Chemistry-Climate Models: 
What we have and what we need

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Outline

• Overview of processes in our current chemistry climate models (what we have)

• Selected results from model studies

• Comments on determining solar signals

• Look to the future - what do we need?
Mechanisms for solar & particle forcing of climate

Q: How are we doing in representing this in a model?

Gray et al., 2010
Mechanisms for solar & particle forcing of climate

Gray et al., 2010

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1. Forcing - Total Solar Irradiance (TSI)

- TSI now typically included in Atmosphere-Ocean GCMs (AOGCM) used in IPCC assessment modeling

- SPARC/SOLARIS RECOMMENDATIONS FOR IPCC-CMIP5 simulations:
  - Lower SORCE value for TSI (~1361 W/m²)
  - TSI time series with varying background (red line) and if desired perform additional sensitivity experiments without the varying background (black line).
1. Forcing - Solar Spectral Irradiance

- Incorporated into **heating and photolysis** calculations in chemistry climate models
- 12 models specified a solar cycle in simulations for CCMVal2
- **SPARC/SOLARIS RECOMMENDATION FOR CMIP5: NRLSSI**
  - ‘Modeler friendly’
  - 3780 spectral bins
  - Annual mean from 1610
  - Monthly mean from 1882
  - Daily fluxes from 1950

- However, there is no clear consensus on how SSI changes with TSI
1. Forcing - SEP

- Electrons
  - 1 keV to 5 MeV
  - Multi-stream method
  - via UBC
  - POES MEPED
- Solar protons
  - up to 500 MeV
  - NOAA-GOES
  - 35 eV / pair
- GCR
  - HAMMONIA used
  - Heaps (1978) - one NO per ion pair.
- GLE
  - up to 20,000 MeV

**AIMOS ionization rates**

**Ionization by electrons**

Fang et al., 2008

Funke et al., 2011
2. Model domains

- There is no model that covers all interfaces from the Sun to the ocean:
  - Most AOGCMs and Earth System Models extend from the surface to mid-stratosphere.
  - CTMs typically restricted to altitude ranges where reanalysis data exist (surface to up to 80 km).
  - Some CTMs and CCMs omit the troposphere (e.g. ROSE, TIME-GCM).
  - ‘Space Weather’ models have lower boundaries in the middle to upper atmosphere (e.g. CISM begins at the mesopause).
  - For CMIP5 there will be a ~11 AOGCMs/ESMs that fully resolve the stratosphere (but most without chemistry).
3. Processes

- A partial list of features needed to simulate various solar/particle effects on the Earth System:
  - Chemistry: Ox, HOx, NOx, ClOx, PSCs, ions (SPARC CCMVal)
  - Short- and longwave radiation codes
  - Correct transport in the stratosphere/mesosphere/thermosphere:
    - A non-orographic GW parameterization
    - Molecular & eddy diffusion
    - Quasi-biennial oscillation (internal or specified)
    - Annular modes - NAM, SAM (DynVar)
    - Stratospheric sudden warmings with correct frequency and timing (DynVar)
  - El Nino - Southern Oscillation with correct amplitude, frequency and timing
  - ...

EPP Chemistry

• Direct: Mesosphere / Stratosphere
  • Following proton and electron ionization:
    • SIC: full D-region ion code accounts for SZA dependence on NOx prod.
    • WACCM: 0.7 \(N(^2D)\) and 0.55 \(N(^4S)\) per ion pair
    • MESSY: 0.7 NO and 0.55 \(N(^4S)\) per ion pair

• Indirect: Thermosphere
  • WACCM & HAMMONIA: major ions \((N_2^+, N^+, O_2^+ \text{ and } O^+)\) produced via auroral electrons, photons/photo-electrons and E-region chemistry leads to production of N or NO, e.g.,

\[
\begin{align*}
O_2^+ + N(^4S) & \rightarrow NO^+ + O \\
NO^+ + e & \rightarrow N(^2D) + O \\
N(^2D) + O_2 & \rightarrow NO + O
\end{align*}
\]
Ion chemistry and effects on neutral constituents

Solar proton event of October/November 2003

MIPAS HNO3 Change

WACCM

FinROSE

From Funke et al., Atmos. Chem. Phys., 2011

- Significant differences exist between observations and models.
SPARC CCMVal-2 SW radiation code evaluation

• Offline calculation of solar cycle change in SW heating vs. LBL code

Table 3.17: Participating offline SW radiation codes and ways of prescribing solar variability.

<table>
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<th>CCM</th>
<th>TSI</th>
<th>Spectral</th>
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<tr>
<td>UMUKCA-UCAM</td>
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</tbody>
</table>
Model improvements important for solar studies

- **ENSO**

- **SSW**
  - Butler and Polvani, 2011

- **NAM**
SD-WACCM simulation of major SSW Jan. 2006

- **U (m/s)** 55-70°N
- **T (K)** 75-90°N
- **CO (vmr)** 75-90°N
- **NOy (vmr)** 75-90°N

Nudged region

Marsh, 2011
Thermosphere to mesosphere transport of NOx

- NOx transport by:
  - Diffusion - 4 orders of magnitude in vmr with height from 70-110 km
  - Residual Circulation

Marsh, 2011
Parcel back-trajectories

- Where have parcels in the NH polar region at 75km on February 1 originated from?

- Backward trajectories using the TEM ($v^*, w^*$) show parcels come from near the mesopause

- This does not mean parcels do not have thermospheric NOx

- Molecular and eddy diffusion can transport auroral NOx downward

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Smith et al., 2011
Selected model results
Long-term effects - WACCM 3.1.9 SPE study (direct)

Jackman et al. [JGR, 2009]
Long-term effects - DJF temperature changes

Semeniuk et al. [ACPD, 2011]

Baumgaertner et al. [ACPD, 2010]
HEPPA/SOLARIS meeting, Boulder, October 2012

HEPPA-1 2003 ‘Halloween’ solar storm MDI

**NOy increase**

26 Oct. to 30 Oct.

**Ozone loss**

29 Oct. – 4 Nov.

70-90N

16-26 November

short-term: HOx-related

mid-term: NOx-related
HEPPA/SOLARIS meeting, Boulder, October 2012

HEPPA-1: Halloween Storm, 2003

Temperature 29 Oct. - 4 Nov.

- MIPAS Temperature
- FinROSE-MIPAS
- HAMMONIA-MIPAS
- WACCM-MIPAS

NOy change from 26 Oct.

- MIPAS NOY Change
- FinROSE

ACPD

Funke et al., 2011
HEPPA-1 overestimation of electron precipitation

SD-WACCM forced only with proton ionization agrees better with MIPAS observations.
HEPPA/SOLARIS meeting, Boulder, October 2012

2005 SPE

Analysis by Bernd Funke

\[
\begin{align*}
HCl + OH & \rightarrow Cl + H_2O \\
Cl + O_3 & \rightarrow ClO + O_2 \\
ClO + HO_2 & \rightarrow HOCl + O_2
\end{align*}
\]
NH polar cap NOy variability
27-day response in a 3-D model - Gruzdev et al., 2009

HAMMONIA whole-atmosphere CCM forced with a constant repeating 27-day irradiance variation shows an intermittent response.
CCMVal2 SC temperature

Annual mean 25°S to 25°N response per 100 units of F10.7
CCMVal2 SC ozone

Annual mean 25°S to 25°N response per 100 units of F10.7

SPARC Report #5, 2010
Ch. 8 Natural variability of stratospheric ozone
Consequences of new SORCE data

January differences 2004 to 2007 averaged 25°C S to 25°C N

Ermolli et al., ACPD 2012
Measurements from the SIM instrument (2004-2007) are extrapolated in time to represent the full solar-cycle amplitude. We estimate the difference between the solar maximum and minimum in the 200-320 nm band to be 1.2 W/m², a 4% change, and distribute this evenly across the ultraviolet band. No changes are made in other bands.
HEPPA/SOLARIS meeting, Boulder, October 2012

WACCM CMIP5 coupled simulations
30 hPa NP GPH vs. UV flux 1960-2004

Easterly
n=17
Ens. 1 0.06  -0.35
Ens. 2  0.05   0.08
Ens. 3 -0.34   0.32

Westerly
n=23

Ens. 1 0.06  -0.35
Ens. 2  0.05   0.08
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Ens. 1
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HEPPA/SOLARIS meeting, Boulder, October 2012

WACCM CMIP5 coupled simulations

ensemble mean DJF solar max. yrs. - climatology

1955-2005
HEPPA/SOLARIS meeting, Boulder, October 2012

WACCM 1960-2005 DJF solar max. yrs. - climatology
MAECHAM5 Solar Cycle Study of Tropical Pacific

**Fig. 4.** Hovmöller diagram of the ensemble-mean annual (a) unfiltered and (b) MSSA-filtered anomalies (K) at the equator (5°S–5°N). (c) F10.7 is shown for reference.
Finding a signal within the “noise”

- ENSO index in 1300 year control integration of NCAR-CCSM4

Deser et al., 2011
How is the solar cycle signal determined?

Multiple linear regression

\[ y(t) = \beta_{\text{offs}(N=4)} \times \text{offset} + \beta_{EESC(N=2)} \times EESC(t) + \beta_{QBO(N=2)} \times QBO(t) + \beta_{\text{QBO}_{\text{or}}(N=2)} \times QBO_{\text{orthog}}(t) + \beta_{\text{solar}(N=0)} \times \text{solar}(t) + \beta_{\text{ENSO}(N=2)} \times ENSO(t) + \beta_{\text{Ag}(N=2)} \times Agung(t) + \beta_{\text{Elc}(N=2)} \times ElChichon(t) + \beta_{\text{Pin}(N=2)} \times Pinatubo(t) + R(t)_{t=1,n} \]

However, correlation of predictors or non-linear interactions adds uncertainty.
ENSO aliasing is an issue for a short record

Marsh & Garcia, 2007
Detecting a regional surface signal is very difficult

- CCSM3 simulations under SRES A1B
- Members 10-20 of a 40-member ensemble
- DJF SLP trends from 2005 to 2060.

Deser et al., 2011
Tropospheric response

Baumgaertner et al. [ACPD, 2010]

Ineson et al. (2011)

A stronger Northern Hemisphere vortex (more positive Northern Annular Mode index) for strong geomagnetic activity.
Where next?
Model input wish list

- Total or spectral solar irradiance
  - Daily irradiances from pre-industrial to 2100
  - Representative solar maximum and solar minimum

- Energetic particle
  - Electron, proton, GCR fluxes - high temporal and spatial resolution

- Boundary conditions that reflect solar and geomagnetic induced changes outside the model domain
Concluding remarks

• Models are advancing to a degree where many of the pathways for solar/particle forcing of climate can be studied.

• There is no consensus from the solar community on the change in spectral irradiance over the solar cycle or longer time scales - the decision as what to use is often taken by the climate modelers, not solar physicists.

• The more complex the model, the harder to determine a clear solar signal - there is a large amount of geophysical noise.

• By ensuring reasonable representation of solar and particle forcing it should be possible to leverage the massive computational investment in IPCC / CCMI simulations.
Thank you