WACCM: The High-Top Model

Michael Mills
WACCM Liaison
mmills@ucar.edu
(303) 497-1425
http://bb.cgd.ucar.edu/

**Whole Atmosphere Community Climate Model - eXtended (WACCM-X):**
surface to 500-700 km

**Whole Atmosphere Community Climate Model (WACCM):**
surface to 145 km

**Community Atmosphere Model (CAM):**
surface to 45 km

- **Aurorally generated waves and heating**
- **Geospace**
- **Charged particle precipitation**
- **Noctilucent clouds**
- **Planetary waves**
- **Tides**
- **Gravity waves**
- **Wave breaking**

Ozone defines the stratosphere

https://scied.ucar.edu/sites/default/files/images/large_image_for_image_content/stratosphere_diagram_big.jpg
WACCM Additions to CAM

- Extends from surface to 5.1x10^{-6} hPa (~150 km), with 70 vertical levels
- Detailed neutral chemistry models
  - **middle atmosphere (MA):** catalytic cycles affecting **ozone**, heterogeneous chemistry on PSCs and sulfate aerosol, heating due to chemical reactions
  - **troposphere, stratosphere, mesosphere, and lower thermosphere (TSMLT):** adds chemistry affecting tropospheric air quality
- Prognostic stratospheric aerosols derived from sulfur emissions
- Model of ion chemistry in the mesosphere/lower thermosphere (MLT), ion drag, auroral processes, and solar proton events
- EUV and non-LTE longwave radiation parameterizations
- Gravity wave drag deposition from vertically propagating GWs generated by orography, fronts, and convection
- Interactive QBO derived from wave forcing
- Molecular diffusion and constituent separation
- Thermosphere extension (WACCM-X) to ~500-700 km
WACCM Motivation

• Coupling between atmospheric layers:
  • Waves transport energy and momentum from the lower atmosphere to drive the QBO, SAO, sudden warmings, mean meridional circulation
  • Solar inputs, e.g. auroral production of NO in the mesosphere and downward transport to the stratosphere
  • Stratosphere-troposphere exchange

• Climate Variability and Climate Change:
  • What is the impact of the stratosphere on tropospheric variability?
  • How important is coupling among radiation, chemistry, and circulation? (e.g., in the response to O₃ depletion or CO₂ increase)
  • Response to solar variability: impacts mediated by chemistry?

• Interpretation of Satellite Observations
CESM2 components

Forcings:
- Greenhouse gases
- Aerosols
- Volcanic eruptions
- Solar variability

Biogeochemistry (Carbon-Nitrogen Cycle)

Land (CLM)

Surface Wave (WaveWatch)

Atmosphere (CAM)

Coupler (CPL)

Ocean (POP)

Biogeochemistry (Marine Ecosystem)

WACCM

CAM-CHEM

WACCM-X

Sea Ice (CICE)

Land Ice (CISM)
# CESM2: WACCM6 & WACCM-X v2

<table>
<thead>
<tr>
<th></th>
<th>WACCM6</th>
<th>WACCM-X v2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertical Levels</strong></td>
<td>70, 88(SD)</td>
<td>126, 145(SD)</td>
</tr>
<tr>
<td><strong>Model Top</strong></td>
<td>6x10^{-6} hPa (~140 km)</td>
<td>4x10^{-10} hPa (500-700 km)</td>
</tr>
<tr>
<td><strong>Horizontal Resolution</strong></td>
<td>0.95°x1.25°, 1.9°x2.5°</td>
<td>1.9°x2.5°</td>
</tr>
<tr>
<td><strong>Time step</strong></td>
<td>30 minutes</td>
<td>5 minutes</td>
</tr>
<tr>
<td><strong>Specified Dynamics</strong></td>
<td>SD-WACCM6 option</td>
<td>SD-WACCM-X option</td>
</tr>
<tr>
<td><strong>Chemistry</strong></td>
<td>TSMLT (233), MA (99), SC (37)</td>
<td>MA (76)</td>
</tr>
<tr>
<td><strong>QBO</strong></td>
<td>Interactive at 0.95°x1.25°., Nudged at 1.9°x2.5°</td>
<td>Nudged</td>
</tr>
<tr>
<td><strong>Tropospheric Physics</strong></td>
<td>CAM6</td>
<td>CAM4</td>
</tr>
<tr>
<td><strong>Radiation</strong></td>
<td>RRTMG</td>
<td>CAM-RT</td>
</tr>
<tr>
<td><strong>Tropospheric Aerosol</strong></td>
<td>Interactive MAM4</td>
<td>Prescribed Bulk</td>
</tr>
<tr>
<td><strong>Stratospheric Aerosol</strong></td>
<td>Interactive MAM4</td>
<td>Prescribed</td>
</tr>
<tr>
<td><strong>Non-orographic GW</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Molecular Diffusion</strong></td>
<td>minor</td>
<td>minor and major</td>
</tr>
<tr>
<td><strong>Auroral Physics</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Ions</strong></td>
<td>E-region or E&amp;D-region</td>
<td>E-region</td>
</tr>
<tr>
<td><strong>Ion transport</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>E Dynamo</strong></td>
<td>No</td>
<td>Yes</td>
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WACCM component configurations

<table>
<thead>
<tr>
<th>CAM</th>
<th>atmosphere</th>
<th>ocean</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>WACCM</td>
<td>free-running</td>
</tr>
<tr>
<td></td>
<td>specified chemistry</td>
<td>static (pre-industrial or present-day)</td>
</tr>
<tr>
<td></td>
<td>free-running</td>
<td>data</td>
</tr>
<tr>
<td></td>
<td>specified dynamics</td>
<td>observations</td>
</tr>
<tr>
<td></td>
<td>transient</td>
<td>climatology</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>land</th>
<th>sea ice</th>
</tr>
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<tbody>
<tr>
<td>free-running</td>
<td>data</td>
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<tr>
<td>data</td>
<td>observations</td>
</tr>
<tr>
<td>observations</td>
<td>climatology</td>
</tr>
<tr>
<td>climatology</td>
<td>free-running</td>
</tr>
</tbody>
</table>
Specified Dynamics: SD-WACCM and SD-CAM-Chem

- Reproduce winds and temperatures from specific periods in analyses from GEOS5 (2004-present) or MERRA (1979-present).
- **FSDW** compset starts on 1 Jan 2005, uses GEOS5, out of the box.
- Increased vertical resolution
  - CAM-Chem: 32 levels → SD-CAM-Chem: 56 levels
  - WACCM: 70 levels → SD-WACCM: 88 levels
- Nudge T, U, V, PS towards analyses at every dynamics timestep. Nudging strength (i.e. 1%, 10% each timestep) and top altitude (50 km default for WACCM) can be adjusted.
- Chemistry interacts with radiation, atmosphere, land, ocean
- Data ocean and sea ice components
1. Orographic GWs:
Uncertain: Efficiency

Orographic GWs:
- McFarlane (1987)
- 1 wave with $c = 0$
- Amplitude dependent on orography height and wind

2. Frontally generated GWs:
Uncertain: Efficiency, amplitude, phase speeds

- 40 waves with $-100 < c < 100$ m/s
- Gaussian distribution in phase speed centered at $U = 600$ mb
- Constant wave amplitude

3. Convectively generated GWs:
Uncertain: Efficiency, amplitude conversion

- 40 waves with $-100 < c < 100$ m/s
- Dominant $c$ related to $h$ (depth of heating)
- Wave Amplitude $= Q^2$
- Wave spectrum impacted by wind in heating

Beres et al. 2004 (Beres = Richter)

Richter et al. 2010
QBO: 70 vs 110L WACCM

Higher vertical resolution

QBO descends to 100 hPa as observed (tropical Kelvin and RG waves are well resolved in the 110L model)

Standard WACCM6

Courtesy Yaga Richter
Water vapor “tape recorder”

- Vertical propagation speed is shifted upward slightly
- Amplitude is well-represented
- Improves on WACCM4 speed in upper stratosphere
- ~0.5 ppmv positive bias in summer

Figure from Gettelman et al., submitted to JGR, 2019
Volcanic eruptions SO$_2$ database (1850-2016)

- Volcanic eruptions increasingly well characterized (Satellite retrievals, in-situ measurements, geochem. & geophys. monitoring)
- 1979 first TOMS volcanic SO$_2$ retrievals
- Compiled volcanic emission dataset for use in climate models

<table>
<thead>
<tr>
<th>Period</th>
<th>Mass of SO$_2$ emitted (Tg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990-1994</td>
<td>12.85</td>
</tr>
<tr>
<td>1995-1999</td>
<td>0.93</td>
</tr>
<tr>
<td>2000-2004</td>
<td>0.93</td>
</tr>
<tr>
<td>2005-2009</td>
<td>7.56</td>
</tr>
<tr>
<td>2010-2015</td>
<td>8.55</td>
</tr>
</tbody>
</table>
Volcanic Aerosol Column Burden (kg S m\(^{-2}\))

- 2e-07
- 3e-07
- 6e-07
- 1e-06
- 2e-06
- 3e-06
- 6e-06

July 2008
Volcanic aerosol optical depth agrees well with lidar observations at multiple latitudes.

Figure from Gettelman et al., submitted to JGR, 2019.
Direct radiative effects of stratospheric sulfate

http://www.comet.ucar.edu
Absorbed shortwave (ASR)

Outgoing longwave (OLR)

Top-of-atmosphere radiative flux response to Pinatubo eruption agrees well with satellite observations.

Mills et al., JGR, 2017
Global stratospheric temperatures compare very well to observations, including volcanic heating.

Figure from Gettelman et al., submitted to JGR, 2019.
Top curves represent volcanic forcing: \(1.15\times\) global average SAOD.

Figure from Gettelman et al., submitted to JGR, 2019.
Polar ozone evolution

- WACCM6 reproduces well the observed evolution of the Antarctic ozone hole, and Arctic ozone loss.
- Nudged with specified dynamics, WACCM6 reproduces the observed interannual variability at both poles.

Figure from Gettelman et al., submitted to JGR, 2019
Total Column Ozone (TOZ), SD configuration

Slide courtesy of D. Kinnison.
WACCM and CAM-Chem Customer Support

CGD Forum: http://bb.cgd.ucar.edu/

Mike Mills
WACCM Liaison
mmills@ucar.edu
(303) 497-1425

Simone Tilmes
CAM-Chem Liaison
tilmes@ucar.edu
(303) 497-1425
Extra slides
CESM2 atmosphere components

Diagram showing the components of the Community Earth System Model (CESM) atmosphere, including CAM (Community Atmosphere Model), WACCM (Whole Atmosphere Community Climate Model), and their interactions with land, sea ice, and ocean environments. The diagram also illustrates the vertical structure of the atmosphere, with layers such as the troposphere, stratosphere, mesosphere, thermosphere, and exosphere, along with electron density and temperature profiles.
## WACCM costs (approximate)

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Resolution</th>
<th>Chemistry</th>
<th>Core-hours / simulation year</th>
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</thead>
<tbody>
<tr>
<td>CAM6</td>
<td>1°, 32L</td>
<td>CAM</td>
<td>3,700</td>
</tr>
<tr>
<td>WACCM6</td>
<td>2°, 70L</td>
<td>MA</td>
<td>5,400</td>
</tr>
<tr>
<td>WACCM6</td>
<td>1°, 70L</td>
<td>TSMLT</td>
<td>22,000</td>
</tr>
<tr>
<td>WACCM6-SC</td>
<td>1°, 70L</td>
<td>SC</td>
<td>6,000</td>
</tr>
<tr>
<td>WACCM6-SD</td>
<td>1°, 88L</td>
<td>TSMLT</td>
<td>23,000</td>
</tr>
<tr>
<td>WACCM5.4</td>
<td>1°, 110L</td>
<td>MA</td>
<td>20,000</td>
</tr>
<tr>
<td>WACCM5.4-SC</td>
<td>1°, 110L</td>
<td>SC</td>
<td>9,000</td>
</tr>
</tbody>
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# WACCM version evolution

<table>
<thead>
<tr>
<th>Common Name</th>
<th>WACCM4</th>
<th>WACCM-CCMI</th>
<th>WACCM5</th>
<th>WACCM6</th>
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</thead>
<tbody>
<tr>
<td>Horizontal Resolution</td>
<td>1.9°x2.5°</td>
<td>1.9°x2.5°</td>
<td>0.95°x1.25°</td>
<td>0.95°x1.25°</td>
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<tr>
<td>Vertical Levels</td>
<td>66</td>
<td>66</td>
<td>70</td>
<td>70</td>
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<tr>
<td>Deep Convection</td>
<td>ZM</td>
<td>ZM</td>
<td>ZM*</td>
<td>ZM*</td>
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<tr>
<td>Boundary Layer</td>
<td>HB</td>
<td>HB</td>
<td>UW</td>
<td>CLU BB</td>
</tr>
<tr>
<td>Shallow Convection</td>
<td>Hack</td>
<td>Hack</td>
<td>UW</td>
<td>CLU BB</td>
</tr>
<tr>
<td>Macrophysics</td>
<td>RK</td>
<td>RK</td>
<td>Park</td>
<td>CLU BB</td>
</tr>
<tr>
<td>Microphysics</td>
<td>RK</td>
<td>RK</td>
<td>MG2</td>
<td>MG2</td>
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<tr>
<td>Radiation</td>
<td>CAMRT</td>
<td>CAMRT</td>
<td>RRTMG</td>
<td>RRTMG</td>
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<tr>
<td>Aerosols</td>
<td>Bulk</td>
<td>Bulk</td>
<td>MAM3</td>
<td>MAM4</td>
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<tr>
<td>QBO</td>
<td>Nudged</td>
<td>Nudged</td>
<td>Interactive</td>
<td>Interactive</td>
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<tr>
<td>Chemical Mechanism</td>
<td>MA(59)</td>
<td>TSMLT (180)</td>
<td>MA(59)</td>
<td>TSMLT1 (228)</td>
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<tr>
<td>Chemical Rates</td>
<td>JPL-06</td>
<td>JPL-11</td>
<td>JPL-06</td>
<td>JPL-15</td>
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<tr>
<td>SOA</td>
<td>2-product</td>
<td>2-product</td>
<td>SOAG</td>
<td>VBS</td>
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<tr>
<td>Sulfate SAD</td>
<td>CCMVal2</td>
<td>CCMI</td>
<td>Interactive</td>
<td>Interactive</td>
</tr>
<tr>
<td>Ice SAD</td>
<td>Bulk</td>
<td>Bulk</td>
<td>Bulk</td>
<td>MG2</td>
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<tr>
<td>Solar Variability</td>
<td>CMIP5-Solar</td>
<td>CCMVal2-Solar</td>
<td>CMIP5-Solar</td>
<td>CMIP6-Solar</td>
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<tr>
<td>GHG Abundances</td>
<td>CMIP5 RCPs</td>
<td>CMIP5 RCPs</td>
<td>CMIP5 RCPs</td>
<td>CMIP6 SSPs</td>
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<tr>
<td>Halogens</td>
<td>CMIP5 RCPs</td>
<td>WMO 2010</td>
<td>CMIP5 RCPs</td>
<td>CMIP6 SSPs</td>
</tr>
</tbody>
</table>

Gettelman et al., submitted to JGR, 2019
WACCM6 highlights
(from Gettelman et al., 2019)

SSW Climatology (Nov-Mar); 3 realizations

Coupled ocean

A) SSW Frequency: Coupled v. NCEP (1975-2014)

Specified SST

B) SSW Frequency: AMIP v. NCEP (1975-2014)
WACCM Sulfate Geoengineering Feedback Simulations

Combined non-equatorial injections

Temperature change goal

Kravitz et al. (2017)
Because the thermosphere-ionosphere system responds to variability from the Earth’s lower atmosphere as well as solar-driven “space weather”

Including:

- Waves and tides
- Tropospheric weather
- Middle-atmosphere events
- Seasonal variations
- Anthropogenic trace gases

Illustration from the ICON mission, T. Immel et al.
Ozone layer evolution

Biases in free-running WACCM6 at mid-latitudes and in the tropics are not seen in SD-WACCM6.

Tropical upwelling vertical velocity is high in WACCM6 compared to SD, enhancing advection of ozone-poor air from the troposphere.

Figure from Gettelman et al., submitted to JGR, 2019
WACCM6 has higher September NH SIE than CAM6, in better agreement with observations.

**Analysis:** Less downward surface SW and LW in WACCM6 due to higher LWP, which results from higher aerosol number. The higher aerosol number increases CCN and cloud drop number, resulting in smaller drops that do not precipitate as readily. Thus the tropospheric aerosol chemistry impacts Arctic sea ice.
WACCM historical and future scenarios

Global average surface temperature

Year

WACCM6
HIST1
WACCM6
HIST2
WACCM6
HIST3

6K warming!

SSP-2.6
SSP-3.0
SSP-3.4OS
SSP-4.5
SSP-5.8.6

NCAR

Whole Atmosphere Community Climate Model
Climate Sensitivity: WACCM vs CAM

Annual Average TS

Surface Temperature (Radiative)

Coupled 4xCO2
piControl
CAM
WACCM

~1 K
Climate Sensitivity: WACCM vs CAM

Annual Average TS

Surface Temperature (Radiative)

CAM: ~13K

WACCM: ~11.3K

WACCM SOM 4xCO₂

CAM SOM 4xCO₂

Coupled 4xCO₂

piControl

300.0 297.0 294.0 291.0 288.0
Climate Sensitivity: WACCM vs CAM

CAM: ~13K
WACCM: ~11.3K

WACCM SOM 4xCO₂
WACCM SOM 4xCO₂ with transient O₃
Coupled 4xCO₂

Annual Average TS
Surface Temperature (Radiative)