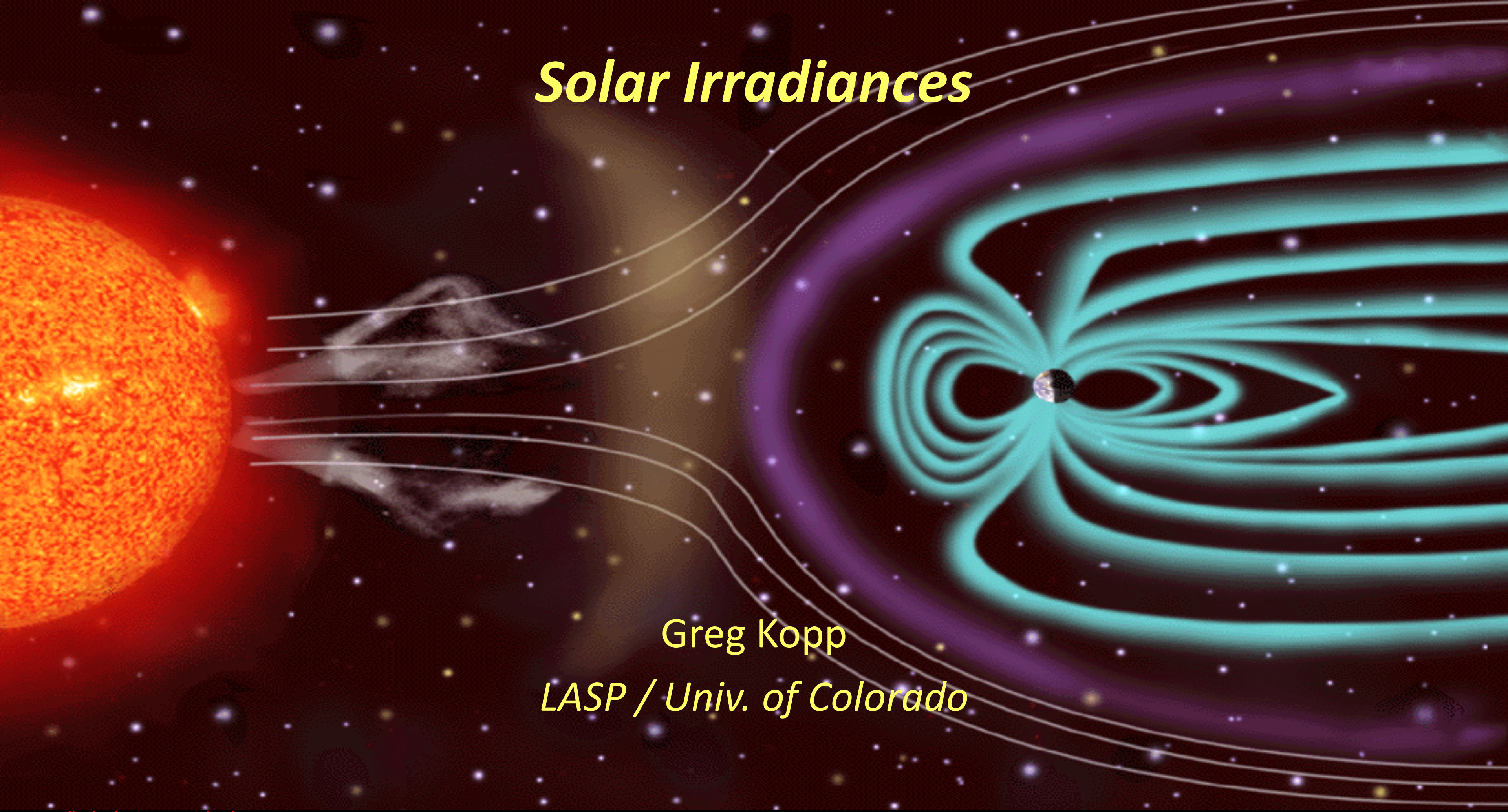


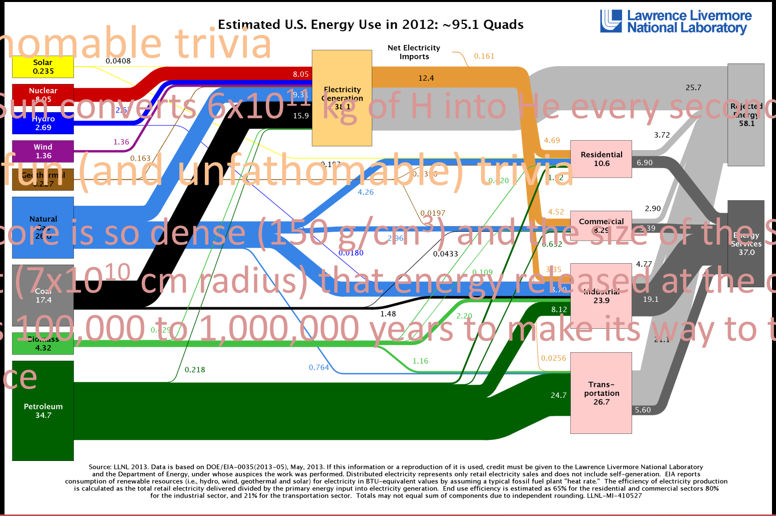
Solar Irradiances

Greg Kopp

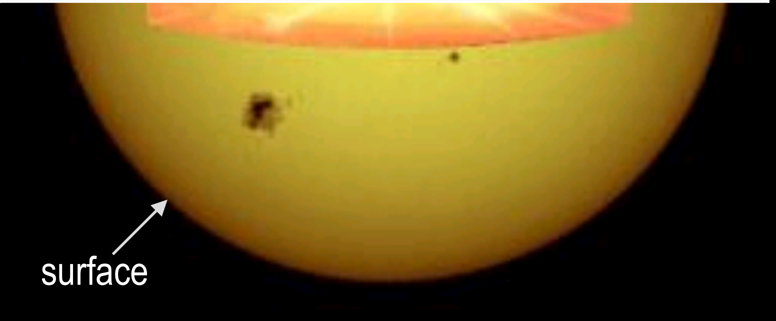
LASP / Univ. of Colorado

The Sun's Energy

- Energy output
  - Sun's total output 3.8×10^{23} kW
  - Energy heating the Earth 1361 W/m^2
- Energy trivia
  - The total output of the Sun in one second would provide the U.S. with enough energy, at its current usage rate, for the next 4,000,000 years
- Unfathomable trivia
  - The Sun converts 6×10^{11} kg of H into He every second
- More fun (and unfathomable) trivia
  - The core is so dense (150 g/cm^3) and the size of the Sun so great (7×10^{10} cm radius) that energy released at the center takes 100,000 to 1,000,000 years to make its way to the surface



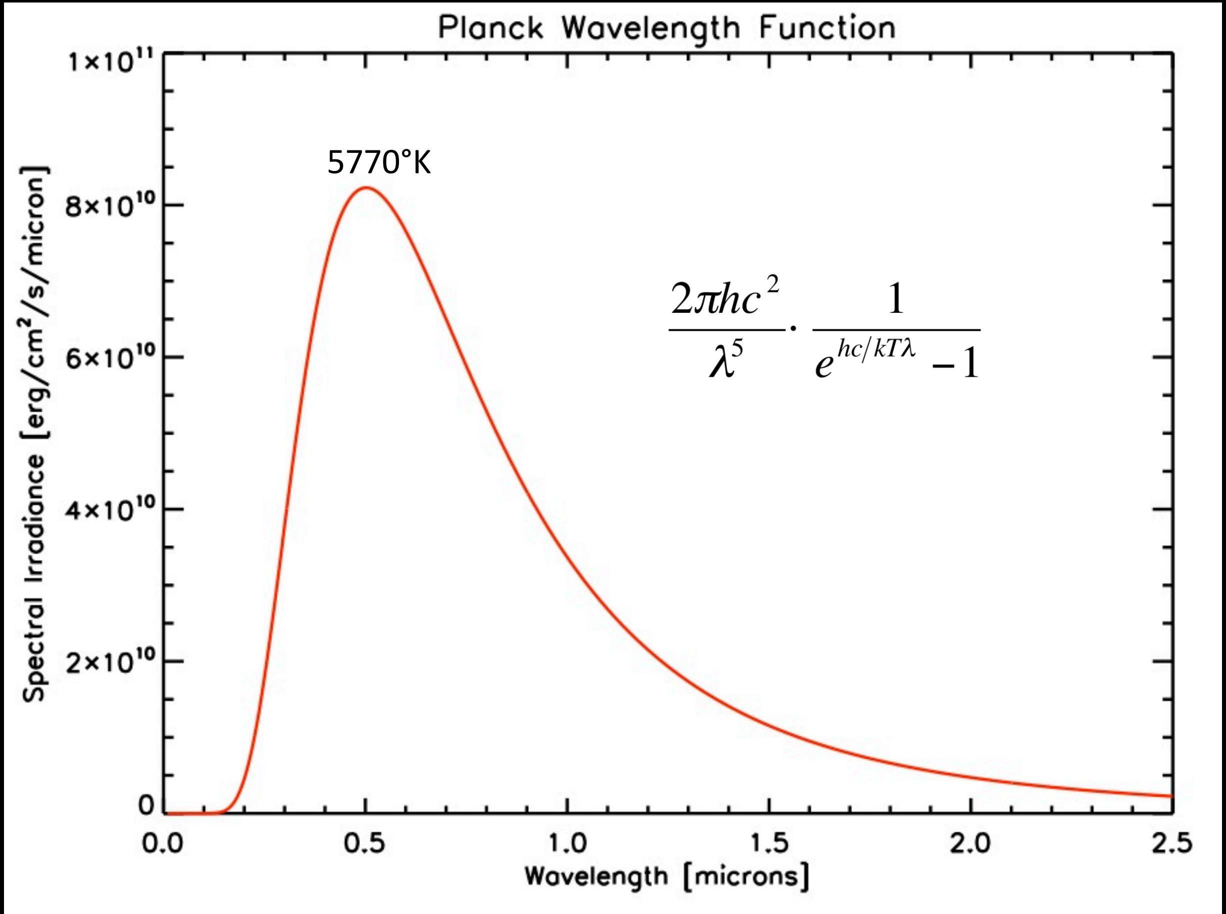
Fuel type	2006 US Consumption [PWh]	2006 World Consumption [PWh]
Oil	11.71	50.33
Gas	6.50	31.65
Coal	6.60	37.38
Hydroelectric	0.84	8.71
Nuclear	2.41	8.14
Geothermal, wind, solar, wood, waste	0.95	1.38
Total	**29.26**	**138.41**



Problems

- Determine the temperature of the Sun needed to produce 1361 W/m^2 irradiance at 1 AU
  - TSI S_E = 1361 W/m^2
  - Sun's radius R_S = 6.96265x10^{10} cm
  - 1 AU R_E = 1.4959787x10^{13} cm
  - Flux at Sun's surface $S_S = S_E * (R_E/R_S)^2$
  - Flux $S_S = \sigma T^4$ (σ = 0.567x10^{-4} erg s^{-1} cm^{-2} K^{-4} = 0.567x10^{-7} W m^{-2} K^{-4})
  - Temperature $T = (S_S / \sigma)^{1/4}$ = <u>5769.6 K</u>

Planck Blackbody Spectrum



Problem

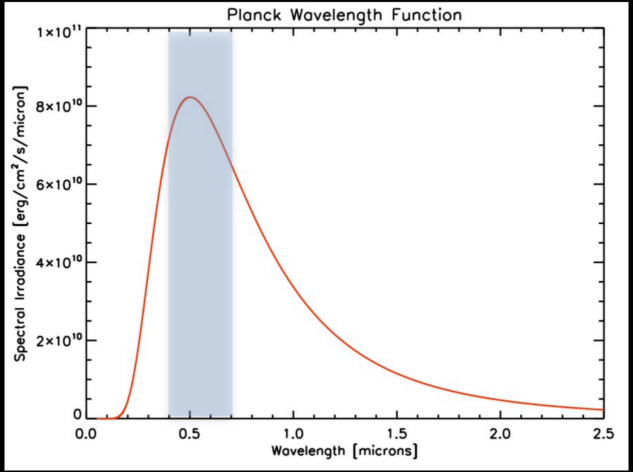
- Integrate the Planck blackbody for a 5770° K Sun to determine the fraction of total energy in:
  - the visible region from 400 to 700 nm; and
  - the NUV, visible, & NIR spectral region from 300 to 2500 nm

Problem

- Integrate the Planck blackbody for a 5770° K Sun to determine the fraction of total energy in:
  - the visible region from 400 to 700 nm; and
  - the NUV, visible, & NIR spectral region from 300 to 2500 nm

$$E(\lambda,T) = \frac{2\pi hc^2}{\lambda^5}\frac{1}{e^{hc/kT\lambda}-1}$$

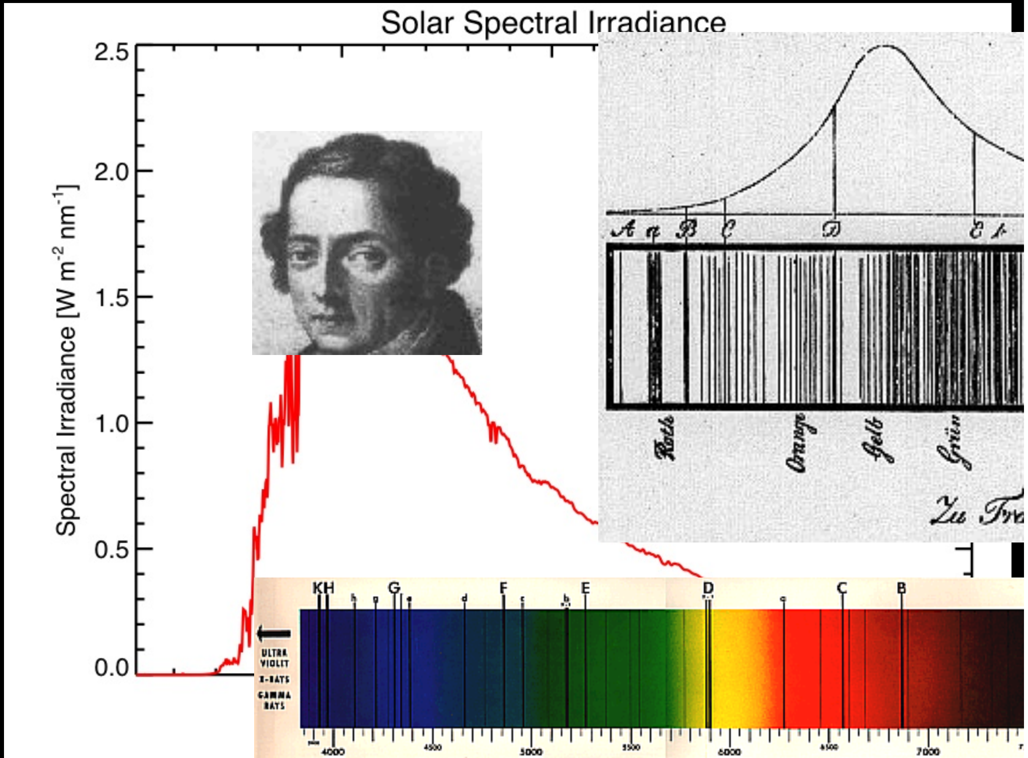
$$E_{total} = \int_0^\infty E(\lambda,T)\cdot d\lambda = \sigma T^4$$

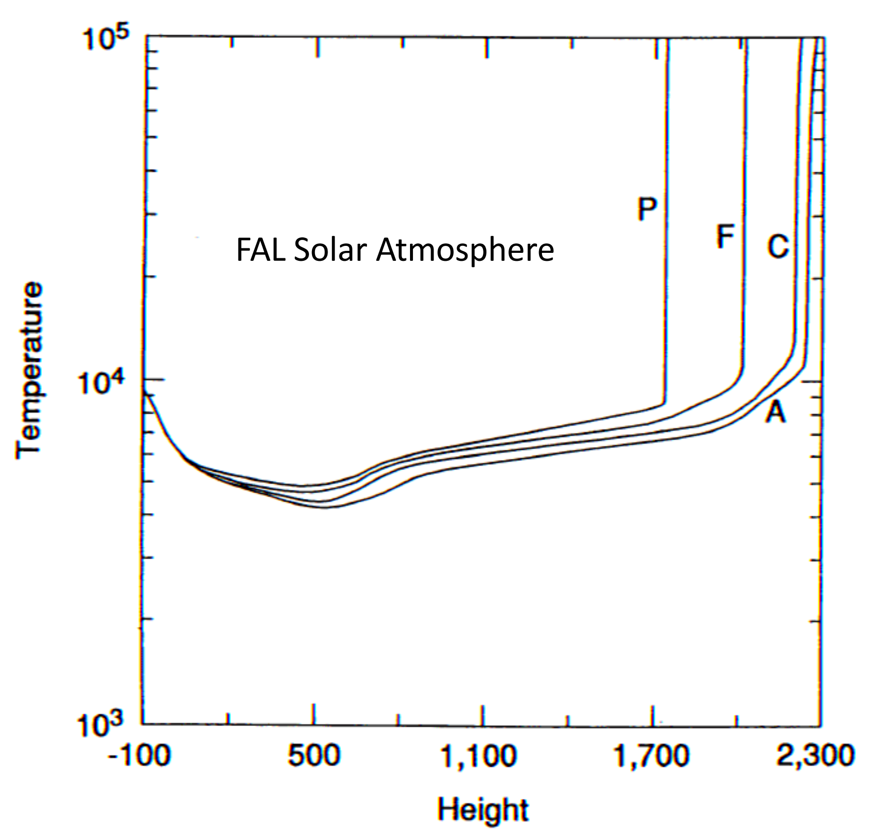


- $E_{total} = \sigma T^4$ ($\sigma = 0.567\text{x}10^{-4}$ erg s^{-1} cm^{-2} K^{-4}) = $6.285\text{x}10^{10}$ erg/s/cm^2
- 1) 400-700 nm: E = $2.299\text{x}10^{10}$ erg/s/cm^2 <u>36.6%</u>
- 2) 300-2500 nm: E = $5.868\text{x}10^{10}$ erg/s/cm^2 <u>93.4%</u>

Solar Spectral Deviations from Planck Blackbody

- Fraunhofer (absorption) lines in visible and NIR
- EUV emission

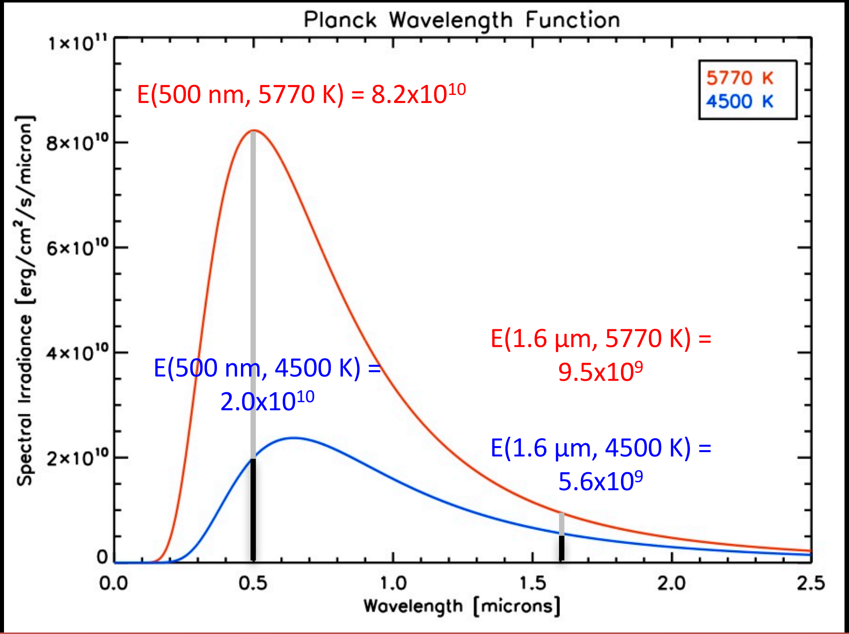




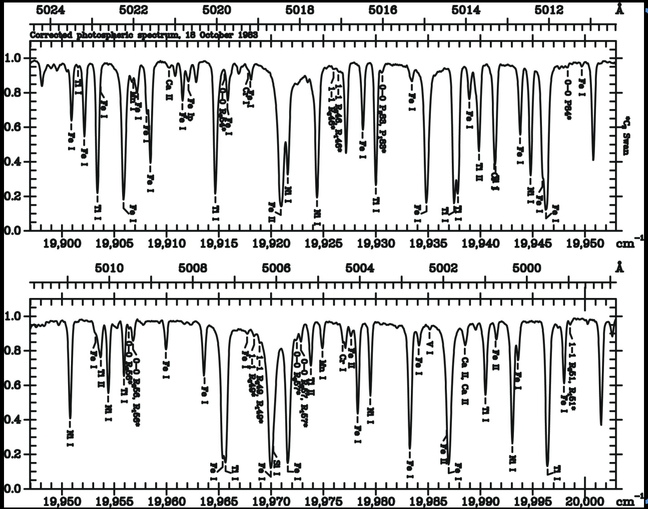
Problem

- Determine the Fraunhofer line depth for a 500 nm (visible) absorption line with that of a line at 1.6 μm (NIR)
  - Assume the continuum is at photospheric temperatures (5770° K) and the absorption lines are formed in local thermodynamic equilibrium at temperature minimum values (~4500° K)
  - This shows one reason that the NIR is less sensitive to scattered light than the visible

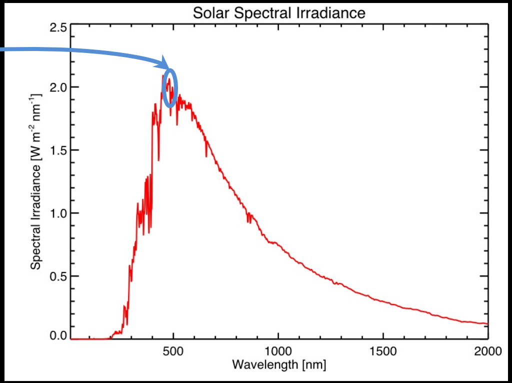
  - 500 nm: 24%
  - 1.6 μm: 59%



The Sun – Condensed to Total Irradiance



Images/plots courtesy of NSO, SOHO, SORCE



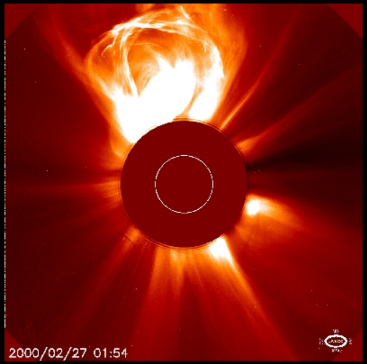
Spectral

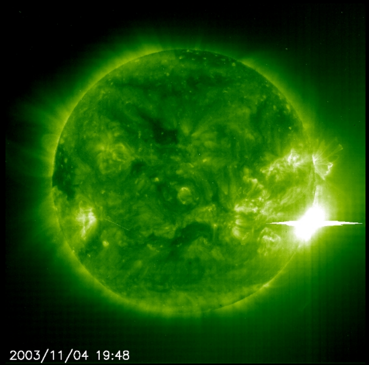
Σ

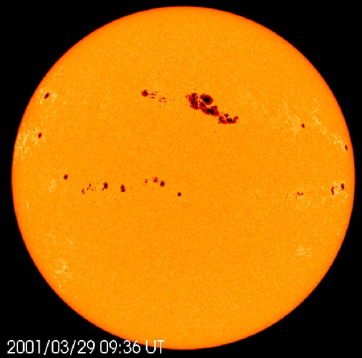
1361 W/m^2

Total Solar Irradiance (TSI)

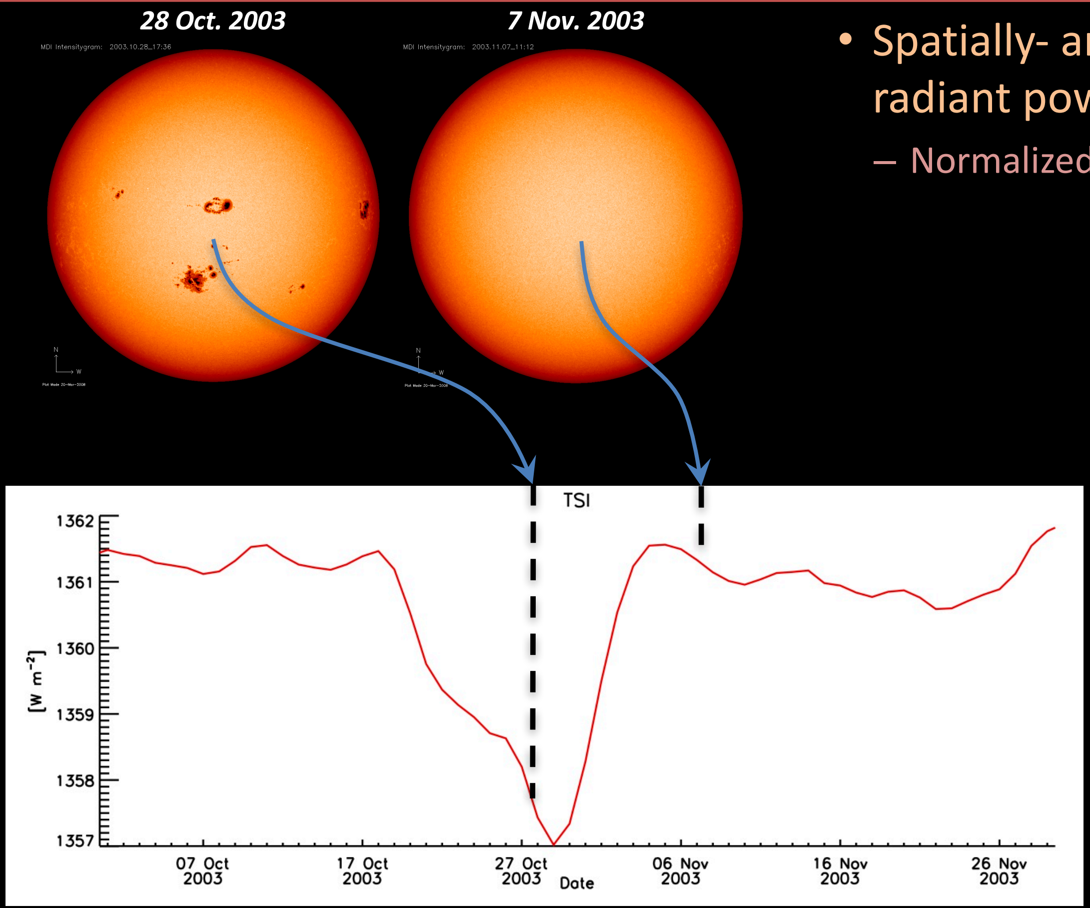
Spatial



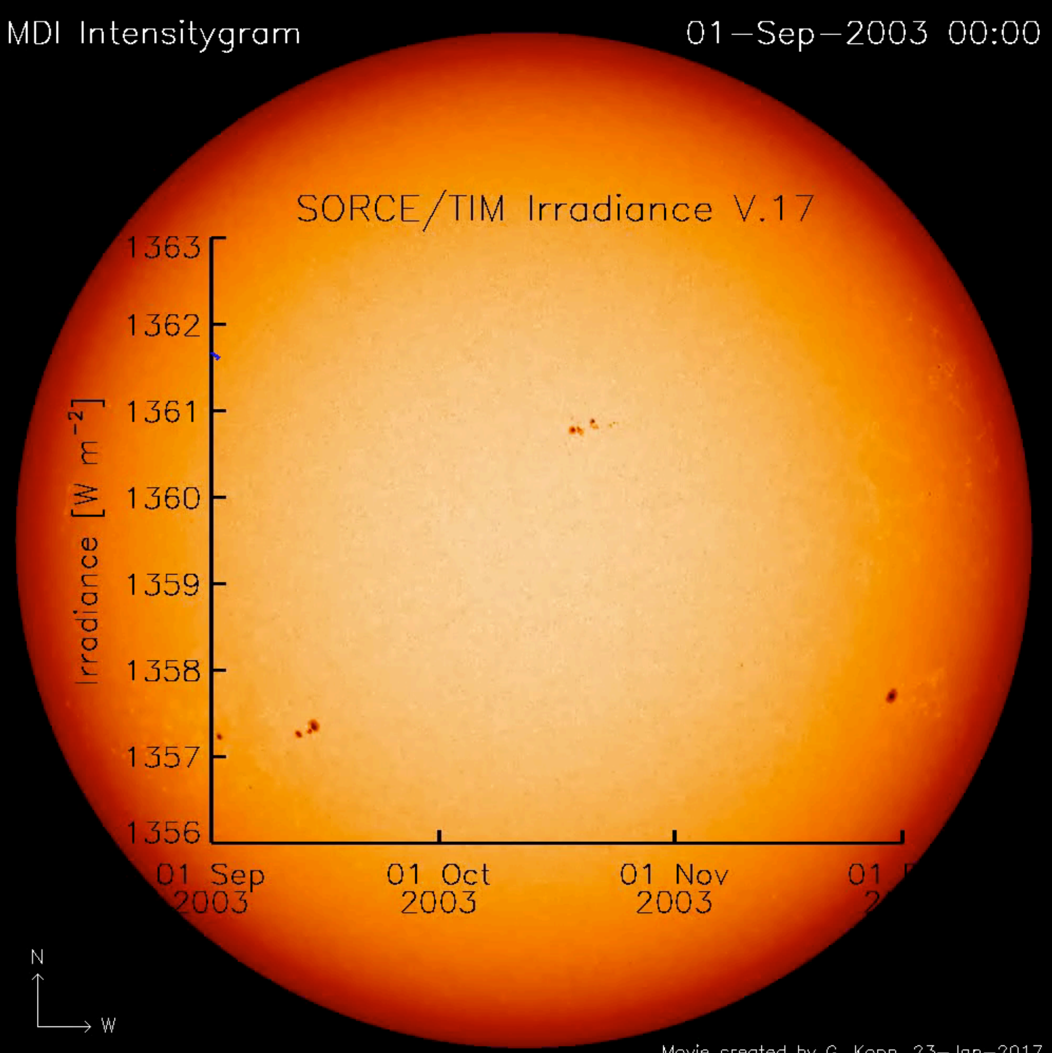




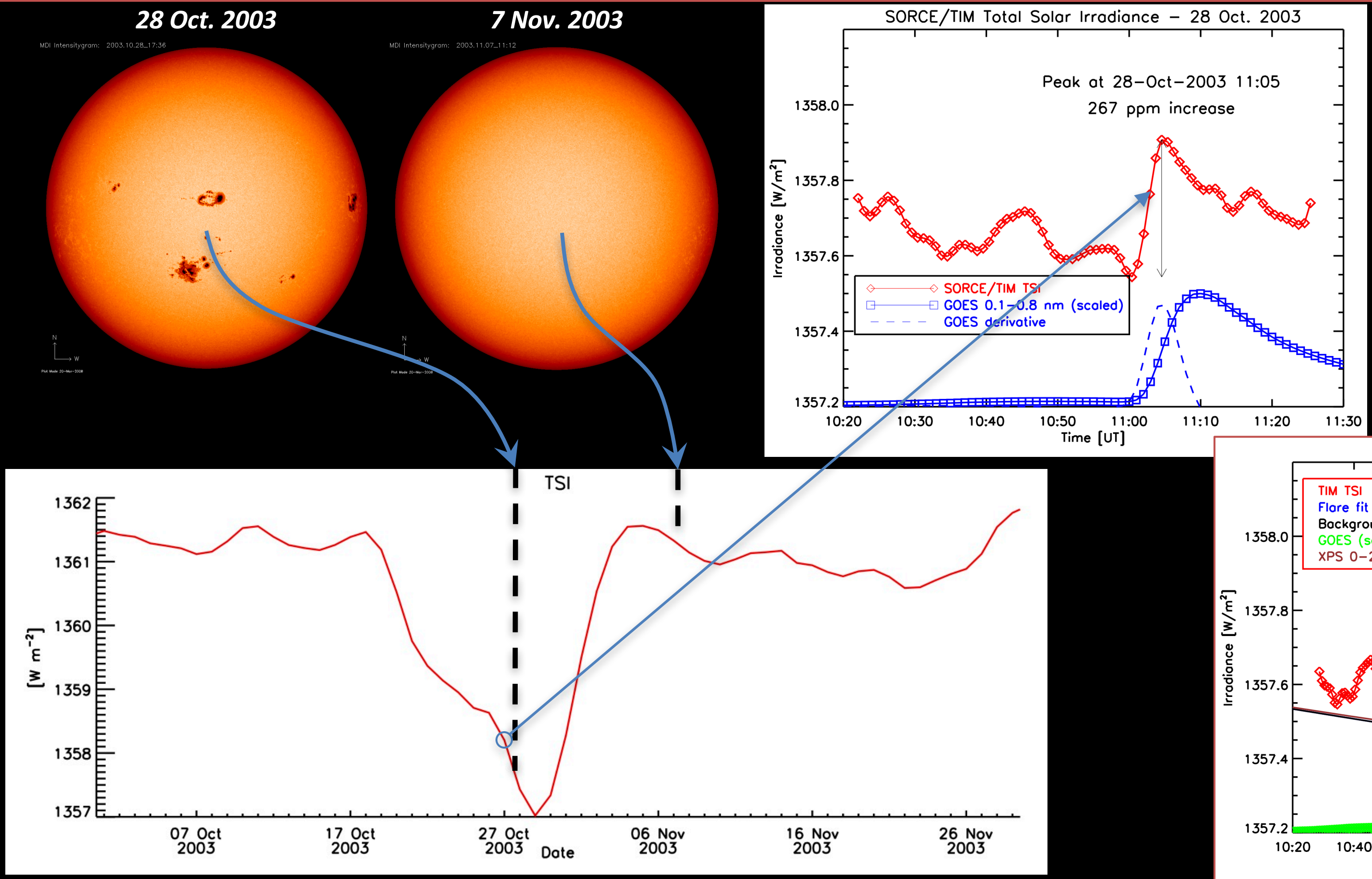
What Is Total Solar Irradiance (TSI)?



- Spatially- and spectrally-integrated radiant power from the Sun per unit area
  - Normalized to 1 AU

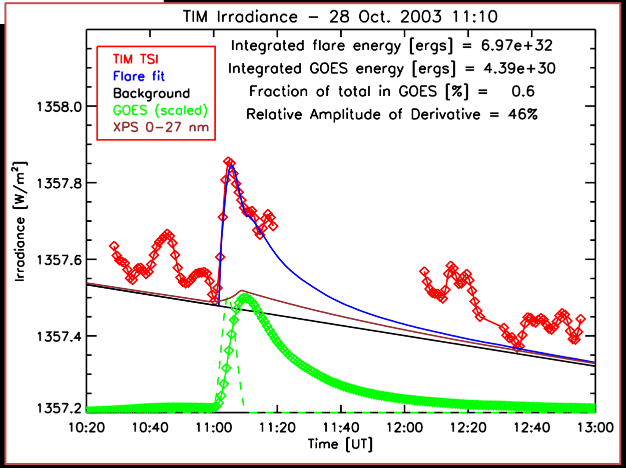

MDI Intensitygram
01–Sep–2003 00:00
SORCE/TIM Irradiance V.17
Irradiance [W m^{-2}]
1363
1362
1361
1360
1359
1358
1357
1356
01 Sep 2003
01 Oct 2003
01 Nov 2003
N
W
Movie created by G. Kopp, 23–Jan–2017

Perspective on Flares Compared to the TSI

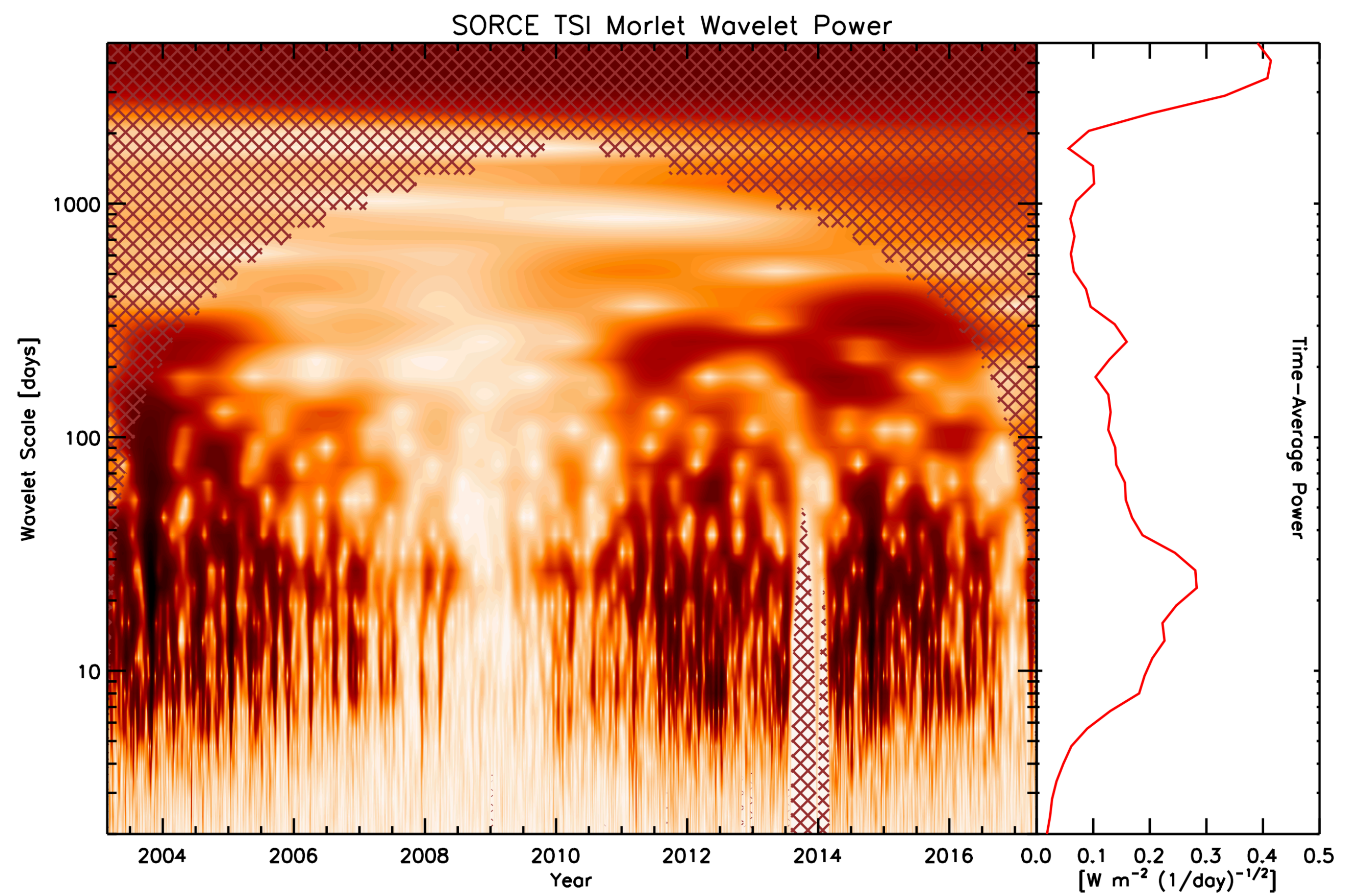


Net flare energy is <0.008% of what the Sun emitted in that ~40-min. time range

Woods et al., 2005

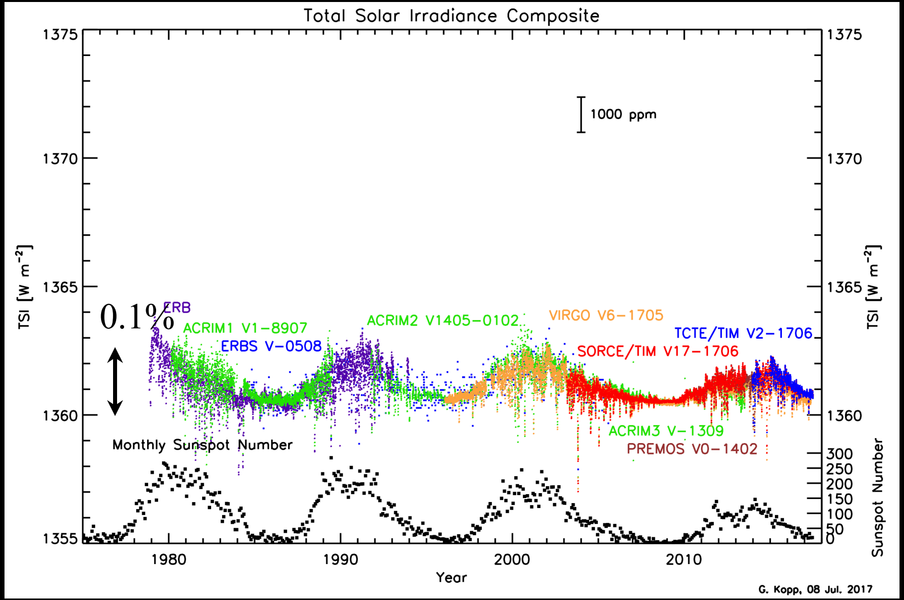


Wavelet Analyses Indicate Timescales of Measured Variability



What Are the Timescales of TSI Variability?

- 0.01% over minutes
- <0.3% over a few days
  - Short duration causes negligible climate effect
- 0.1% over 11-year solar cycle
  - Small but detectable effect on climate
- 0.05-0.3% over centuries (unknown)
  - Direct effect on climate (Maunder Minimum and Europe's Little Ice Age)
- 10^{-10}/yr on evolutionary timescales

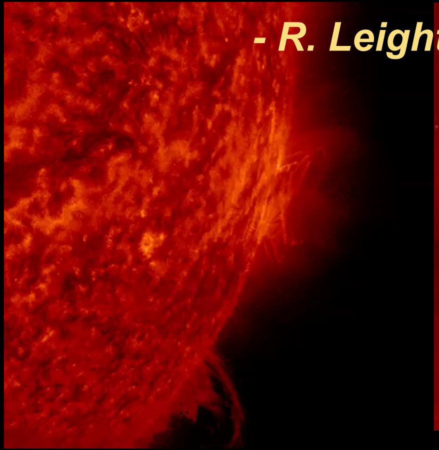


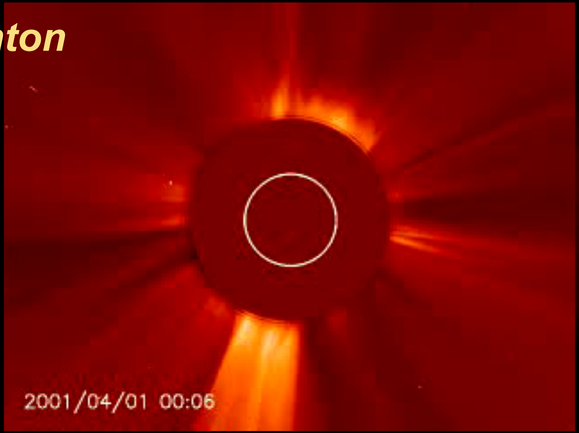
- An unequivocal link between climate change and TSI has been established over the past three decades
  - Magnitude of natural climate forcing needs to be known for setting present and future climate policy regulating anthropogenic forcings
  - Future long-term solar fluctuations, similar to historical variations, are not known from current measurements or TSI proxies

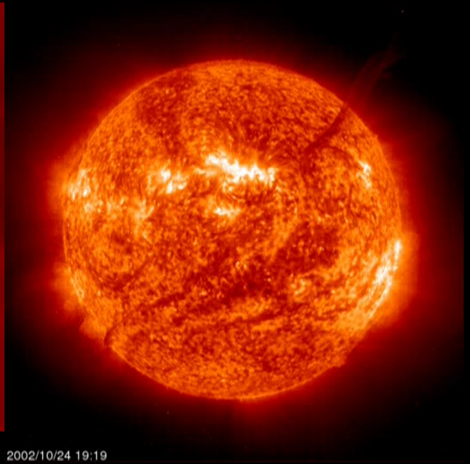
The Sun is Very Different at Different Wavelengths

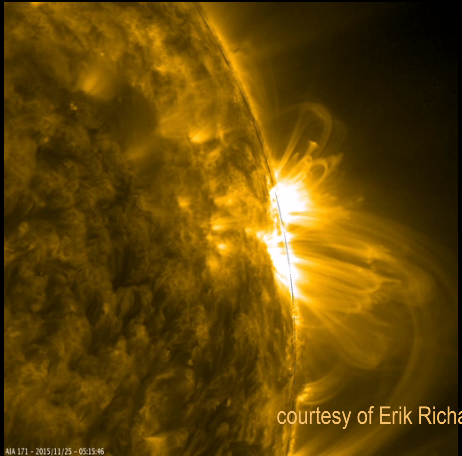
*“If the Sun had no magnetic field…
it would be as boring as most astronomers seem to believe it is”*

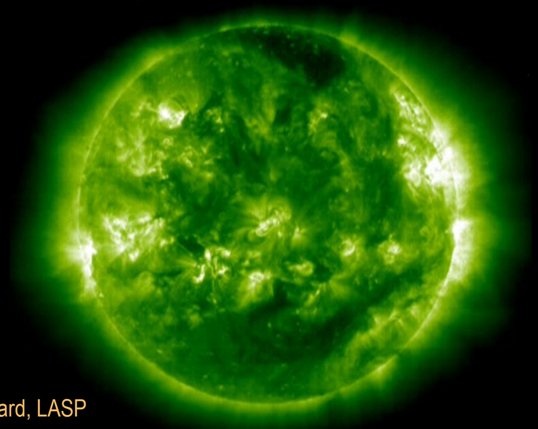
- R. Leighton

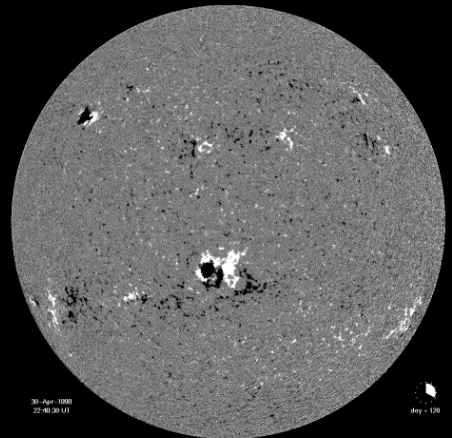






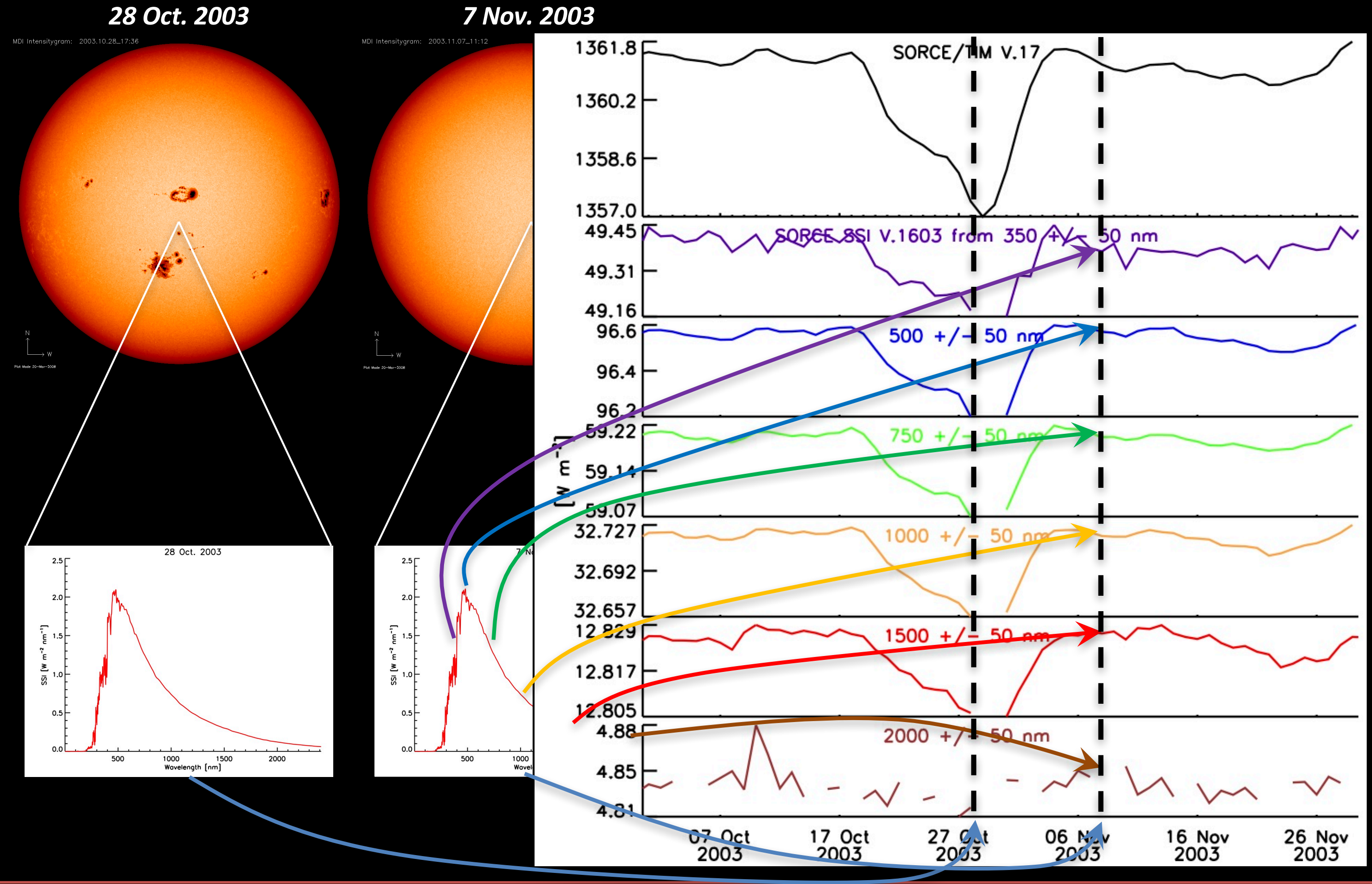




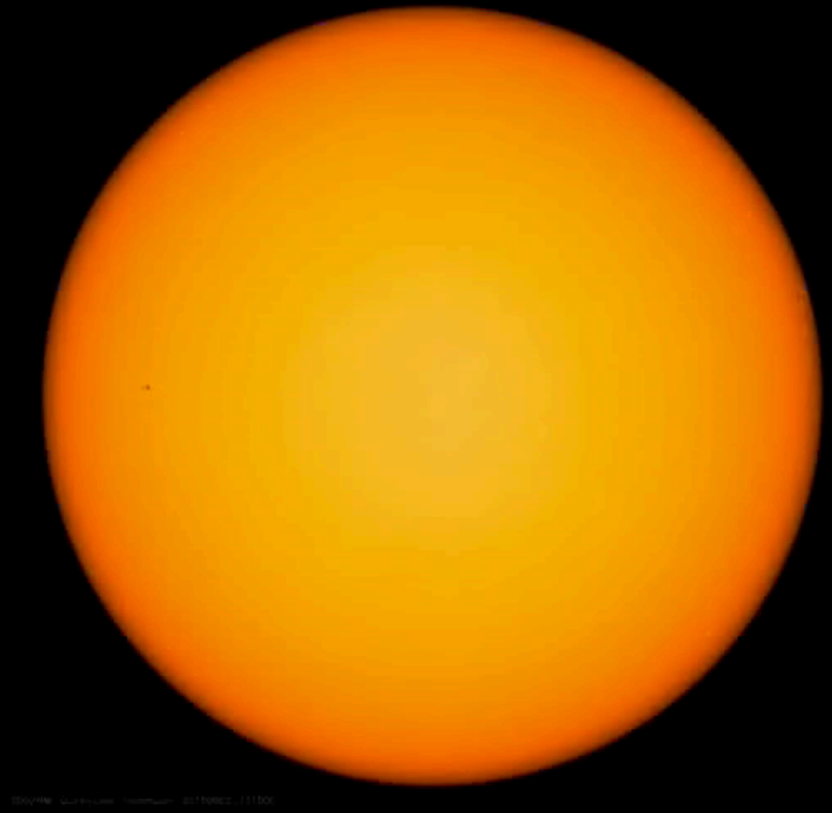


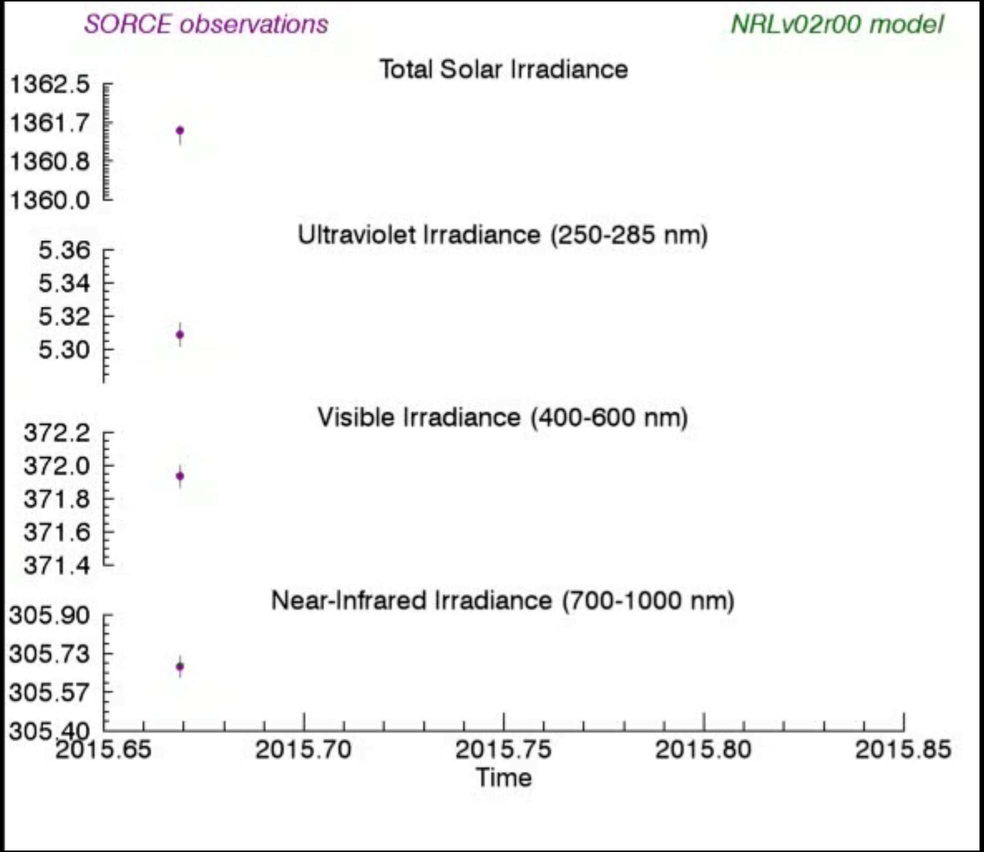
courtesy of Erik Richard, LASP

What Is Spectral Solar Irradiance (SSI)?



Short-Term Spectral-Solar-Irradiance Variability





courtesy of Odele Coddington, LASP

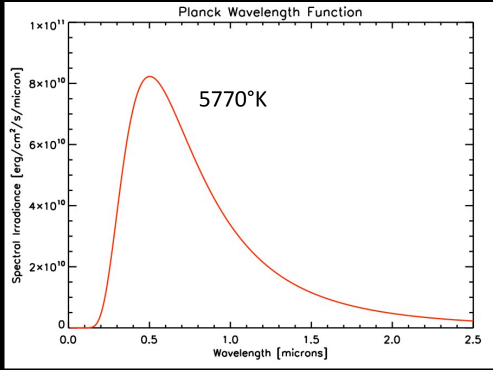
What Is "Irradiance"?

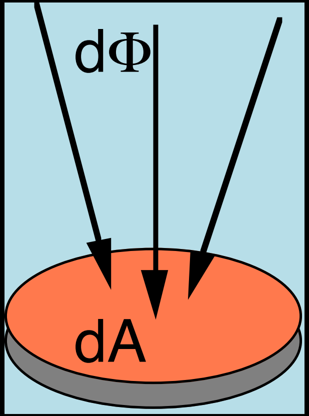
- Integrated radiant flux through an area
  - Total irradiance: spectrally integrated radiant flux through an area

$$E = \frac{d\Phi}{dA}$$

  - Spectral irradiance: radiant flux per wavelength unit through an area

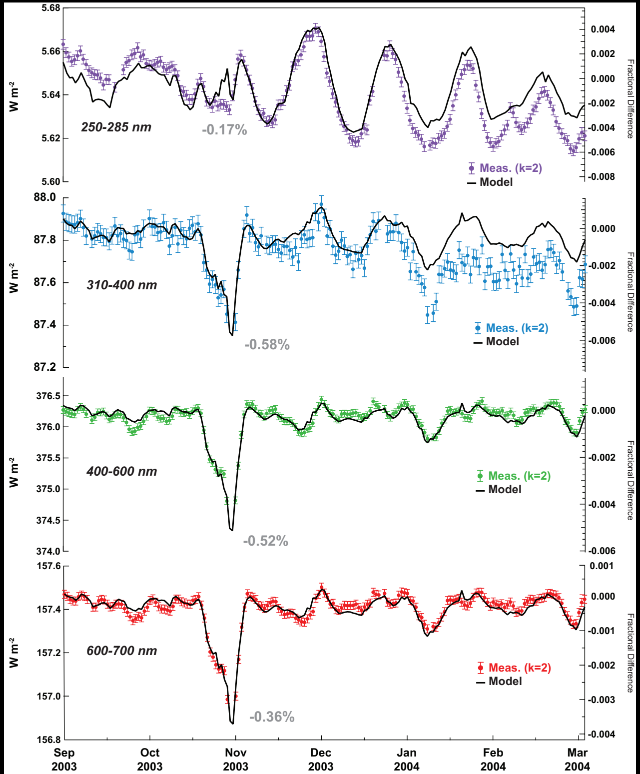
$$E_\lambda = \frac{d^2\Phi}{dA\,d\lambda}$$

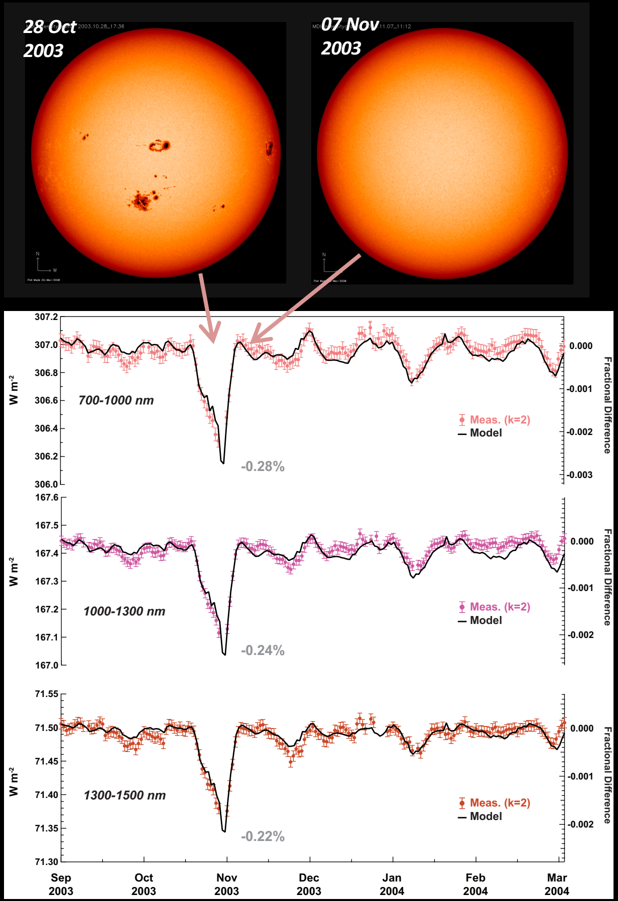




Short-Term Spectral Variability

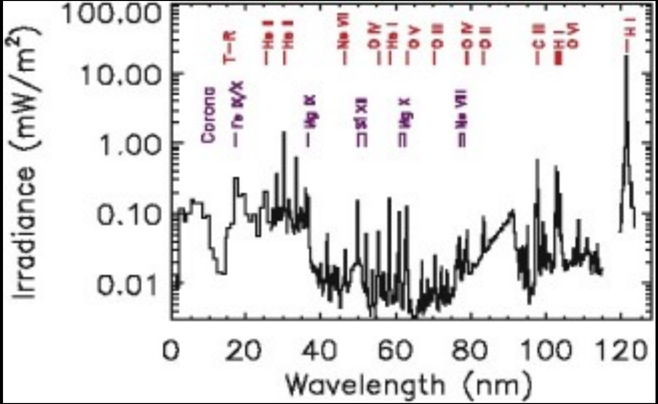
6-month spectral variability around "Halloween Storms"

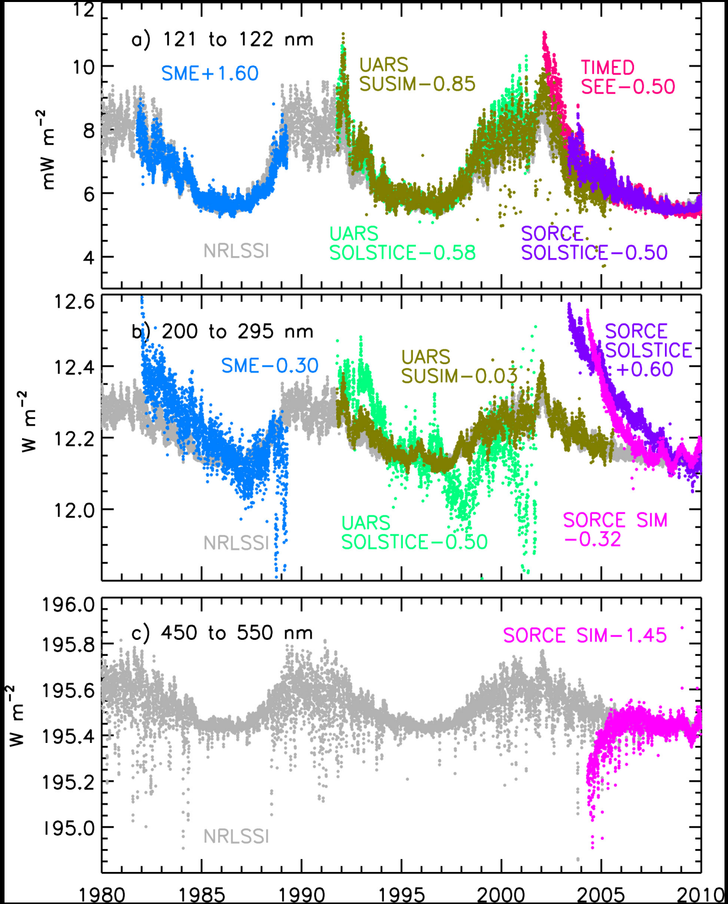




courtesy of Erik Richard, LASP

Measured Spectral Irradiances

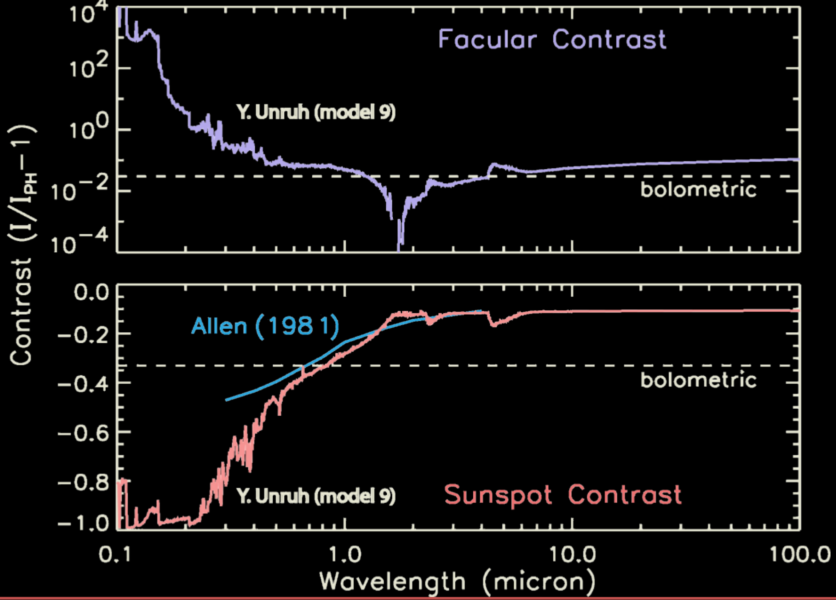


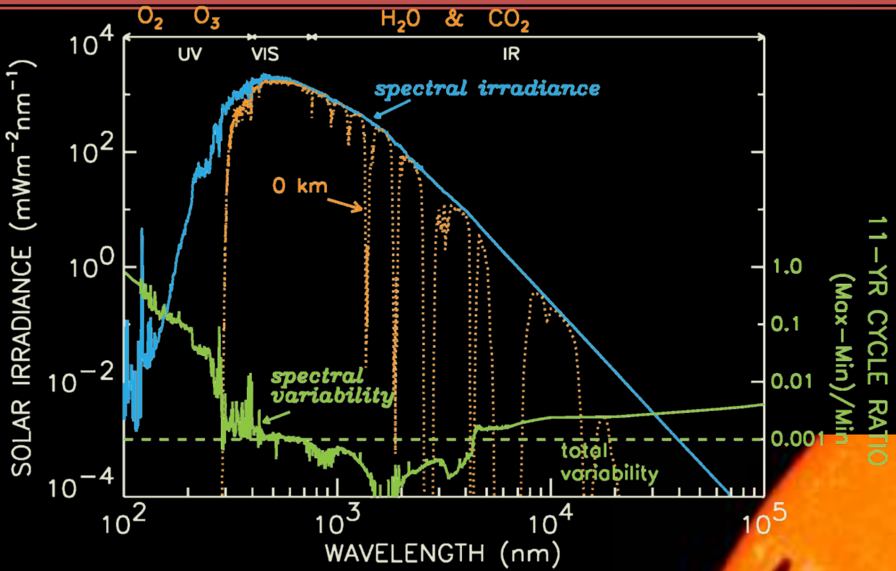


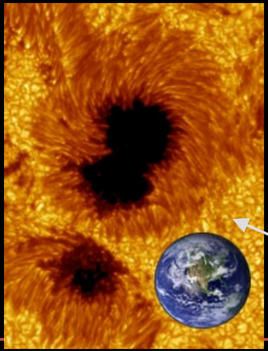
Solar Activity Causes Spectral Irradiance Variations

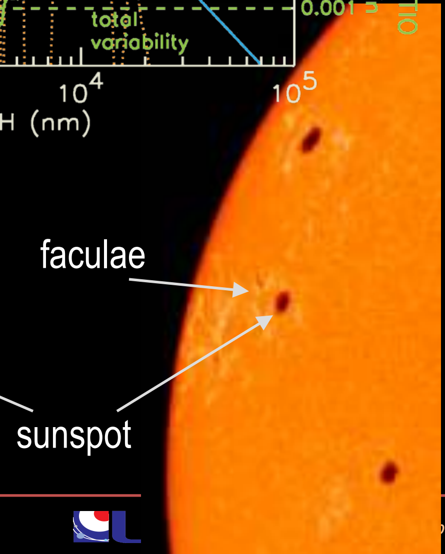
Solar variability sources are wavelength-dependent…

thus, irradiance variations depend on wavelength



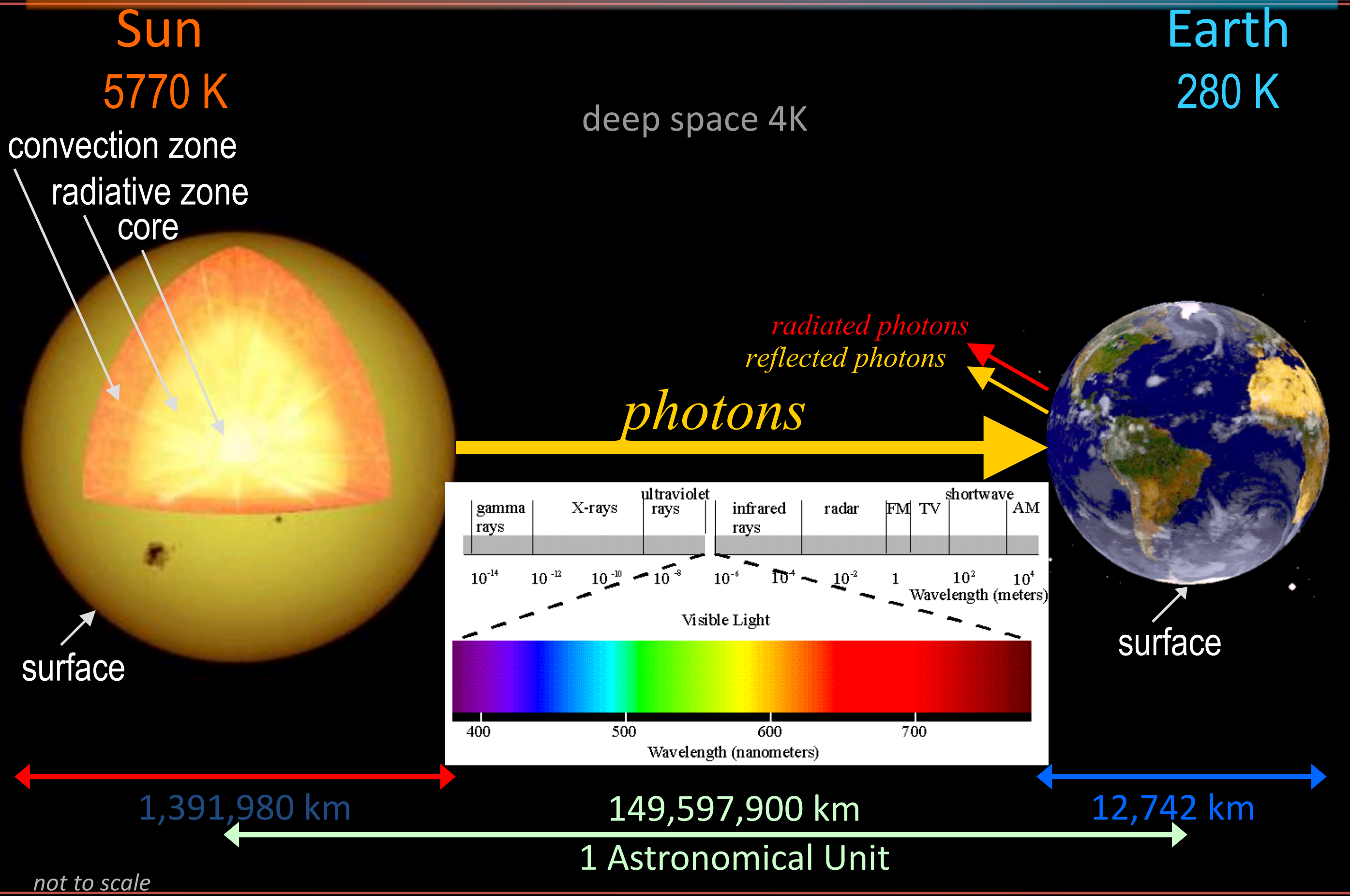






courtesy of Judith Lean, NRL

4.5 billion years



courtesy of Judith Lean, NRL

Problems

- Compute the Earth temperature resulting from 1361 W m^{-2} of total solar irradiance
  - Assume Earth is a grey-body with equal albedo and emissivity

$$\text{Incoming Energy} = \pi R^2 \cdot A \cdot S$$

$$\text{Outgoing Energy} = 4\pi R^2 \cdot \varepsilon \cdot \sigma T^4$$

$$\text{Energy Balance} \Rightarrow T = \sqrt[4]{\frac{A}{\varepsilon}\frac{1}{4\sigma}S} = 280K$$

  - S = 1361 W/m^2
  - T = 278 K

Where Does the Earth Get Its Energy?

Energy Source	Heat Flux* [W m^{-2}]	Uncertainty or Range [W m^{-2}]	Relative Input
Solar Irradiance	**340.2**	**0.0000%**	**1.000E+00**
Secondary Sources of Solar Origin (Total)	**0.0268**		**7.90E-05**
Infrared Radiation from the Full Moon	0.01	-	2.90E-05
Combustion of Coal, Oil, and Gas (in U.S.)	0.0052	-	1.50E-05
Dissipation of Magnetic Storm Energy	0.00362	1.0E-05 to 1.0E-03	1.10E-05
Airglow Emission	0.0036	-	1.10E-05
Sun's Radiation Reflected from Full Moon	0.0018	-	5.30E-06
Energy Generated by Solar Tidal Forces in the Atmosphere	0.00168	-	4.90E-06
Energy Dissipated in Lightning Discharges	4.95E-04	9.0E-05 to 9.0E-04	1.50E-06
Auroral Emission	3.70E-04	1.0E-05 to 1.0E-03	1.10E-06
Zodiacal Irradiance	5.67E-05	5.65E-05 to 5.68E-05	1.70E-07
Earthshine	1.93E-07	-	5.70E-10
Secondary Sources of Non-Solar Origin (Total)	**0.0900**		**2.60E-04**
Heat Flux from Earth's Interior	0.09	± 0.006	2.60E-04
Energy Generated by Lunar Tidal Forces in the Atmosphere	1.96E-05	-	5.80E-08
Galactic Cosmic Rays	8.50E-06	7.0E-06 to 1.0E-05	2.50E-08
Total Radiation from Stars	6.78E-06	5.62E-06 to 7.94E-06	2.00E-08
Cosmic Microwave Radiation Background	3.13E-06	±2.62E-09	9.20E-09
Dissipation of Mechanical Energy from Micrometeorites	1.10E-06	1.9E-08 to 2.0E- 06	3.20E-09
Total of All Secondary Energy Sources	**0.1169**		**3.39E-04**

* global average

Total Input (relative)	1.000E+00
Temperature [°K]	278
[°F]	42

3000 X

*Greenhouse gases are not an energy **source**.*

from "Where does Earth's atmosphere get its energy?" by A.C. Kren, P. Pilewskie, and O. Coddington, *Space Weather and Space Climate,* 2017

Problems

- Compute Earth's temperature due to:
  - Solar radiation; and
  - Earth's internal energy sources alone

$$\text{Incoming Energy} = \pi R^2 \cdot A \cdot S$$
$$\text{Outgoing Energy} = 4\pi R^2 \cdot \varepsilon \cdot \sigma T^4$$
$$\text{Energy Balance} \Rightarrow T = \sqrt[4]{\frac{A}{\varepsilon}\frac{1}{4\sigma}S} = 280K$$

  - $\sigma = 0.567 \times 10^{-4}$ erg s^{-1} cm^{-2} K^{-4} = 0.567×10^{-7} W m^{-2} K^{-4}
  - Sun's radiation $S_S = 1361$ W/m^2 T = 278 K
  - Earth's internal sources $S_E = 2.6 \times 10^{-4}\, S_S$ T = 35 K

What If We Didn't Have the Sun?

Energy Source	Heat Flux* [W m^{-2}]	Uncertainty or Range [W m^{-2}]	Relative Input
Solar Irradiance	340.2	0.0000%	1.000E+00
Secondary Sources of Solar Origin (Total)	0.0268		7.90E-05
Infrared Radiation from the Full Moon	0.01	-	2.90E-05
Combustion of Coal, Oil, and Gas (in U.S.)	0.0052	-	1.50E-05
Dissipation of Magnetic Storm Energy	0.00362	1.0E-05 to 1.0E-03	1.10E-05
Airglow Emission	0.0036	-	1.10E-05
Sun's Radiation Reflected from Full Moon	0.0018	-	5.30E-06
Energy Generated by Solar Tidal Forces in the Atmosphere	0.00168	-	4.90E-06
Energy Dissipated in Lightning Discharges	4.95E-04	9.0E-05 to 9.0E-04	1.50E-06
Auroral Emission	3.70E-04	1.0E-05 to 1.0E-03	1.10E-06
Zodiacal Irradiance	5.67E-05	5.65E-05 to 5.68E-05	1.70E-07
Earthshine	1.93E-07	-	5.70E-10
Secondary Sources of Non-Solar Origin (Total)	**0.0900**		**2.60E-04**
Heat Flux from Earth's Interior	0.09	± 0.006	2.60E-04
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Dissipation of Mechanical Energy from Micrometeorites	1.10E-06	1.9E-08 to 2.0E- 06	3.20E-09
Total of All Secondary Energy Sources	**0.1169**		**3.39E-04**

* global average

from "Where does Earth's atmosphere get its energy?" by A.C. Kren, P. Pilewskie, and O. Coddington, *Space Weather and Space Climate,* 2017

Total Input (relative)	2.601E-04
Temperature [˚K]	35
[˚F]	-396

The Sun Is THE Dominant Driver of Earth's Climate

Fortunately, this 800 lb gorilla is very placid

Energy Source	Heat Flux* [W m^{-2}]	Uncertainty or Range [W m^{-2}]	Relative Input
Solar Irradiance	**340.2**	**0.0000%**	**1.000E+00**
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Zodiacal Irradiance	5.67E-05	5.65E-05 to 5.68E-05	1.70E-07
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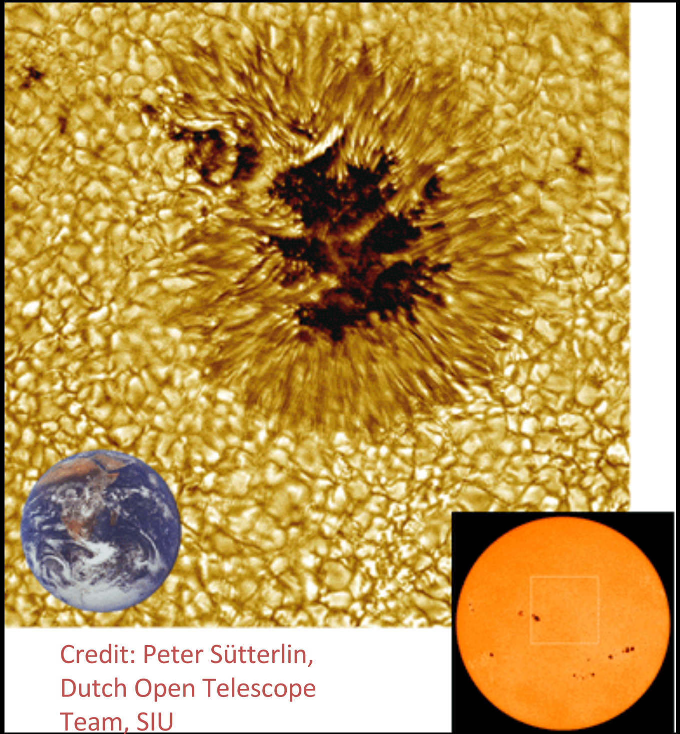
Secondary Sources of Non-Solar Origin (Total)	**0.0900**		**2.60E-04**
Heat Flux from Earth's Interior	0.09	± 0.006	2.60E-04
Energy Generated by Lunar Tidal Forces in the Atmosphere	1.96E-05	-	5.80E-08
Galactic Cosmic Rays	8.50E-06	7.0E-06 to 1.0E-05	2.50E-08
Total Radiation from Stars	6.78E-06	5.62E-06 to 7.94E-06	2.00E-08
Cosmic Microwave Radiation Background	3.13E-06	±2.62E-09	9.20E-09
Dissipation of Mechanical Energy from Micrometeorites	1.10E-06	1.9E-08 to 2.0E- 06	3.20E-09
Total of All Secondary Energy Sources	**0.1169**		**3.39E-04**
* global average			

from "Where does Earth's atmosphere get its energy?" by A.C. Kren, P. Pilewskie, and O. Coddington, *Space Weather and Space Climate,* 2017

Sunspots

- Dark, “cool” regions - 4000° K (as opposed to 6000° K)
- Magnetically active (~4000 Gauss fields)
- Sites of flares commonly
- Duration
  - Days to months



Credit: Peter Sütterlin, Dutch Open Telescope Team, SIU

History - Sunspots

1610-1801 - Explanations of sunspots

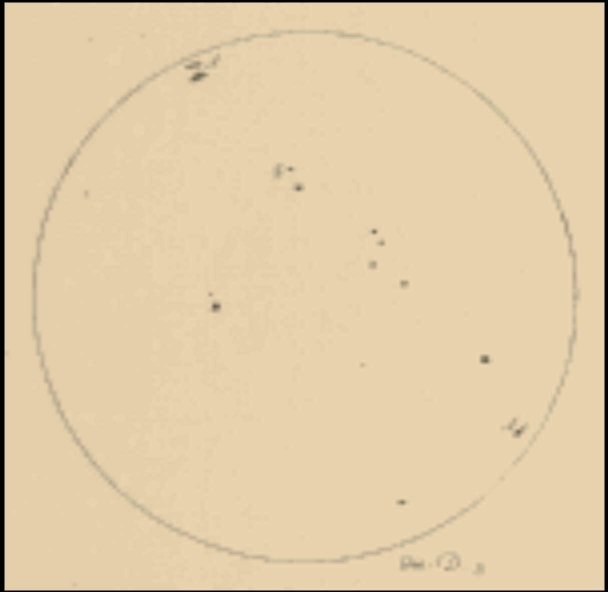
- **Galileo Galilei** (1564-1642) - *cloud-like structures in the solar atmosphere*
- **Christoph Scheiner** (1575-1650) - *intra-Mercurial objects; dense objects embedded in the Sun's luminous atmosphere*
- **René Descartes** (1596-1650) - *floating aggregates of etheral matter accreted along the Sun's rotational axis, where centrifugal forces are negligible*
- **William Herschel** (1738-1822) & **A. Wilson** in 1774 - *openings in the Sun's luminous atmosphere, allowing a view of the underlying, cooler surface of the Sun (which was likely inhabited)*

Herschel [1801]: Correlated the price of wheat in London with the number of visible sunspots, attributing the connection to reduced rainfall when the Sun was less spotted

History - Use of Telescope

1610 - First telescopic observations of sunspots

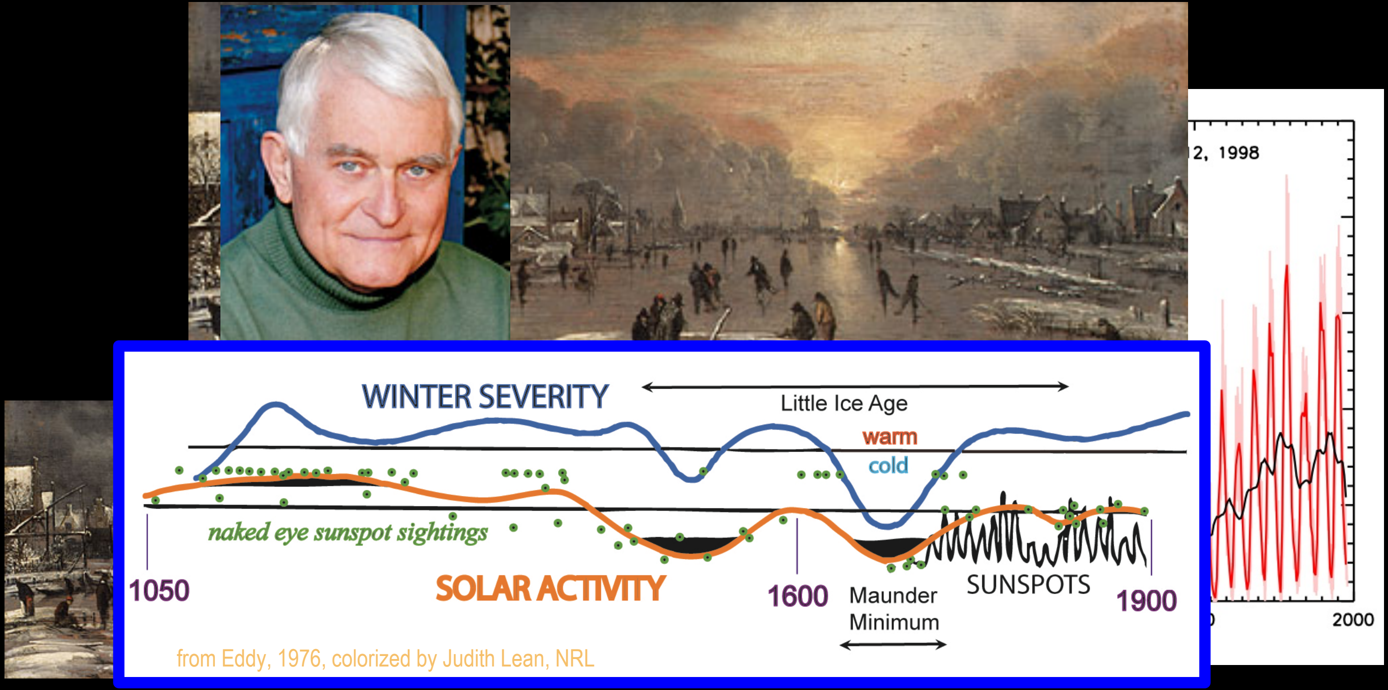
- Johann Goldsmid (1587-1616) in Holland
- Thomas Harriot (1560-1621) in England
- Galileo Galilei (1564-1642) in Italy
- Christoph Scheiner (1575-1650) in Germany



History – Europe's Little Ice Age

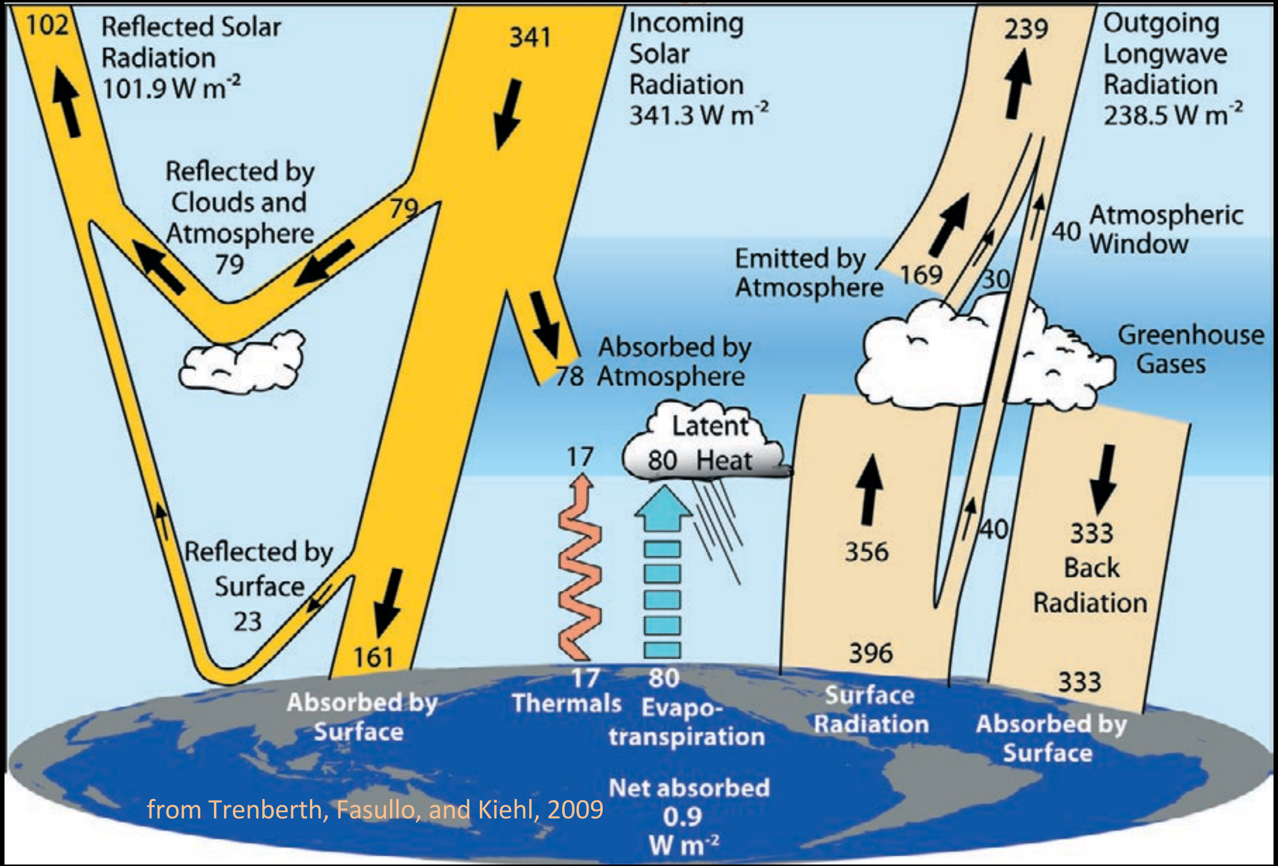
1645-1715 – Maunder Minimum

– Solar output decreased 0.1-0.3% for 70 years
– Earth temperatures were ~0.2-0.4 C colder than the early 1900s



What Determines Climate?

Shortwave | Total Solar Irradiance | Infrared



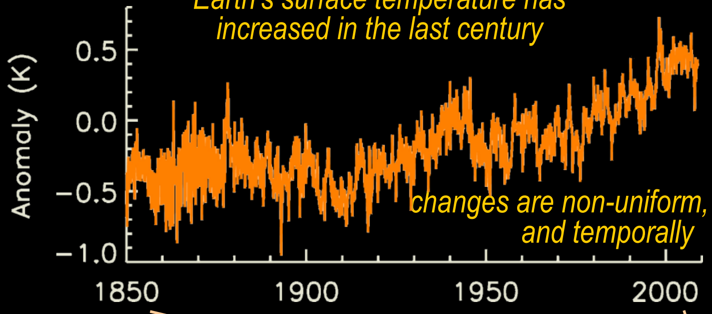
from Trenberth, Fasullo, and Kiehl, 2009

What Is Climate?

- Climate – the total of all statistical weather information that helps to describe the variation of weather at a given place for a specified interval of time. In popular usage, the synthesis of weather at some locality averaged over some time period (usually 30 years) plus statistics to include extremes in weather.
- " 'Climate' is what you expect; 'weather' is what you get." [Gary Rottman, 2003]

Temperatures Are Changing

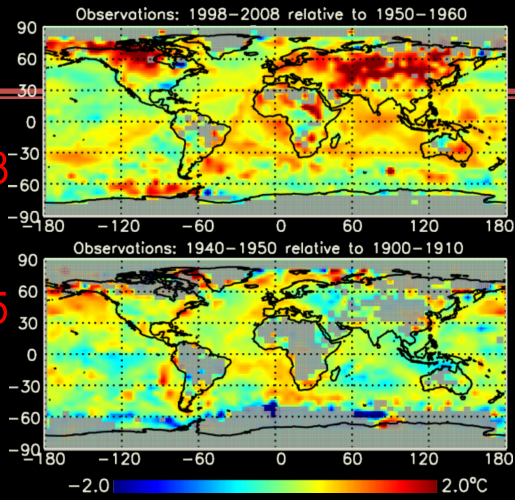
Earth's surface temperature has increased in the last century



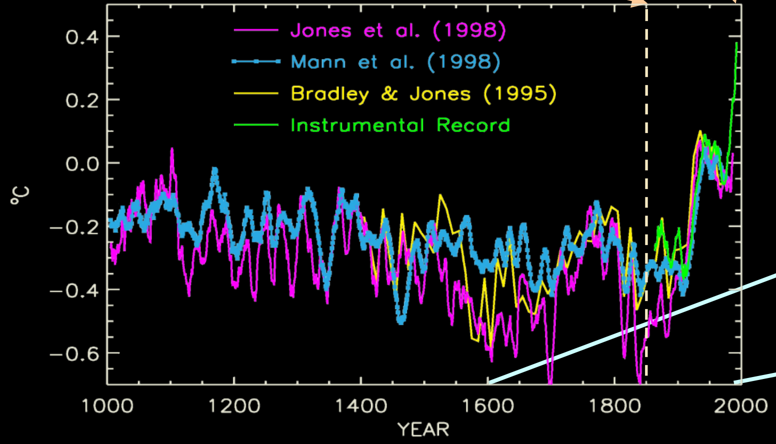
changes are non-uniform, globally and temporally

1955-2003

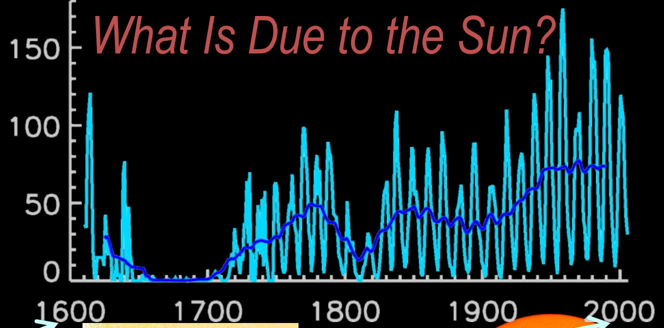
1905-1945

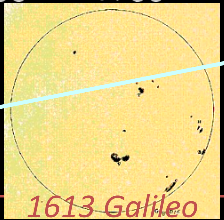


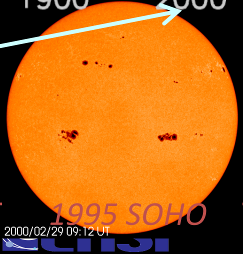
http://ftp.cru.uea.ac.uk/



courtesy of Judith Lean, NRL







There Are Many Causes of Climate Change

Natural Forcings

- solar variability - *direct and indirect effects*
- volcanic eruptions - *stratospheric aerosols*

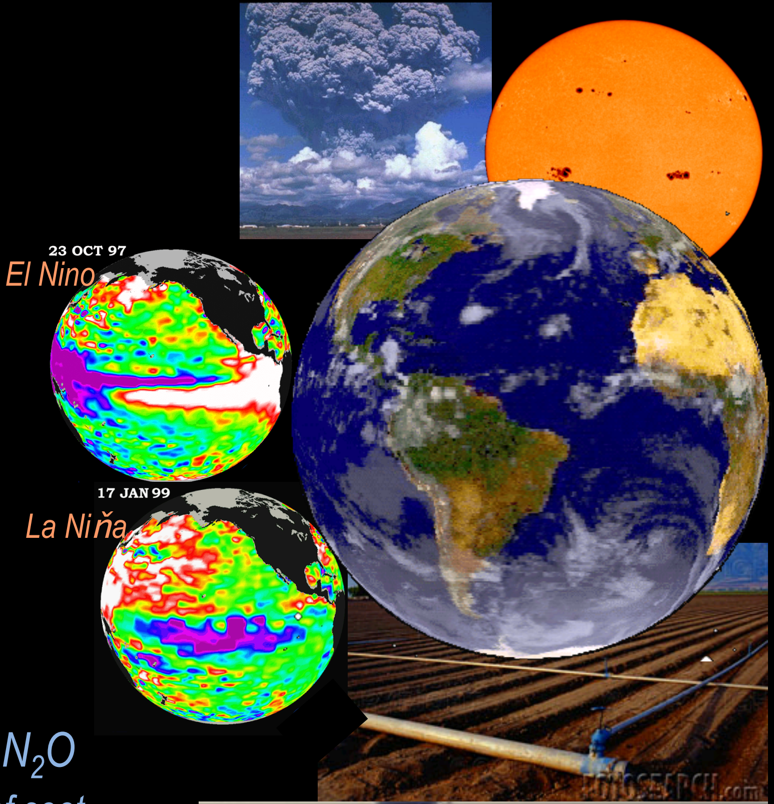
Internal Oscillations

- atmosphere-ocean couplings
  - *El Niño Southern Oscillation (ENSO)*
  - *North Atlantic Oscillation (NAO)*

Land Cover Changes

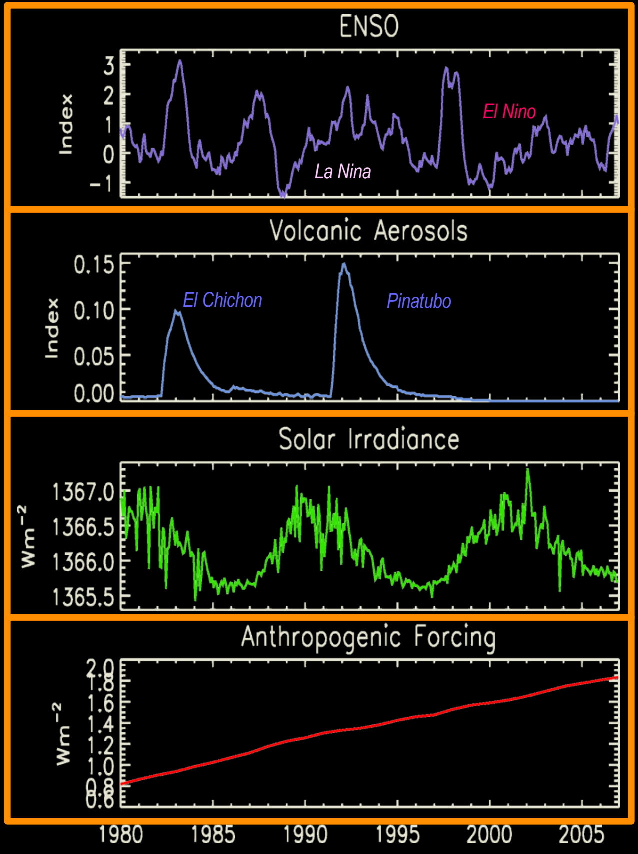
Anthropogenic Forcings

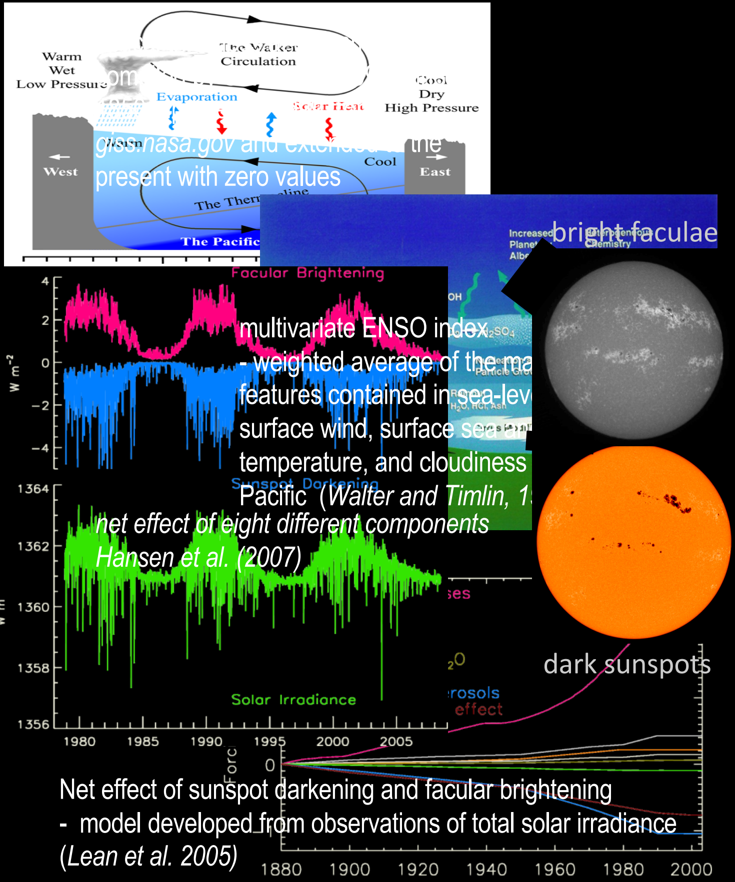
- atmospheric GH gases - *CO_2, CH_4, CFCs, O_3, N_2O*
- tropospheric aerosols - *direct and indirect effects of soot, sulfate, carbon, biomass burning, soil dust*



courtesy of Judith Lean, NRL

Climate Influences





multivariate ENSO index
- weighted average of the ma… features contained in sea-lev… surface wind, surface sea air temperature, and cloudiness … Pacific (*Walter and Timlin, 1…*

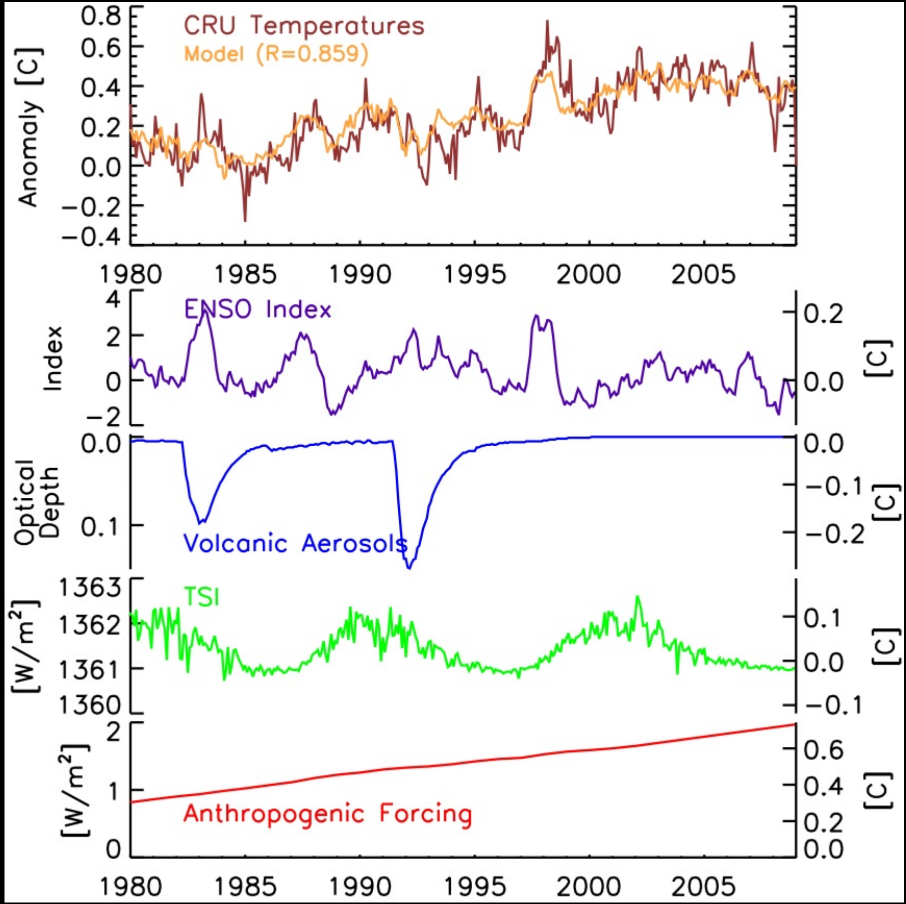
giss.nasa.gov and extended to the present with zero values

net effect of eight different components Hansen et al. (2007)

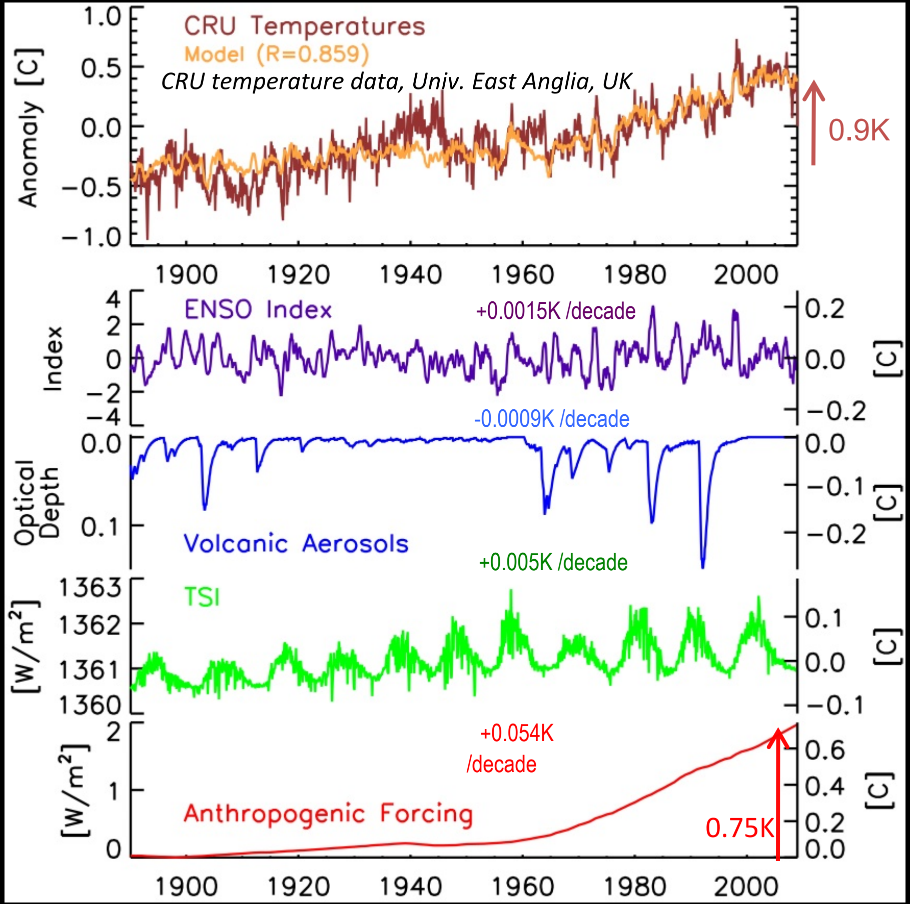
Net effect of sunspot darkening and facular brightening
- model developed from observations of total solar irradiance (*Lean et al. 2005*)

courtesy of Judith Lean, NRL

"Components" of Global Temperatures



Global Surface Temperature Responses Since 1890

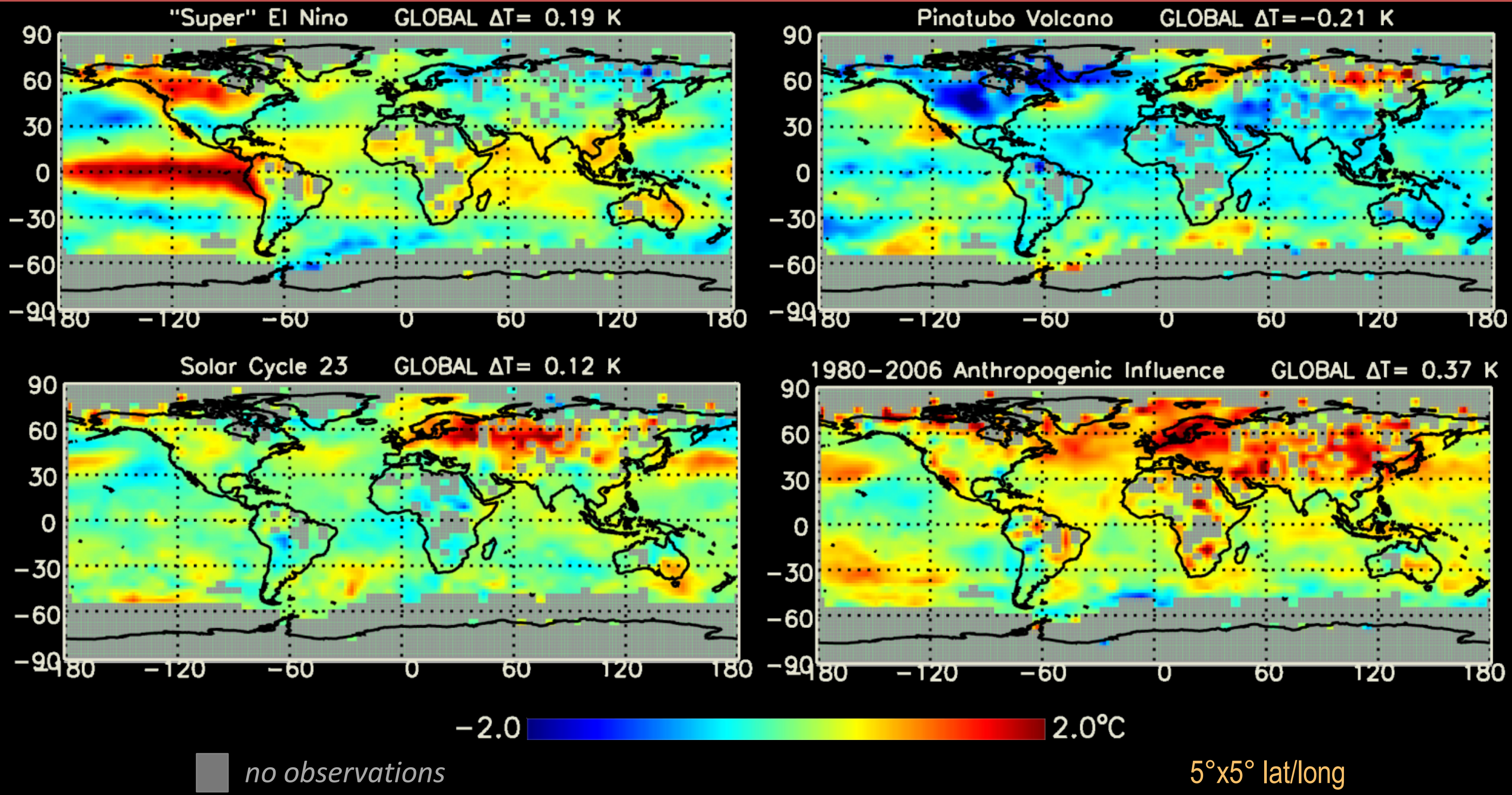


Decompositions of historical and recent global surface temperatures give consistent individual natural and anthropogenic components:

Natural components account for <15% of warming since 1890

courtesy of Judith Lean, NRL

Regional Annual Response Patterns



5°x5° lat/long

courtesy of Judith Lean, NRL

Problems

- Compute the sensitivity of Earth's temperature to TSI variations
  - Compute the expected temperature changes for a 0.04% lower Maunder Minimum TSI value
  - Compute the expected temperature changes for a 0.1% higher solar maximum TSI value (assuming the climate system has time to respond)

$$\text{Energy Balance} \Rightarrow T = \sqrt[4]{\frac{A}{\varepsilon}\frac{1}{4\sigma}S} = 280K$$

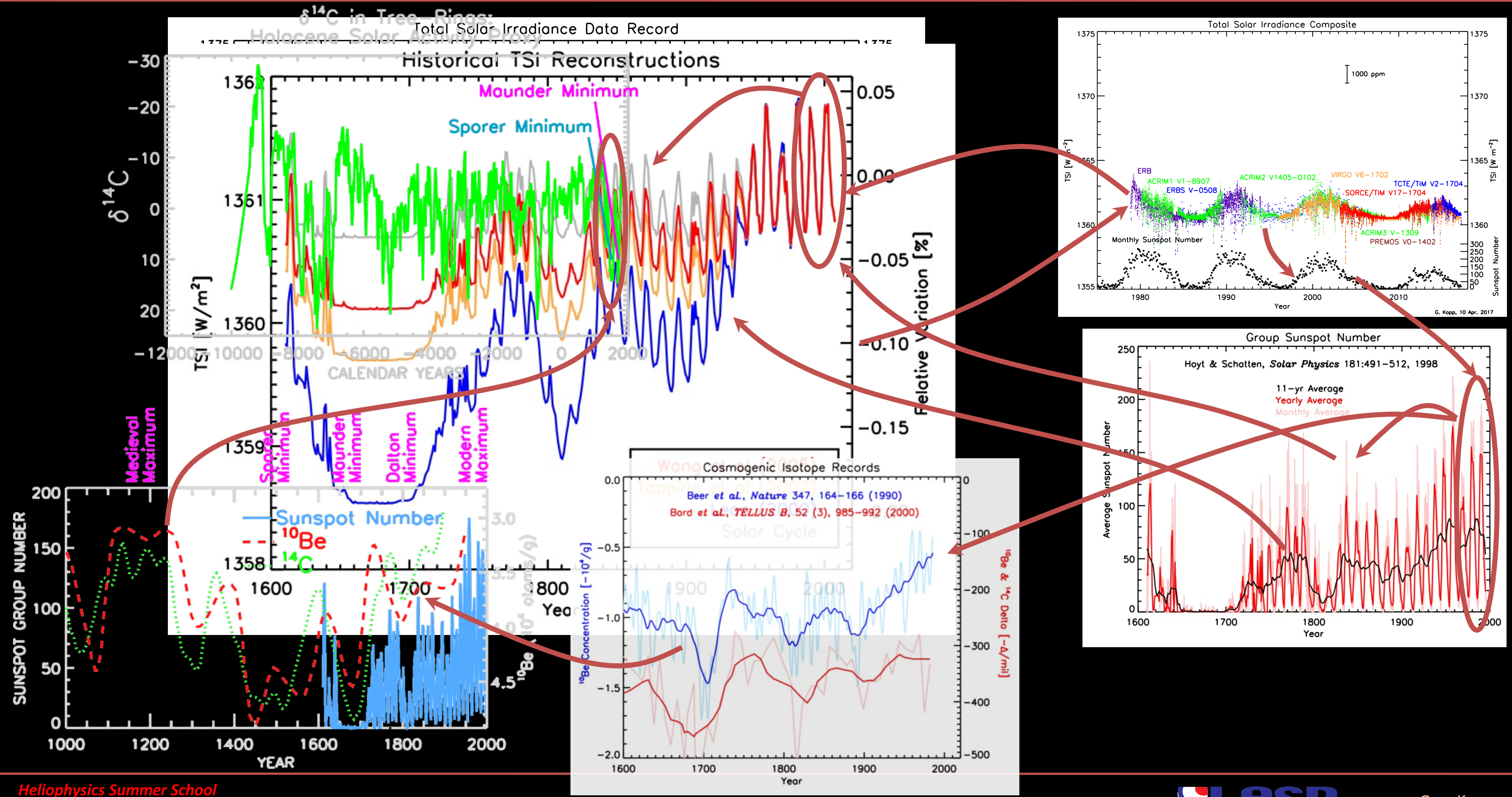
$$\Delta T = \frac{dS}{4S} \cdot T$$

  - 1) ΔT = -0.028 C
  - 2) ΔT = 0.070 C
  - Sensitivity κ = ΔT/ΔS = 0.051 C per W/m^2
    (neglects x4 global average)

What Do You Need for a Climate Data Record?

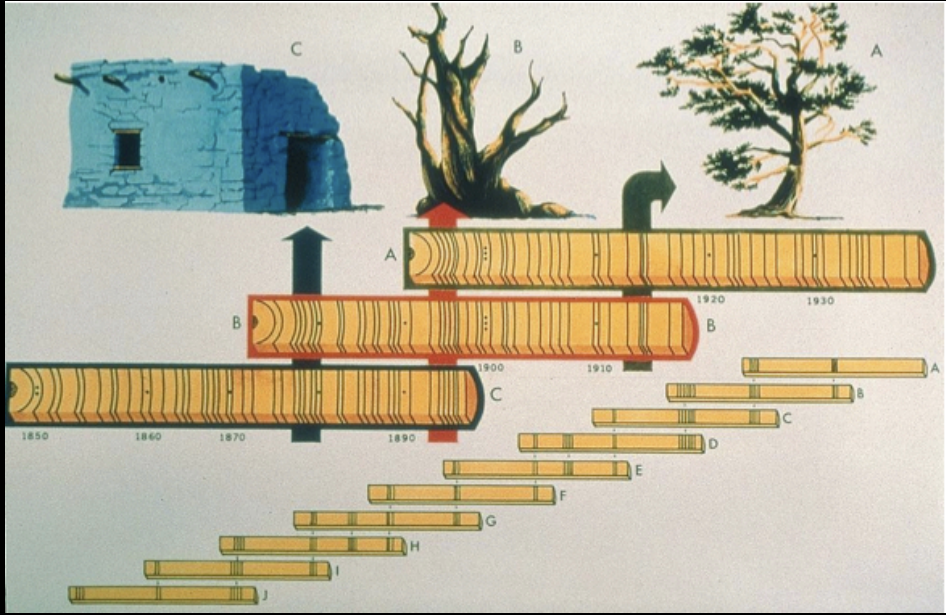
- Accurate measurements over long (climate scale) time periods
  - How accurate? How long?
    - Must detect small changes above natural fluctuations
    - Need estimates of expected variability
  - Drives modeling capability
  - Drives measurement stability and duration
- Patience...
  - ...Or a historical record...

Historical TSI Reconstructions Rely on Proxies

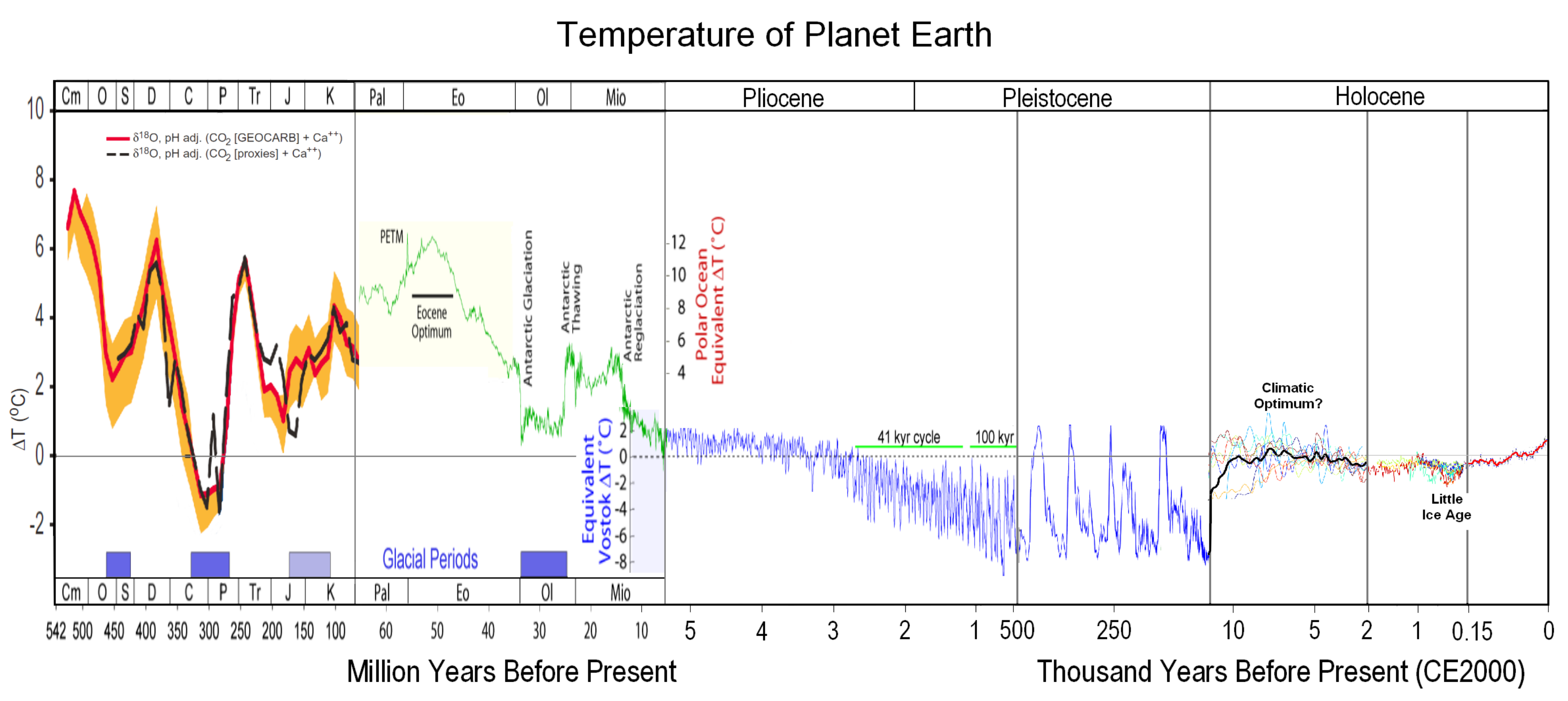


Climate Records Similarly Rely on Proxies

- Ice core samples (trapped air, dust, volcanoes)
- Tree rings (moisture, temperature, existence of plants, fires)
- Sea surface levels and ocean sedimentation (dust, ice floas)
- Rocks and sedimentation, corals, microfossils

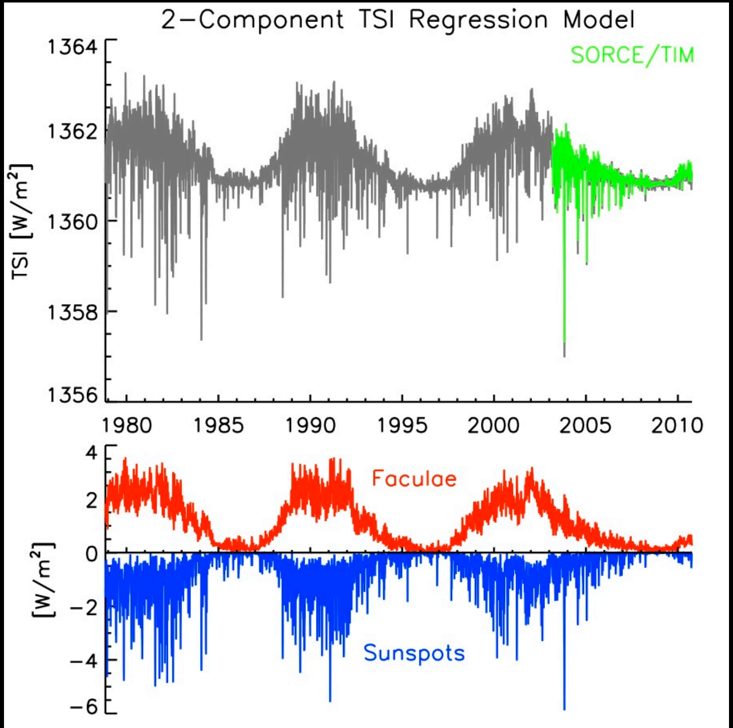


Paleo-Climate Temperatures



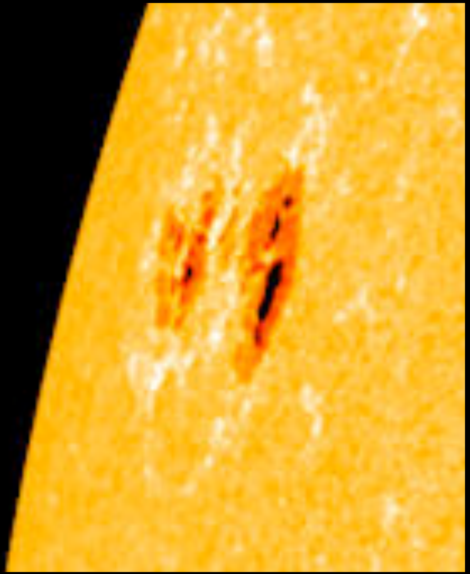
Models of Solar Irradiance Variations

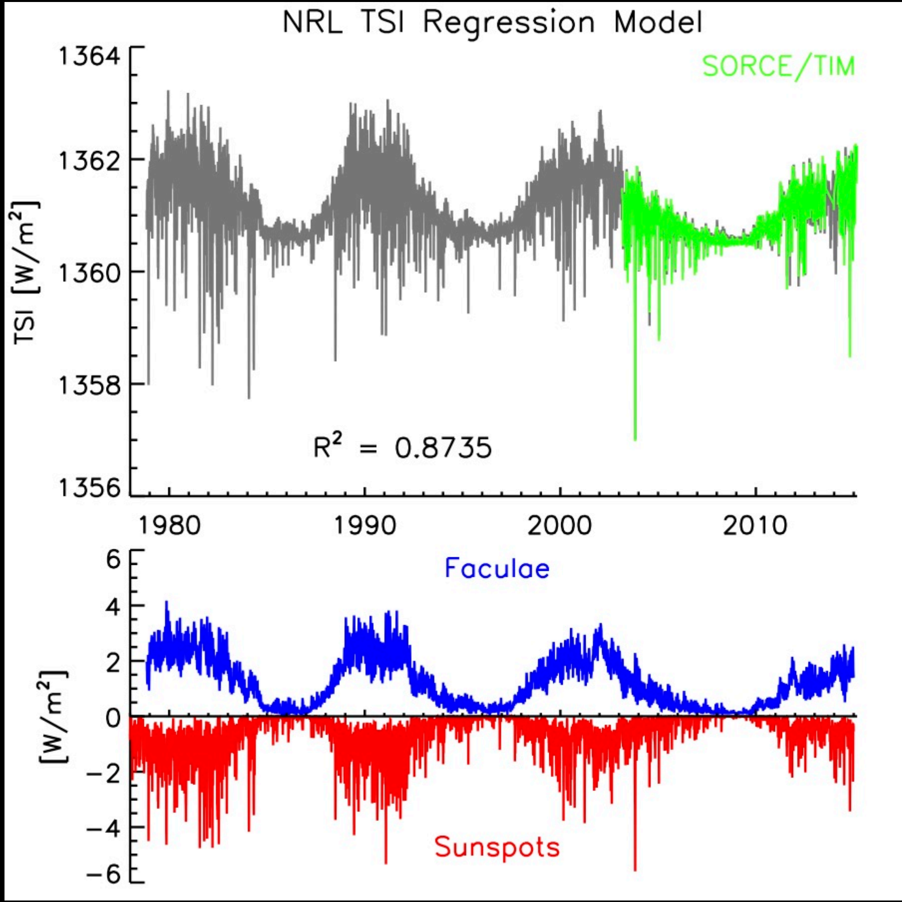
- Empirical (regression)
  - TSI with sunspots and faculae (or other solar activity proxies)
  - SSI below 300 nm less sensitive to sunspot darkening
- Physical
  - Atomic processes and solar atmospheric models
- Summary of effectiveness
  - Good for short-term variations, poor for long-term (secular)



Proxy Models of TSI Variations

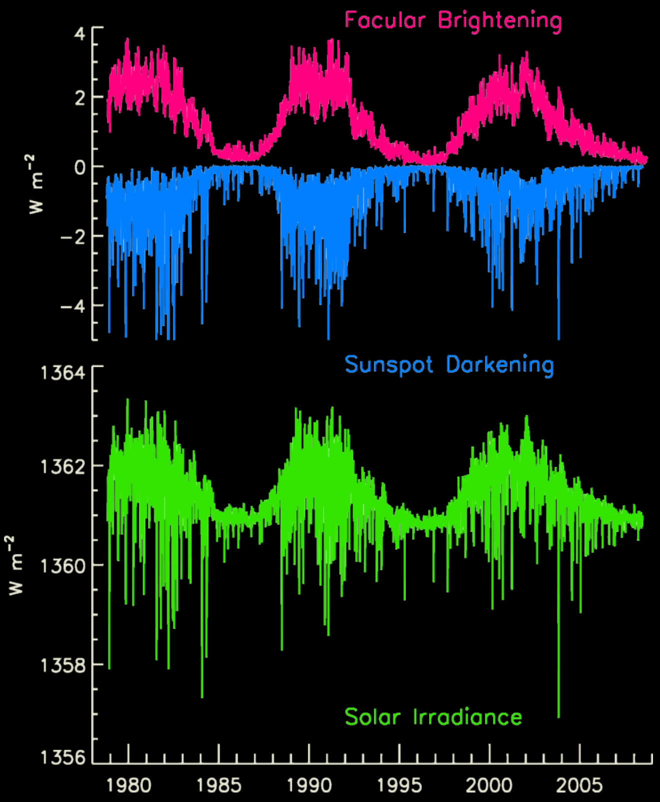
- NRLTSI2 model has two components:
  - Bright faculae
    - e.g. Mg II C/W index
  - Dark sunspots
    - e.g. sunspot area





courtesy of Judith Lean, NRL

Sunspots and Faculae



Net effect of sunspot darkening and facular brightening - model developed from observations of total solar irradiance (*Lean et al. 2005*)

courtesy of Judith Lean, NRL

Proxy Models of SSI Variations

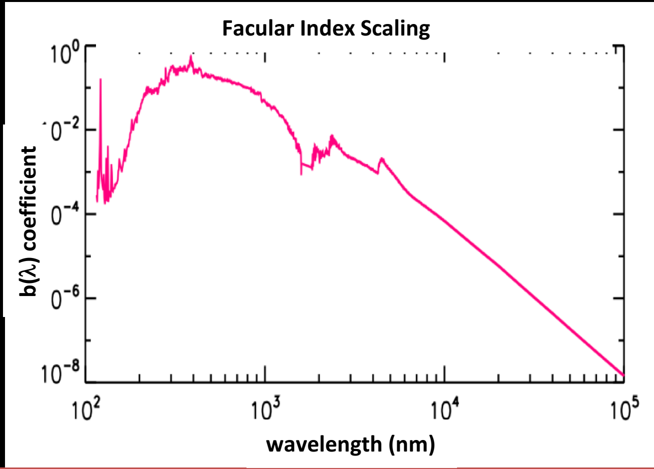
Naval Research Lab. Solar Spectral Irradiance (NRLSSI: Lean 1990, 2005, 2015)

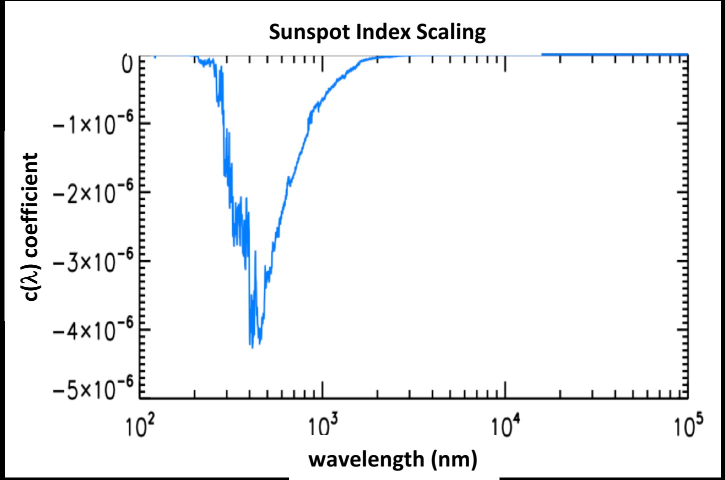
Determines wavelength-dependence of rotational modulation by multiple regression of SORCE/SSI with facular and sunspot indices

$$F(\lambda,t)-F(\lambda)_{smooth} = a(\lambda) + b(\lambda)\times[Mg(t)-Mg_{smooth}] + c(\lambda)\times[S(t)-S_{smooth}]$$

Uncertainties in modeled SSI scale with solar activity, including

- *Absolute-scale uncertainty of Quiet Sun reference*
- *Scaling-coefficient statistical uncertainties*
- *Facular-brightening & sunspot-darkening value uncertainties*





courtesy of Erik Richard, LASP

Climate Model Response to Radiative Forcing

surface temperature change ↘ *forcing* ↓

$$\Delta T = \kappa F$$

↗ *climate sensitivity*

IPCC range: 0.2-1°C per Wm^{-2}
paleoclimate: 0.75°C per Wm^{-2}
Hansen, 2004

Anthropogenic Influence

$\Delta T = 0.4°C$ (1980-2006)
$F = 1\ Wm^{-2}$ (total, not all radiative)
$\therefore\ \kappa \approx 0.4°C$ per Wm^{-2}

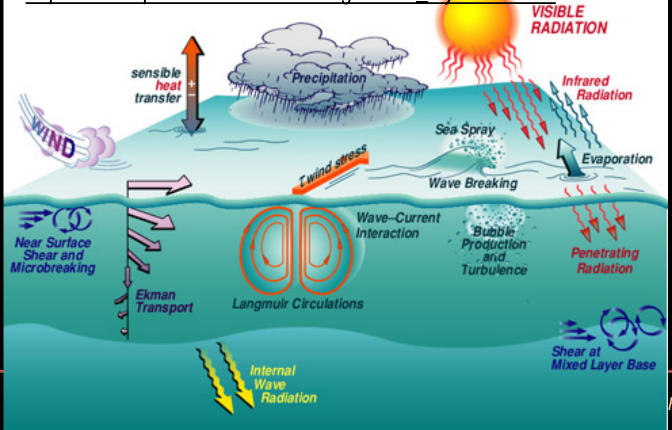
BUT…. response to cyclic decadal forcing is assumed to be attenuated by ~ 5× compared with "equilibrium" response

Current understanding assumes that climate response to solar radiative forcing is thermodynamic --
BUT empirical evidence suggests it
…. is dynamic, rather than (or as well as) thermodynamic
… engages existing circulation patterns (Hadley, Ferrel, and Walker cells) and atmosphere- ocean interactions (ENSO)
… involves both direct (surface heating) and indirect (stratospheric influence) components.

Solar irradiance provides a well specified external climate forcing for testing models and understanding

http://www.hpl.umces.edu/~lzhong/mixed_layer/sml.htm

mixed layer



courtesy of Judith Lean, NRL

Atmospheric Absorption of Solar Radiation

Photochemistry

EUV (Ionosphere)

$N_2 + h\nu\ (\lambda < 80nm) \rightarrow N_2^+ + e^-$
$O_2 + h\nu\ (\lambda < 103nm) \rightarrow O_2^+ + e^-$
$O + h\nu\ (\lambda < 92nm) \rightarrow O^+ + e^-$

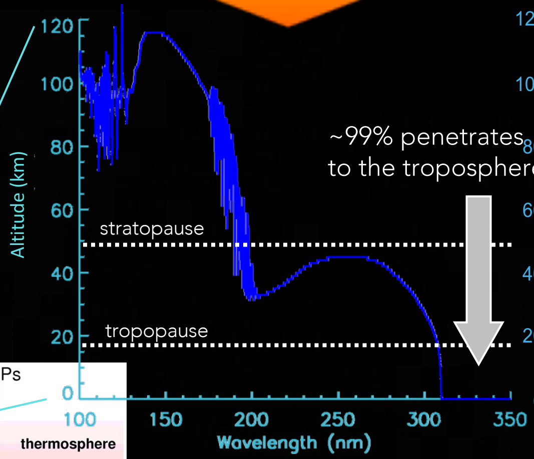
FUV (Ozone Creation)

$O_2 + h\nu\ (\lambda < 242nm) \rightarrow O + O$
$O + O_2\ (+M) \rightarrow O_3$

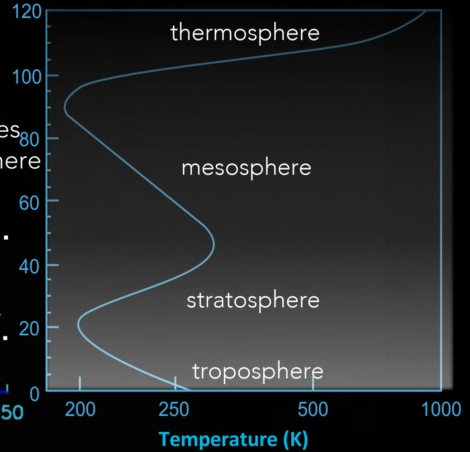
MUV (Ozone Destruction)

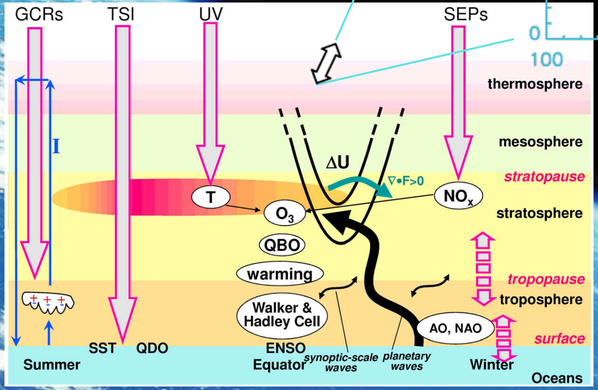
$O_3 + h\nu\ (\lambda < 310nm) \rightarrow O_2 + O$

Solar Input



Heating



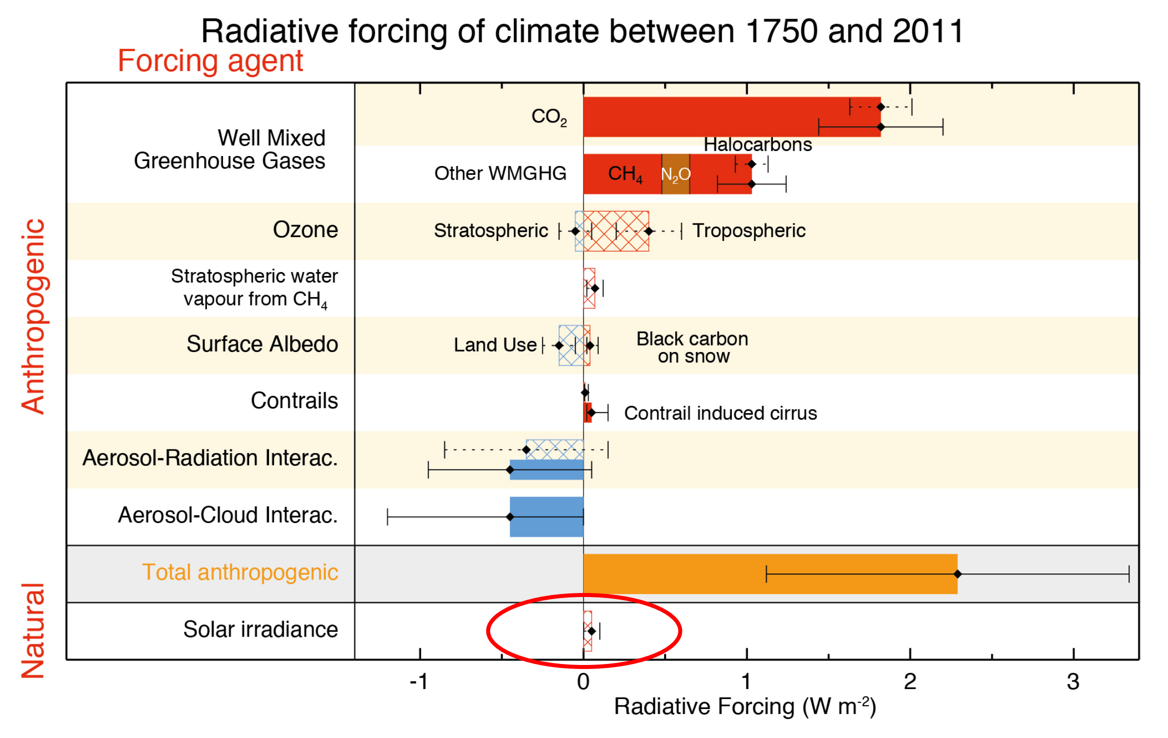


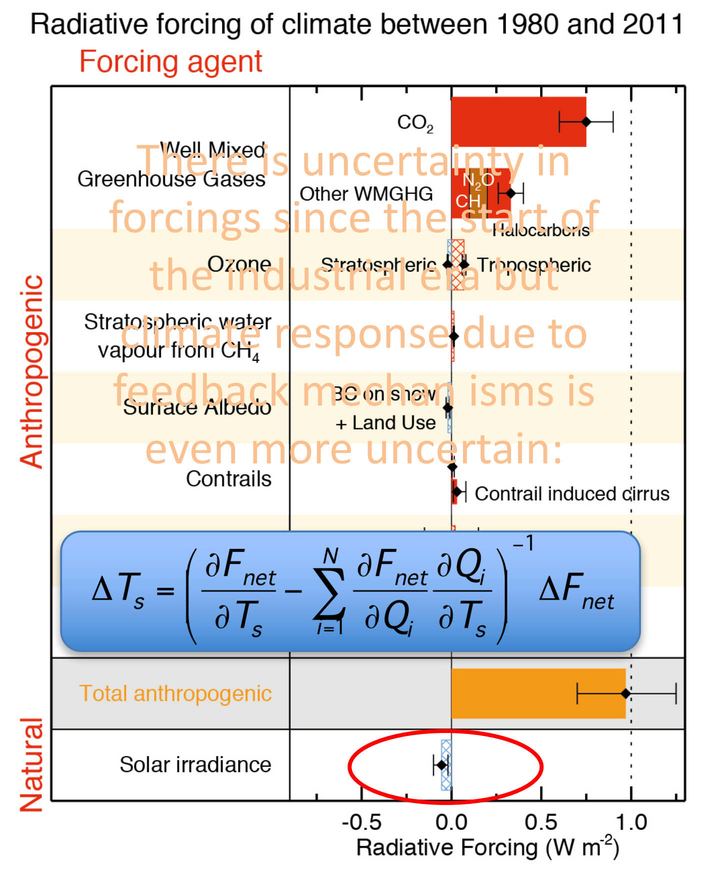
Gray et al., *Rev. Geophys.*, **48**, 2010

courtesy of Erik Richard, LASP

$\lambda < 120$ nm	= 0.003	± 0.001	Wm^{-2}	0.0002%
$120 \leq \lambda < 300$	= 14.9	± 0.1	Wm^{-2}	~1%
$\lambda \geq 300$	= 1346	± 0.5	Wm^{-2}	99%

Fifth Assessment Report (AR5) of the IPCC, 2013

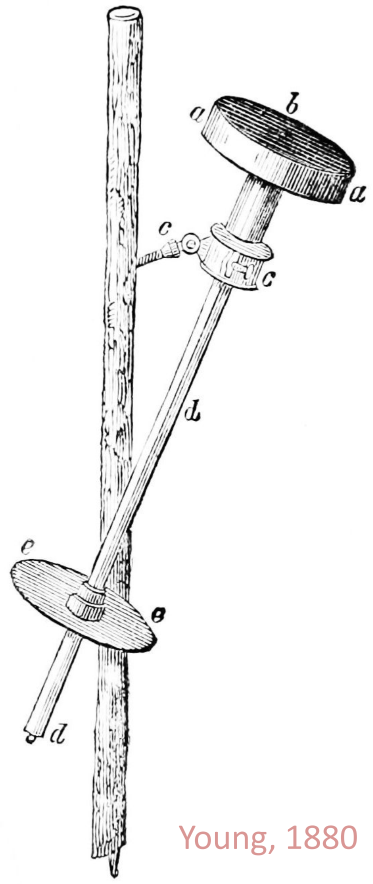




There is uncertainty in forcings since the start of the industrial era but climate response due to feedback mechanisms is even more uncertain:

$$\Delta T_s = \left(\frac{\partial F_{net}}{\partial T_s} - \sum_{i=1}^{N} \frac{\partial F_{net}}{\partial Q_i} \frac{\partial Q_i}{\partial T_s} \right)^{-1} \Delta F_{net}$$

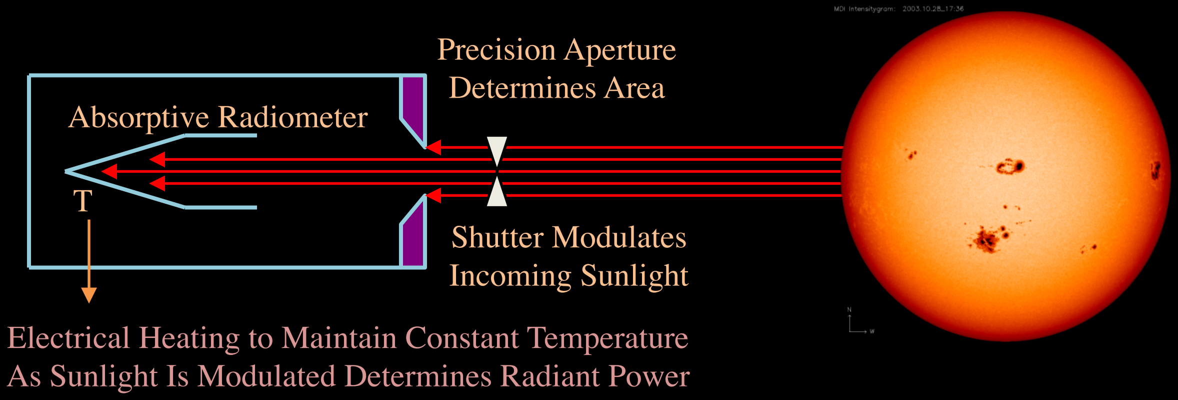
Historical Measurements of the "Solar Constant"



Young, 1880

- Claude Poullet (1837)
  - 1227 W m^{-2} (17.6 kcal m^{-2} min^{-1})
- John Hershel (1837)
- Sam Langley (1881)
  - 2903 W m^{-2}
- Charles Abbot (1958)
  - 1465 W m^{-2}
  - Solar variations ~0.1%
- Labs and Neckel summary (1971)
  - 1360 W m^{-2} ± 1%

Accurate Radiometry Requires Subtle Corrections



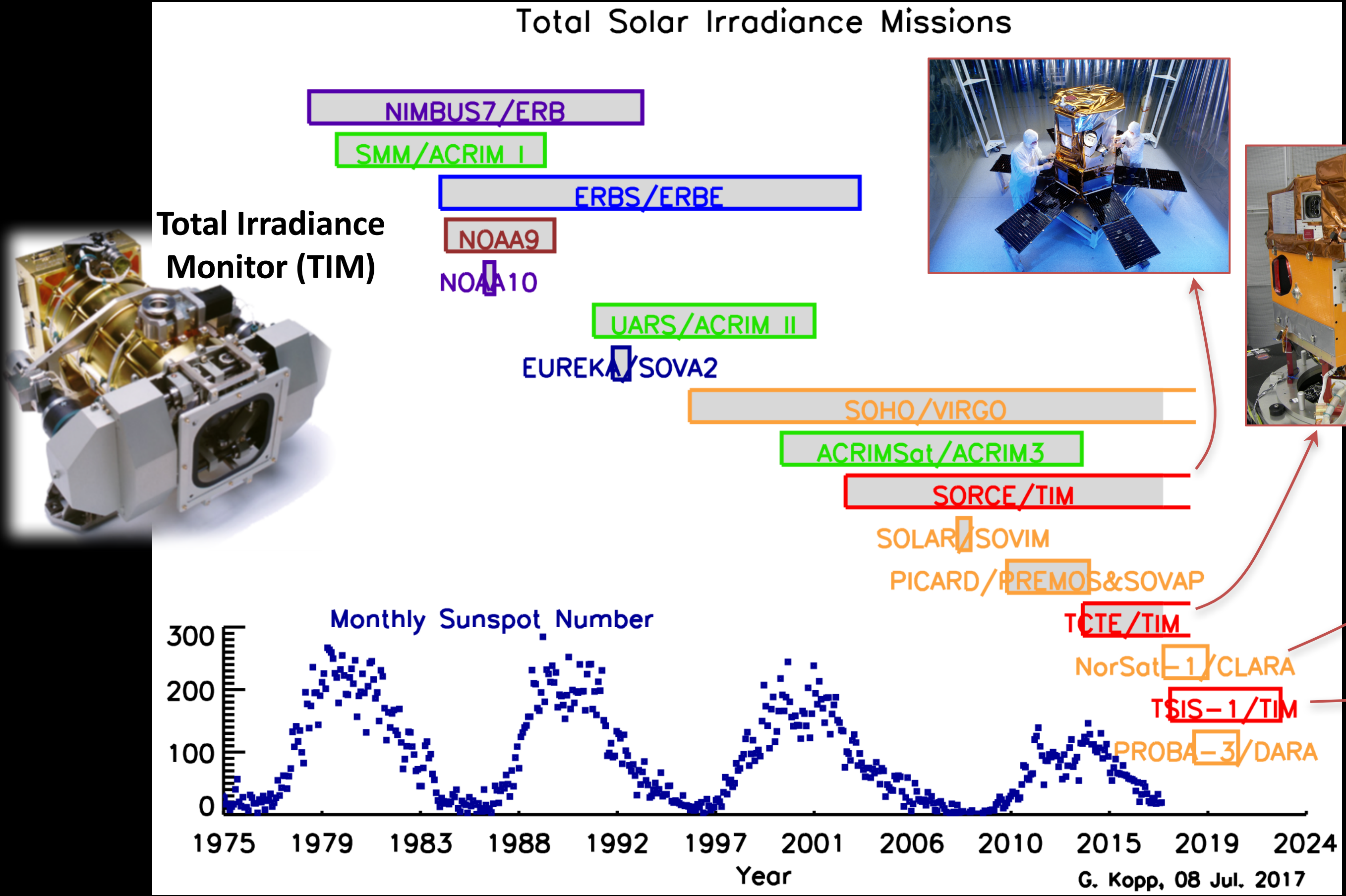
- Aperture knowledge accuracy

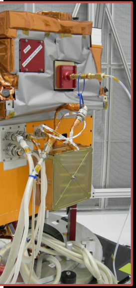
$$\frac{\Delta A}{A} = \frac{2\pi r \cdot \Delta r}{\pi r^2} = 10^{-4} \ \ (100 \text{ ppm}) \quad \Rightarrow \quad \Delta r = 200 \text{ nm}$$

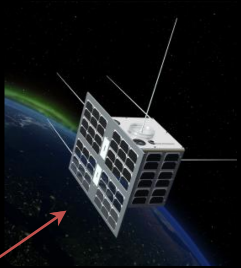
- Doppler correction due to S/C orbit velocity

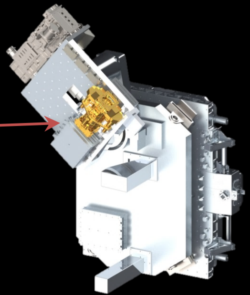
$$2\frac{v}{c} = 2 \cdot \frac{8\text{x}10^5 \text{ cm/s}}{3\text{x}10^{10} \text{ cm/s}} \approx 5\text{x}10^{-5} \quad \Rightarrow \quad \pm 50 \text{ ppm}$$

TSI Missions



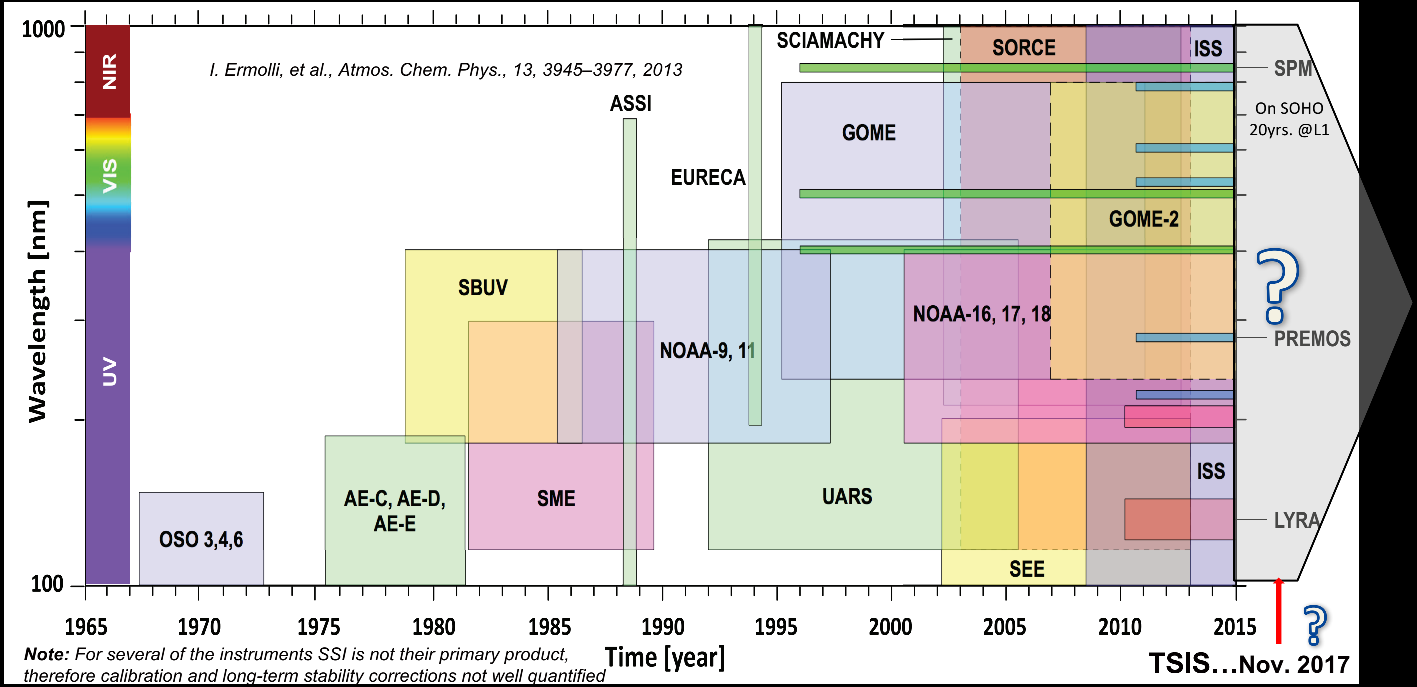






SSI Measurement Continuity

- **Continuity applies to both temporal and spectral coverage**
  - **However, continuity is only beneficial if measurements have good long-term stability**



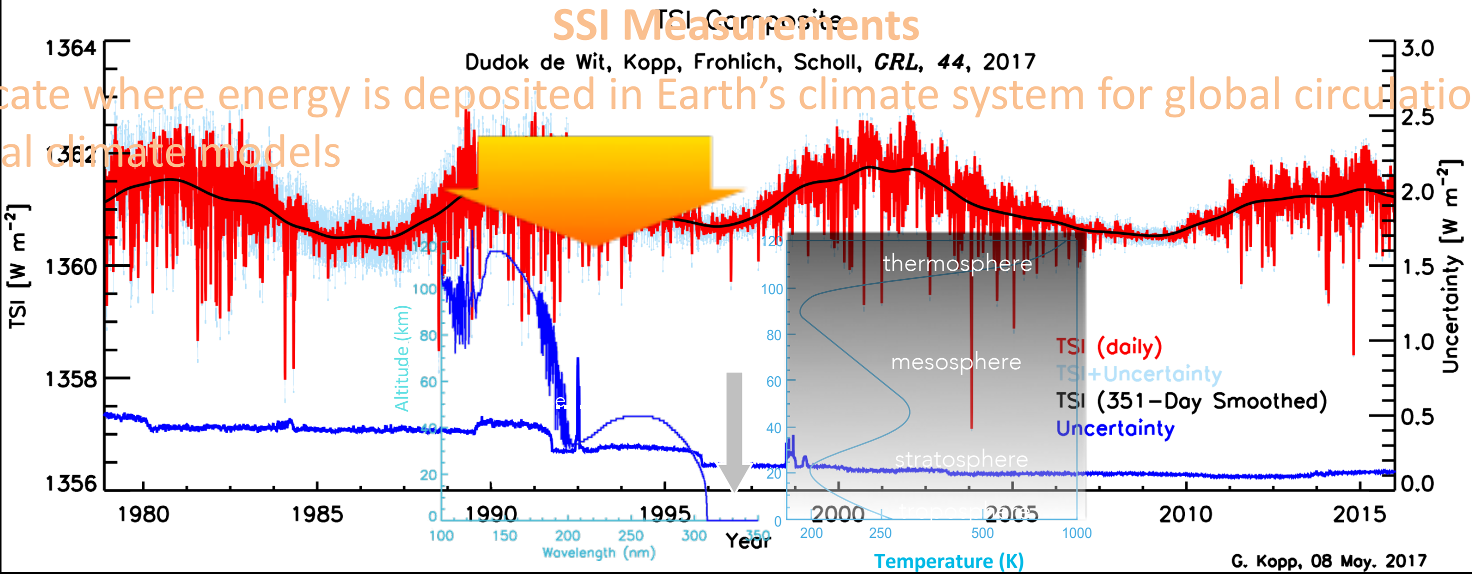
Value of Spectral-Irradiance Measurements for Climate Science

TSI Measurements

1. Are the most stable solar irradiance measurements
   – Achieve stabilities necessary to detect climate-relevant solar variability
2. Provide ~40 year solar-irradiance record of entire radiative input to Earth's climate system

SSI Measurements

1. Indicate where energy is deposited in Earth's climate system for global circulation and global climate models



Fundamental Solar-Irradiance Science Questions

- What are secular (long-term) variations in solar irradiance?
- What solar activities cause variability at different wavelengths?
- What was the solar irradiance during the Maunder Minimum?
- How good are sunspot and isotope proxies of solar irradiances?
- How much solar variability is expected?
  - Based on observations of the Sun and observations of other stars?
  - Based on physical models?
- What is the Earth's climate sensitivity to solar variability?