The Influence of Solar Spectral Variations on Climate

Joanna D. Haigh

Department of Physics
Imperial College London, UK
Outline

• Observed impact of solar variability on temperature and zonal wind in lower atmosphere.
• Mechanisms?
• GCM study of impact of UV variation.
• Simplified model to study stratosphere-troposphere coupling mechanisms.
• Implications for stratospheric composition (and solar forcing of climate) of recent SSI measurements.
• Attempt to combine solar and stratospheric observations, with atmospheric model, to advance understanding of both.
Solar cycle signal in zonal mean temperature

NCEP reanalysis data 1979-2004

Heating in tropical lower stratosphere and throughout troposphere in mid-latitudes

after Haigh (Phil Trans Roy Soc, 2003)
Solar cycle signal in westerly wind (observed)

Weakening and poleward shift of the mid-latitude jets

Haigh et al (J.Clim., 2005)
Pacific Sea Surface Temperatures

White and Touree (2003)

solar max anomaly (van Loon et al 2007)
Composites: choice of time periods for sunspot max years and for reference climate period

a) as van Loon et al (2007)  
b) as Meehl et al (2008)  
c) as a) but different reference period  
d) as van Loon and Meehl (2011)
Solar variability & ENSO

Roy and Haigh (2010)

peak SSN years have negative ENSO – but there is no overall correlation between SSN & ENSO
Solar variability & ENSO

years of peak annual sunspot number

peak SSN years usually occur before broad solar max

Roy and Haigh (2010)
Tropical Pacific SST: evolution relative to sunspot peak year

observations

GCMs

Meehl and Arblaster (2009)
Little evidence of cold to warm evolution (?)

<table>
<thead>
<tr>
<th>Solar cycle number</th>
<th>Years</th>
<th>Peak year</th>
<th>State of ENSO (DJF)</th>
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<tr>
<td></td>
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<td>Peak year</td>
</tr>
<tr>
<td>10</td>
<td>1856–67</td>
<td>1860</td>
<td>C</td>
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<tr>
<td>11</td>
<td>1867–78</td>
<td>1870</td>
<td>C</td>
</tr>
<tr>
<td>12</td>
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<td>1883</td>
<td>C</td>
</tr>
<tr>
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<td>1890–1901</td>
<td>1893</td>
<td>C</td>
</tr>
<tr>
<td>14</td>
<td>1901–13</td>
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<tr>
<td>15</td>
<td>1913–23</td>
<td>1917</td>
<td>C</td>
</tr>
<tr>
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<td>1928</td>
<td>C</td>
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<tr>
<td>17</td>
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<td>1937</td>
<td>–</td>
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<td>1947</td>
<td>–</td>
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<td>1957</td>
<td>C</td>
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<td>1968</td>
<td>C</td>
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<tr>
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<td>1976–86</td>
<td>1979</td>
<td>–</td>
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<tr>
<td>22</td>
<td>1986–96</td>
<td>1989</td>
<td>C</td>
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| Total              |          |           |           |           |
|--------------------|----------|-----------|-----------|
|                    | C        | 9         | 7         | 8         |
|                    | –        | 3         | 1         | 0         |
|                    | W        | 2         | 6         | 6         |

Roy and Haigh (2012)
Mechanisms for a solar influence on climate

Gray et al (Rev. Geophys., 2010)
Solar forcing of climate: radiative mechanisms

“Top-down” via UV heating the stratosphere

and/or

“Bottom-up” via visible radiation warming surface?
Mean circulation and waves

Transfer heat and momentum within atmosphere.
Tropical TSI/ evaporation/ convection mechanism

Absorption of solar radiation within atmosphere

Lean & Rind (J. Clim., 1998)
Solar spectral irradiance & heating rate

irradiance (Dec, 57N) heating rate

Ozone absorption

Haigh (Nature, 1994)
Solar cycle variability

Solar Spectral Irradiance

Spectral Irradiance Variability

Lean & Rind (J. Clim., 1998)
Background:
Solar cycle variation in spectral irradiance

Solar min (Dec, 57N) max-min

Solar irradiance reaching lower atmosphere depends on response in stratospheric ozone.
Solar signal in zonal wind: obs cf climate model

Haigh et al (J. Clim., 2005)

N.B. Similar pattern in response but much smaller amplitude without O$_3$ changes
GCM UV experiment: mean overturning circulation

Hadley cells weaker and broader when Sun more active

Control

Solar max - min

Larkin (2000)
Study using a simple climate model

• Uses U. Reading “Intermediate GCM”
  – full dynamics but highly simplified physics
    (so can try out ideas and do many runs cheaply)
  – no orography
    (so no planetary scale waves but retaining synoptic scale waves)
• Apply simplistic heating perturbation to the stratosphere:

Haigh, Blackburn & Day (J.Clim., 2005)
Heating applied ONLY in the stratosphere:

Simple model  zonal wind  Observations of solar impact

the jet weakens and moves polewards

Haigh, Blackburn & Day (J.Clim., 2005)
Spin-up of temperature anomalies

Simpson, Blackburn & Haigh (JAS, 2009)
Spin-up of wind anomalies

Simpson, Blackburn & Haigh (JAS, 2009)
Simple model results:

Mean meridional circulation

Horizontal wave momentum flux

Simpson, Blackburn & Haigh (JAS, 2009)
Solar UV heats the stratosphere

Temperature gradients altered

Accelerations to zonal wind near tropopause

Changes in fluxes of wave momentum

Changes to Hadley circulation

Zonal wind accelerations at lower levels

feedback loop

Simpson, Blackburn and Haigh, 2009
Simpson et al mechanism…

…depends on UV impact in stratosphere.

How large is that?
SORCE data availability (as of 2009)

Lean, SIM, SOLSTICE, 2004–2007

SORCE SIM
SORCE SOLSTICE
NRLSSI model

Questions

• What do these spectra imply for changes in the atmosphere?

• Are the implied changes detectable in observations?
2D model $O_3$ differences (%) 2004-2007

O$_3$ destruction due to increase in $J_3/J_2 \rightarrow$ inc $O(^1D) \rightarrow$ inc OH
Multiple regression analysis of AURA MLS O$_3$ data 2004-2007

Opposite trends also seen in independent ozone data
Integrated solar flux 2004-2007 (Wm$^{-2}$)

200-242 nm

242-310 nm

310-500 nm

500-700 nm
### Solar Radiative Forcing of Climate*
**2004-2007** (mW m⁻²)

<table>
<thead>
<tr>
<th>NRLSSI</th>
<th>200-310 nm</th>
<th>310-500 nm</th>
<th>500-700 nm</th>
<th>700-1600 nm</th>
<th>Total solar 200-1600 nm</th>
<th>Thermal (LW)</th>
<th>Net</th>
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<td>30</td>
<td>10</td>
<td>20</td>
<td>60</td>
<td>20</td>
<td>80</td>
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<table>
<thead>
<tr>
<th>SIM</th>
<th>200-310 nm</th>
<th>310-500 nm</th>
<th>500-700 nm</th>
<th>700-1600 nm</th>
<th>Total solar 200-1600 nm</th>
<th>Thermal (LW)</th>
<th>Net</th>
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<tbody>
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<td>110</td>
<td>-130</td>
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<td>90</td>
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<td>90</td>
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<tr>
<td>105hPa</td>
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<td>60</td>
<td>-170</td>
<td>-50</td>
<td>-160</td>
<td>60</td>
<td>-100</td>
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</tbody>
</table>

*IPCC: global average net downward radiative flux at the tropopause
Solar forcing of climate: radiative mechanisms

“Top-down” via UV heating the stratosphere

SIM (2009) data would make much larger

and/or

“Bottom-up” via visible radiation warming surface?

SIM (2009) data would invert
Climate model UV experiment

Ineson et al (Nature Geoscience, 2011)

Model:
• UK Met Office HadGEM3 coupled atmosphere-ocean GCM, extends from surface to 85km, 42 levels in ocean.

Experiment:
• UV in 200-320nm band decreased by 4% representing solar cycle variation based on SIM data (Harder et al, 2009)
• No changes in other spectral bands.
• 80-year control run (solar min)
• 20x5-year experiment runs (max)

Reanalysis data:
• ERA-40/Interim 1957-2010
• Winter data composited into thirds (min, n/a, max) according to solar open flux.
Surface climate response (solar min – max)

Model                   Reanalysis

SLP

surface T

Ineson et al (2011)
Climate model SIM-like UV experiment

Ineson et al (Nature Geoscience, 2011)

Surface pressure gradients  N. Europe surface air temperature

model (x)  reanalysis (○)
solar minimum  solar maximum
error bars indicate +/- 1 s.e.
Consider...

These results depend fundamentally on the changes in solar spectrum.

SIM data being recalibrated.
Other SSI data include SOLSTICE
Modelled spectra include SATIRE

Can we better combine information available on solar spectrum with that on ozone to constrain variations in either?
Modelled $O_3$ response to different spectra

Ozone change (%/100 units $F_{10.7}$)

Spectra

Will Ball (Imperial College)
Solar cycle signal in ozone

Hood et al (2010)

Hood & Soukharev (2012)
Comparison of model $O_3$ response to different spectra with observations.

Ozone change (%/100 units $F_{10.7}$)

- SABER: 02/03-08/09
- 04-07
- Model w/NRLSSI
- Model w/SORCE


WACCM model & SABER obs (daytime)
Multiple regression of Aura MLS tropical O$_3$ data 2003-2012

Jack Egerton (Imperial College)
Multiple regression of Aura MLS tropical O$_3$ data 2003-2012

Percentage ozone change per 100 F10.7 units

NB: would not expect 2D model results to be good in lower stratosphere

Jack Egerton (Imperial College)
Statistical analysis of sensitivities

Tropical O₃ change profile from 512 model runs with variations in imposed UV spectrum applied in 4 broad bands

[Very preliminary analysis …]
O₃ (difference from solar minimum)

EOFs
weightings

spectral

EOF1 84.9 %
EOF2 13.0 %
EOF3 1.7 %
EOF4 0.4 %
Statistical analysis of sensitivities

Can make linear combinations of EOFs to match any given $O_3$ change and deduce required spectrum.

Some examples…
Spectrum constructed to produce best match to SOLSTICE - derived O$_3$ profile

Will Ball (Imperial College)
Spectrum constructed to produce best match to SOLSTICE-derived $O_3$ in upper stratosphere/lower mesosphere

Will Ball (Imperial College)
Spectrum constructed to produce best match to SAGE/SBUV/HALOE

Will Ball (Imperial College)
Can we better combine information available on solar spectrum with that on ozone to constrain variations in either?

Answer probably yes – but a work in progress.
Summary 1/3

- Solar cycle variability in Pacific SST – uncertain.

- Troposphere: shifts in jets & storm tracks (greater solar activity → jets poleward).

- UV heating of stratosphere produces similar patterns in low-top GCM.

- Mechanistic model: thermal perturbation near tropopause influences deposition of eddy momentum, with feedback on wave propagation and impact on jets and overturning circulation.

- Magnitude of effect is crucially dependent on magnitude of lower stratospheric heating & thus on changes in UV spectrum (& stratospheric response).
Summary 2/3

• SORCE spectra very different to semi-empirical models of SSI implying at higher solar activity:
  ➢ a reduction in O$_3$ in lower mesosphere
  ➢ a large increase in O$_3$ in mid- to upper stratosphere.
  ➢ an out-of-phase solar radiative forcing of climate

• These are not inconsistent with contemporaneous measurements of O$_3$ from AURA-MLS and TIMED-SABER, but appears at odds with values from earlier instruments over previous solar cycles.
• SIM spectra also imply
  ➢ an out-of-phase solar radiative forcing of climate
• This is difficult to align with regression results from surface temperature data
• Intelligent use of available solar spectra and stratospheric observations, with atmospheric models, should be able to better constrain values.
• Need ongoing, well-calibrated measurements of SSI and atmospheric variables.
Evolution of wind anomaly through winter

Model

Reanalysis

Imperial College
London
Winter polar stratosphere

Solar min – solar max in JF

Zonal wind (contours)

EP flux divergence (colours)