WACCM: The High-Top Model

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

Whole Atmosphere Community Climate Model - eXtended (WACCM-X): surface to 750 km

Community Atmosphere Model (CAM): surface to 45 km

Jarvis, “Bridging the Atmospheric Divide”, Science, 293, 2218, 2001
Ozone defines the stratosphere
WACCM Additions to CAM

- Extends from surface to $5.1 \times 10^{-6}$ 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 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 $O_3$ depletion or $CO_2$ 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)

Sea Ice (CICE)

Land Ice (CISM)

WACCM-X

WACCM

CAM-CHEM
CESM2 atmosphere components
## CESM2: WACCM6 & WACCM-X

<table>
<thead>
<tr>
<th></th>
<th>WACCM6</th>
<th>WACCM-X</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># levels</strong></td>
<td>70-88</td>
<td>125-145</td>
</tr>
<tr>
<td><strong>Model top</strong></td>
<td>$6 \times 10^{-6}$ hPa (~140 km)</td>
<td>$4 \times 10^{-10}$ hPa (500-600 km)</td>
</tr>
<tr>
<td><strong>Horizontal resolution</strong></td>
<td>0.95°x1.25°</td>
<td>1.9°x2.5°</td>
</tr>
<tr>
<td><strong>Time step</strong></td>
<td>30 min.</td>
<td>5 min.</td>
</tr>
<tr>
<td><strong>Specified Dynamics</strong></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Chemistry</strong></td>
<td>TSMLT, MA</td>
<td>MA</td>
</tr>
<tr>
<td><strong>Non-orographic GW</strong></td>
<td>X</td>
<td>X</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>X</td>
<td>X</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></td>
<td>X</td>
</tr>
<tr>
<td><strong>E Dynamo</strong></td>
<td></td>
<td>X</td>
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Why WACCM-X?

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.
WACCM-X in CESM2
Now with an ionosphere (750km)

Ionosphere F-region Peak Electron Density Height

WACCM-X
COSMIC Observations

July 2008

- WACCM-X in CESM2 interactive ionosphere
  - ionospheric electrodynamics, ion transport and ion temp
  - Image ionosphere peak electron density height matches COSMIC obs
  - Measure of ionosphere electrodynamics
### WACCM Component Configurations

<table>
<thead>
<tr>
<th>Component</th>
<th>WACCM Configuration</th>
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<tbody>
<tr>
<td>Atmosphere</td>
<td></td>
</tr>
<tr>
<td>CAM</td>
<td>Specified chemistry</td>
</tr>
<tr>
<td></td>
<td>Free-running</td>
</tr>
<tr>
<td></td>
<td>Specified dynamics</td>
</tr>
<tr>
<td></td>
<td>Static (pre-industrial or present-day)</td>
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<tr>
<td></td>
<td>Transient</td>
</tr>
<tr>
<td>Ocean</td>
<td></td>
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<td></td>
<td>Free-running</td>
</tr>
<tr>
<td></td>
<td>Data</td>
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<tr>
<td></td>
<td>Observations</td>
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<tr>
<td></td>
<td>Climatology</td>
</tr>
<tr>
<td>Land</td>
<td></td>
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<tr>
<td></td>
<td>Free-running</td>
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<tr>
<td></td>
<td>Data</td>
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<tr>
<td></td>
<td>Observations</td>
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<tr>
<td></td>
<td>Climatology</td>
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<tr>
<td>Sea Ice</td>
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<td>Free-running</td>
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<td>Data</td>
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<td>Climatology</td>
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WACCM Specified Chemistry (WACCM-SC)

- Specifies Ozone (among other species)
- 2x as fast as WACCM: for stratospheric dynamics studies, with nearly identical results

Below: Tropical H2O Tape Recorder looks like WACCM (good), not CCSM4 (bad)
WACCM-SC also gets sudden stratospheric warming (SSW) frequency right.

SSWs trigger the negative mode of the North Atlantic Oscillation, which affects weather over Europe and the eastern US.
WACCM6-SC
SH 60°S-90°S Temperatures

Temperatures are reasonable in Southern Hemisphere

Note: Lower stratosphere difference not significant

Courtesy Rolando Garcia
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**: 30 levels $\rightarrow$ **SD-CAM-Chem**: 56 levels
  - **WACCM**: 70 levels $\rightarrow$ **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

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Community Earth System Model

Volcanic eruptions SO₂ database (1850-2016)

- Volcanic eruptions increasingly well characterized (Satellite retrievals, in-situ measurements, geochem. & geophys. monitoring)
- 1979 first TOMS volcanic SO₂ retrievals
- Compiled volcanic emission dataset for use in climate models

Volcanic eruptions since 1990

<table>
<thead>
<tr>
<th>Decade</th>
<th>Mass of SO₂ emitted / Tg of SO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990-1994</td>
<td>12.85 Tg of SO₂</td>
</tr>
<tr>
<td>1995-1999</td>
<td>0.93 Tg of SO₂</td>
</tr>
<tr>
<td>2000-2004</td>
<td>0.93 Tg of SO₂</td>
</tr>
<tr>
<td>2005-2009</td>
<td>7.56 Tg of SO₂</td>
</tr>
<tr>
<td>2010-2015</td>
<td>8.55 Tg of SO₂</td>
</tr>
</tbody>
</table>
Volcanic Aerosol Column Burden (kg S m⁻²)

July 2008

WACCM compares well to lidar observations.
WACCM compares well to lidar observations

Northern mid-latitudes

WACCM compares well to lidar observations
WACCM compares well to lidar observations

Aerosol Optical Depth, visible


WACCM > TP, 19.9°N
Mauna Loa Lidar (19.5°N) > TP
CCMI > TP, 17.5°N
Sato et al., 0-30°N

Tropics

Direct radiative effects of stratospheric sulfate
Prognostic Stratospheric Volcanoes
Prognostic stratospheric aerosol is coupled to radiation and chemistry.

Stratospheric temperature anomalies due to heating from volcanic aerosols are improved with **prognostic treatment** over prescribed treatment in CCSM4/ CESM1.

Mills et al. (JGR, 2016)
WACCM Gravity Wave Parameterization

1. Orographic GWs:

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

Mills et al. (submitted to JGR, 2017)
1. Orographic GWs:
   Uncertain: Efficiency
   
   Orographic GWs:
   • McFarlane (1987)
   • 1 wave with $c = 0$
   • Amplitude dependent on orography height and mean 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 $\propto Q^2$
   • Wave spectrum impacted by wind in heating

   Beres et al. 2004 (Beres = Richter)

   Richter et al. 2010

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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

QBO in EXP 1: 110L WACCM @ 20 hPa
**OBS**

**Westerly Amplitude**
- Amplitude vs. Density
- Mean: 28.0 months

**Easterly Amplitude**
- Amplitude vs. Density
- Mean: 27.5 months

**Period**
- Period vs. Density

**WACCM**

**EXP1–CHEM**

**Total Column Ozone (TOZ), SD configuration**

*Courtesy Yaga Richter*
Temperature change goal

Combined non-equatorial injections

Kravitz et al. (2017)
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