How Variable Is the Sun, and What Are the Links Between This Variability and Climate?*

By

Judith Lean¹

Search and Discovery Article #110055 (2008)
Posted August 5, 2008

*Adapted from oral presentation at AAPG Annual Convention, San Antonio, Texas, April 20-23, 2008

¹Space Science Division, Naval Research Laboratory, Washington, DC (jlean@ssd5.nrl.navy.mil)

Abstract

During the past three decades a suite of space-based instruments has monitored the Sun’s brightness as well as the Earth’s surface and atmospheric temperatures. These datasets enable the separation of climate’s responses to solar activity from other sources of climate variability (anthropogenic gases, El Niño Southern Oscillation, volcanic aerosols). The empirical evidence indicates that the solar irradiance 11-year cycle increase of 0.1% produces a global surface temperature increase of about 0.1 K, with larger increases at higher altitudes. Historical solar brightness changes are estimated by modeling the contemporary irradiance changes in terms of their solar magnetic sources (dark sunspots and bright faculae) in conjunction with simulated long-term evolution of solar magnetism. In this way, the solar irradiance increase since the seventeenth century Maunder Minimum is estimated to be slightly larger than the increase in recent activity cycles, and smaller than early estimates that were based on variations in Sun-like stars and cosmogenic isotopes. Ongoing studies are beginning to decipher the empirical Sun-climate connections as a combination of responses to direct solar heating of the surface and lower atmosphere, and indirect heating via solar UV irradiance impacts on the ozone layer and middle atmospheric, with subsequent communication to the surface and climate. The associated physical pathways appear to involve the modulation of existing dynamical and circulation atmosphere-ocean couplings, including the ENSO and the Quasi-Biennial Oscillation. Comparisons of the empirical results with model simulations suggest that models are deficient in accounting for these pathways.
How Variable is the Sun? What are the Links Between Solar Variability and Climate?

Judith Lean

Space Science Division, Naval Research Laboratory, Washington DC

Solar Variability and Climate

Space-Era Linkages—surface, troposphere and stratosphere
- sources of climate variability.. global and regional
- GISS climate model simulations

Relationships in the Past
- instrumental era, Holocene
sunspot cycle amplitudes have increased from the Maunder Minimum to the Modern Maximum

- 5-min oscillation ~ 0.003%
- 27-day solar rotation ~ 0.2%
- 11-year solar cycle ~ 0.1%
- longer-term variations not yet detectable —......do they occur?

Past Solar Activity
sunspot cycle amplitudes have increased from the Maunder Minimum ... to the Modern Maximum

Radiative Processes in the Earth’s Atmosphere Depend on Wavelength

- **UV radiation** ($\lambda < 315$ nm): $20$ Wm$^{-2}$
- **near UV, VIS, IR Radiation** ($\lambda > 315$ nm): $1346$ Wm$^{-2}$

TOTAL Irradiance = $\int$ SPECTRAL Irradiance $\approx 1366$ Wm$^{-2}$
There are Many Causes of Climate Change

Anthropogenic Forcings
- atmospheric GH gases - \( \text{CO}_2, \text{CH}_4, \text{CFCs}, \text{O}_3, \text{N}_2\text{O} \)
- tropospheric aerosols - direct and indirect effects of soot, sulfate, carbon, biomass burning, soil dust

Natural Forcings
- solar variability - direct and indirect effects
- volcanic eruptions - stratospheric aerosols

Land Cover Changes

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

http://realclimate.org
Surface Temperatures Respond to Natural and Anthropogenic Influences

- Greenhouse gases
- Industrial aerosols
- Volcanic aerosols
- Monthly means
- El Niño
- La Niña

Data: [http://data.giss.nasa.gov/](http://data.giss.nasa.gov/)

CRU Land+Ocean Temperatures

Global Surface Temperature

- Model: ENSO+VOL, $r = 0.48$
- ENSO
- Volcanic Aerosols

Surface Temperature Residuals

- Model: SUN+ANTH, $r = 0.71$
- Sun
- Anthropogenic gases

Climate forcing (W m$^{-2}$)
Earth’s Atmosphere Responds to Natural and Anthropogenic Influences

**SURFACE**
- **TOTAL SOLAR IRRADIANCE**
- **GHG TREND**
- **ENSO MEI INDEX**
- **AEROSOL OPTICAL DEPTH**
- **GISS SURFACE**

**MIDDLE TROPOSPHERE**
- **SOLAR IRRADIANCE**
- **TEMPERATURE ANOMALY (K)**
- **ENSO MEI INDEX**
- **AEROSOL OPTICAL DEPTH**
- **MSU MT**

**LOWER STRATOSPHERE**
- **SOLAR UV IRRADIANCE**
- **CFC TREND**
- **ENSO MEI INDEX**
- **MSU**

**Solar increase → warming**
**CO₂ increase → warming**
**Volcanoes → cooling**

**Solar increase → warming**
**CO₂ & CFC increase → cooling**
**Volcanoes → warming**
The Ozone Layer Responds to Natural and Anthropogenic Influences

UV radiation: 200-295 nm

GSFC TOMS Total
Ozone Sep 16, 2001

Total Ozone 50S-50N ~ 280 DU

TOMS TOTAL OZONE 50S–50N (deseasonalized)

SOLAR UV IRRADIANCE

CFC–12

VOLCANIC AEROSOLS

QBO: 30 mb zonal wind index

2000-02-25

1996-06-16

Solar upper photosphere/chromosphere

+1.2%

+4%

2.2%

Observed
modeled, r=0.89

4%
Temperature Correlation Spatial Patterns

**SURFACE**
- CRU 5° (lat) × 5°(long)

**MIDDLE TROPOSPHERE**
- Solar Irradiance

**LOWER STRATOSPHERE**
- MSU 2.5° (lat) × 2.5°(long)

**Anthropogenic Gases**

- CRU SURFACE TEMP vs. TOTAL SOLAR IRRADIANCE 1979-2006.logs: 4 6 1 0
- MSU MIDDLE TROPOS. TEMPERATURE vs. TOTAL SOLAR IRRADIANCE
- MSU LOWER STRAT TEMP vs. SOLAR UV IRRADIANCE

**Correlation Coefficients:**
- CRU SURFACE TEMP vs. TOTAL SOLAR IRRADIANCE: -0.4 to 0.4
- MSU MIDDLE TROPOS. TEMPERATURE vs. TOTAL SOLAR IRRADIANCE: -0.2 to 0.2
- MSU LOWER STRAT TEMP vs. SOLAR UV IRRADIANCE: -0.4 to 0.4
- MSU SURFACE TEMP vs. HEMISPHERIC ROSSBY WAVES: -0.7 to 0.7
- MSU MIDDLE TROPOS. TEMPERATURE vs. HEMISPHERIC ROSSBY WAVES: -0.8 to 0.8
- MSU LOWER STRAT TEMP vs. HEMISPHERIC ROSSBY WAVES: -0.5 to 0.5

**Temperature Correlation Spatial Patterns**

- [Mapping of Correlation Coefficients](chart)
- [Mapping of Correlation Coefficients](chart)
- [Mapping of Correlation Coefficients](chart)
Surface temperature responses to the solar cycle occur at interfaces of primary zonal circulation patterns: Hadley and Ferrel (and Polar ?) Cells.
**Stratosphere – Climate Coupling**

**Radiative Coupling via Absorption and Emission**

- $O_3$ increase causes cooling
- $O_3$ increase causes warming

**Dynamical Coupling via Wind-Wave Interactions**

- Change Ozone & Temperature
- Change Winds & Planetary Waves
- Change Temperature Advection & Temperature
- Change Winds & Planetary Waves
- Change Climate

**NORTH ATLANTIC OSCILLATION**

- solar irradiance cycle modulates stratospheric polar vortex
- tropospheric circulation
- NAO (solar min)  AO (solar max)

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Climate Model Response to Radiative Forcing

\[ \Delta T = \kappa F \]

**Climate Sensitivity**

- IPCC range: 0.2-1°C per Wm\(^{-2}\)
- Paleoclimate: 0.75°C per Wm\(^{-2}\)

\[ \Delta T = 0.1^\circ C \]
\[ F = 0.15 \text{ Wm}^{-2} \text{ (0.85}\times 0.7/4) \]
\[ \therefore \kappa = 0.67^\circ C \text{ per Wm}^{-2} \]

**Solar Irradiance Cycle**

- Response to cyclic decadal forcing is assumed to be attenuated by \(\sim 5\times\) compared with “equilibrium” response

**Current Understanding**

- Response to solar radiative forcing is thermodynamic
- 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

**Feedbacks**

- Water vapor
- Sea ice/snow cover
- Cloud cover

Observed and Modeled Temperature Spatial Patterns (all months): SOLAR

**SURFACE**

Multiple regression

**MIDDLE TROPOSPHERE**

**LOWER STRATOSPHERE**

GISS General Circulation Middle Atmosphere Model: Rind et al., JGR, © AGU 2007
Holocene Sun-Climate Connections

INTERTROPICAL CONVERGENCE ZONE

$\delta^{18}O$ in stalagmites in Oman track $\delta^{14}C$ for 3,000 years in mid-Holocene

*Neff et al., Nature, 2001*

NORTH ATLANTIC CLIMATE

Surface winds and ocean hydrography affected by solar variability -- North Atlantic Deep Water may amplify solar signals

*Bond et al., Science, 2001*
**Centennial-Millennial Solar Variability**

**$\delta^{14}C$ in Tree-Rings: Holocene Solar Activity Proxy**

- $^{14}C$ in tree-rings, $^{10}Be$ in icecores - imply long-term solar activity

... do they also imply long-term solar irradiance variations?

**Total Solar Irradiance Cycle**

**Total Solar Irradiance Cycle and Background**

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**Cosmogenic Isotope Changes**

- $^{14}C$ in tree-rings, $^{10}Be$ in icecores - imply long-term solar activity
Estimating Long-Term Solar Variability

**Sub-surface Dynamo**
- Surface magnetic fields of opposite polarity
- Transformed by...
  - Differential rotation
  - Meridional flow
  - Diffusion

**Closed Flux Modulates Irradiance**
- Irradiance at Earth: 1365 Wm⁻²
- Galactic Cosmic Ray Flux at Earth: 0.0000007 Wm⁻²

**Open Flux Modulates Cosmogenic Isotopes**

NRL Flux Transport Model

**Total Solar Irradiance**
- Flux transport simulations
- Range of cycle + background

Wang et al., 2005
Lean, 2000
Solar and Anthropogenic Signals in the Instrumental Era

(normalized to 0.1 K global change)
Regional Surface Air Temperature Change
Annual 1900 – 2000

SOLAR IRRADIANCE
CRU Solar (Ann. 1900 to 2000) GLOBAL ΔT = 0.08 K

NET ANTHROPOGENIC
CRU Anthropogenic Gases (Ann. 1900 to 2000) GLOBAL ΔT = 0.48 K

Extrapolation of CRU Empirical Analysis for 1979-2006

GISS ModelE (with indirect aerosols)

4° (lat) × 5° (long) M20 Schmidt et al., 2006 http://www.giss.nasa.gov
Sun – Climate - Ozone: Future Variability

How active will solar cycle 24 be?
- 40% higher than cycle 23 (Dikpati et al, 2005)
- less active than cycle 23

Sun’s role in future climate change depends on irradiance cycles and trends relative to anthropogenic scenarios

Radiative Forcing

Total Ozone

C. Jackman, GSFC
Solar Variability and Climate: SUMMARY

Solar-driven and natural climate change occurs simultaneously with anthropogenic influences
... volcanic influences, internal modes (ENSO, QBO), greenhouse gases, aerosols

Surface and atmospheric temperatures respond to the solar irradiance cycle with complex spatial patterns
... CRU, GISS and MSU temperature datasets give consistent characterizations
... global +0.07K at 0 km +0.1K at ~5km +0.3 K at ~19 km

Interactive ozone is crucial for modeling responses to solar forcing

 Longer-term solar Irradiance changes are uncertain
... +0.1% solar forcing in instrumental period (3× smaller increase than in prior estimates)
... +0.1K (Sun) versus +0.7K (Anth) surface temp increase from 1900 to 2000

Model simulations and empirical results have different spatial patterns and magnitudes of change
... modeled fingerprints may not be correct for solar (and other?) forcings

An accurate, precise, long solar irradiance record is crucial to constrain solar-driven climate change.
Comparison of Total Solar Irradiance Records

Using the Nimbus 7 ERB sensor (which lacked in-flight responsivity tracking) to cross calibrate ACRIM I & ACRIM II added an uncertainty of 0.05% to the record.

... half the solar cycle amplitude
... jump in ACRIM composite in 1990 often misinterpreted as real upward trend in solar irradiance at cycle minima... underlying activity cycle... spawned a new generation of sun-climate studies claiming incorrectly that the “long-term trend” in solar irradiance contributed 20% to 30% of warming since 1980, and as much as 65% of C20th warming.
a) CRU Land + Ocean 1889–2006: $r=0.87$

b) GISS Land + Ocean 1889–2006: $r=0.85$

CRU Surface Temperature Variability Components

- ENSO: +0.0015 K /decade
- Volcanic Aerosols: -0.0009 K /decade
- Solar Irradiance: +0.005 K /decade
- Anthropogenic Gases: +0.054 K /decade
Solar, Volcanic and ENSO variations all exhibit decadal power...

**ENSO and volcanic decadal power can project onto solar cycle temperature changes** ...

*multiple regression separates the components simultaneously*
Measuring Long-Term Solar Brightness Changes

Current missions

With TSIS demanifested from NPOESS the 28-year solar irradiance record will end with the Glory mission in 2012
Climate Change in Recent Centuries

forcings

**GCM simulation:** $\kappa \sim 4^\circ C$ for $2 \times CO_2$
Robinson et al., 2001

**EBM simulation:** $\kappa \sim 2^\circ C$ for $2 \times CO_2$
Crowley, 2000

omitting solar forcing $\rightarrow$
.. poorer tracking of centennial variations
.. higher sensitivity to GHGs
<table>
<thead>
<tr>
<th>Run</th>
<th>Resolution</th>
<th>Forcing</th>
<th>Ozone</th>
<th>Ocean</th>
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<td>B30TRoims1M23 4X5 (lat, lon) 23 layer (pressure)</td>
<td>solar (monthly mean spectra)</td>
<td>non-interactive</td>
<td>Q-flux, no diffusion (thru bottom of mixed layer)</td>
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<td>2</td>
<td>B30TVOims1M23 4x5 23 layer</td>
<td>solar, trace gases, volcanic aerosols</td>
<td>non-interactive</td>
<td>Q-flux, no diffusion</td>
</tr>
<tr>
<td>3</td>
<td>B30TAoims1M23 4x5 23 layer</td>
<td>solar, trace gases, trop. + volcanic aerosols, trop + strat. ozone</td>
<td>non-interactive</td>
<td>Q-flux, no diffusion</td>
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<td>B465trsoioTM23 4x5 23 layer</td>
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<td>Linoz chemically-unresponsive</td>
<td>Q-flux, no diffusion</td>
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References

References

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