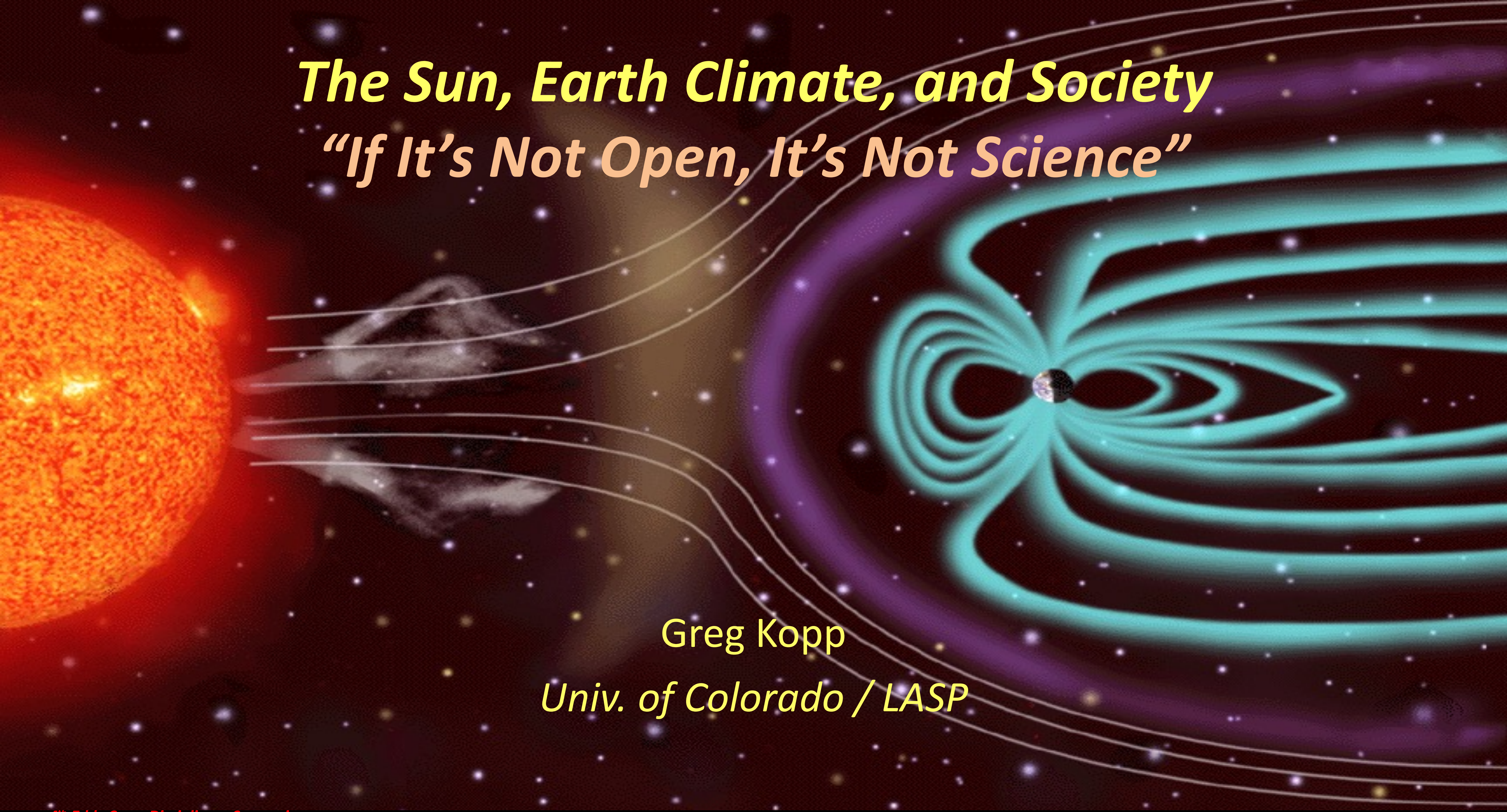
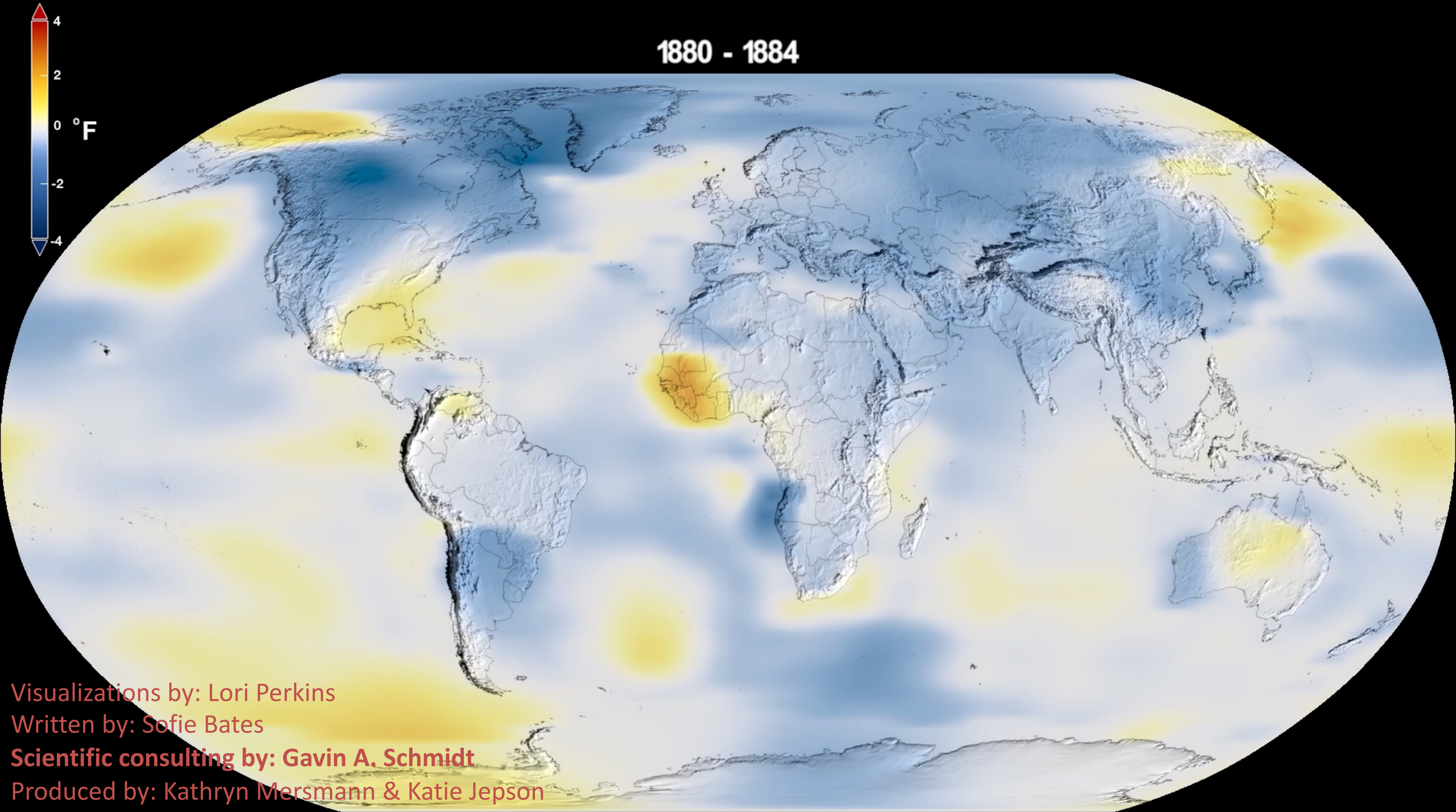
The Sun, Earth Climate, and Society
“If It’s Not Open, It’s Not Science”



Greg Kopp

Univ. of Colorado / LASP



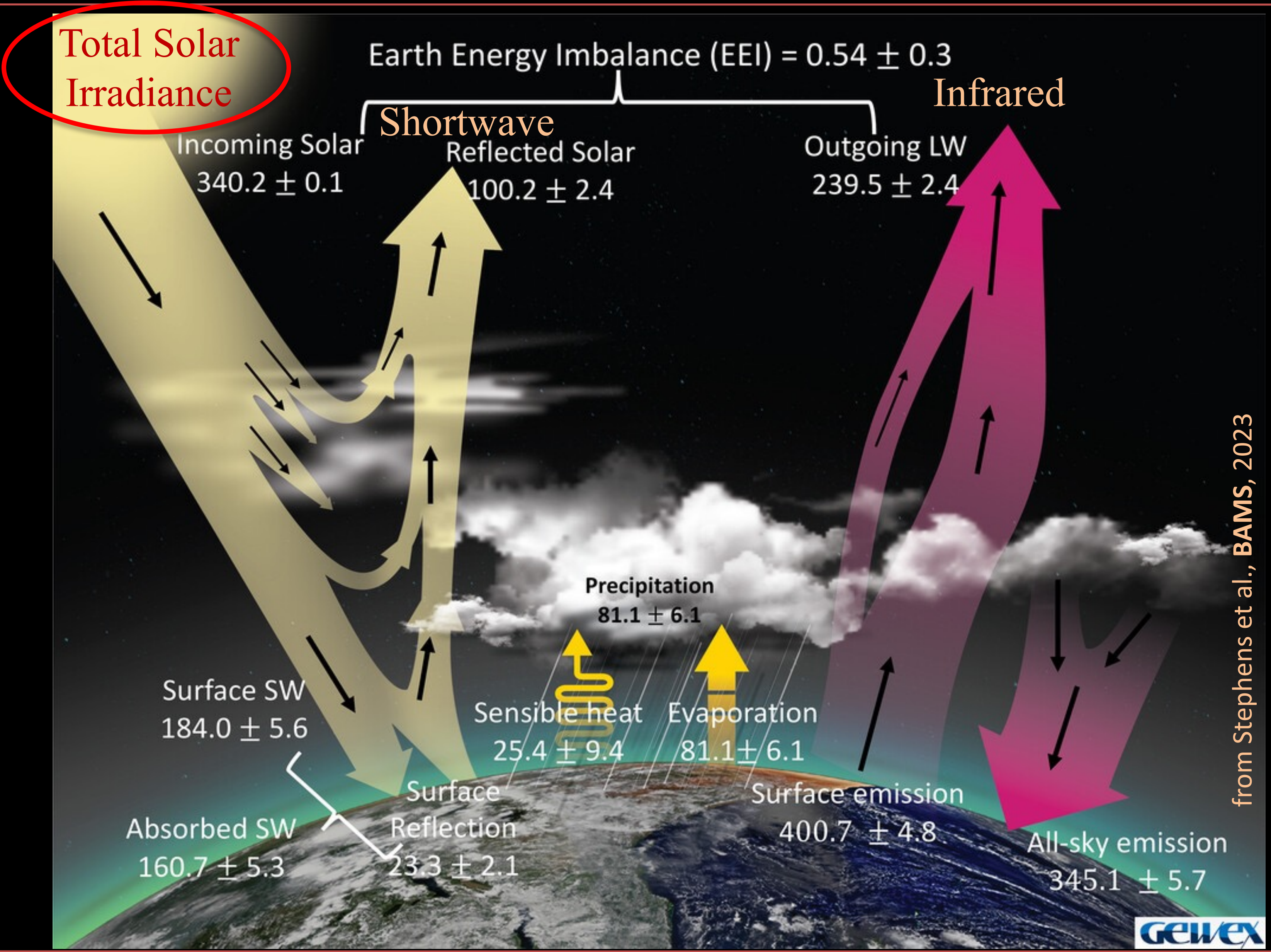
Visualizations by: Lori Perkins
Written by: Sofie Bates
Scientific consulting by: Gavin A. Schmidt
Produced by: Kathryn Mersmann & Katie Jepson

No, It's Not the Sun, Despite What You Might Read

courtesy of Thierry Dudok de Wit, Univ. of Orleans

Total Solar Irradiance Is Nearly All of the Earth's Energy Input

What is this value?



from Stephens et al., **BAMS**, 2023

What Is The Answer?

"There really is an answer?"

"A simple answer?"

"Yes"

~~42~~

1361 W m^{-2}

The solar constant…

…that isn't

The Answer to the Ultimate Question
The Hitchhiker's Guide to the Galaxy (BBC)

99.974 % of the Energy Heating the Earth Comes from 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
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

4000 X

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

Why You Might Expect the Sun to Affect Earth's Climate – and Why It Doesn't (Much)

Fortunately, for an 800-lb gorilla, the Sun is very placid

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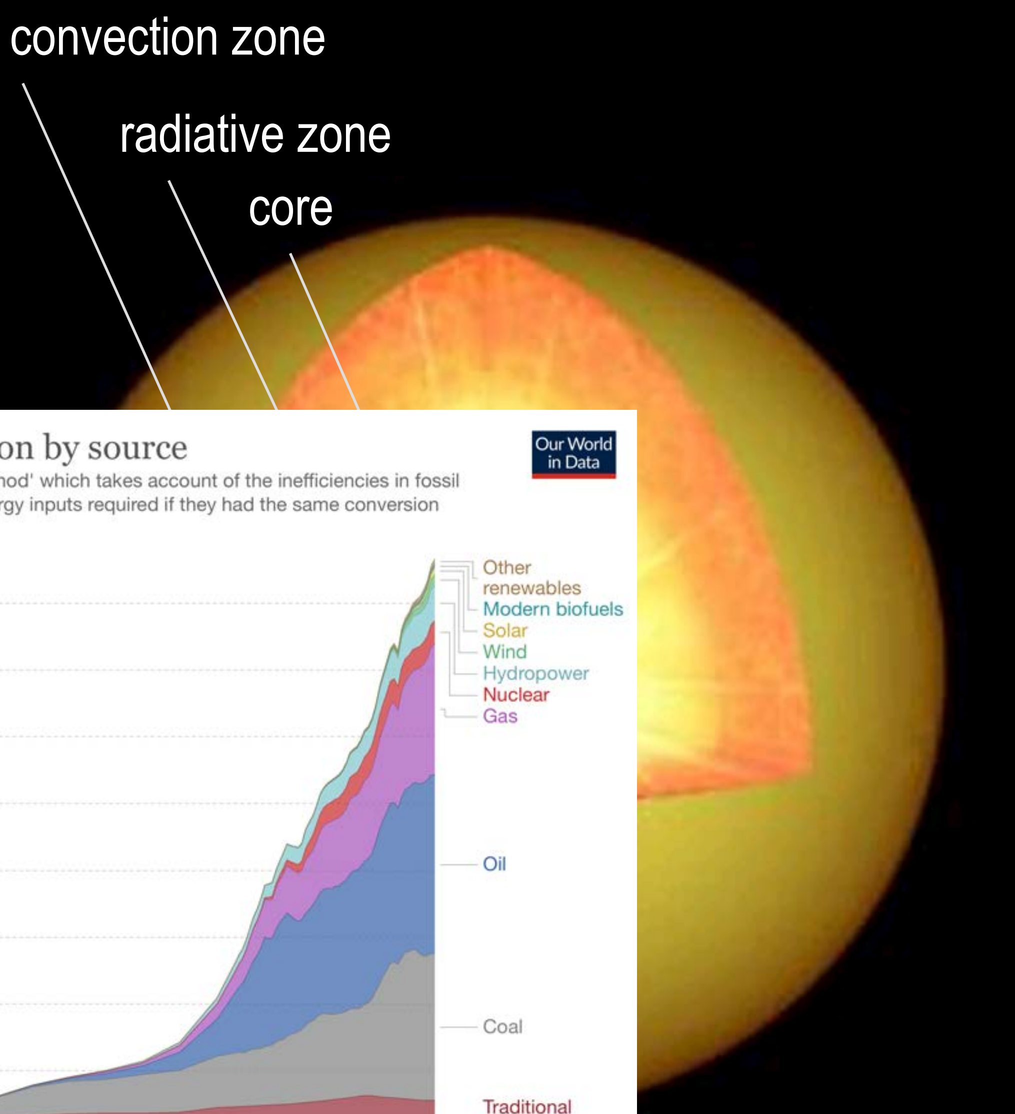
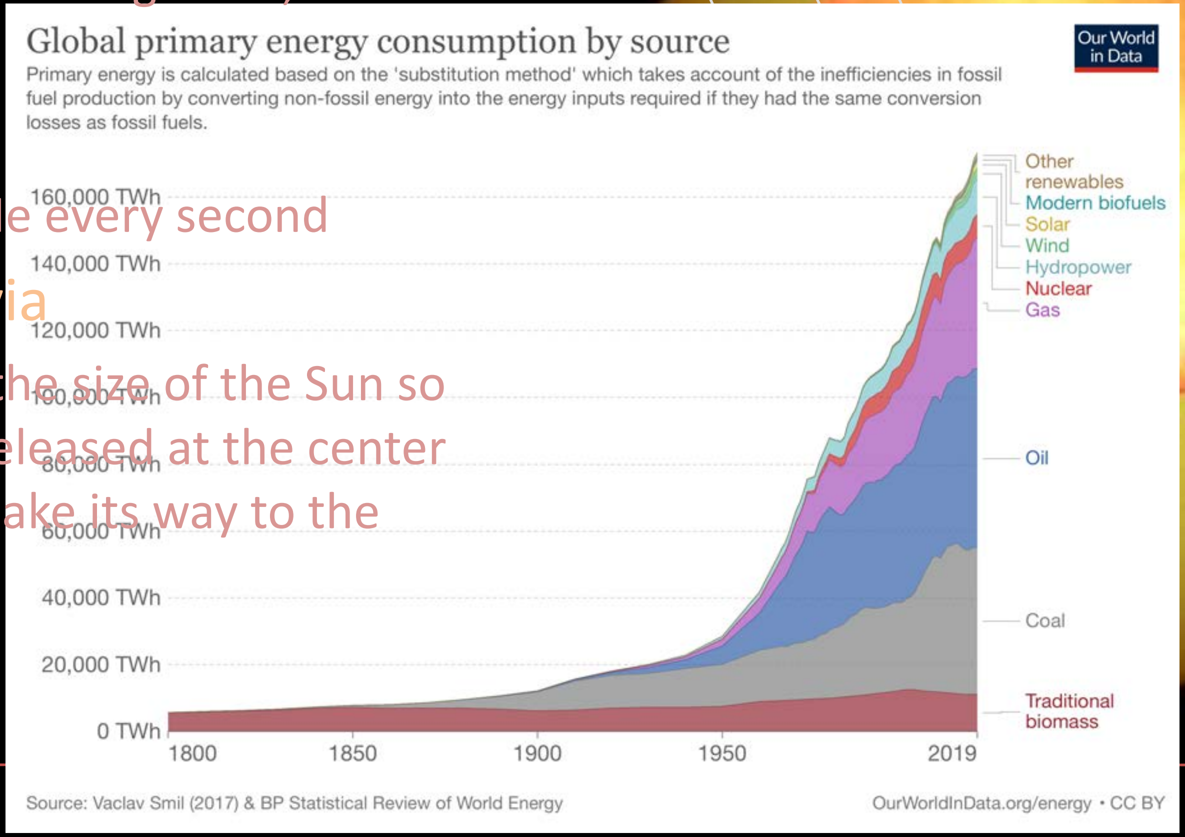
from "Where does Earth's atmosphere get its energy?" by A.C. Kren, P. Pilewskie, and O. Coddington, *Space Weather and Space Climate,* 2017

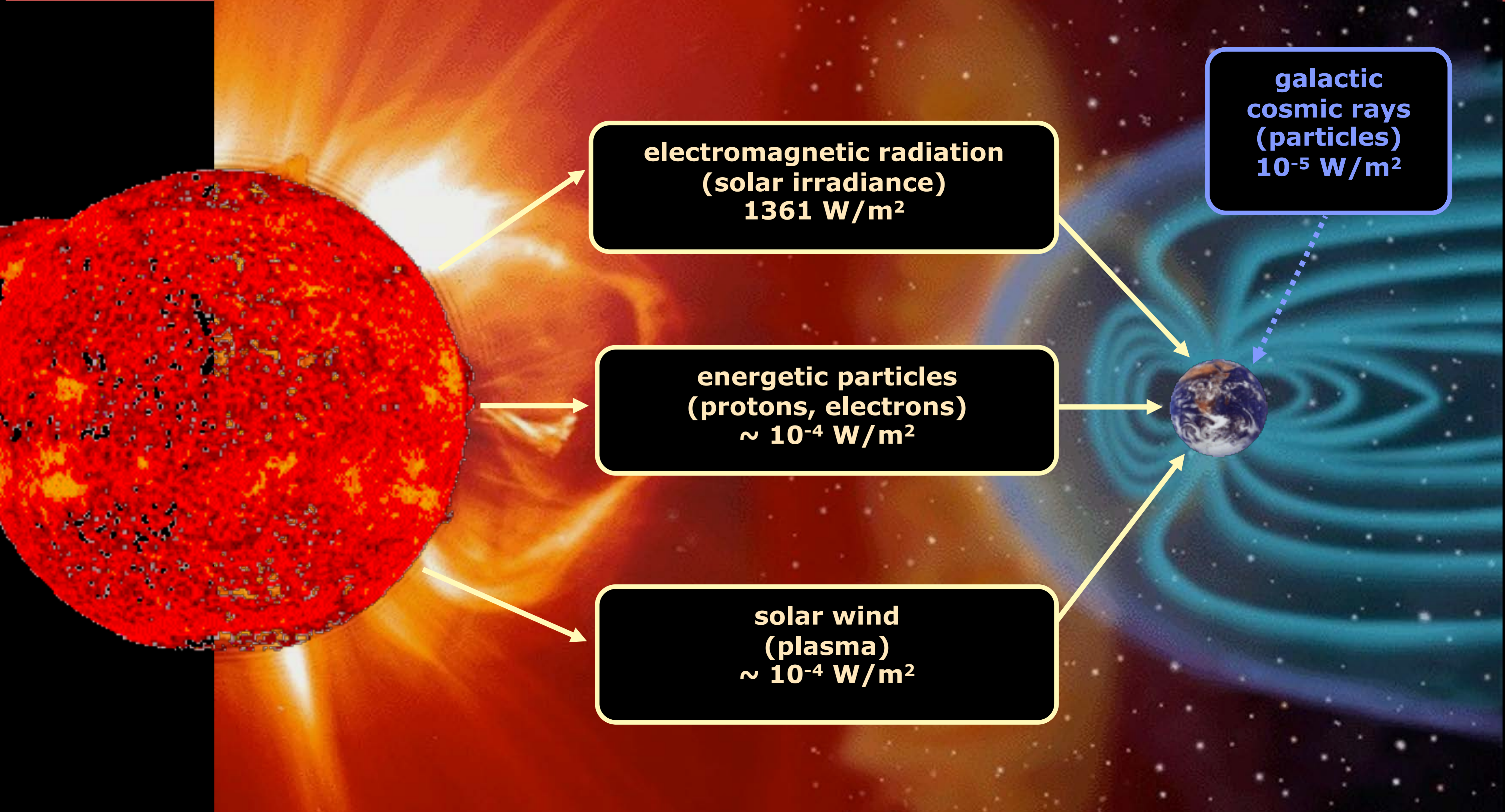
The Sun's Energy

- Energy output
  - Energy heating the Earth 1361 W/m^2
  - Sun's total output 3.8×10^{23} kW
- Energy trivia
  - The total output of the Sun in one second would provide the world with enough energy, at its current usage rate, for the next ~600,000 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

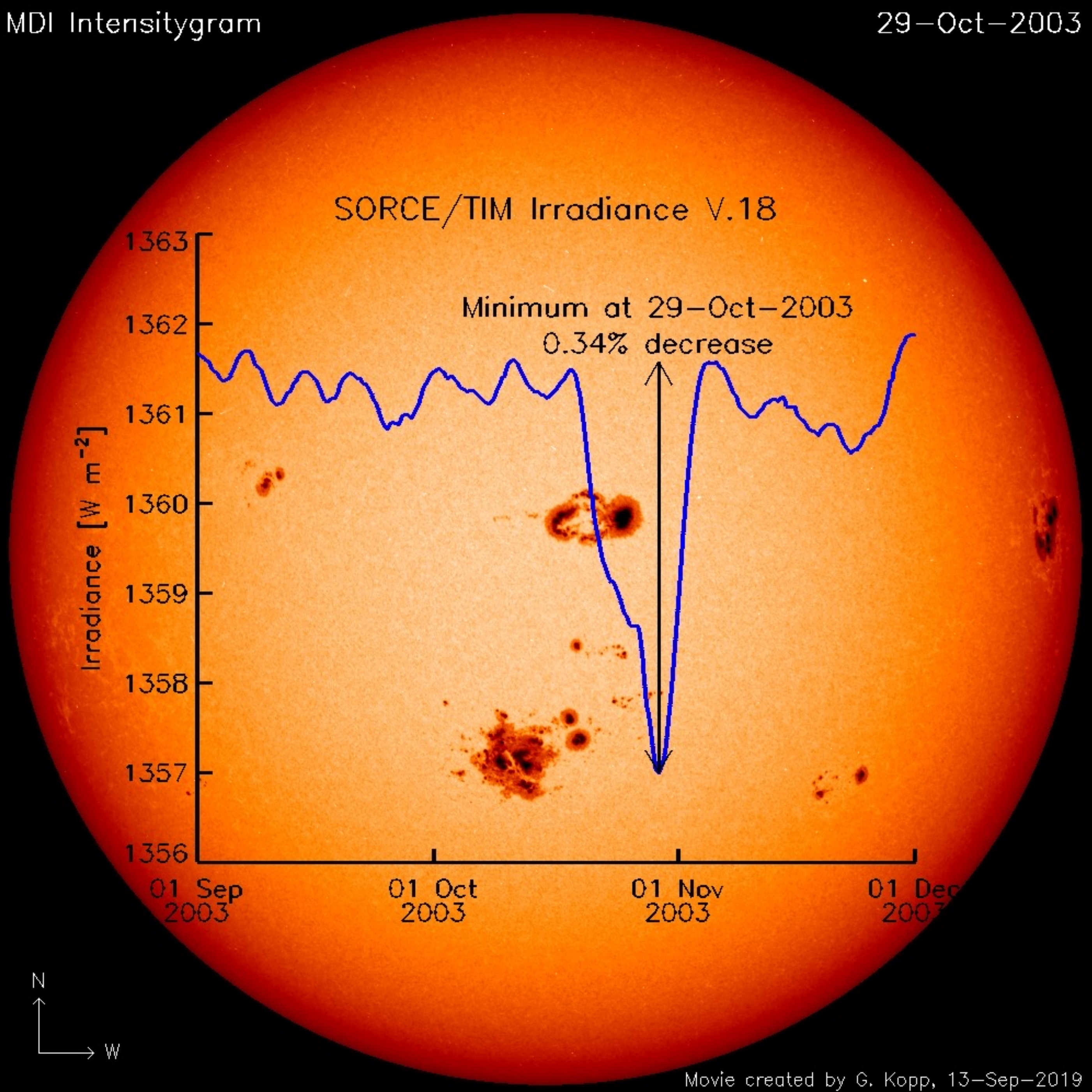




Means of Energy Input from the Sun



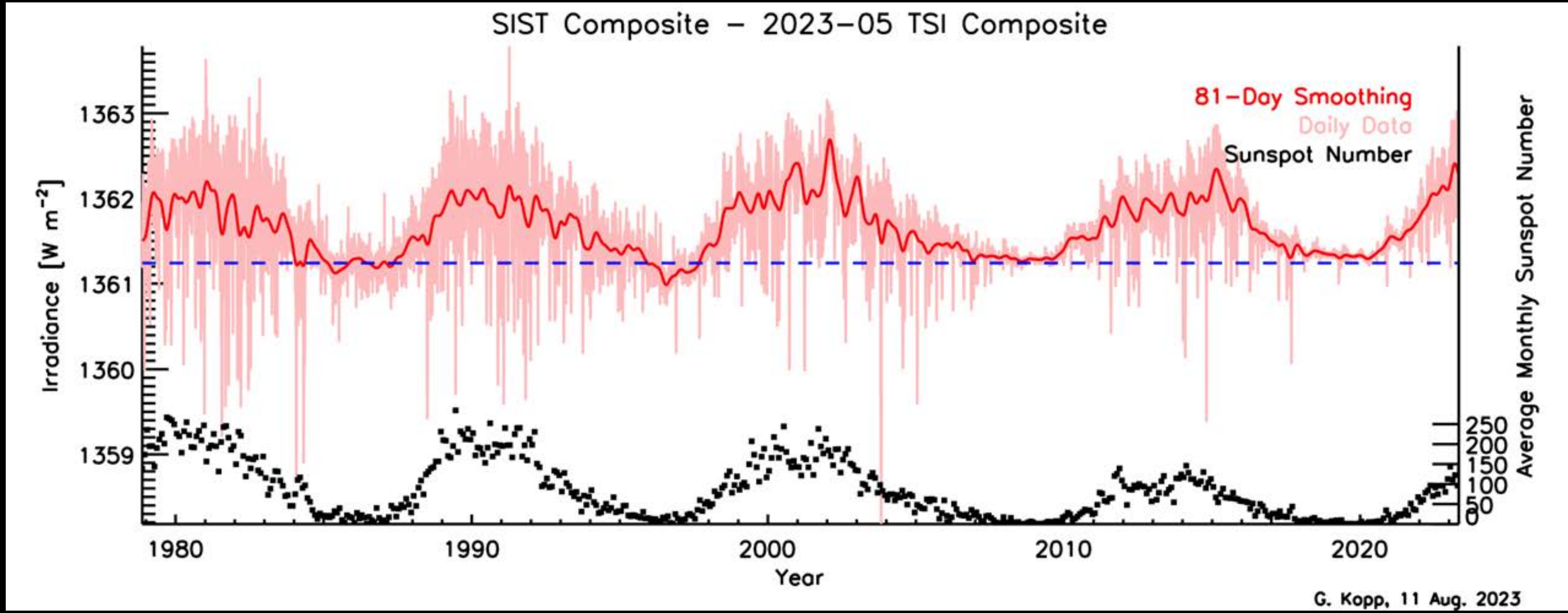
courtesy of Thierry Dudok de Wit



MDI Intensitygram
29-Oct-2003
SORCE/TIM Irradiance V.18
Minimum at 29-Oct-2003
0.34% decrease
Irradiance [W m^-2]
1363
1362
1361
1360
1359
1358
1357
1356
01 Sep 2003
01 Oct 2003
01 Nov 2003
01 Dec
N
W
Movie created by G. Kopp, 13-Sep-2019

The Earth's Incoming Energy

- TSI provides **99.974%** of Earth's incoming energy
  - **Mean TSI: 1361 ± 0.5 W m^{-2}**
    - = 340.2 ± 0.1 W m^{-2} in "today's talk units" (not an SI unit)
  - Accepted by IAU
- "Community-Consensus TSI Composite" provides time series and updated absolute values
- SSI determines where energy is absorbed and thus affects outgoing radiation
- The "solar constant" is not a constant



Where Does Energy Go?

- Blackbody temperature of Earth

$$\text{Incoming Energy} = \pi R^2 \cdot (1 - A) \cdot S$$

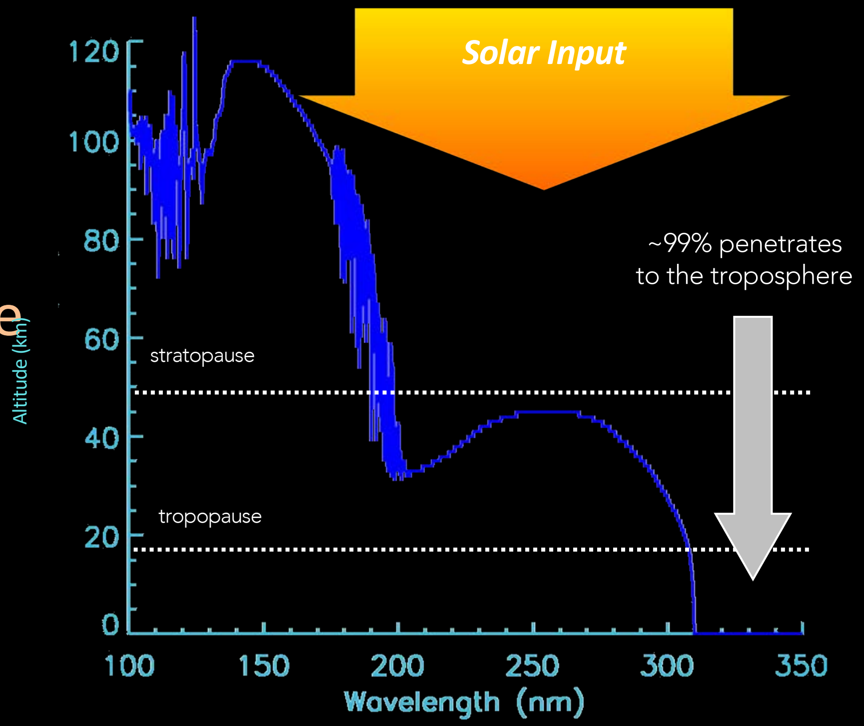
$$\text{Outgoing Energy} = 4\pi R^2 \cdot \varepsilon \cdot \sigma T^4$$

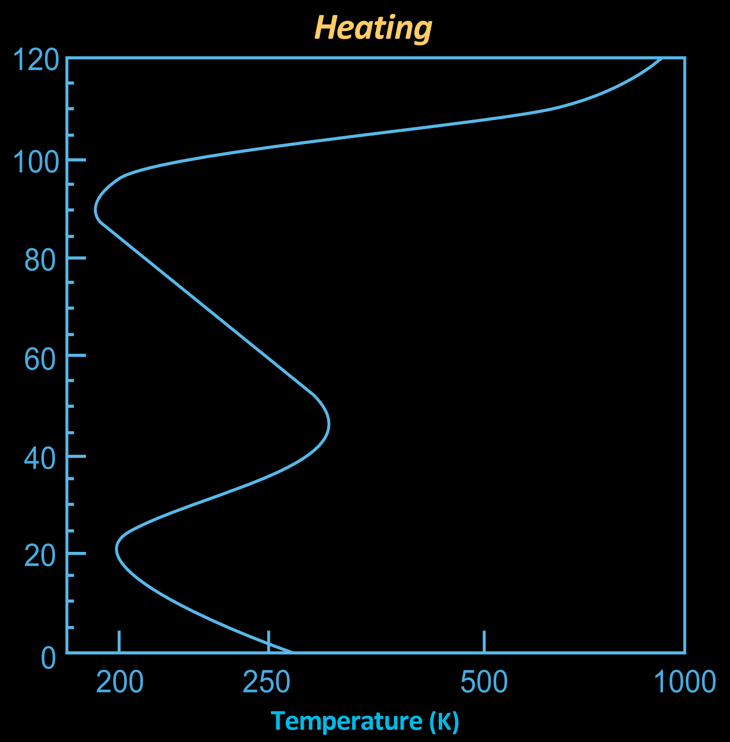
$$\text{Energy Balance} \Rightarrow T = \sqrt[4]{\frac{1-A}{\varepsilon}\frac{1}{4\sigma}S} = 280\ \text{K}$$

- Forcing sensitivity κ

$$\Delta T = \kappa \Delta S$$

- < ½ is absorbed by surface
- 1/3 is reflected
- ¼ is absorbed by atmosphere
- Feedback mechanisms

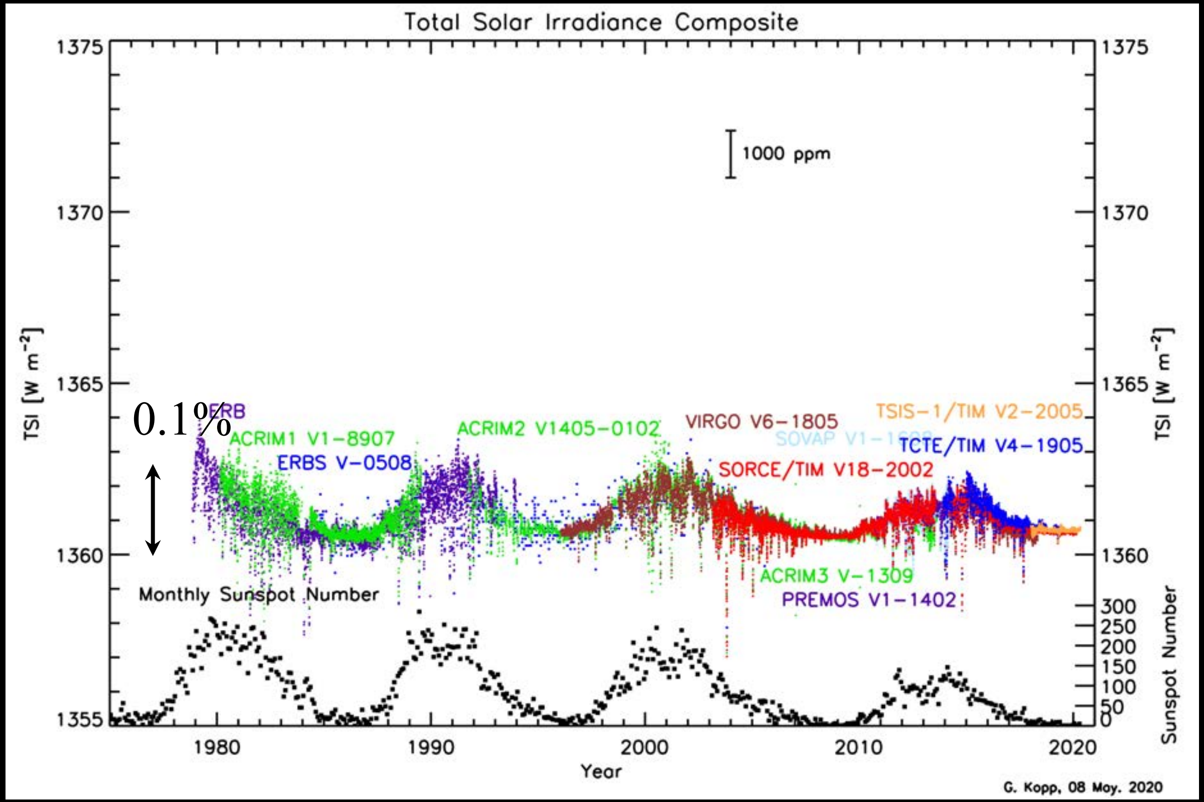




What Are the Timescales of Solar Variability?

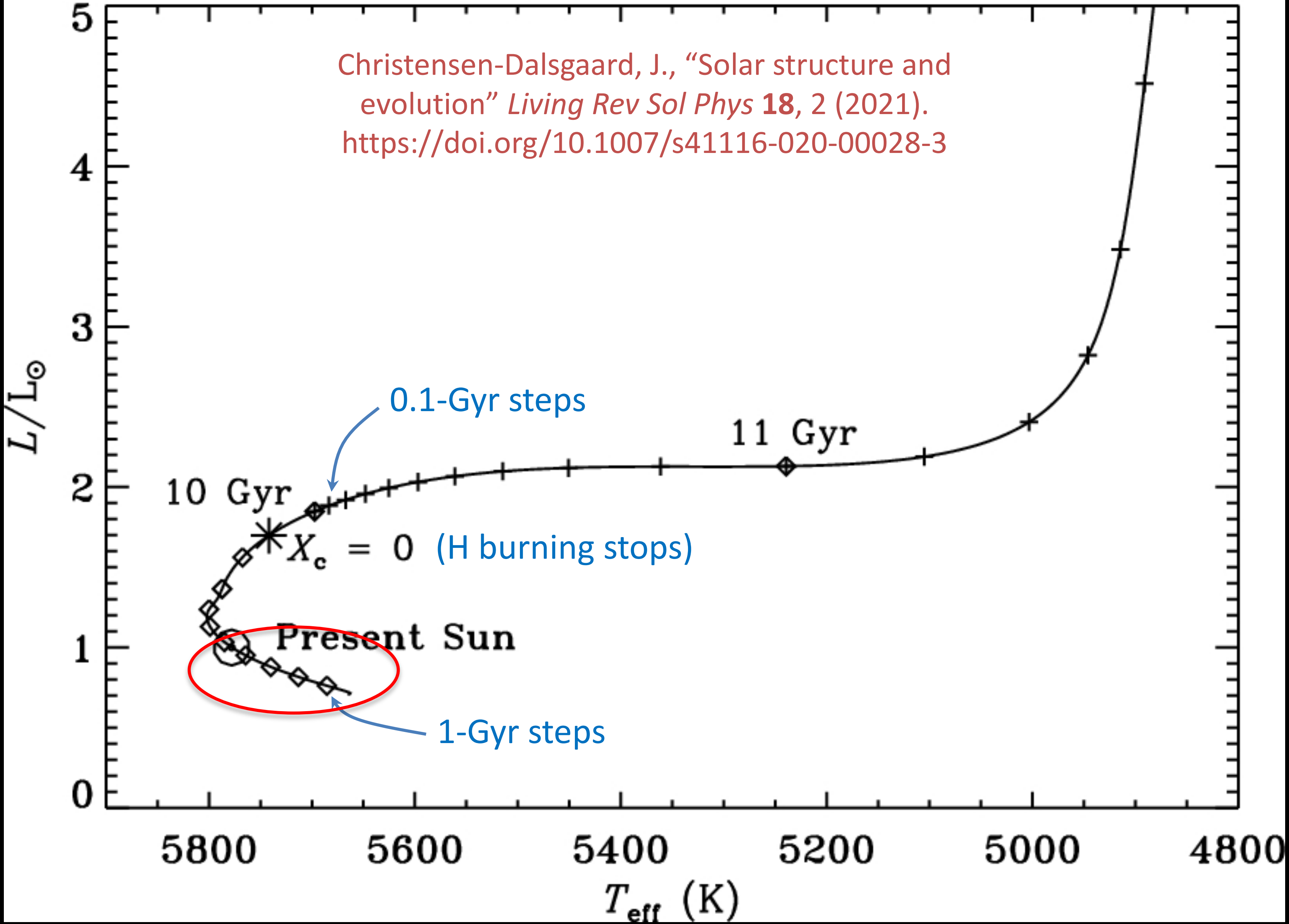
- 0.01% over minutes
- <0.3% over a few days
  - Short duration causes negligible climate effect
- 0.1% over 11-year solar cycle
  - Small but detectable effect on climate
- 0.05-0.3% over centuries (unknown)
  - Direct effect on climate (Maunder Minimum and Europe's Little Ice Age)
- 10^{-10}/yr on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

Misnomer
It is *not* the "solar constant"



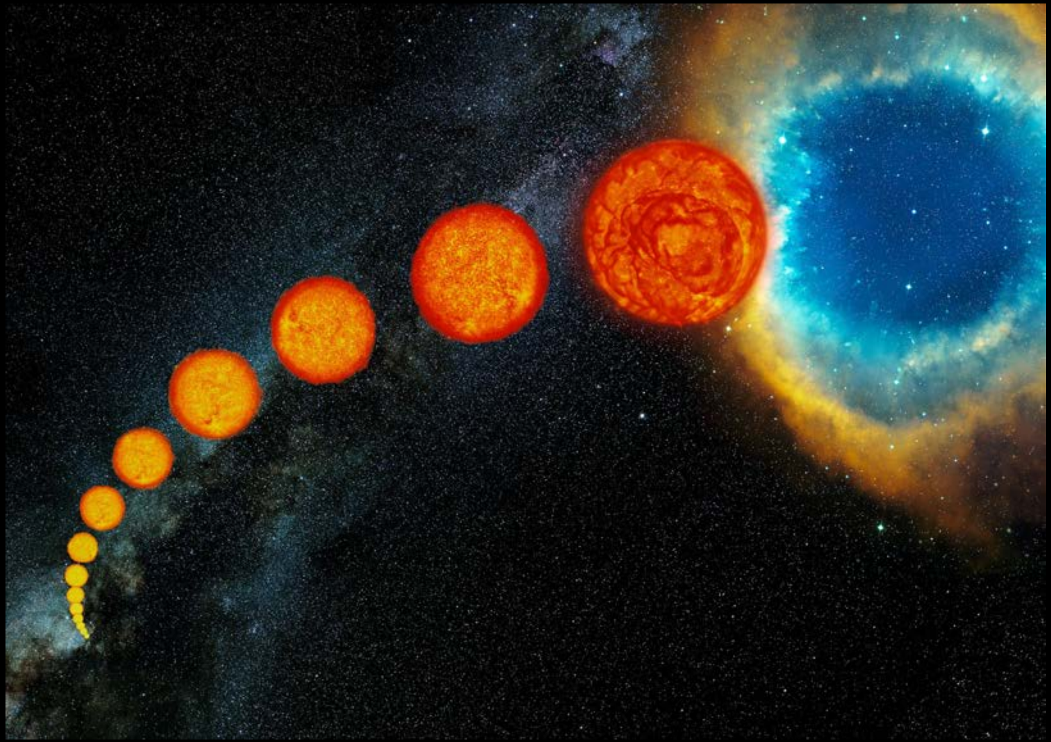
- An unequivocal link between climate change and TSI has been established
  - Magnitude of natural climate forcing needs to be known for setting present and future climate policy regulating anthropogenic forcings

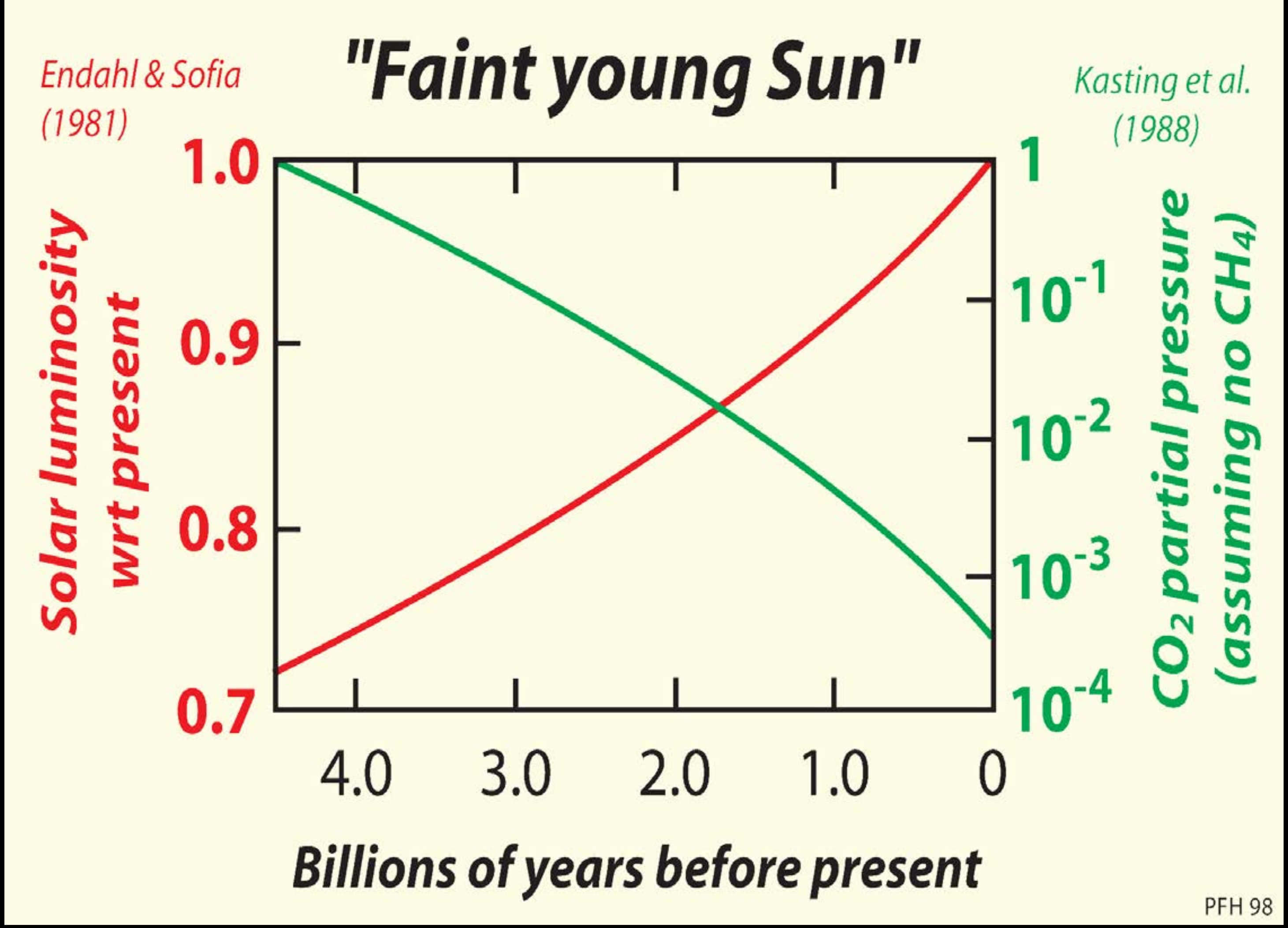
Solar Evolution and Faint Young Sun



Faint Young Sun Paradox

- How did liquid H_2O exist?
  - Greenhouse gases
  - Radiogenic heating
  - Tidal heating

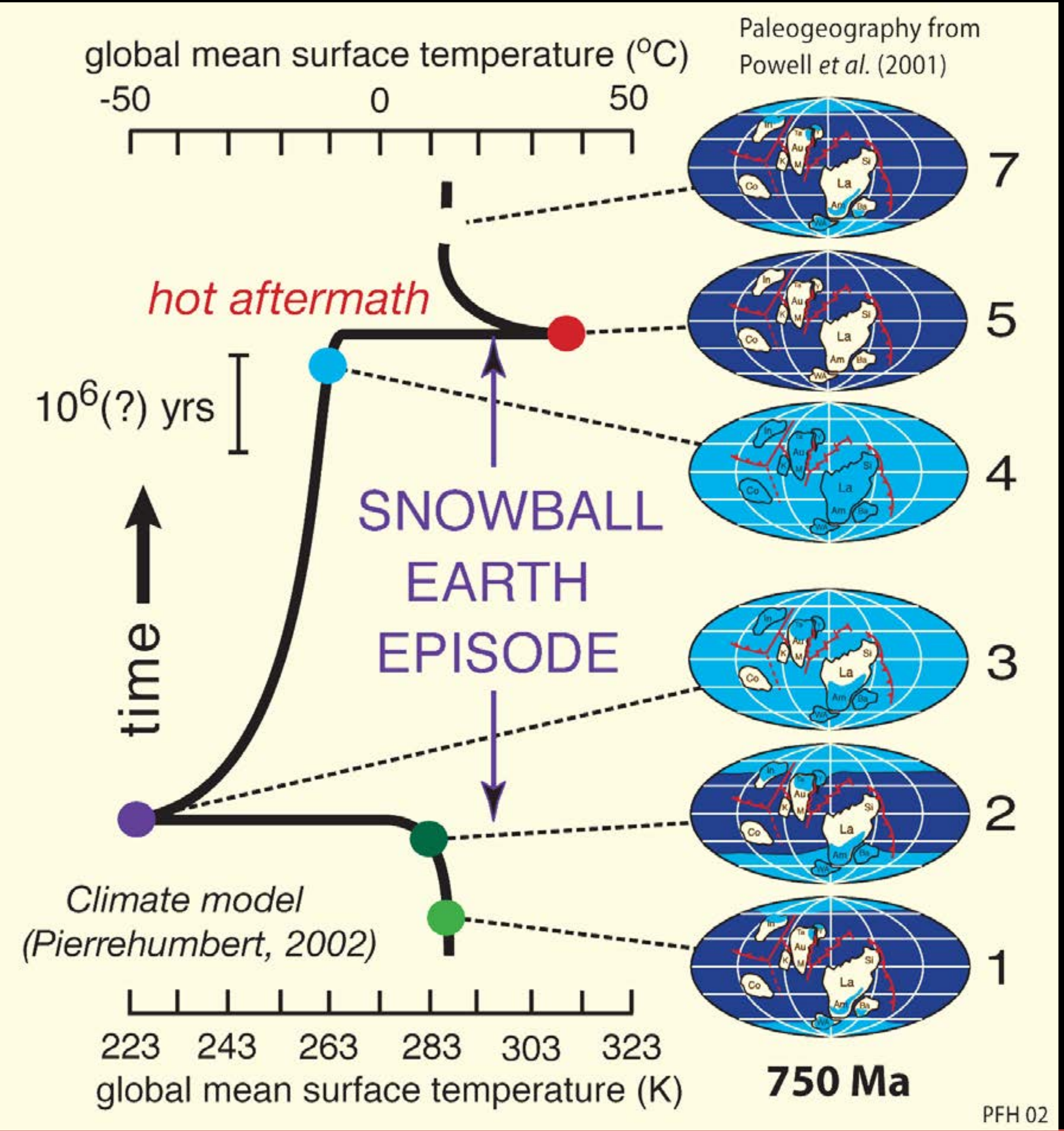




Snow/Slush-Ball Earth Cycle

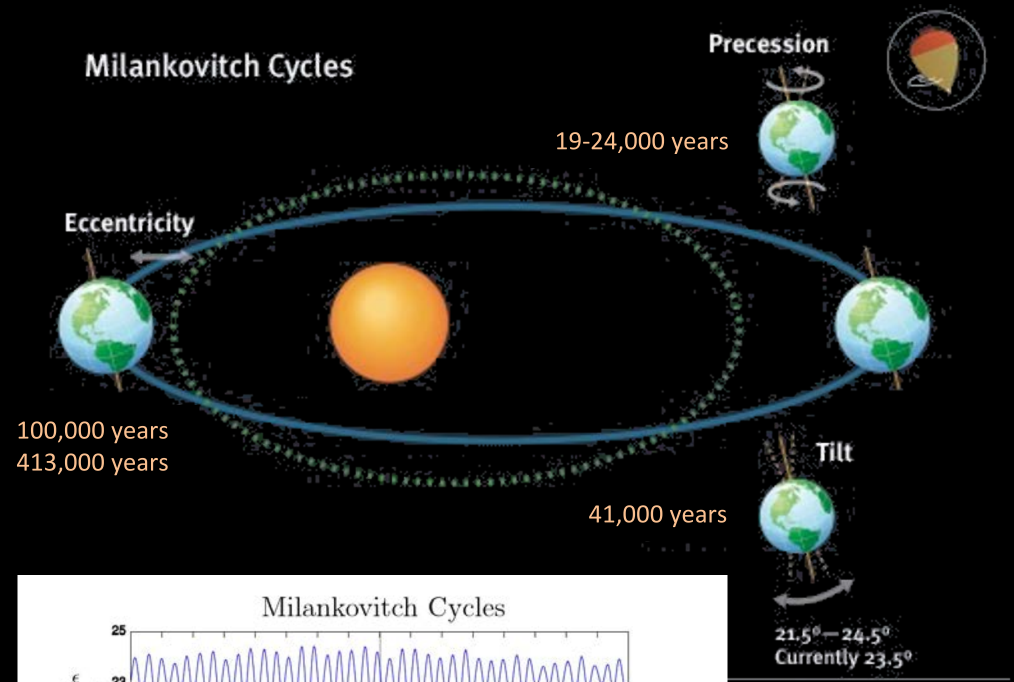
- Polar-ice extent has negative CO_2 feedback
  - Exposed areas are CO_2 sinks: silicate weathering, CO_2 ocean-uptake, photosynthesis
  - CO_2 sources: volcanoes & geothermal
- Ice extent has positive albedo feedback
  - Once more than ½ Earth's surface becomes ice covered, albedo feedback is unstoppable → "Snowball Earth"
- Volcanic activity continues to release CO_2 → Greenhouse gas warming
- Once ice melts in tropics, continued melt is unstoppable → warm, ice-free Earth
- Increased silicate weathering and photosynthesis → lower CO_2 → cooling

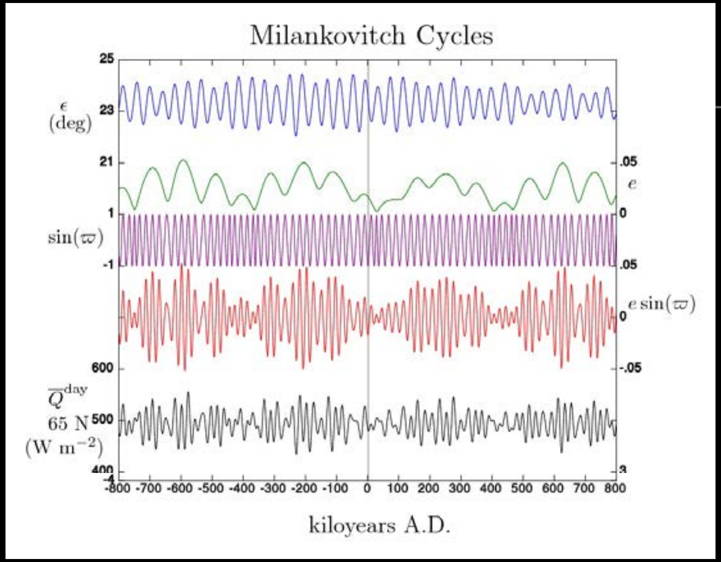
~4 periods 750 million to 580 million years ago



from Hoffman & Schrag

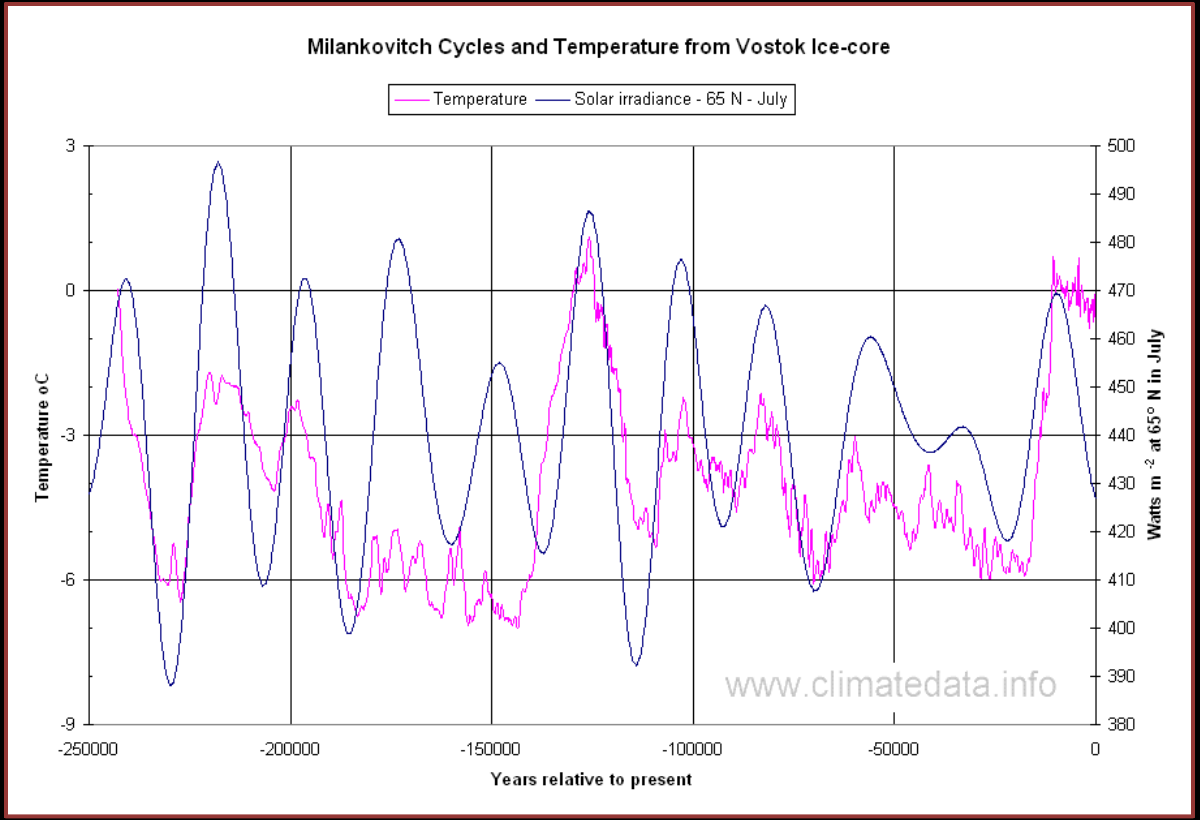
Milankovitch Cycles Cause Direct Radiative Forcing





http://commons.wikimedia.org/wiki/File:MilankovitchCyclesOrbitandCores.png#/media/File:MilankovitchCyclesOrbitandCores.png

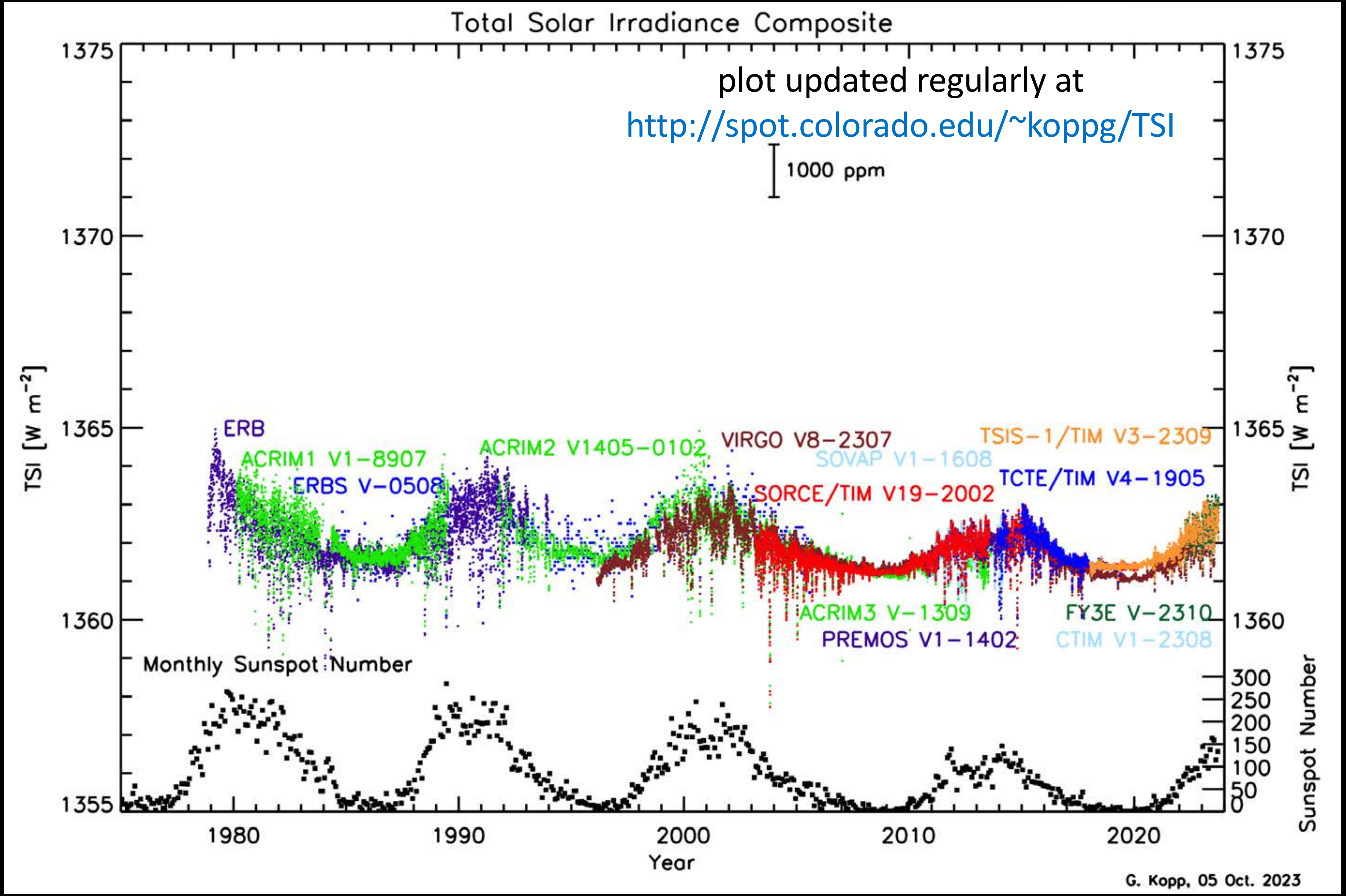
"Observations show climate behavior is much more intense than the calculated variations."
Joanna Haigh, "Solar Influences on Climate," 2011



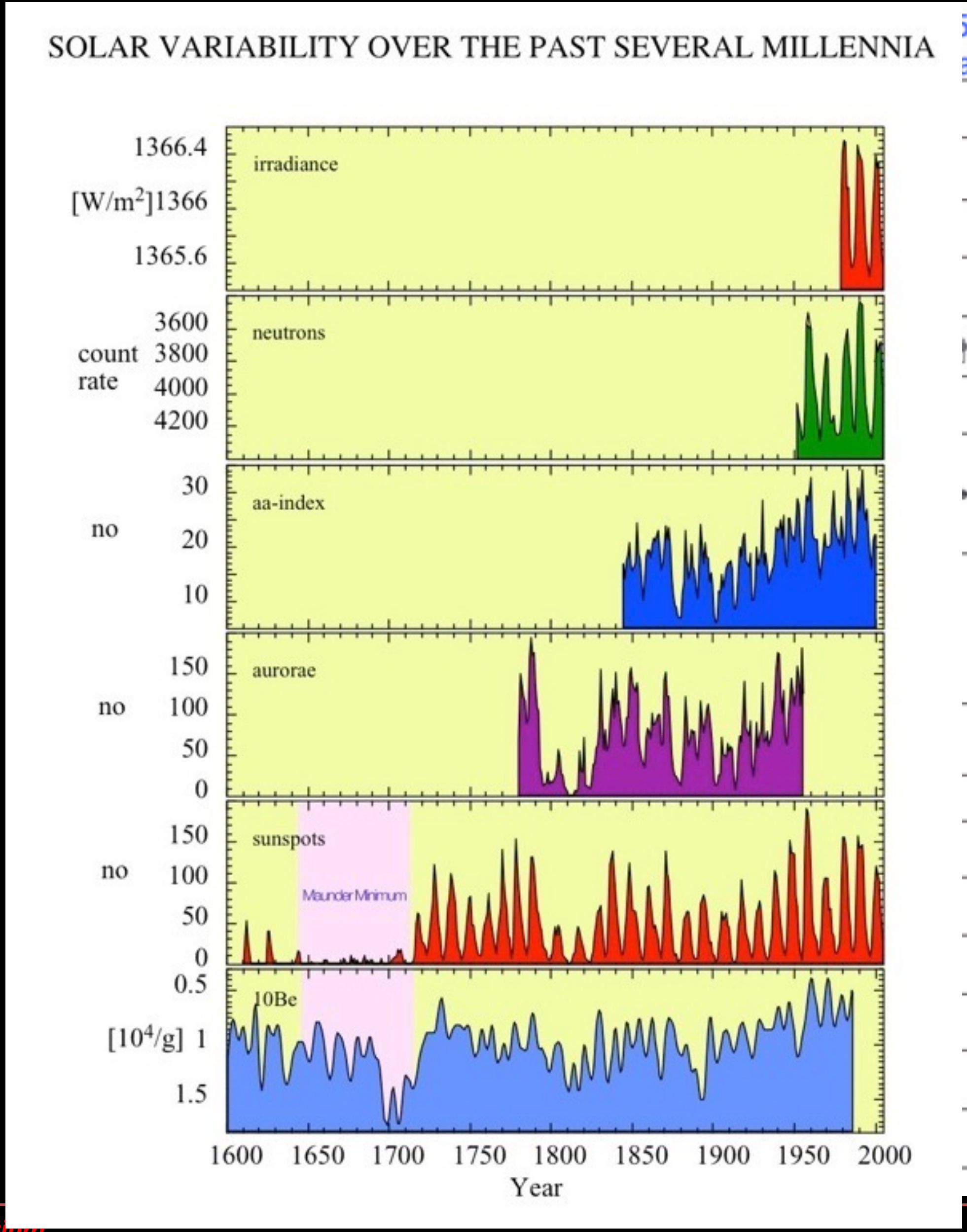
Jouzel *et al.* (1987, 1993 and 1996) and
Wahlen, M., *et al*, (2000), Vostok Ice Core CO_2 Data, 1105-2856 m

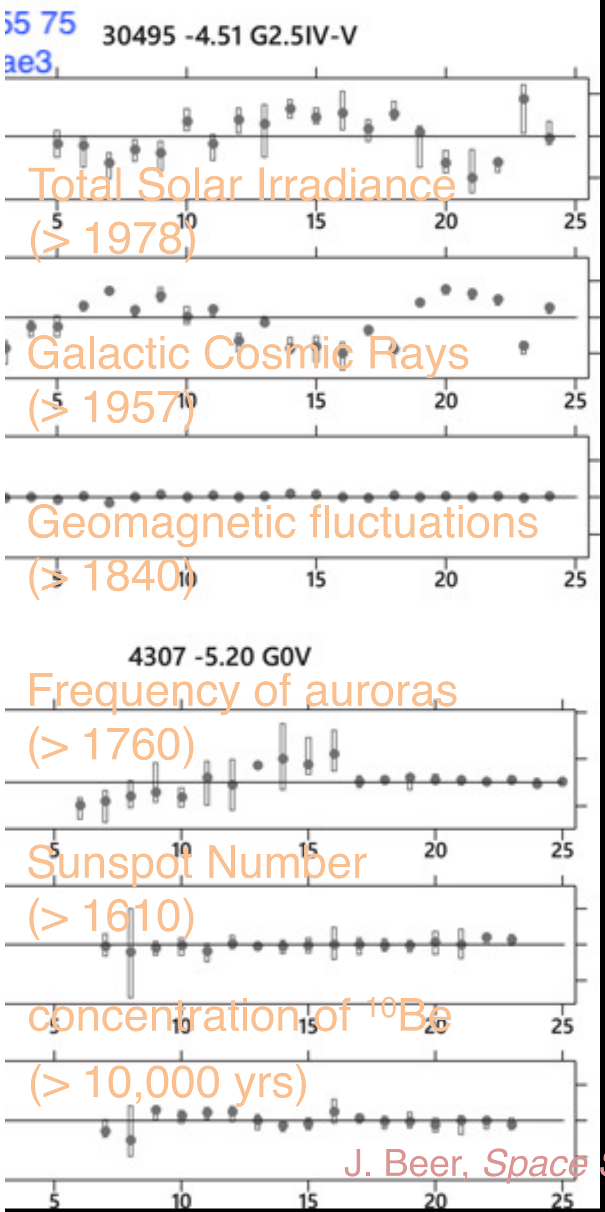
The Current Total Solar Irradiance Record

- The uninterrupted, 45-year-long spaceborne TSI record includes contributions from more than 15 NASA, ESA, and NOAA instruments
  - Improvements have been made to absolute accuracy
  - The record continues to rely on continuity and stability



Proxies of Solar Activity





Total Solar Irradiance (> 1978)

Galactic Cosmic Rays (> 1957)

Geomagnetic fluctuations (> 1840)

Frequency of auroras (> 1760)

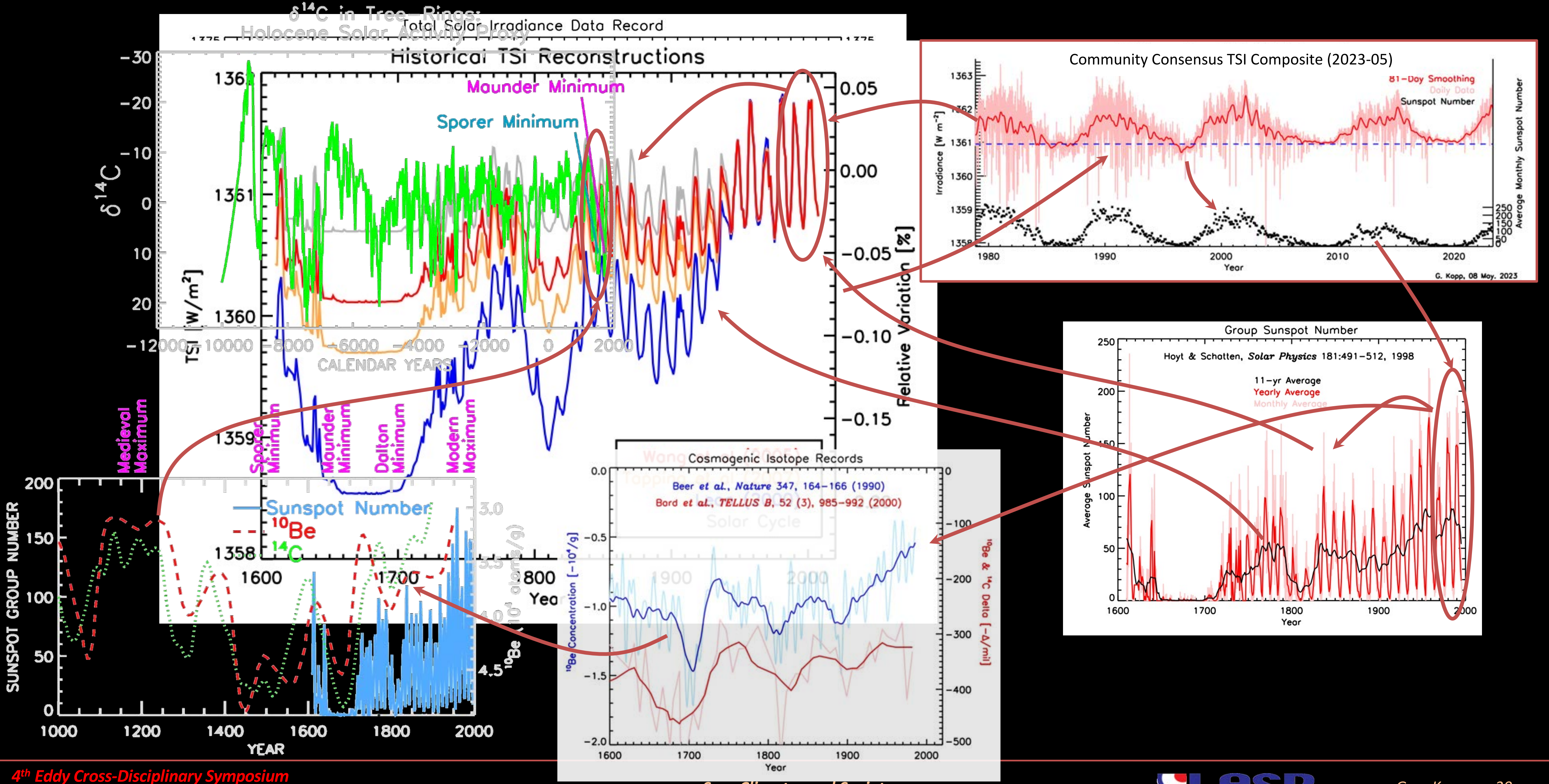
Sunspot Number (> 1610)

concentration of ^{10}Be (> 10,000 yrs)

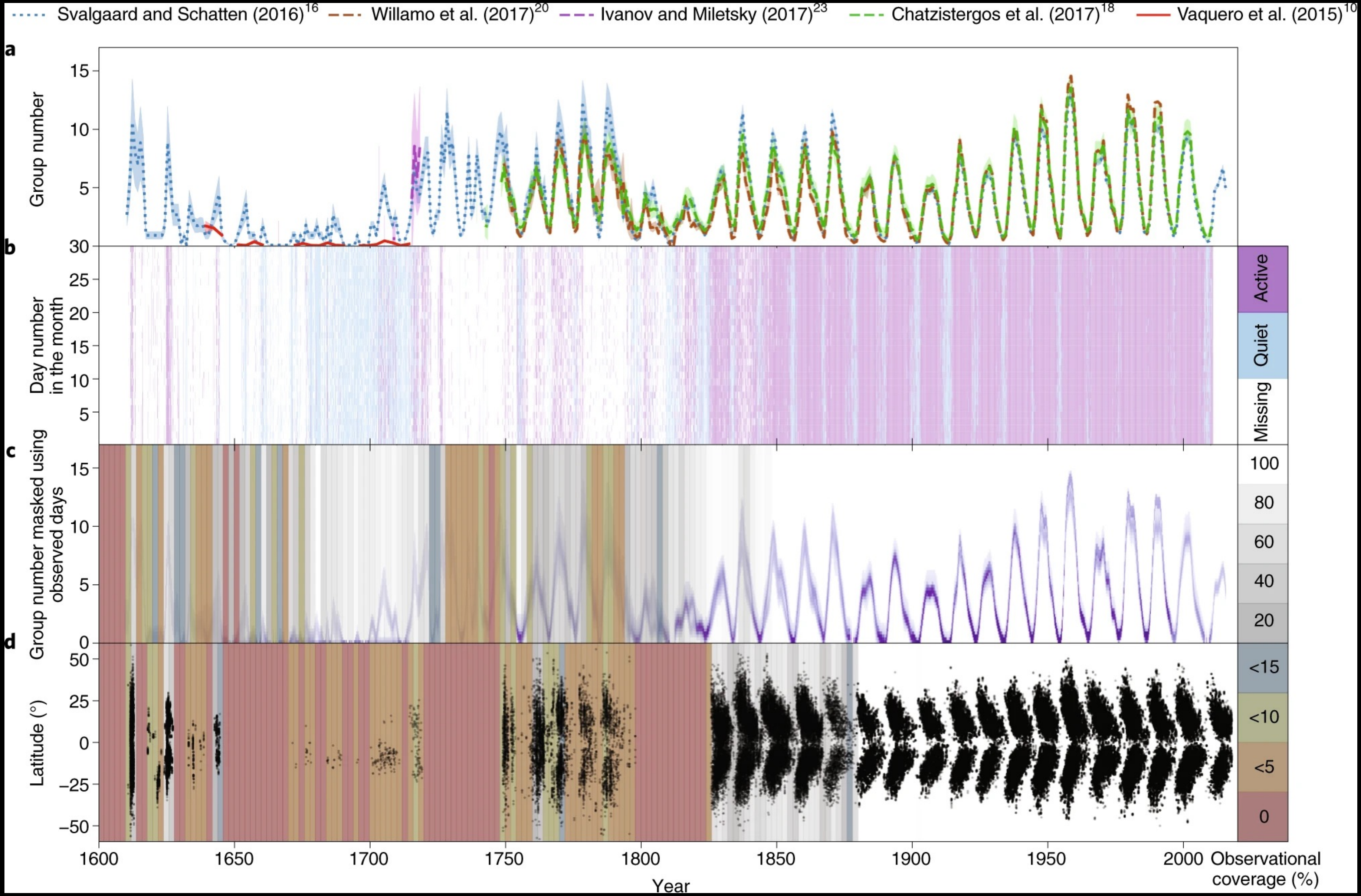
J. Beer, *Space Science Reviews* (2008)

courtesy of Thierry Dudok de Wit, Univ. of Orleans

Proxies Reconstruct Historical TSI Based on Measurement Record



400-Year Sunspot Record (and Reconstructions)



Muñoz-Jaramillo and Vaquero, *Nature Astronomy*, 2019

Sunspots Are Linked to Climate

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)*

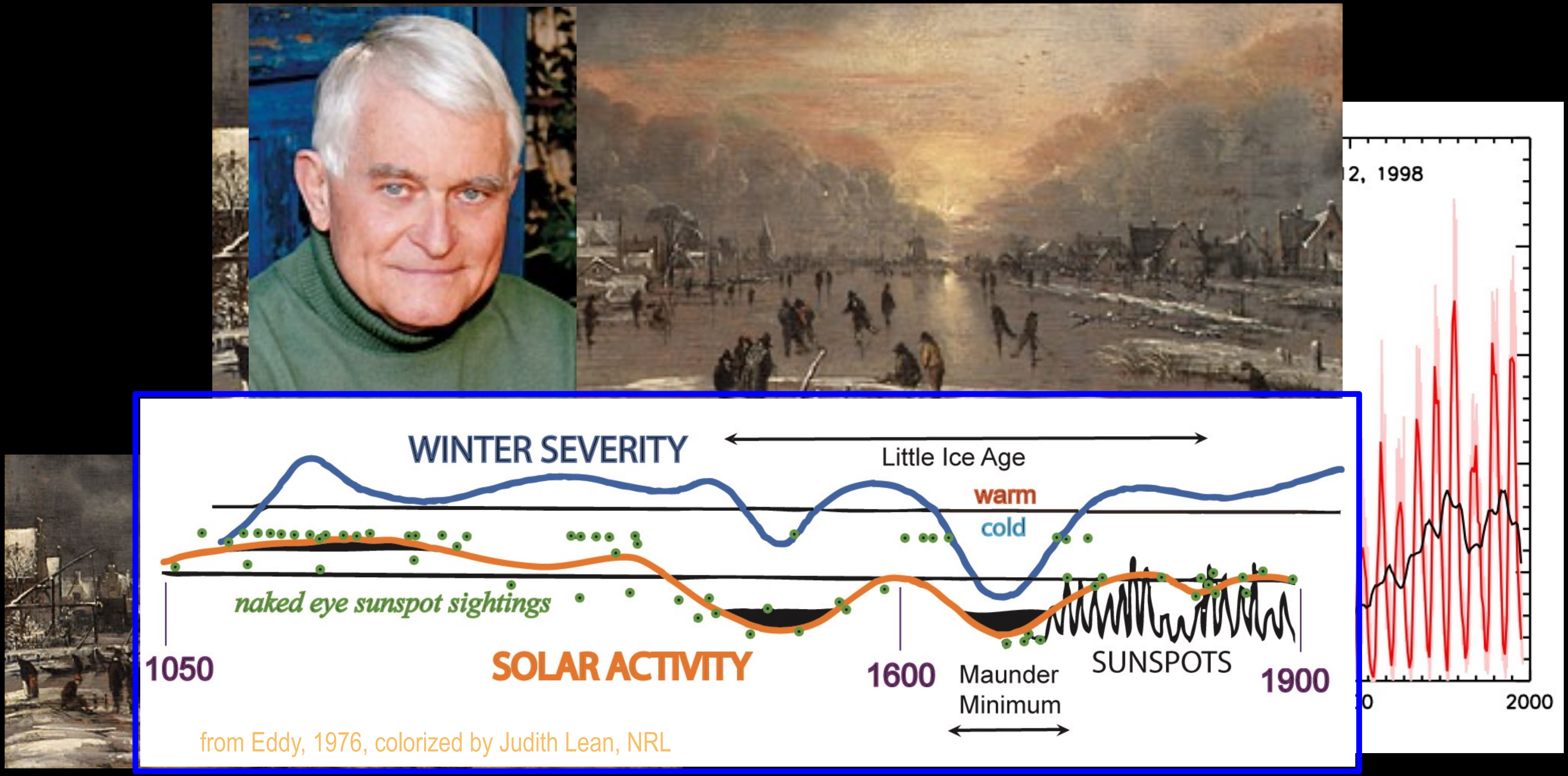
Herschel [1801]: Correlated the price of wheat in London with the number of visible sunspots, attributing the connection to reduced rainfall when the Sun was less spotted

Sunspots – and Europe's Little Ice Age

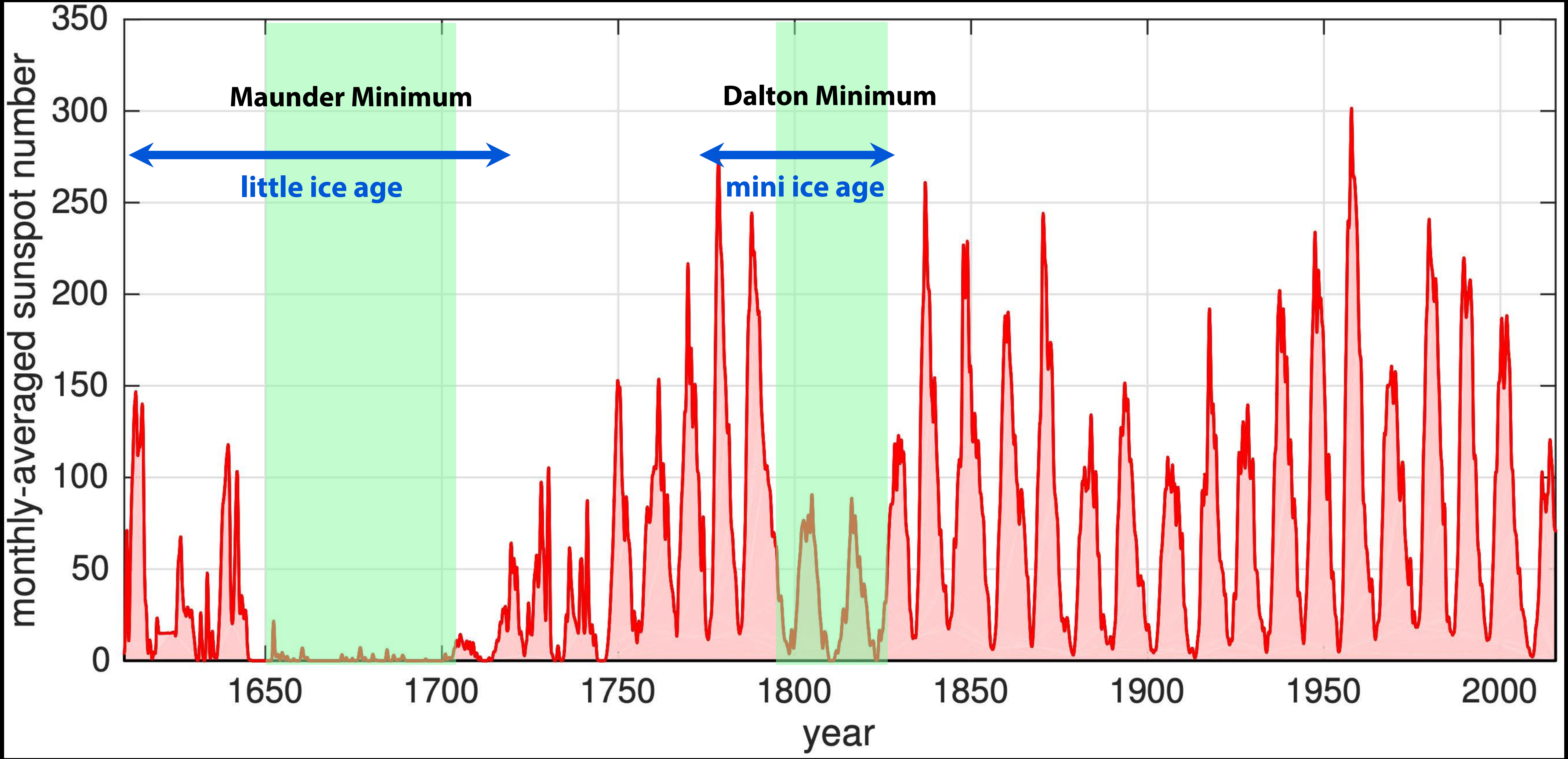
1645-1715 – Maunder Minimum

– Solar output decreased 0.1-0.3% for 70 years

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



Solar Sunspot Activity



The Little Ice Age

- Start
  - 12… the… …bly triggered or enhanced by …olcanic winter
  - 12… …y glaciation
  - 13…
  - 13…
  - 15…
- Peak
- End:
- Mau…

- Norse colonies in **Greenland** *starved and vanished* by the early 15th century
- *Crop practices* throughout **Europe** had to be altered
- There were many years of *scarcity and famine*
  - Famines in **France** 1693–94, **Norway** 1695–96 and **Sweden** 1696–97 claimed roughly *10 percent of the population* of each country
  - In **Estonia** and **Finland** in 1696–97, losses have been estimated at a *fifth and a third* of the national populations
- Some storms and flooding resulted in the permanent *loss of large areas of land* from the **Danish, German, and Dutch** coasts
- **Swedish** army marched across the Great Belt to **Denmark** to attack Copenhagen in 1658
- The colder climate may have caused the wood that was used in Antonio **Stradivari's** violins to be denser than in warmer periods and contribute to the tone of his instruments

Wikipedia

ISSI Team Reevaluating Sunspot-Number

Team Leaders:
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Royal Observatory of Belgium
Mathew Owens (UK)
University of Reading

Team Members:
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National Solar Observatory
Thierry Dudok De Wit (France)
LPC2E
Greg Kopp (USA)
Univ. of Colorado / LASP
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SouthWest Research Institute
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Sodankylä Geophysical Observatory and ReSoLVE Centre of Excellence
Lidia Van Driel-Gesztelyi (UK, Hungary, France)
University College London
José Vaquero (Spain)
Departamento de Física

Young Scientist:
Theodosios Chatzistergos (Germany)
Max-Planck-Institut fur Sonnensystemforschung

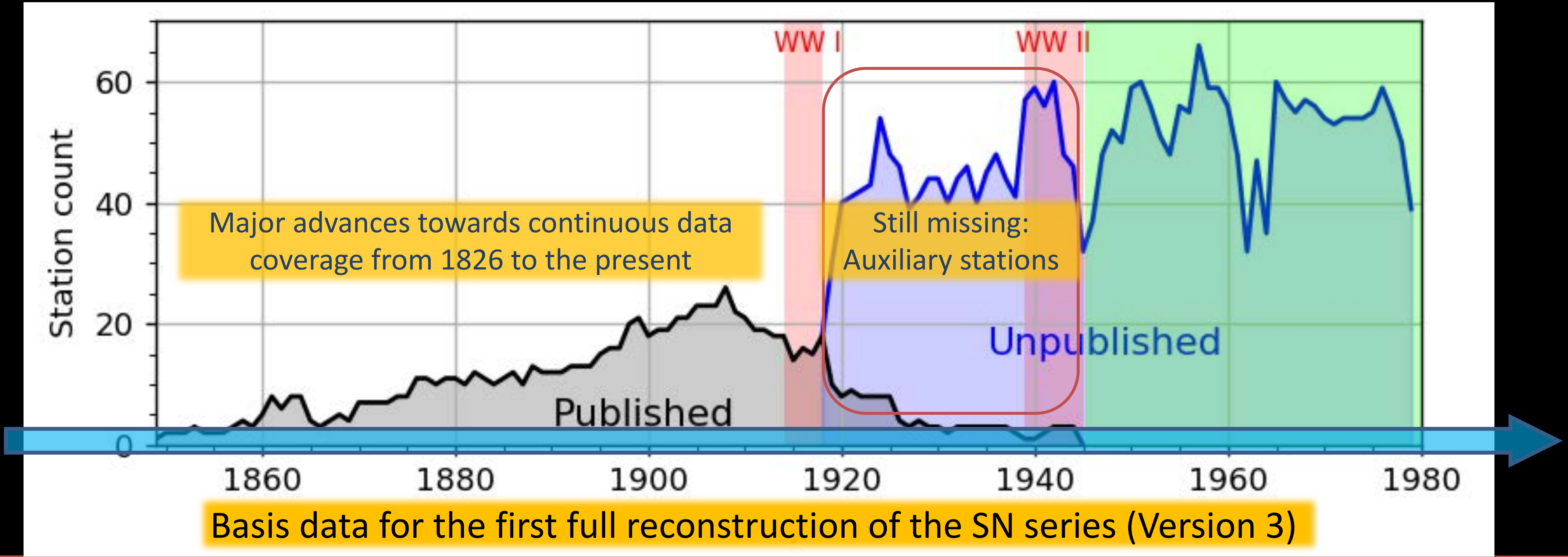
Self-supported experts:
Thomas Friedli (Switzerland), Dean Pesnell (USA), and Alexei Pevtsov (USA)

1. Recovered historical data
2. Evaluated corrections for specific observers
3. Explored combination methodologies

Recalculating TSI reconstructions by incorporating this forthcoming sunspot record into the reconstruction models will be important for estimating historical solar forcing and its uncertainties

Acquired Much More Historical Sunspot Data

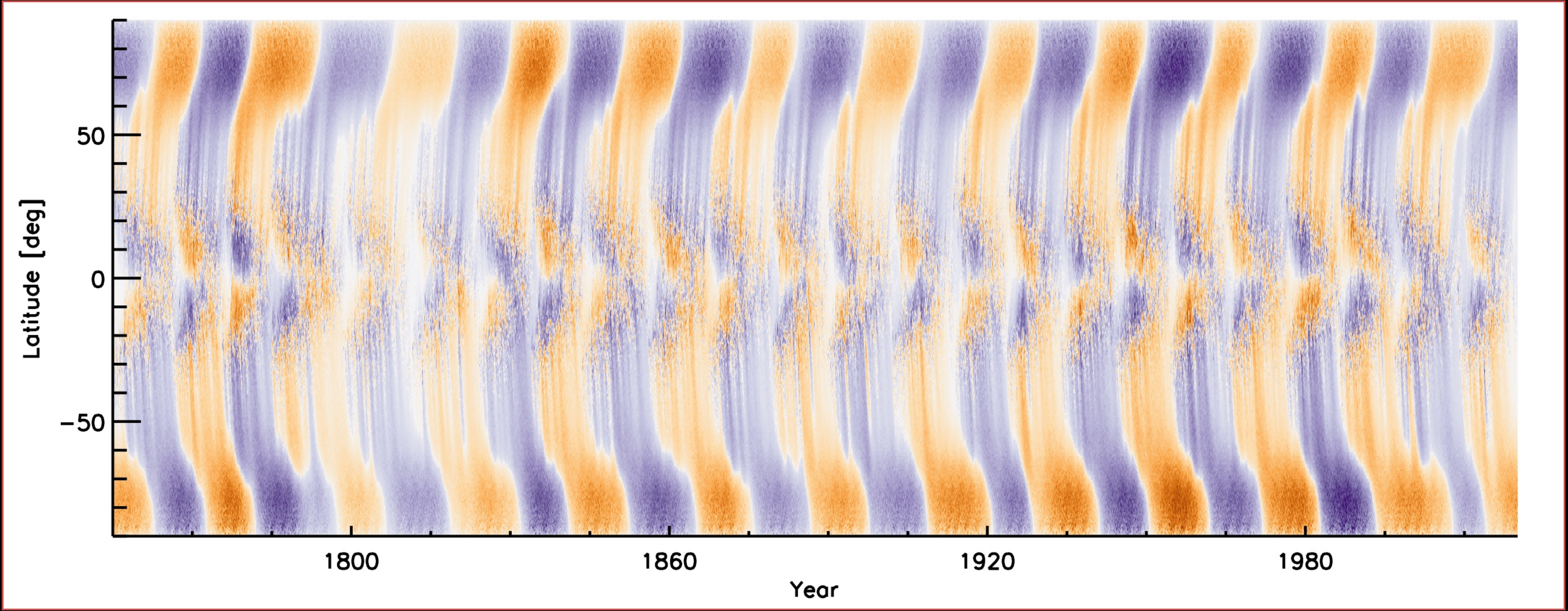
- Long-lost archive of Zürich SN source data from 1945 to 1980 fully recovered in 2018
- Full digitization of the SN source data in the Zürich *Mittheilungen*
- Corrections of misinterpreted GSN data in the Hoyt & Schatten 1998 original database
- Newly-recovered GSN series and drawings in 17th and 18th centuries (incl. observers in Asia)
- New GSN version (V 1.3) (Vaquero, Carrasco, Gallego) and Hisashi data recoveries



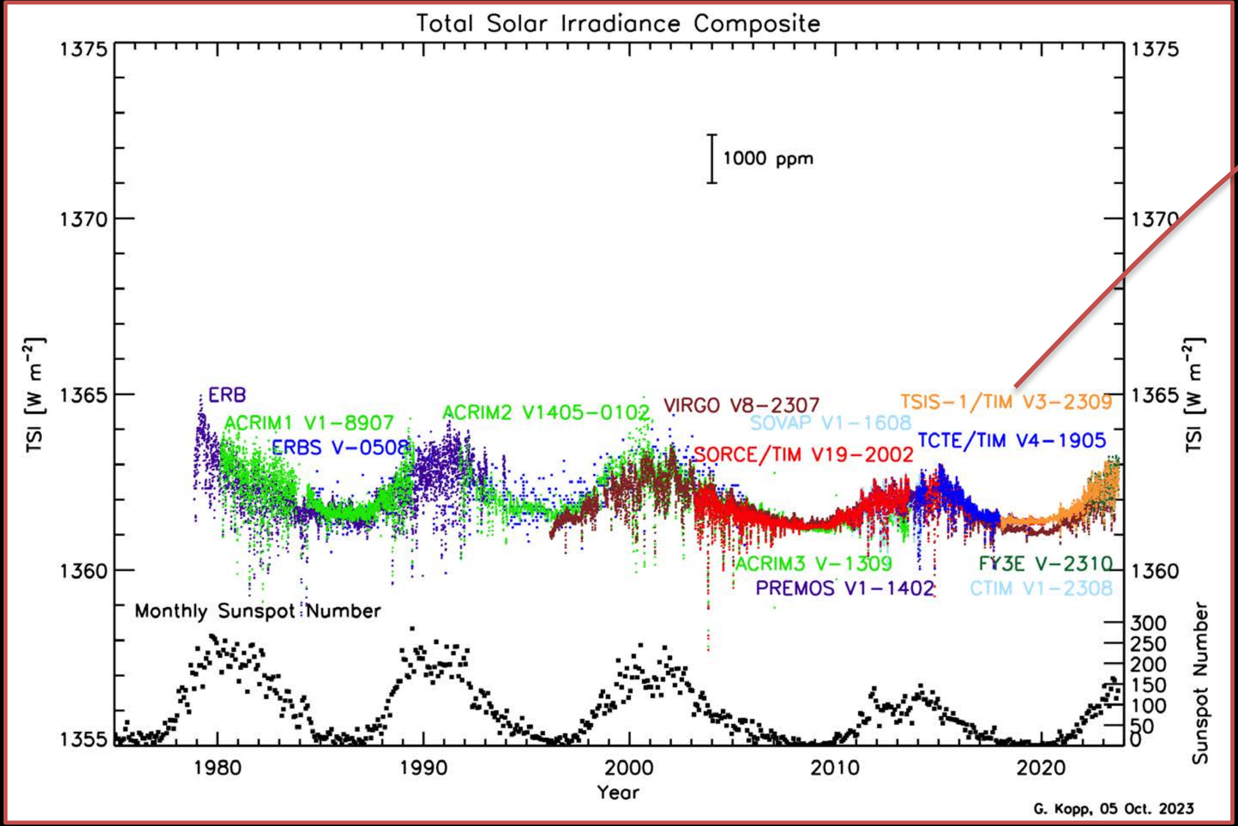
courtesy of Frédéric Clette

Improving the Historical TSI Record Based on Sunspot Records

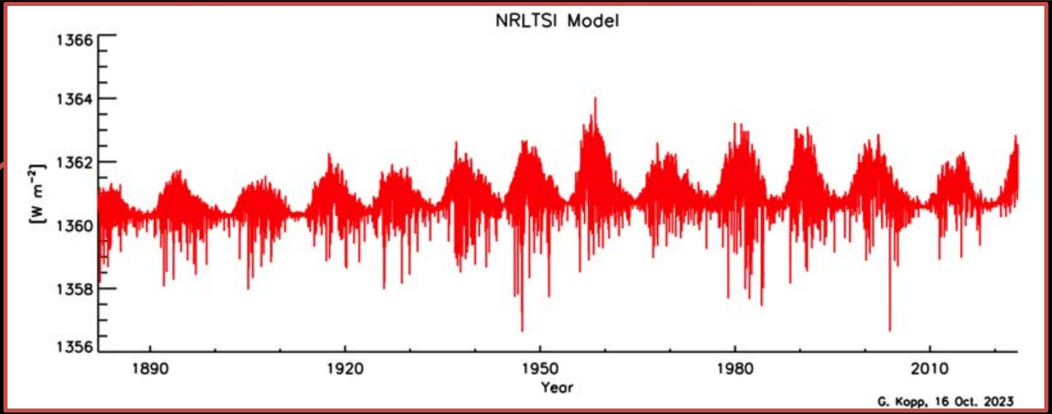
Created continuous simulations of magnetic flux from 1750 to near-present using Advective Flux Transport Model (Hathaway and Upton)

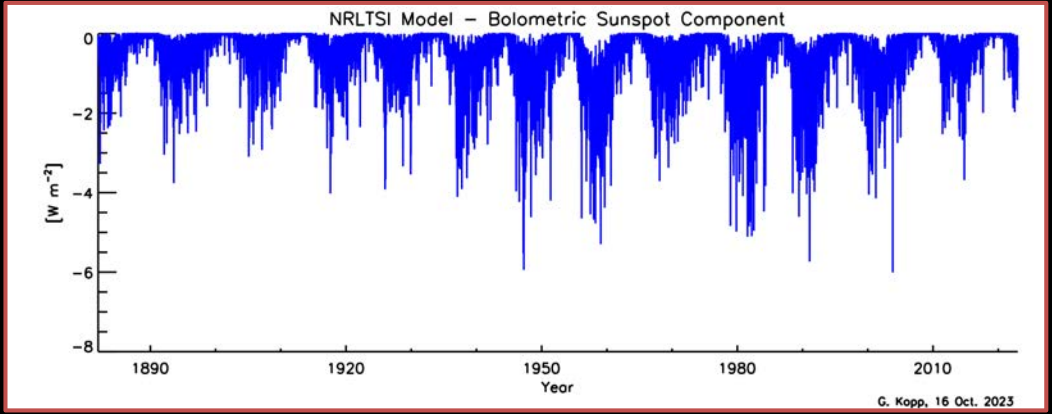


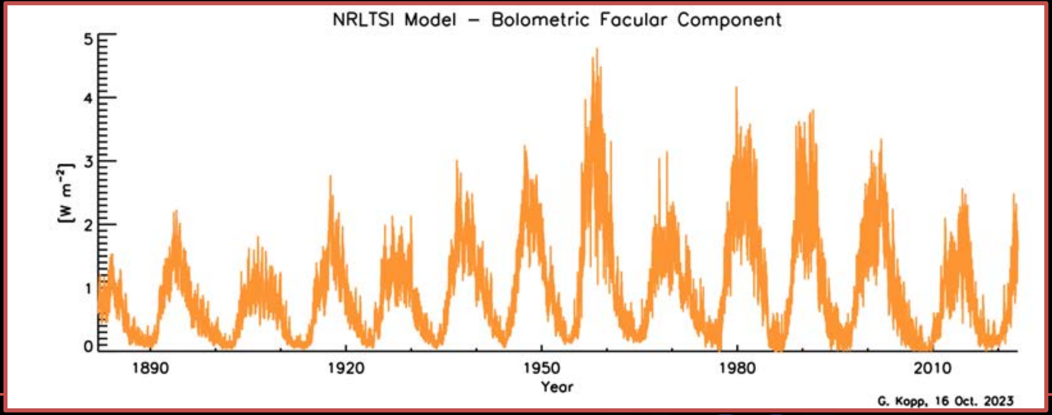
Regress Solar-Activity Components to TSI Over Measurement Era



then extend via components

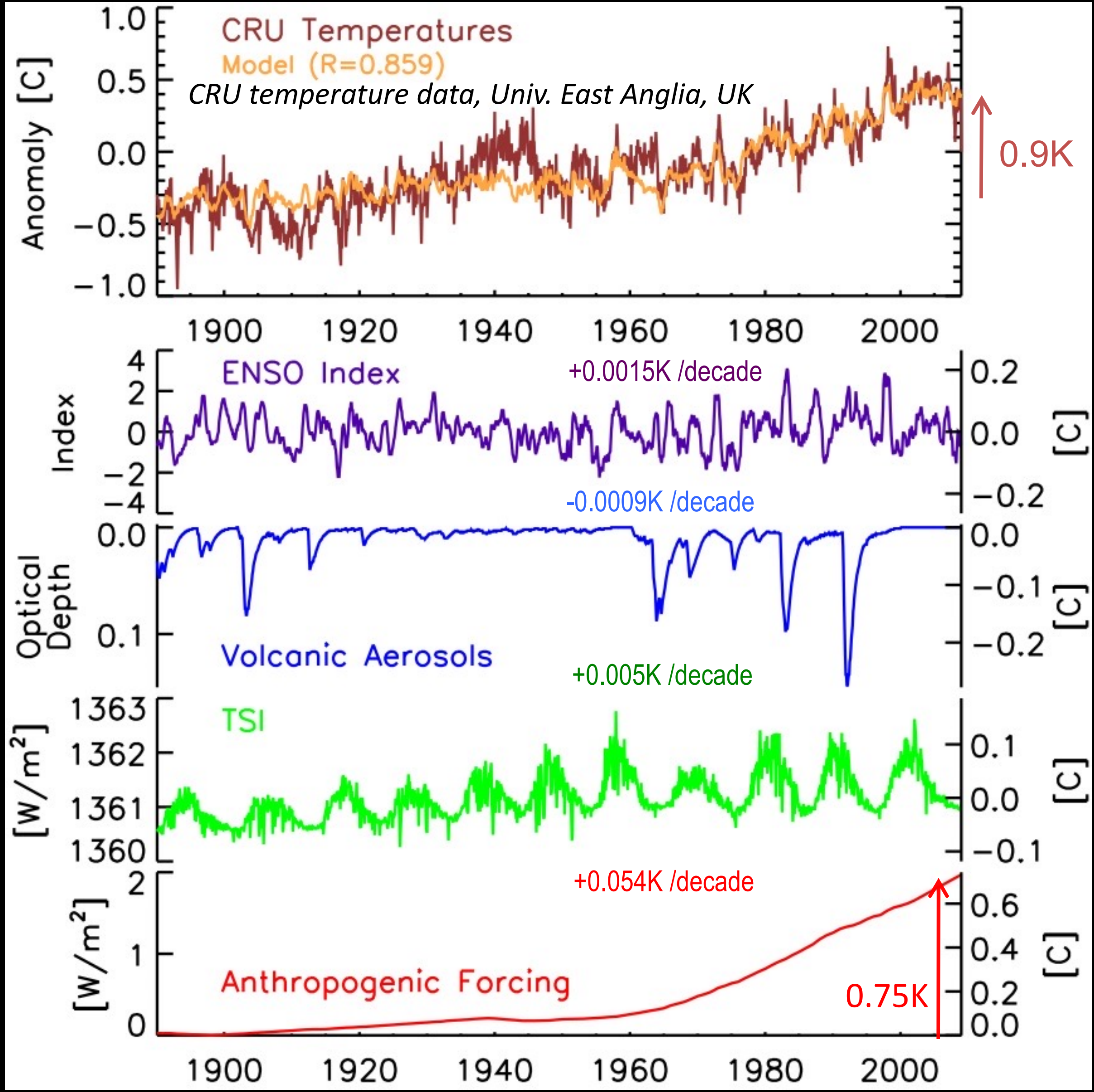






NRLTSI data courtesy of Judith Lean

"Components" of Global Temperature Changes



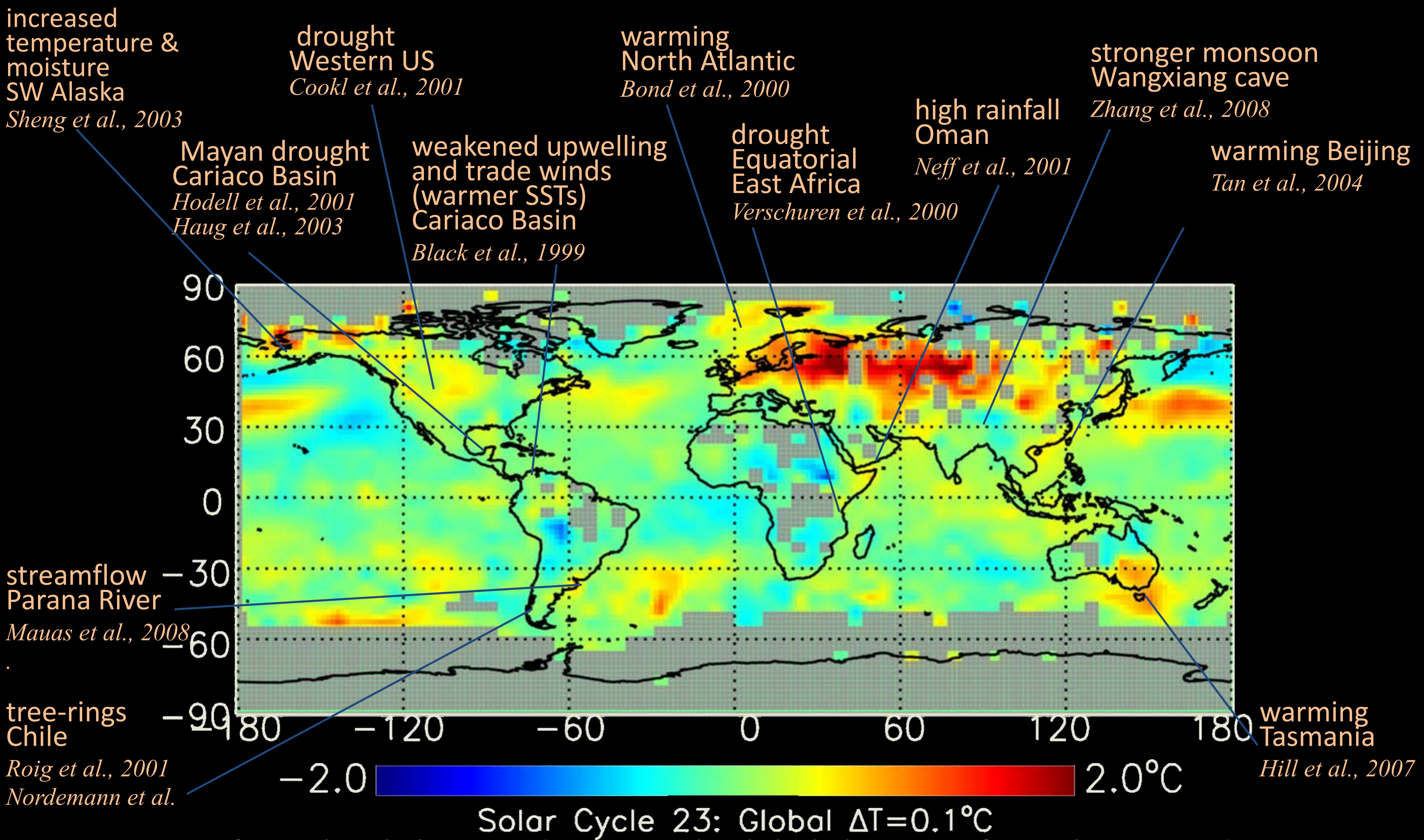
courtesy of Judith Lean, NRL

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

Natural components account for <15% of warming since 1890

Paleo Sun–Climate Synopsis

…when solar activity is high…



significant local changes do not imply global changes of equal magnitude

courtesy of Judith Lean, LASP

Regional Temperature Change – Surface

Determined Statistically from Observations

Lean and Rind, GRL, 2008

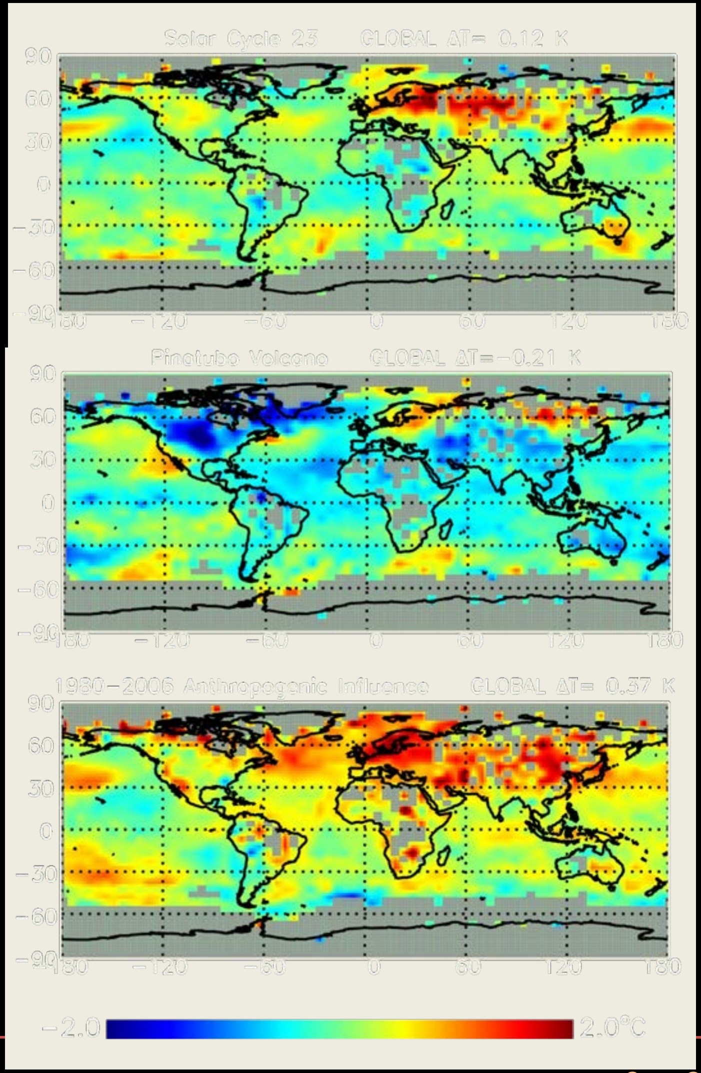
Modeled with GISS Model 3

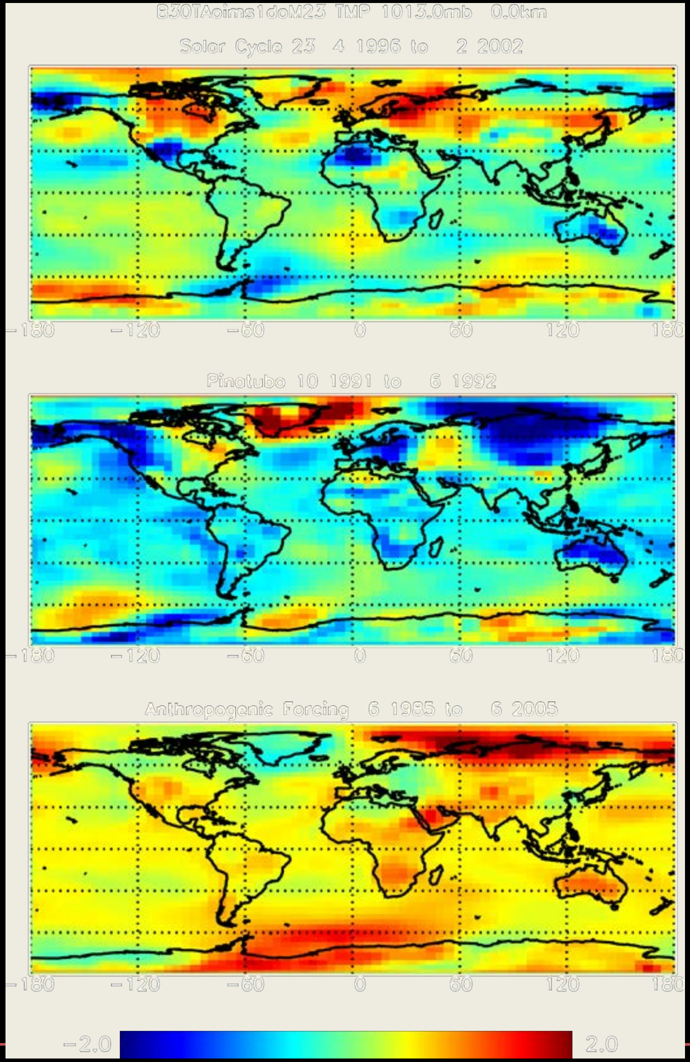
Rind et al., JGR, 2008

Solar Activity

Volcanic Activity

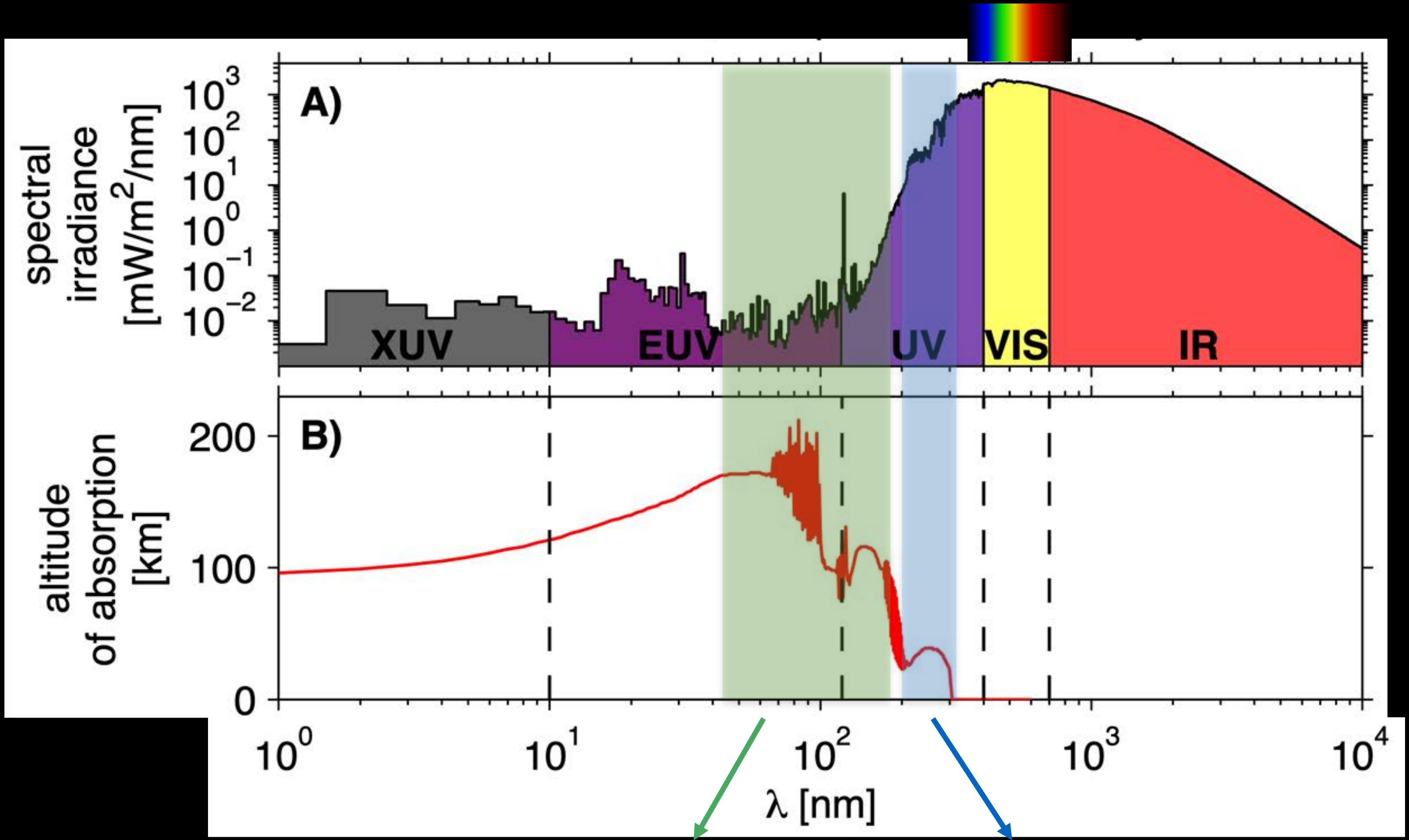
Greenhouse Gases





courtesy of Judith Lean, LASP

Spectral Distribution of Incoming Energy – SSI



Spectrally resolved irradiance

Altitude at which the absorption is strongest

Impact on satellite drag and radio communications

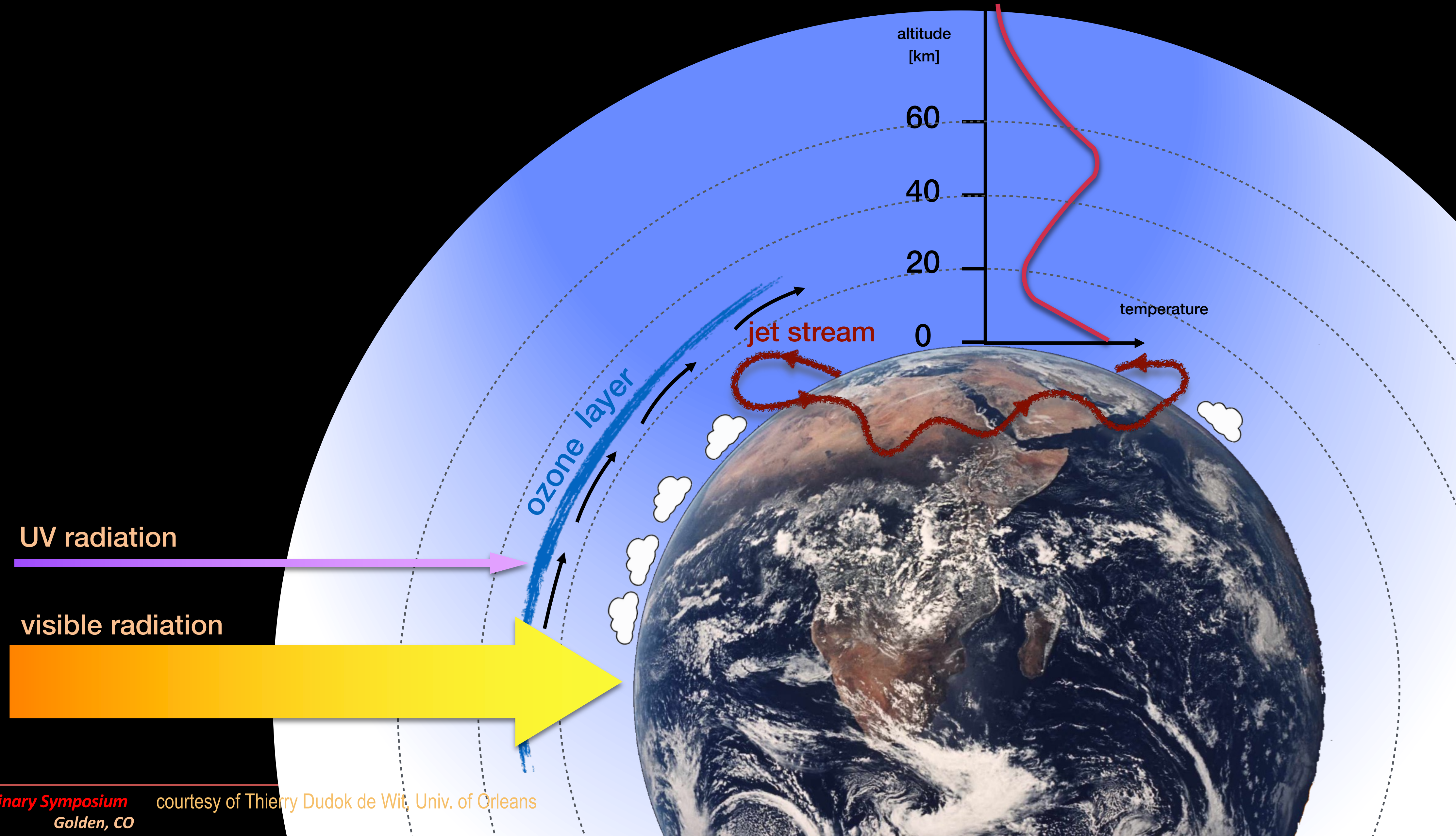
Lilensten et al., *AG* (2008)

Impact on the ozone layer

Haigh, *LRSP*, (2007)

courtesy of Thierry Dudok de Wit, Univ. of Orleans

How Solar UV Variability Impacts Climate



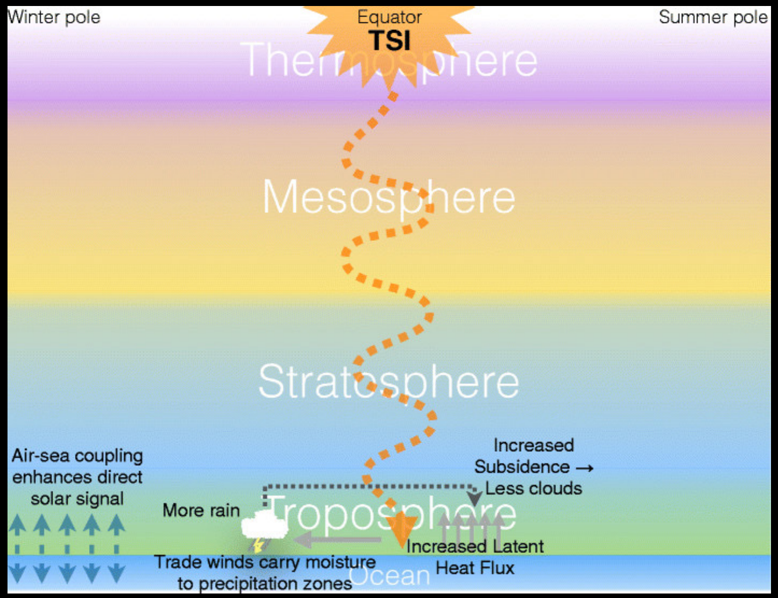
courtesy of Thierry Dudok de Wit, Univ. of Orleans

Solar Influences on Climate

"Bottom Up"

(Vis-IR "TSI" Influence : Meehl et al.)

A. Seppälä, et al., Progress in Earth and Planetary Science, 2014



Involves solar radiation being absorbed over the oceans

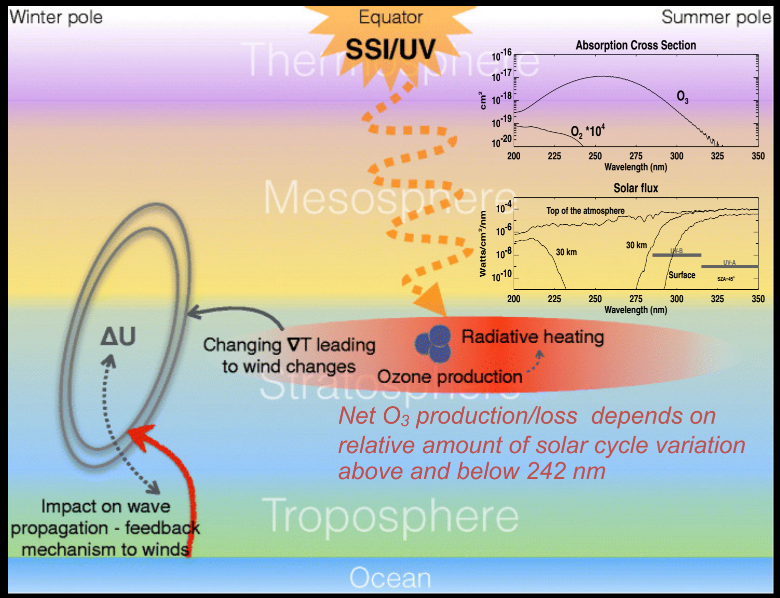
- *Produces increases in evaporation*
- *Increased moisture converging in the precipitation zones*

This leads to further changes in precipitation patterns and vertical motions, influencing the trade winds and ocean upwelling.

- *Produces stronger Hadley and Walker circulations and associated colder sea-surface temperatures at solar maximum*

"Top Down"

(UV "SSI" Influence : Haigh et al.)



Originates in the stratosphere where UV radiation modulates local radiative heating at the tropical stratopause

- *Direct effect on O_3 production rates in upper stratosphere via UV photolysis of O_2 (λ<242 nm)*
- *Radiative heating through O_3 absorption and dissociation (λ>242 nm)*

Changes in equatorial stratospheric heating affect meridional temperature gradient

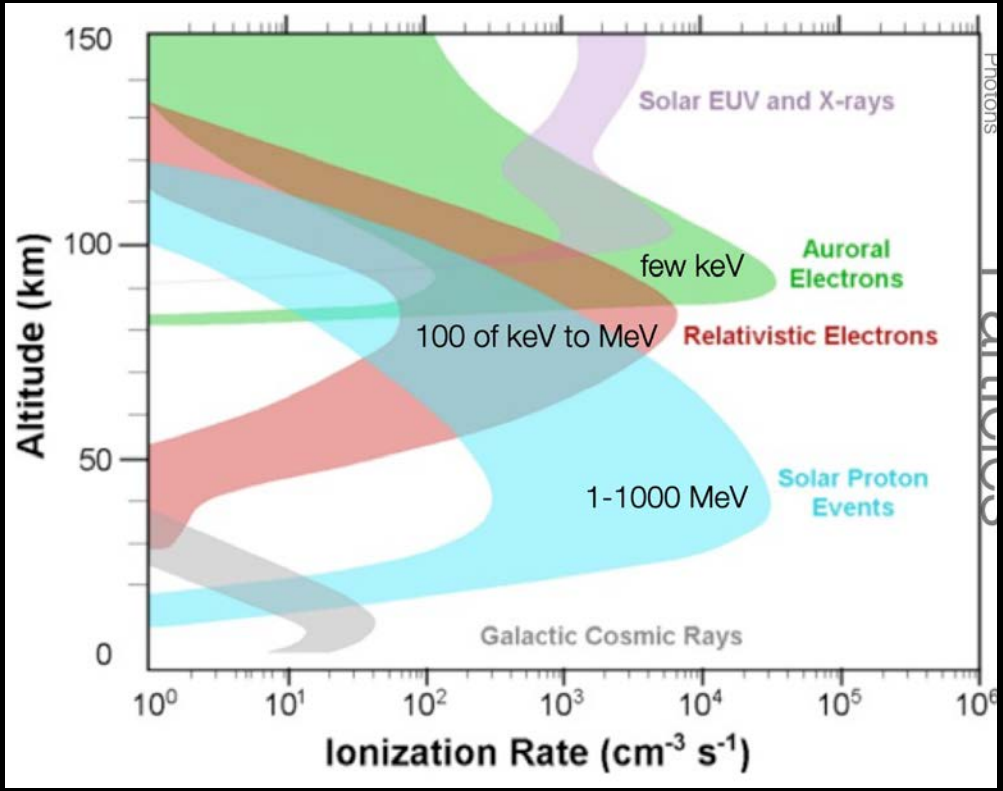
- *Modulates the zonal winds*
- *Influences the planetary wave propagation (positive feedback mechanism)*

courtesy of Erik Richard, LASP

Other (Lesser) Drivers

- Galactic cosmic rays and cloud nucleation
- Solar wind and CMEs
  - Solar wind transients store energy in the Earth's magnetosphere
  - Geomagnetic storms accelerate particles and generate intense currents
  - Energetic particles generate NO_x in upper atmosphere and alter dynamics
- Solar Flares
  - UV can ionize upper atmosphere and ozone

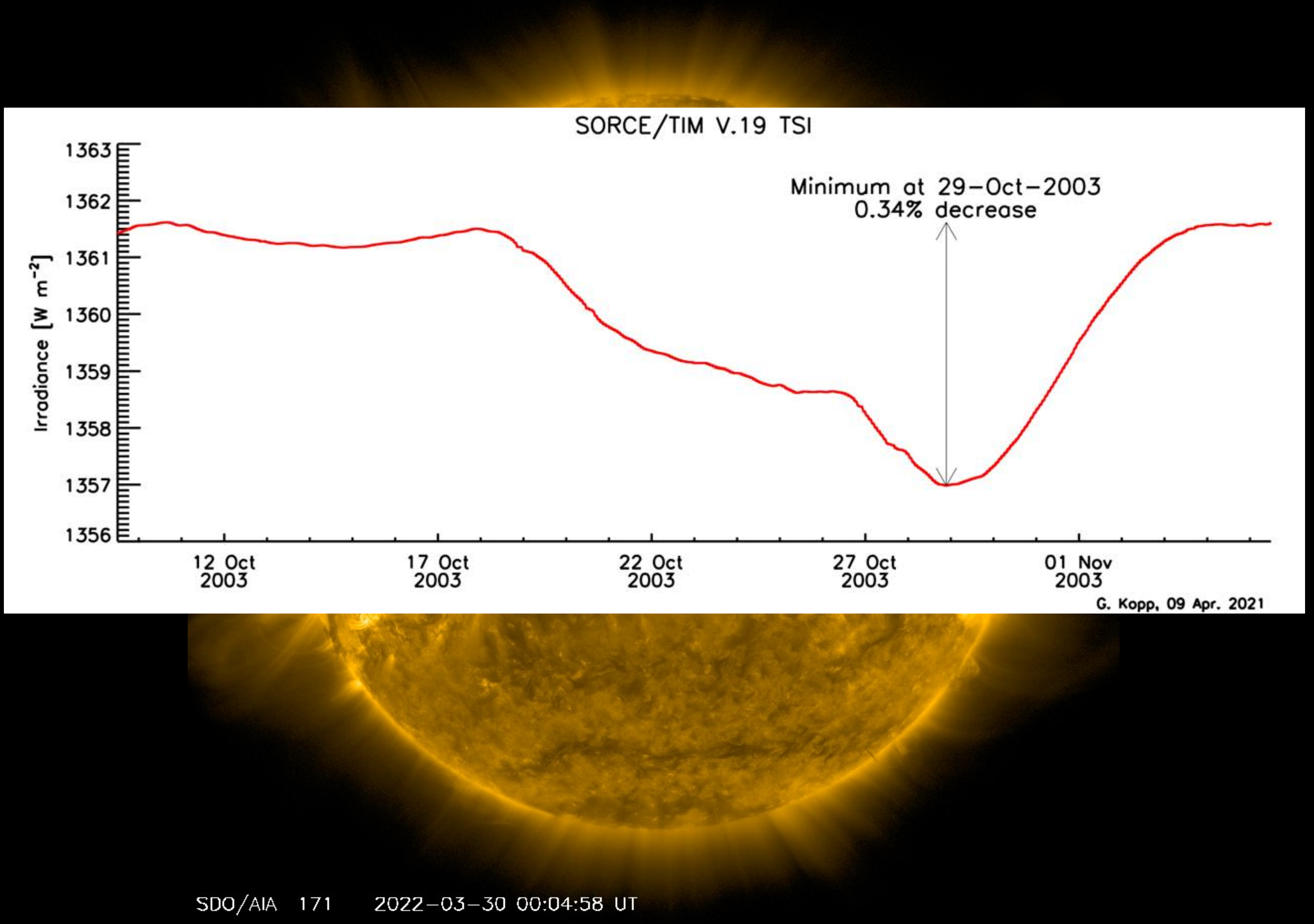
Climate
depends on long-term effects
(Tomorrow we'll talk about these short-term non-climatic effects)



A. Seppälä (2013)

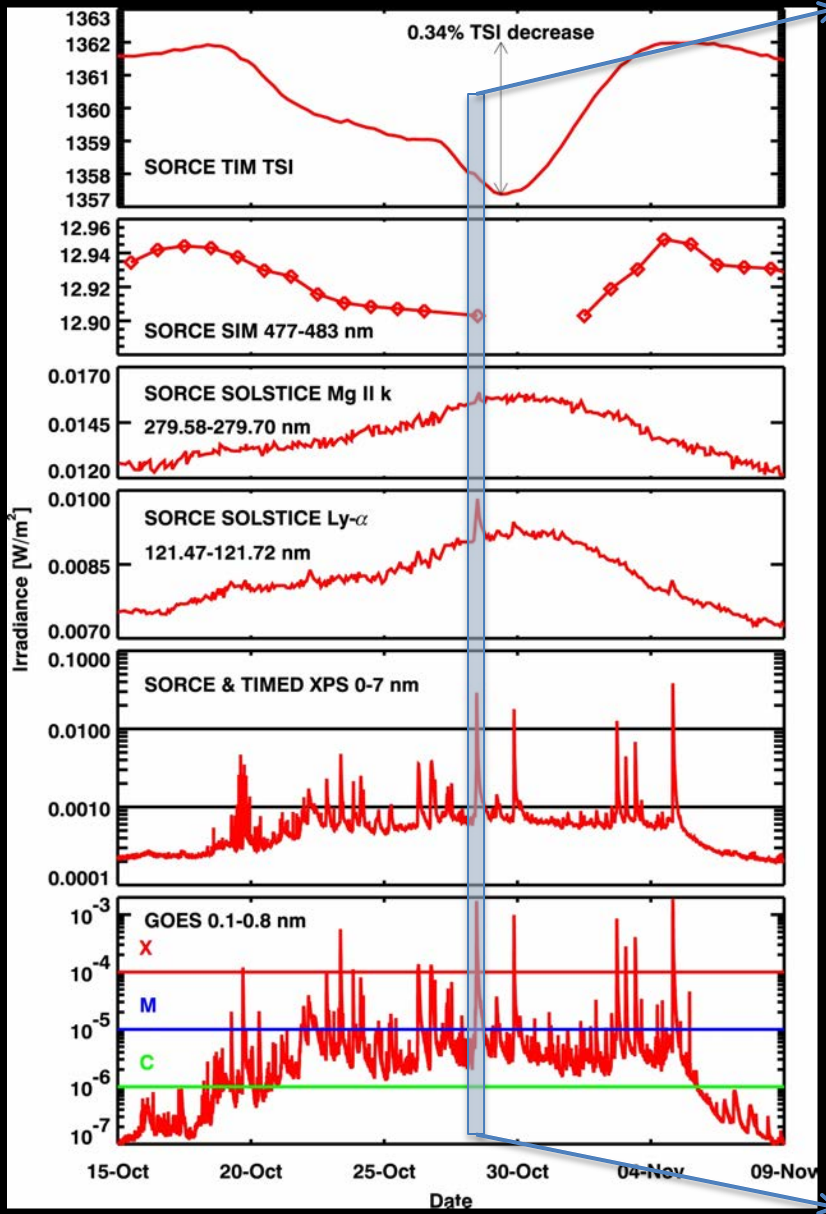
What About Those Headline-Grabbing Energetic Solar Flares?

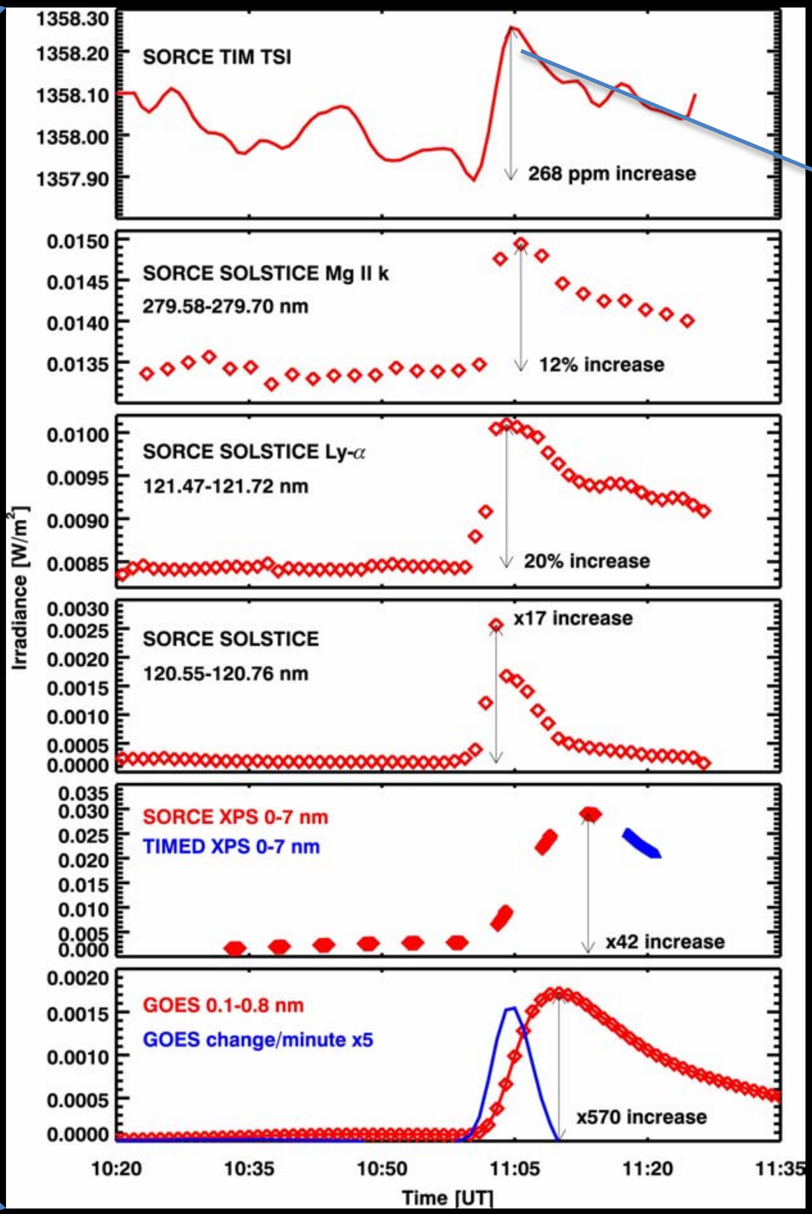
- Flares are largest explosive events in the solar system
  - Equivalent to ~ 40 billion Hiroshima-type atomic bombs
- The SORCE/TIM recorded the first measurement of a solar flare in TSI
  - This quantified the net radiative energy released by the flare

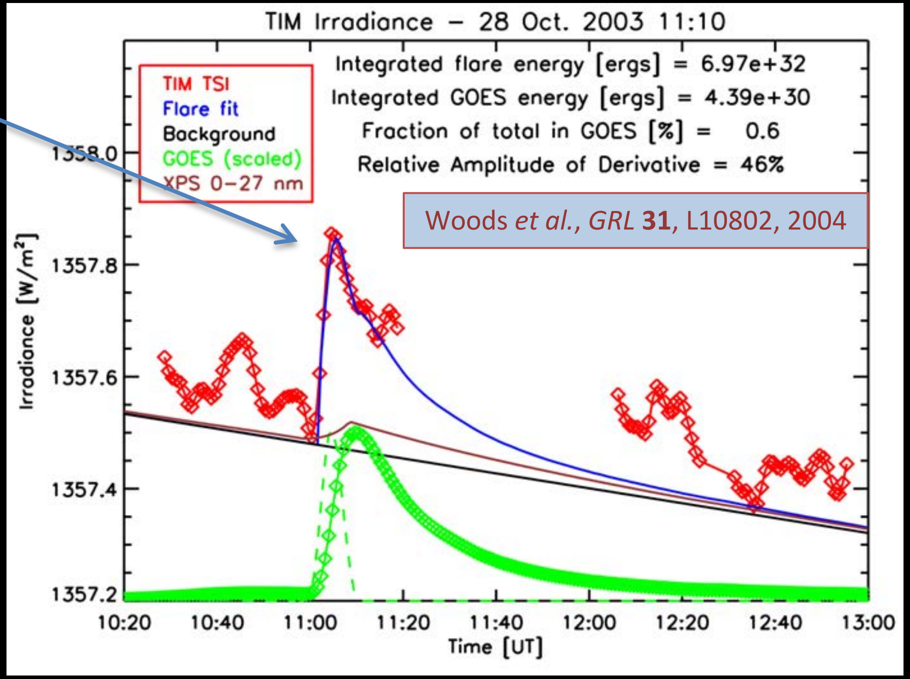


plots available at
http://spot.colorado.edu/~koppg/TSI

It's Not Flares. Or CMEs. 28 Oct. 2003 X17 SORCE Flare Observations



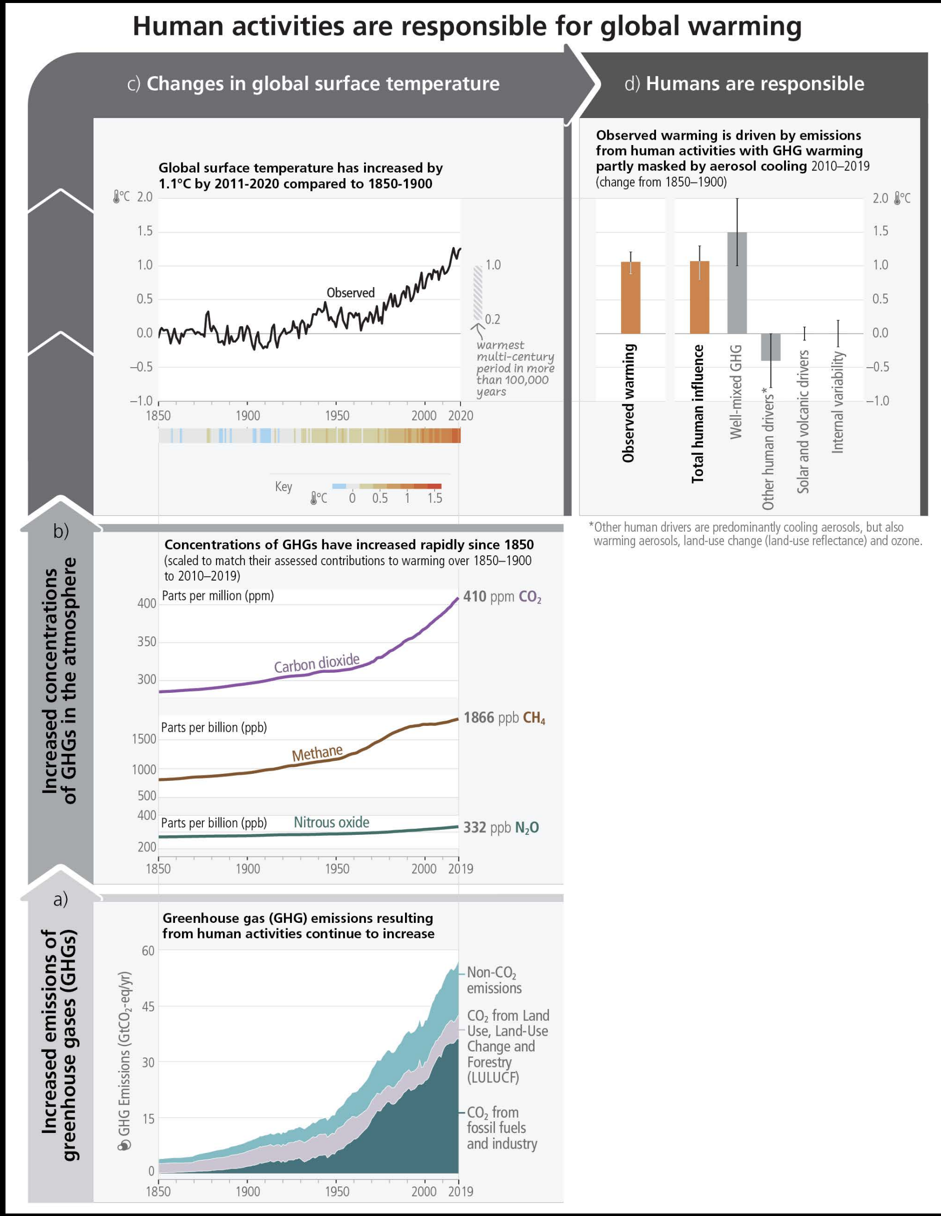


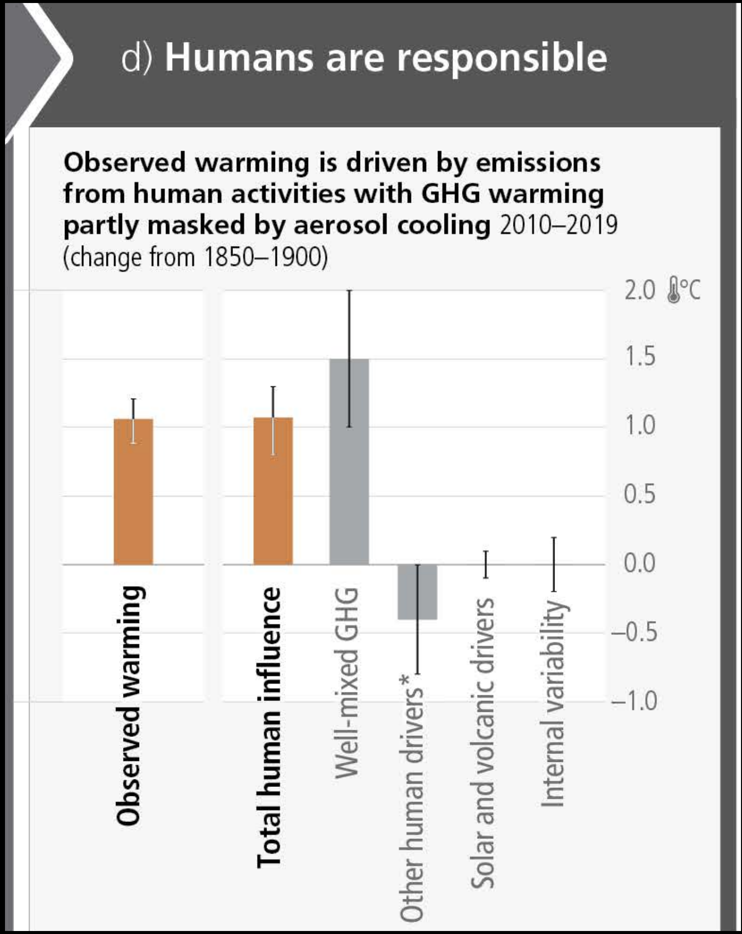


Perspective

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

IPCC AR6

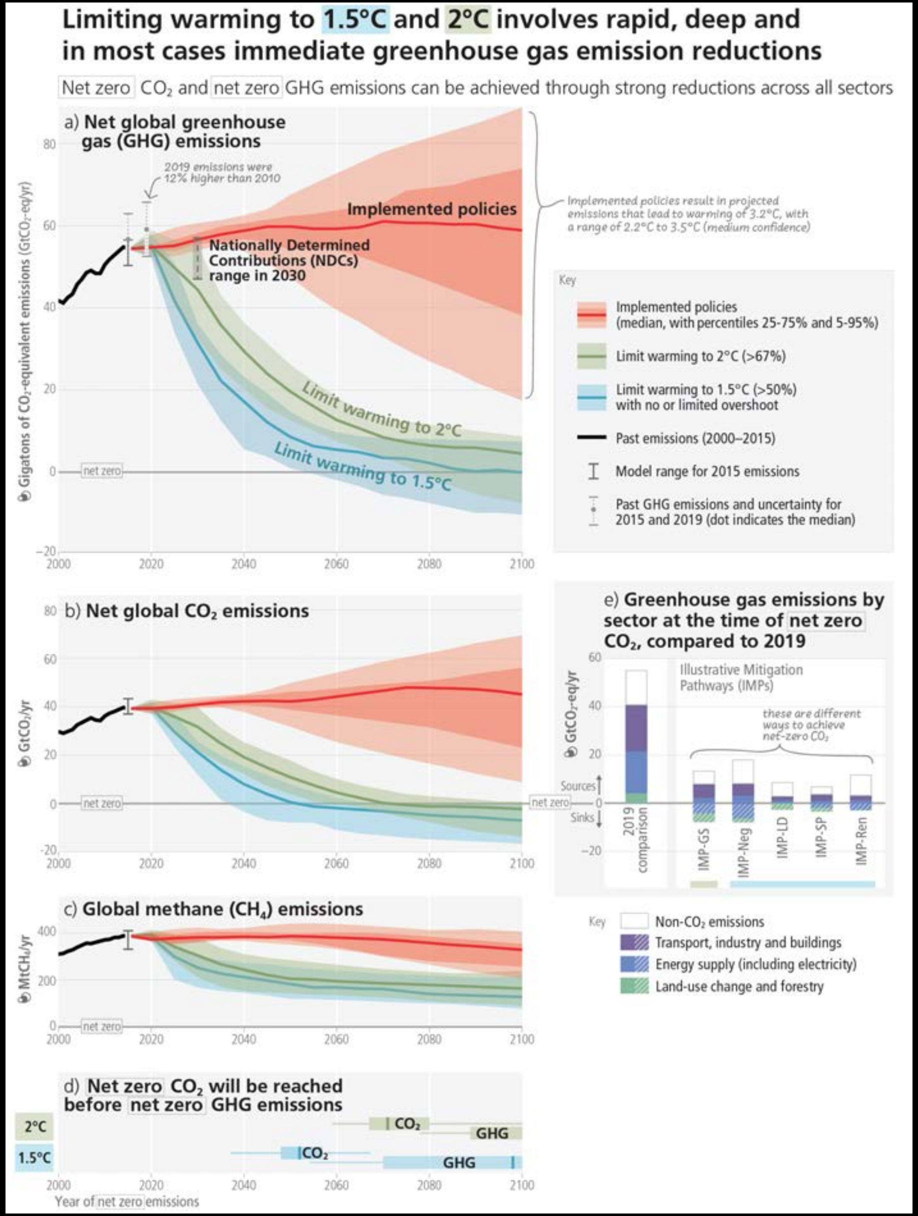




- It's not the Sun
- But it's important to discriminate natural from anthropogenic effects

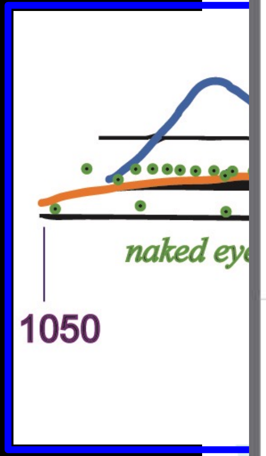
The Future – Our Future

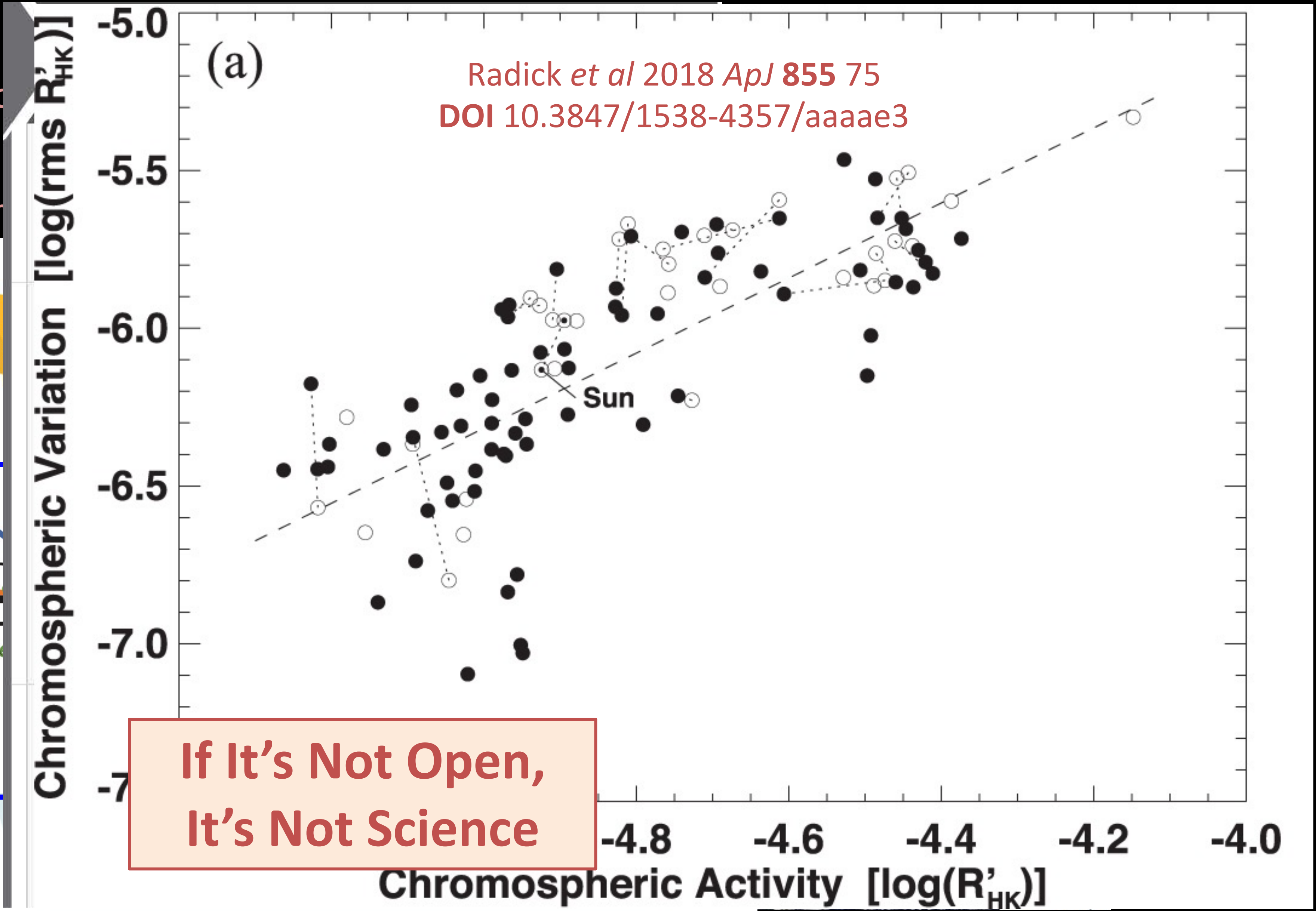
- Can we limit increase to 2 C?
- CO_2 lasts 1000's of years
  - Ocean uptake and response can be longer
  - We won't get back to pre-industrial environment
- Approaches to climate change
  - Mitigate
  - Adapt (proactively or responsively)
  - Suffer
- (Hint: We'll do all three)



Who’s Involved in This Cross-Disciplinary Sun-Climate Topic?

- Science
  - Spacecraft and ground-based
  - Climate and solar modelers
  - Ocean and land monitoring r
  - Long-term observers (suns
  - Stellar-variability researche
  - History buffs, archeologists
- Society
  - Policy makers
  - All nations
  - IPCC
  - Media
  - **You!!!**





If It’s Not Open, It’s Not Science