A Vintage 2009 Assessment of the Sun-Climate Connection in Paleoclimate Records

Thomas Crowley
University of Edinburgh
Main Topics Covered

role of the Sun in:

- 20th c. warming
- Little Ice Age
- Centennial-Millennial scale climate change
Overarching Goal:

to temper “irrational exuberance” about the role of solar variability in past climate change
In the beginning.....
Atmospheric CO$_2$ at Mauna Loa Observatory

1974-2006 NOAA ESRL/GMD

CONCENTRATION (parts per million)

YEAR
CO2 Radiative Forcing Changes
Poor Man’s Climate Model

\[ \Delta T_{eq} = \lambda [(1 - \alpha) \Delta Q] \]

where

\( \Delta T_{eq} \) = change in equilibrium global temperature
\( \lambda \) = climate feedback factor (~0.4 - 1.2 Wm\(^{-2}/\degree C\))
\( \alpha \) = average Earth albedo (~0.3)

\( \Delta Q \) = change in average global radiative solar forcing
\( (L_0/4 = Q = 340 \text{ Wm}^{-2}) \)

Example 1 – if 1% \( \Delta Q \sim 3.4 \text{ Wm}^{-2} \)
then \( \Delta T_{eq} \sim 1.0 - 2.9\degree C \) (0.1-0.3\degree C for 11 year \( \Delta Q - \text{max} \))

Example 2 – if RF change from doubling of CO\(_2\) is 3.7 Wm\(^{-2}\),
then \( \Delta T_{eq} \sim 1.5 - 4.5\degree C \) (best guess \( \lambda \) yields 2.5-3.0\degree C)
(note – albedo effect of changing IR forcing effectively zero)
AMPLITUDE OF ML-MODEL RESPONSE TO 11-YR FORCING
“Transient Response \((f)\) ” to Solar Forcing (ie, \(f \lambda\))

(Poor Man’s Time-Dependent Climate Model)

example 1, Texas, high noon, summer solstice

\(~1360\ W/m^2\) in low cloud state, 0 at night

equilibrium response \(\sim 1300^\circ C\)

observed \(\sim 15^\circ C\), therefore \(f_{\text{max}} \sim 1/200\) (max over large land areas)

11 year cycle \(f \sim 1/2\)

annual cycle \(f_{\text{max}} \sim 1/10\)

(e.g. orbital forcing changes over the last 10,000 years yield \(40\ W/m^2\), with about \(4^\circ C\) summer warming over central Asia)

10 day transient response should be between \(1/200\) to \(1/10\) of \(f_{\text{max}}\)

example 2, large sunspot, lifetime \(\sim 10\) days, \(\Delta L_o \sim 2\ W/m^2\) (\(Dq = 0.5\ W/m^2\))

and that \(f_{\text{max}} = 1/100\)

if so \(\Delta T_{\text{max}} \sim 0.5/100 = 0.005\) --- undetectable by 1-2 orders of magnitude

nevertheless, should realistic solar irradiance changes in forcing?

why not?
Global Temperatures (1890-2008) vs Solar and CO2 Forcing

- Temp_Global sm
- Solar scl to temp
- CO2 scl to temp

Global Temperature Anomalies (5 pt smoothing)

\[ r \text{ (solar)} = 0.700 \ (= 49.0\%) \]
\[ r \text{ (CO2)} = 0.925 \ (= 85.6\%) \]

Crowley - Fig 2
Best Fit to Global Temperature

Decadal Temperature Variations (°C)

BF (C + V) = 0.936 (87.7%)
BF (C, V, S) = 0.945 (89.4%)
Greenhouse gas forcing has very likely caused most of the observed global warming over the last 50 yrs. Based on distinguishing time-space pattern of warming between solar and ghg forcing. However, the response to solar forcing could be underestimated by climate models. Early 20th century warming may have a solar contribution, results vary between studies. Other contributors: early greenhouse gas signal or internal variability with warming pattern centered around North Atlantic.
Melting on Greenland Ice Sheet

R. Braithwaite, Science
12 July 2002
St. Anselm – Archbishop of Canterbury (1033-1109), philosopher and theologian

one role of theology involves “faith seeking understanding”
St. Anselm – Archbishop of Canterbury (1033-1109), philosopher and theologian

one role of theology involves “faith seeking understanding”

Tom Crowley: “also solar scientists?”
Plate 4.1 The Mer de Glace reached out on to the floor of the Arve valley in 1823 when it was painted by Samuel Birmann. (Au village des Prats, Öffentliche Kunstsammlung Basel, Kupferstichkabinett, Inv. Bi. 30. 125)
CROSS SECTION of a CONIFER

- bark
- phloem
- vascular cambium
- false ring
- annual ring
- latewood
- earlywood
- pith
Summer Half-Year Temperature Anomalies (30-90N, land) 755-2008
MTM Spectrum of 1000 Year Tree Ring Time Series (755-1800)

Spectral Density (MTM)

Frequency (year\(^{-1}\))

- 10.8 !!
- 17.8 ??
- 51.1 ??

El Nino band
Comparison of Tree Ring/Ice Core Reconstruction with Alpine Glacial Advances

Year
N. Hemisphere Alpine Glacial Advances

Temperature Variations (°C)

Observ.Inst  30-90N  sm10
Paleo.CH5.est.
N. Hemisphere Alpine Glaciers
Causes?
- natural variability, chaos?
- “natural forcing” – sun, volcanism?
- carbon dioxide?
White Noise Forcing (10 day time step) of 15,000 Year Energy Balance Model Run

Ocean Heat Content

Surface Temperature

Frequency
Comparison of Two Cosmogenic Indices

- Be10/Lean

Year AD Bond

Graph showing the comparison of C14.Bond.sol. and Be10/Lean indices over time.
Tambora Volcano
Standard Volcanic Time Series for Climate Modellers

SATO  2002  GLOBAL AOD
Extruding a core

Geoffrey Hargreaves, Curator
USGS/National Ice Core Laboratory
Droning Maud Land (core 05) Sulphate Flux vs Sato AOD (30-90S)

SO4 Flux [ng/g]

Sato 30-90S AOD

Year

(2.5 Yrs)

Pinatubo ++

El Chichon?

Fuego (extrapolated from N. Hemisphere?)

SO4 [ng/g]
Calibration of Ice Core Sulphate Signal

- Sato AOD
- Ice Core Pinatubo Global AOD
- Lunar AOD
- Ice core uncert.

Global AOD (adjusted for background)

Year

4 year avg: Sato (0.056) ICI (0.056)
Calibration and Validation of New Volcanism Ice Core Index (ICI) Version 9.8

ICI 9.8 Global
Sato Global
Lunar AOD
Geol. Est.
Stothers AOD*

Global AOD

Year

1800 1850 1900 1950 2000
Comparison of Solar and Volcano Forcing (800-2000)

Volcanism (dec. sm temp variability)
Solar Variability (Possible Temp Variability)

Crowley - Fig 6
Annual Be10 values in a Greenland Ice Core (Beer, 2009)
Best-Fit Forcing for Volcanic Interval 1450-1850

Decadal Temperature Variations (°C)

Crowley - Fig 8

BF (C + V) = 0.686 (47.1 %)
BF (C, V, S) = 0.711 (50.6 %)
Model-Data Comparisons for 30-90N

30-90N Anomalies (°C)

Year
Model-Data Comparisons for 30-90N

30-90N Anomalies (°C)

Year

r**2 (1480-1840):
all forcing    -  60.4
volcanism      -  38.4
solar          -    5.4
Model-Data Comparisons for 30-90N

30-90N Anomalies (°C)

Year

r^2 (1480-2002):

all forcing   -  83.4
## Detection of forced change in records of last millennium

<table>
<thead>
<tr>
<th>record</th>
<th>Briffa</th>
<th>CH-blend</th>
<th>Mann</th>
<th>Esper</th>
<th>Moberg</th>
</tr>
</thead>
<tbody>
<tr>
<td>volc</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>solar</td>
<td>No</td>
<td>No (Yes 1100on)</td>
<td>No (Yes periods)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Ghg+ aer</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Not robust</td>
</tr>
<tr>
<td>Res std</td>
<td>0.09  57%</td>
<td>0.09  70%</td>
<td>0.07  49%</td>
<td>0.15  70%</td>
<td>0.11  61%</td>
</tr>
</tbody>
</table>

Hegerl et al., J Climate 2007
C14 vs Smoothed Hemispheric Temperatures 215-2000

$r = 0.37$ (215-1900) = 14% variance

but

$r = -0.14$ (215-1250)
Heat Flow Experiments (HFEs) from Apollo 15 & 17 show very small thermal diffusivity of lunar regolith $\approx 10^{-8} \text{m}^2/\text{s}$, 100 X smaller than that of Earth’s crust.

Temperature anomalies as response to two scenarios of reconstructed TSI at the equator, mid-latitude and near south pole.
“Hope springs eternal in the human breast”  Alexander Pope
10 year bandpass at 512 years peak with 10 years low resolution
(intra-interpolate Y2K data into 10 year resolution)

Y2K bandpass ~512
C14 bandpass ~512
<table>
<thead>
<tr>
<th>Period</th>
<th>~420</th>
<th>~200</th>
<th>~120</th>
<th>~187</th>
<th>~56</th>
<th>$r$</th>
<th>$r_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glaciers</td>
<td>x</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>-0.11</td>
<td>0.15 (330)</td>
</tr>
<tr>
<td>Sierra TR</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>-0.10</td>
<td>0.22 (70)</td>
</tr>
<tr>
<td>China TR</td>
<td></td>
<td></td>
<td>X*</td>
<td>x</td>
<td>X*</td>
<td>-0.54</td>
<td>-0.54 (0)</td>
</tr>
<tr>
<td>Grn O18</td>
<td>X</td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td>-0.01</td>
<td>0.39 (45)</td>
</tr>
<tr>
<td>Peru O18</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>0.05</td>
<td>0.08 (15)</td>
</tr>
<tr>
<td>Spole O18</td>
<td>X*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.37</td>
<td>0.42 (-20)</td>
</tr>
</tbody>
</table>
Sunspot Cycle vs Alaskan Tree Ring

Alaska n 11 Year Solar

Year
Comparison of Band Passed Solar and Alaskan Tree Ring Lean (8-14) Alaska (8-14)
Solar Forcing vs N. Atlantic Sea Ice

Detrended Sea Ice Composite

C14

Detrended Sea Ice Composite

C14 Production Rate

Year BP

(Data Courtesy G. Bond)
N. Hemisphere Alpine Glaciers vs C14 Residuals

Normalized Glacier Extent
Scaled, Lagged C14 (100 yr smoothing)
Calendar Years BP

"Hits"?

Crowley Fig 10
Comparison of power spectra from last three glaciations

Source: Steven Obrochta, U. of Tokyo
Main Conclusion:

Solar Imprint on Climate – Overstated
For Little Ice Age but sometimes detected on longer time scales in composite records and in some local records

present but not necessarily dominant
<table>
<thead>
<tr>
<th>Period</th>
<th>~420</th>
<th>~200</th>
<th>~120</th>
<th>~187</th>
<th>~56</th>
<th>r</th>
<th>$r_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glaciers</td>
<td>x</td>
<td></td>
<td>X</td>
<td></td>
<td>X</td>
<td>-0.11</td>
<td>0.15 (330)</td>
</tr>
<tr>
<td>Sierra TR</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>-0.10</td>
<td>0.22 (70)</td>
</tr>
<tr>
<td>China TR</td>
<td></td>
<td>X*</td>
<td></td>
<td></td>
<td></td>
<td>-0.54</td>
<td>-0.54 (0)</td>
</tr>
<tr>
<td>Grm O18</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X*</td>
<td>-0.01</td>
<td>0.39 (45)</td>
</tr>
<tr>
<td>Peru O18</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td>0.05</td>
<td>0.08 (15)</td>
</tr>
<tr>
<td>Spole O18</td>
<td>X*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.37</td>
<td>0.42 (-20)</td>
</tr>
</tbody>
</table>
Volcanoes vs Little Ice Age Temperatures


Year

Volcanoes vs temperature
Is Solar Significant?

Smoothed Temperature Variations (°C)

Y2k.2.temp.sm70
Solar

EBM Solar (°C)

Year

r = 0.2
Global Volcanism 1220-2000

\[ y = 35.422 \times x^{-0.83034} \quad R = 0.95232 \]

(Outliers 121, 194, 300)

\~ 1 significant climate eruption every 30 years
Model-Data Comparisons for 30-90N

<table>
<thead>
<tr>
<th>Year range</th>
<th>r**2 (1480-1840)</th>
</tr>
</thead>
<tbody>
<tr>
<td>all forcing</td>
<td>60.4</td>
</tr>
<tr>
<td>volcanism</td>
<td>38.4</td>
</tr>
<tr>
<td>solar</td>
<td>5.4</td>
</tr>
</tbody>
</table>

```
30-90N Anomalies (°C)
```
White Mtns, Nevada Ring Width (mm?)

Jones 30-90N land (April-Sept) temperature

Year

White Mtns, Nevada

Inst April-Sept

Jones 30-90N land (April-Sept) temperature

Year

2000 Year Bristelcone Pine Time Series

White Mtns, Nevada Ring Width (mm?)
Jones 30-90N land (April-Sept) temperature

2000 Year Bristelcone Pine Time Series
MTM Spectrum of 1000 Year Tree Ring Time Series (755-1800)

Spectral Density (MTM)

Frequency (year\(^{-1}\))

10.8  !!
17.8  ??
51.1  ??

El Nino band
TSI_WLS2005

Year

11yr+background

1600 1650 1700 1750 1800 1850 1900 1950 2000
Plate 4.1 The Mer de Glace reached out on to the floor of the Arve valley in 1823 when it was painted by Samuel Birmann. (Au village des Prats, Öffentliche Kunstsammlung Basel, Kupferstichkabinett, Inv. Bi. 30. 125)
North Atlantic Oscillation
Volcanoes vs Little Ice Age Temperatures

Jones et al. (1998) Temperature Reconstruction

Year

Volcanoes vs Little Ice Age Temperatures
Global Temperatures (1856-2006)

Global Temperature Anomalies (°C)

Year

Data from Climate Research Unit
Univ. of East Anglia U.K.