WACCM-X Updates

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### Major CESM WACCM/WACCM-X Components

<table>
<thead>
<tr>
<th>Model Framework</th>
<th>Chemistry</th>
<th>Physics</th>
<th>Physics</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atmosphere component of NCAR Community Earth System Model (CESM)</td>
<td>MOZART+ Ion Chemistry (~60+ species)</td>
<td>Long wave/short wave/EUV</td>
<td>Parameterized electric field at high, mid, low latitudes. IGRF geomagnetic field.</td>
<td>Horizontal: 1.9° x 2.5° (lat x lon configurable as needed)</td>
</tr>
<tr>
<td>Extension of the NCAR Community Atmosphere Model (CAM)</td>
<td>Fully-interactive with dynamics.</td>
<td>RRTMG IR cooling (LTE/non-LTE)</td>
<td>Auroral processes, ion drag and Joule heating</td>
<td>Vertical: 66 levels (0-140km) 81/126 levels 0~-600km</td>
</tr>
<tr>
<td>Finite Volume Dynamical Core (modified to consider species dependent Cp, R, m)</td>
<td></td>
<td>Modal Aerosol CARMA</td>
<td>Ion/electron energy equations</td>
<td>Mesoscale-resolving version: 0.25 deg/0.1 scale height.</td>
</tr>
<tr>
<td>Spectral Element Dynamical Core</td>
<td></td>
<td>Convection, precip., and cloud param.</td>
<td>Ambipolar diffusion</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Parameterized GW</td>
<td>Ion/electron transport</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Major/minor species diffusion (+UBC)</td>
<td>Ionospheric dynamo</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Molecular viscosity and thermal conductivity (+UBC)</td>
<td>Coupling with plasmasphere/magnetosphere</td>
<td></td>
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</tbody>
</table>
What’s New In CESM2/WACCM-X

• Interactive Ionosphere Modules
  – Interactive electric wind dynamo.
  – F region O+ transport.
  – Time dependent Te/Ti solver, and thermal electron heating of neutral atmosphere.
  – O+(2P) and O+(2D) included in ion chemistry and energetics.
• Thermosphere Modules
  – Ability to take flare time EUV input.
  – O(3P) cooling.
  – H escape flux parameterization implemented.
• Dynamic core: Species dependent specific heats and gas constant.
• Model domain extended to 4x10^-10 hPa, with ¼ scale height resolution.
• Reduced divergence damping improves tides.
• WACCM-X with specified dynamics.
• Data Assimilation with WACCM/WACCM-X DART.
• Improved model throughput: 0.57 model year/1 wallclock day with 144 processors on cheyenne.
• **WACCM-X now on the trunk of CESM2**
Adapting FV Dycore for Variable Species: Momentum Equations

• Treatment of pressure gradients in horizontal momentum equations.
  – Standard FV core uses Exner function ($p^\kappa$) as the vertical coordinate for the contour integral of the pressure gradient terms ($\kappa=R/C_p$).
  – When $\kappa$ is a variable, Exner function is not a constant on an isobaric surface, so can’t be used as a vertical coordinate.
  – Use pressure or log-pressure instead for computing the contour integral (latter has been used in our implementation).
Horizontal winds and divergence are solved incorrectly (and often become too strong) with the standard formulation. Causes excessive upwelling in the summer and downwelling in the winter.
Adapting FV Dycore for Variable Species: Thermal Equation and Hydrostatic Equation

- Thermal equation using potential temperature:
  \[
  \frac{\partial (\Theta \delta p)}{\partial t} + \nabla_H \cdot (\vec{V}_H \Theta \delta p) = \Theta \ln(p / p_0) \left( \frac{\partial (\kappa \delta p)}{\partial t} + \nabla_H \cdot (\vec{V}_H \kappa \delta p) \right)
  \]
  Advection of \( \kappa \) should be considered.

- Hydrostatic relation \( \delta \phi = C_p \Theta \delta (\rho^\kappa) \) is used in rebuilding geopotential. This is correct if \( \kappa \) is a constant, but yields an extra term if \( \kappa \) is variable. Should use \( \delta \phi = C_p \kappa \rho^\kappa \Theta \delta (\ln \rho) \).
Without advecting $k$

With $k$ advecting
Thermal Structures

Daytime mean T 2002 Nov

Daytime mean T 2007 Jul

GUVI/NRLMSIS Courtesy of Bob Meier
O And N2

Daytime mean [O] 2002 Nov

Daytime mean [O] 2007 Jul

Daytime mean [N2] 2002 Nov

Daytime mean [N2] 2007 Jul
O Peak in MLT

Smith et al., 2010

Solid: WACCM-X
Dotted: WACCM

Table:

<table>
<thead>
<tr>
<th>Pressure</th>
<th>0.01 hPa</th>
<th>0.003 hPa</th>
<th>0.001 hPa</th>
<th>0.0004 hPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean altitude (km)</td>
<td>79.2</td>
<td>86.2</td>
<td>92.7</td>
<td>97.9</td>
</tr>
<tr>
<td>Day O density (cm⁻³)</td>
<td>1.58 e+10</td>
<td>1.43 e+11</td>
<td>6.22 e+11</td>
<td>7.66 e+11</td>
</tr>
<tr>
<td>Night O density (cm⁻³)</td>
<td>5.44 e+09</td>
<td>2.23 e+11</td>
<td>6.56 e+11</td>
<td>5.58 e+11</td>
</tr>
</tbody>
</table>
Thermospheric Density at 400km

Liu et al. 2005
Electron Density at 400km

Liu et al., 2005
Comparison with COSMIC 2008 Jan-Feb

J. Liu
Comparison with COSMIC 2008 Jan-Feb

J. Liu
Vertical ExB Drift: Comparison with Smax Climatology

Scherliess and Fejer, 1999
Zonal ExB Drift: Comparison with Smax Climatology

Fejer et al., 2005
Monthly vs Daily Variability
WACCM-X Ionosphere: PRE Variability

Gentile et al., 2006

WACCM-X Solar Max: Constant F107 and Kp
SD-WACCM-X : 2003 “Halloween” Storms

- 1.9° x 2.5°, 145 levels
- Specified dynamics from MERRA meteorology (nudged to 55 km)
- New forcing files
  - 3 hour solar (Kp, Ap, f10.7, f10.7a, sunspots)
  - 5 minute solar EUV
  - Hourly solar proton
- Results in good agreement with Madrigal GPS TEC data
- Offset between WACCM-X and SD-WACCM-X suggests coupling with lower atmosphere is affecting electron density
WACCMX+DART, SD and Obs Ionosphere

Pedatella and Marsh
Summary

• WACCM-X now includes interactive ionospheric wind dynamo, O+ transport, as well as ionospheric chemistry.
• Finite volume dynamical core has been improved to consider variable species, and along with it variable specific heats and mean molecular mass.
• Thermospheric temperature and composition are in general agreement with observations.
• Ionosphere plasma density and drifts are in general agreement with observations.
• Storm time ionospheric structure in general agreement with observations.
• WACCM-X+DART produces realistic short-term variability in the ionosphere.