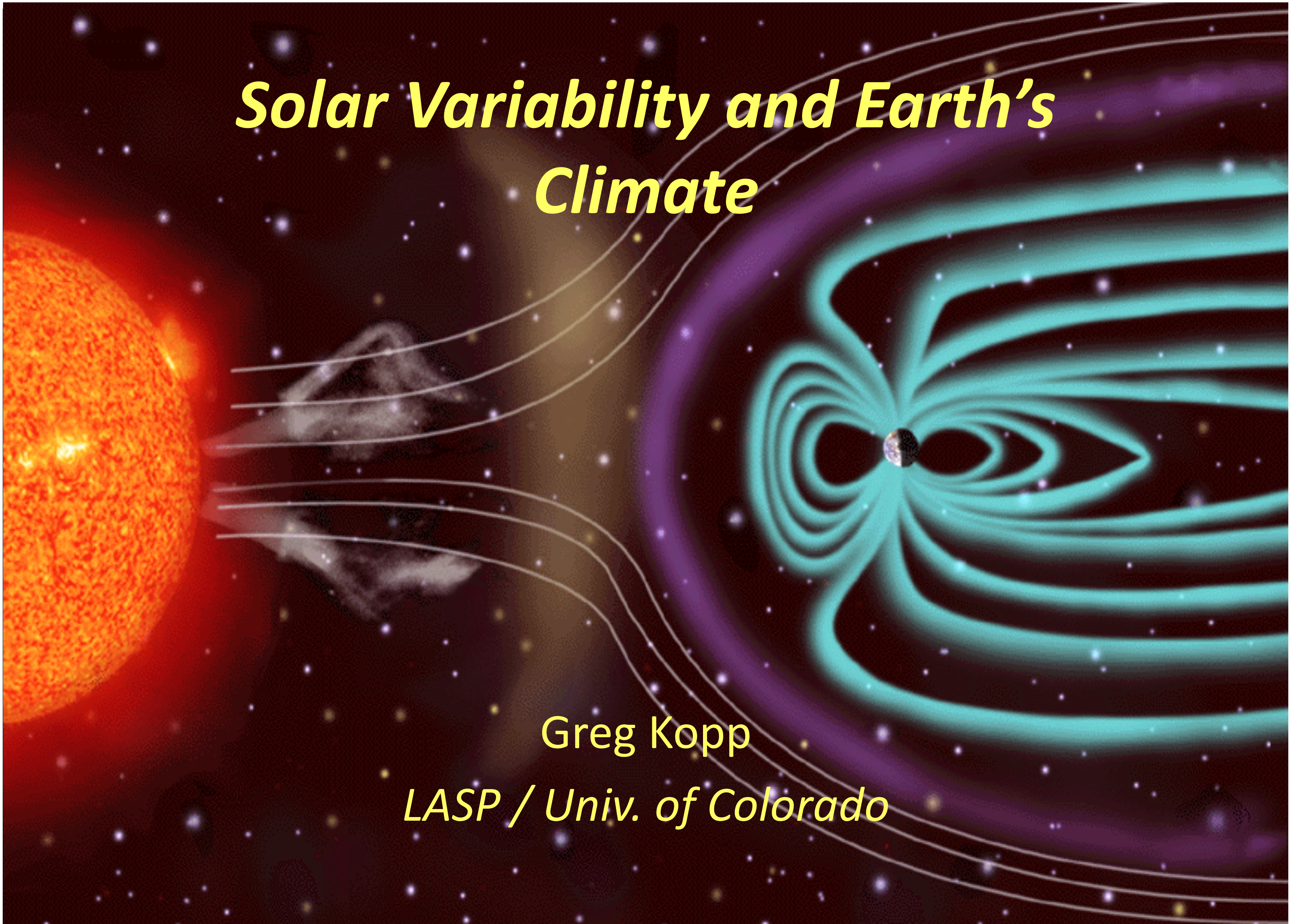


Solar Variability and Earth's Climate

Greg Kopp

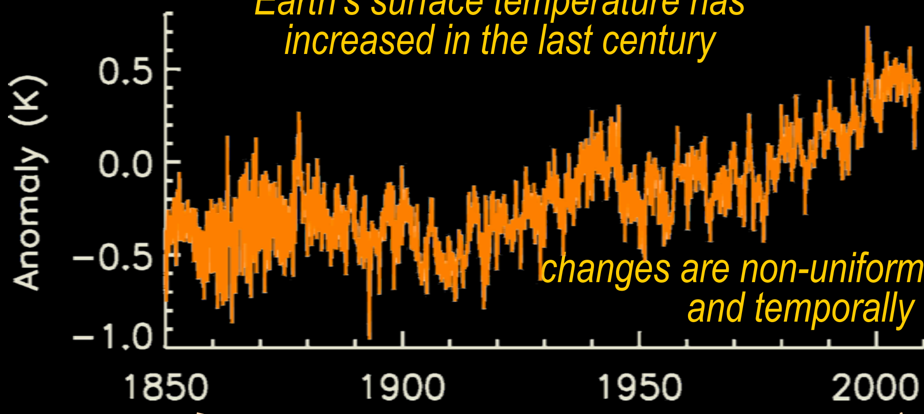
LASP / Univ. of Colorado

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

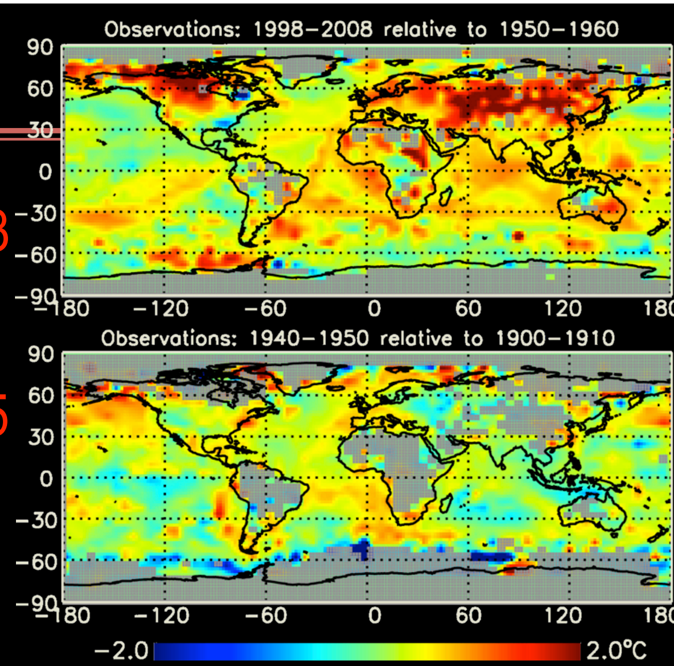
Earth's surface temperature has increased in the last century



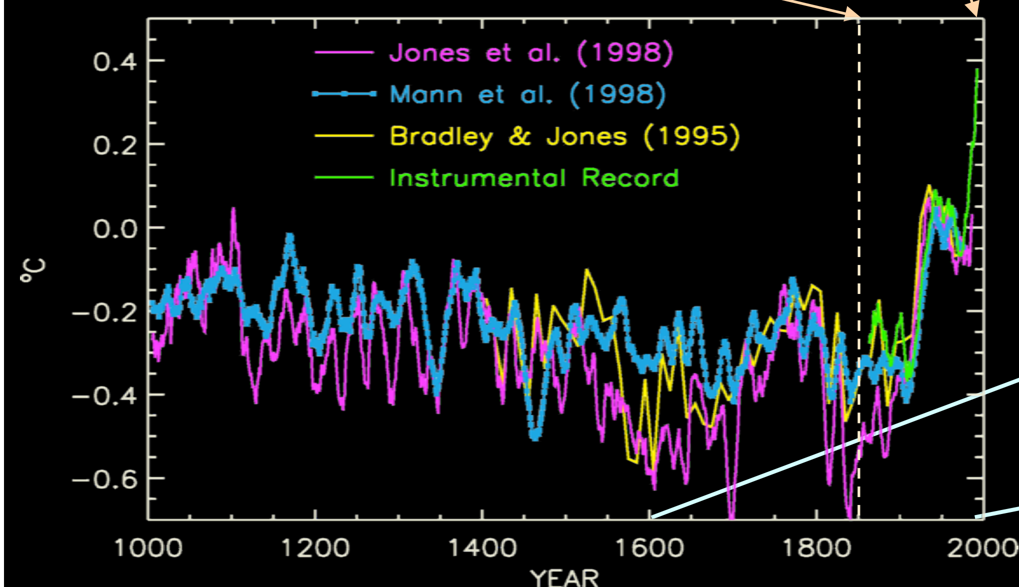
changes are non-uniform, globally and temporally

1955-2003

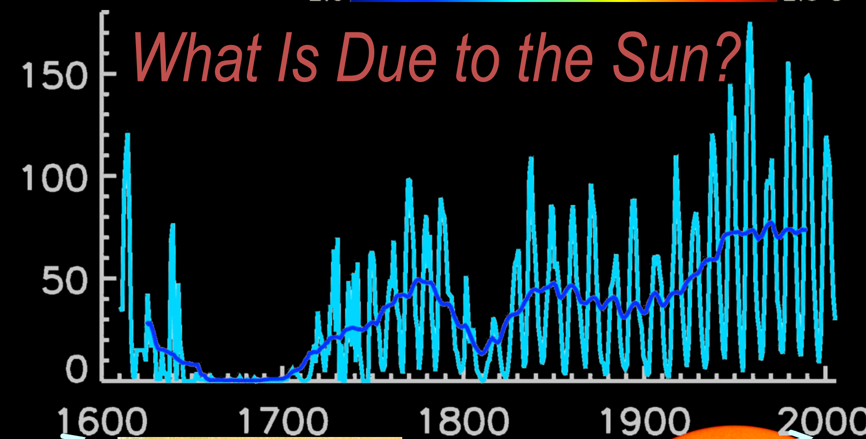
1905-1945

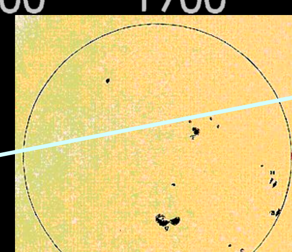


http://ftp.cru.uea.ac.uk/

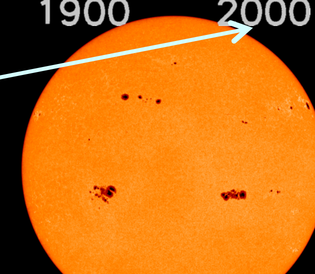


What Is Due to the Sun?





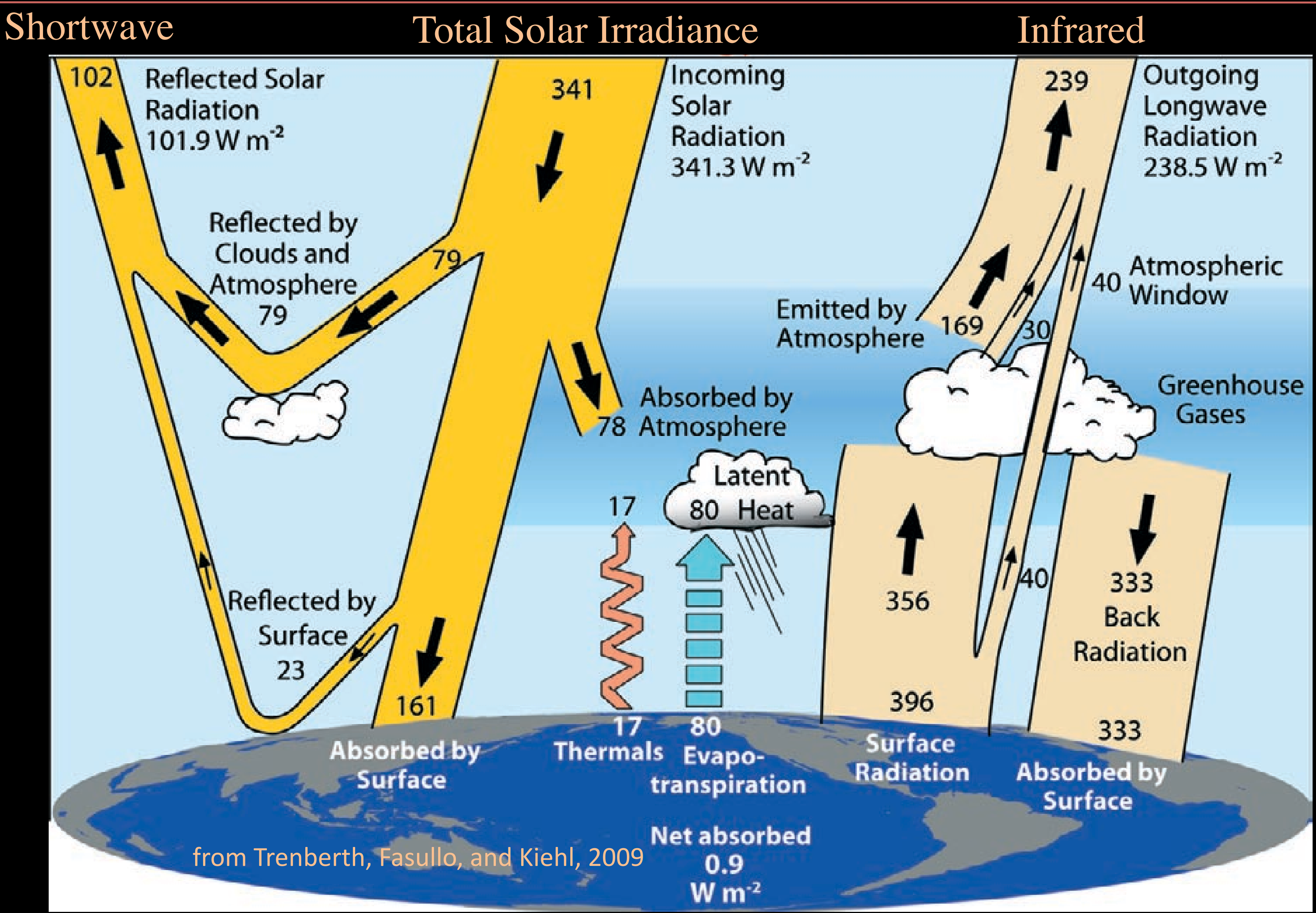
1613 Galileo



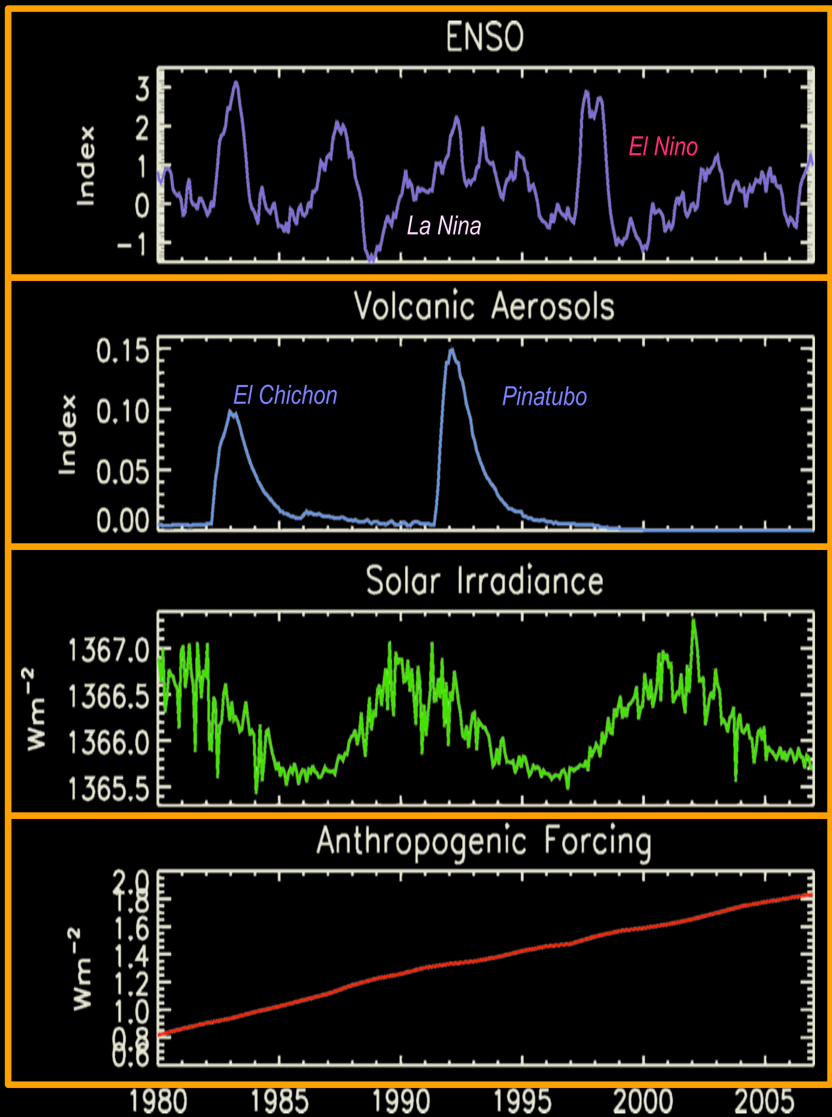
1995 SOHO

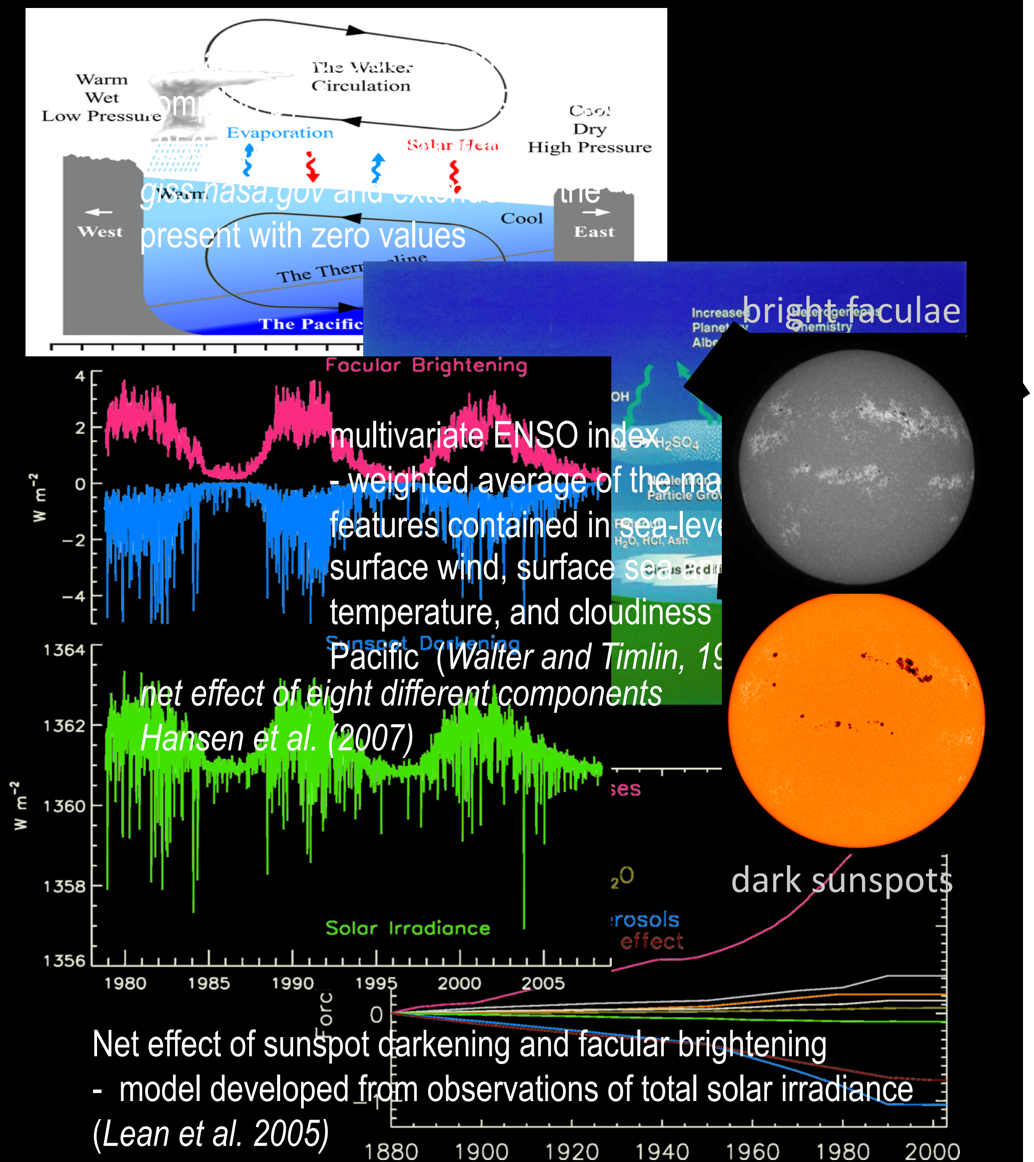
courtesy of Judith Lean, NRL

What Determines Climate?



Climate Influences





giss.nasa.gov and external ...
present with zero values

multivariate ENSO index
- weighted average of the ma...
features contained in sea-leve...
surface wind, surface sea...
temperature, and cloudiness ...
Pacific (*Walter and Timlin, 19*...

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

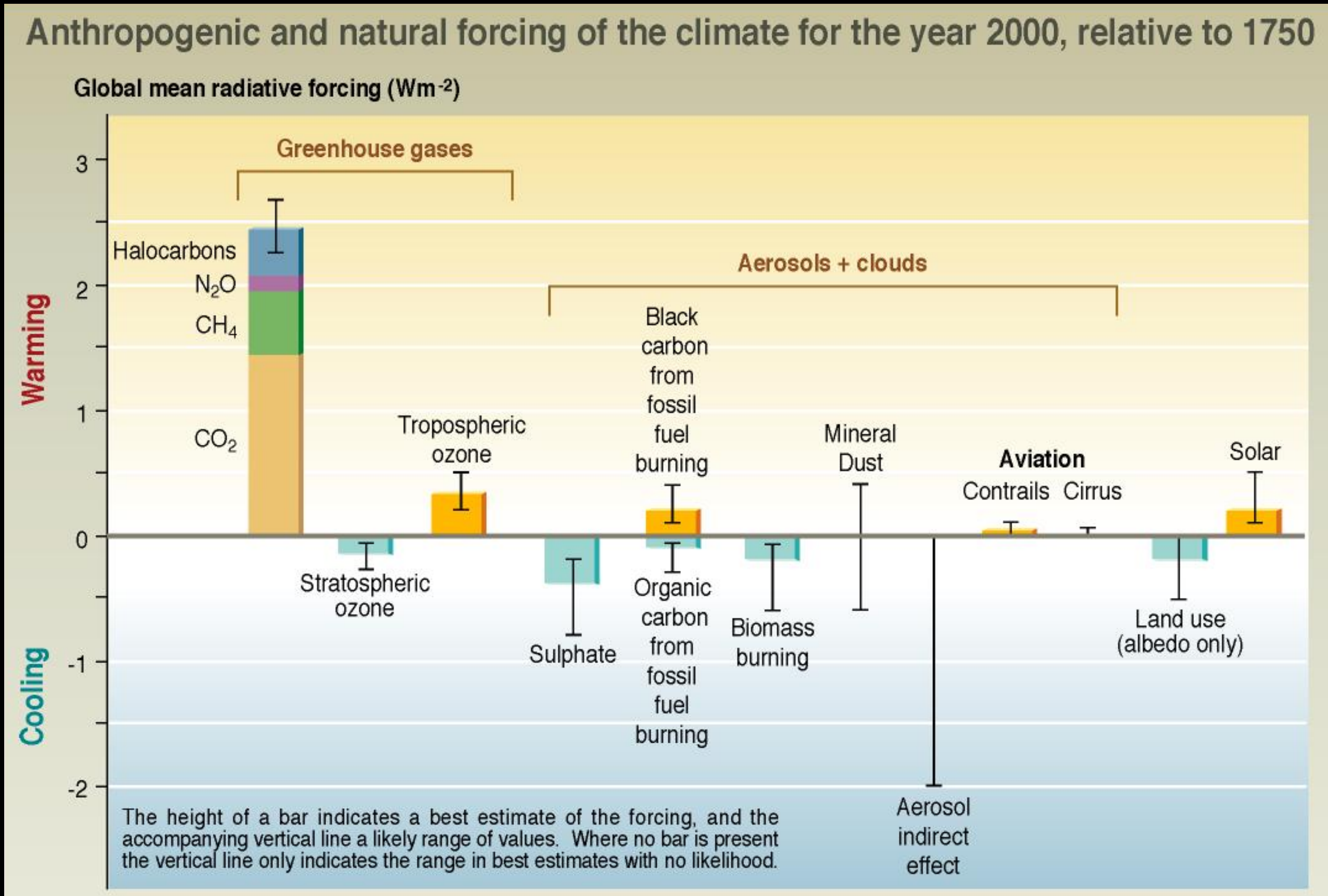
bright faculae

dark sunspots

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

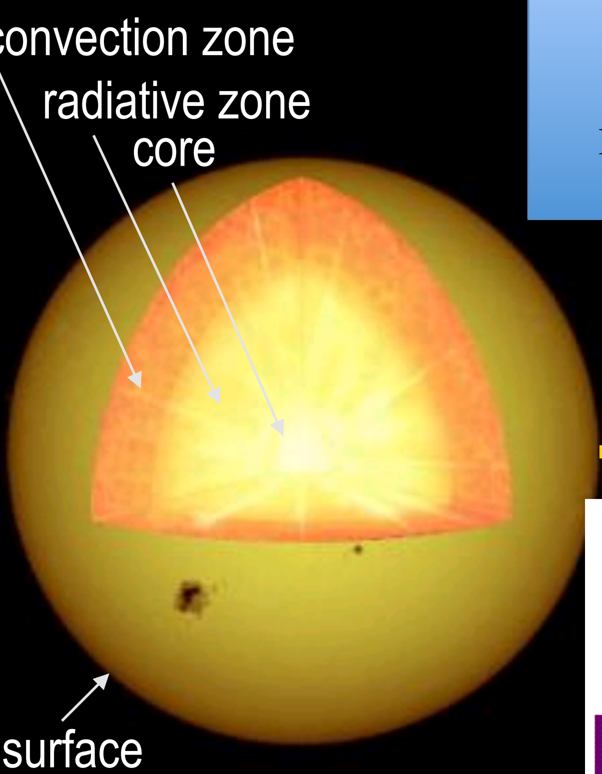
courtesy of Judith Lean, NRL

Primary Climate Forcing Agents



4.5 billion years

Sun
5770 K



Earth
280 K

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

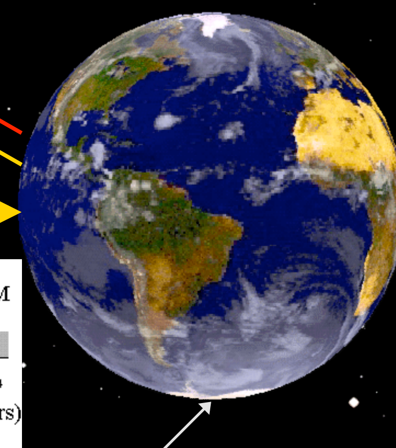
$$\text{Outgoing Energy} = 4\pi R^2 \cdot \varepsilon \cdot \sigma T^4$$

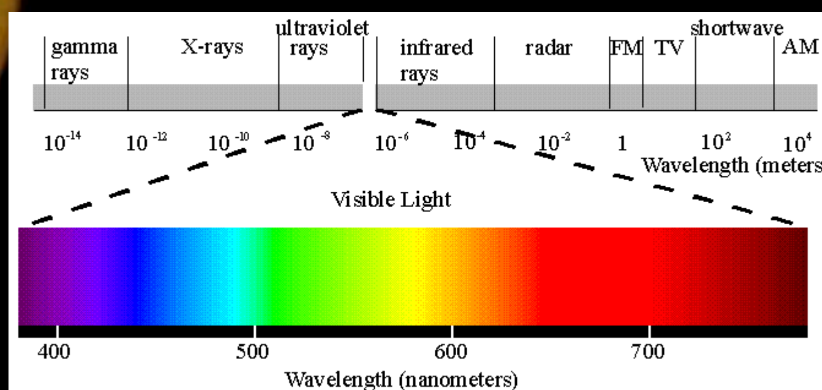
$$\text{Energy Balance} \Rightarrow T = \sqrt[4]{\frac{A}{\varepsilon}\frac{1}{4\sigma}S} = 280K$$

radiated photons

reflected photons

photons





1,391,980 km

149,597,900 km

12,742 km

1 Astronomical Unit

not to scale

courtesy of Judith Lean, NRL

Where Does the Earth Get Its Energy?

Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	340.25	1.000
Heat Flux from Earth's Interior	0.0870	2.6E-04
Radioactive Decay	0.0550	1.6E-04
Geothermal	0.0320	9.4E-05
Worldwide Combustion of Coal, Oil, and Gas	0.0279	8.2E-05
Infrared Radiation from the Full Moon	0.0102	3.0E-05
Sun's Radiation Reflected from Moon	0.0037	1.1E-05
Energy Generated by Solar Tidal Forces in the Atmosphere	0.0017	5.0E-06
Dissipation of Magnetic Storm Energy	8.2E-04	2.4E-06
Radiation from Bright Aurora	4.8E-05	1.4E-07
Energy Dissipated in Lightning Discharges	2.0E-05	5.9E-08
Dissipation of Mechanical Energy of Micrometeorites	2.0E-05	5.9E-08
Energy Generated by Lunar Tidal Forces in the Atmosphere	2.0E-05	5.9E-08
Total Radiation from Stars	1.4E-05	4.1E-08
Energy of Cosmic Radiation	1.3E-05	3.8E-08
Radiation from Zodiacal Light	3.4E-07	1.0E-09
Total of All Non-Solar Energy Sources	*0.1315*	*3.9E-04*

* global average

2500 x

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

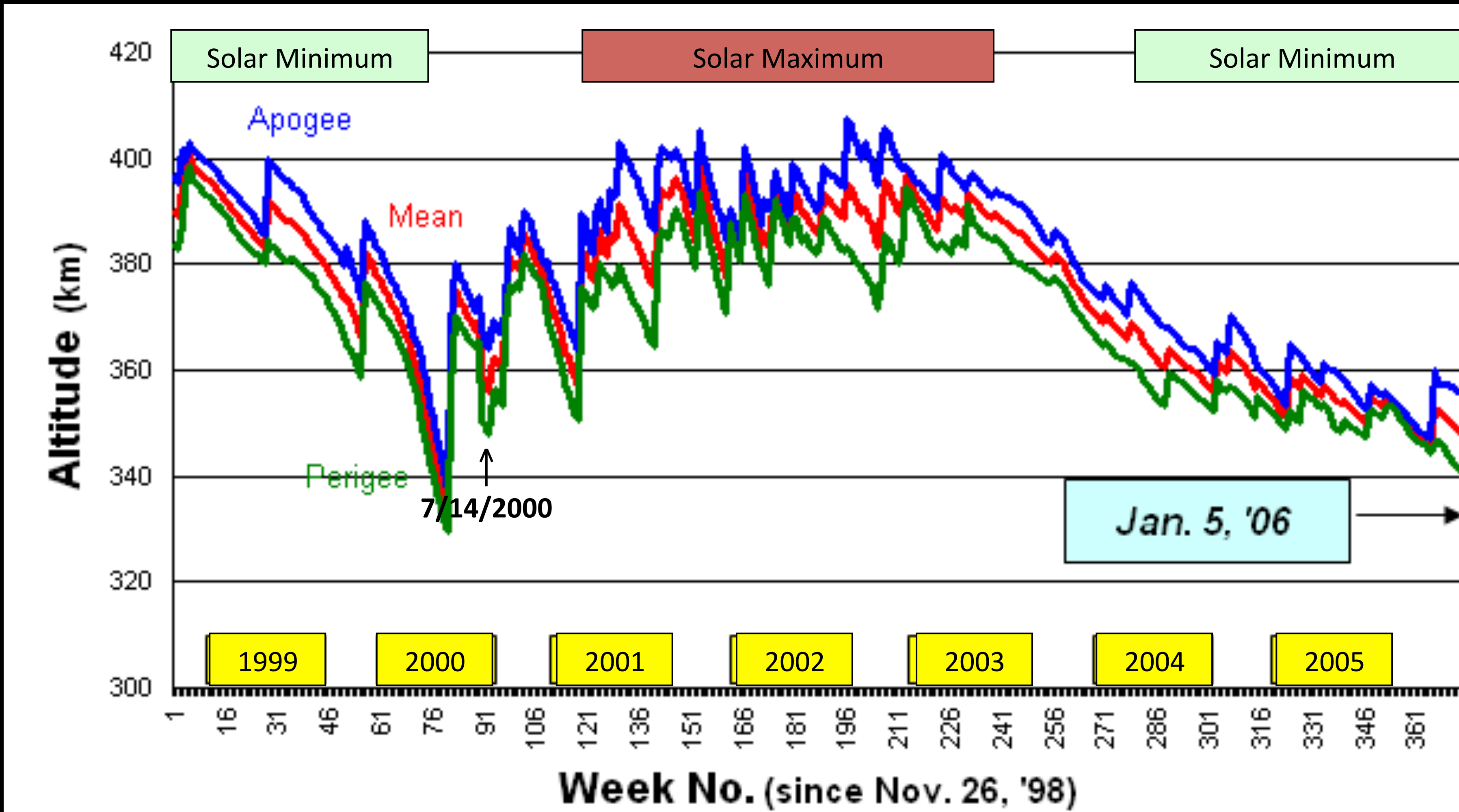
based on Physical Climatology, W.D. Sellers, Univ. of Chicago Press, 1965
Table 2 on p. 12 is from unpublished notes from
H.H. Lettau, Dept. of Meteorology, Univ. of Wisconsin.

The Sun Is THE Dominant Driver of Earth's Climate

Fortunately, this 800 lb gorilla is very placid

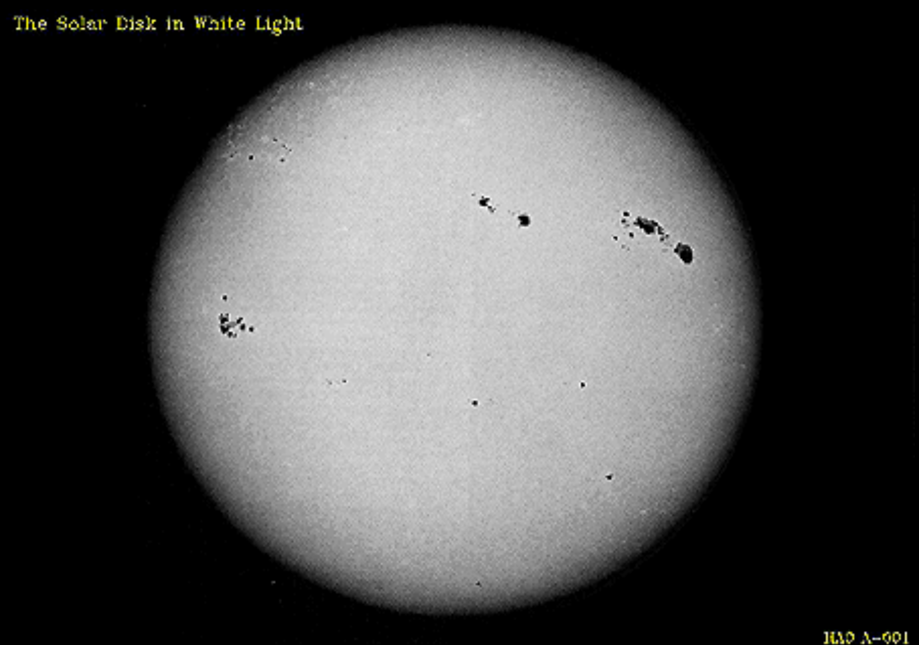
Heat Source	Heat Flux* [W/m^2]	Relative Input
Solar Irradiance	340.25	1.000
Heat Flux from Earth's Interior	0.0870	2.6E-04
Radioactive Decay	0.0550	1.6E-04
Geothermal	0.0320	9.4E-05
Worldwide Combustion of Coal, Oil, and Gas	0.0279	8.2E-05
Infrared Radiation from the Full Moon	0.0102	3.0E-05
Sun's Radiation Reflected from Moon	0.0037	1.1E-05
Energy Generated by Solar Tidal Forces in the Atmosphere	0.0017	5.0E-06
Dissipation of Magnetic Storm Energy	8.2E-04	2.4E-06
Radiation from Bright Aurora	4.8E-05	1.4E-07
Energy Dissipated in Lightning Discharges	2.0E-05	5.9E-08
Dissipation of Mechanical Energy of Micrometeorites	2.0E-05	5.9E-08
Energy Generated by Lunar Tidal Forces in the Atmosphere	2.0E-05	5.9E-08
Total Radiation from Stars	1.4E-05	4.1E-08
Energy of Cosmic Radiation	1.3E-05	3.8E-08
Radiation from Zodiacal Light	3.4E-07	1.0E-09
Total of All Non-Solar Energy Sources	*0.1315*	*3.9E-04*
* global average		
based on Physical Climatology, W.D. Sellers, Univ. of Chicago Press, 1965		
Table 2 on p. 12 is from unpublished notes from		
H.H. Lettau, Dept. of Meteorology, Univ. of Wisconsin.		

International Space Station Altitude Profile



The Present Sun

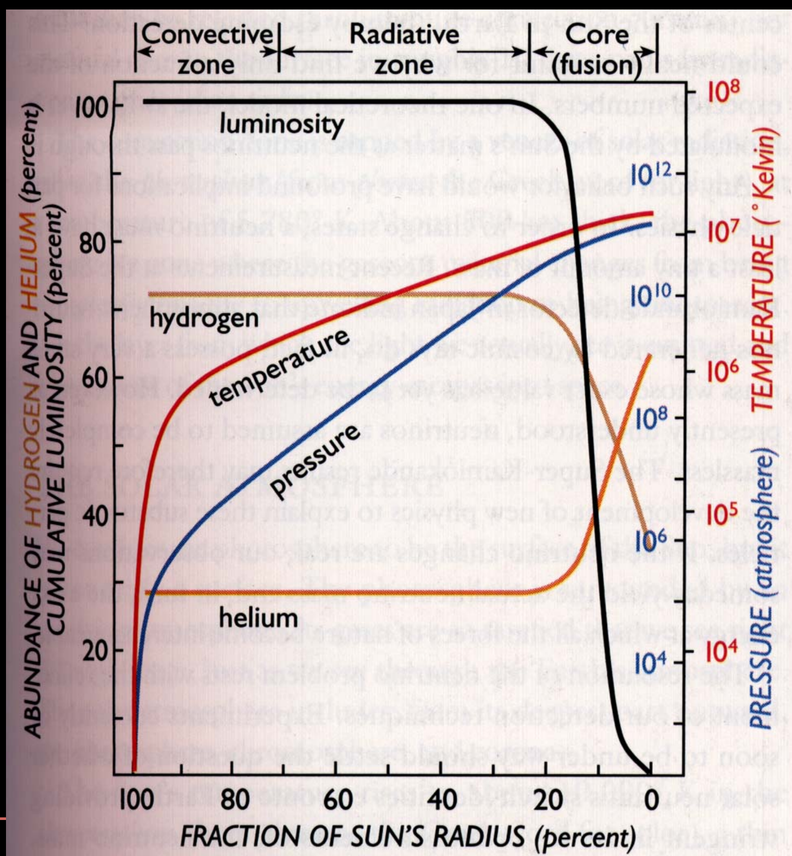
- Age: 4.5×10^9 years
- Radius: 7×10^{10} cm (100x Earth's)
- Mass: 2×10^{33} g (300,000x Earth's)
- Temperature: 5770°K surface,
  16,000,000°K core heats Sun

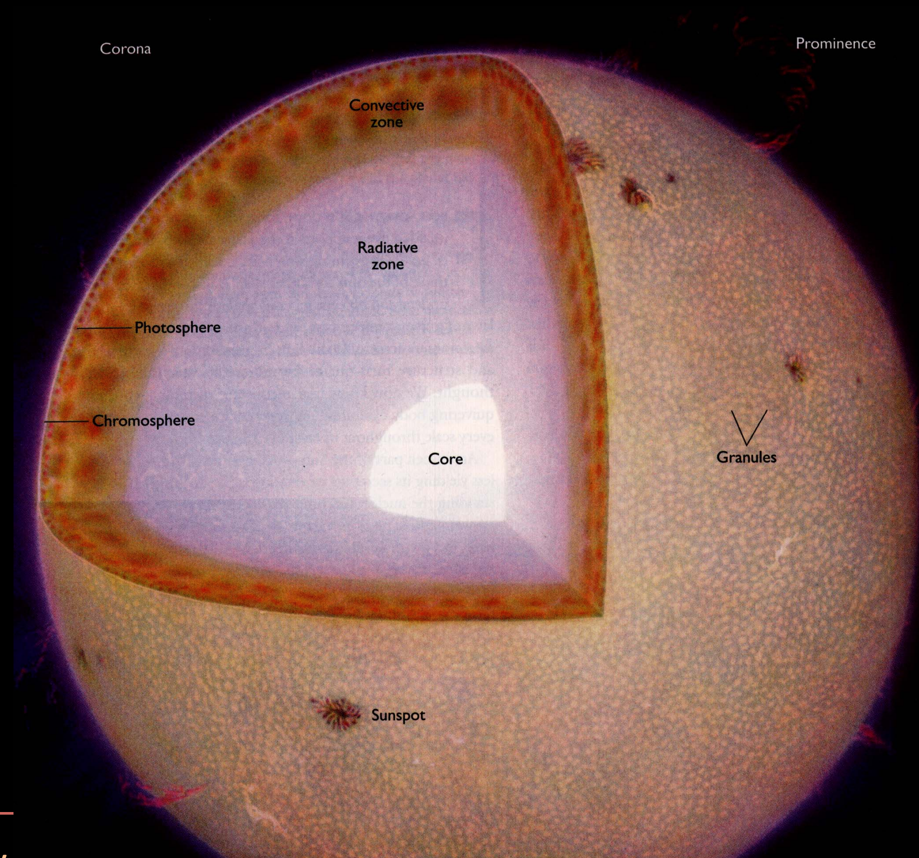


The Sun is larger and hotter than it would be if it were an inert ball of gas held together by gravity.

Solar Interior

- Core (1/64 solar volume but 1/2 of solar mass)
  - pressure: 233 billion x Earth atmospheric pressure
  - density: 150 g/cm^3 (13x lead, yet this is H)
  - temperature: 16,000,000°K
  - nuclear processes burn 700,000,000 tons/sec of H, converting 4,200,000 tons/sec to energy
- Radiative zone (0.72 solar radius)
  - ~5,000,000°K
  - radiation dominates heat flow
- Convective zone (to surface)
  - ~1,000,000°K
  - convective motions dominate flow



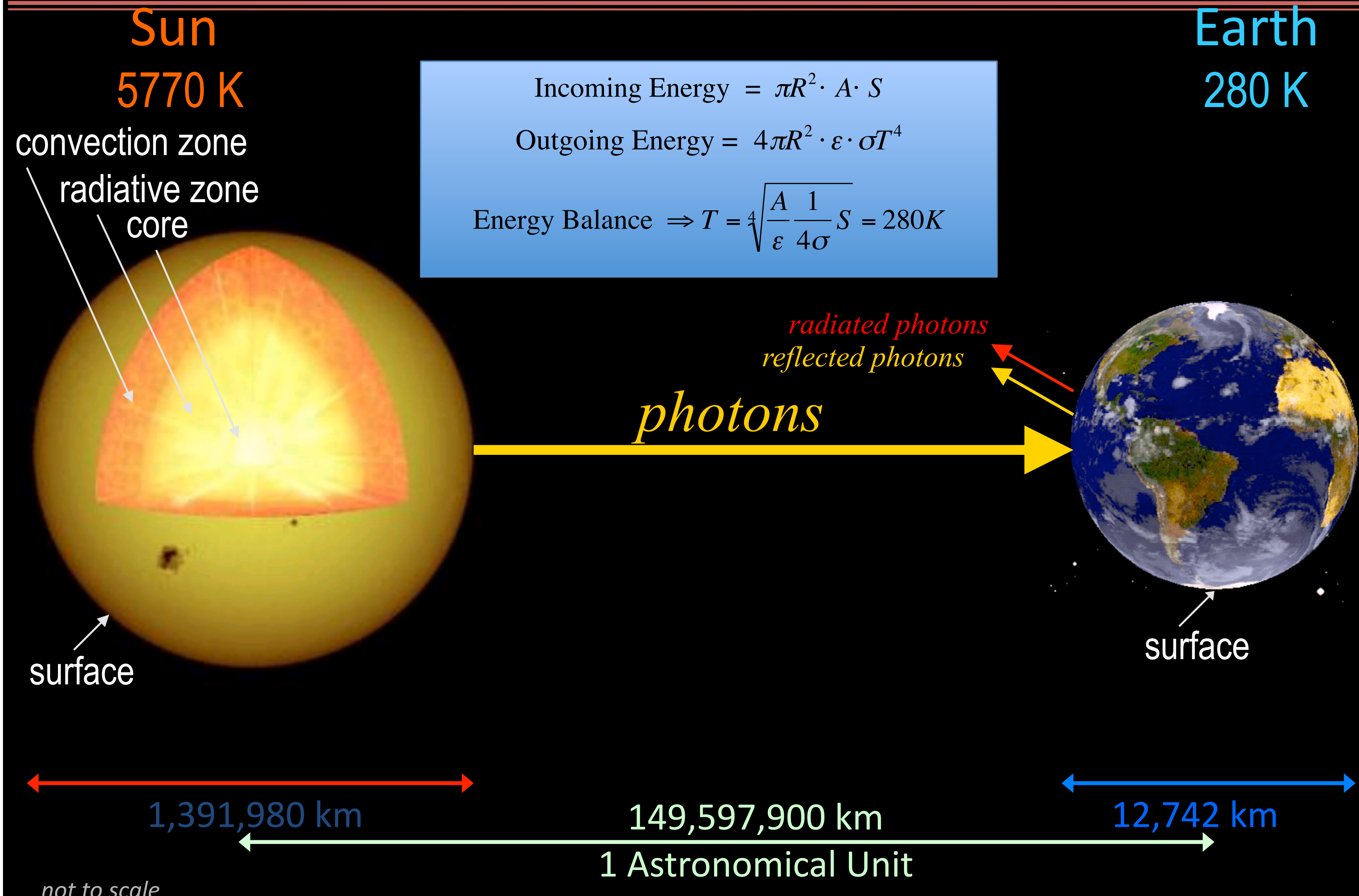


Energy Balance Depends on Orbital Parameters

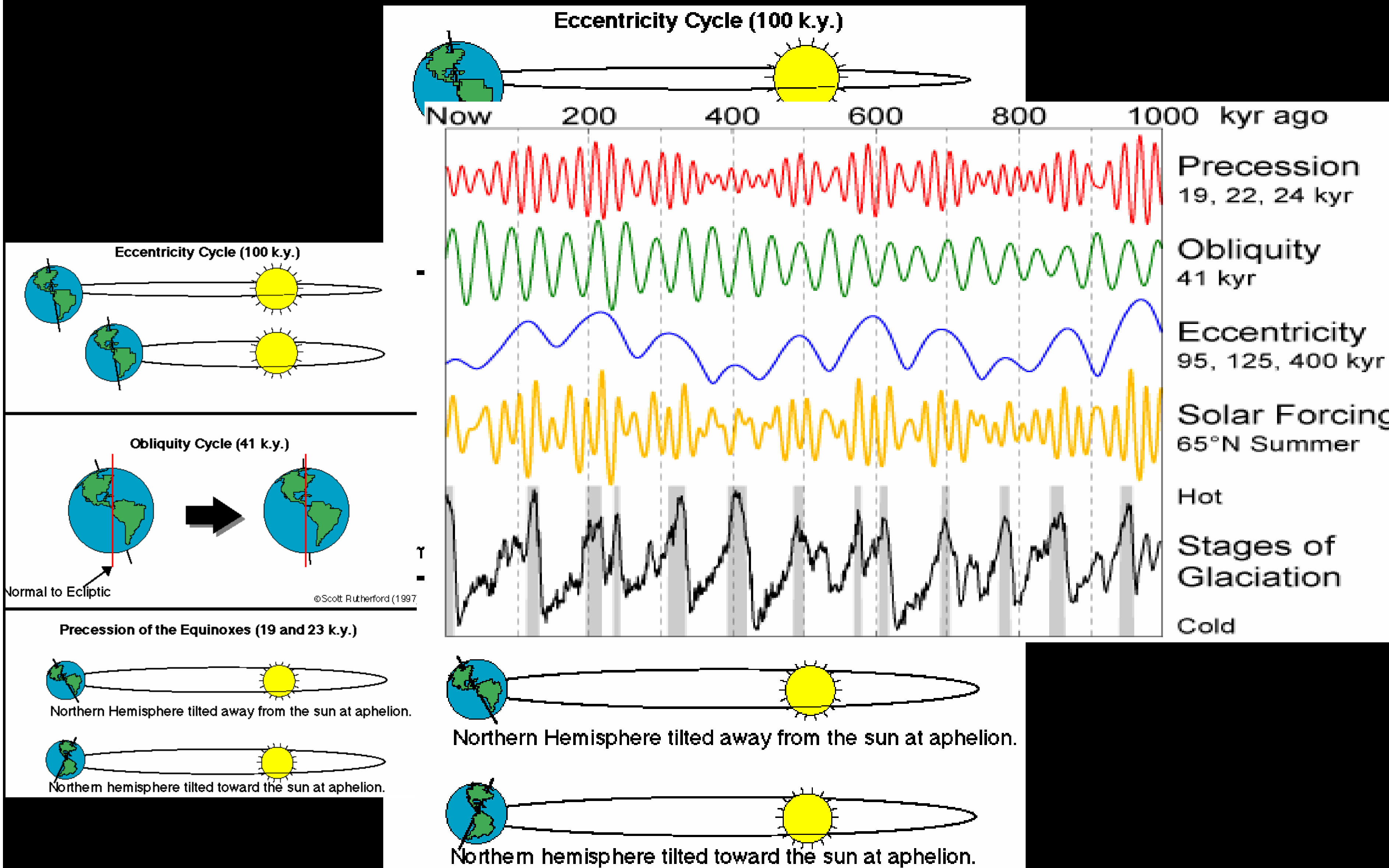
$$\text{Incoming Energy} = \pi R^2 \cdot A \cdot S$$

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

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



Earth's Orbit Around Sun Affects Climate



Orbital Dynamics

- Gravitational force

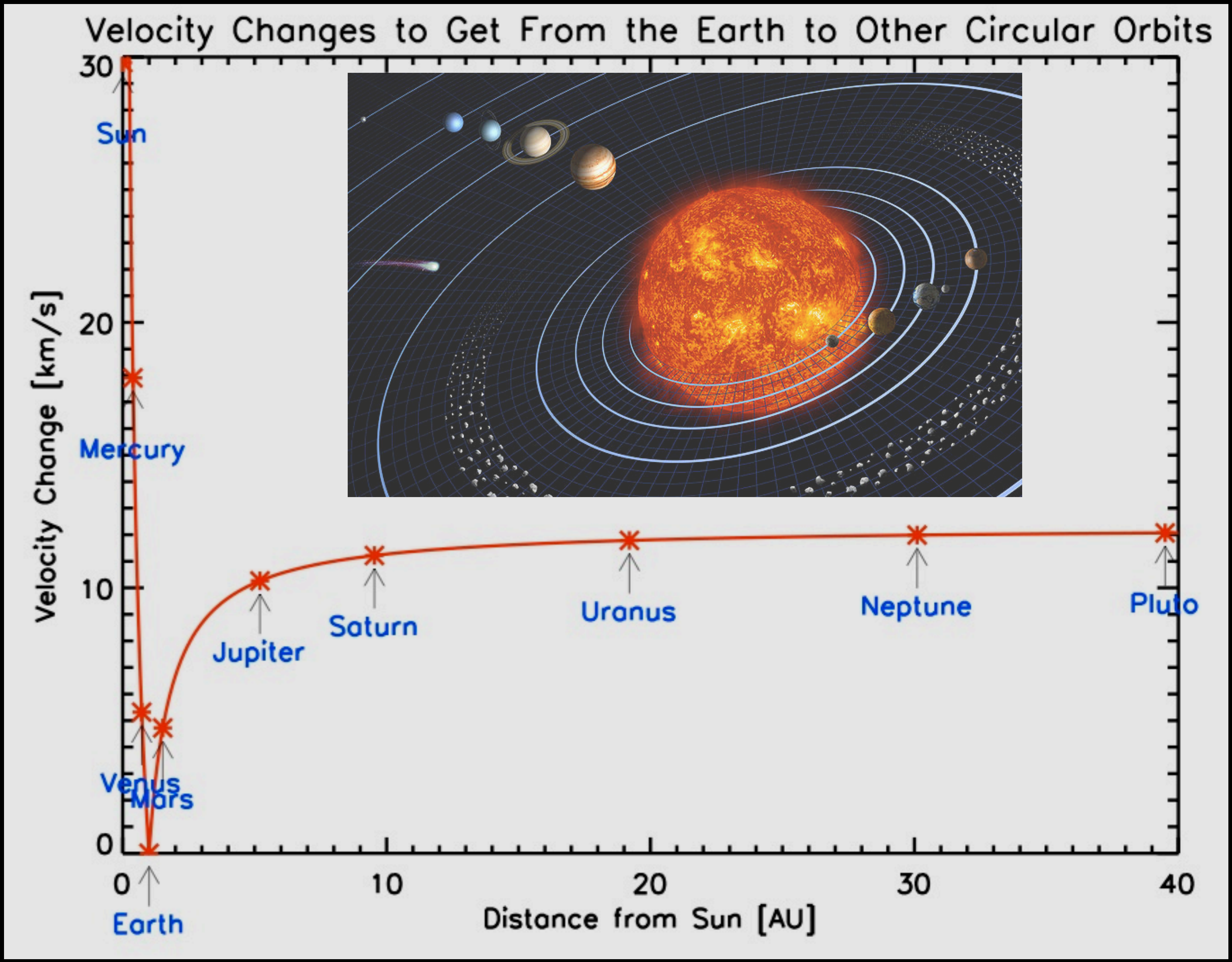
$$F_g = -G \cdot \frac{m_1 m_2}{r^2}$$

- Planetary orbital motions are conics

$$r(\theta) \sim \frac{1}{1 + e\cos\theta}$$

Planet	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
e	0.2056	0.0068	0.0167	0.0934	0.0483	0.056	0.0461	0.0097

Sun Is Most Difficult Solar System Object to Reach

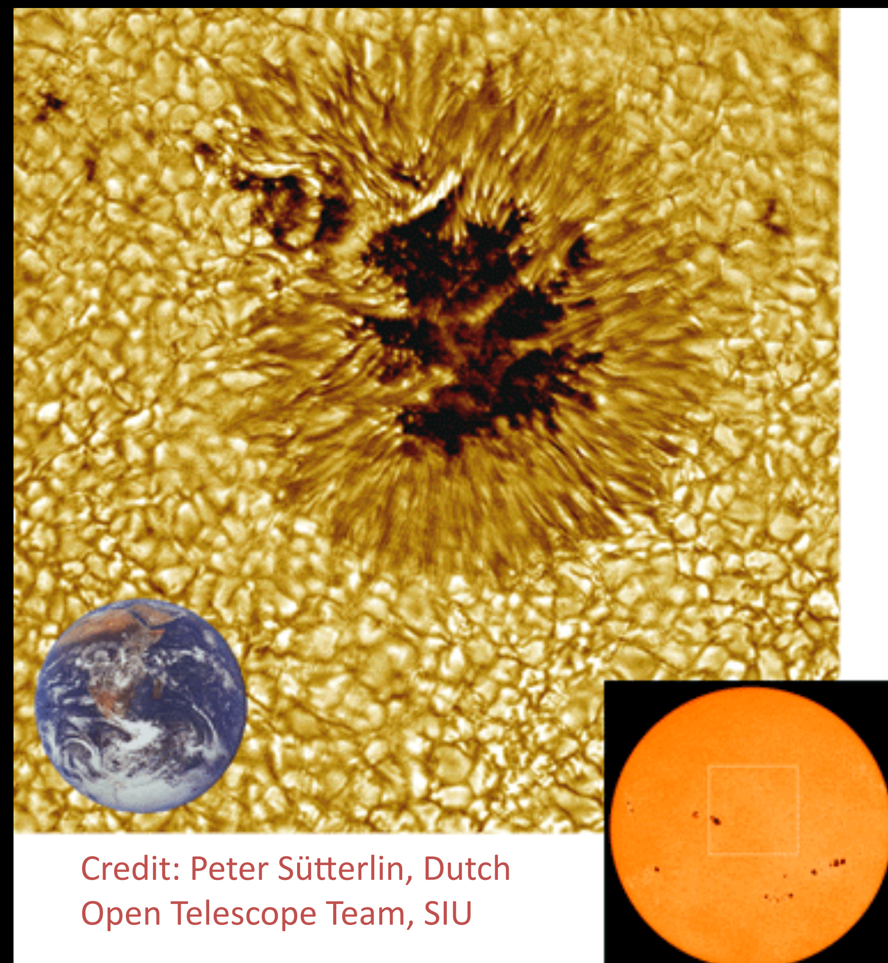


Problems

- Compute the center of mass of the solar system
  - Base on the Sun and Jupiter only and express in solar radii from Sun center
- Compute approximate tidal force deflections on Earth's and Sun's surfaces
  - For Earth, use Moon and Sun; for Sun, use Jupiter
- Compute Earth's temperature due to:
  - Solar radiation; and
  - Earth's internal energy sources alone
- Estimate and compare expected temperature changes from winter to summer due to both:
  - Sun-Earth distance variations; and
  - Axial tilt (assume 40° latitude and 23.5° axial tilt)

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)*

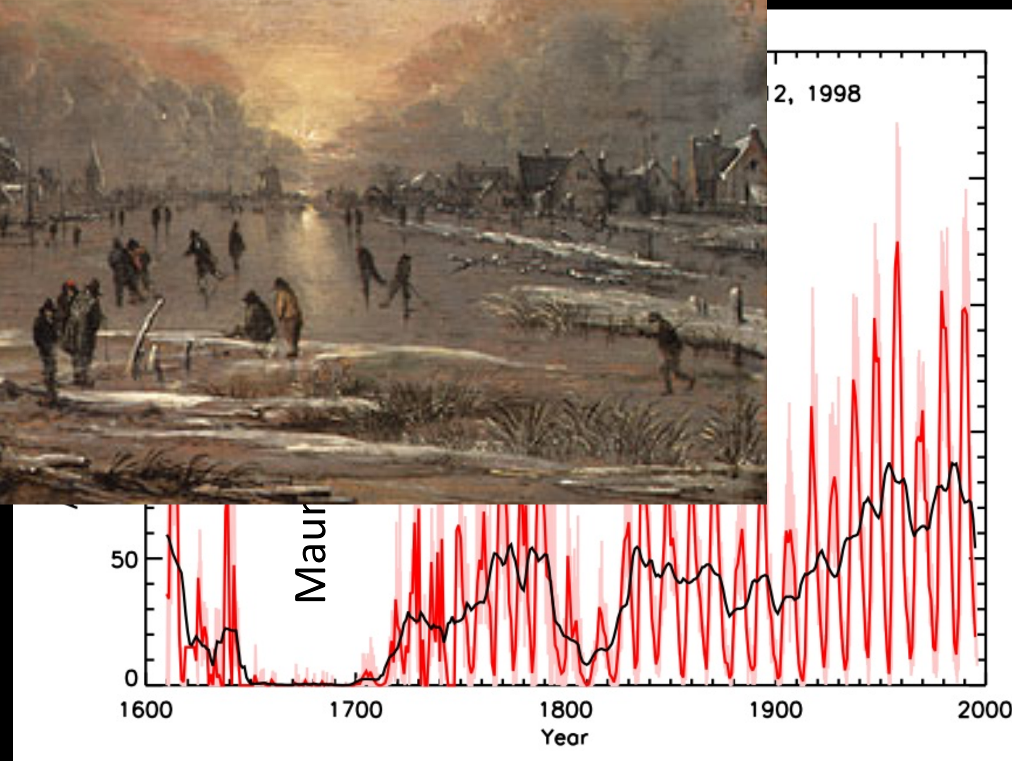
Herschel [1801]: Correlated the price of wheat in London with the number of visible sunspots, attributing the connection to reduced rainfall when the Sun was less spotted

History – Europe's Little Ice Age

1645-1715 – Maunder Minimum

– Solar output decreased 0.1-0.3% for 70 years

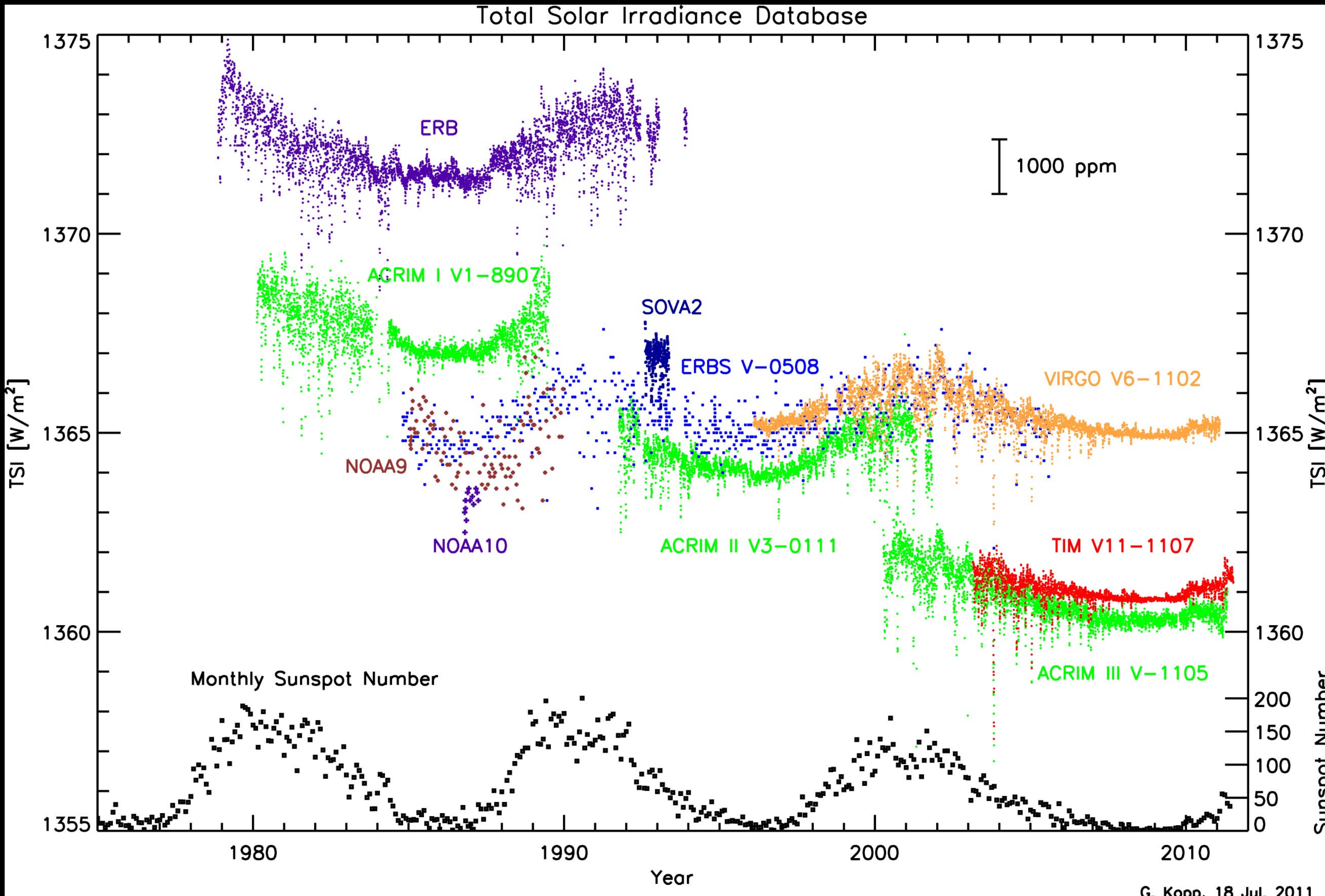
– Earth temperatures were ~0.2-0.4 C colder than the early 1900s



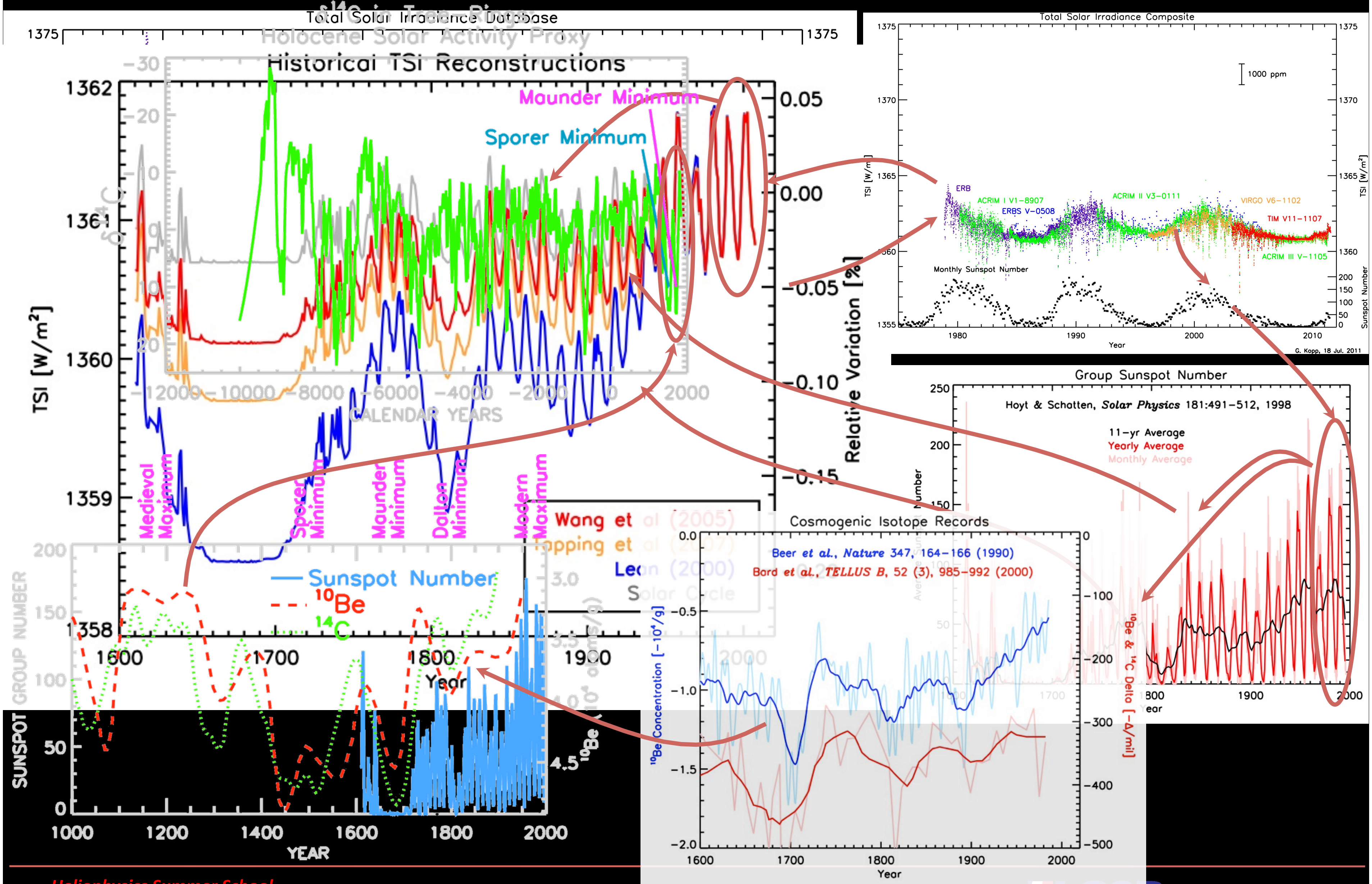
Sun-Climate Connections

- The 70 years (1645 - 1715) of the Maunder Minimum, when very few sunspots were seen, coincided with Europe's Little Ice Age
- 11 yr cycle
  - Affects plant growth
  - Variations in ozone, temperatures, winds, clouds, precipitation, monsoons
  - Varies ocean/atmosphere circulation patterns (North Atlantic Oscillation)
  - Changes in forest fires in N. America, rainfall in Africa, warm temperatures in Alaska, hurricanes in N. Atlantic
- Understanding and prediction are difficult

The Total Solar Irradiance Data Record

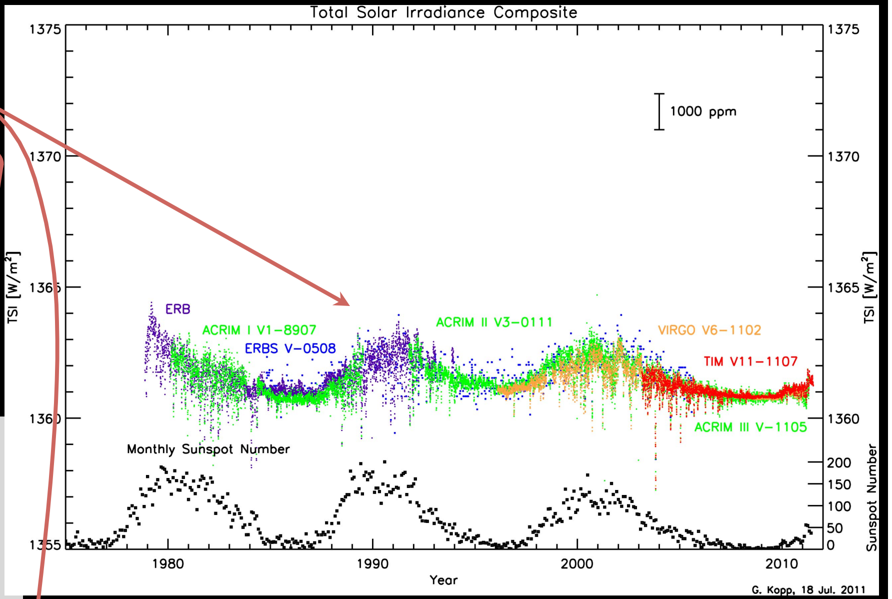


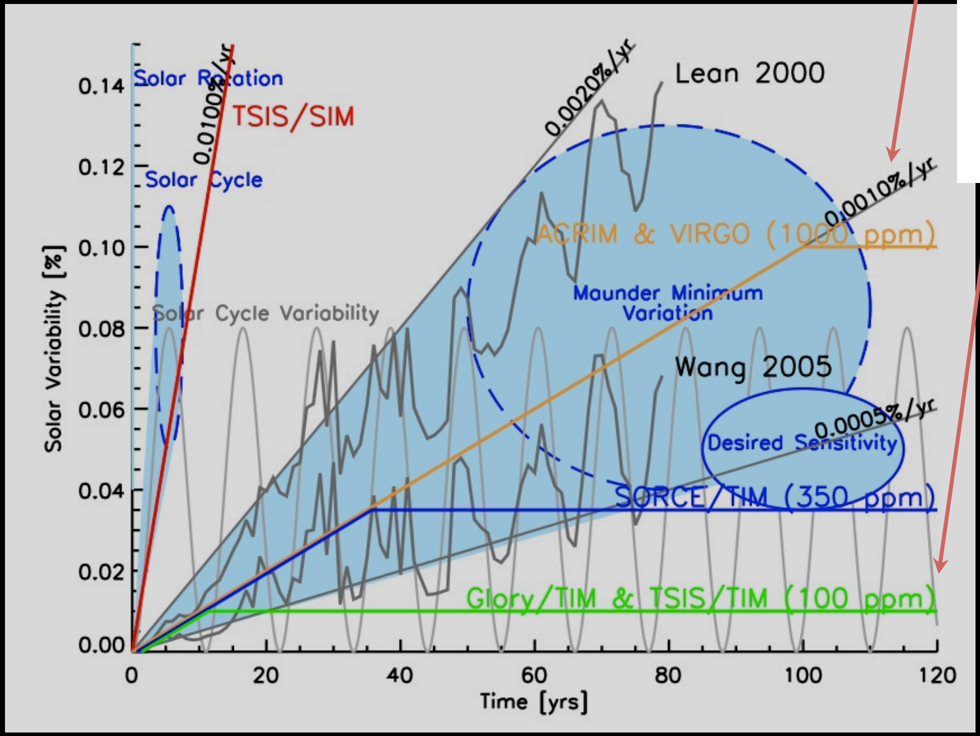
Constructing Historical Irradiances



TSI Requirements To Address Climate Needs

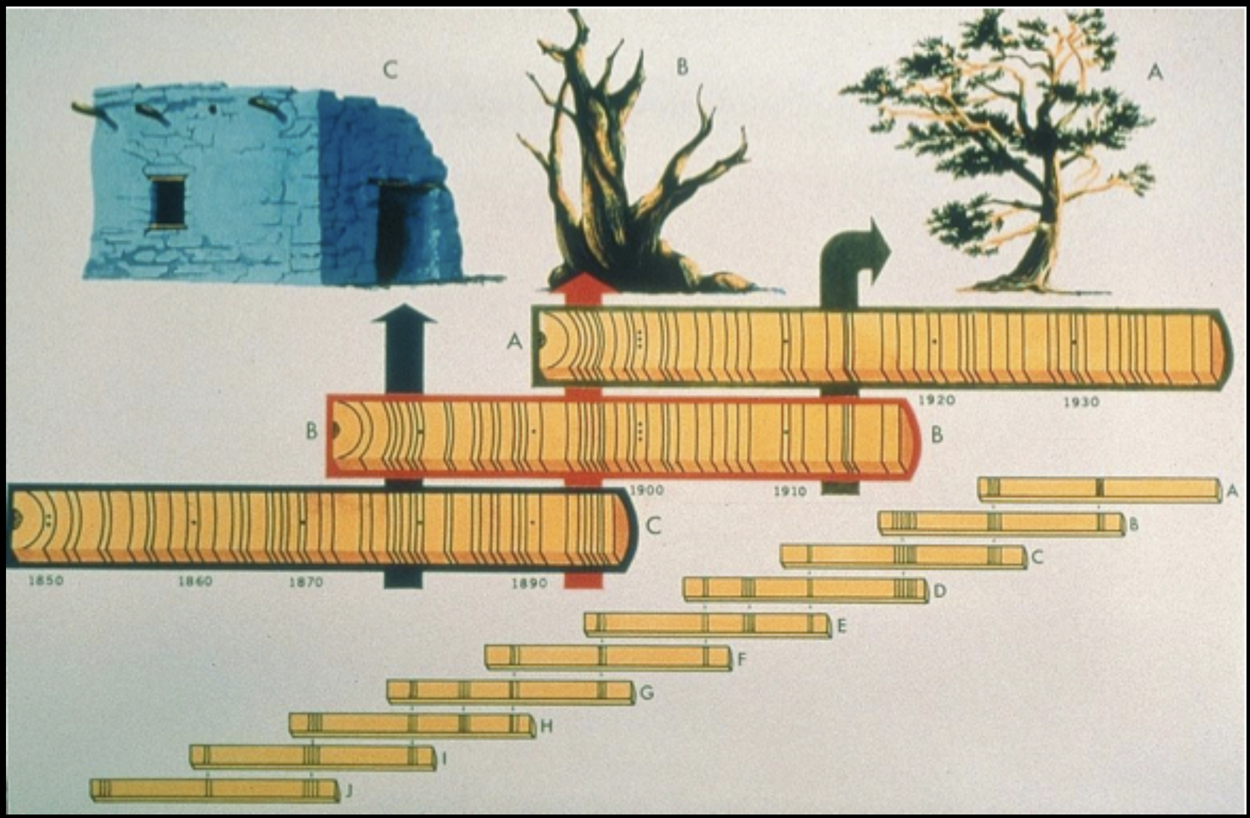
- TIM Performance Requirements
  - Accuracy 0.01% (1 σ)
  - Stability 0.001%/yr (1 σ)
  - Noise 0.001% (1 σ)



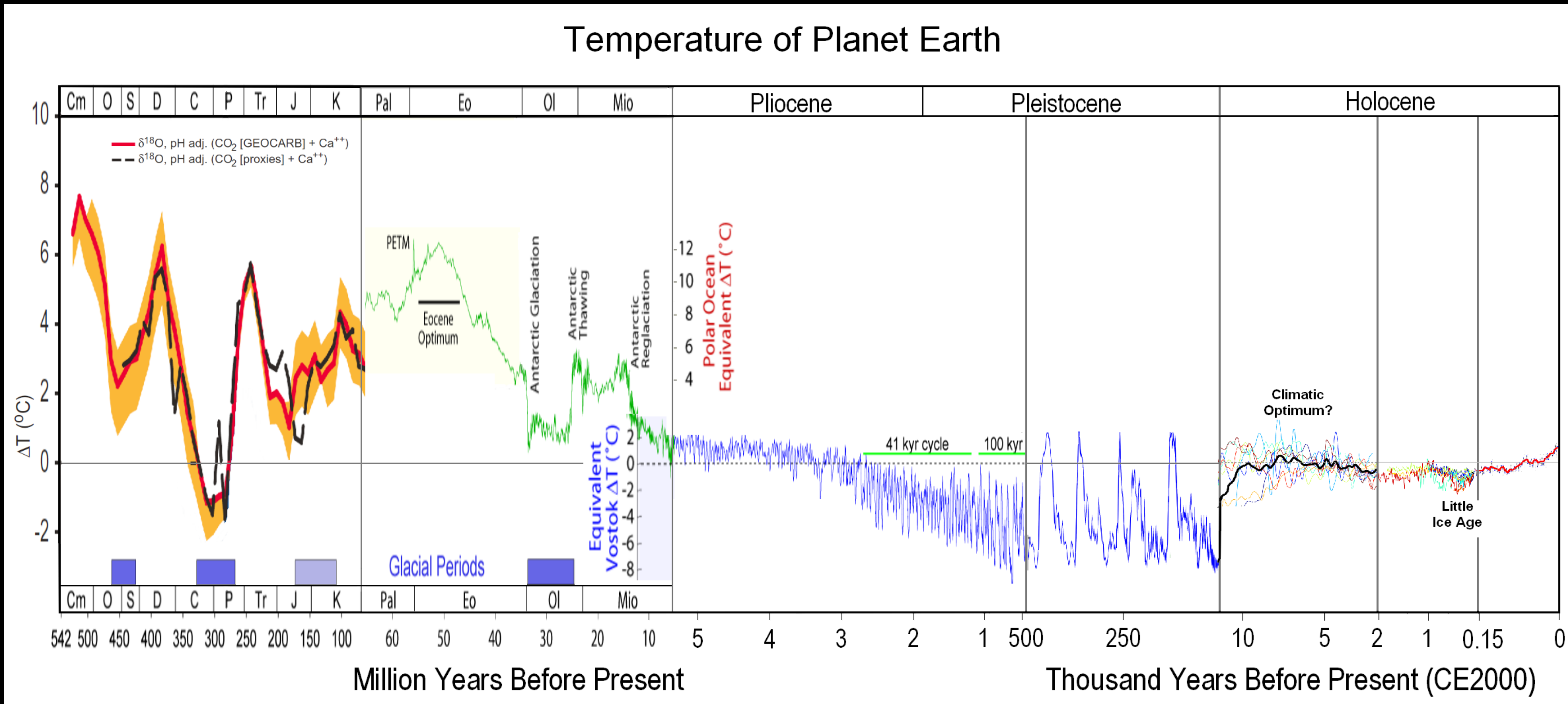


Climate Proxies

- 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, corals, microfossils



Paleo-Climate Temperatures



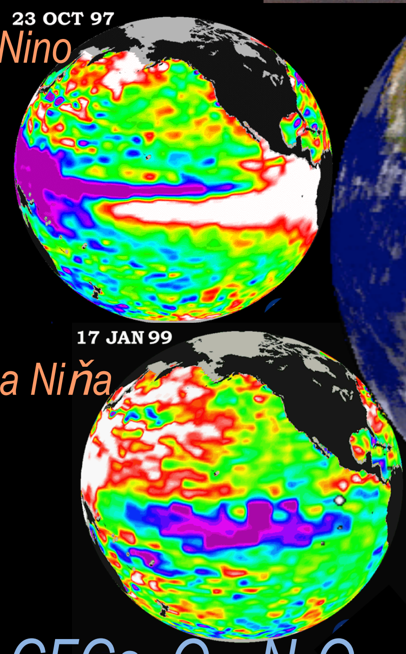
There Are Many Causes of Climate Change

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)*

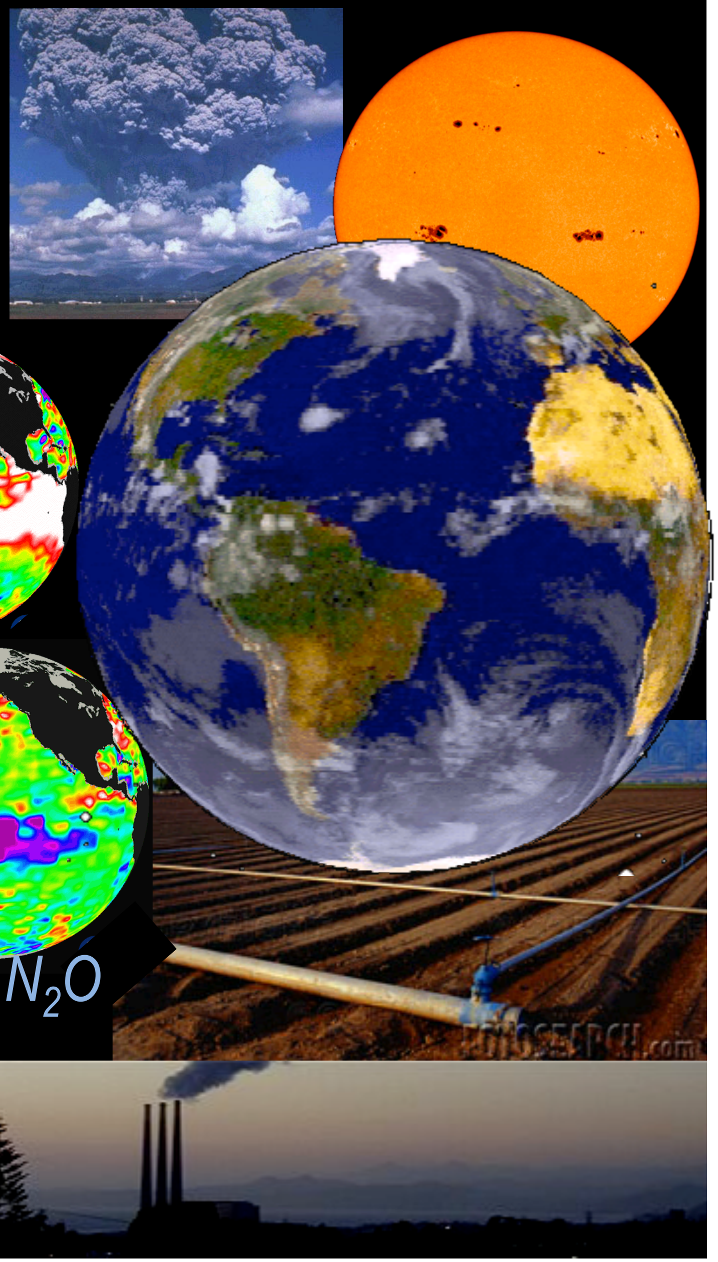


Land Cover Changes

Anthropogenic Forcings

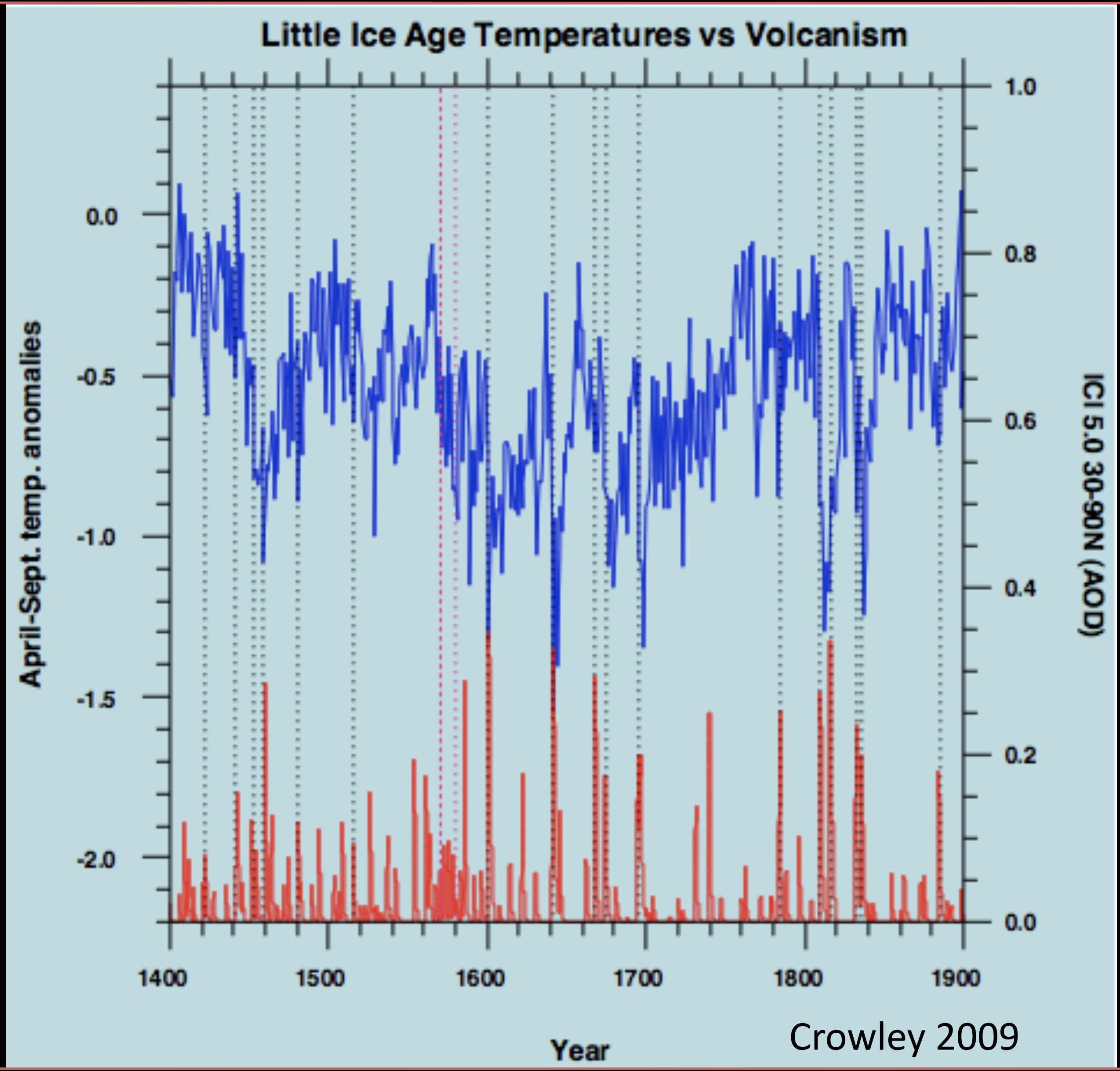
- atmospheric GH gases - *CO_2, CH_4, CFCs, O_3, N_2O*
- tropospheric aerosols - *direct and indirect effects*

of soot, sulfate, carbon, biomass burning, soil dust

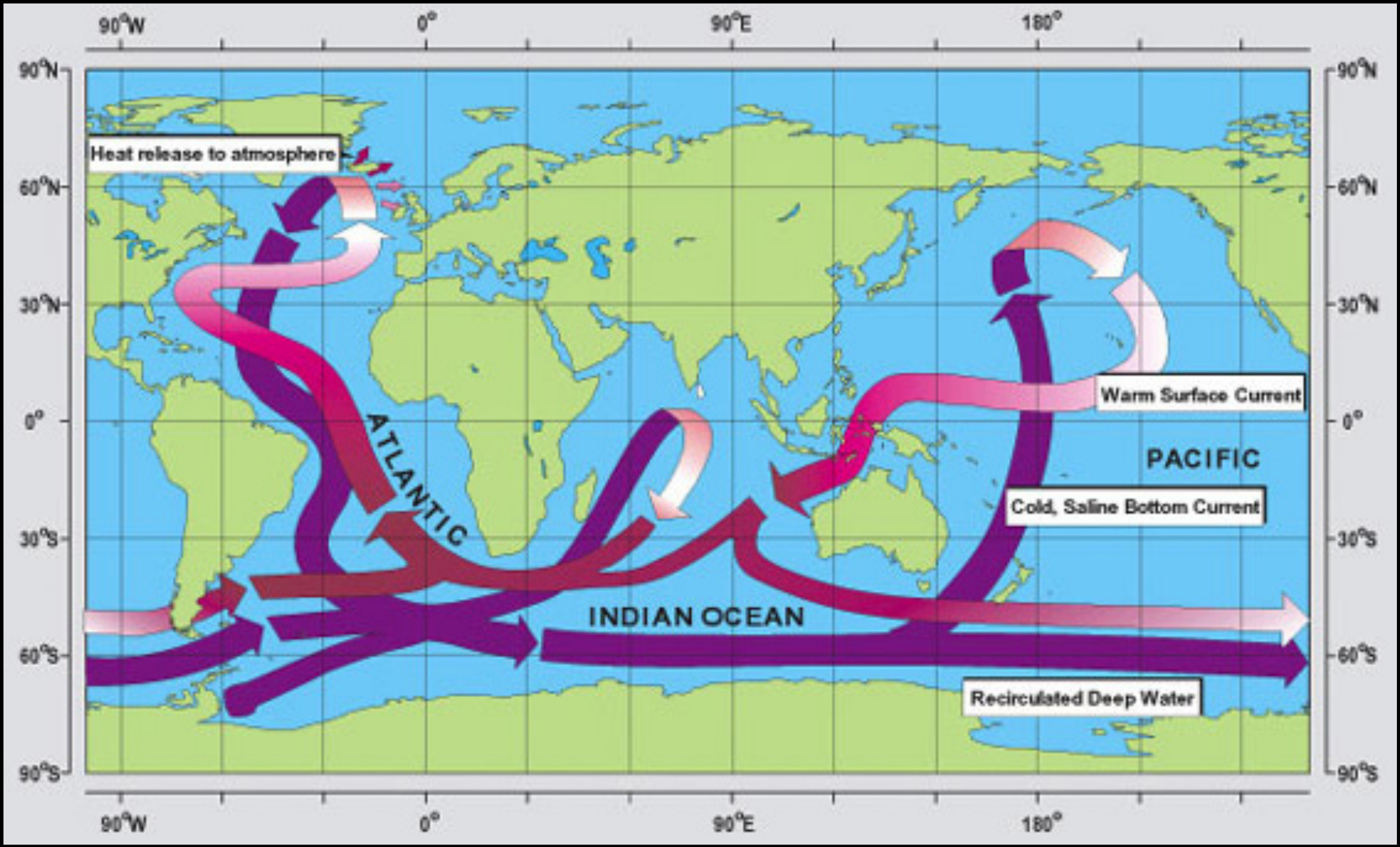


courtesy of Judith Lean, NRL

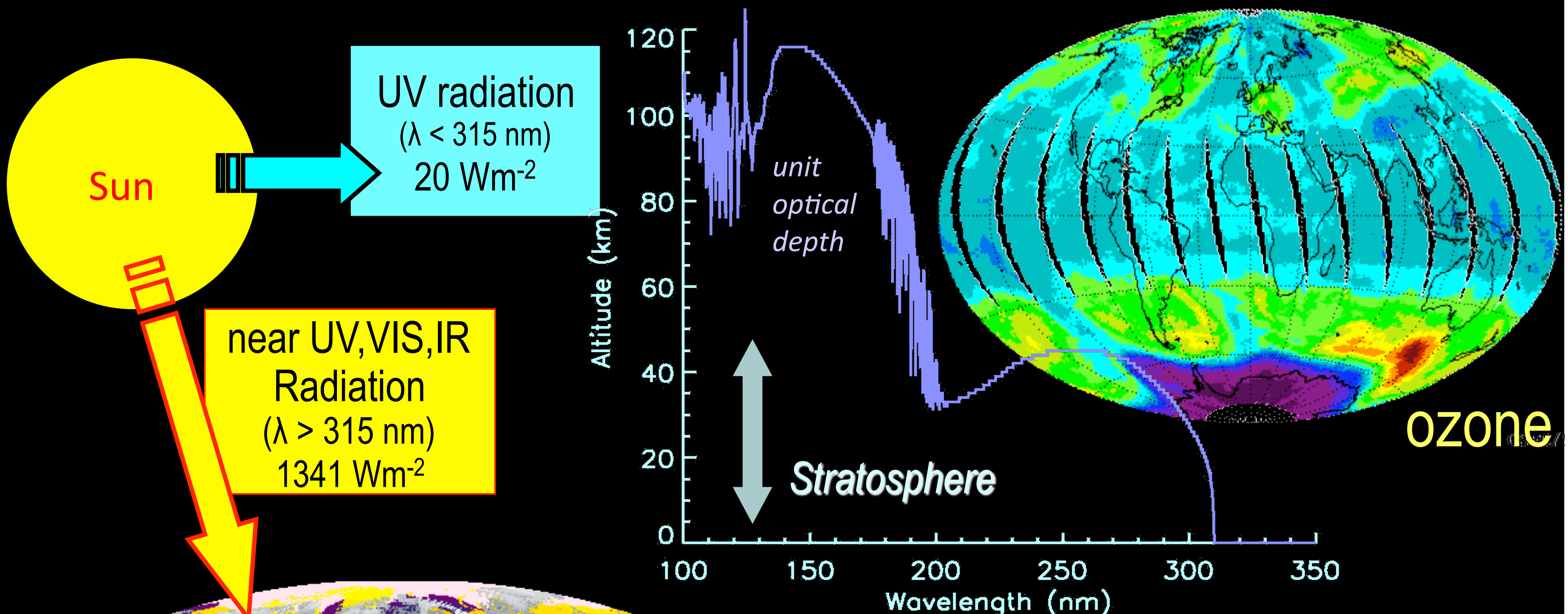
Volcanism Causes Cooling

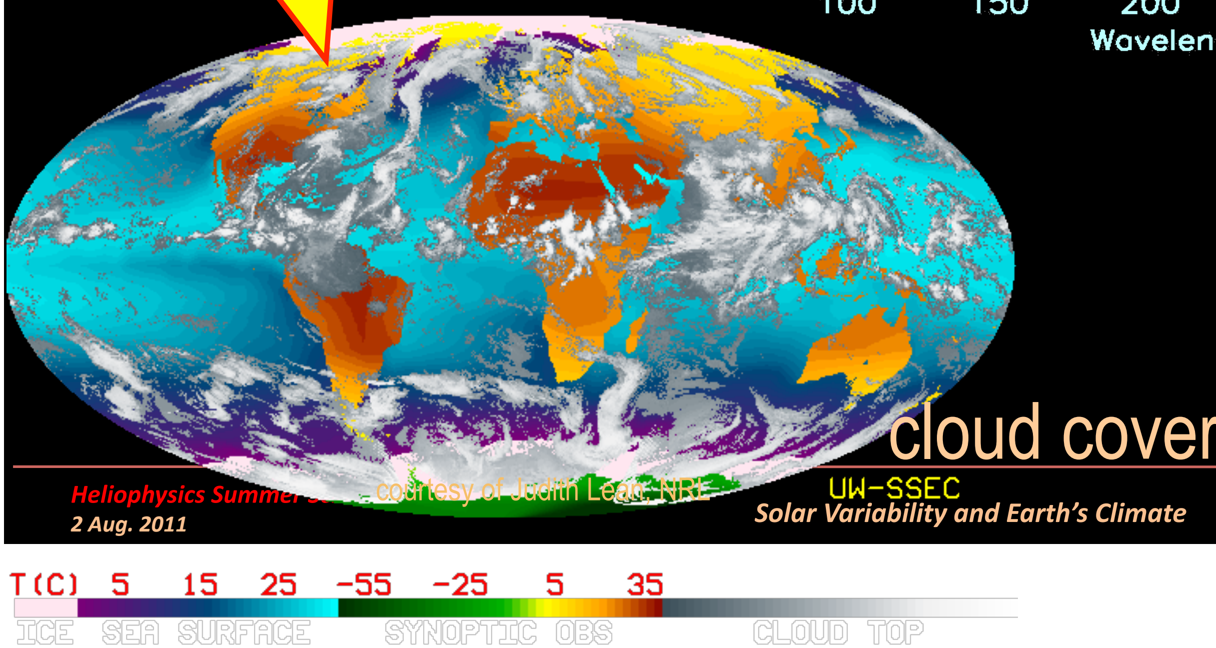


Ocean/Atmosphere Coupling

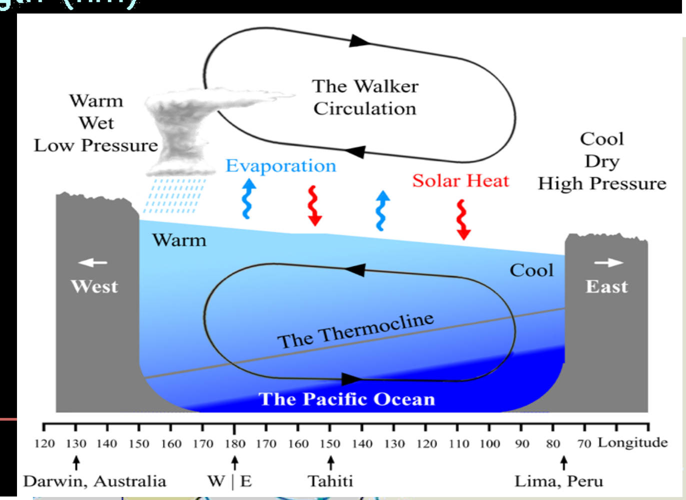


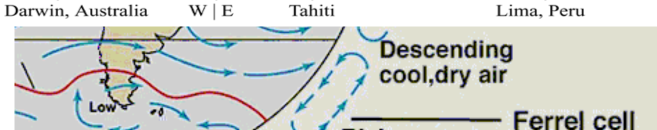
Solar-Terrestrial Radiative Processes Depend on Wavelength, Geography, Altitude





courtesy of Judith Lean, NRL





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

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

Anthropogenic Influence

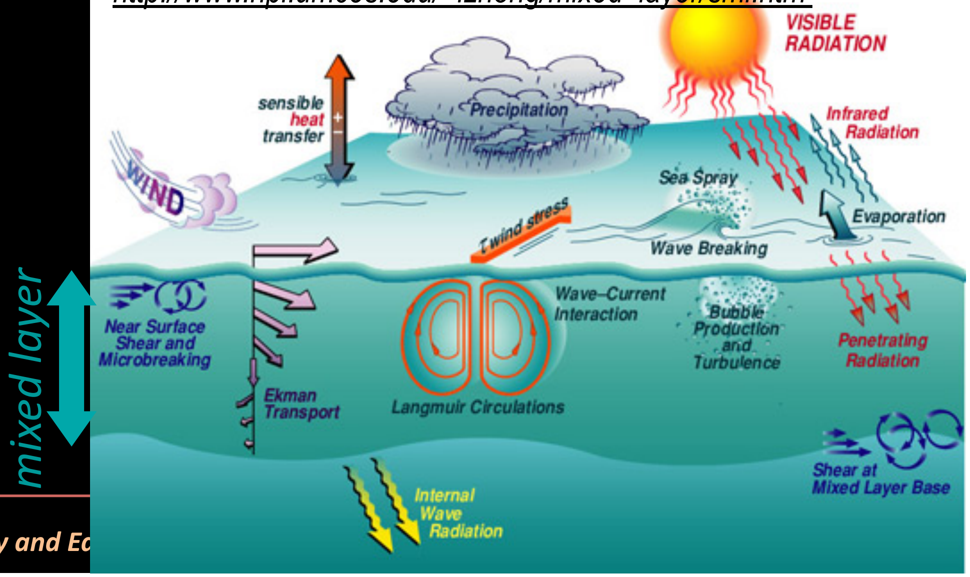
$\Delta T = 0.4°C$ (1980-2006)

$F = 1\ Wm^{-2}$ (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

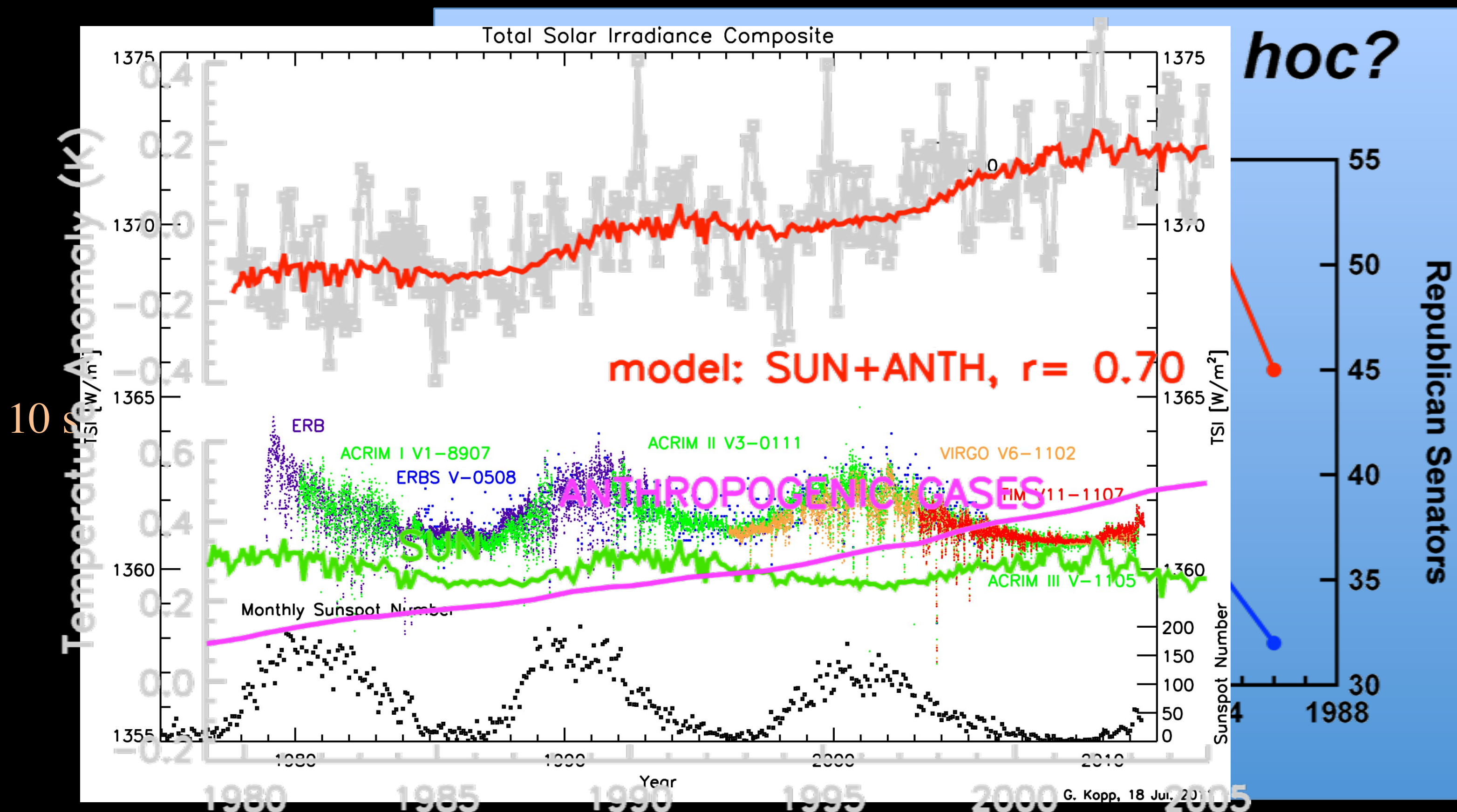
http://www.hpl.umces.edu/~lzhong/mixed_layer/sml.htm



courtesy of Judith Lean, NRL

What's Needed to Determine Climate Sensitivities?

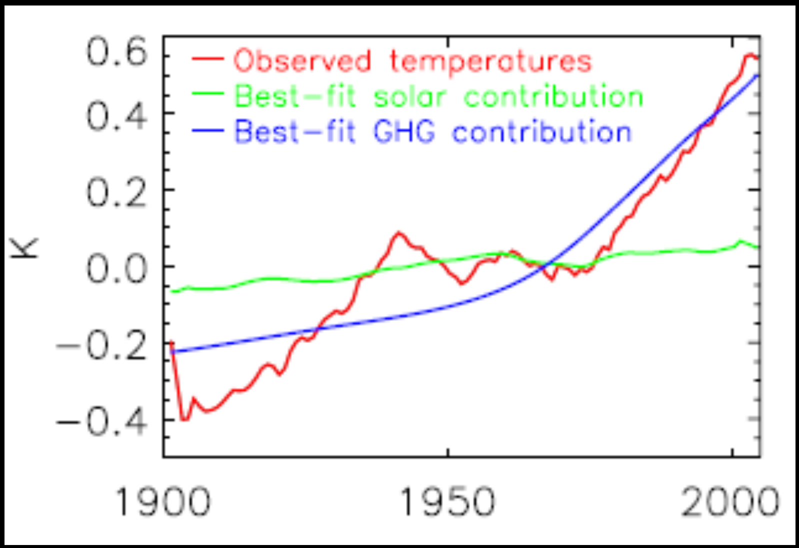
1. Need <u>accurate and stable long-term records</u> of both climate and driving causes
2. Need to understand <u>cause and effect</u> mechanism
   – Correlation does not imply causation



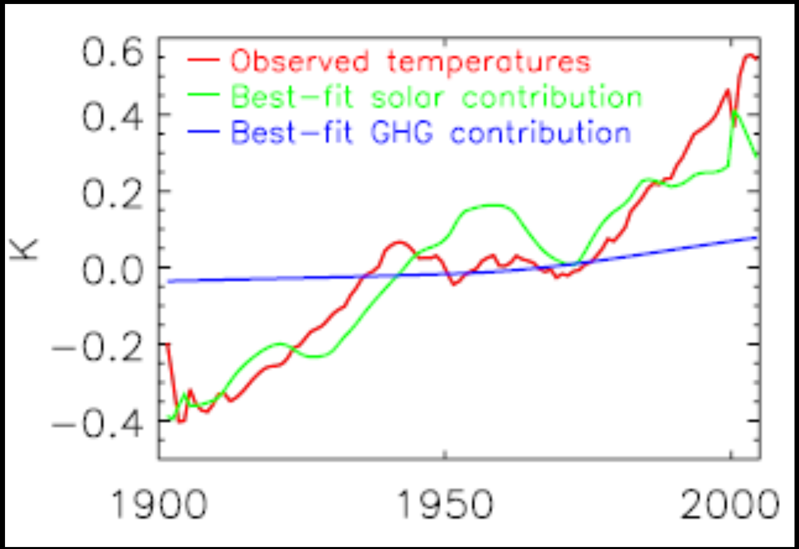
Sun or Greenhouse Gases? It Depends How You Fit...

- Stepwise iterative regression
  1. Fit using variable with highest correlation
  2. Remove that variable
  3. Repeat with next highest correlation

Ch. 12 uses iterative fits –
Need simultaneous regressions



9-year running mean smoothing

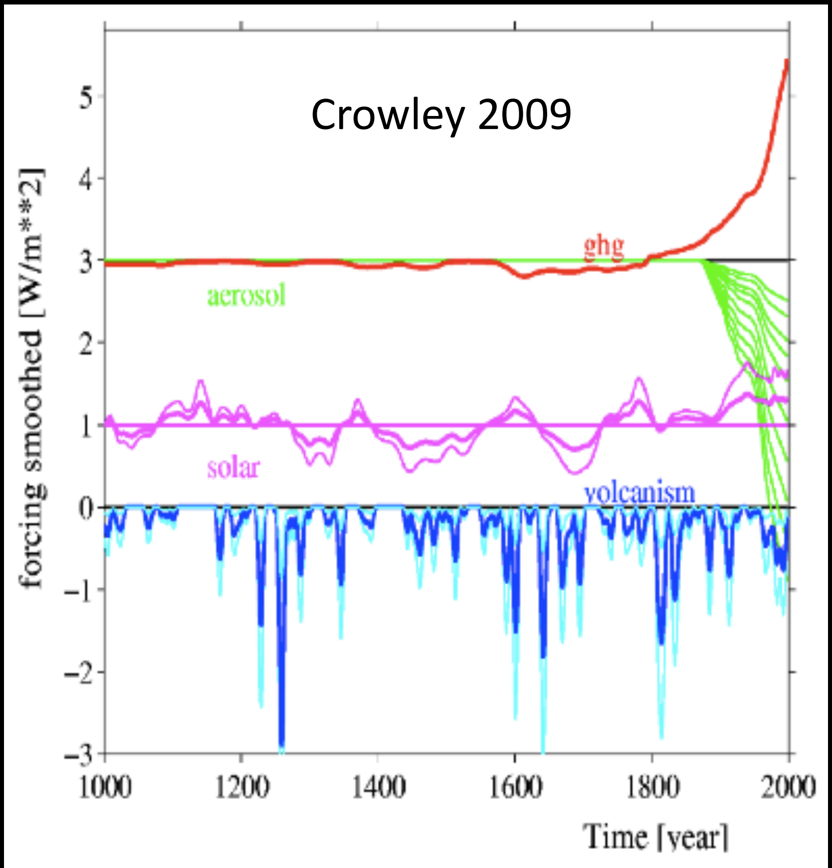


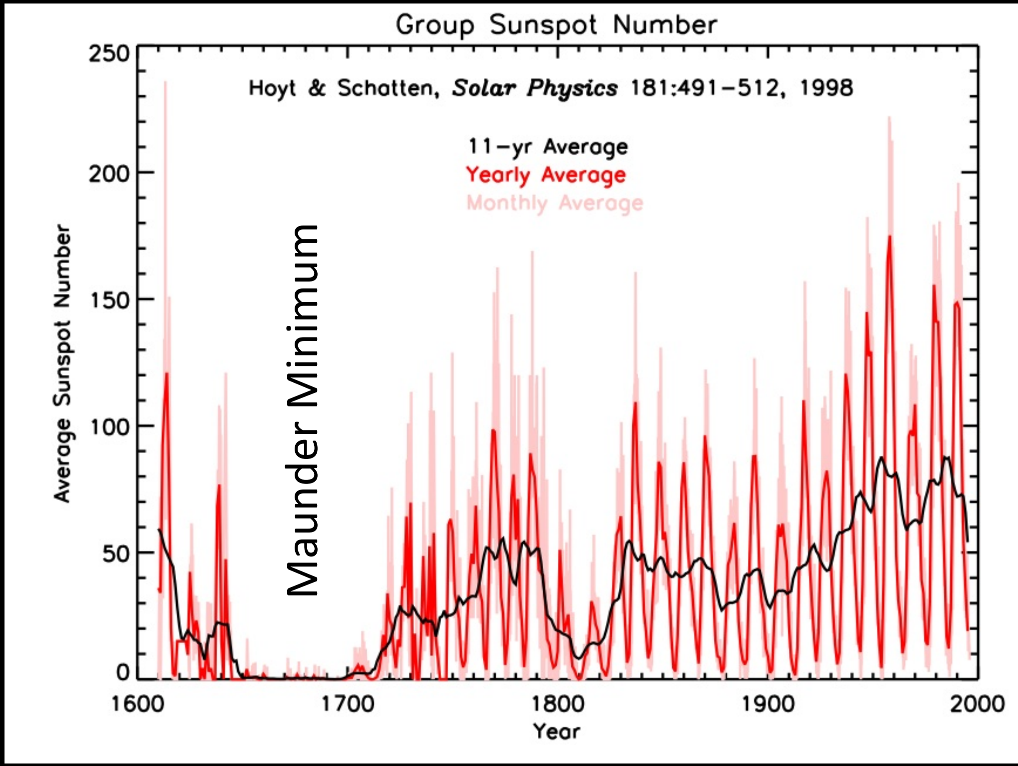
11-year running mean smoothing

From Ingram, W.J., *Space Science Reviews* 125: 199–211, 2006.

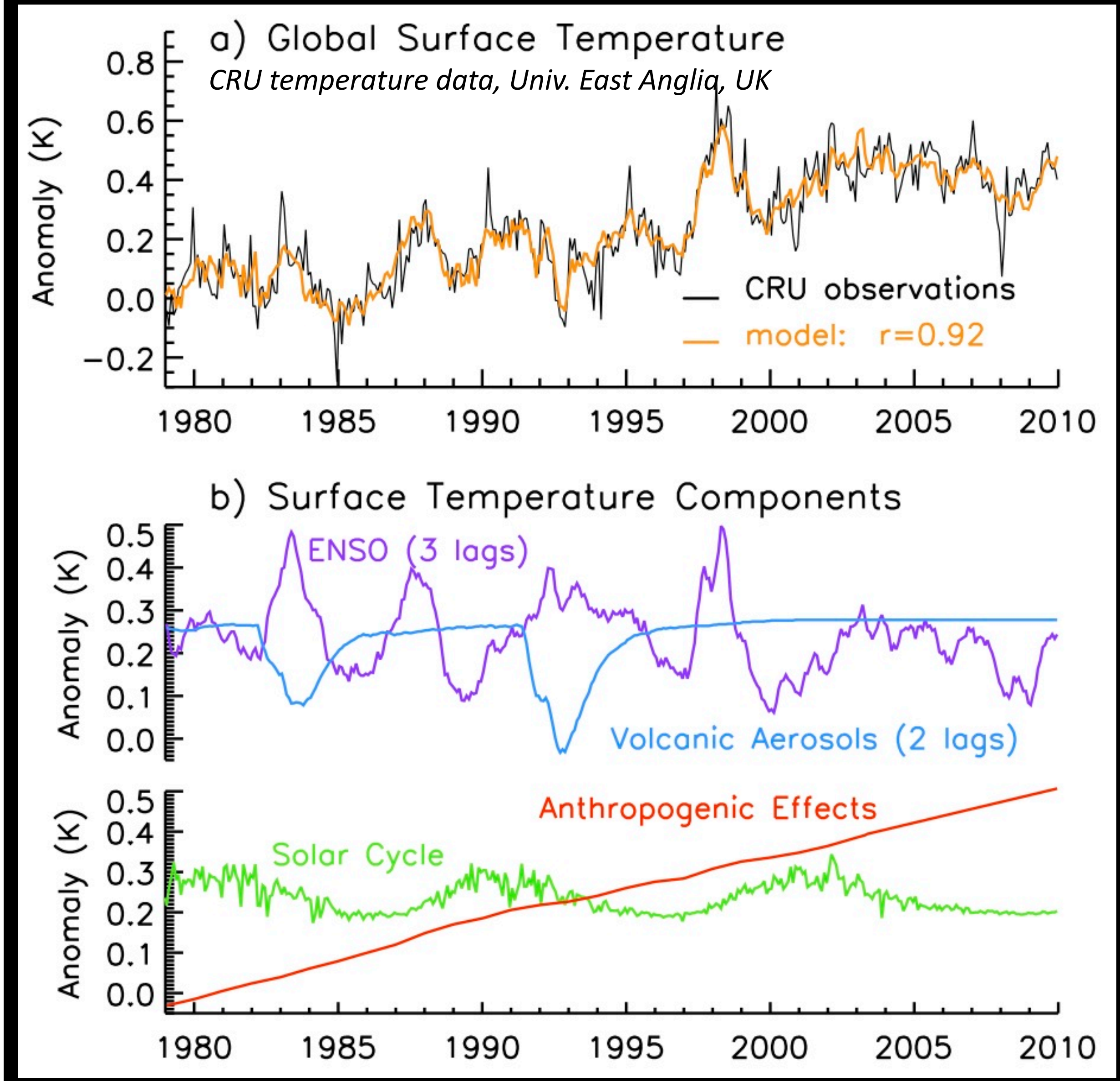
What Caused Europe's Little Ice Age?

- Maunder Minimum
  - Solar output decreased 0.1-0.3% for 70 years
- Or volcanism





Global Surface Temperature Responses



Combined ENSO + volcanic aerosols + solar activity + anthropogenic effects explain 85% of observed temperature variance

+0.2°C 1997-98 "super" ENSO

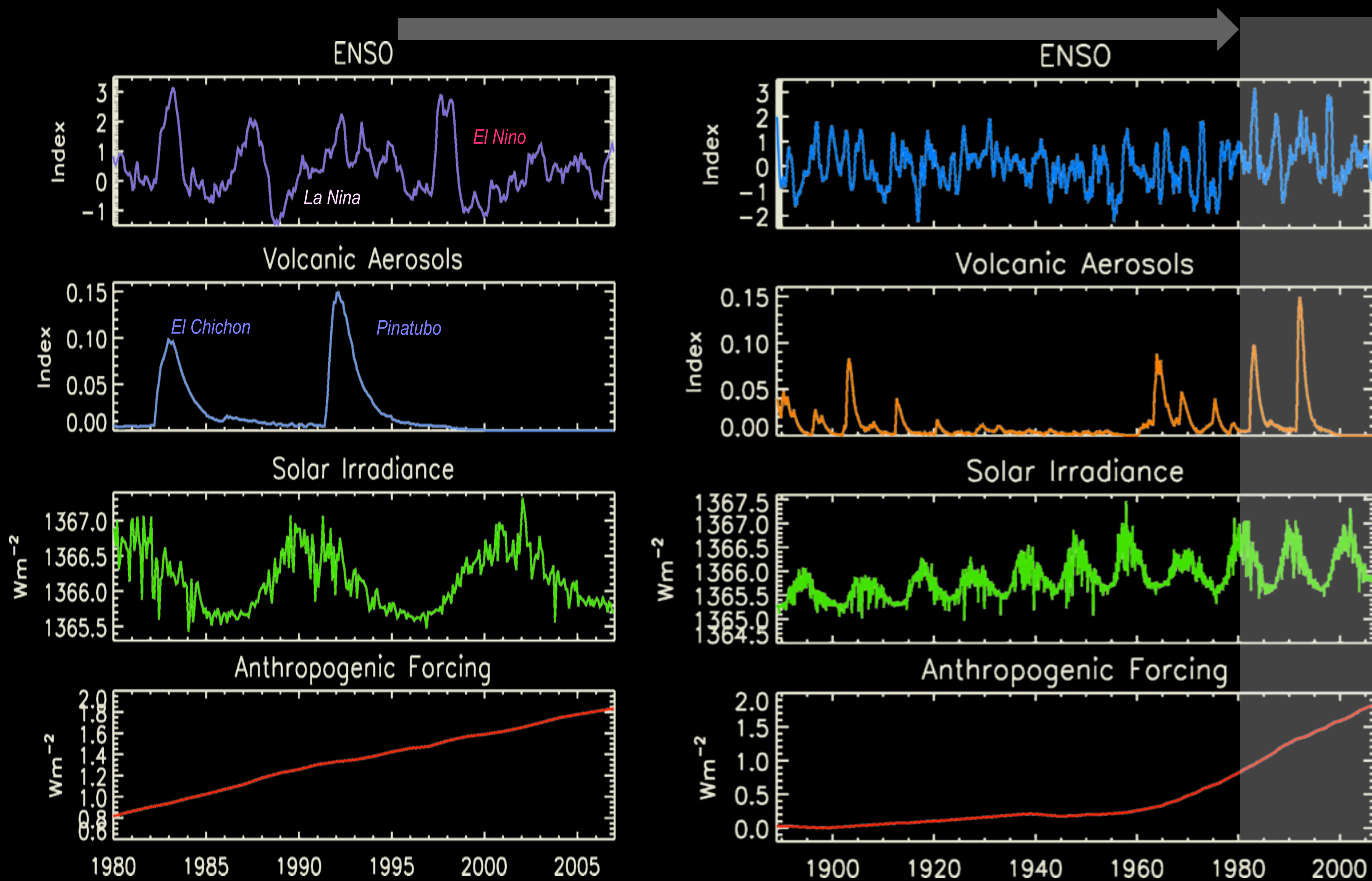
-0.3°C Pinatubo volcano

+0.1°C Solar cycle

+0.4°C Anthropogenic effects

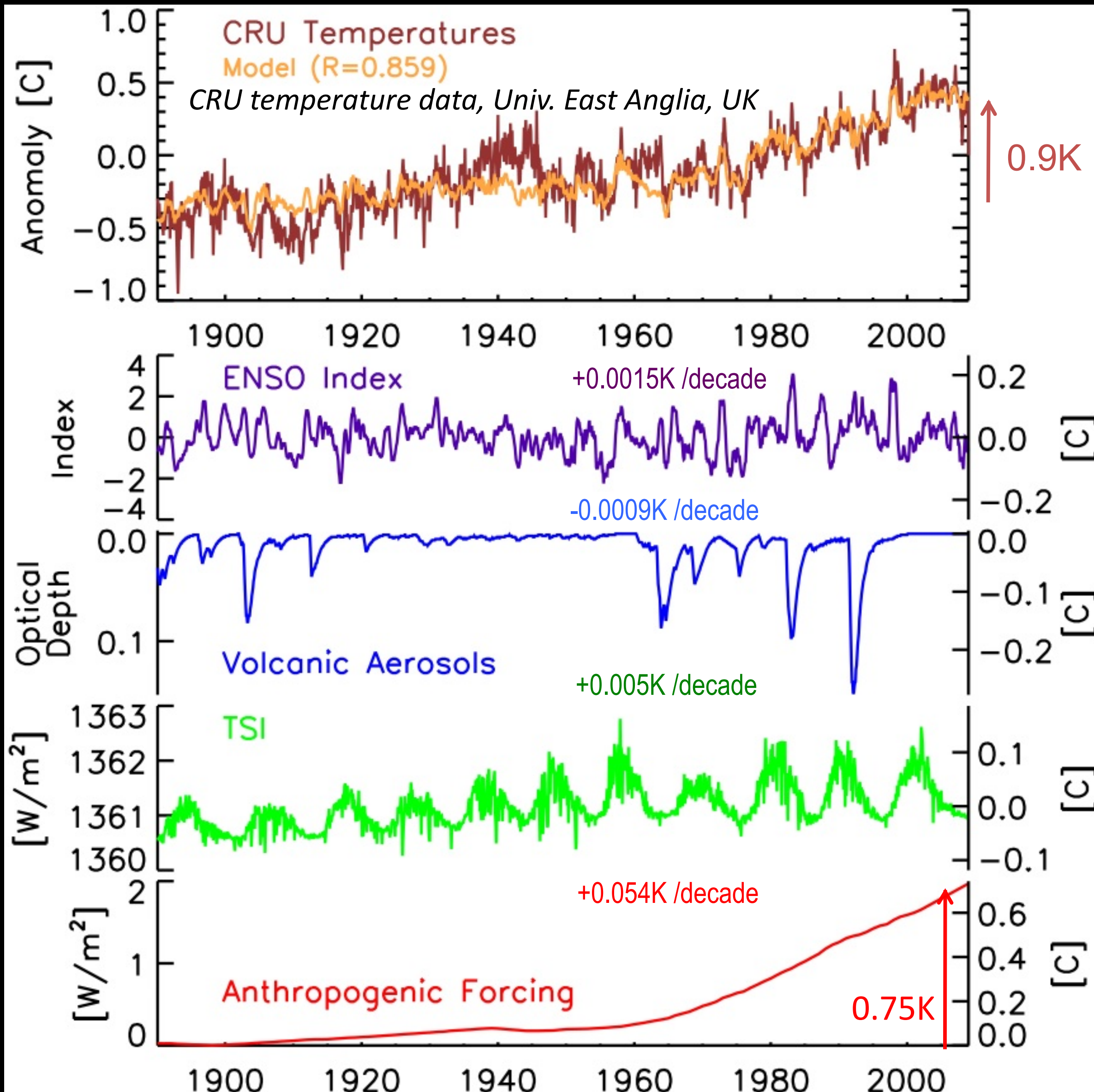
from Kopp & Lean 2011

Climate Influences Since 1890



courtesy of Judith Lean, NRL

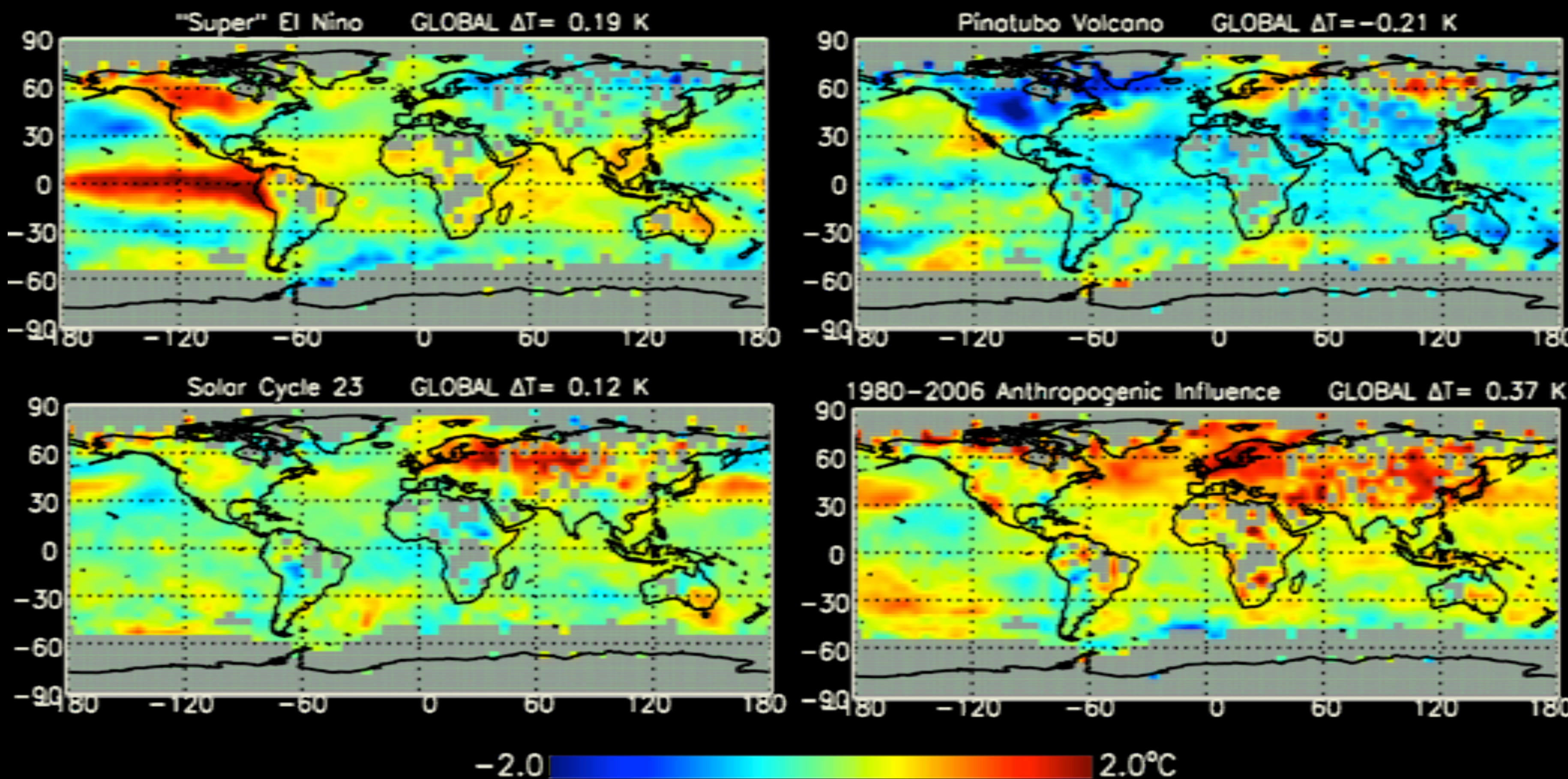
Global Surface Temperature Responses Since 1890



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

Natural components account for <15% of warming since 1890

Regional Annual Response Patterns

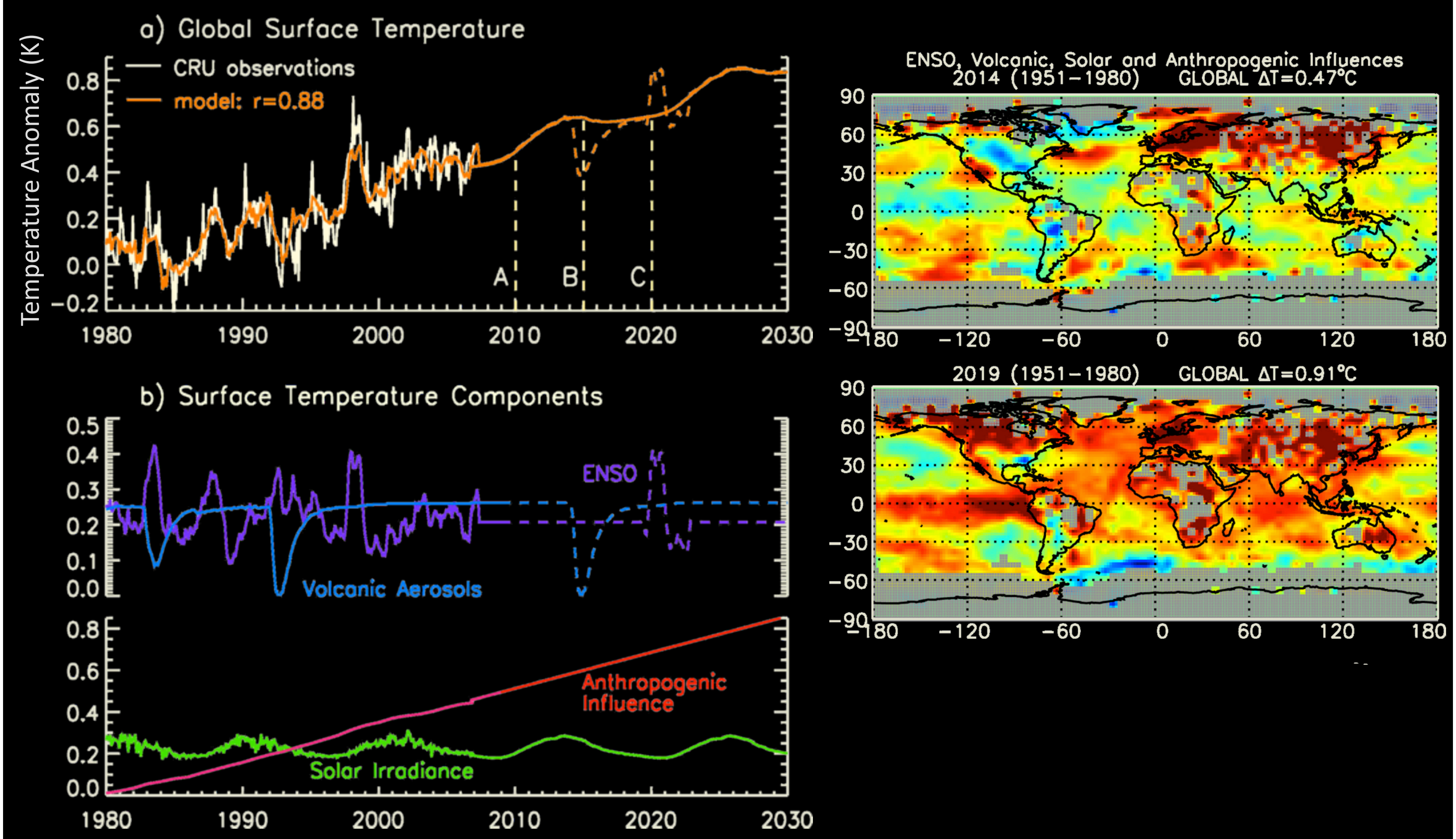


no observations

5°x5° lat/long

courtesy of Judith Lean, NRL

Climate Change in Next Decades



courtesy of Judith Lean, NRL

Paleo Sun–Climate Synopsis

…when solar activity is high….

increased temperature & moisture SW Alaska
Sheng et al., 2003

drought Western US
Cookl et al., 2001

warming North Atlantic
Bond et al., 2000

stronger monsoon Wangxiang cave
Zhang et al., 2008

high rainfall Oman
Neff et al., 2001

Mayan drought Cariaco Basin
Hodell et al., 2001
Haug et al., 2003

weakened upwelling and trade winds (warmer SSTs) Cariaco Basin
Black et al., 1999

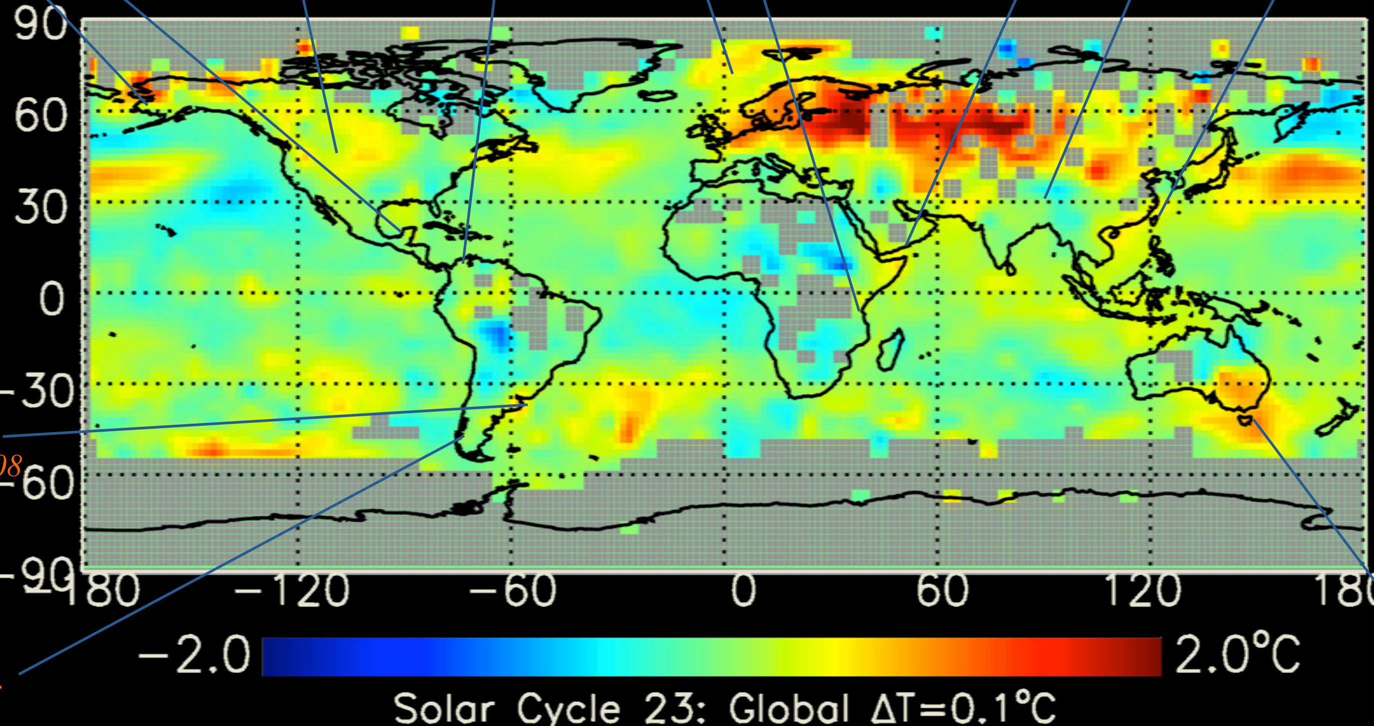
drought Equatorial East Africa
Verschuren et al., 2000

warming Beijing
Tan et al., 2004

streamflow Parana River
Mauas et al., 2008
.

tree-rings Chile
Roig et al., 2001
Nordemann et al.

warming Tasmania
Hill et al., 2007



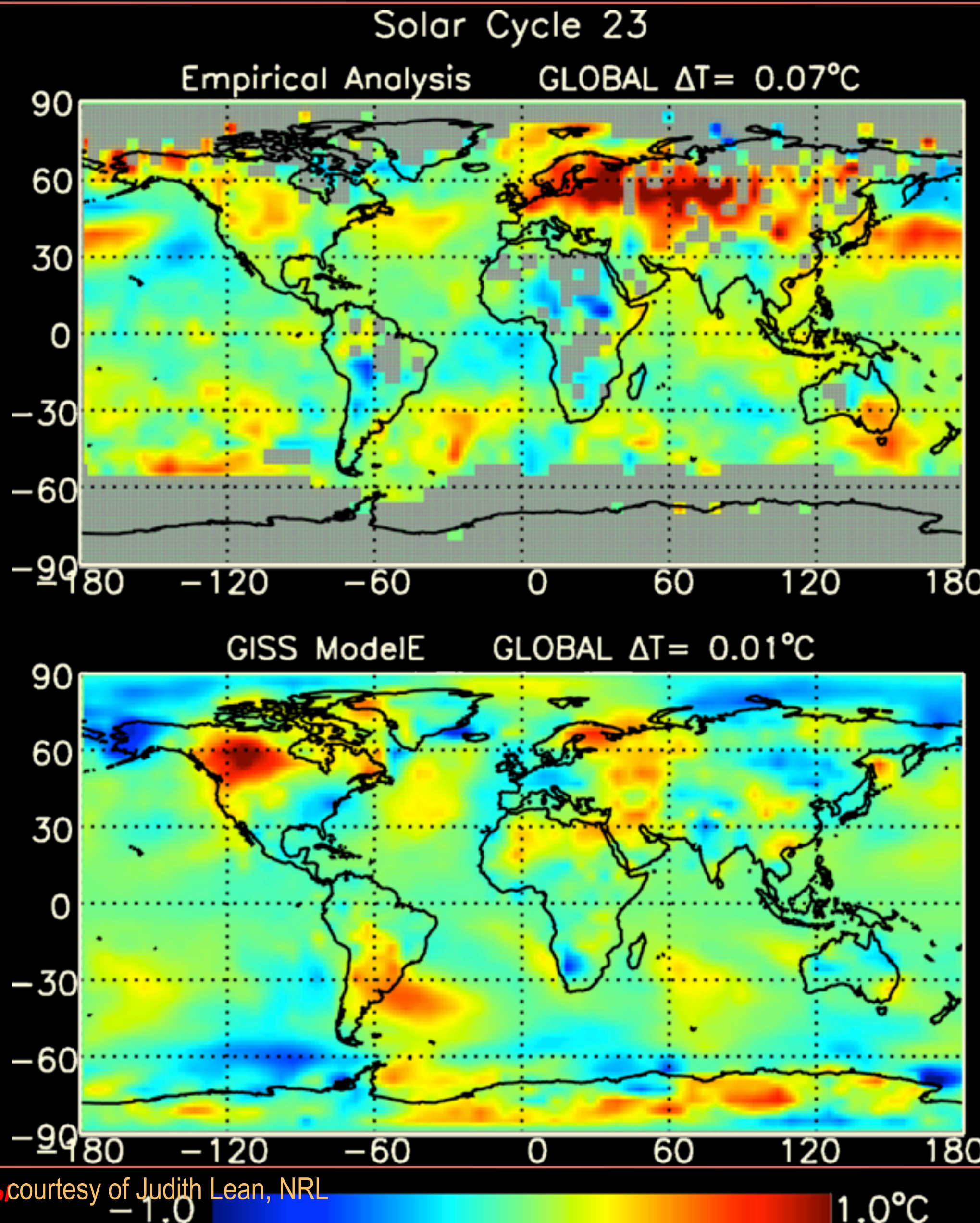
significant local changes do not imply global changes of equal magnitude

courtesy of Judith Lean, NRL

Current Climate Modeling Capability

derived from observations

simulated by GISS Model E climate model



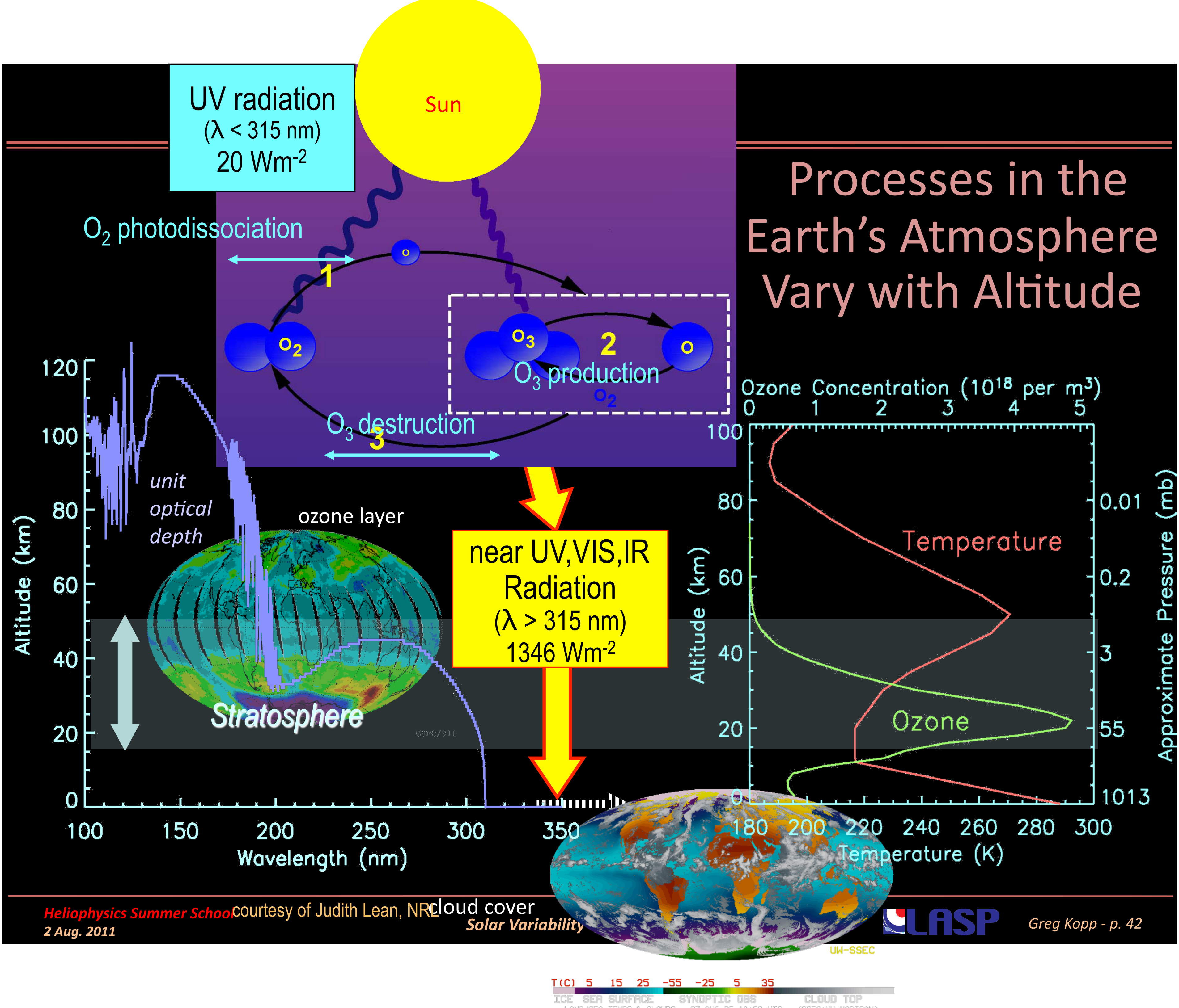
courtesy of Judith Lean, NRL

IPCC AR5 climate change simulations now underway input solar spectral irradiance (AR4 used TSI)

Schmidt et al., 2011 "Climate Forcing Reconstructions for use in PMIP simulations in the last millennium"

.. ..inputs are based on NRL SSI solar spectral irradiance variability model

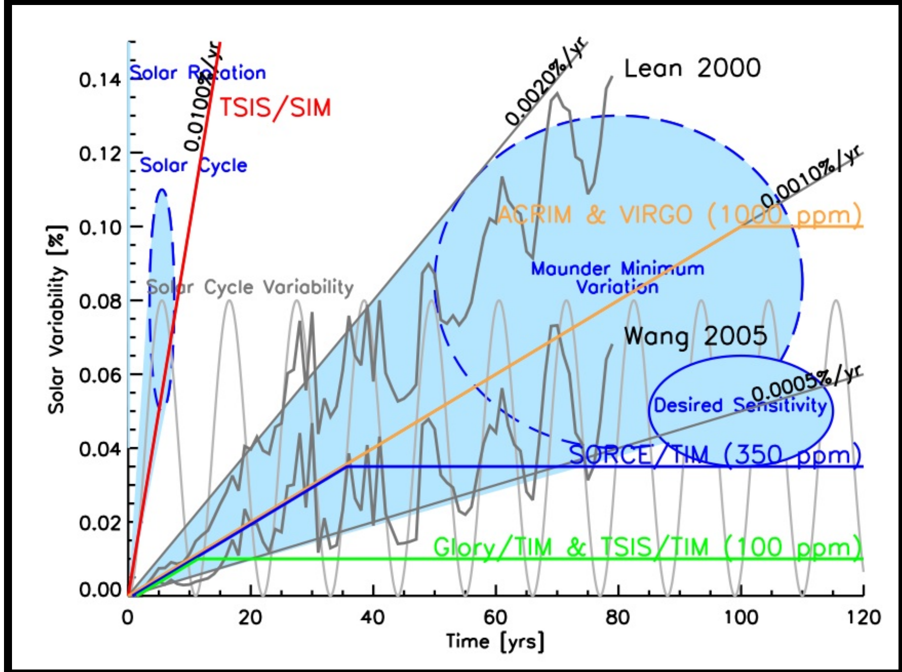
Processes in the Earth's Atmosphere Vary with Altitude

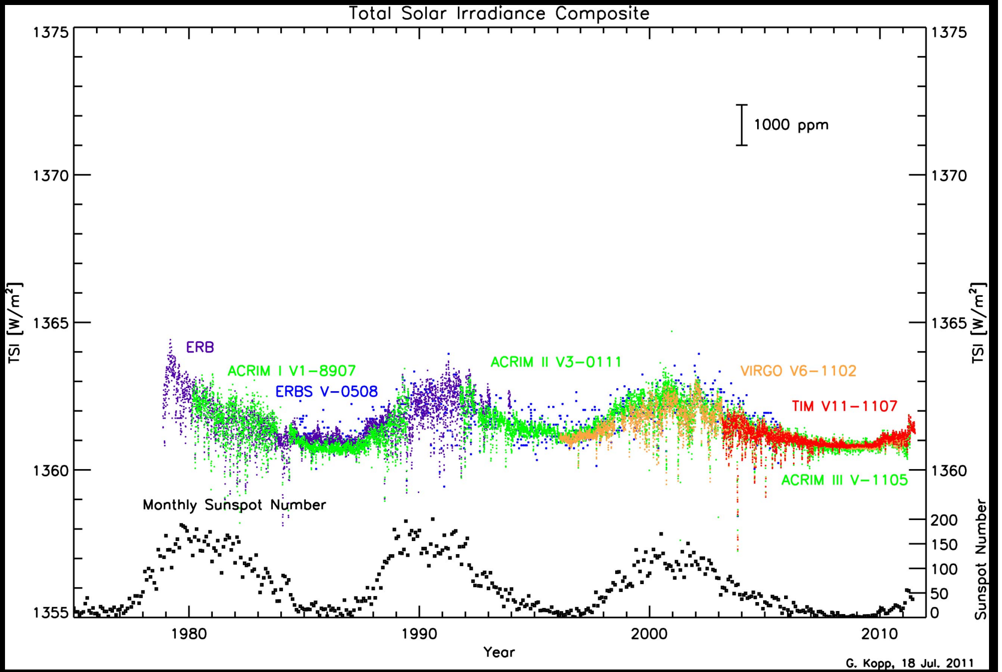


Value of TSI Measurements for Climate Science

TSI Measurements

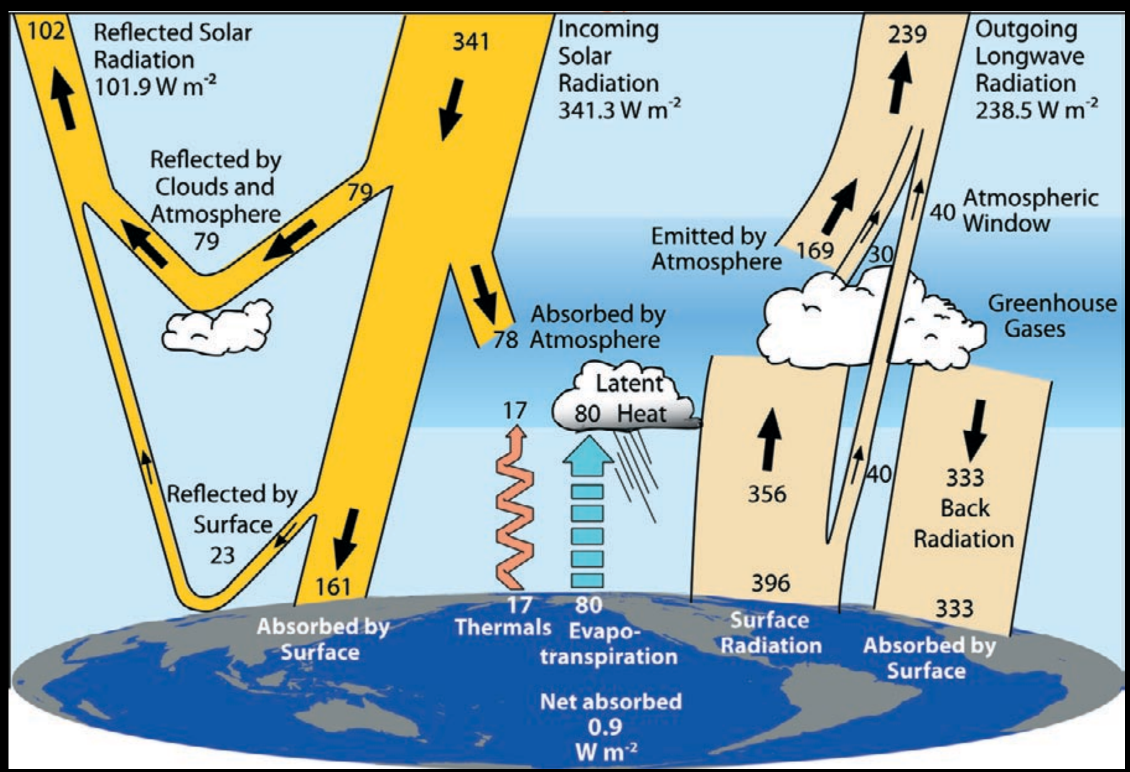
1. Are the most stable solar irradiance measurements
   – Achieve stabilities necessary to detect climate-relevant solar variability
2. Provide >30 year solar irradiance record of entire radiative input to Earth's climate system





Measurements Help Attribute Climate Change

- Shortwave spatial/spectral measurements help identify
  - Clouds
  - Land use (deforestation, urbanization)
  - Atmosphere (aerosols, water, CO_2, ...)
  - Ice/snow cover
  - Albedo
- IR helps identify
  - Temperature profile
  - Atmosphere
  - GHG emission
- TSI
  - Net energy
- Incoming & outgoing
  - Energy balance



from Trenberth, Fasullo, and Kiehl, 2009

CERES and TIM Are Improving Radiative Balance Understanding

Imbalance: 4.2±2.2 W/m²

(1-σ uncertainties)

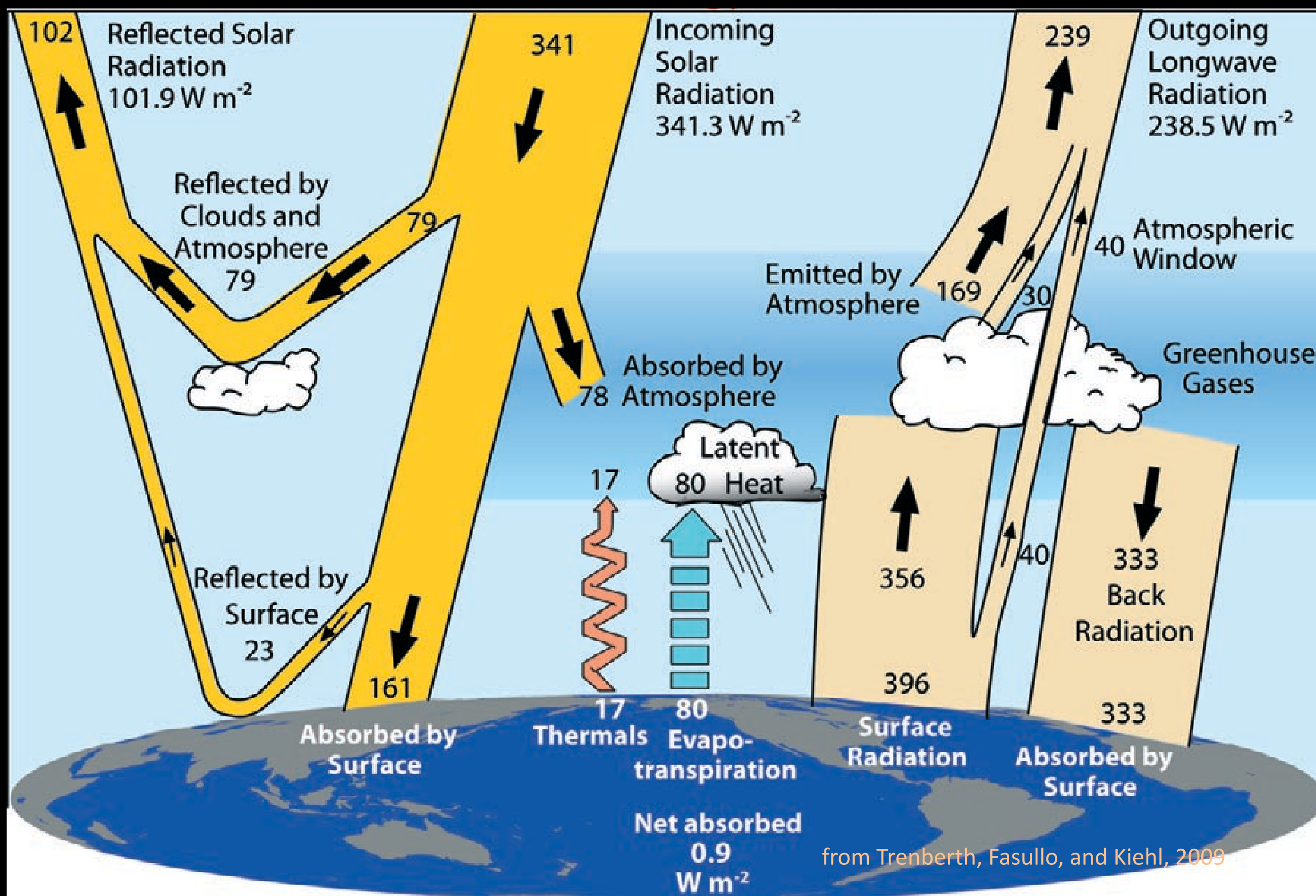
TIM: 340.3 W/m²

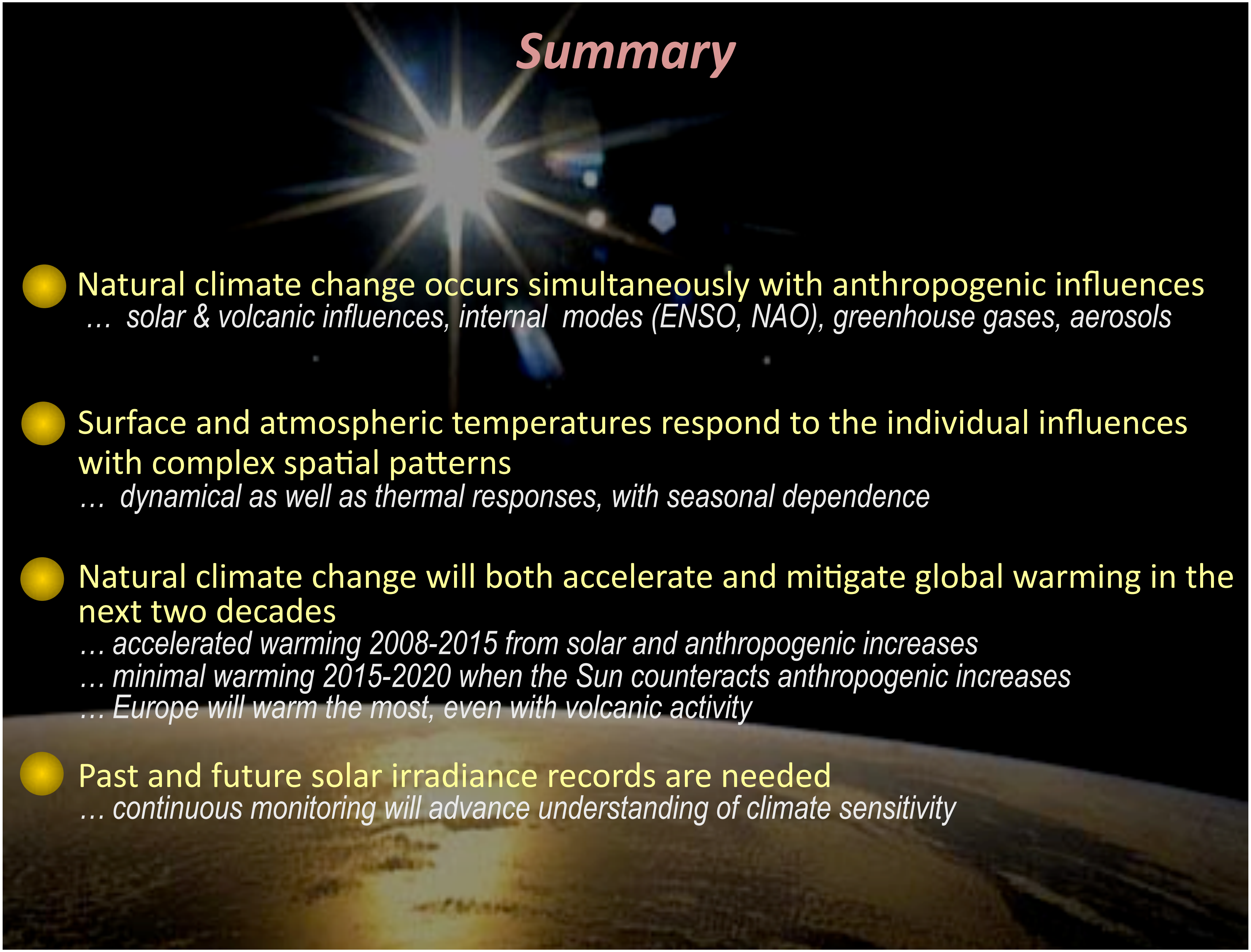
Oceans: 0.85 W/m²
Earth Sph: 0.16 W/m²
Terminator: 0.3 W/m²

CERES SW: 97.7 W/m²

CERES LW: 237.1 W/m²

values from Loeb *et al.*, 2008




Summary
Natural climate change occurs simultaneously with anthropogenic influences
… solar & volcanic influences, internal modes (ENSO, NAO), greenhouse gases, aerosols
Surface and atmospheric temperatures respond to the individual influences with complex spatial patterns
… dynamical as well as thermal responses, with seasonal dependence
Natural climate change will both accelerate and mitigate global warming in the next two decades
… accelerated warming 2008-2015 from solar and anthropogenic increases
… minimal warming 2015-2020 when the Sun counteracts anthropogenic increases
… Europe will warm the most, even with volcanic activity
Past and future solar irradiance records are needed
… continuous monitoring will advance understanding of climate sensitivity