Energetic particles, meteoritic dust, PMCs, sulfate aerosol, and nuclear war:

WACCM and WACCM/CARMA studies at LASP

Michael Mills, Cora Randall, Brian Toon, Charles Bardeen, Lynn Harvey, Xiaohua Fang, Laura Holt, Jeff France, Donavan Wheeler:
University of Colorado

Rolando Garcia, Doug Kinnison, Dan Marsh:
NCAR
WACCM, CAM & CARMA at LASP

Talk outline:

- **WACCM**
  - Energetic particle precipitation - Cora Randall, Xiaohua Fang, Mike Mills, Laura Holt
  - Stratopause height & temperature - Jeff France, L. Holt, Lynn Harvey, C. Randall
  - Cold air outbreaks - Donovan Wheeler, Lynn Harvey
- **WACCM/CARMA**
  - PMCs, dust - Chuck Bardeen, Brian Toon
  - Stratospheric & mesospheric sulfate - Mike Mills, Brian Toon
  - Regional nuclear war - Mike Mills, Brian Toon

Ongoing Toon group studies:

- **WACCM/CARMA**
  - Upper tropospheric sulfates - Jason English
  - Archean Earth - Eric Wolf
- **CAM**
  - Tropospheric dust - Lin Su
  - Sea salt - Tianyi Fan
  - Titan - Krystyna Dillard
  - Mars - Richard Urata
  - Subvisible cirrus - David Stokowski, Eric Jensen, Chuck Bardeen, Andrew Gettelman
Energetic particle precipitation

- Ionization: $N_2 \rightarrow NO_x$
- Auroral electrons
  - 1 - 30 kev
- Add medium-energy electrons (MEE)
  - 30 kev - 2.5 Mev

Figure from Fang et al., submitted to JGR, 2008.
Randall et al. (AGU 2007): On average, auroral precipitation causes >10% increases in NO$_x$ down to ~35 km in SH
Aurora + MEE

Aurora only

Difference (ppbv)

MEE increases NO$_x > 25\%$ down to 20 km

Courtesy of Cora Randall
WACCM, GEOS, SABER, and MLS
Stratopause Temperature and Height

Courtesy of J. France and L. Holt
WACCM and ERA-40 Cold Air Outbreaks

ERA-40 Surface Temperature

WACCM 1000 hPa Temperature

ERA40 12Z Surface CAO Algorithm

WACCM ~1000mb CAO Algorithm

Courtesy of D. Wheeler
CARMA Microphysical Model

Coagulation

Meteoric Influx

Meteoric Dust
28 Bins
0.2-100 nm

Nucleation
$m=0.95$

Sublimation

Deposition
$\alpha_c=0.93$

Sublimation

Ice Crystal

Core Mass
28 Bins
0.2-1000 nm

Radiation

Heat
$\alpha_t=1.0$

Water Vapor

Courtesy of Chuck Bardeen
Reduced Dust At Summer Mesopause

Bardeen et al. (JGR, 2008)
Polar Mesopause Temperatures

WACCM vs. Lubken [1999], 70°N

Lubken [1999], Tmin=129.00

New, Tmin=127.25

Default, Tmin=127.07

Courtesy of Chuck Bardeen
How Does WACCM/CARMA Compare To SOFIE on AIM?

Summary

<table>
<thead>
<tr>
<th></th>
<th>SOFIE</th>
<th>WACCM/CARMA</th>
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<tbody>
<tr>
<td>Events</td>
<td>1423</td>
<td>1423</td>
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<tr>
<td>Clouds</td>
<td>1134</td>
<td>1010</td>
</tr>
<tr>
<td>Zmax &lt; 79 km</td>
<td>289</td>
<td>0</td>
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</tbody>
</table>

SOFIE: Clouds 79.69%, Zmax < 79 km 20.31%
WACCM/CARMA: Clouds 70.98%, Zmax < 79 km 0.00%
Zonal average sulfate concentration \((r>1 \text{ nm}) \ [\# \text{ cm}^{-3}]\) 

\[>1000 \text{ cm}^{-3}\]

**May 31**

**July 17**

**90°N**

![Graph showing particle radius (nm) vs. dN/dlogr (\# cm^{-3}) for dust and sulfate particles.](image)

![Color map showing pressure and altitude with concentration levels ranging from 100 to 1000 cm^{-3}.](image)
Sulfate Geoengineering (Rich Turco, 1997)

50 Tg S/y → 100 Tg OCS/y

~80% loss in troposphere

20% → 20 Tg SO$_2$/y

Tropospheric OCS x 300
~170 ppbv

cooling: several °C

Decomposition by plants and soils

Emission by power stations

Atmospheric transport

Tropopause

Stratosphere
Changes in Monthly-Averaged Global Ozone From 1979-2001

Source: TOMS (NASA) via Mark Jacobson, Atmospheric Pollution
Effective radius (µm)

March Zonal Average

Background

Geoengineered
Column Ozone Annual Average and Range

Background sulfur
Geoengineered OCS x 50
Global effects of regional nuclear war

Mills et al., PNAS, 2008.

Soot global mean mass mixing ratio (ppbm, $10^{-9}$ kg/kg air)

Global mean temperature change (K), soot - control
Year 2 ozone column

Near-global ozone hole (< 220 DU)
Conclusions & Poster Plugs

• Energetic particle precipitation (poster, Randall et al.)
  – Aurora: >10% NOx increase down to 35 km
  – MEE: >25% NOx increases down to 20 km
• WACCM stratopause (poster, Harvey et al.): ~10K warmer than SABER in November
• Cold air outbreaks (poster, Harvey et al.): WACCM produces statistics similar to ERA40 observations
• PMCs & meteoritic dust (poster, Bardeen et al.):
  – Winds deplete meteoritic dust at summer mesopause
  – WACCM/CARMA tuned to observed temperatures produces PMCs in agreement with SOFIE observations
• Mesospheric sulfates: sufficient concentrations at summer mesopause for PMC nuclei
• Sulfate geo-engineering: O$_3$ depletion ~2% globally, ~10% near poles
• Regional nuclear war: could produce a near-global ozone hole.
WACCM/CARMA

Component

WACCM
3.1.9 tag 9
4° x 5°
125 levels

State

Pressure (P)
Temperature (T)
Water Vapor (Q)
...

Process

Advection
Vertical Diffusion
Molecular Diffusion
Gravity Waves
Wet Deposition
Chemistry
Radiation

Meteoric Dust (DUST01-28)
Ice Core (CRCORE01-28)
Ice Crystal (CRICE01-28)

Meteoric Influx
Sedimentation
Brownian Diffusion
Coagulation
Nucleation
Deposition/Sublimation
*Radiative Heating

Tendencies

State

CARMA 2.3

Courtesy of Chuck Bardeen
Polar Mesospheric Clouds

PMC Nucleation

Homogeneous nucleation of water vapor is too slow to account for observed PMC particles.

Proposed nuclei:

- meteoritic dust
- proton hydrates
- sulfates
Important PMC Temperatures

WACCM vs. Lubken [1999], 70°N

Temperature at 82.0 km

Mesopause Temperature

Mesopause Height

Temperature (K)

Month

WACCM

Default (tb* = 6.00, eff = 0.1250)
Previous (tb* = 2.00, eff = 0.125)
New (tb* = 1.50, eff = 0.0875)

Lubken [1999]

Courtesy of Chuck Bardeen
Global Mean Ox Column Loss Rates (Geoeng - Control)

Column loss (x10^8 molec/cm^2/s)

- ClO_x
- HO_x
- O_x
- BrO_x
- ClO_x + NO_x
- NO_x

Month:
- J
- F
- M
- A
- M
- J
- J
- A
- S
- O
- N
- D
Sulfate Microphysical Model

1. meteoritic dust
   emission profile based on Kalashnakova et al. [2000]

2. pure sulfates
   Homogeneous nucleation
   $\text{H}_2\text{SO}_4$
   $\text{H}_2\text{O}$
   Condensation
   Evaporation
   Coagulation

3. “mixed” sulfates
   with dust cores
   $\text{H}_2\text{SO}_4$
   $\text{H}_2\text{O}$
   Condensation
   Evaporation
   Coagulation
   Coagulation

Heterogeneous nucleation
Coagulation
How Does GW Tuning Impact CN?

Dust, Previous Tuning, July

Dust, New Tuning, July
Total Ozone Loss

(Soot - Control)/Control

O$_3$ Column Change(%)
Other Properties ...
Less Total Ice Mass Than Estimates?

[Stevens et al. 2007]
Aerosol Size bins

- 38 aerosol size bins x 3 groups
- volume doubling
- minimum radius 0.1 nm
\[ \text{H}_2\text{SO}_4 + h\nu \rightarrow \text{SO}_2 \]

- UV ruled out [Burkholder et al., 2000]
- Visible + near IR proposed [Vaida et al., 2003]
- Rate does not increase exponentially with altitude

Rinsland et al., GRL, 1995.
Garcia-Solomon 2D Model

Figure 3 from Mills et al. [2005b]