Overview of
The Effects of Solar Variability on Earth's Climate: A Workshop Report

Presented by Dr. Larry J. Paxton
The Johns Hopkins University
Applied Physics Laboratory

STATEMENT OF TASK

- An ad hoc committee will plan and conduct a public workshop that will examine the state of knowledge regarding the climate response to solar variability and will explore some of the outstanding scientific issues that might guide future research thrusts.

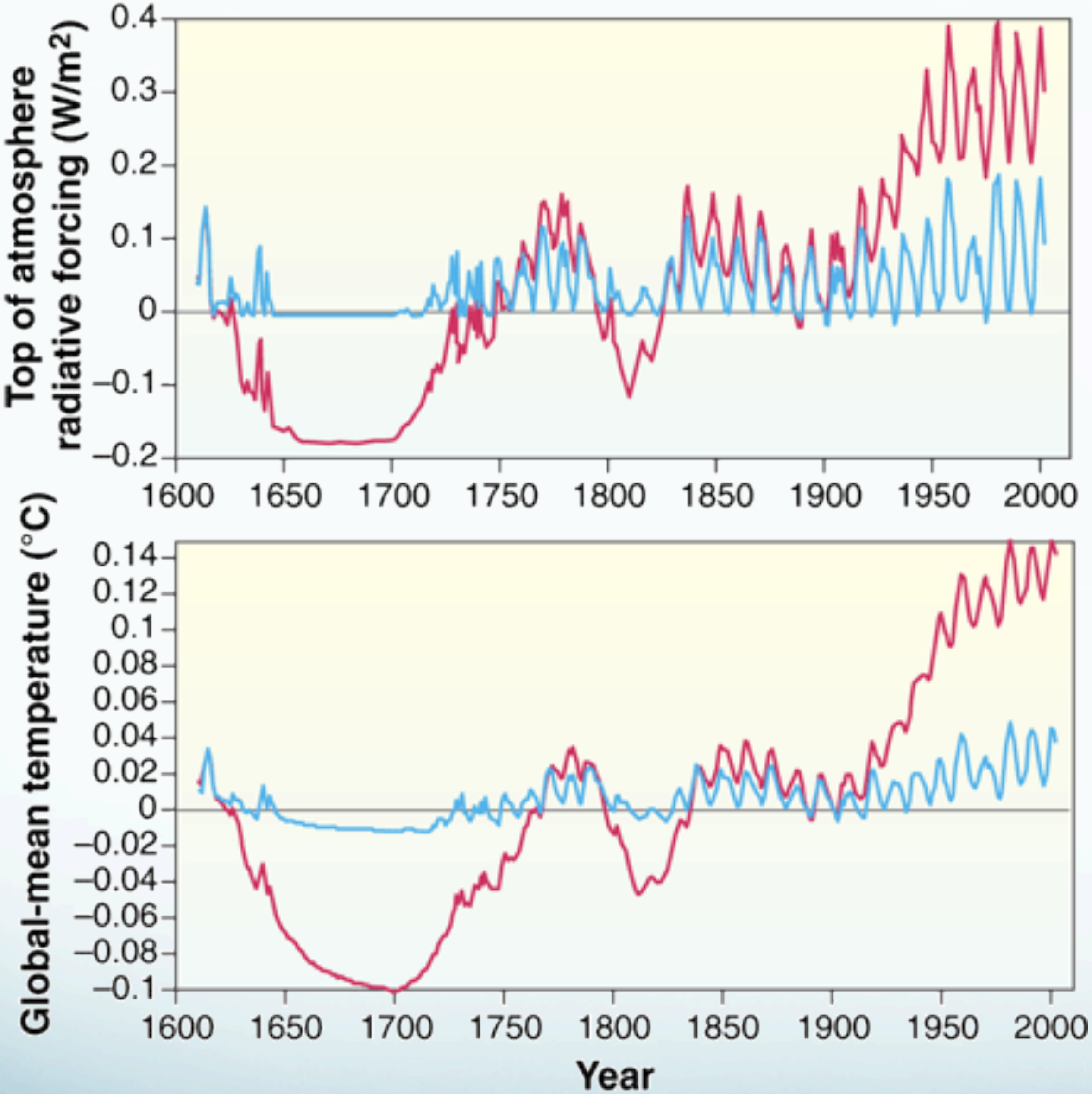
- The committee will hold a data-gathering meeting in the process of developing the agenda for the workshop and defining the specific topics for invited presentations and discussions.

- The committee will subsequently select and invite speakers and other participants and moderate the discussions at the event.

- The committee will prepare a workshop report that will summarize what transpired at the event but will not contain any findings or recommendations.

COMMITTEE ON THE EFFECTS OF SOLAR VARIABILITY ON EARTH.'S CLIMATE

- GERALD R. NORTH, Texas A&M University, Chair
- DANIEL N. BAKER, University of Colorado, Boulder
- RAYMOND S. BRADLEY, University of Massachusetts
- PETER FOUKAL, Heliophysics, Inc.
- JOANNA D. HAIGH, Imperial College, London
- ISAAC M. HELD, National Oceanic and Atmospheric Administration Geophysical Fluid DynamicsLaboratory
- GERALD A. MEEHL, National Center for Atmospheric Research
- LARRY J. PAXTON, Johns Hopkins University
- PETER PILEWSKIE, University of Colorado, Boulder
- CAROLUS J. SCHRIJVER, Lockheed Martin Advanced Technology Center
- KA-KIT TUNG, University of Washington
- ABIGAIL A. SHEFFER, Associate Program Officer, Study Director
- ARTHUR A. CHARO, Senior Program Officer



Apparent magnitude of solar forcings.
(**Top**) Top-of-atmosphere solar forcing (red) from (1), showing the sunspot cycle component separately (blue). (**Bottom**) Global-mean temperature responses to the forcings shown in the top panel, calculated with the MAGICC climate model using best estimate parameters (2). Forcings and responses are zeroed in 1900. The temperature response to the speculative long-term component is much larger than to the sunspot-cycle component alone.

1. J. Lean, J. Beer, R. Bradley, Geophys. Res. Lett. **22**, 3195 (1995).
2. T. M. L. Wigley, S. C. B. Raper, Science **293**, 451 (2001)

Peter, Foukal, Gerald North, Tom Wigley, A Stellar View on Solar Variations and Climate
Science 1 October 2004:
Vol. 306 no. 5693 pp. 68-69
DOI: 10.1126/science.1101694

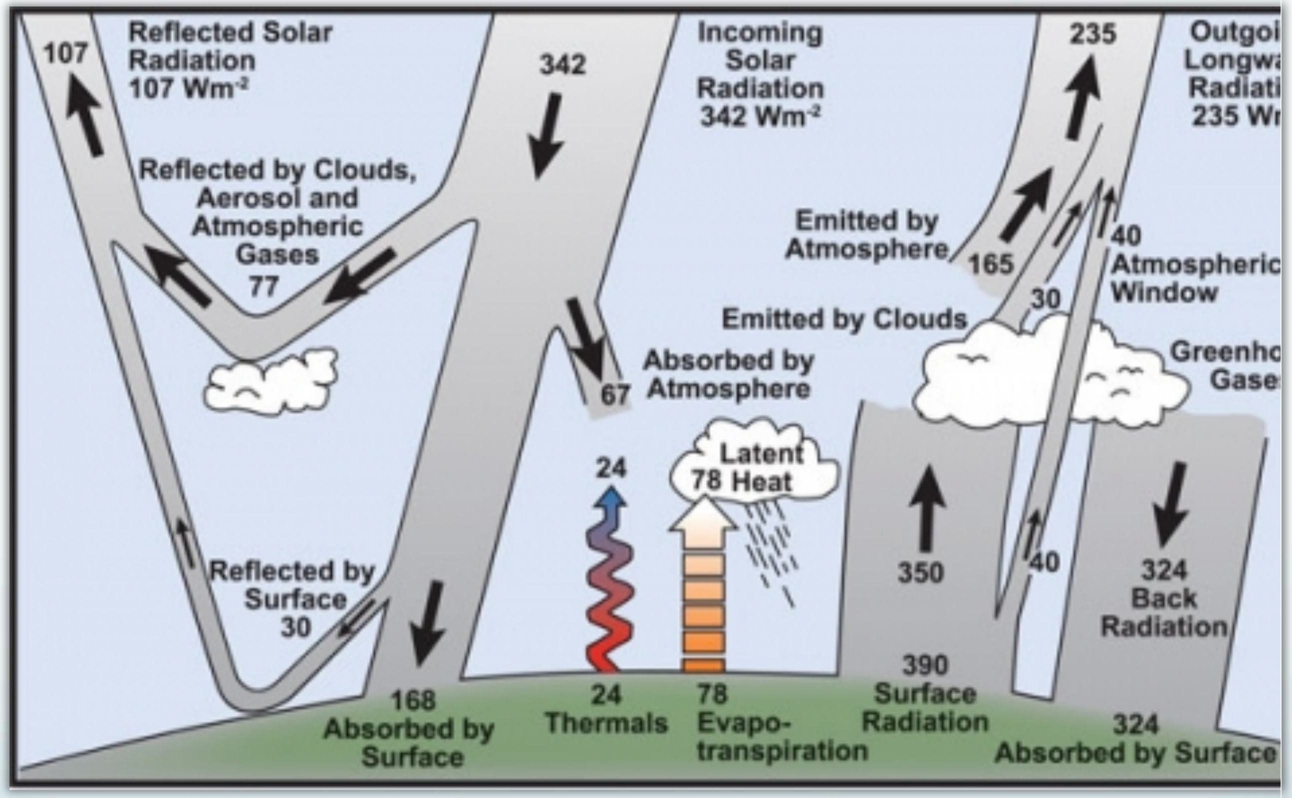
Report Scope is Defined and Focused

- This workshop report contains no recommendations, findings, or statements of consensus.
- Instead, this workshop report summarizes the views expressed by individual workshop participants (invited speakers and guests).
- Some background information was included in the report to provide context to the reader on both the solar and climate science topics presented at the workshop; however, this is not intended to be an exhaustive review of the current state of the science.

Topic Areas Address Major Aspects of the Problem

- **There is no substantive scientific evidence that an increase in solar irradiance is the cause of the global warming of the last 50 years.**
- Mechanisms by which solar variations can affect climate remains an open area of research.
- The Sun and Solar Variability: Past and Present
  - Overview of solar and heliospheric variability
  - Observations of the Sun's variable outputs
  - Techniques for revealing past solar changes
- Sun-Climate Connections on Different Timescales
  - Evidence of solar influences in the troposphere and stratosphere
  - How the climate system works and how it might respond to solar influences
  - Indications of influence based on paleoclimate records

Solar Irradiance is Connected to Terrestrial Climate Thru a Complex Transfer Function



Estimate of the Earth's Annual and Global Mean Energy Balance: Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation.

Credit: IPCC, 2007. http://www.ipcc.ch/ Kiehl and Trenberth (1997)

Challenge Areas Were Identified

What do we know about TSI variability now and in the past?

What do we need to model the processes and test our understanding?

What do we know about the variability of climate on global and regional spatial scales on timescales of years, decades, and longer?

What data need to be collected and how often?

How do we make sure these data are widely available and 'curated'?

Do we understand the mechanisms for Sun-climate connections accurately?

The workshop provided an overview of some of these connections

- galactic cosmic ray forcings
- chemical couplings
- the top-down
- bottom-up

Challenge: There are Many Connections to the Climate Record

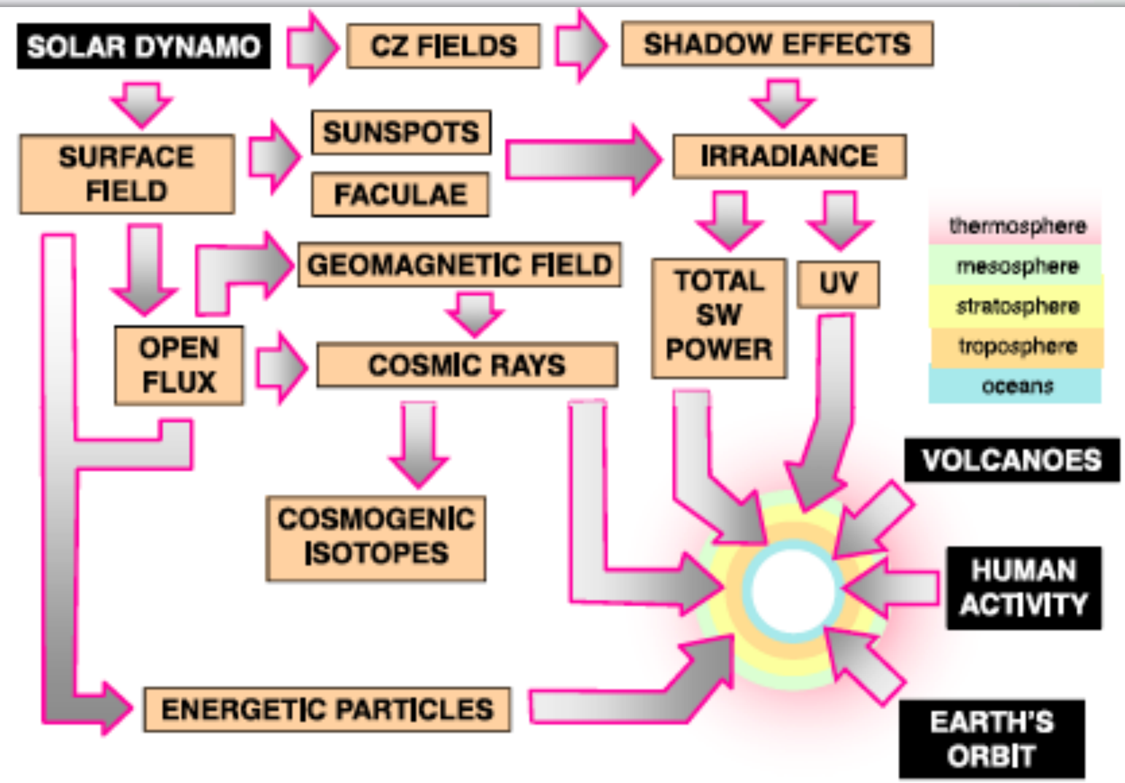
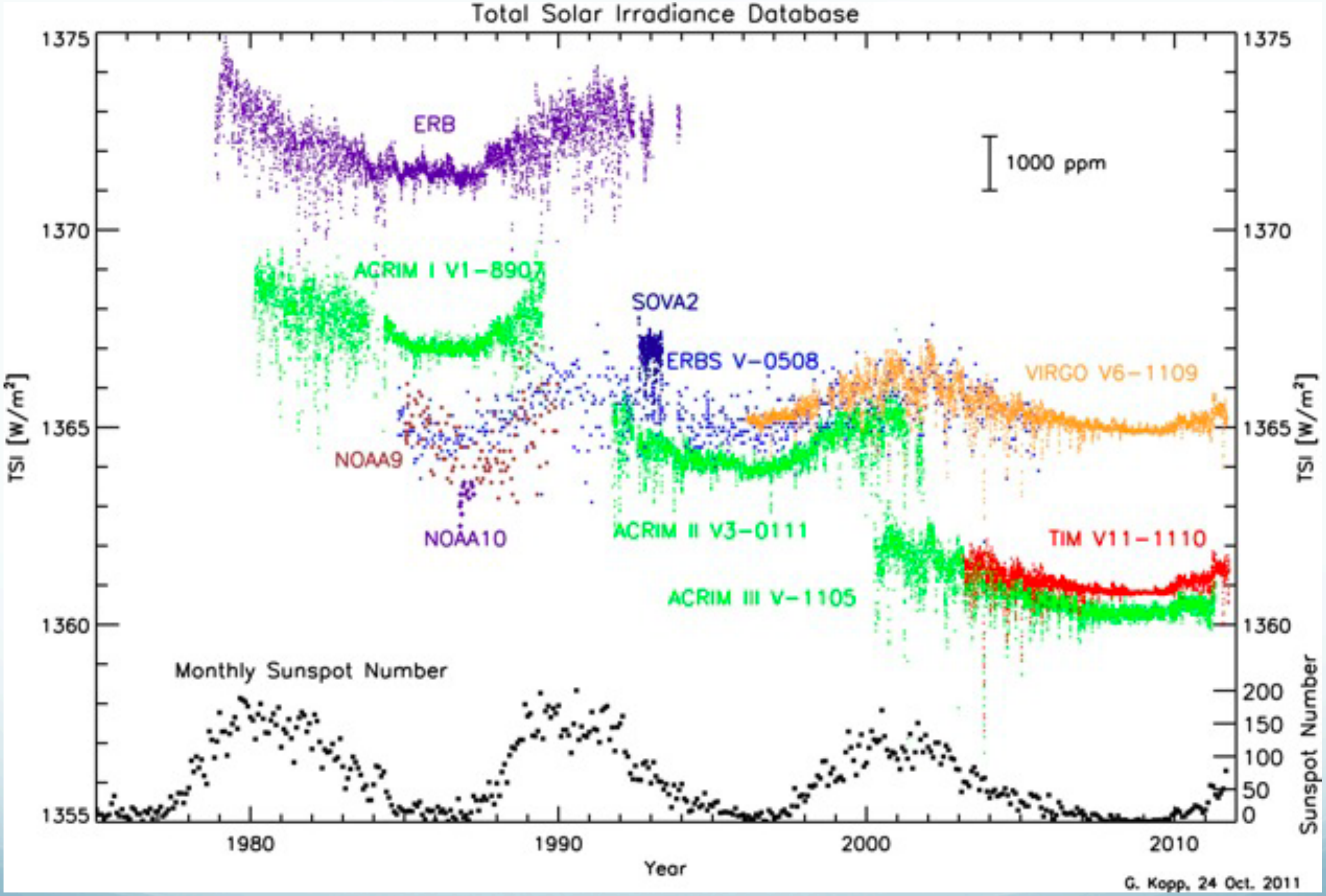


Figure 20. Schematic overview showing various climate forcings of the Earth's atmosphere, with fa tors that influence the forcing associated with solar variability (irradiance and corpuscular radiatio shown in more detail on the left-hand side, as discussed in section 2.

Gray, L. J., et al. (2010), Solar influences on climate, Rev. Geophys., 48, RG4001, doi:10.1029/2009RG000282

Challenge: Understanding and Quantifying Solar Variability

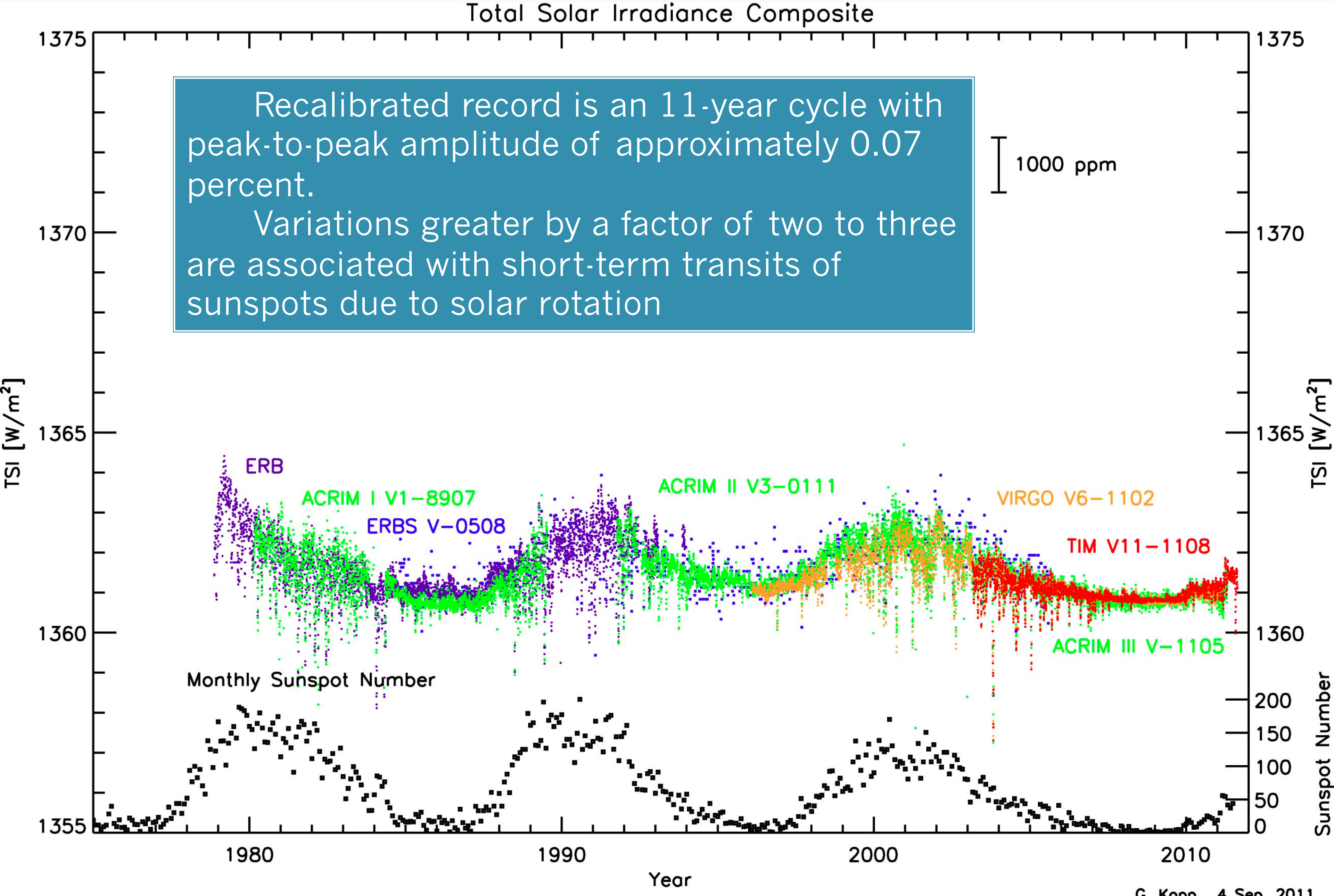
- Solar irradiance, the flux of the Sun.'s output directed toward Earth, is Earth's main energy source.
- The Sun itself varies on several timescales—over billions of years its luminosity increases as it evolves on the main sequence toward becoming a red giant; about every 11 years its sunspot activity cycles; and within just minutes flares can erupt and release massive amounts of energy.
- Most of the fluctuations from tens to thousands of years are associated with changes in the solar magnetic field.



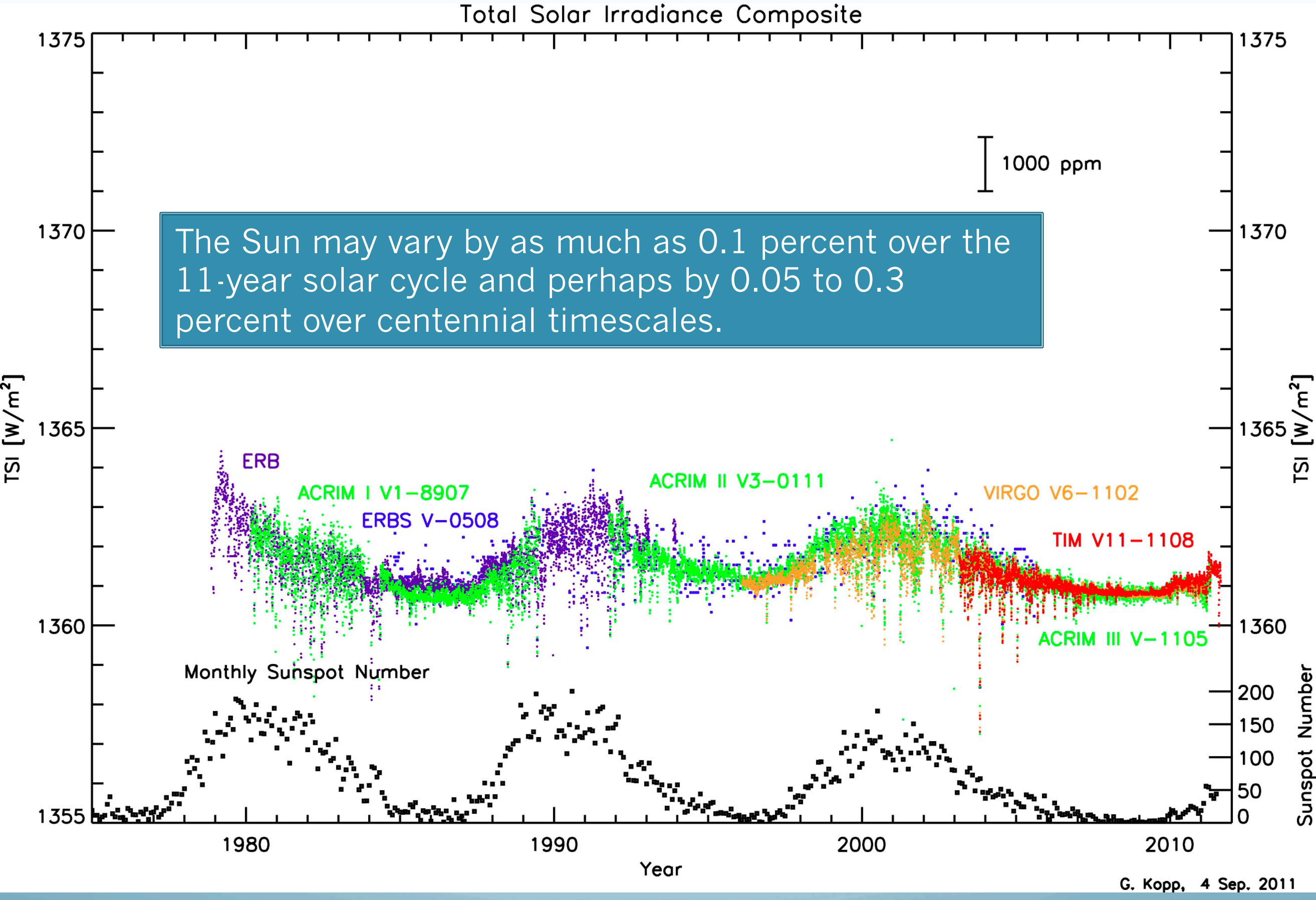
Total Solar Irradiance Database
1375
1370
1365
1360
1355
TSI [W/m²]
ERB
1000 ppm
ACRIM I V1-8907
SOVA2
ERBS V-0508
VIRGO V6-1109
NOAA9
NOAA10
ACRIM II V3-0111
TIM V11-1110
ACRIM III V-1105
Monthly Sunspot Number
200
150
100
50
0
Sunspot Number
1980
1990
2000
2010
Year
G. Kopp, 24 Oct. 2011

Recalibrated record is an 11-year cycle with peak-to-peak amplitude of approximately 0.07 percent.

Variations greater by a factor of two to three are associated with short-term transits of sunspots due to solar rotation



The Sun may vary by as much as 0.1 percent over the 11-year solar cycle and perhaps by 0.05 to 0.3 percent over centennial timescales.



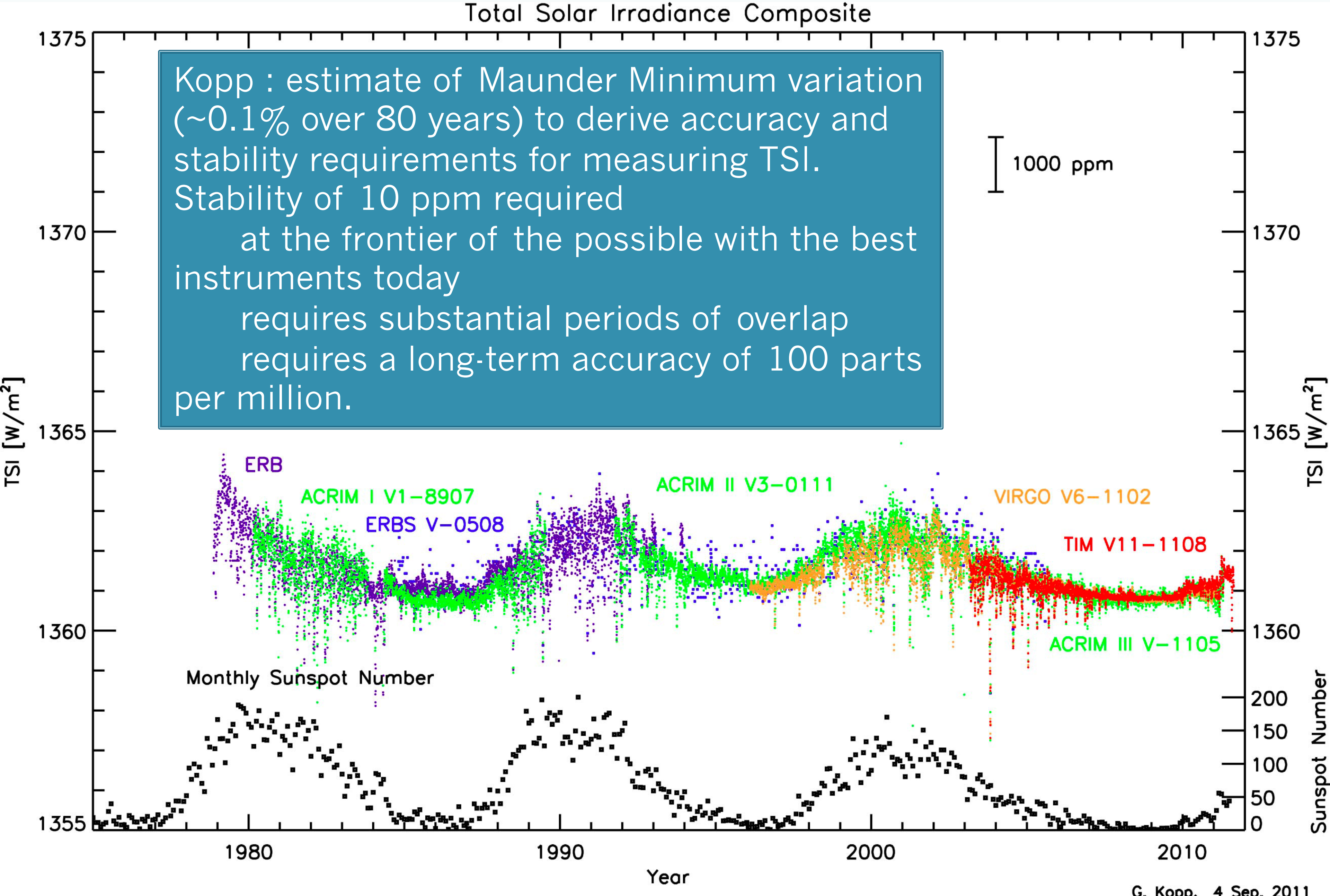
Kopp : estimate of Maunder Minimum variation (~0.1% over 80 years) to derive accuracy and stability requirements for measuring TSI.

Stability of 10 ppm required

at the frontier of the possible with the best instruments today

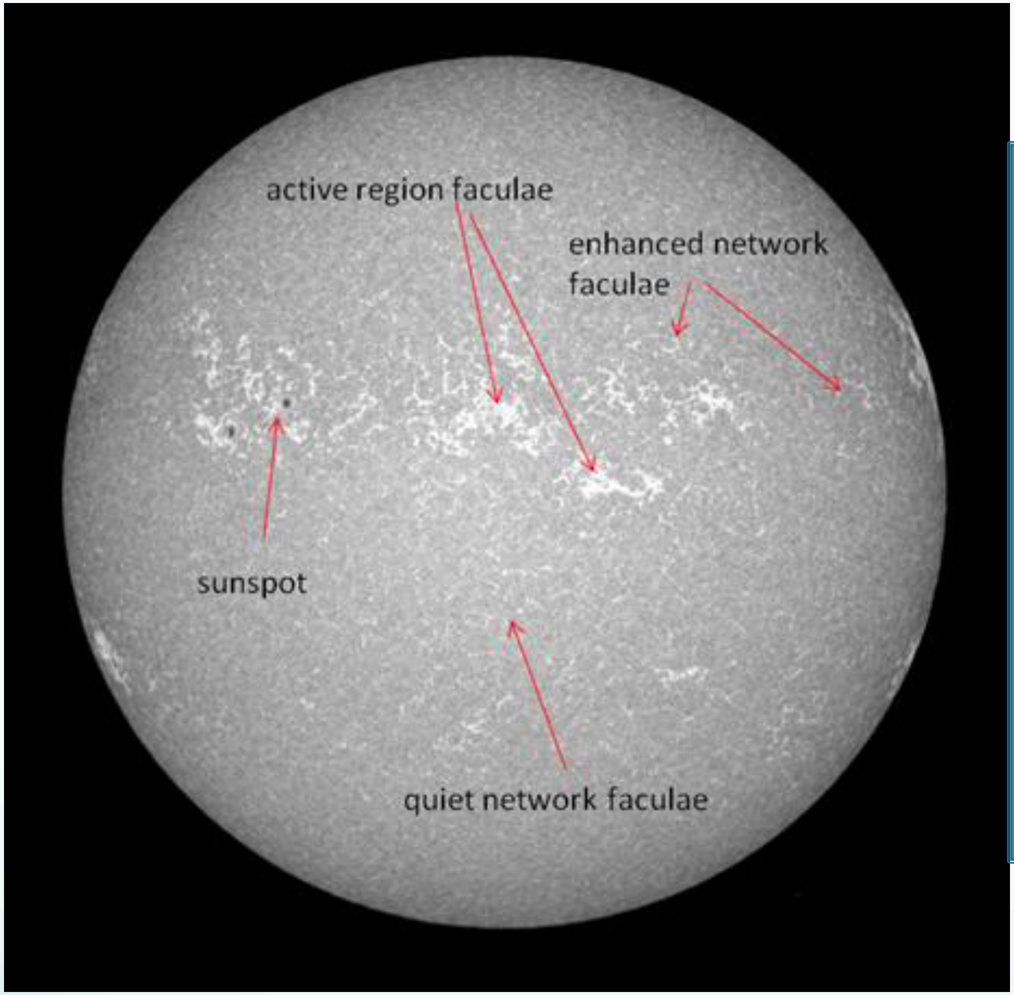
requires substantial periods of overlap

requires a long-term accuracy of 100 parts per million.



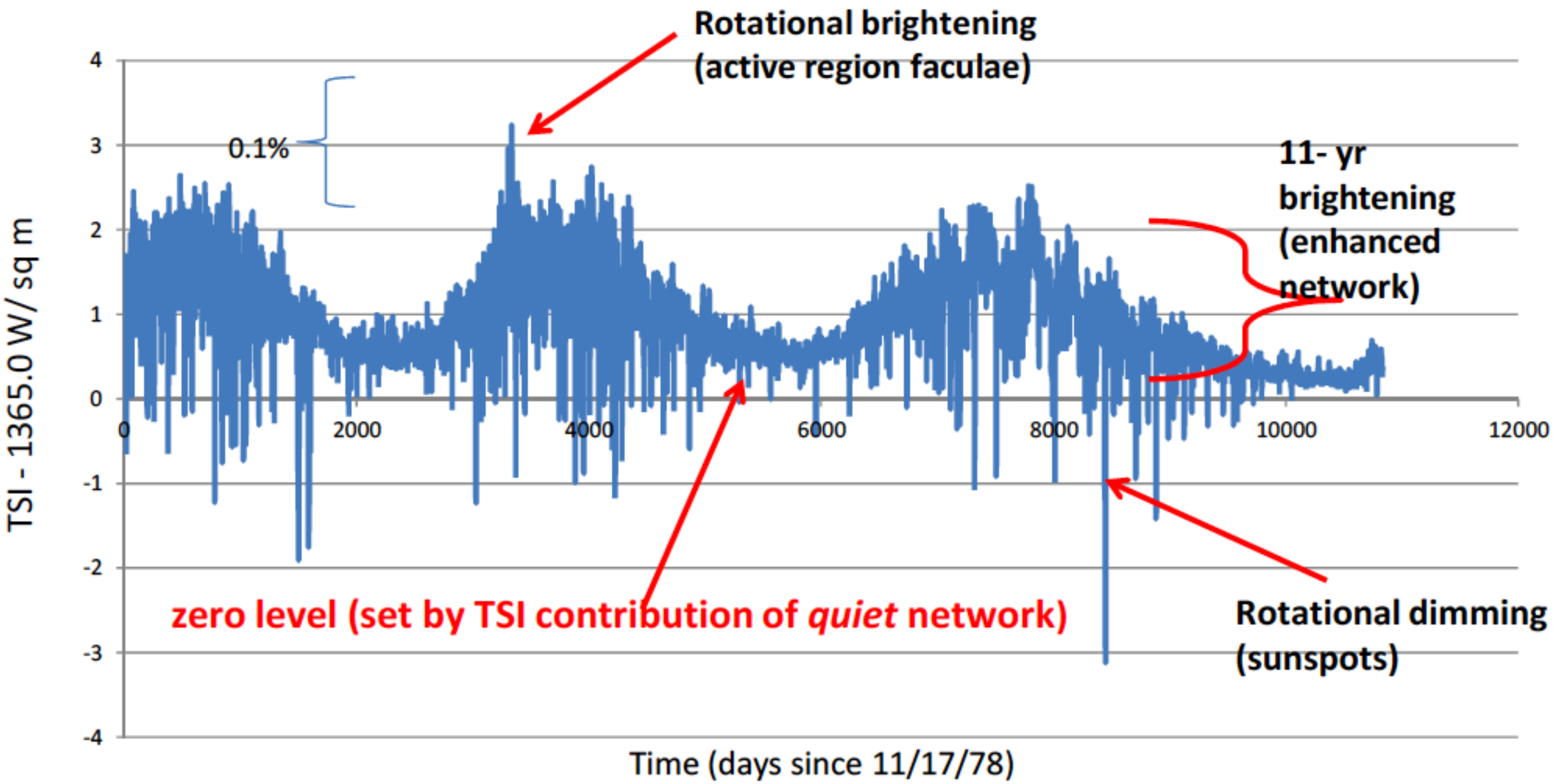
Challenge: Modeling Solar Variability

- Solar variability is closely related to the structure and magnitude of the solar magnetic field, and so the ability to reconstruct past solar outputs, or predict them, is only as good as the understanding of how the solar magnetic field varies in time and location on the Sun.
- Precise helioseismic measurements reveal the complex depth dependence of solar rotation throughout the convection zone and well into the radiative core.
- There is still no precise predictive model of the dynamo that drives solar magnetism over the 11-year cycle or of its modulation envelope over centuries and millennia.



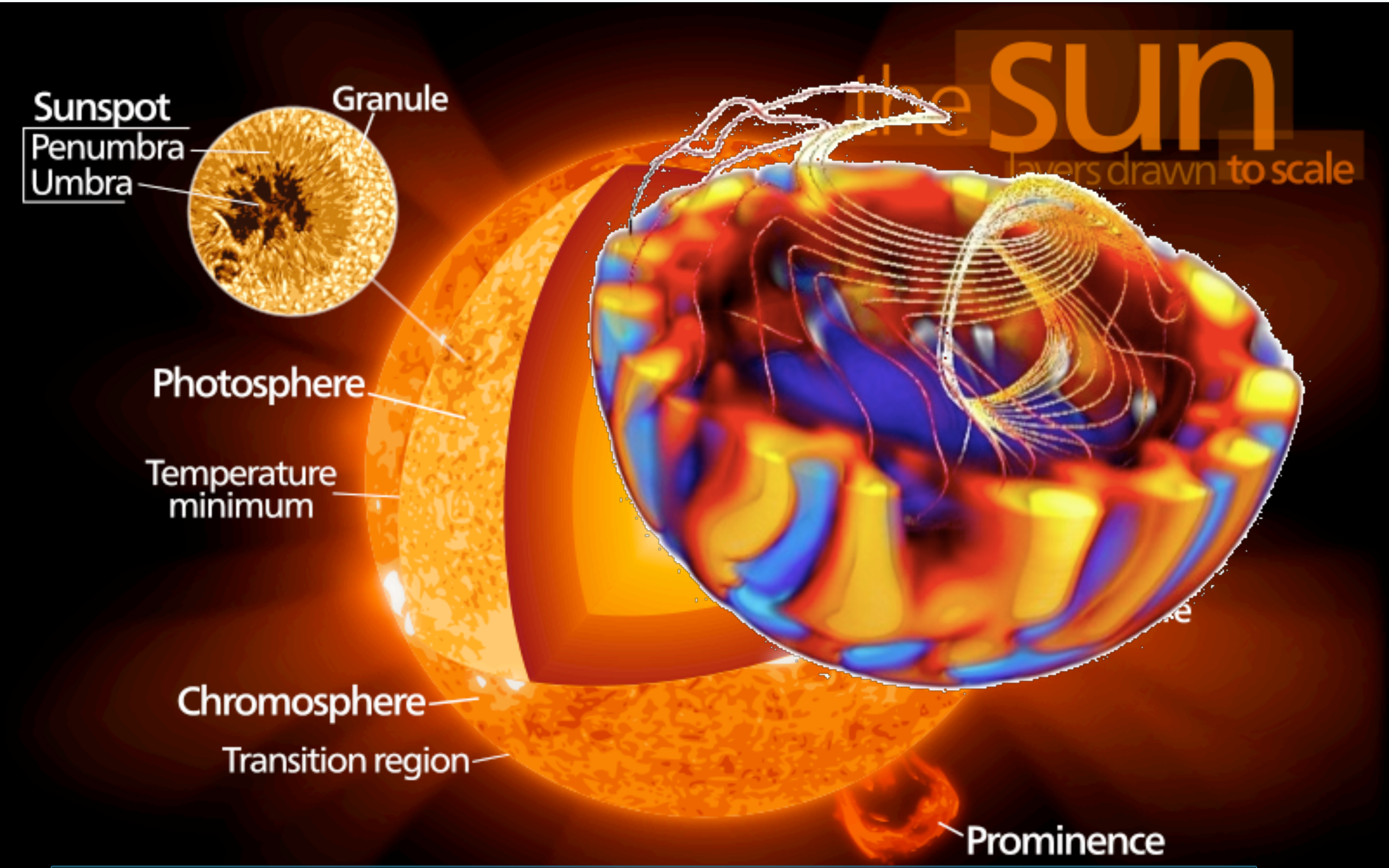
Challenge area: present estimates of the quiet network's contribution to total irradiance (Figure 2.3) are uncertain because of limitations on angular resolution, angular coverage, or wavelength coverage.
TSI and SSI measurements are required to illuminate differences in solar output.

FIGURE 2.2 Image of the Sun.'s upper photosphere in the 170 nm continuum showing the magnetic structures responsible variation in for TSI and in 130-240 nm UV irradiance. SOURCE: Courtesy of P. Foukal, Heliophysics, Inc



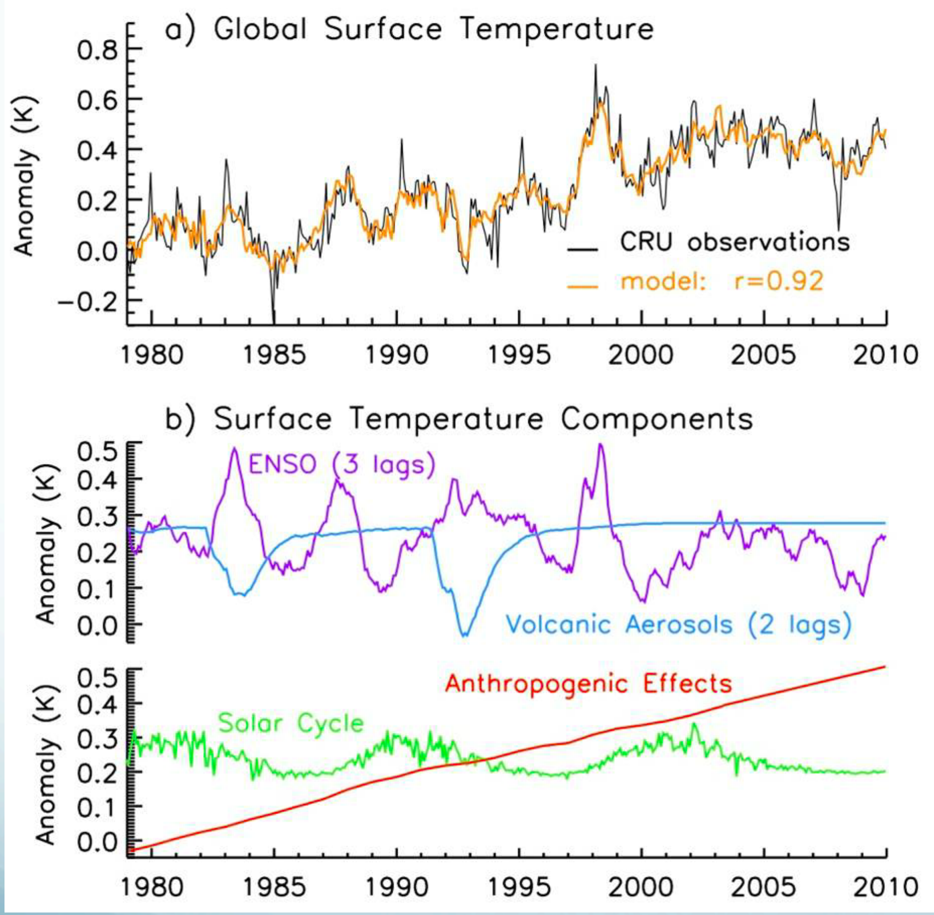
Foukal stressed that there is no evidence for the large (~0.3 percent) increase in TSI during the early 20th century

That level of increase in TSI would require the complete disappearance of the quiet network and internetwork going back in time to 1900.



Tachocline image from: http://murmitoyen.com/events/images/thumbs/source2/1354829132.jpg

Challenge: Separate Solar Driver from Other Factors



Combined ENSO, volcanic aerosols, solar activity, and anthropogenic effects explain 85 percent of observed temperature variance.

SOURCE: G. Kopp and J.L. Lean, A new, lower value of total solar irradiance: Evidence and climate significance, Geophysical Research Letters 38:L01706, 2011

Climate Proxies Provide Insight into Past Solar Activity Levels

- **Ice cores:** $\delta^{18}O$, δD, gas content, glaciochemistry, accumulation, conductivity, melt %, particulates…
- **Marine Sediments:** [planktonic, benthic] $\delta^{18}O$, Mg/Ca, faunal assemblages, ice-rafted material…
- **Loess:** magnetic susceptibility, grain-size
- **Tree rings:** ring width, density, isotopes
- **Banded corals:** $\delta^{18}O$, Mg/Ca, luminescence
- **Lake sediments:** pollen, diatoms, sedimentology, geochemistry, fauna, biomarkers
- **Stalagmites:** $\delta^{18}O$, trace elements, lamination

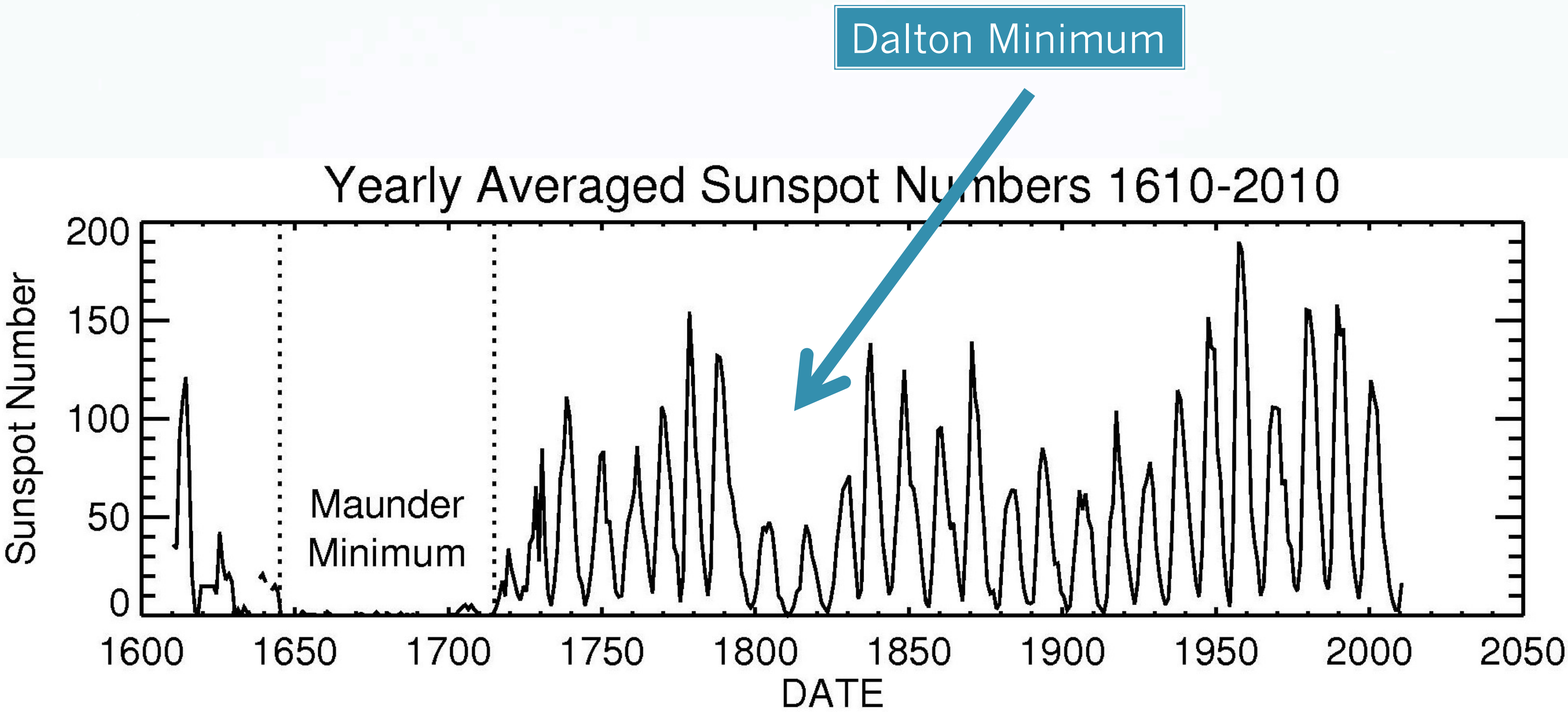
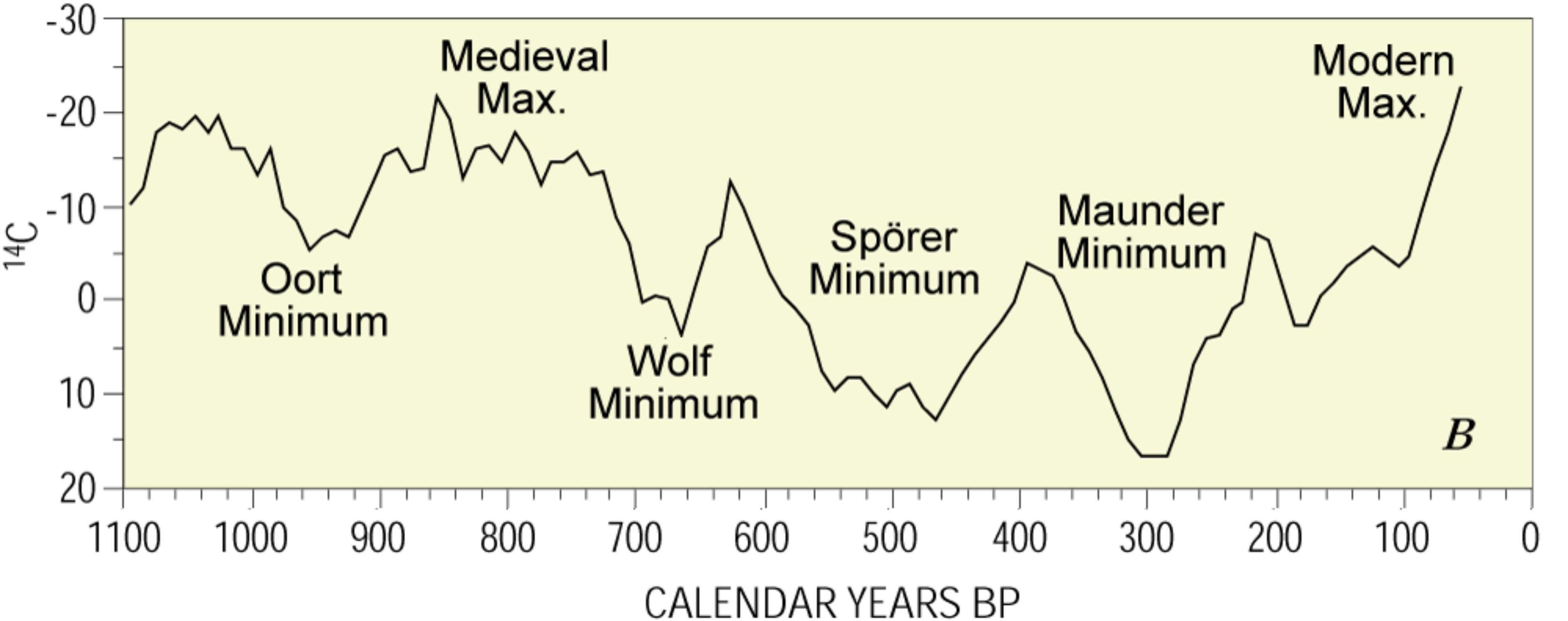


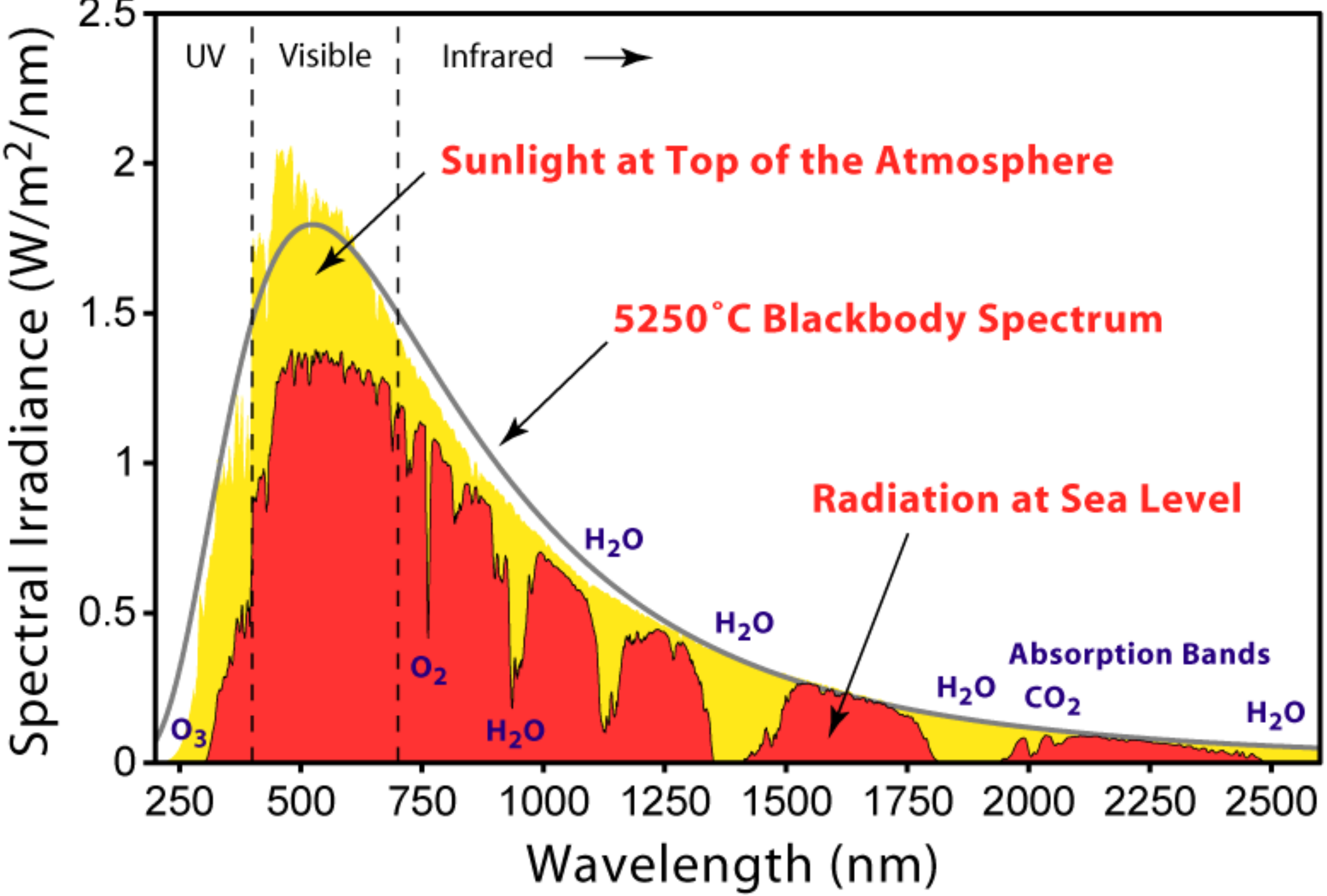
FIGURE 1.2 The yearly averaged sunspot number for a period of 400 years (1610-2010). The Maunder Minimum is shown during the second half of the 16th century. SOURCE: Courtesy of NASA Marshall Space Flight Center.

Did the Sun dimmed enough during Maunder Minimum to influence climate?

Peter Foukal argued that the simplest way to achieve sufficient dimming is through a decline in the area coverage of small flux tubes in the quiet magnetic network and internetwork.



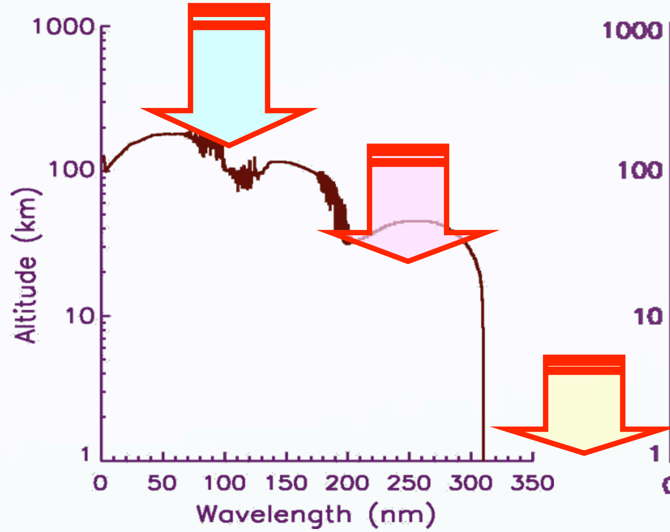
Solar Radiation Spectrum

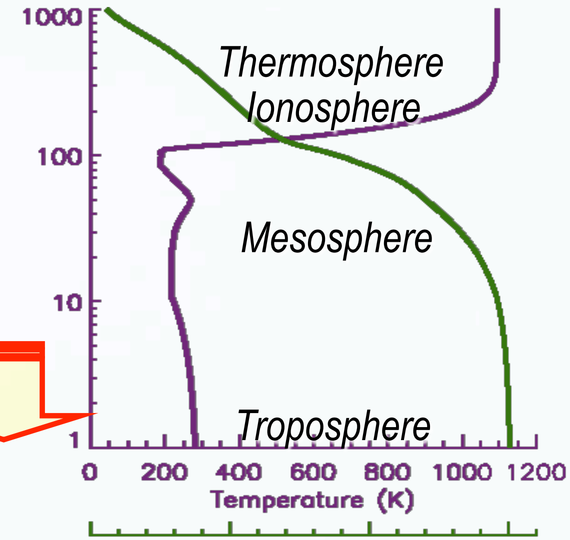


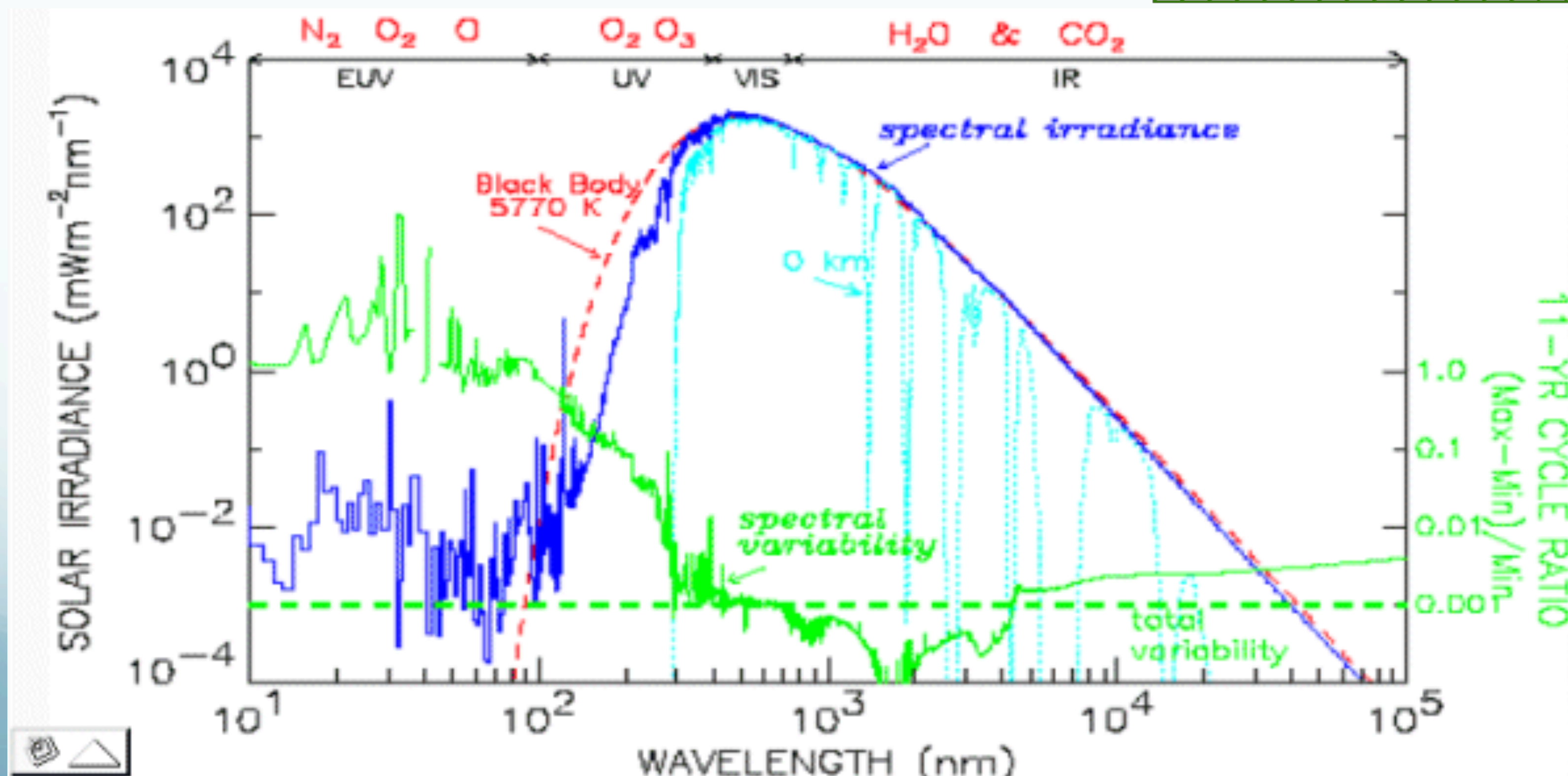
wavelengths < 120 nm
0.003±0.001 Wm^{-2}

wavelengths 120-300 nm
14.9±0.1 Wm^{-2}

wavelengths > 300 nm
1346 ± 0.5 Wm^{-2}



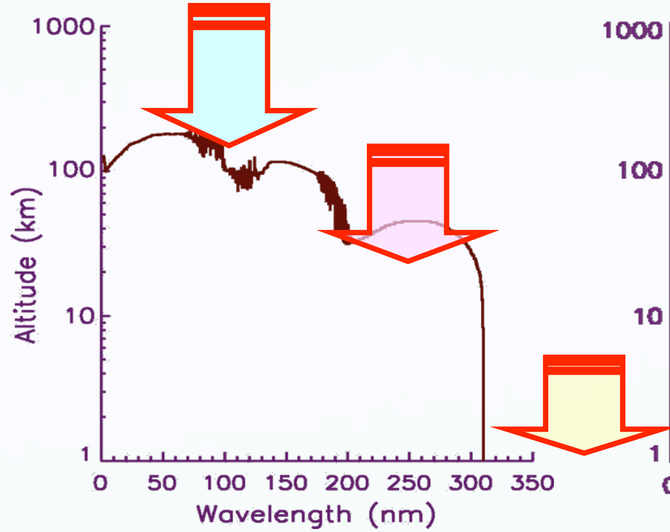


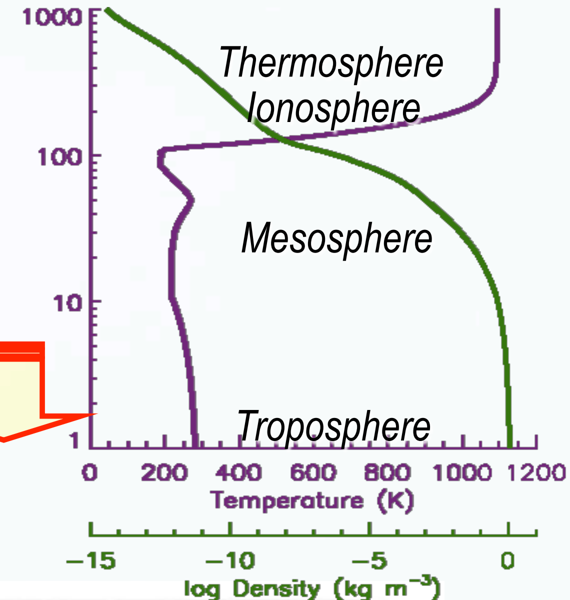


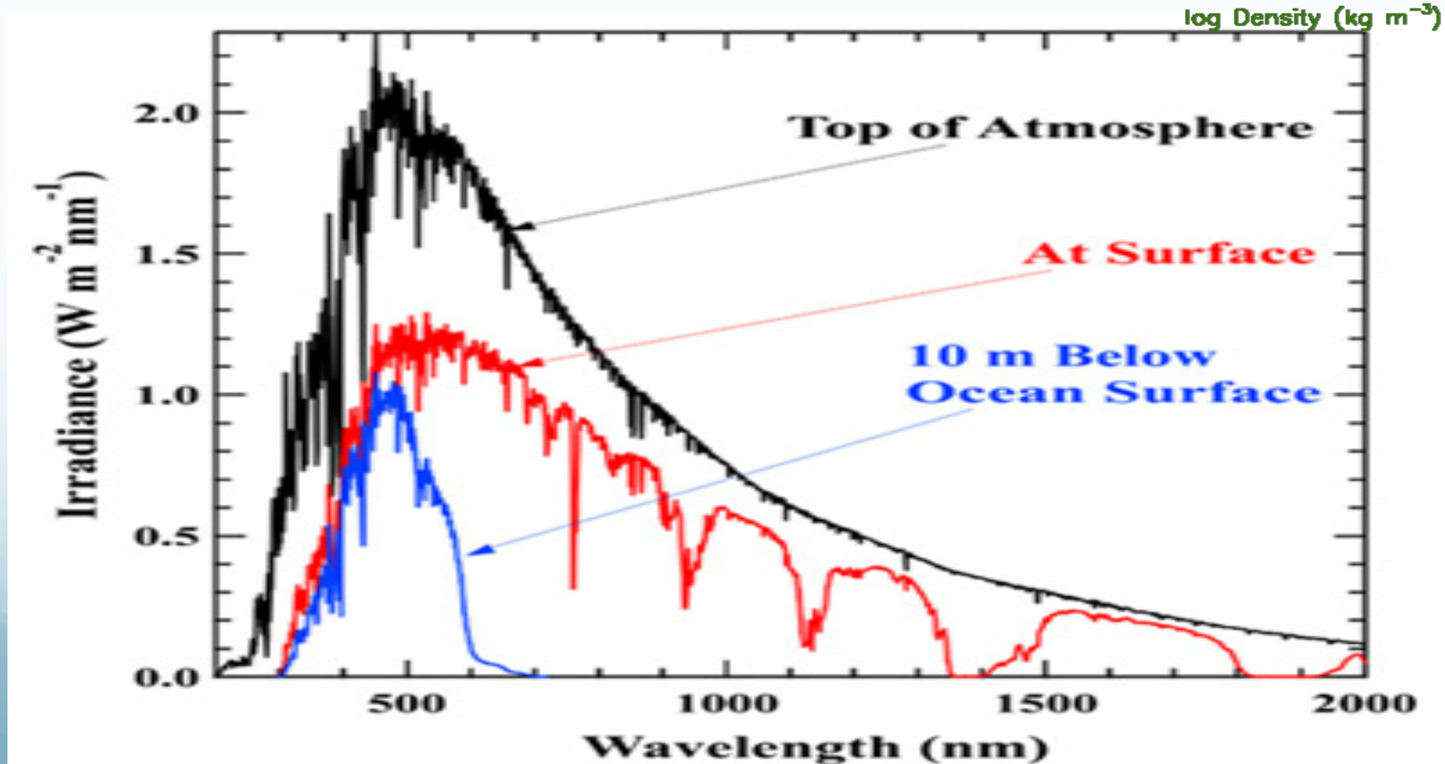
wavelengths < 120 nm
0.003±0.001 Wm^{-2}

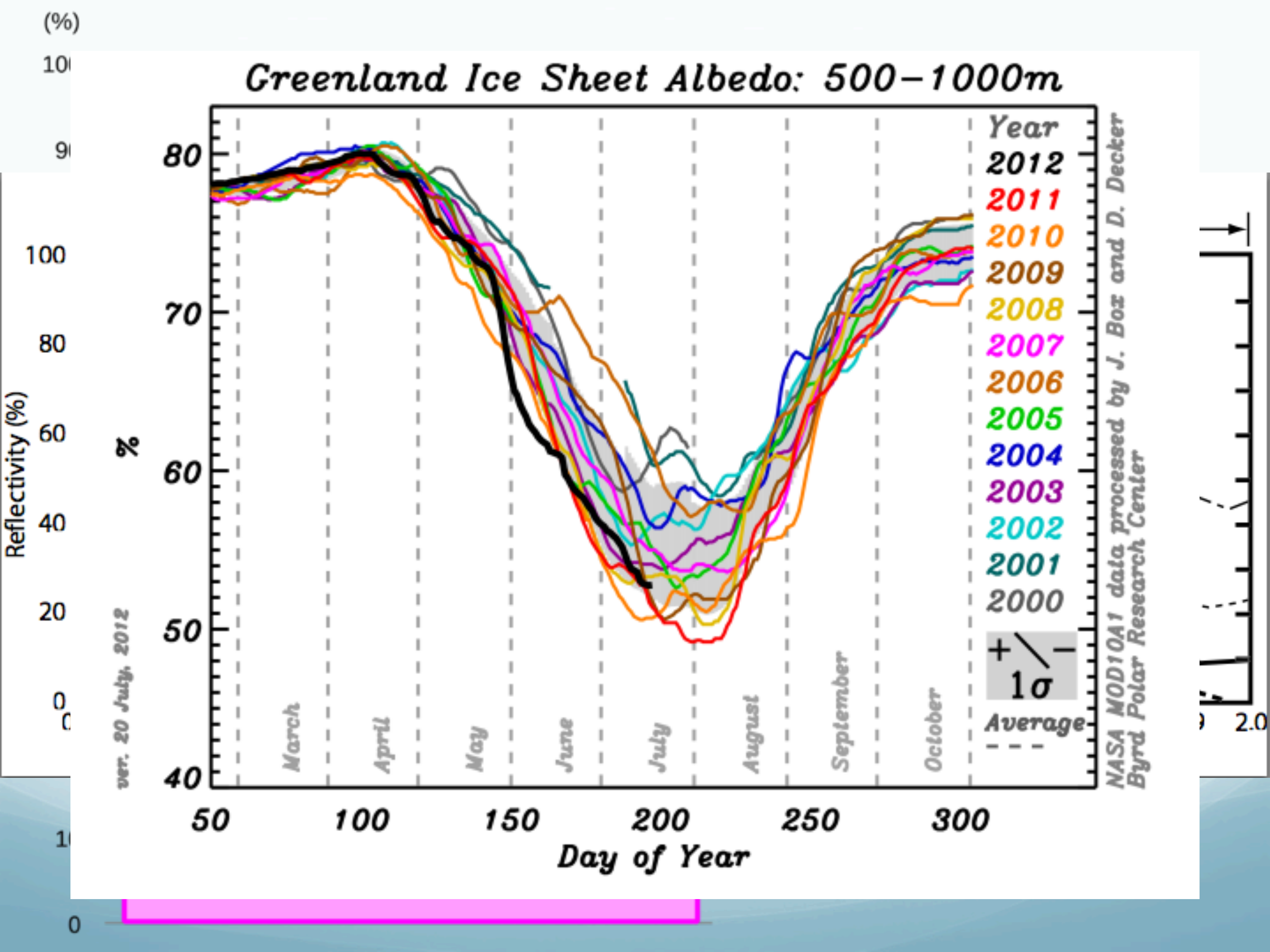
wavelengths 120-300 nm
14.9±0.1 Wm^{-2}

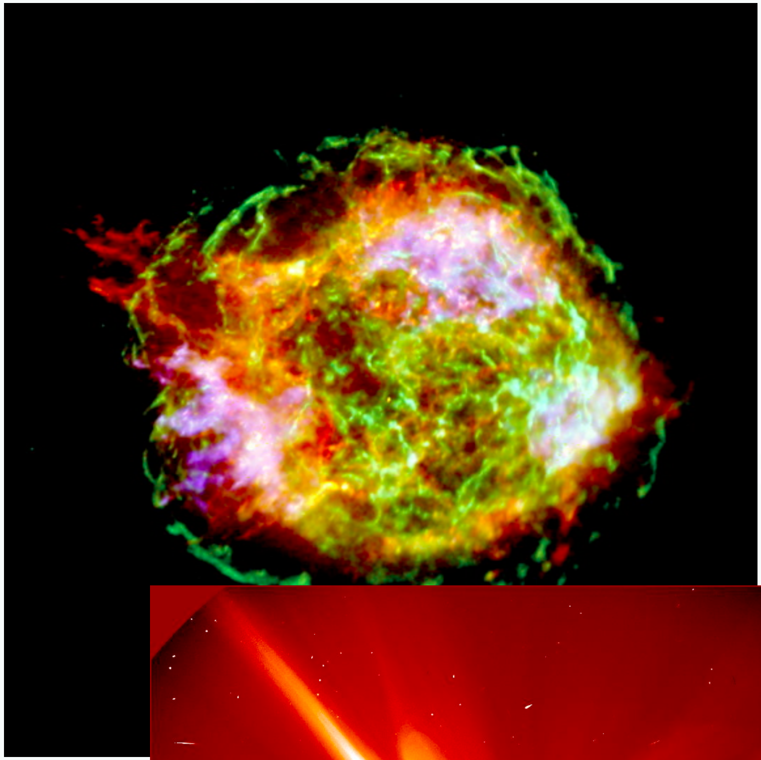
wavelengths > 300 nm
1346 ± 0.5 Wm^{-2}

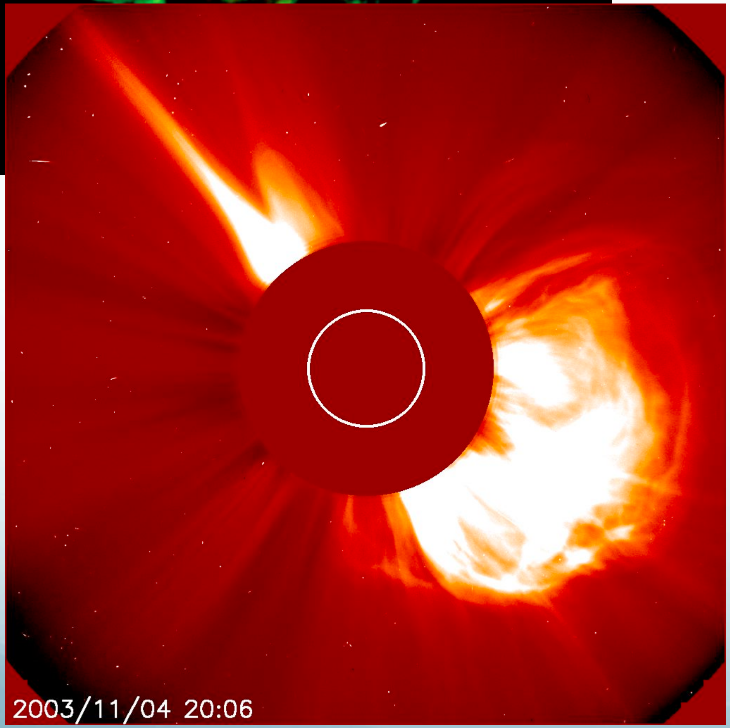







Greenland Ice Sheet Albedo: 500–1000m
%
80
70
60
50
40
50
100
150
200
250
300
Day of Year
March
April
May
June
July
August
September
October
Year
2012
2011
2010
2009
2008
2007
2006
2005
2004
2003
2002
2001
2000
+ −
1σ
Average
ver. 20 July, 2012
NASA MOD10A1 data processed by J. Box and D. Decker
Byrd Polar Research Center
(%)
Reflectivity (%)
100
80
60
40
20
0
2.0

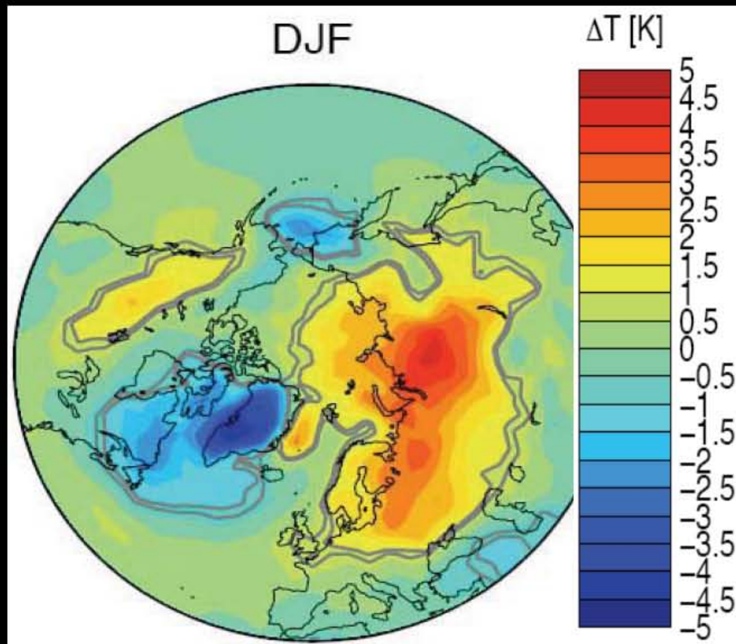


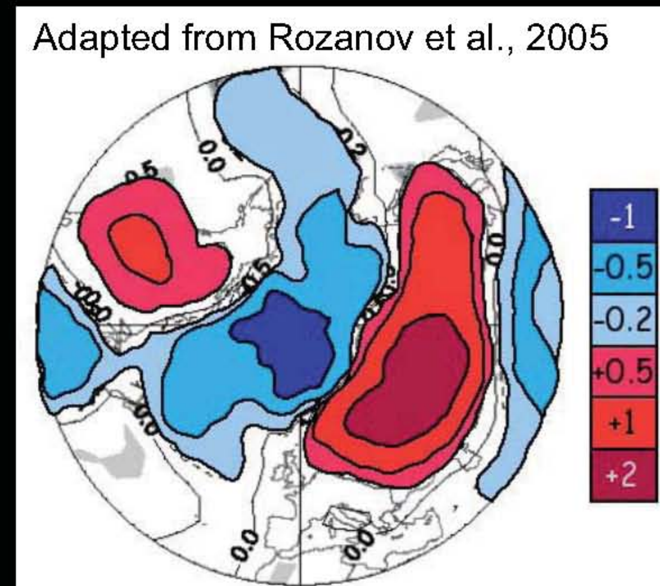


Galactic Cosmic-Rays (GCRs) are accelerated by shock-waves from supernovae
Their integrated intensity varies by about a factor of 2-3 over the solar cycle
V ~ 10,000 km/s
~10^{52} ergs

Solar Energetic Particles (SEPs) are accelerated by flares and by shocks driven by Coronal Mass Ejections (CMEs)
Their intensity can increase by a million times in hours
V ~ 1500-2500 km/s
~10^{32} ergs

Challenge Question: Do short

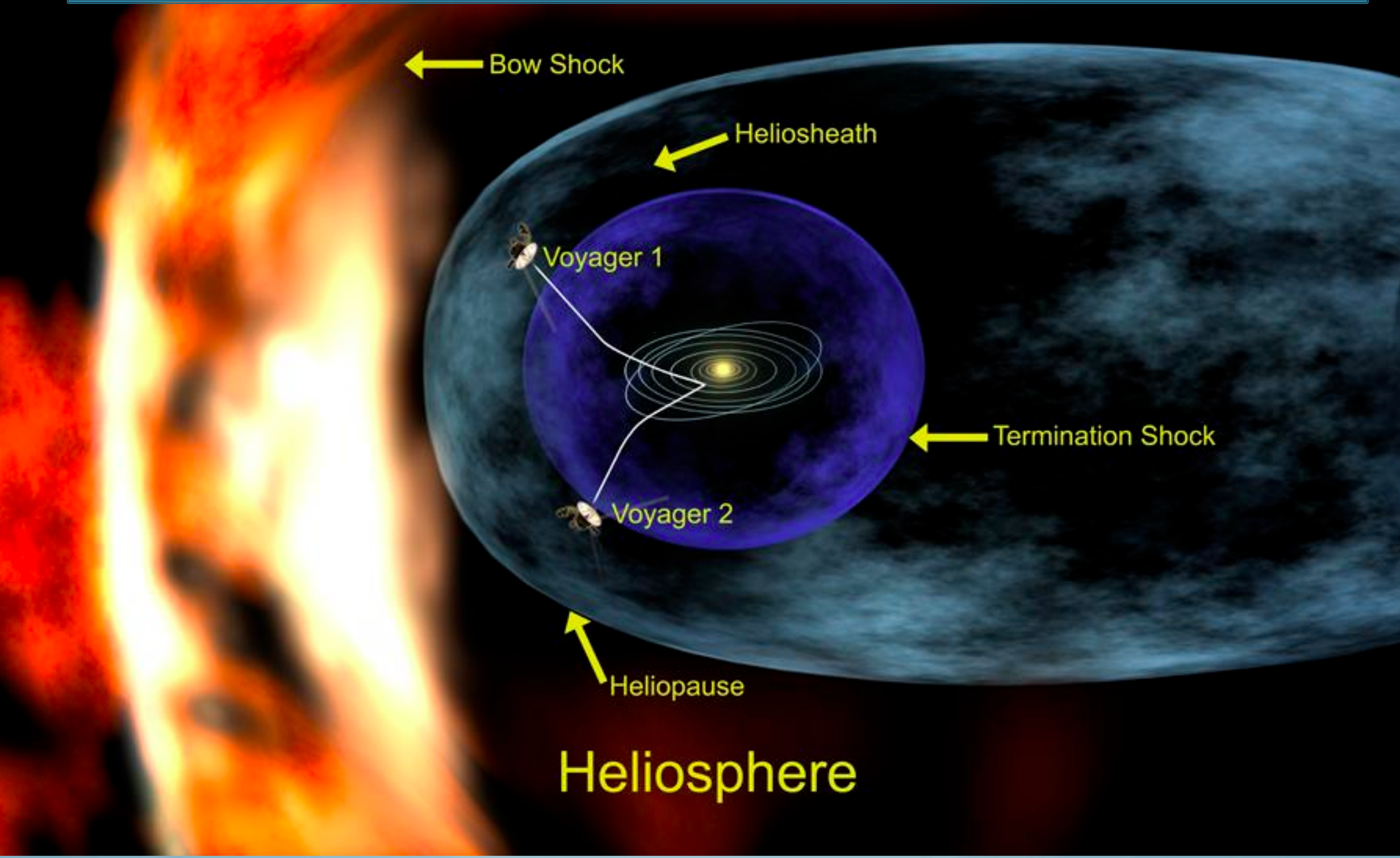




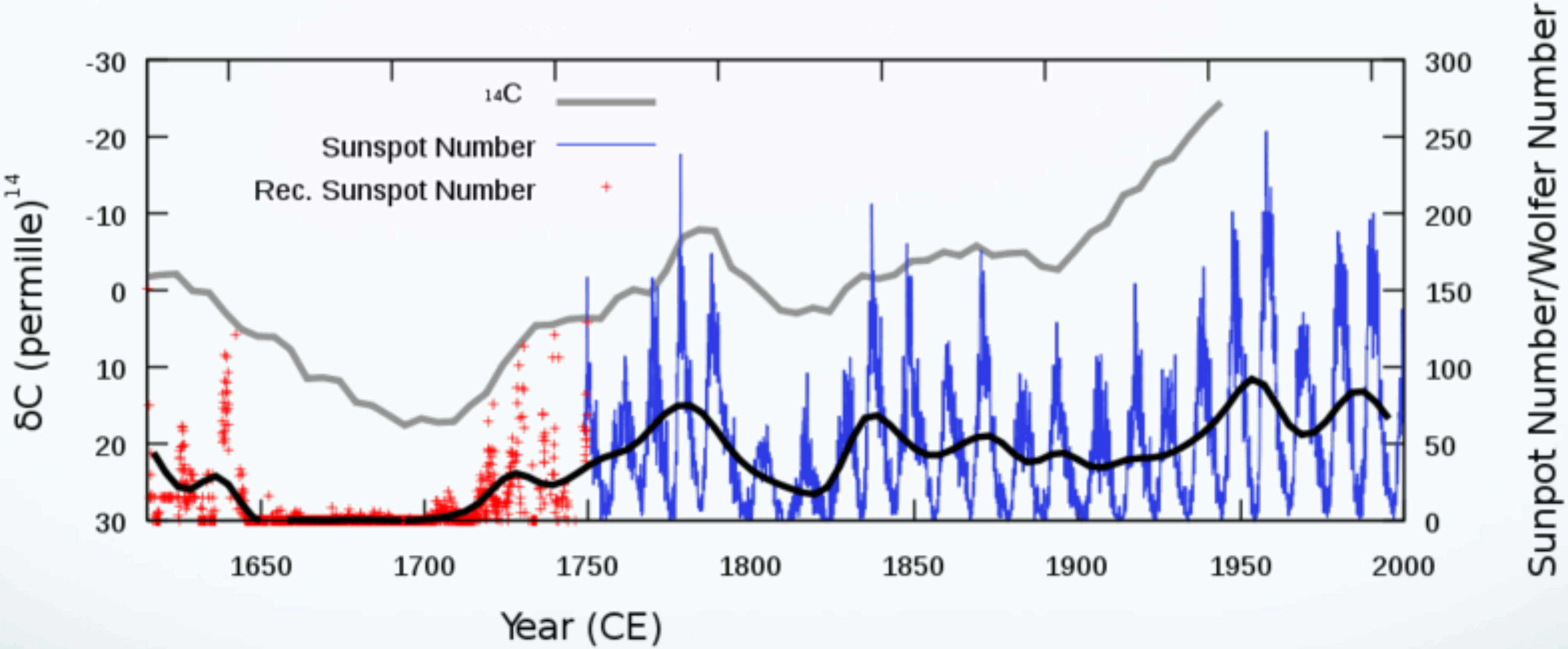
Seppälä et al., JGR 2009:

- **Analysis of ERA-40 temperatures yields statistically significant surface air temperature differences between years with high and low EPP.**
- **Can rule out correlation with solar flux, QBO, ENSO, SAM**
- **Possible correlation with NAM or random variations in SST**

The intensity of cosmic rays that reach in the inner solar system is modulated by the solar wind and its embedded magnetic field

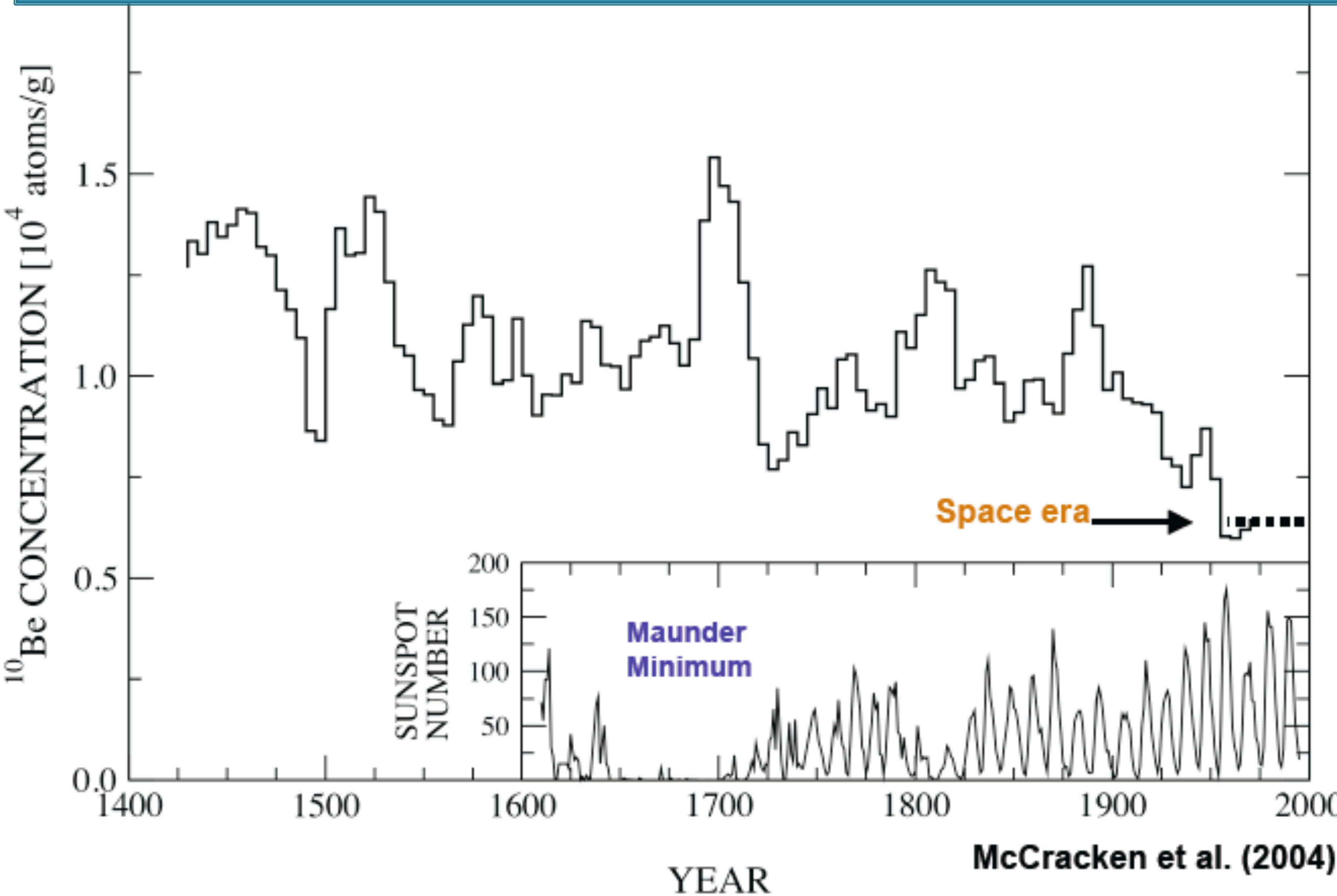


Sunspot activity and δC14



^{14}C is produced by GCR spallation of atmospheric N which decays by beta particle emission. Isotopic abundances are influenced by production rates as well as biospheric processes.
GCR input rate depend on energy and geomagnetic latitude (geomagnetic cutoff rigidity).

^{10}Be record in ice cores shows that over the past 600 years the cosmic-ray intensity has been 1.5 - 2.5 times as great as during the space era.



McCracken et al. (2004)

GCRs may have a role in cloud formation and/or alter the global electric circuit

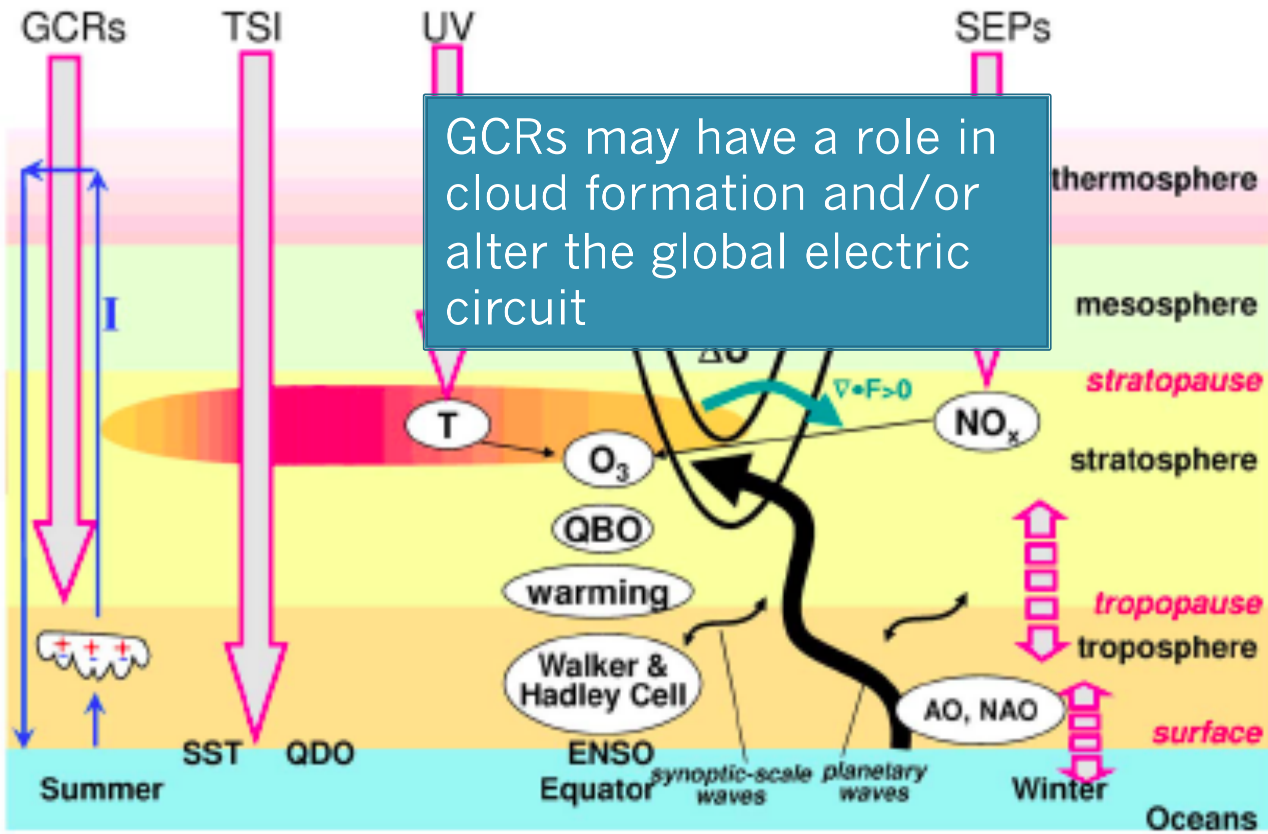


Figure 21. Schematic diagram of solar influence on climate based on *Kodera and Kuroda* [2002]. Shown are the direct and indirect effects through solar irradiance changes (TSI and UV) with respect to S_{max} as well as corpuscular radiation effects (energetic particles and GCRs). The two dashed arrows denote the coupling between the stratosphere and the troposphere and the coupling between the ocean and the atmosphere.

Gray, L. J., et al. (2010), Solar influences on climate, Rev. Geophys., 48, RG4001, doi:10.1029/2009RG000282

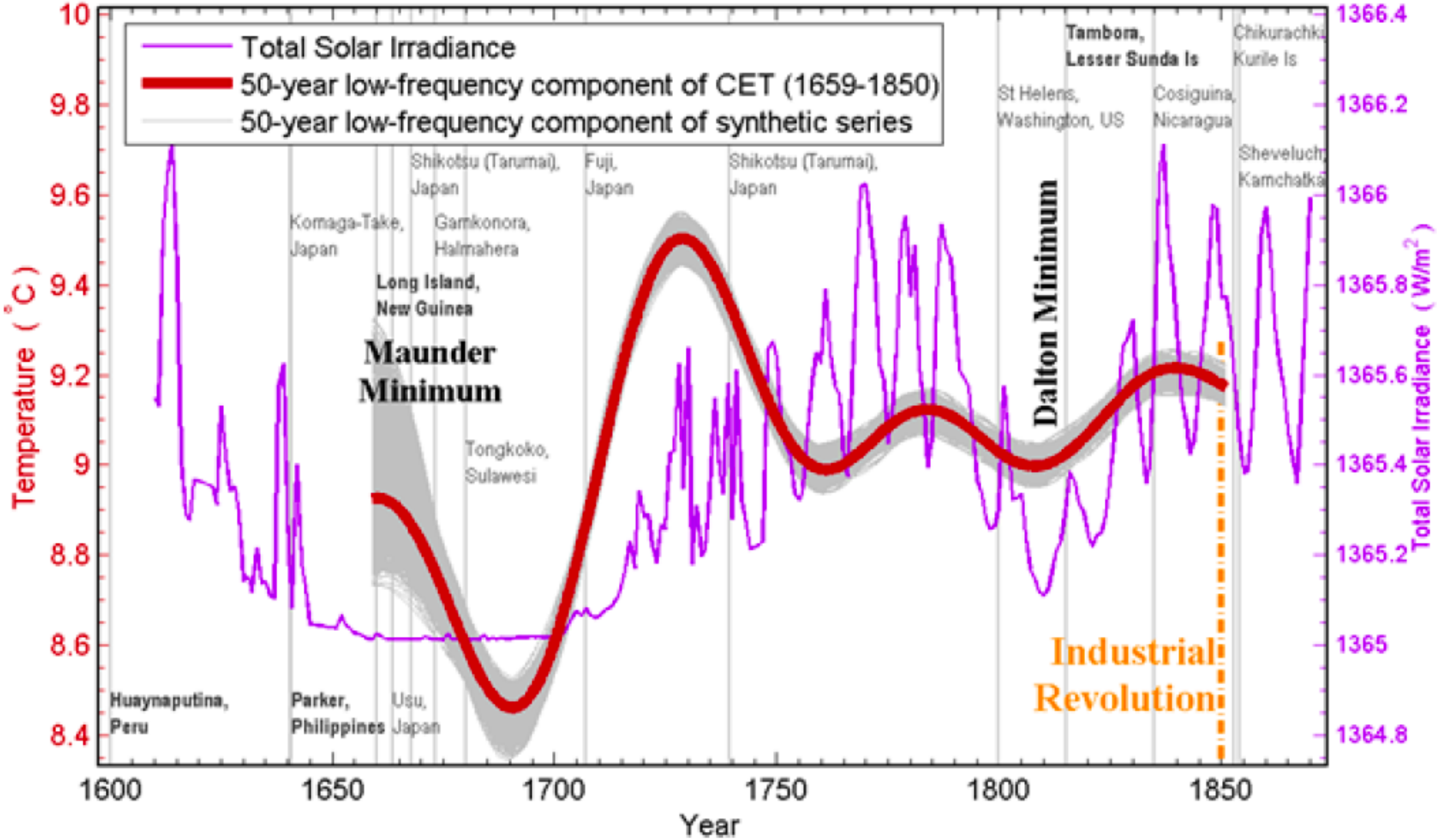


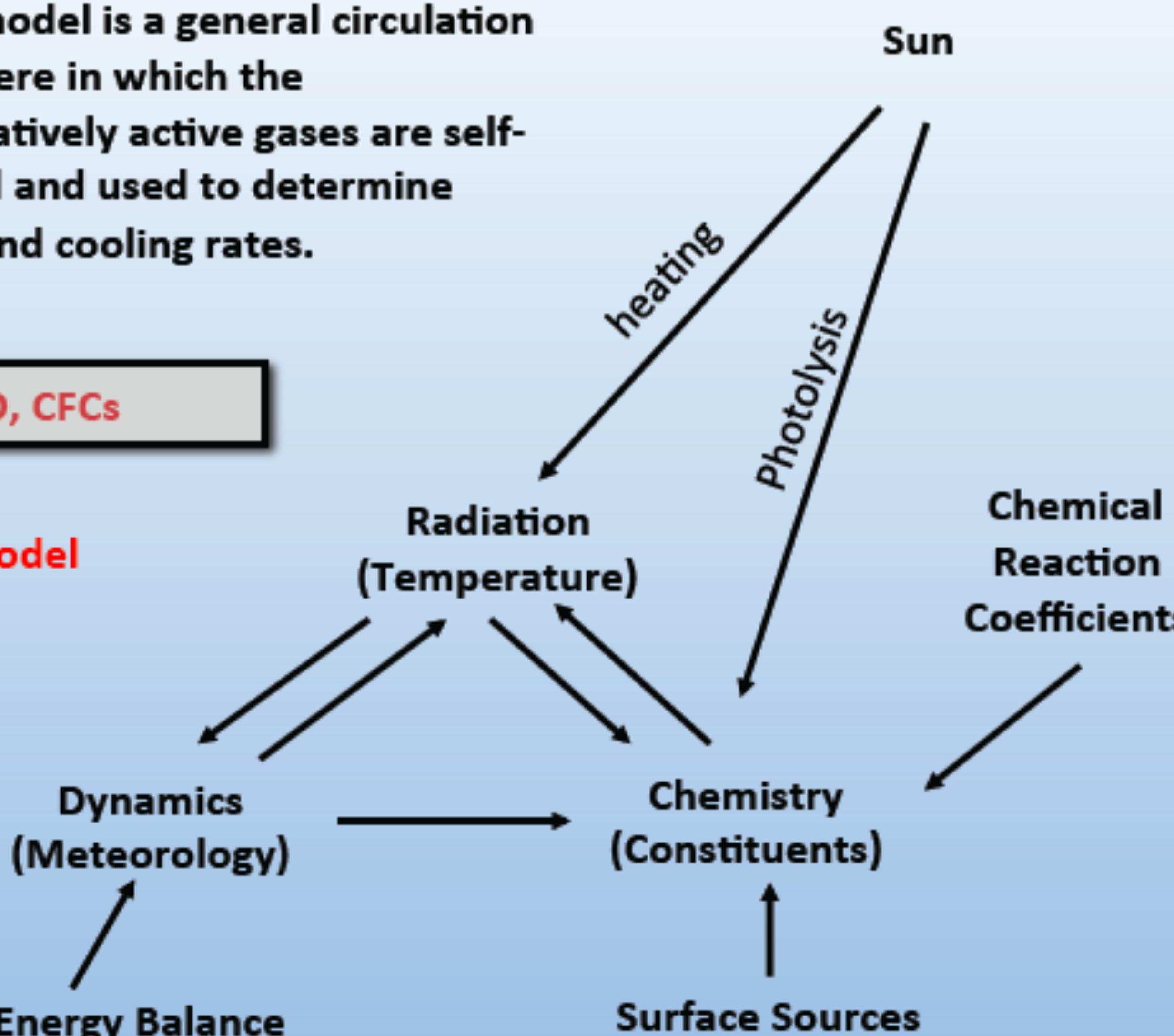
FIGURE 2.5 The low-frequency portion of the Central England temperature record, which could represent the Northern Hemisphere mean, is plotted along with the solar TSI index and the occurrence of known large volcanic explosions. The figure indicates that the warming at the end of the Maunder Minimum around 1700 leads the increase in TSI by about 20-30 years and suggests that the warming may instead be a recovery from the cooling produced by the aerosols from a series of large volcanic eruptions between 1660 and 1680. SOURCE: Courtesy of K.K. Tung and J. Zhou, University of Washington, "Climate Response at Earth's Surface to Cyclic and Secular Forcing," presentation to the Workshop on the Effects of Solar Variability on Earth's Climate, September 9, 2011.

Chemistry-climate Models are a Key Tool for Elucidating Teleconnections

A chemistry–climate model is a general circulation model of the atmosphere in which the concentrations of radiatively active gases are self-consistently calculated and used to determine atmospheric heating and cooling rates.

O_3, CO_2, H_2O, CH_4, N_2O, CFCs

Chemistry–Climate Model



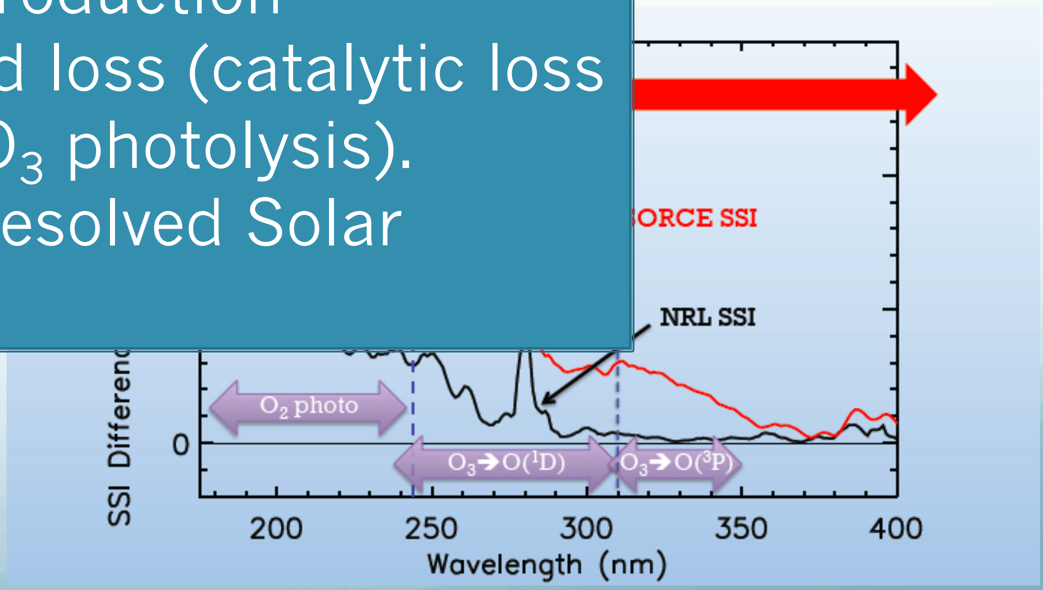
Swartz et al 2011

Top-down Ozone Influence on Climate

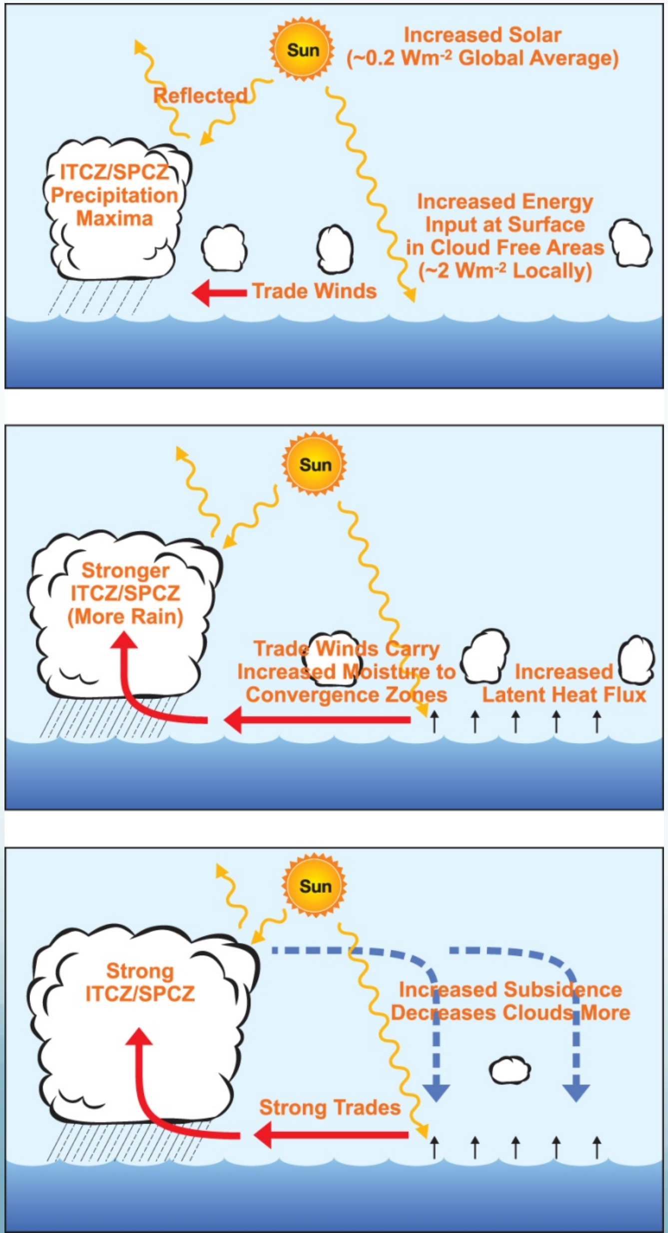
- Increased solar flux
- Increased ozone heating/ increased ozone amount
- Modif… zonal…
- Altere…
- Chang… energ… circul…
- Enhan… precip…
- Altered cloud albedo and sea surface temperature

- Direct heating
  - $h\nu$ + O_3, O_2 → T increase
  - speeds ozone loss reactions → O_3 decrease
- Photolysis
  - …
  - … T increase
  - … decrease

Challenge: Net ozone response to solar cycle depends on the relative contributions of production (O_2 photolysis) and loss (catalytic loss driven by O from O_3 photolysis).
Need: Spectrally-resolved Solar Irradiance



The Bottom-up Coupled Air-sea Mechanism



Increased solar input over cloud-free regions of the subtropics translates into greater evaporation, and moisture convergence and precipitation in the ITCZ and SPCZ (and south Asian monsoon), stronger trades, and cooler SSTs in eastern equatorial Pacific

Meehl, G.A., W.M. Washington, T.M.L. Wigley, J.M. Arblaster, and A. Dai, 2003, *J. Climate*

Van Loon, Meehl and Arblaster, 2004, *JASTP*

Meehl, G.A., J.M. Arblaster, G. Branstator, and H. Van Loon, 2008, *J. Climate*

Observed

Coupled Air-Sea mechanism

Ozone chemisty

Top-down and bottom-up model

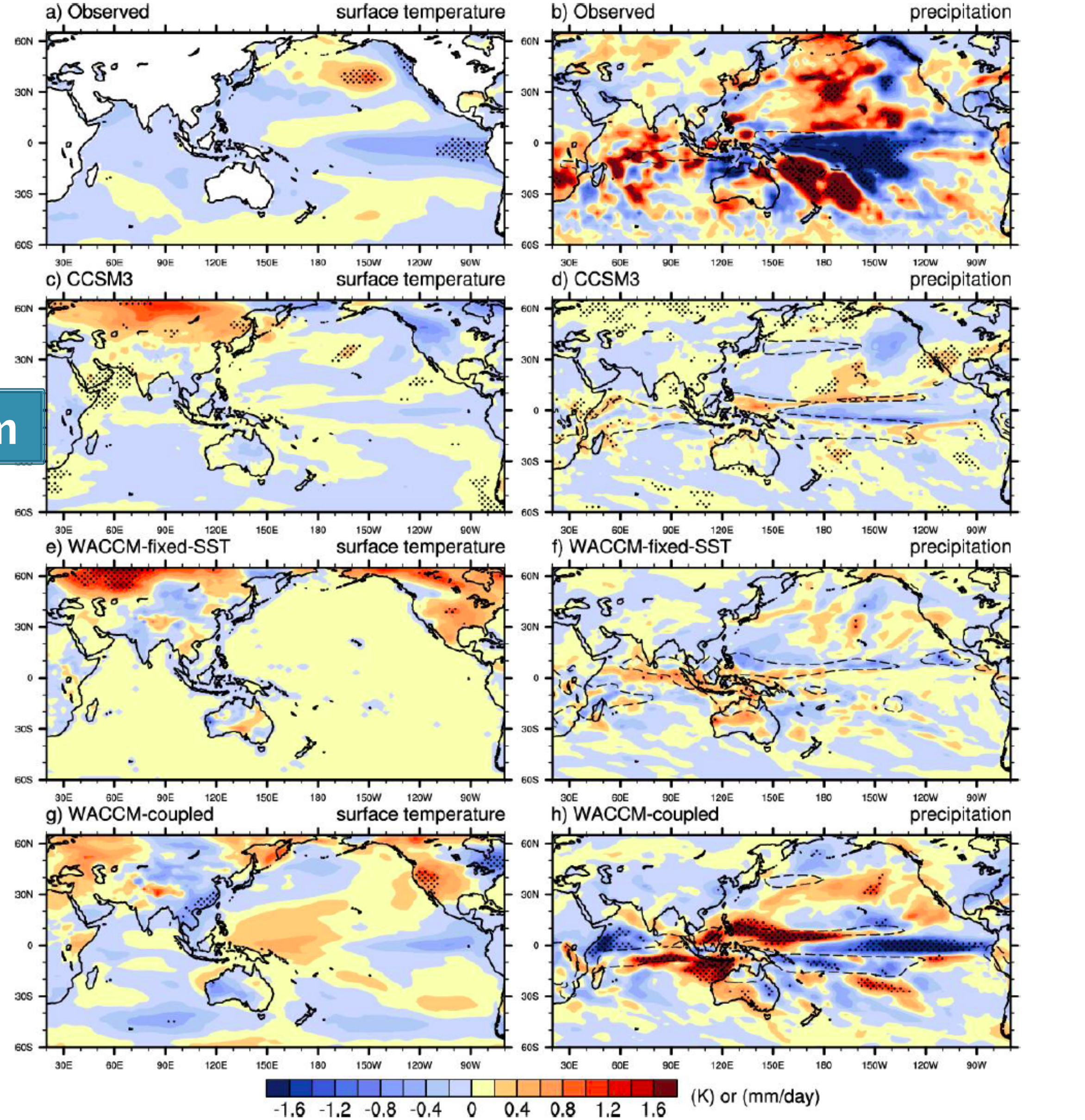


FIGURE 2.8 Composite averages for December-January-February for peak solar years (a,b). Observed, bottom-up coupled air-sea mechanism only (c,d); top-down stratospheric-ozone mechanism only (e,f); and both bottom-up and top-down mechanism (g,h). SOURCE: G.A. Meehl, J.M. Arblaster, K. Matthes, F. Sassi, and H. van Loon, Amplifying the Pacific climate system response to a small 11 year solar cycle forcing, *Science* 325:1114-1118, 2009; reprinted with permission from AAAS.

Understanding the Sun's role in climate is an important and compelling issue.

- **Primary questions:**
  - **understand the Sun's variability**
  - **how it can be tied to proxy measurements to understand the past, and**
  - **with what degree of accuracy**
- Radiometric imaging of the Sun is important to extrapolate irradiance
  - need to understand the substructure of the magnetic field and its relationship to spectral irradiance.
  - understanding the Sun, its output, and the various proxies used to infer its output may inform the ability to specify the accuracy of back-projections of paleo-TSI based on various proxies (including sunspot number).
- Relationship between the galactic cosmic-ray flux and details of the interaction with the variable solar wind and magnetic field configuration
  - The extended solar minimum ends, would be an excellent time to study this phenomenon.
  - Current understanding limited by time series length
  - Need to continue with accurate measurements in the future.

Data, Models and Predictions

- Gerald North (workshop Chair) summarized the issues that were developed during the workshop.
- 1. NASA has led the way in providing a model for ready access to data from many sources.
  - The challenge is to provide better access to paleoclimate data while recognizing the effort it takes to acquire and archive those data in a form accessible to the community.
- 2. Coupled models, with their inherent complexity, are the future and need to be used more widely for well-designed studies.
  - Climate modeling has advanced to the point that such projects can be undertaken with some confidence.
  - Role galactic cosmic rays may play in cloud nucleation
- 3. The directly measured record is limited. Challenges:
  - to make sure that a means is developed to infer the time history of TSI variability
  - understanding variability and the sources of variability in TSI arising from the details of the quiet network.
  - Need a better understanding of how solar brightness, TSI, and the spectral and spatial distribution of energy are affected by the faculae and the dynamics of the Sun
  - Understand the limitations on the ability to specify that past behavior.
    - the isotope record may reflect influences of atmospheric circulation
    - variations in geomagnetic field effect the inferred paleo-climate record