11-year solar cycle
Mechanisms and Modelling
in the Stratosphere
and Troposphere

Lesley Gray
University of Reading U.K.

1. Overview of Gray et al. 2010, Solar Influence on Climate,


3. Mechanisms for transmitting stratospheric signals to the troposphere and surface.
1. Introduction

2. Solar Variability
   • Causes of TSI variability
   • Decadal-scale solar variability
   • Century-scale variability
   • TSI and Galactic cosmic rays

3. Climate Observations
   • Decadal variations in the stratosphere
   • Decadal variations in the troposphere
   • Decadal variations at the Earth’s surface
   • Century-scale variations

4. Mechanisms
   • TSI
   • UV
   • Centennial-scale irradiance variations
   • Charged particle effects

5. Solar variability and global climate change

6. Summary / future directions
R: Sunspot number

F10.7 cm flux

Magnesium ii

Open solar flux

Galactic cosmic ray counts

Total solar irradiance

Geomagnetic Ap index
Composites of TSI 1978-2007

Reconstructions of past variations of TSI using different solar proxies
Observations:

composite SSTs / precipitation in DJF
S_{max} - S_{min}
(Meehl et al. 2009)

Winter temperature trends K/decade
1684 - 1738
(Luterbacher et al. 2004)
IPCC model simulations

anthropogenic + natural forcings

natural forcings only
Schematic overview: climate forcings associated with solar variability
Schematic overview
mechanisms for solar UV influence on climate
(based on Kodera and Kuroda 2002)
Mechanisms affecting the Stratosphere

Spectrum of solar irradiance (black) and spectrum of radiation reaching the Earth’s surface (blue)

Indicator of altitude of penetration of shortwave radiation

Percentage variability
S_{max} - S_{min}

~6% near 200nm (ozone formation)

~4% 240-320nm (absorption by ozone)

~0.07% in TSI
11-yr Temperature Signal in the Stratosphere (K)

$\text{S}_{\text{max}} - \text{S}_{\text{min}}$

SSU (Scaife et al. 2000)

Possible contamination by volcanic signal

ERA-40 reanalysis

Crooks and Gray 2005 J. Clim
Frame and Gray 2010 J. Clim
Solar and volcanic signal
ERA-40

Solar max - min
1979-2001
Volcanic

Crooks and Gray 2005
Temperature Trends: SSU observations

Black = SSU/MSU obs

Purple = radn model with CO2, O3 trends plus solar cycle

S. Rumbold, 2009 PhD thesis
Relative contributions of CO2, ozone, solar influence (high-res radiative heating calculations)

~3 hPa

Observed SSU temperature

Anthro O₃ + CO₂ + Solar, (0.17)
Anthro O₃ + CO₂, (0.39)

~15 hPa

Anthro O₃ + CO₂ + Solar, (0.15)
Anthro O₃ + CO₂, (0.19)

Ozone observations ($\% \text{ Smax-Smin}$)

Soukharev and Hood 2006

SAGE

Randel and Wu 2007

SAGE

SBUV

HALOE
Modelled radiative response to irradiance and ozone changes

Use a very high-res radiation model to assess temp response to

(a) irradiance changes
(b) ozone changes

(Gray, Rumbold and Shine JAS, 2009, see also Shibata and Kodera 2005)

\[ S_{\text{max}} - S_{\text{min}} \]

\[ T \ (K) \]

(a) temp response to irradiance changes (from Lean et al).

(b) temp response to ozone changes (SAGE)

(a) + (b)
Model / Obs comparison
Temperature response $S_{\text{max}}$ minus $S_{\text{min}}$ (K)

**ERA**

Radiative model response to irrad + ozone (a) + (b)

**SSU**

Radiative model response (a) + (b) sampled using the SSU weighting functions
Why does the lower stratospheric signal matter?

Correlation:
Observed DJF 100 hPa equatorial T
with T elsewhere
Salby and Callaghan 2005

Model: zonal wind response to an
imposed temp anomaly in equatorial lower strat.
Haigh and Blackburn 2006
1. Where does the lower stratospheric temp / ozone signal come from? (polar route vs equatorial route)
ERA-40
temperature response
Smax minus Smin (K)
annual average 1979-2008

ERA-40
zonal wind response
Smax minus Smin (m/s)
annual average 1979-2008
Frame and Gray, J. Clim 2010
ERA-40
zonal wind response
(m/s)
Smax-Smin
month-by-month
Frame and Gray, 2010
see also Kodera et al.
papers
Polar route

Modelled solar response in zonal winds
Gnossen et al. 2010

Observed solar response
NCEP zonal winds
Haigh and Blackburn 2006

Gnossen et al. 2010
See also Matthes et al. 2006
The quasi biennial oscillation (QBO)
Complicating influence on the polar response
Plus possible equatorial route
The Quasi Biennial Oscillation (QBO)

Equatorial wind time-series

Corr: F10.7 with February 30 hPa T

Labitzke, van Loon 1987+
The Quasi Biennial Oscillation (QBO)

Lu, Gray et al. 2009

Pascoe, Gray et al. 2005

Corr (F10.7 with T@85N, 50hPa in February)

Corr (F10.7 with zonal wind @80N)

Figure 5. December-January zonal mean zonal wind for (a) QBO west and (b) QBO east years. Easterly zonal mean wind is shown shaded, and contours are at 10 m s⁻¹ intervals. (c) West minus east zonal wind difference with t-test confidence shading shown at 95% and 99%; contours are at 5 m s⁻¹ intervals.

Lu, Gray et al. 2009
How well do models reproduce the temperature signal?

- Double peak structure in vertical - good match to ERA
- Lower strat peak wrong shape (role of QBO?)
- Upper strat temperature maximum too small and too wide

Average temperature response from coupled chemistry models (Austin et al. JGR 2008)
Why is upper strat temperature maximum too small and too wide?

Mid-lat signals OK – possibly too far poleward?

Upper strat peak ~50km is missing

Lower strat peak has wrong structure (QBO?)

SAGE ozone response (%)

Modelled ozone response (%)

Model mean (solar forcing)
Summary / Discussion UV Influence

Mechanism
- Solar UV influences stratospheric temps directly and via ozone
- Resulting temp gradient influences zonal winds
- Winds then influences wave propagation, enabling signal to extend deeper into the lower stratosphere and thence into the troposphere

Stratospheric response
Inclusion in coupled chemistry models reproduces some of the observed 11-yr solar signals in the stratosphere, but still many details unresolved e.g. lower stratospheric temperature signal; solar / QBO interaction, surface response. BUT - are models using the correct UV variations (c.f. Recent SIM results, Harder et al. 2009)

Tropospheric response
Inclusion of UV mechanism leads to a response in the troposphere (the 'top-down' response); coupled ocean models with TSI forcing produce a tropospheric response (the 'bottom-up' response); The 2 effects appear to be additive; we need more fully coupled chemistry - stratosphere - troposphere - ocean models simulations to investigate this.
Major question: are we using the correct estimates of UV variations in our models?

SIM Spectra differences 2004 - 2007

Harder et al. 2009
Spares
Cahalan et al. 2010

Haigh 2010 2-d model

SIM

Cahalan et al. 2010
2D model O₃ differences (%) 2004-2007

Lean

SIM
Climate change simulations with an improved stratosphere
Observed SSU temperature anomalies

![Graph showing observed SSU temperature anomalies with four lines representing different altitudes: 50 km, 42 km, 30 km, and 22 km, and two regions labeled E and P.](image)
Stratospheric Influence on the Troposphere

Baldwin and Dunkerton 2001

strong vortex regime

weak vortex regime

see also Woollings et al 2009
Solar min-to-max temp difference

Ramaswamy et al. 2001
see also: Scaife et al 2000, Keckhut et al 2005

Haigh 2003
Corrected Crooks and Gray plot
in Frame and Gray 2009, submitted
Multiple Linear Regression using ERA-40 dataset:

Question / objections to using re-analyses:
• Jumps in data due to changing instruments and data streams
• Possible contamination by volcanic signal
The 11-solar cycle signal  

Solar signal in temperature (K) 1979-2001

Volcanic signal in temperature (K) 1979-2001

Solar signal in temperature (K) 1979-2008

c)

Solar min-to-max differences

Crooks and Gray 2005
Gray, Rumbold and Shine JAS 2009
Frame and Gray J. Clim 2009
Comparison of solar and volcanic signal

Solar max - min 1979-2001 Volcanic

Crooks and Gray 2005
QBO / Solar Interaction: observations

Warming occur in Smax/W And Smin/E

NH polar temp anomaly 24 km
10.7 cm Solar flux

10.7 cm Solar flux

QBO west phase
Smax - Smin = +ve

QBO east phase
Smax - Smin = -ve

Labitzke and van Loon
Example of a Stratospheric Sudden Warming

PV on the 1250K isentropic surface

Aleutian High (~42 km)

• Gray, Drysdale, Dunkerton and Lawrence, QJRMS, 2001

• Gray, Sparrow, Juckes, O’Neill and Andrews, QJRMS, 2003
Stratospheric Influence on the Troposphere

Baldwin and Dunkerton 2001

1998 - 1999 Northern Annular Mode

strong vortex regime

weak vortex regime

see also Woollings et al 2009
ERA-40

Composites of zonal mean wind anomalies

Blue=easterly
Red=westerly

Gray et al. 2005, JAS
Easterly anomaly imposed in subtropics at 40-50km to mimic a solar minimum anomaly

Timing of sudden warmings is very variable in control run
Total solar irradiance

[\text{W/m}^2]\text{1366}

Galactic cosmic ray counts

Geomagnetic aa index

Aurora sightings

Sunspot number

Beryllium$^{10}$ concentrations

Year

1600  1650  1700  1750  1800  1850  1900  1950  2000
Why is upper strat temperature maximum too small and too wide?

Mid-lat signals OK – possibly too far poleward?
Upper strat peak ~50km is missing (see also Soukharev and Hood 2006)
Comparison with obs in Austin et al. is skewed by HALOE
Lower strat peak has wrong structure (QBO?)