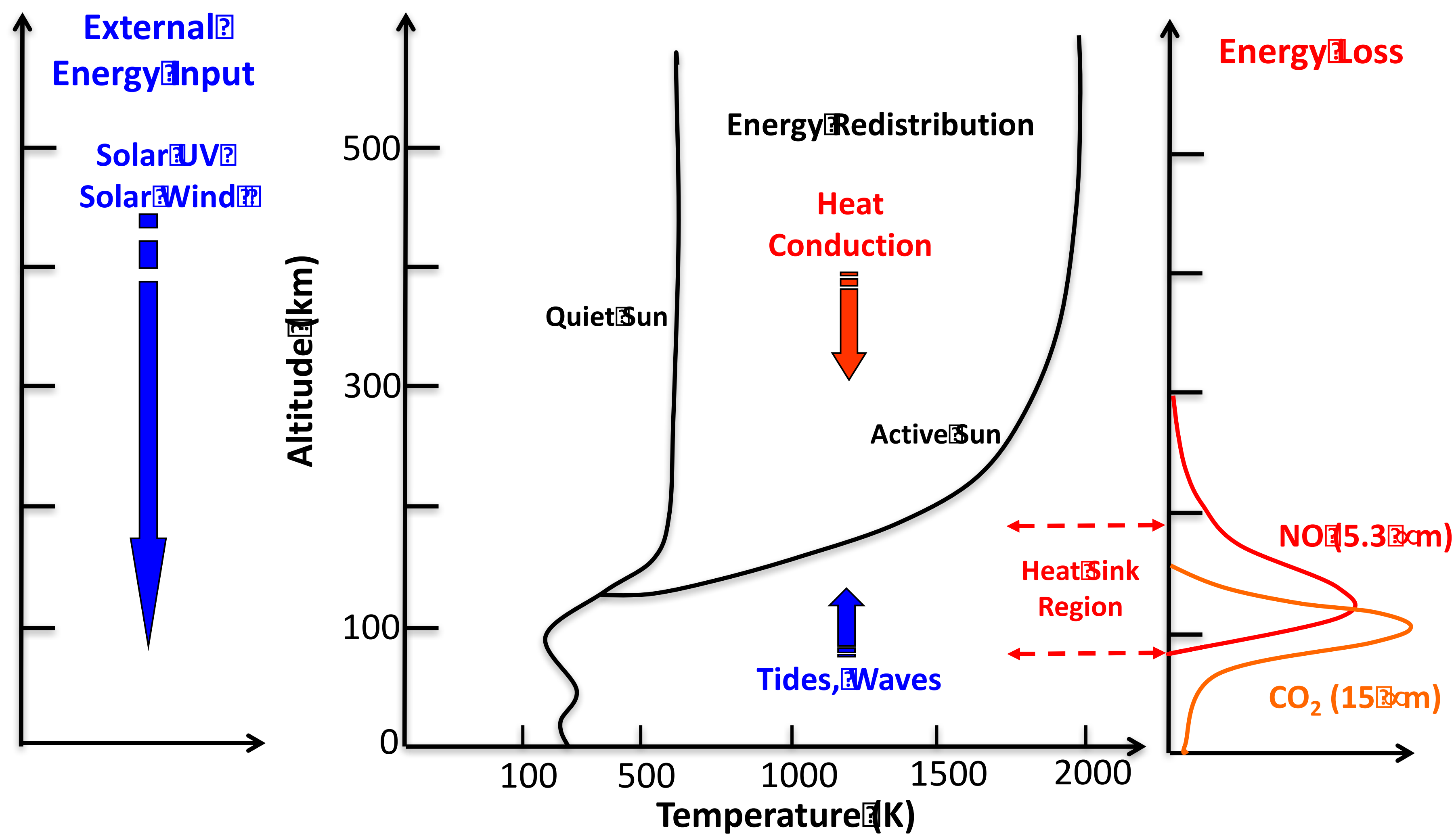
- Limb viewing, 400 km to Earth surface
- Ten channels 1.27 to 16 μm
- Over 30 routine data products including energetics parameters
- Over 98% of all possible data collected
  (8.9 million profiles per channel!)
- Focal plane cryo-cooler operating excellently at 74 K
- SABER on-orbit performance is excellent and as-designed
- Noise levels at or better than measured on ground

SABER Instrument

75 kg, 77 watts; 4 kbs



Energy Deposition and Loss Processes



Infrared Radiative Cooling in the Thermosphere

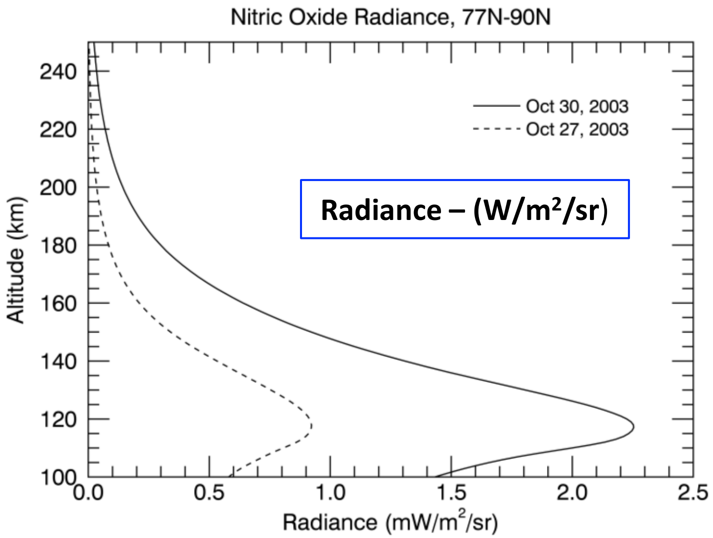
- Radiative cooling is the action of infrared radiation to reduce the kinetic temperature of the neutral atmosphere

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

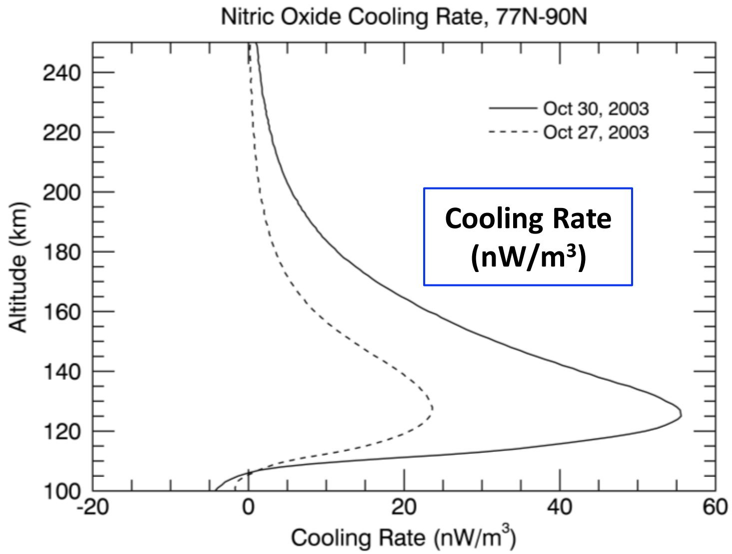
- Collisions between atomic oxygen (O) and CO_2 and NO initiate the cooling process
  - NO (υ = 0) + O → NO (υ = 1) + O (Kinetic Energy Removal)
  - NO (υ = 1) → NO (υ = 0) + hν (5.3 μm) (Kinetic Energy Loss)
  - NO (υ = 1) + O → NO (υ = 0) + O (Kinetic Energy Returned)

- Collisional process are highly temperature dependent!

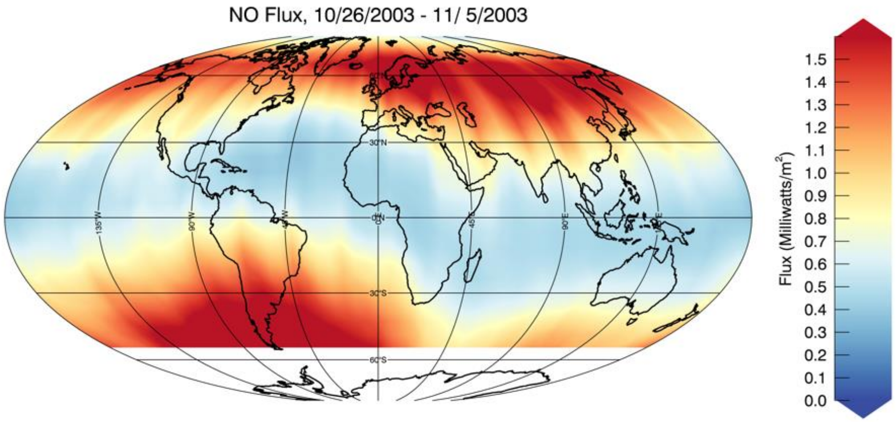
From SABER Limb Radiances to Global Infrared Power



Abel Transform

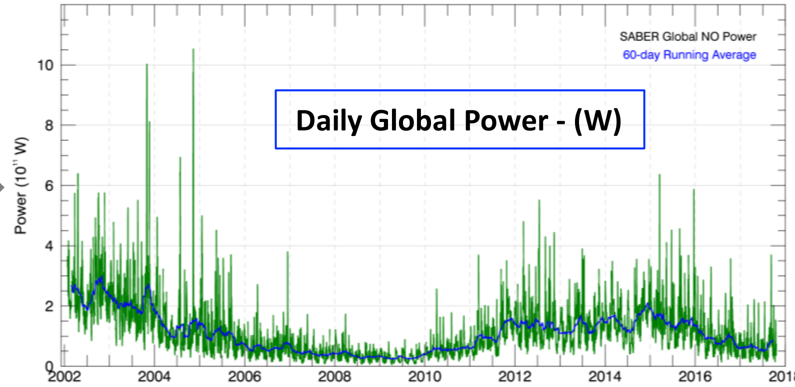


Vertical Integration



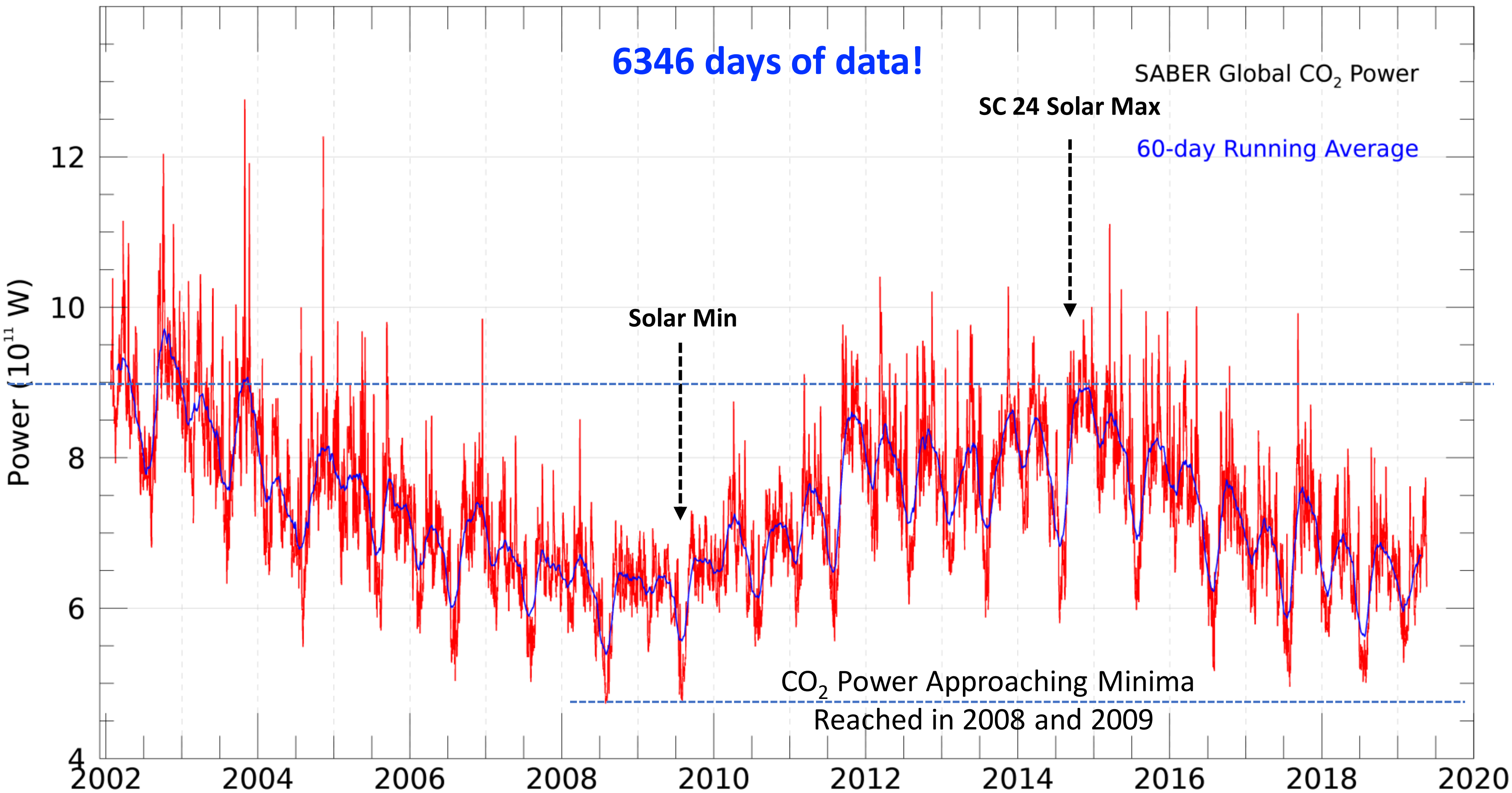
Flux – (W/m²)

Area Integration



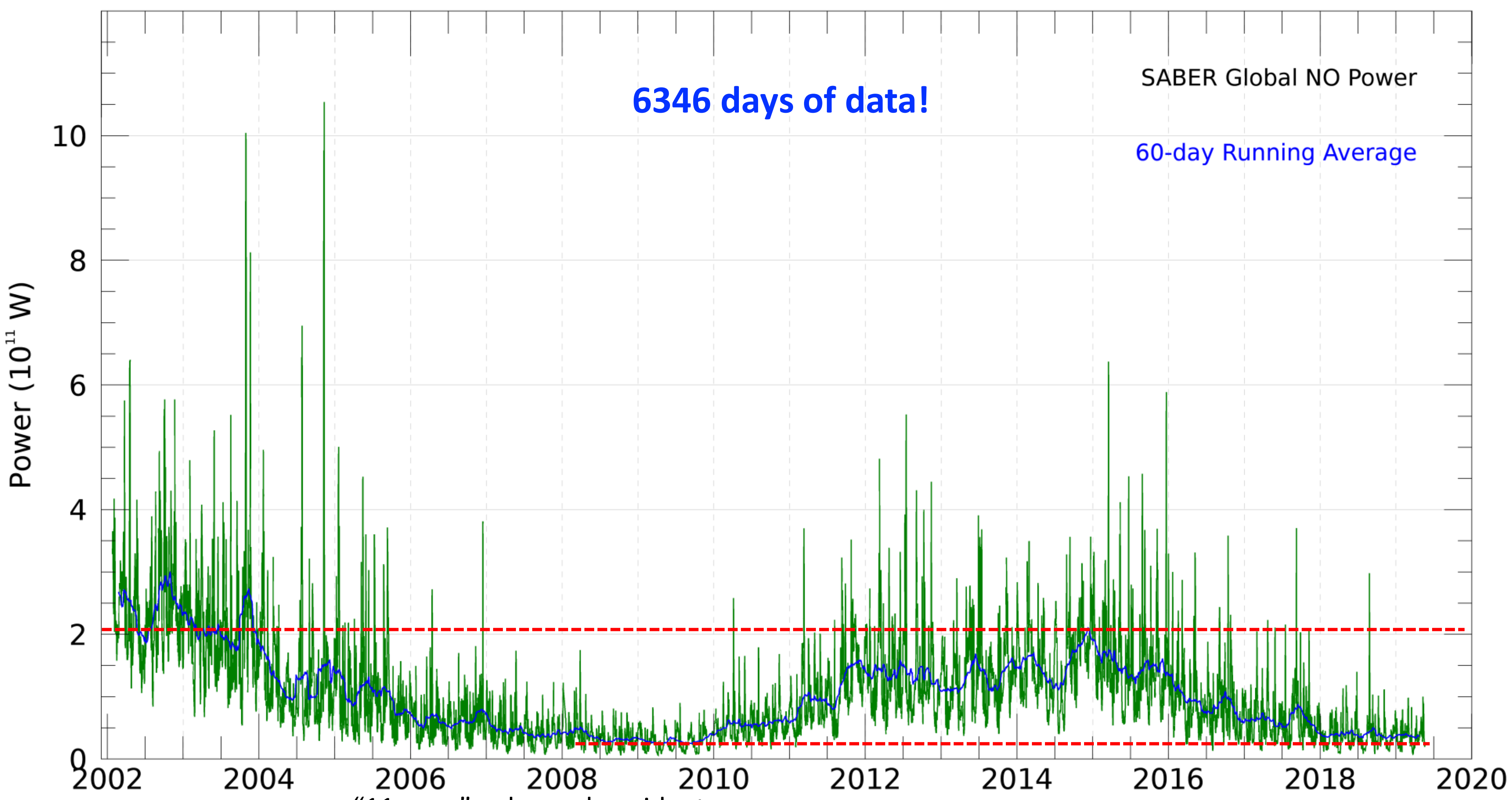
Current State of the Infrared Thermosphere

Daily CO_2 Global Power – Jan 2002 – May 2019



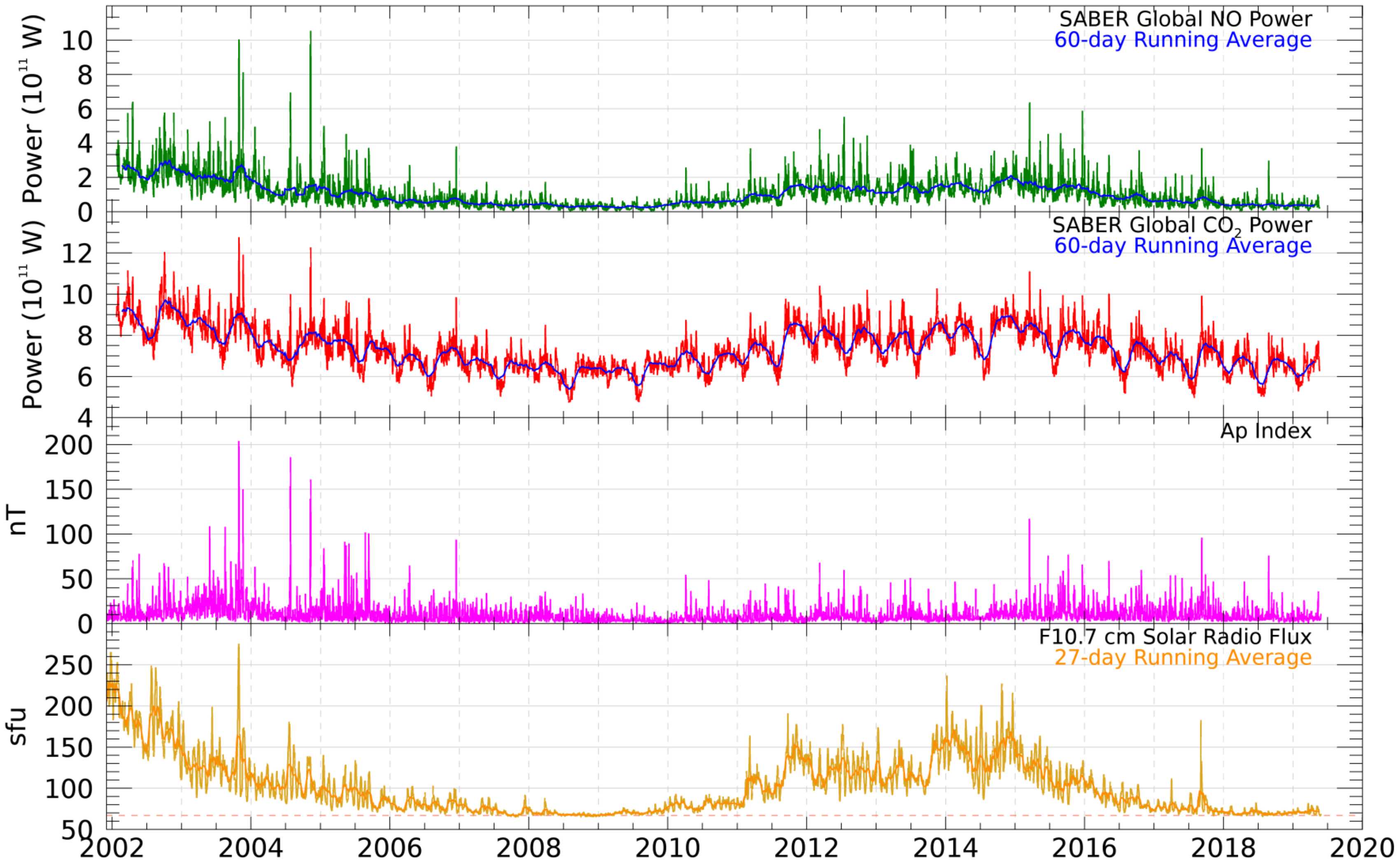
- Persistent space weather effects evident in every data "spike"
- Semi-annual & annual variability evident (blue curve, 60 day running mean)
- "11-year" solar cycle evident
- SC 24 presently at 3786 days (Min 2009 to present: ~10 years)

Daily Global NO Power – Jan 2002 to Oct 2017

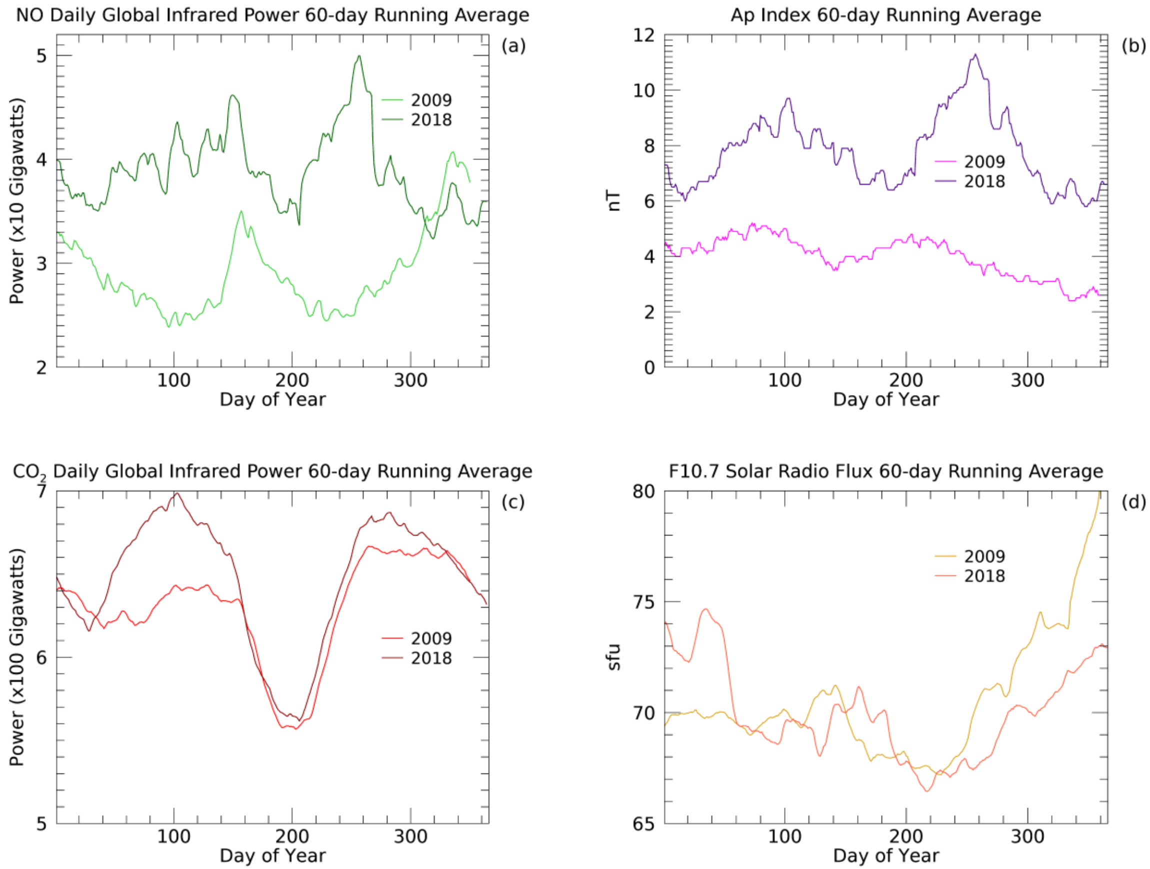


- “11-year” solar cycle evident
- Substantially larger excursions in power associated with space weather
- No evidence of annual or semi-annual cycles
- Shorter-term periodicities revealed in Fourier/Lomb analyses

Thermosphere Infrared Response over TIMED Mission Epoch

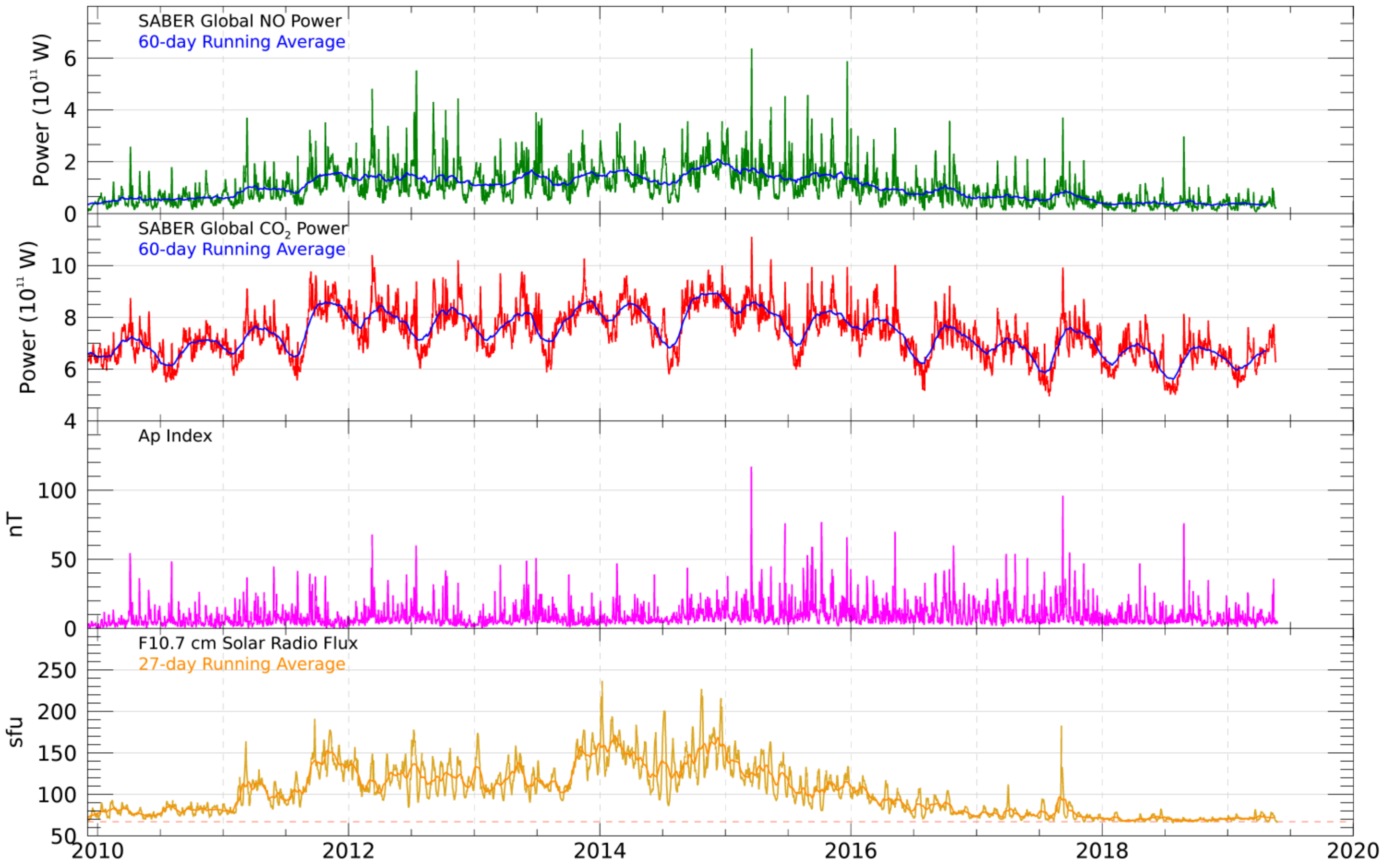


NO, CO2, Ap, and F10.7 In 2009 and 2018



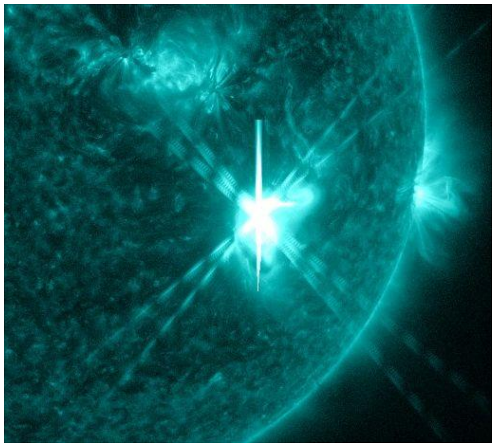
Mlynczak et al., GRL 2018 10.1029/2018GL080389

Thermosphere Infrared Response in Solar Cycle 24



SABER Observes Strong September 2017 Storm

Major X9.3 Class Solar Flare on Sept. 6 – strongest in a decade!
Flare followed by CME sparking **severe** G4 class geomagnetic storm Sept. 7-9
SABER observes "thermostat effect" of NO and CO_2 infrared emission as thermosphere warms

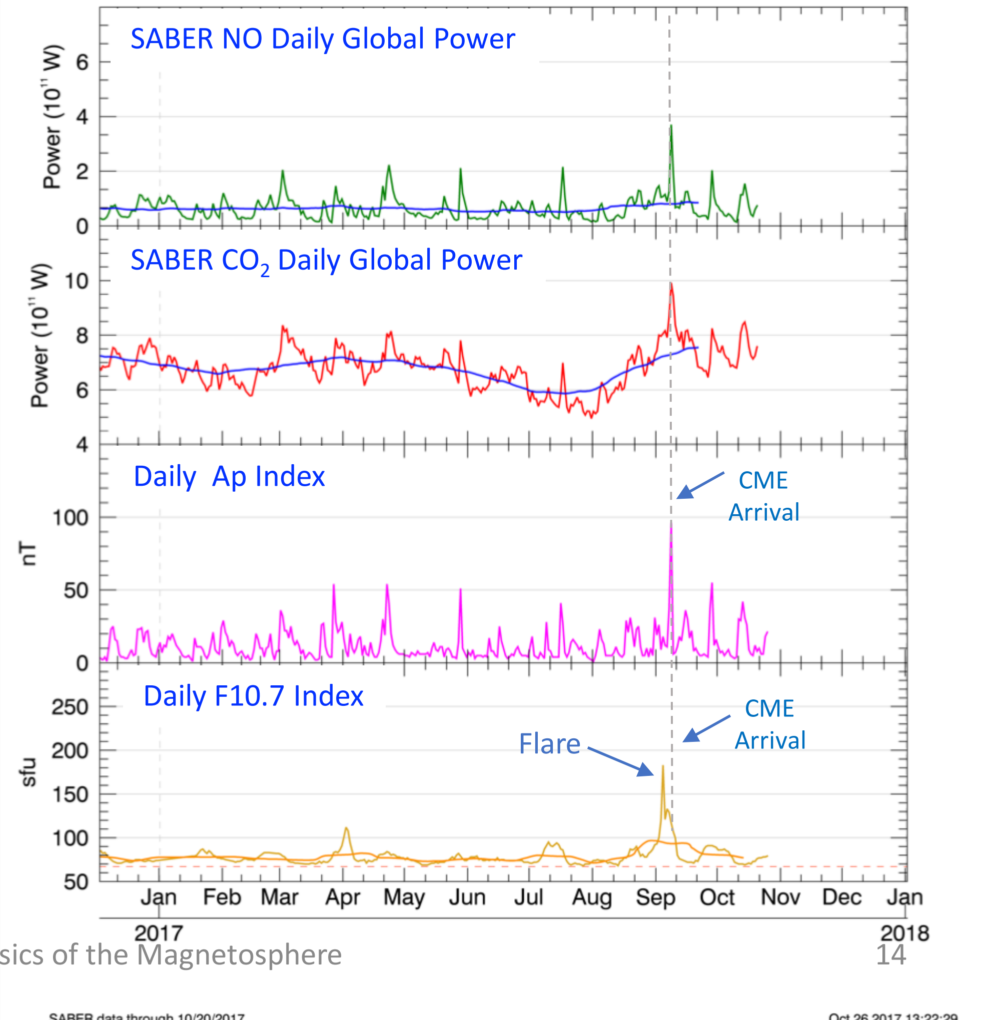


X-Class Flare Captured by SDO

Storm 8th strongest on TIMED record

Year	Days	NO + CO_2 Power (TW)	Percent NO	Percent CO_2
2003	302-304	3.03	65	35
2004	313-315	2.88	68	32
2004	207-209	2.35	63	37
2002	108-110	2.00	70	30
2015	76-80	1.74	62	38
2002	274-277	1.53	66	34
2012	67-70	0.83	66	34
2017	**250-252**	**0.81**	**54**	**46**

NO, CO_2 Cooling Response Coincident with Ap
Response comes AFTER Flare – solely CME driven!

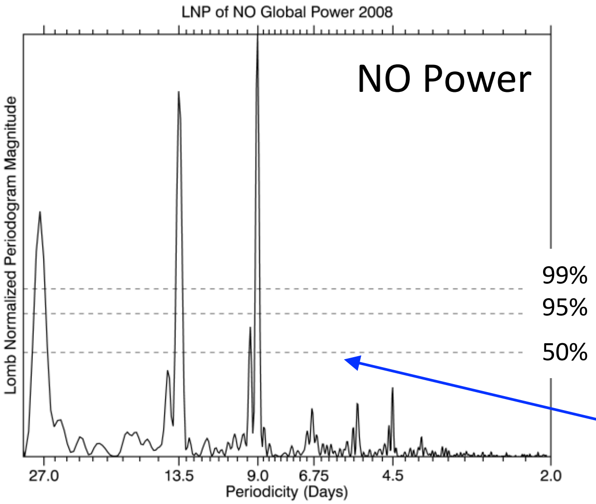


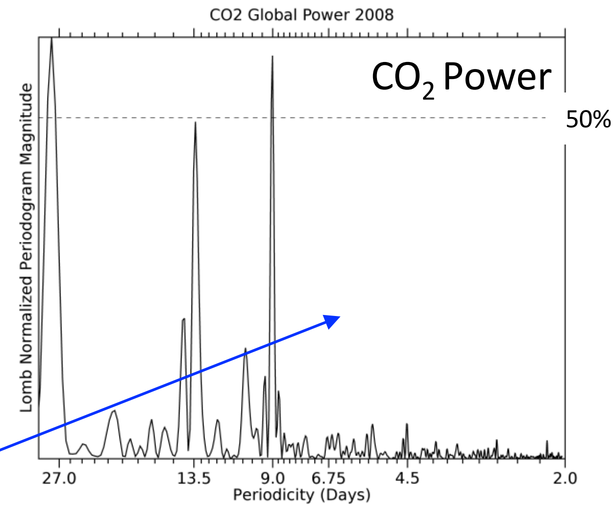
Short Term Periodicities in Global Power

Short-term Periodic Features Return in 2017

- **In 2008, periodic features that are harmonics of the solar rotation period were discovered in the density, composition, and energy budget of the thermosphere**
- **Periodic features were found to be present in geomagnetic indices (Kp, Ap) and solar wind speed, but not F10.7**
- **Thus the origin of the periodicities is not due to solar irradiance but rather particle precipitation**
- **Harmonic (27, 13.5, 9, 6.75, 5.4 day) periods occur also only in the declining period to solar minimum**
- **Harmonics are associated with high speed streams emanating from coronal holes approximately equally spaced in solar longitude**

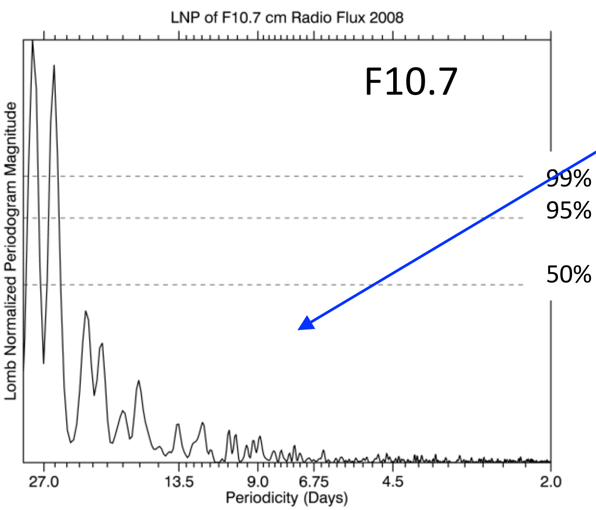
Lomb Periodograms of NO & CO_2 Power, Ap, F10.7 for 2008

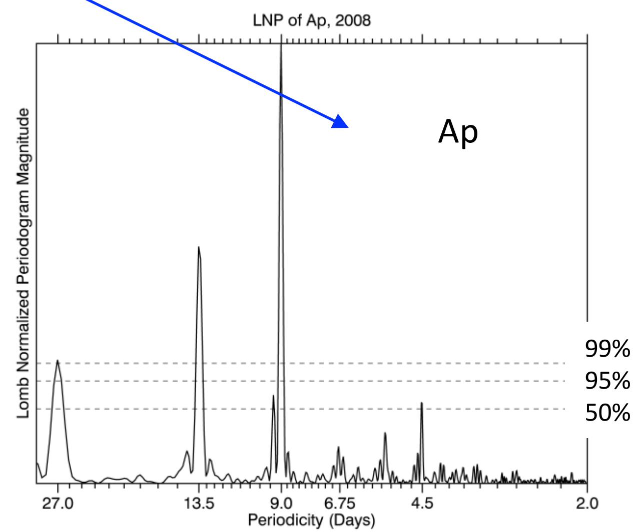




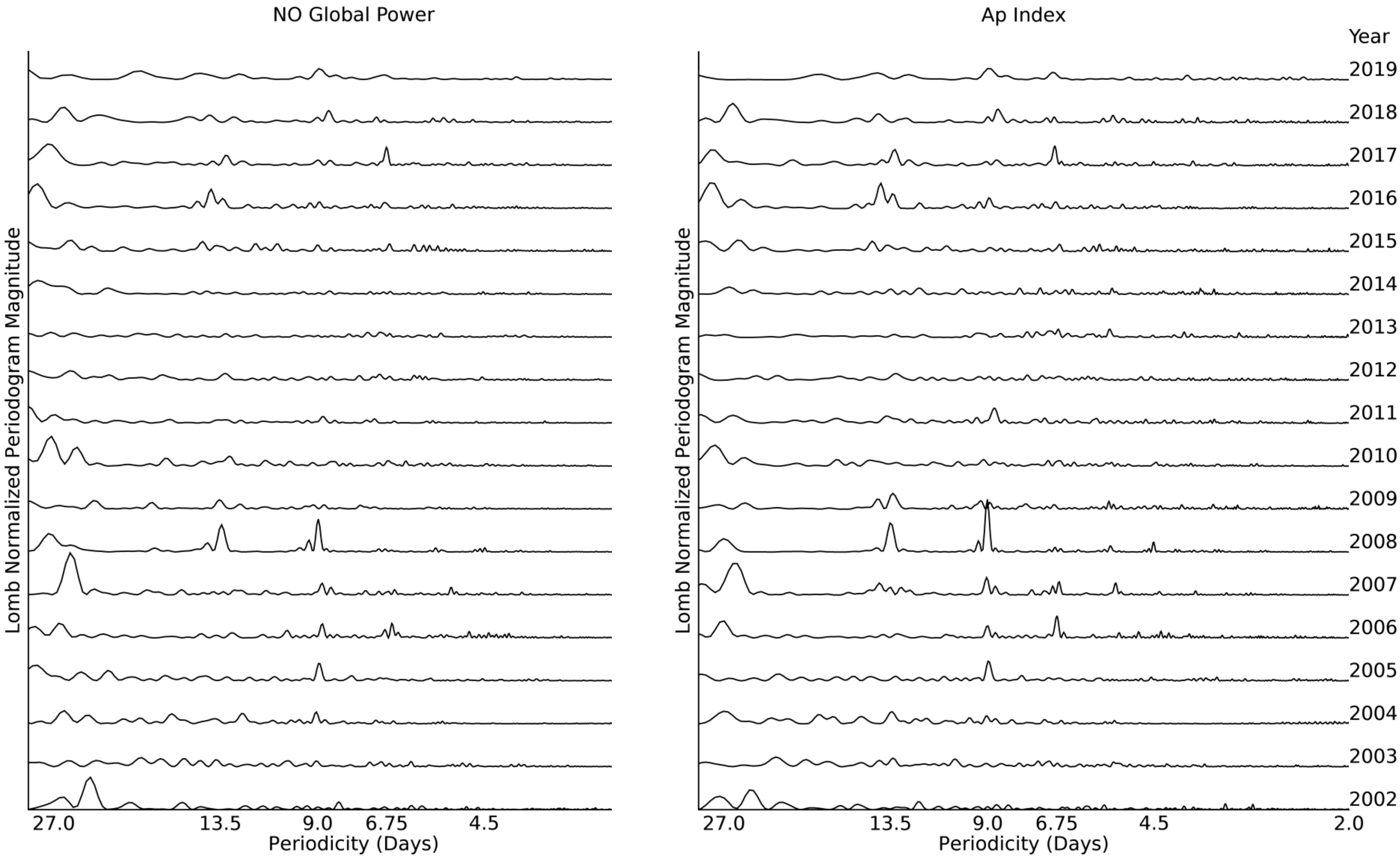
Strong 13 day and 9 day period in NO, CO_2, and Ap

These are absent in F10.7



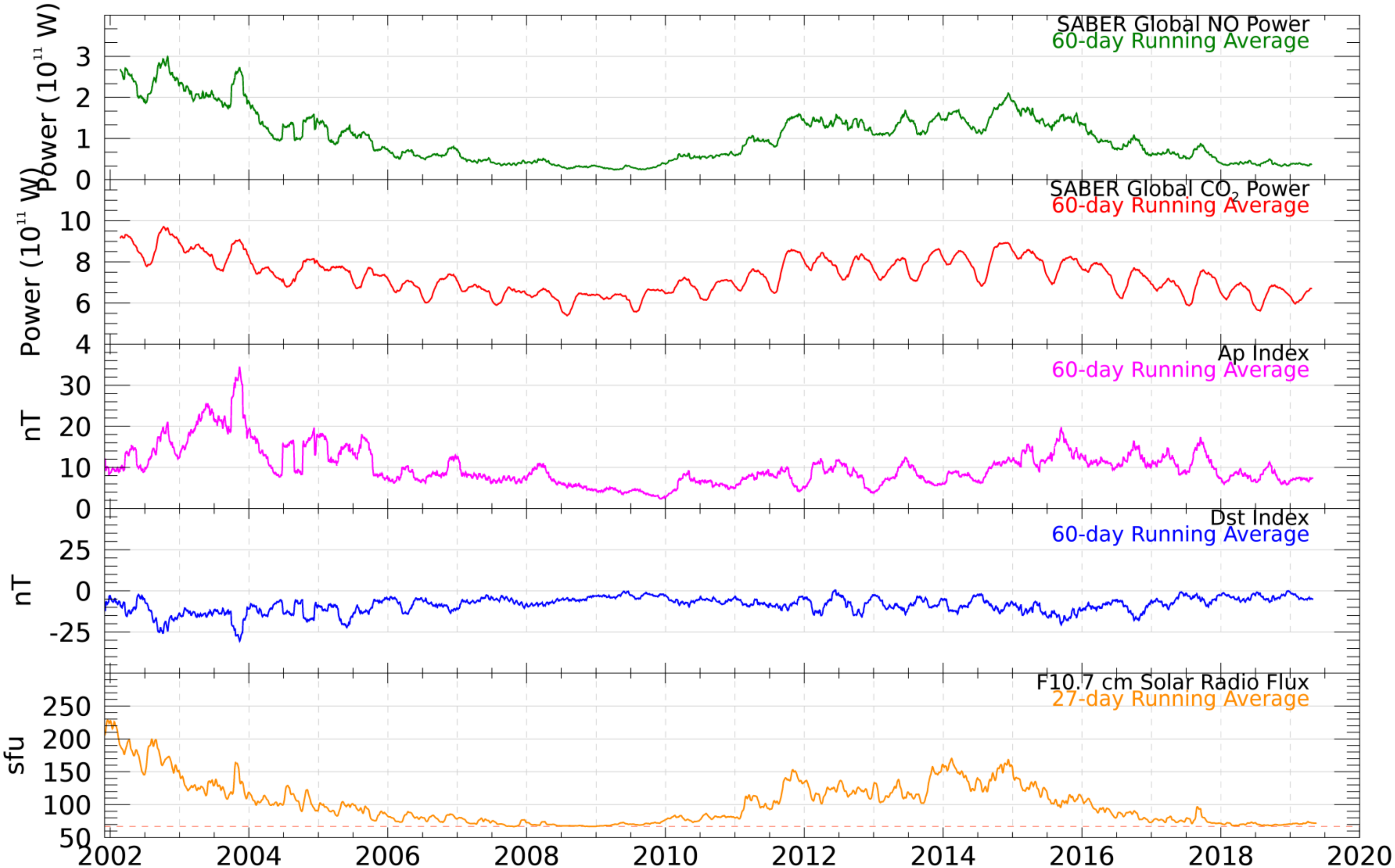


LNP of NO Power and AP - 2002 through 2019

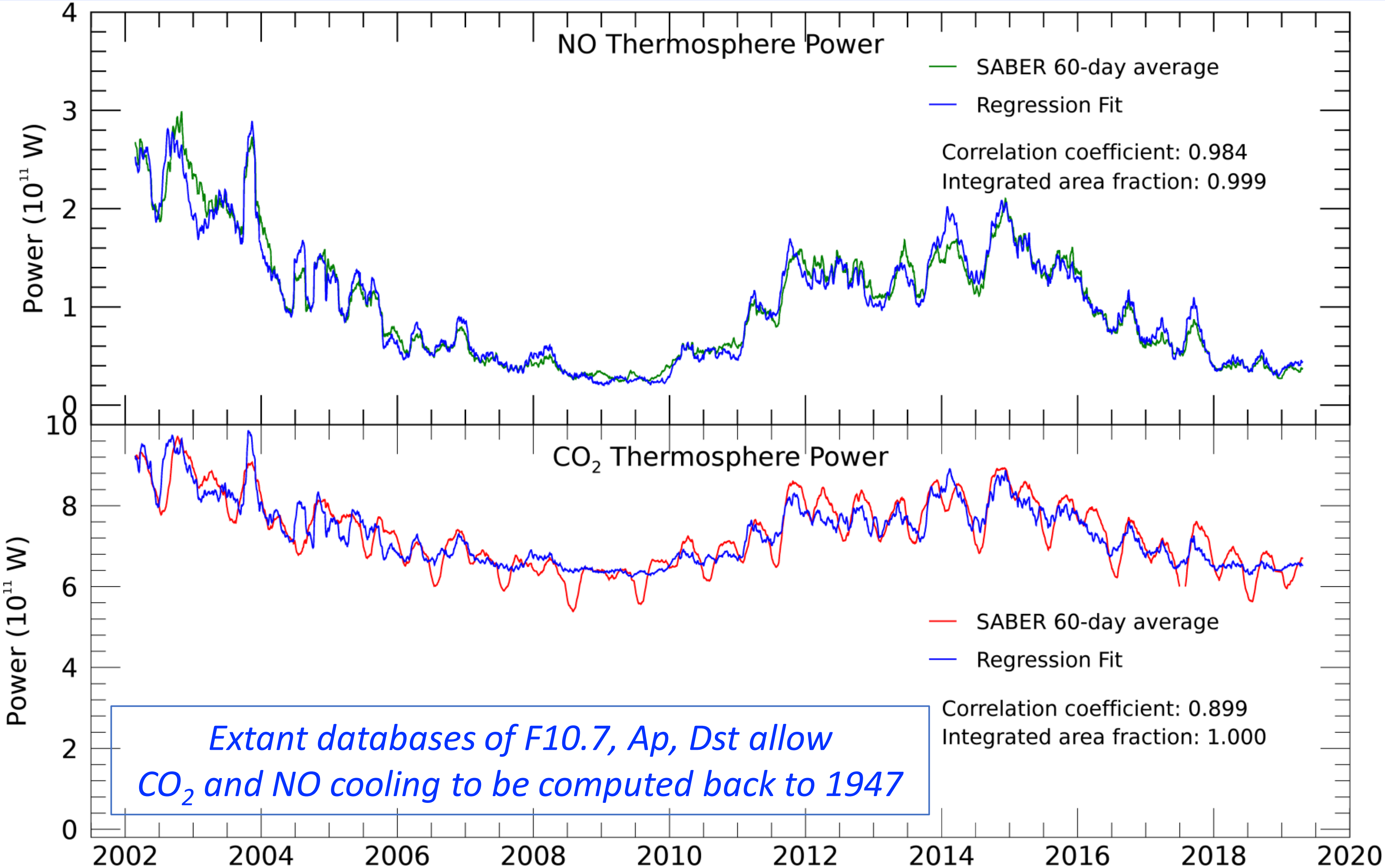


Thermosphere Climate Indexes

60-day Running Means – Nitric Oxide Power
Strong Visual Correlation in NO, Ap, Dst, F10.7

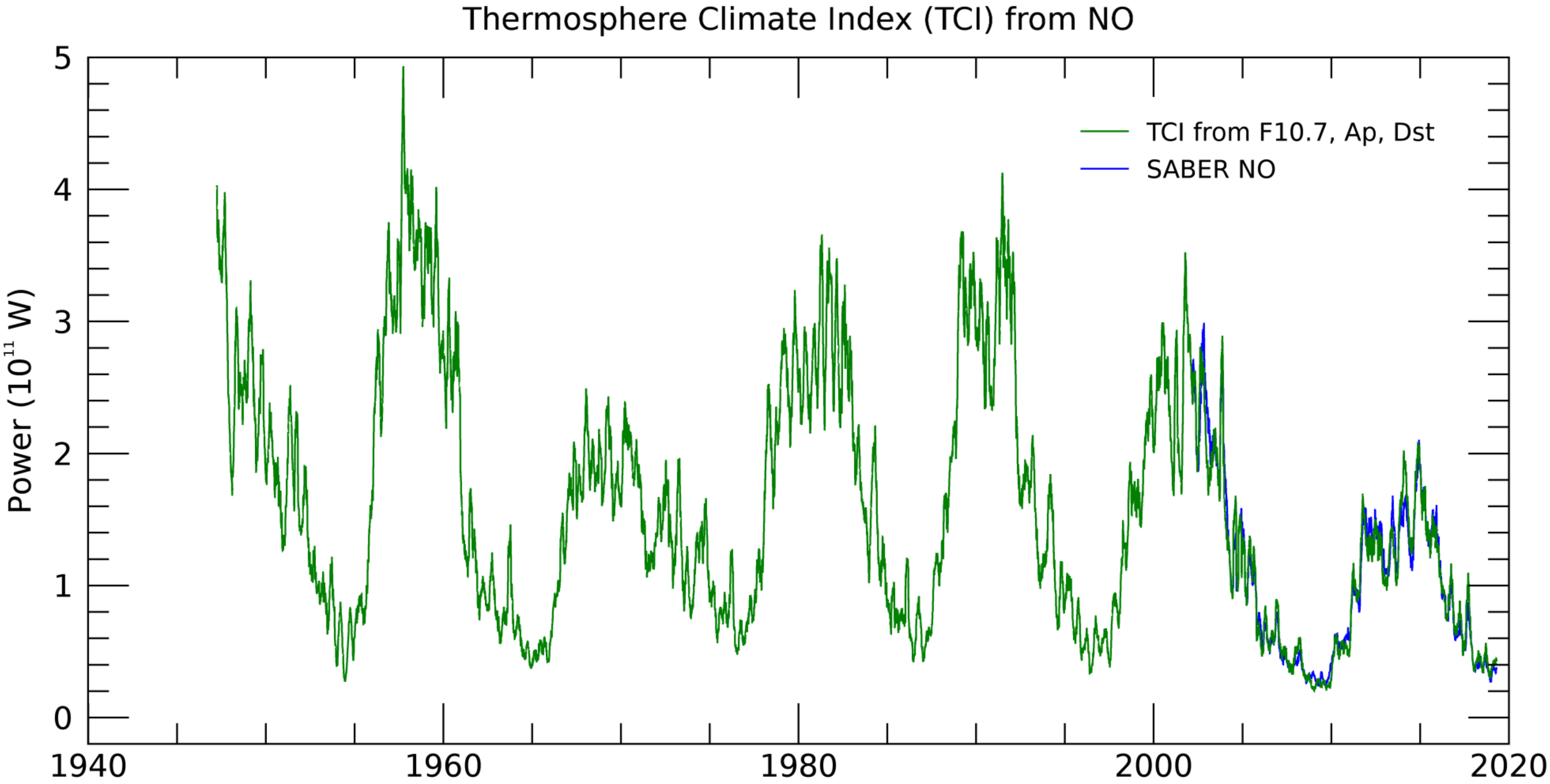


Multiple Linear Regression Fit
SABER NO, CO_2 Power as Function of F10.7, Ap, Dst



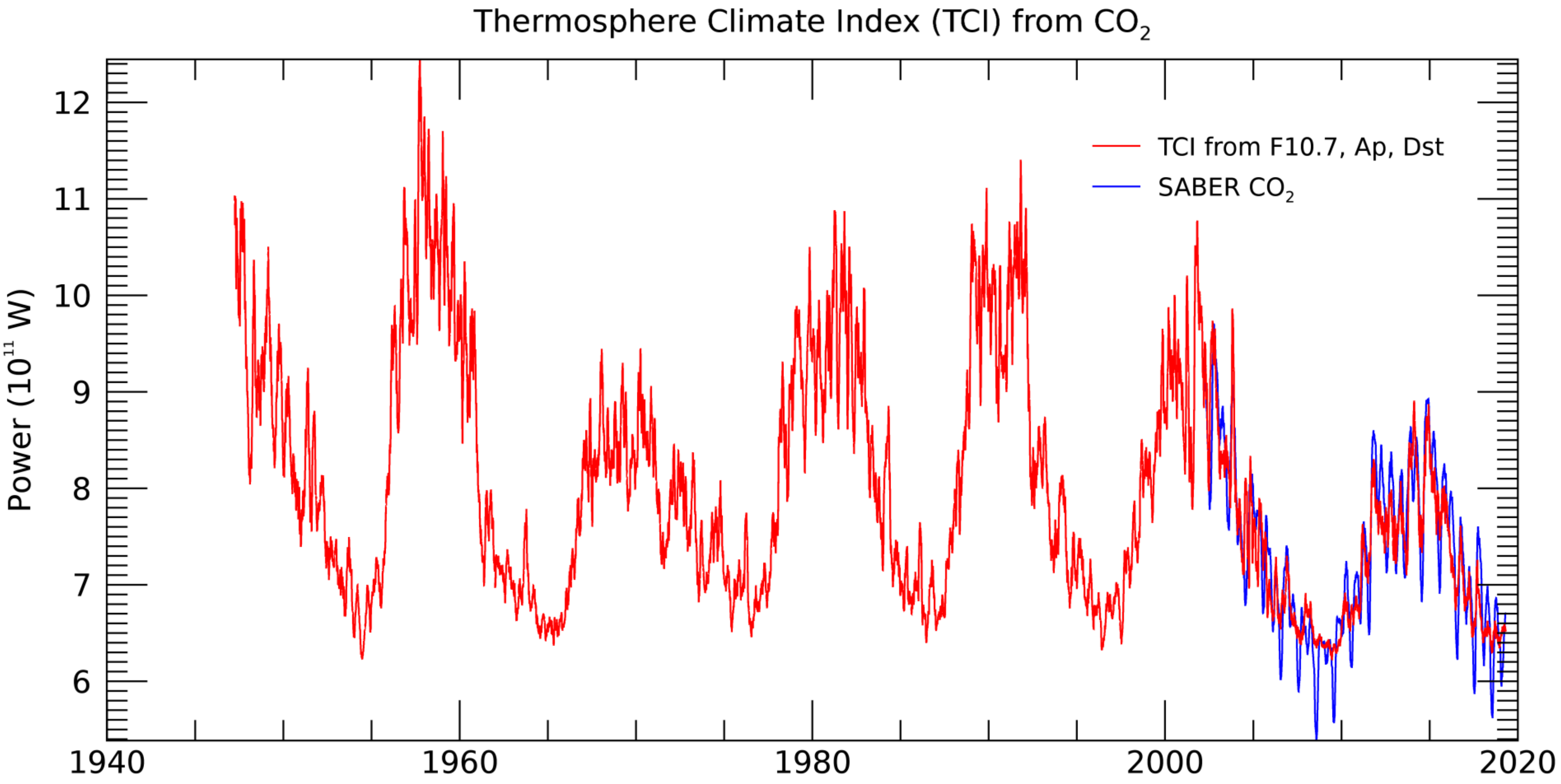
Extant databases of F10.7, Ap, Dst allow CO_2 and NO cooling to be computed back to 1947

Thermosphere Climate Index 1947-2019
Based on SABER NO Power as Function of F10.7, Ap, Dst

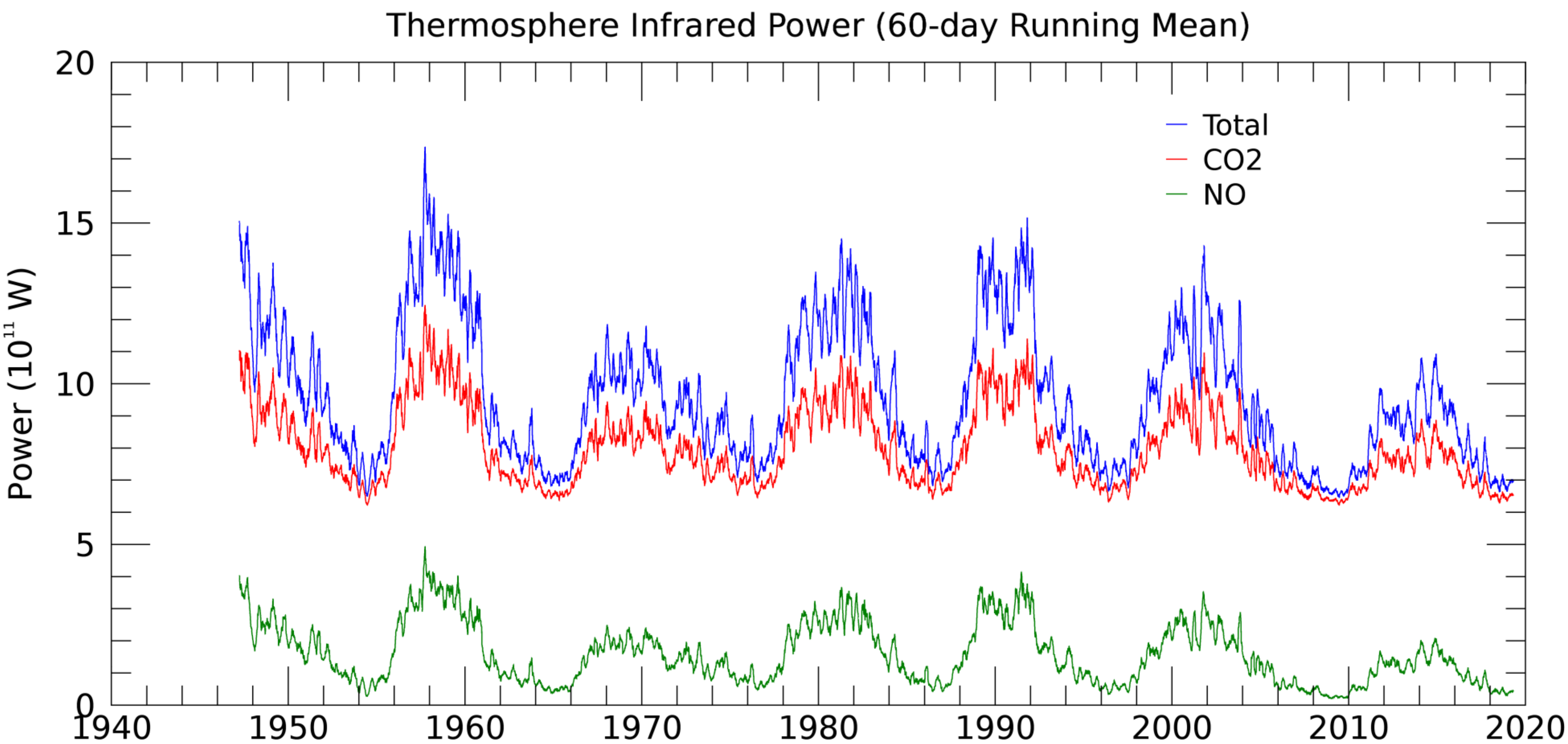


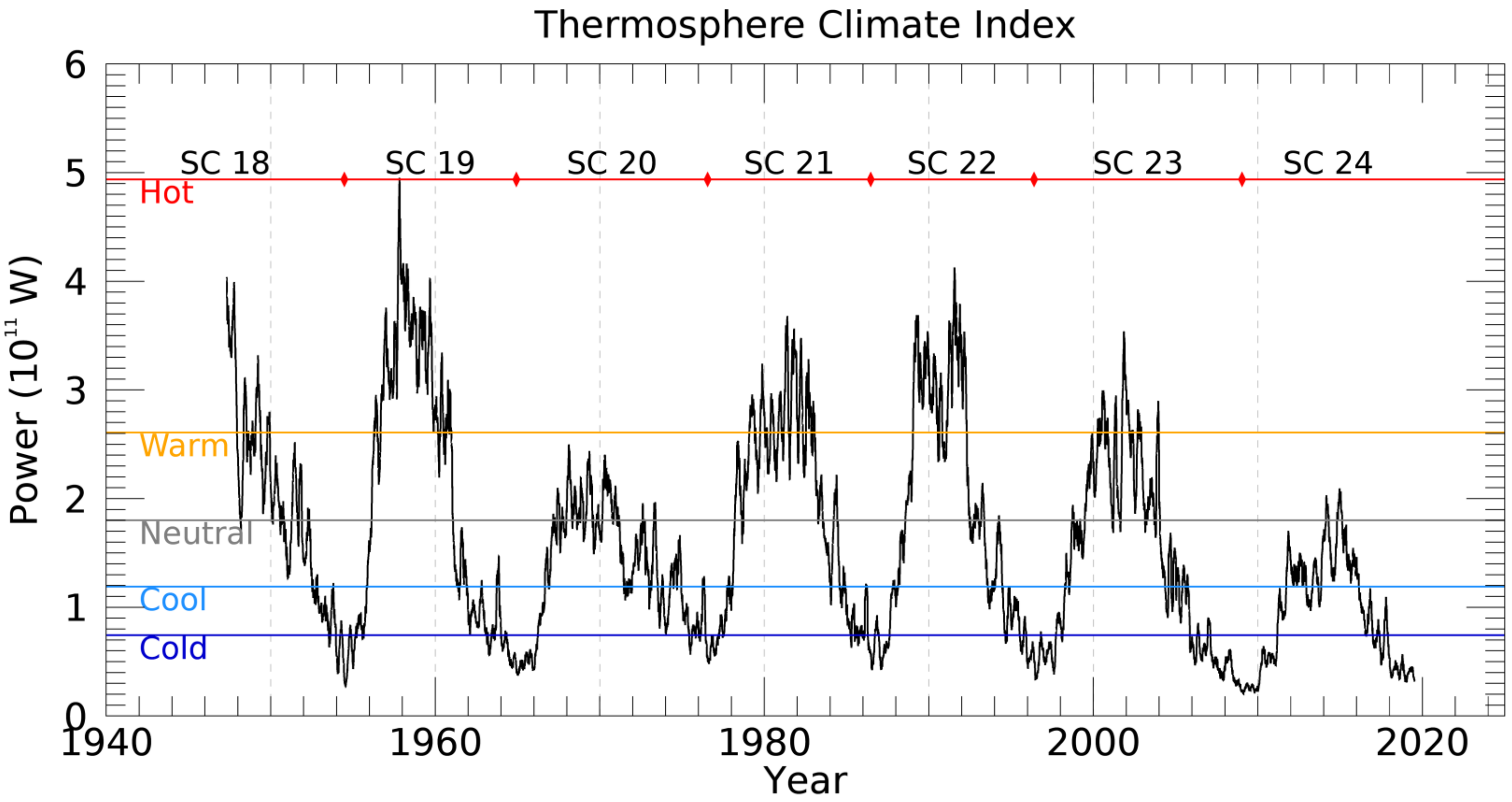
Thermosphere Climate Index 1947-2019

Based on SABER CO_2 Power as Function of F10.7, Ap, Dst



Thermosphere Climate Index 1947-2019
NO, CO, and Total





Thermosphere Climate Index
Power (10^{11} W)
Year
SC 18
SC 19
SC 20
SC 21
SC 22
SC 23
SC 24
Hot
Warm
Neutral
Cool
Cold
0
1
2
3
4
5
6
1940
1960
1980
2000
2020

TCI on SpaceWeather.com

spaceweather.com
News and information about the Sun-Earth environment

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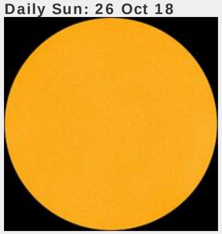
Current Conditions

Solar wind
speed: **407.4** km/sec
density: **5.6** protons/cm^3
more data: ACE, DSCOVR
Updated: Today at 2347 UT

X-ray Solar Flares
6-hr max: **A1** 1801 UT Oct26
24-hr: **A1** 1801 UT Oct26
explanation | more data
Updated: Today at: 2300 UT

Daily Sun: 26 Oct 18



The sun is blank--no sunspots. Credit: SDO/HMI

Sunspot number: 0
What is the sunspot number?
Updated 26 Oct 2018

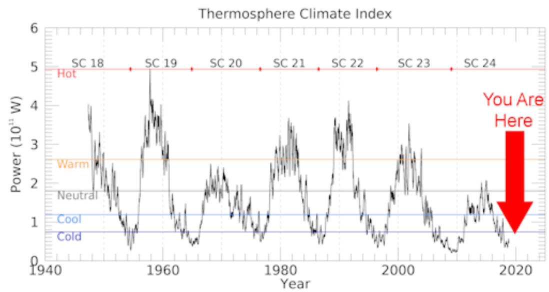
Spotless Days
Current Stretch: 8 days
2018 total: 174 days (58%)
2017 total: 104 days (28%)
2016 total: 32 days (9%)
2015 total: 0 days (0%)
2014 total: 1 day (<1%)
2013 total: 0 days (0%)
2012 total: 0 days (0%)
2011 total: 2 days (<1%)
2010 total: 51 days (14%)
2009 total: 260 days (71%)
2008 total: 268 days (73%)
2007 total: 152 days (42%)

What's up in space — Friday, Oct. 26, 2018

Lights Over Lapland has a brand-new website full of exciting adventures in Abisko National Park, Sweden! Take a look at our aurora activities and book your once-in-a-lifetime trip with us today!

ATMOSPHERIC COSMIC RAYS ARE INCREASING: So you thought Solar Minimum was boring? Think again. High-altitude balloon flights show that atmospheric radiation is intensifying from coast to coast over the USA--a direct result of low solar activity. Get the full story.

A NEW SPACE WEATHER METRIC: The Thermosphere Climate Index (TCI) is now on Spaceweather.com. TCI is a relatively new space weather metric that tells us how the top of Earth's atmosphere (or "thermosphere") is responding to solar activity. During Solar Max the top of our atmosphere heats up and expands. Right now the opposite is happening. Solar minimum is here and the thermosphere is cooling off:

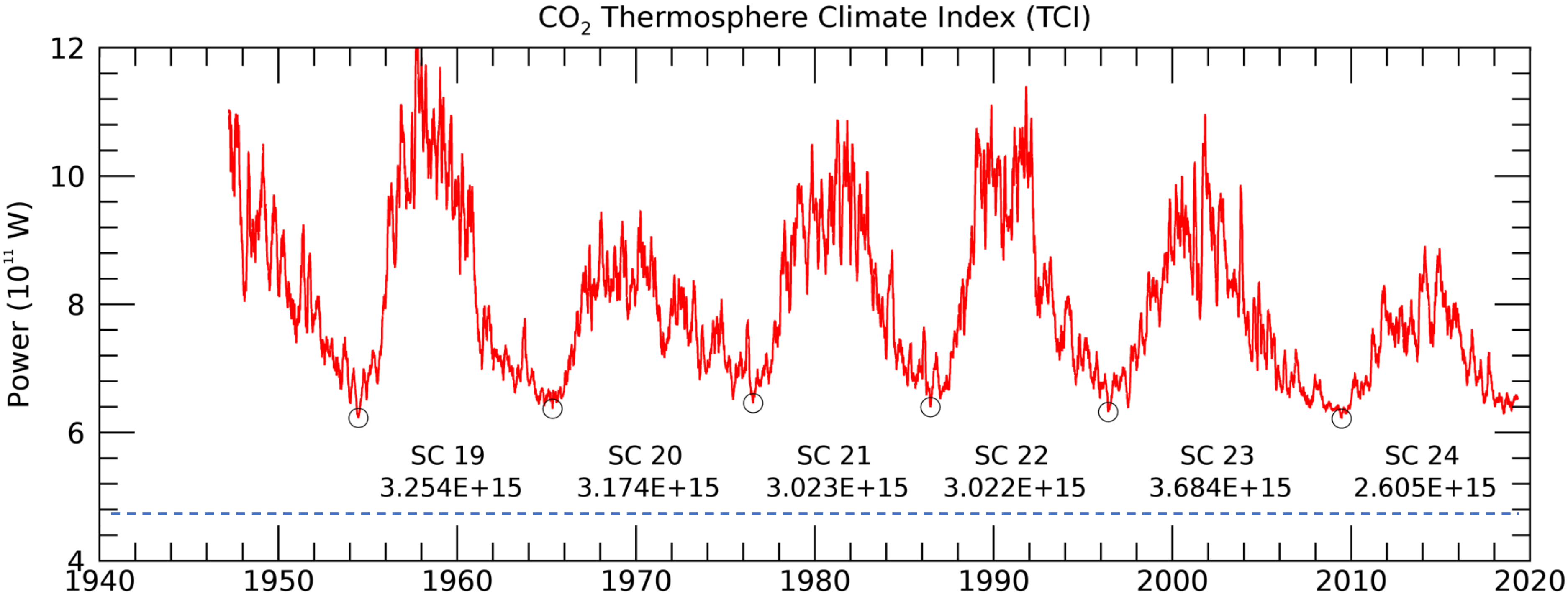


TCI was invented by Martin Mlynczak of the Langley Research Center along with other NASA and university colleagues. For the past 17 years they have been using the SABER instrument onboard NASA's TIMED satellite to monitor the wattage of infrared emissions from the top of the atmosphere. Recently, they realized that these measurements could be used to summarize the state of the thermosphere in a single daily number–the TCI. Moreover, they learned to calculate TCI going back in time all the way to the 1940s, thus placing current conditions in a historical context.

So where *do* we stand? Right now TCI=4.6x10^{10} W. That means the top of Earth's atmosphere is approximately 10 times cooler than it was during the record-setting Solar Max of 1957-58 (TCI=49.4x10^{10} W). The current record low, TCI=2.1x10^{10} W, was set in 2009 less than ten years ago during the previous Solar Minimum. We're not quite there yet, but were getting close.

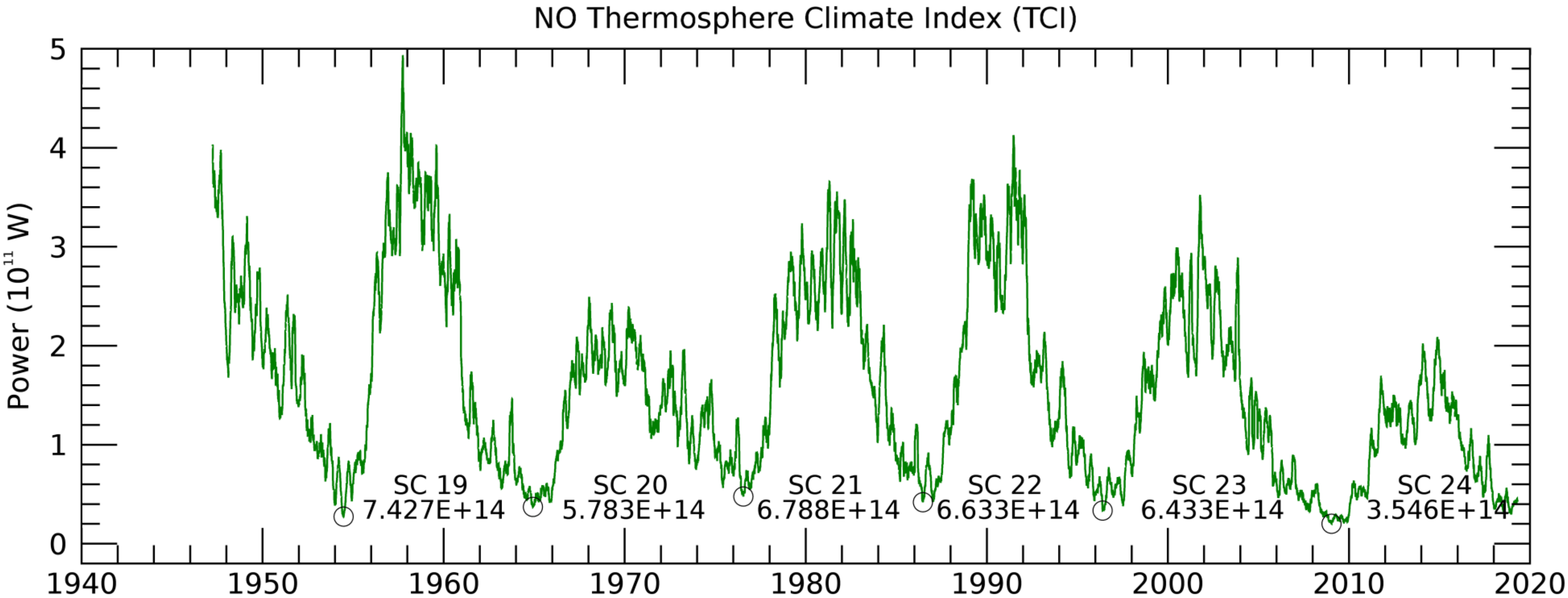
Thermosphere Climate Index
today: 4.12x10^{10} W Cold
Max: 49.4x10^{10} W Hot (10/1957)
Min: 2.05x10^{10} W Cold (02/2009)
explanation | more data
Updated 05 Jun 2019

CO_2 Thermospheric IR Cooling Integrated Over Solar Cycles



- Five complete solar cycles (19 – 23) computed
- Integrated CO_2 power is remarkably constant over these five cycles
- Minimum power is also nearly identical in the six minima developed
- SC 24, to date, has radiated only 80% of mean power of 5 prior cycles, 10 years past mimimum (6/2009)

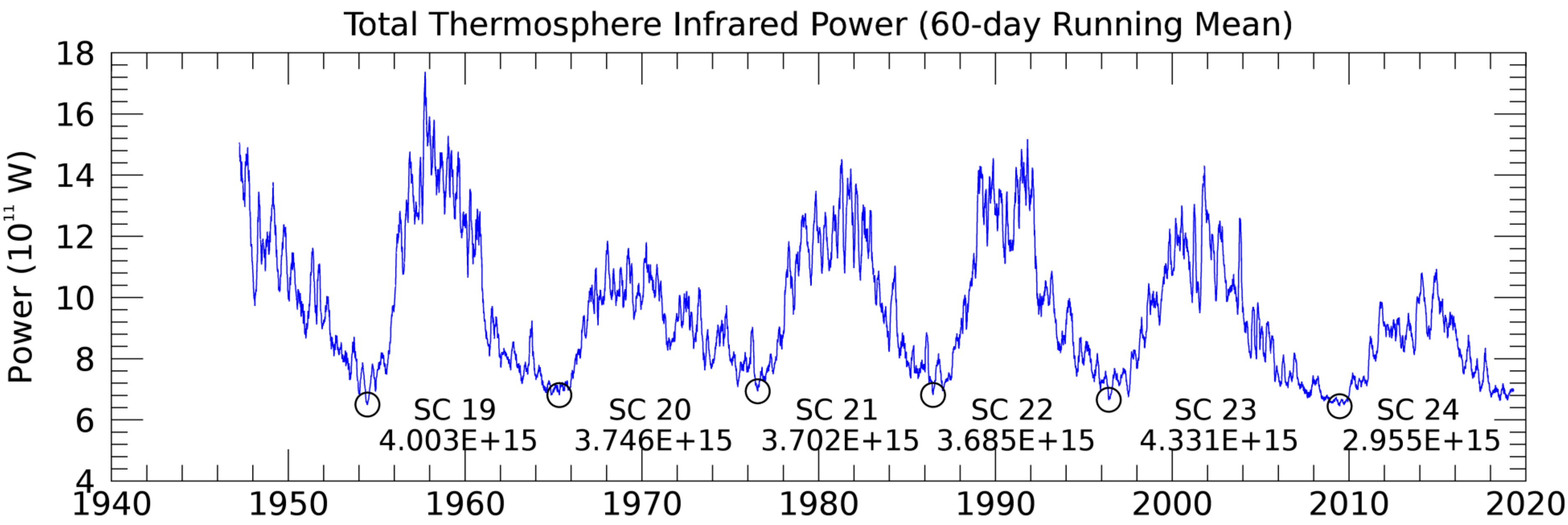
NO Radiative Cooling 1947-2019



- Power at previous six minima is also quite constant
- Integrated power across the five complete cycles (19 – 23) is also relatively constant
- NO Power in SC 24 to date is 53% of the mean of five prior cycles

SC 24 appears to be substantially different than its 5 predecessors based on the quantitative metric of radiated infrared energy

Total Thermospheric IR Cooling Integrated Over Solar Cycles



- Total Power in SC 24 to date is 76% of the mean of five prior cycles
- Number of days to date in SC 24 is nearly 93% of average days in previous five solar cycles
- Would need ~1500 more days or about four more years in SC 24 to reach the average power of the last five solar cycles

Integrated IR Power, F10.7, and Ap

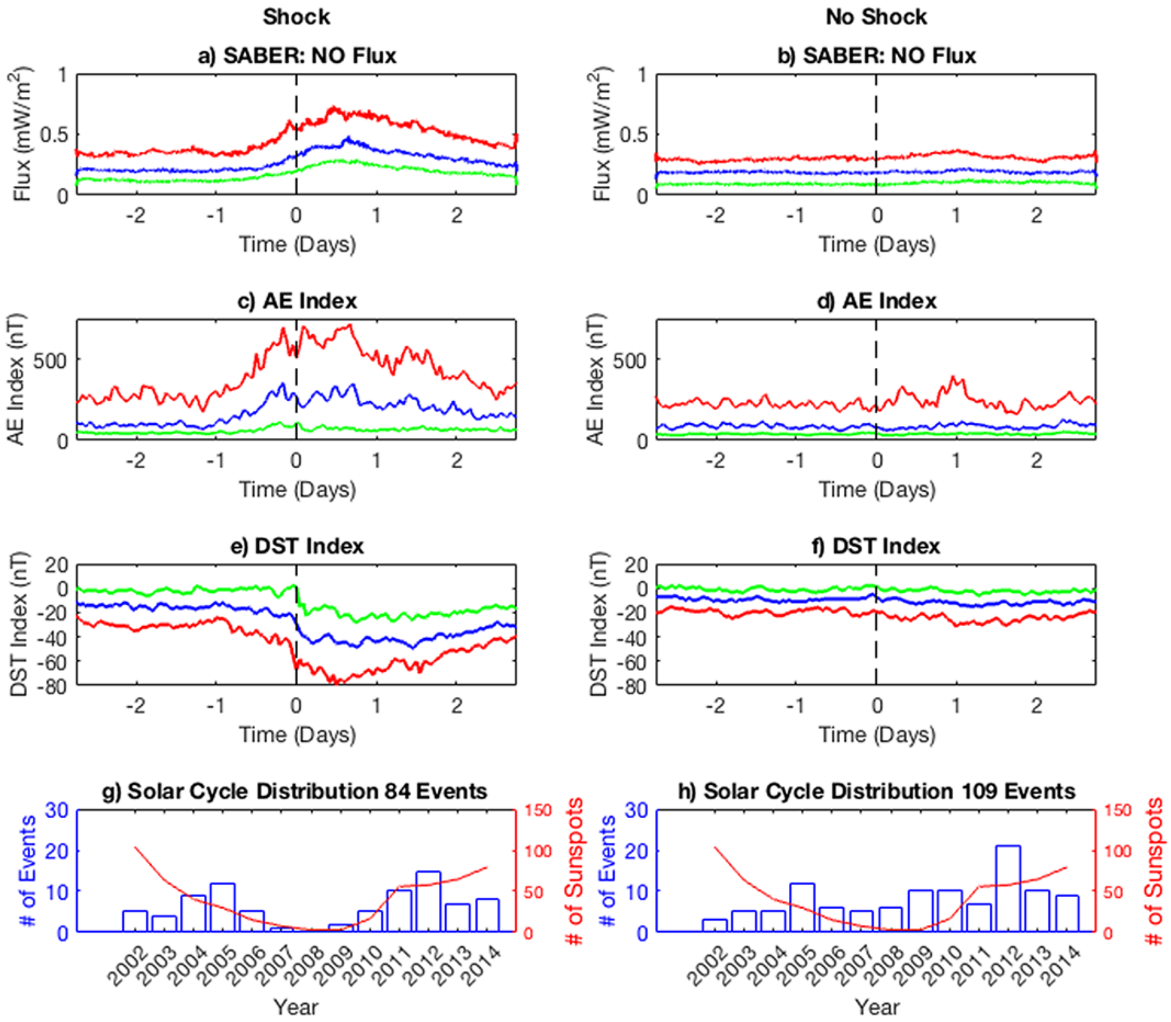
Solar Cycle	Total Days	NO Power	CO2 Power	Total Power	SRFlux	Ap Index
19	3966	7.43E+14	3.26E+15	4.00E+15	5.42E+05	6.08E+04
20	4245	5.78E+14	3.18E+15	3.75E+15	4.70E+05	5.36E+04
21	3622	6.79E+14	3.02E+15	3.70E+15	4.97E+05	5.67E+04
22	3630	6.63E+14	3.02E+15	3.69E+15	4.85E+05	5.66E+04
23	4774	6.43E+14	3.69E+15	4.33E+15	5.54E+05	5.58E+04
Mean	4047	6.61E+14	3.23E+15	3.89E+15	5.10E+05	5.67E+04
StdDev	431	5.32E+13	2.44E+14	2.45E+14	3.25E+04	2.33E+03
StdDev Pct	10.65%	8.04%	7.54%	6.29%	6.37%	4.12%
24 (to date)	3753.00	3.55E+14	2.61E+15	2.96E+15	3.63E+05	2.19E+04
Percent of Mean	92.73%	53.62%	80.63%	76.04%	71.21%	38.55%

New Understanding of Solar-Magnetosphere-Atmosphere Coupling

What Factors Determine IR Response to Storms?

- SABER IR cooling data exhibit substantial variability from storm to storm to storm
- The variability depends on the changes in
  - Kinetic temperature
  - NO abundance (chemically induced)
  - CO_2 changes (dynamically induced)
  - Atomic oxygen
- Is there something about storm type, structure, intensity, etc., that leads to major thermal, chemical, and dynamical response?
- Yes – SABER data reveal shock-led storms have significant IR response vs. non-shock storms [*Knipp et al*., 2017]

Thermospheric NO response to shock-led storms



Knipp et al., Space Weather, 2017 10.1002/2016SW001567

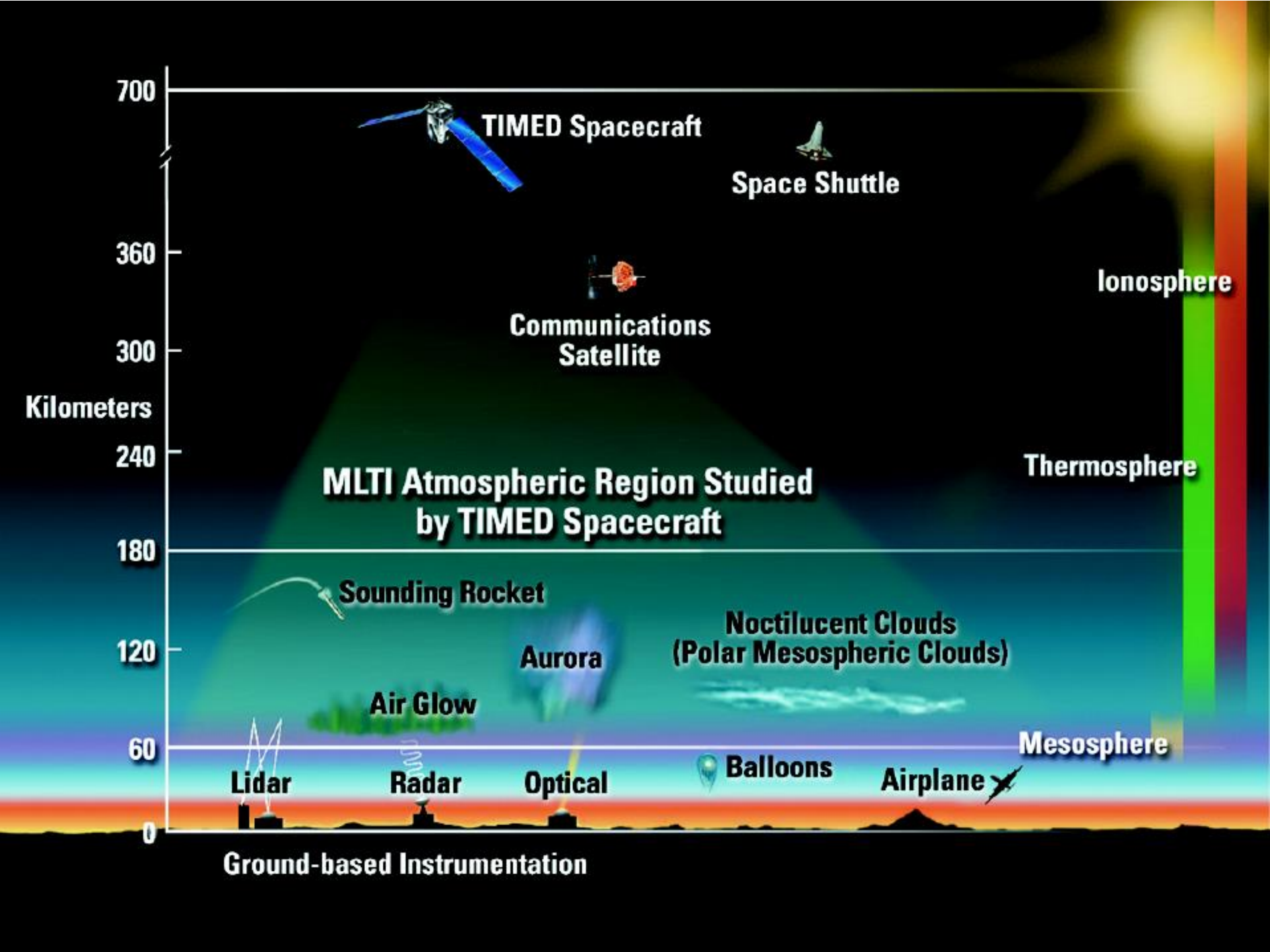
Summary and Future Questions

- Focus has generally been on NO cooling:
  - What is role of CO_2 cooling and is it dependent on storm structure and type the in the same way as NO cooling?
- Infrared response influences short-term changes in density and hence aerodynamic drag on satellites:
  - Can IR cooling be predicted 24-48 hours in advance with real time observations of NO and CO_2 cooling?
- Is the Sun heading into a period of weaker activity?

Acknowledgments

- Ap Index and F10.7 Solar Radio Flux data obtained from NOAA Space Weather Prediction Center
- Dst data obtained from University of Oulu, Finland, Dcx index server

Backups



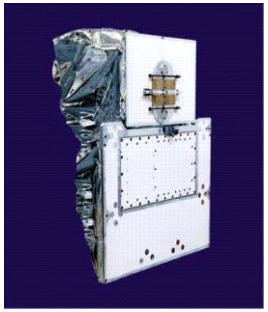
700
TIMED Spacecraft
Space Shuttle
360
Ionosphere
Communications
Satellite
300
Kilometers
240
Thermosphere
MLTI Atmospheric Region Studied
by TIMED Spacecraft
180
Sounding Rocket
Noctilucent Clouds
(Polar Mesospheric Clouds)
120
Aurora
Air Glow
60
Mesosphere
Balloons
Lidar
Radar
Optical
Airplane
0
Ground-based Instrumentation

A Brief History of TIMED

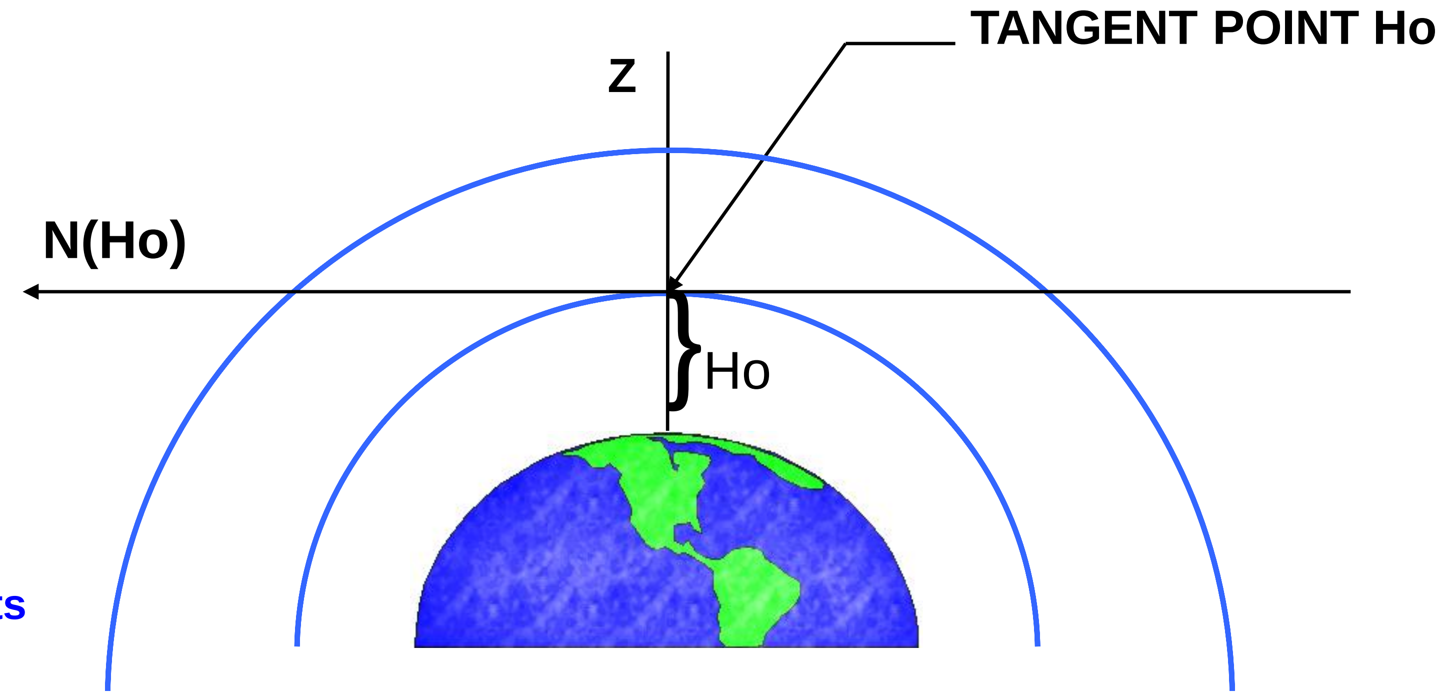
Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics

- Prior proposals for Mesosphere-Thermosphere Explorer in **1986** and **1989**
- NASA initiates TIMED Science Definition Team in **1991**
- Proposals for TIMED instruments submitted July **1992**
- NASA selects instruments in July **1993**
- Mission pre-formulation **1993 - 1995**
- TIMED Mission approved for formulation in **1996**
- Instruments built **1996-1999**
- Launch December 7, **2001**
- Baseline Mission – Originally 2 years
- More than 17 years on orbit today!
- Nominal operations ongoing
- Senior Review in **2020**
- Anticipate approval to operate through **2023**

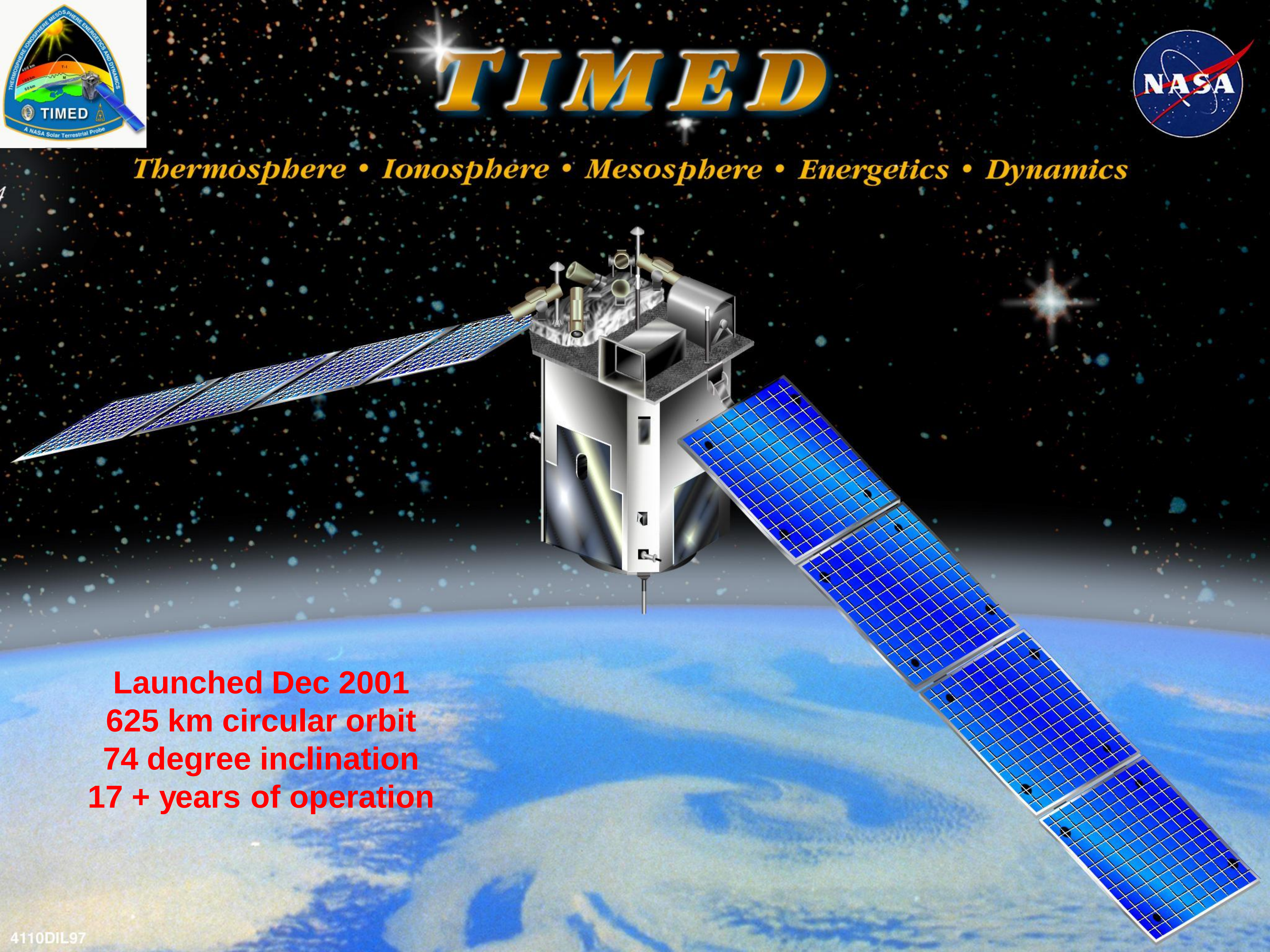
SABER Experiment Viewing Geometry and Inversion Approach



SABER Measurements
NO (5.3 μm)
CO_2 (15 μm)
OH(υ)
$O_2(^1\Delta)$
Temp.
O_3
H_2O
etc.



$$N(H_o) = \int_x \int_\nu J_\nu \frac{\partial \tau(p, T, q, \nu)}{\partial x} dx\, d\nu \qquad (\mathbf{W\ m^{-2}\ sr^{-1}})$$


TIMED
Thermosphere • Ionosphere • Mesosphere • Energetics • Dynamics
Launched Dec 2001
625 km circular orbit
74 degree inclination
17 + years of operation
4110DIL97

Basic Concept of Infrared Cooling

$$\frac{\partial Q}{\partial t} = \frac{[N]\, A_{10}\, k_{10}\, [O] \exp(-E_{10}/k_b T)\; E_{10}}{A_{10} + k_{10}\,[O]}$$

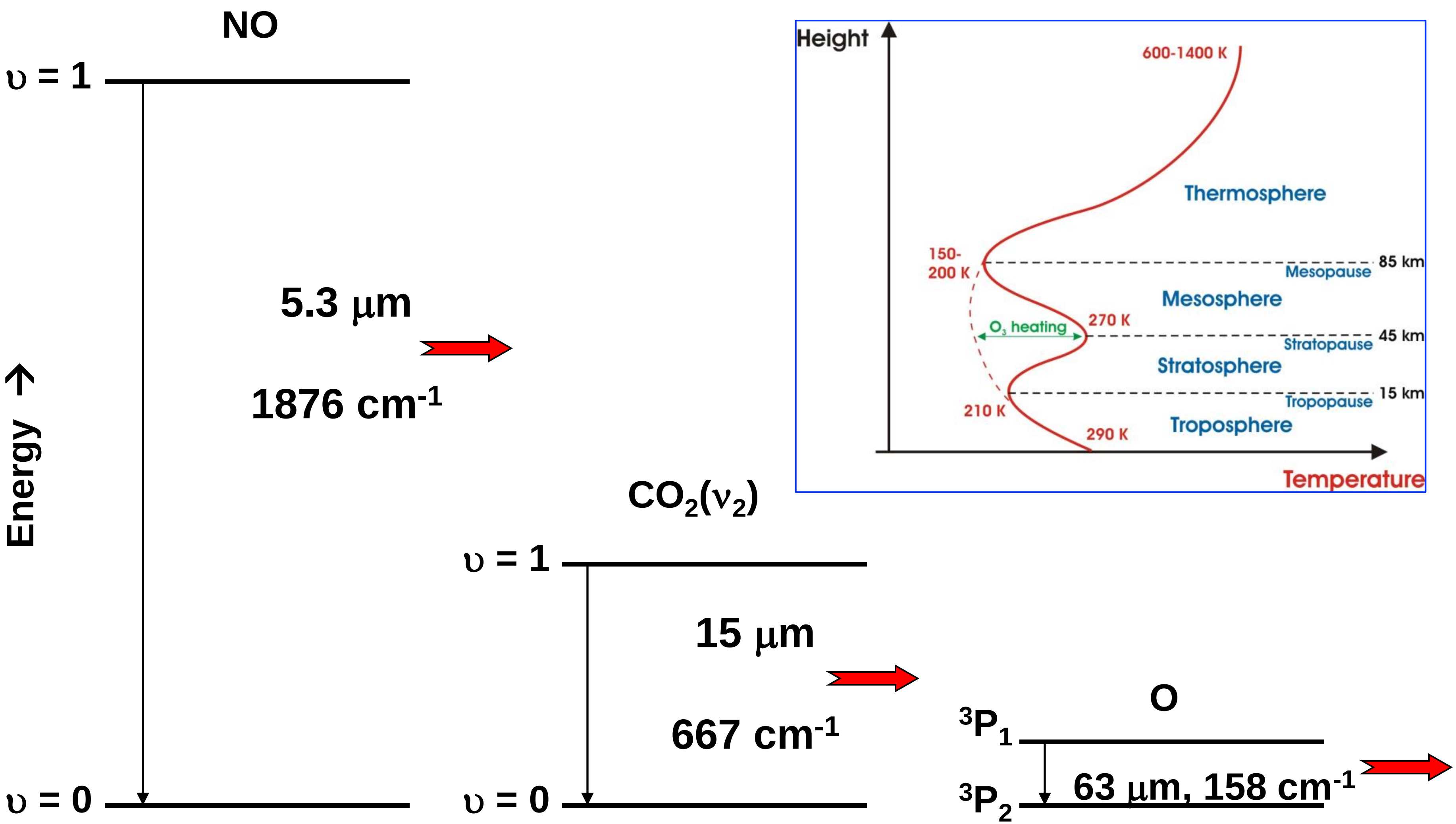
- dQ/dt is cooling rate (W/m^3)
- [N] is species abundance, NO or CO_2
- A_{10} is inverse radiative lifetime (Einstein A coefficient)
- [O] is the atomic oxygen density
- E_{10} is the energy of the photon for the 1-0 fundamental transition
- k_b is Boltzmann's constant
- T is kinetic temperature
- k_{10} is rate of collisional quenching of upper state of transition by [O]

Cooling depends on T, [O], and NO or CO_2 amount

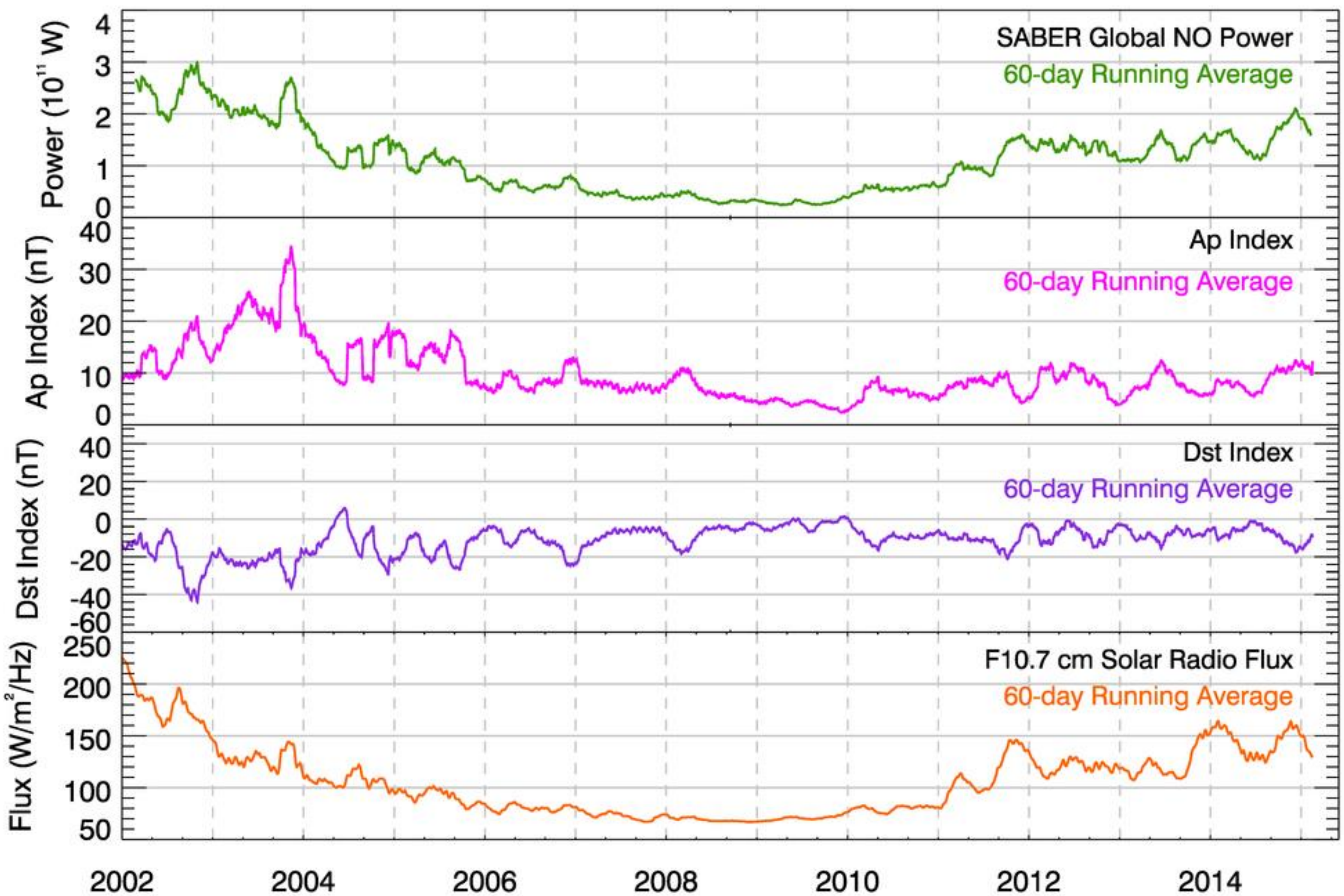
SABER measures the cooling rate dQ/dt

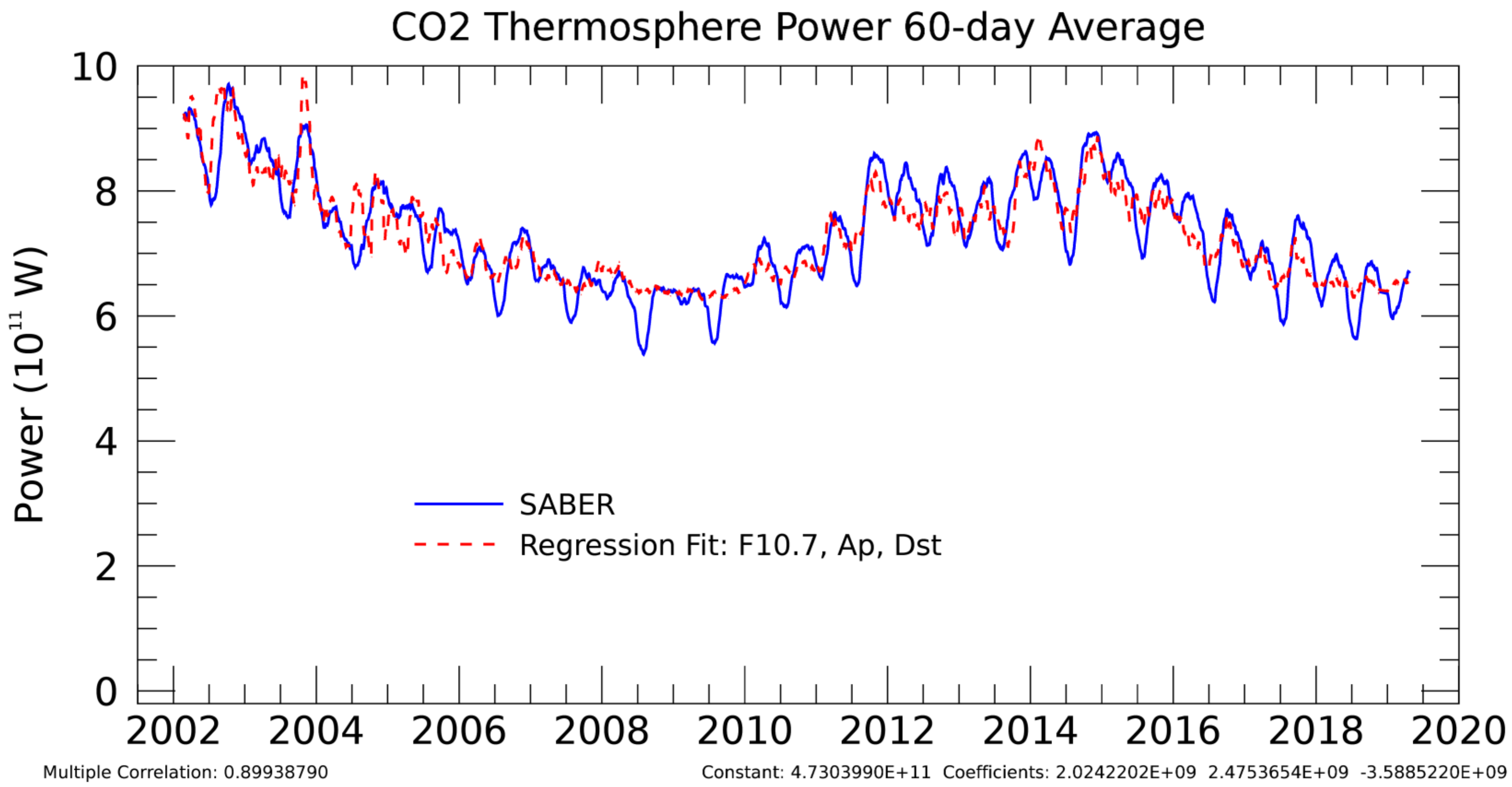
Thermospheric Radiative Cooling Mechanisms

- figure is to scale in energy -



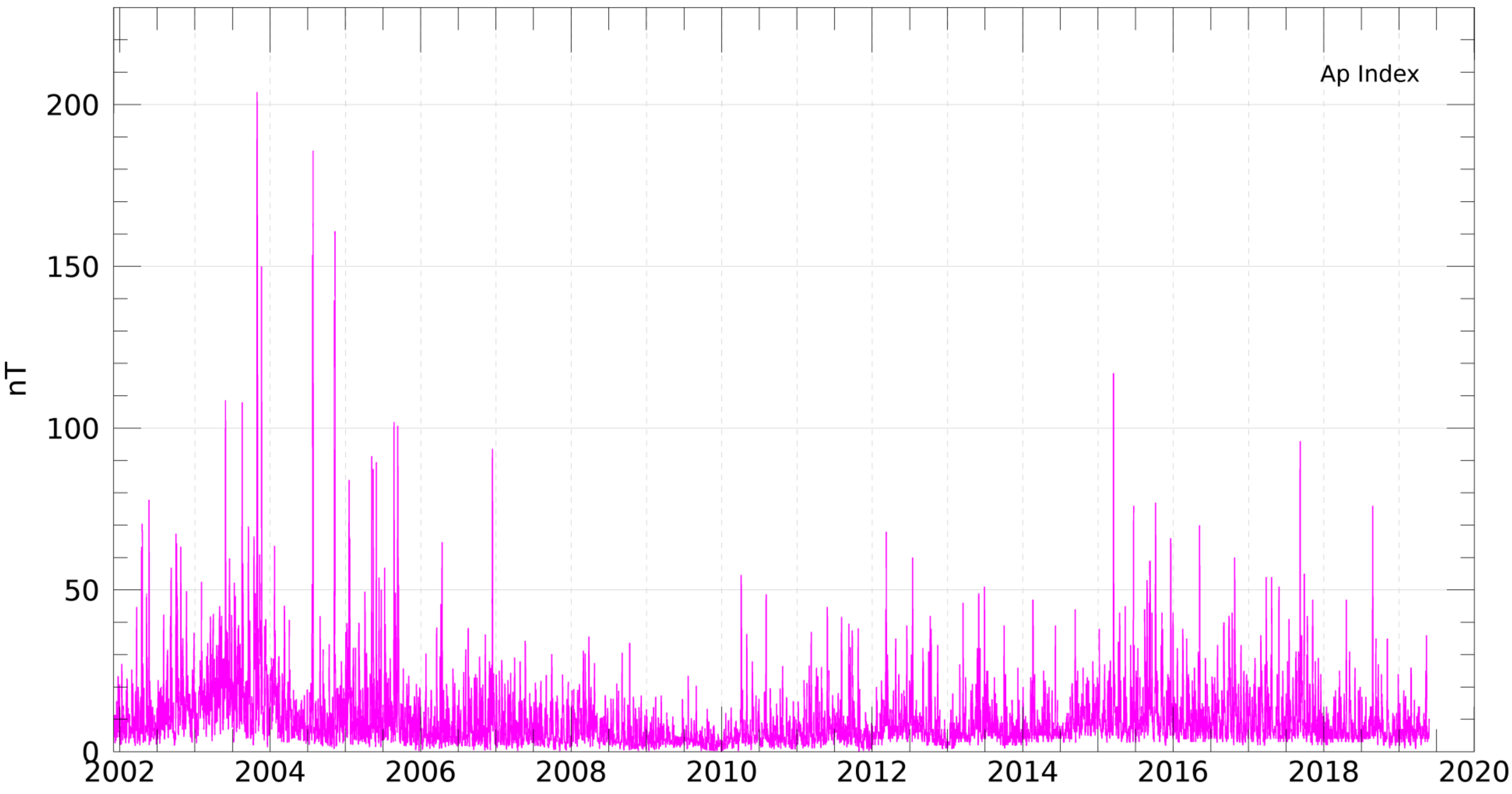
60-day Running Means – Nitric Oxide Power
Strong Visual Correlation in NO, Ap, Dst, F10.7





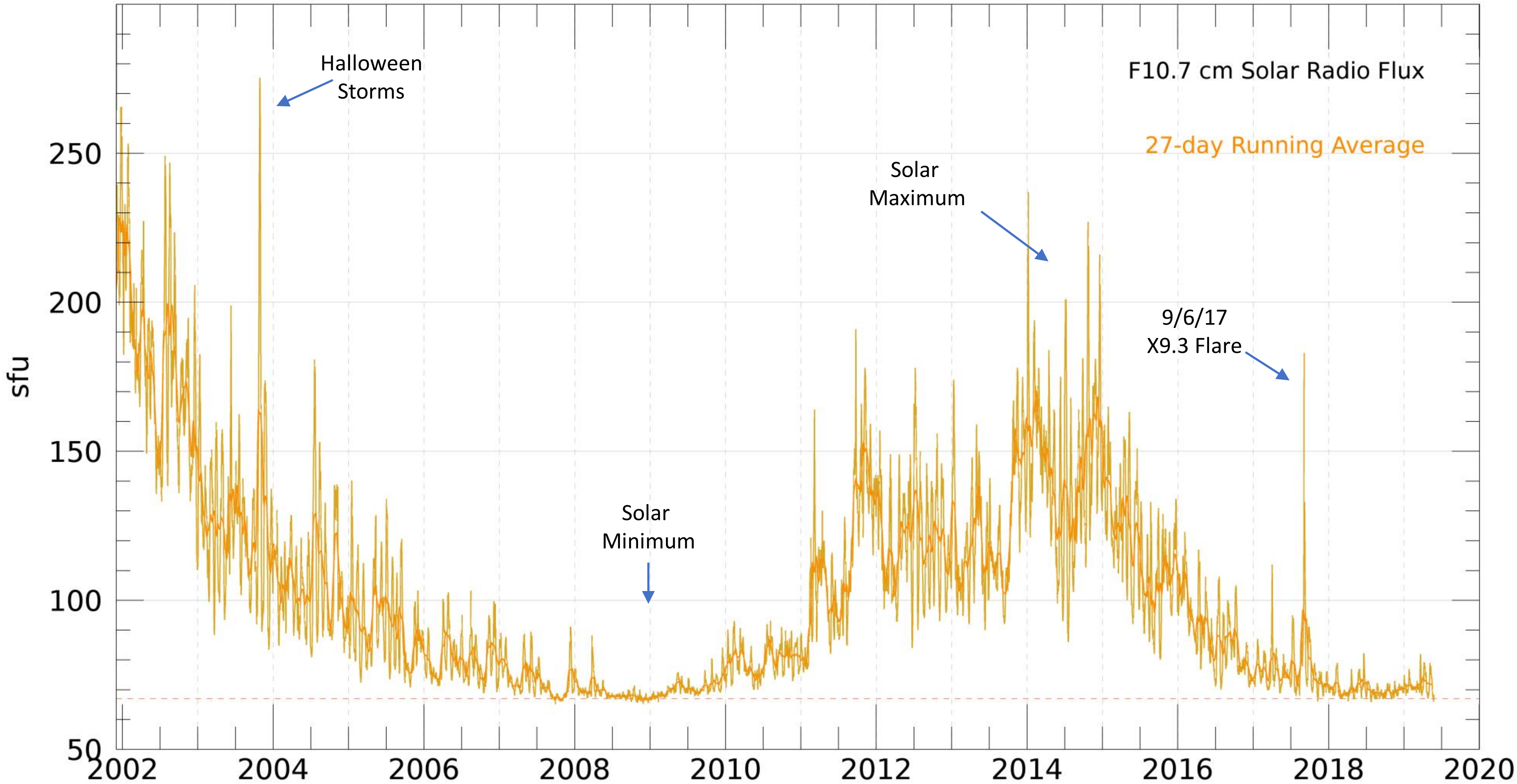
CO2 Thermosphere Power 60-day Average
Power (10^{11} W)
10
8
6
4
2
0
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
SABER
Regression Fit: F10.7, Ap, Dst
Multiple Correlation: 0.89938790
Constant: 4.7303990E+11 Coefficients: 2.0242202E+09 2.4753654E+09 -3.5885220E+09

Daily Ap Index – Jan 2002 to May 2019

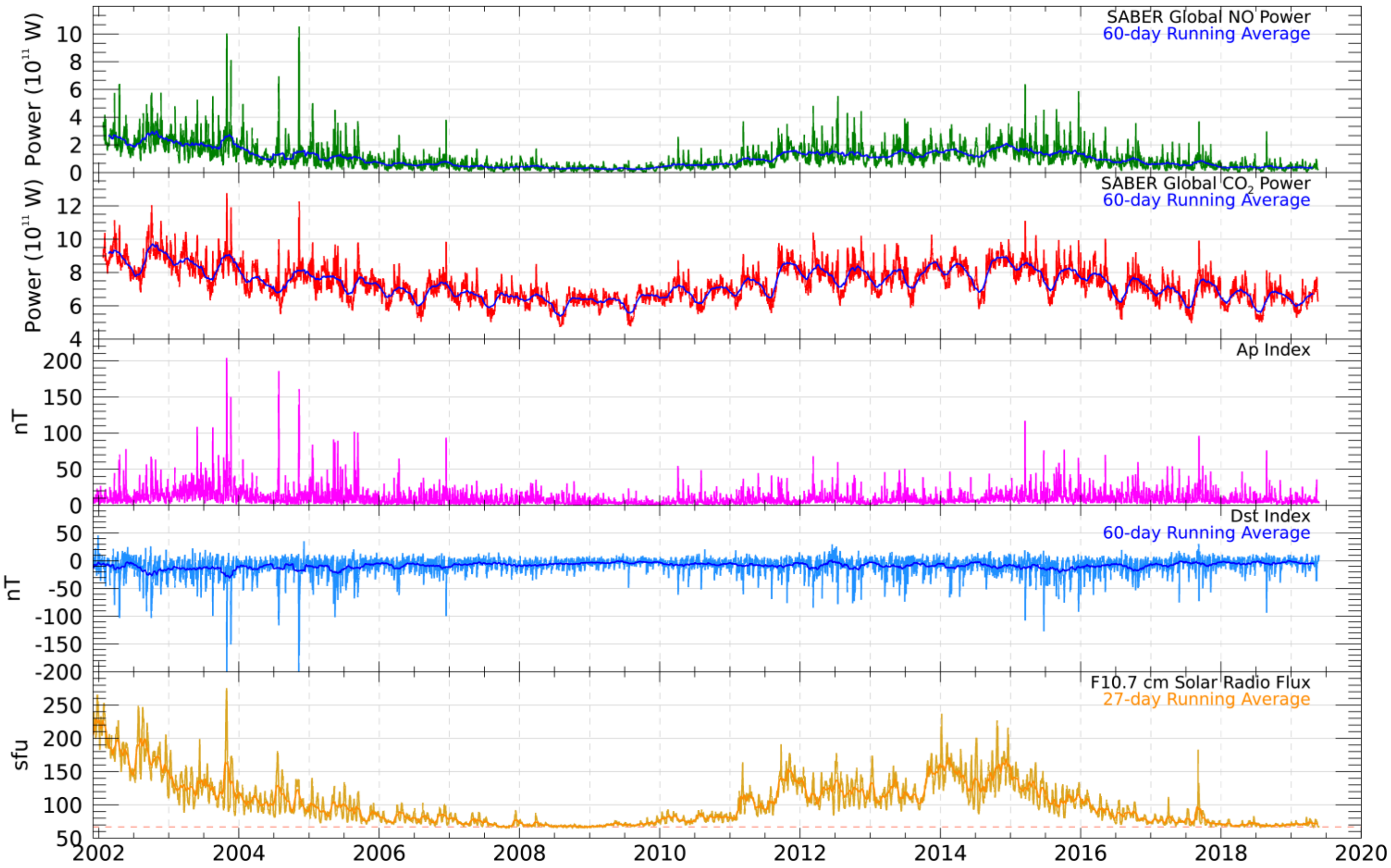


Source: NOAA SWPC

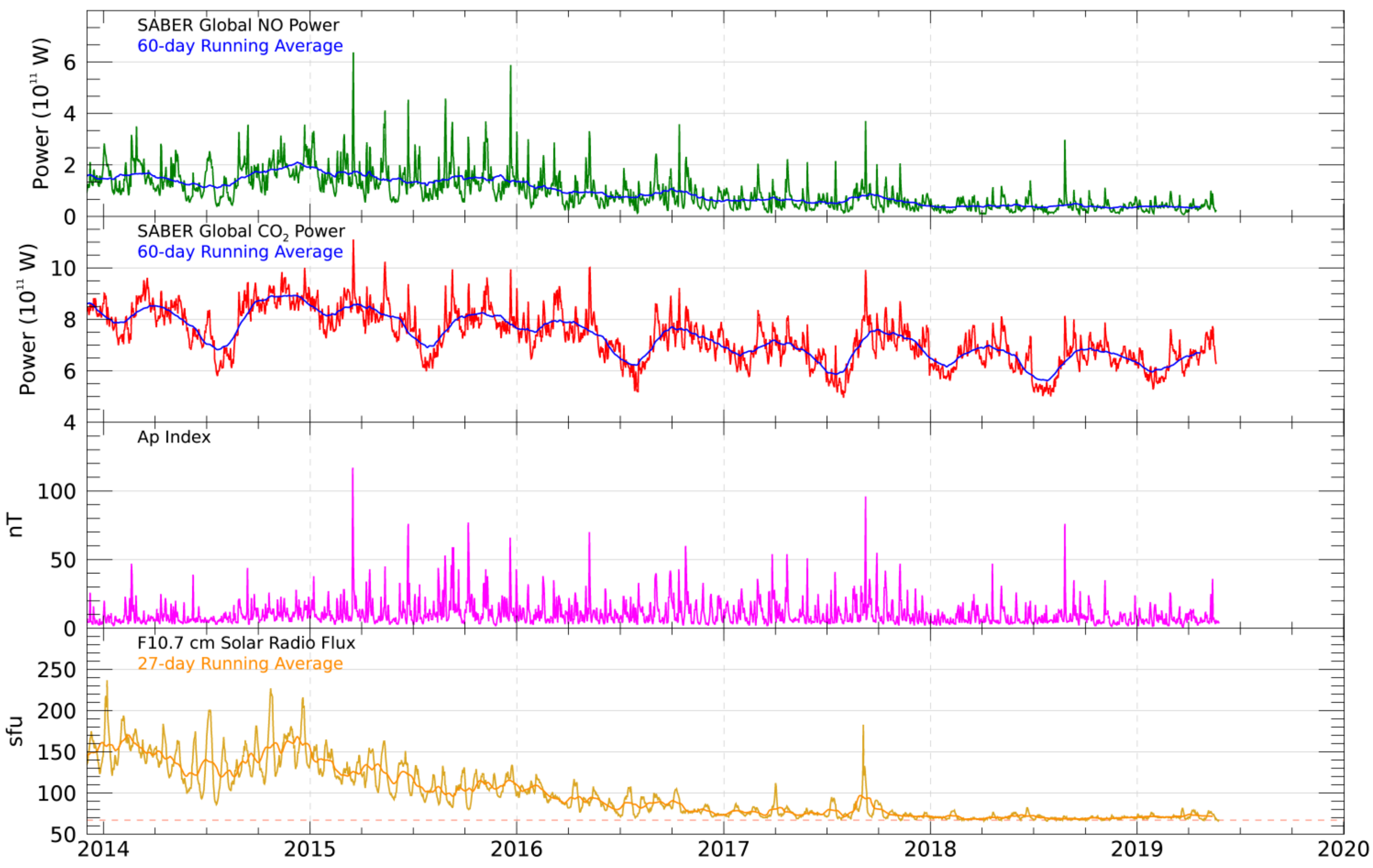
F10.7 Solar Radio Flux – Jan 2002 to May 2019



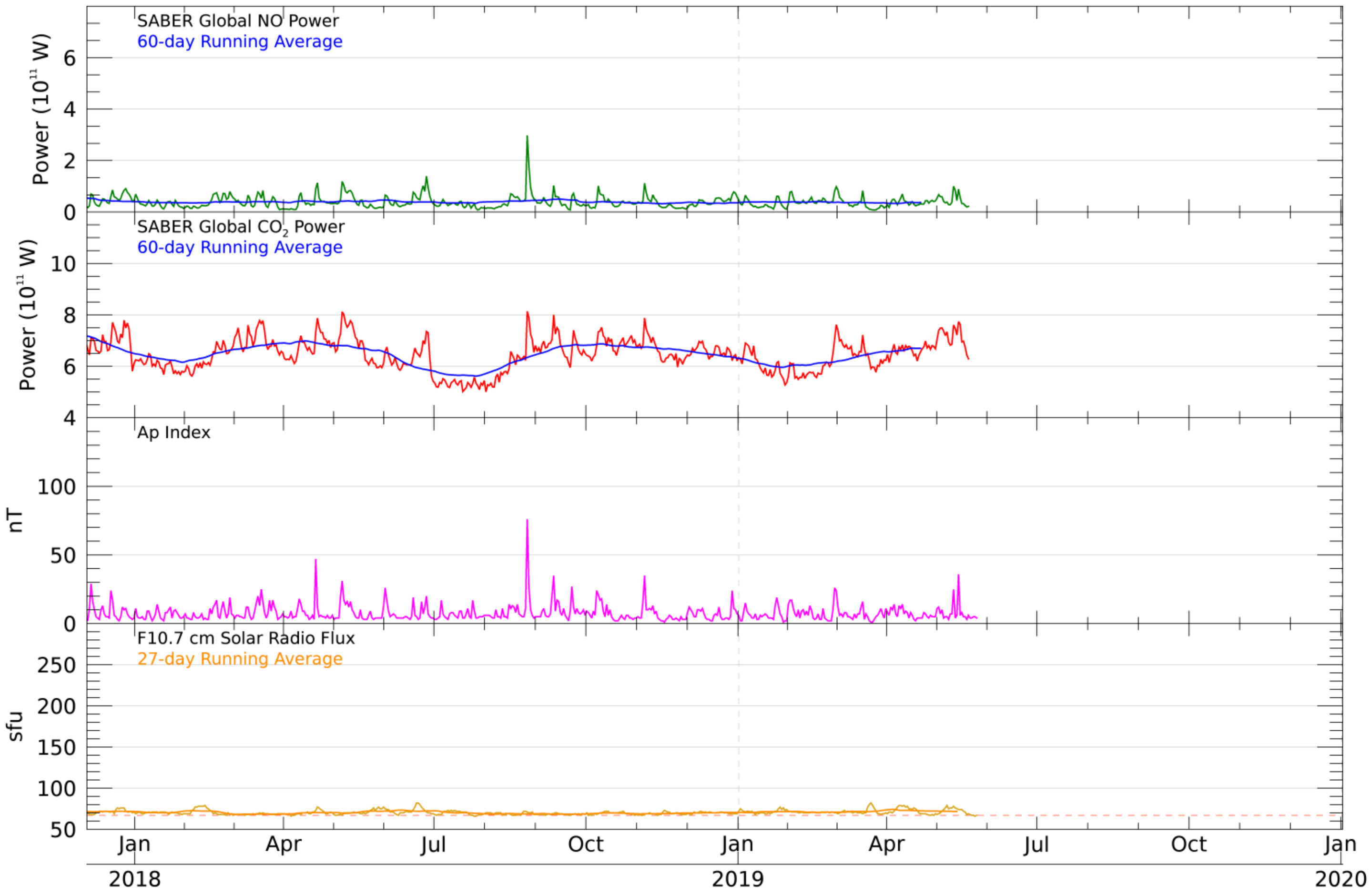
Source: NOAA SWPC

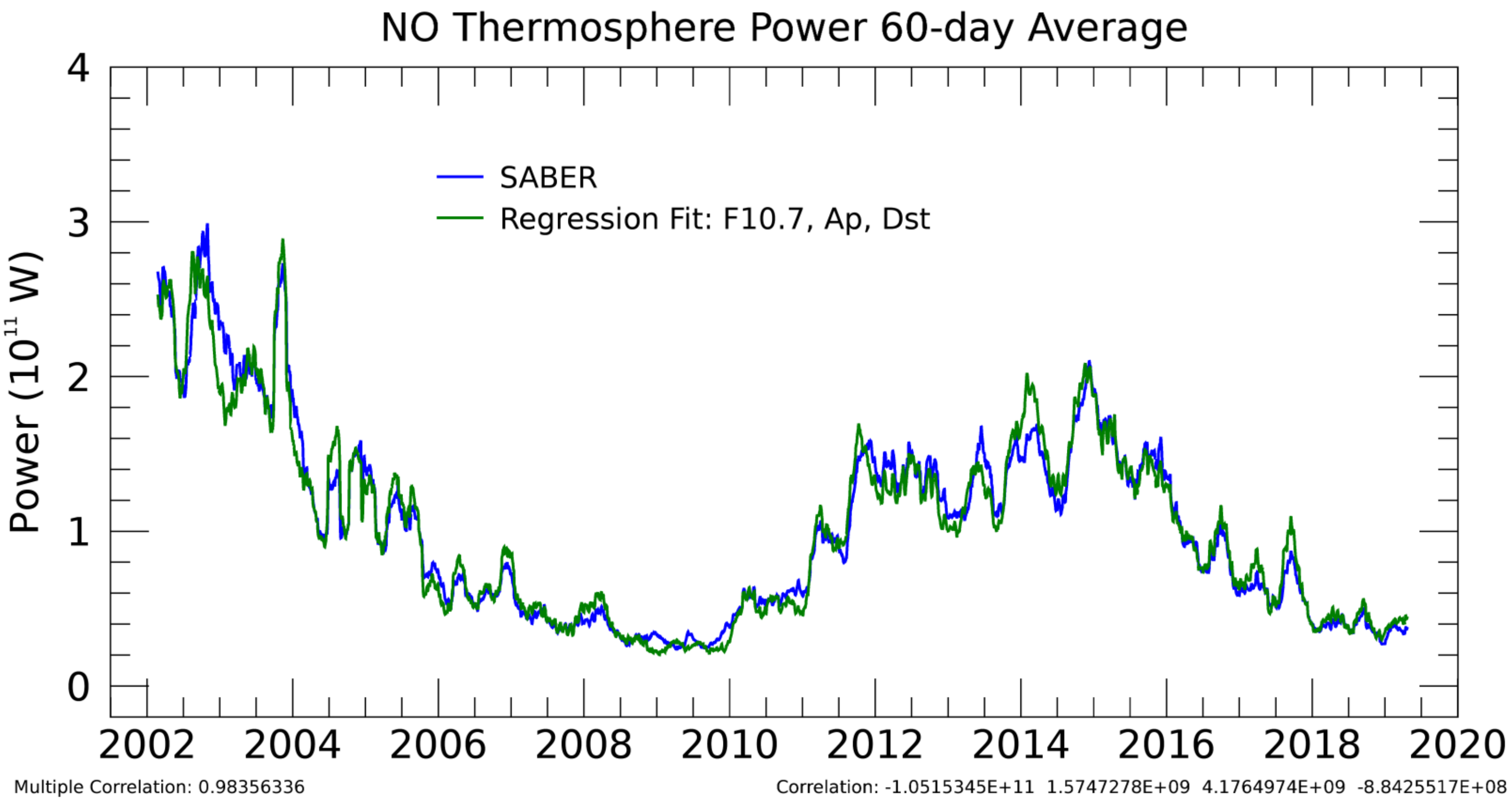


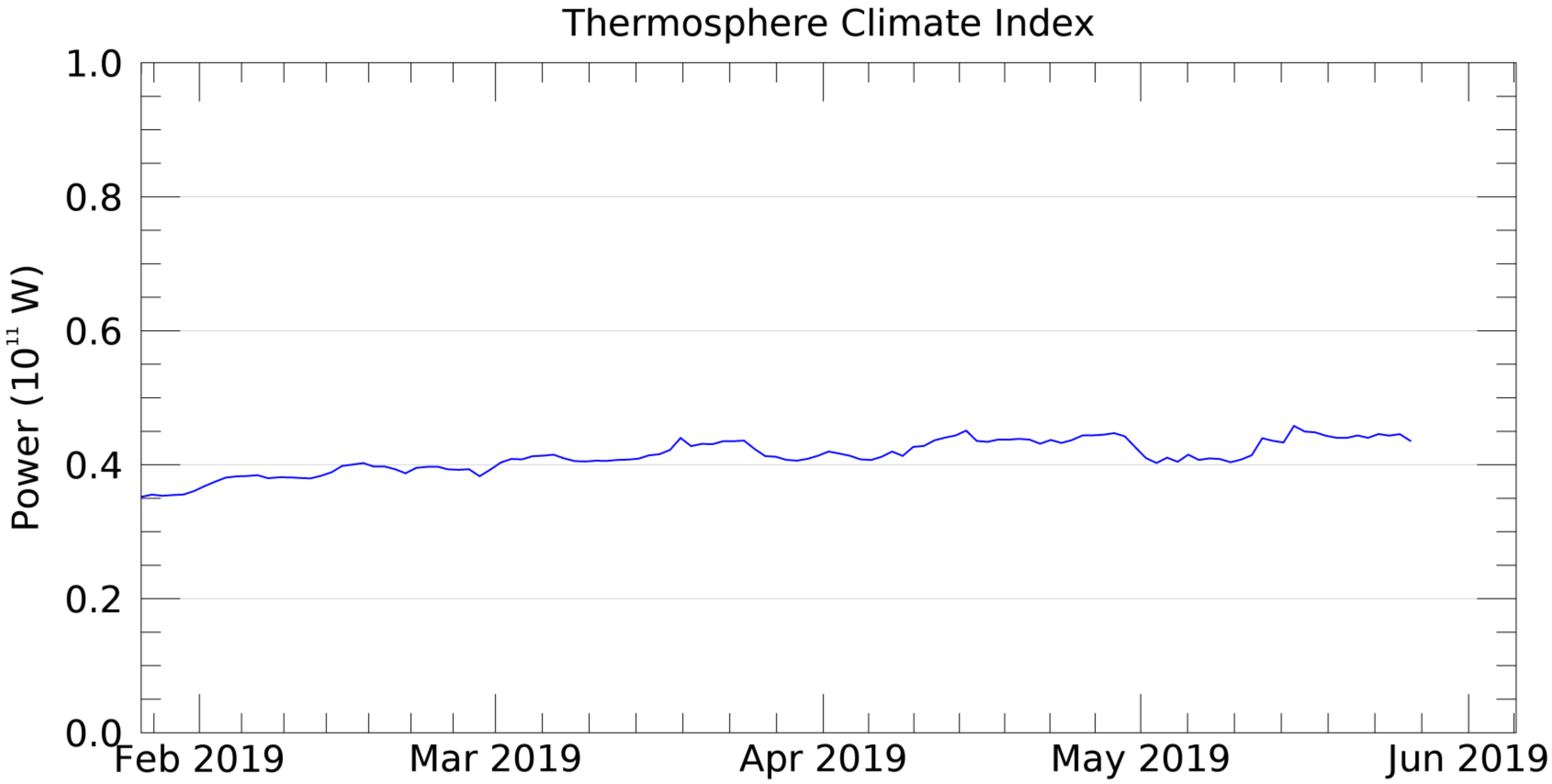
SABER Global NO Power
60-day Running Average
Power (10^{11} W)
SABER Global CO_2 Power
60-day Running Average
Power (10^{11} W)
Ap Index
nT
Dst Index
60-day Running Average
nT
F10.7 cm Solar Radio Flux
27-day Running Average
sfu
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020

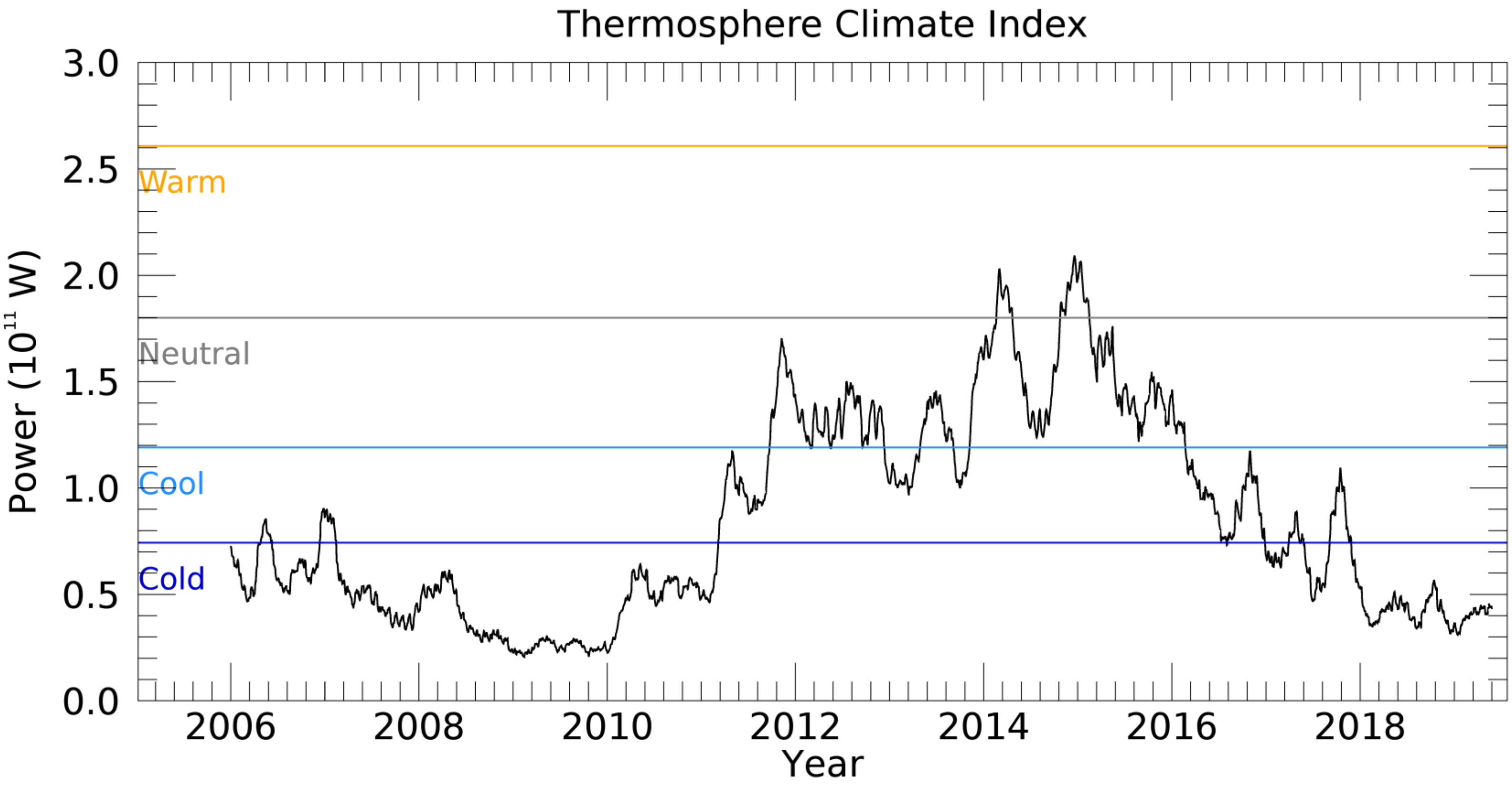


SABER Global NO Power
60-day Running Average
Power (10^{11} W)
0
2
4
6
SABER Global CO_2 Power
60-day Running Average
Power (10^{11} W)
4
6
8
10
Ap Index
nT
0
50
100
F10.7 cm Solar Radio Flux
27-day Running Average
sfu
50
100
150
200
250
2014
2015
2016
2017
2018
2019
2020

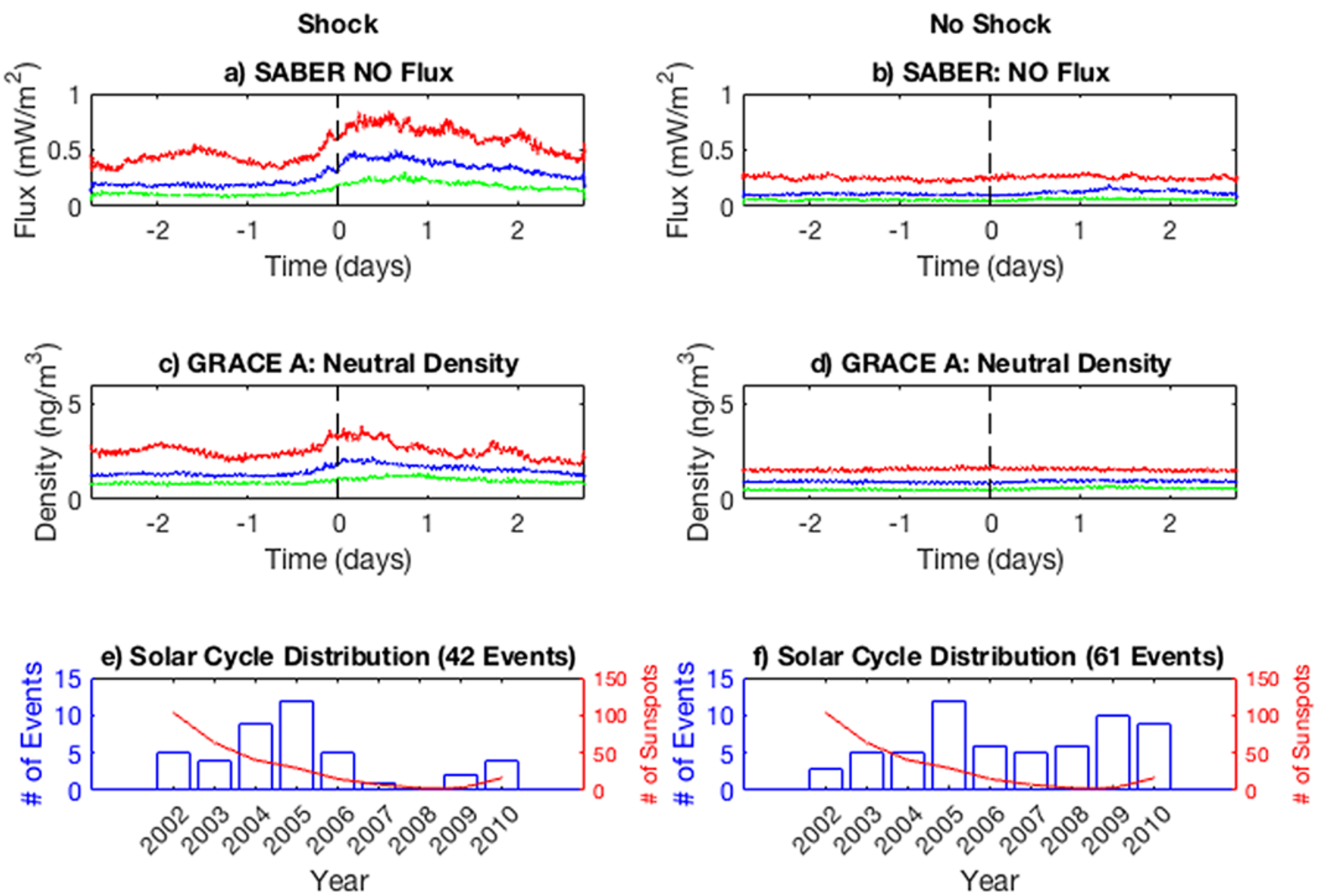

SABER Global NO Power
60-day Running Average
Power (10^{11} W)
SABER Global CO_2 Power
60-day Running Average
Power (10^{11} W)
Ap Index
nT
F10.7 cm Solar Radio Flux
27-day Running Average
sfu
Jan
Apr
Jul
Oct
Jan
Apr
Jul
Oct
Jan
2018
2019
2020


NO Thermosphere Power 60-day Average
SABER
Regression Fit: F10.7, Ap, Dst
Power (10^{11} W)
0
1
2
3
4
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
Multiple Correlation: 0.98356336
Correlation: -1.0515345E+11 1.5747278E+09 4.1764974E+09 -8.8425517E+08

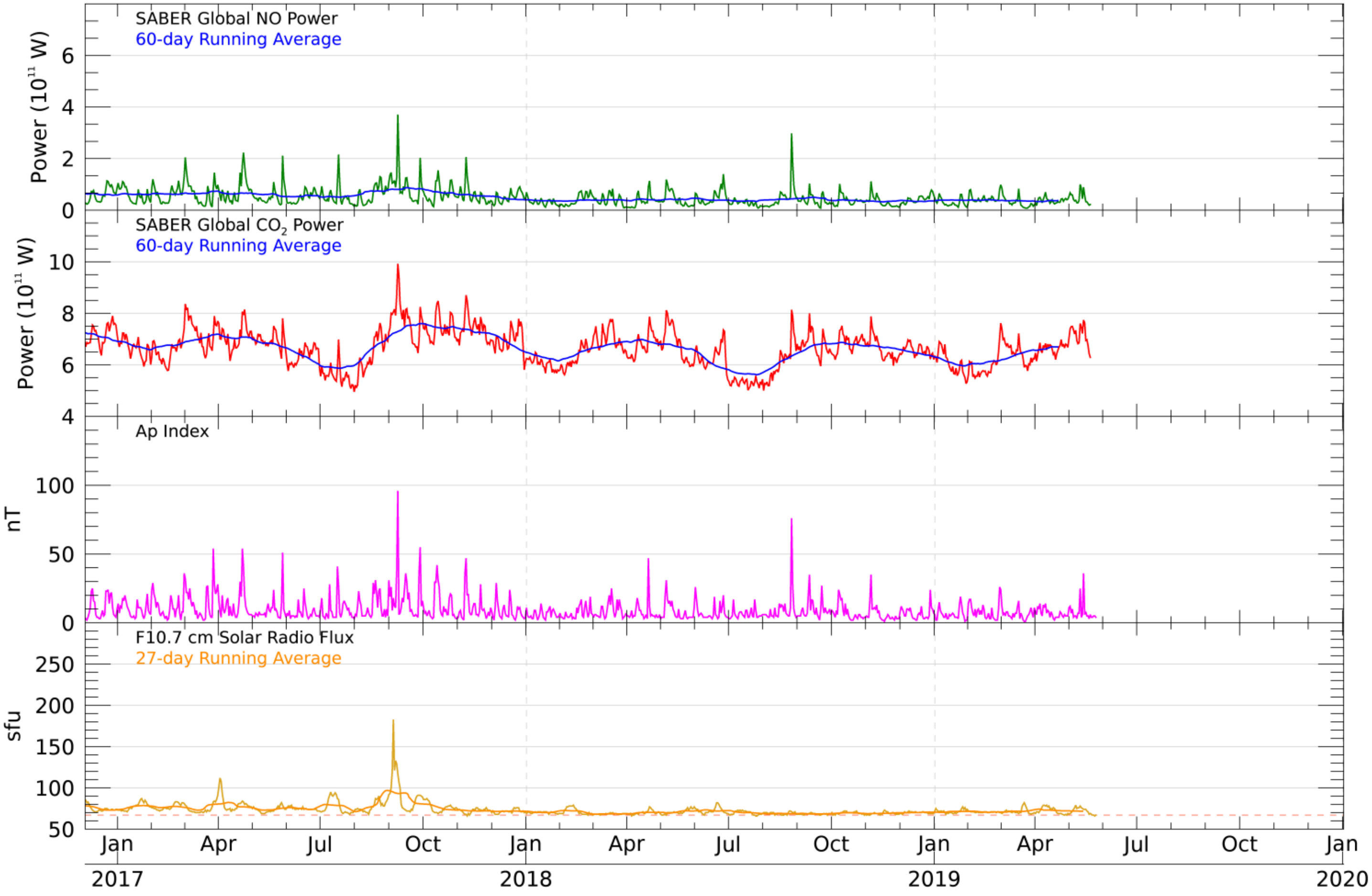

Thermosphere Climate Index
Power (10^11 W)
1.0
0.8
0.6
0.4
0.2
0.0
Feb 2019
Mar 2019
Apr 2019
May 2019
Jun 2019


Thermosphere Climate Index
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Power (10^11 W)
Warm
Neutral
Cool
Cold
2006
2008
2010
2012
2014
2016
2018
Year

Thermospheric NO response to shock-led storms



Thermosphere Infrared Response Since January 2017



Questions for the Future