Whole Atmosphere Community Climate Model

– X –

Development Status

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National Center for Atmospheric Research

and

NCAR ACOM WACCM Group
Objectives of Whole Atmosphere – Ionosphere Modeling

Advances in whole atmosphere modeling are critical to addressing outstanding fundamental questions in ionosphere-thermosphere research.

– How do solar and geomagnetic influences affect the whole atmosphere?

– What are the relative roles of lower atmosphere and solar/geomagnetic forcing on the ionosphere-thermosphere system?

– How does anthropogenic change affect the thermosphere and ionosphere?

– How do atmospheric waves affect the energy and momentum coupling between the lower atmosphere and the ionosphere-thermosphere?

– What are the connections between small and large scale features in the system, e.g., “plasma bubbles”?

– How does the ionosphere-thermosphere vary over multiple time scales, e.g., “space weather” and “space climate”? 
Electron density (m⁻³)

Thermosphere

Ionosphere

Magnetosphere

Dynamo region

WACCM-X

WACCM

CAM

Singh et al., 2011
## 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</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</td>
<td></td>
<td>IR cooling (LTE/non-LTE)</td>
<td>Ion/electron energy equations</td>
<td>Mesoscale-resolving version:0.25 deg/0.1 scale height.</td>
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<tr>
<td>Spectral Element Dynamical Core</td>
<td></td>
<td>Modal Aerosols</td>
<td>Ambipolar diffusion</td>
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<td></td>
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<td>CARMA</td>
<td>Ion/electron transport</td>
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<td>Convection, precip., and cloud param.</td>
<td>Ionospheric dynamo</td>
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<td>Parameterized GW</td>
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<td>Major/minor species diffusion (+UBC)</td>
<td>Coupling with plasmasphere/magnetosphere</td>
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<td>Molecular viscosity and thermal conductivity (+UBC)</td>
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<td>Species dependent Cp, R, m.</td>
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</tbody>
</table>
d-π Coupler: dynamics-physics-ionosphere-electrodynamics (D-PIE) coupler
Electric Dynamo: calculates global electric potential resulting from wind-driven ions
ρ: density  v: velocity  T: temperature  n: neutral  i: ion  e: electron  Φ: electric potential
Recent Progress on WACCM-X

- Ion and electron energetics implemented
  - Thermal electron heating -> neutral temperature increase
- Improvements in thermosphere
  - Time dependent solar EUV input, O(3P) cooling, H escape flux, helium as a minor species (being tested)
- Parallel equatorial electrodynamo added using geomagnetic coordinates
- Ionospheric dynamics installed
  - Vertical diffusion ("ambipolar diffusion") of O⁺
  - Horizontal transport of O⁺ in the upper ionosphere
- O⁺(2P) and O⁺(2D) included in ion chemistry and energetics
- Bug fixes
  - Nighttime E-region ionization rate, EUV heating, CO₂ cooling
- Model domain vertically extended to 4x10⁻¹⁰ hPa, with ¼ scale height resolution
- Dynamical core now includes species dependent specific heat and gas constant (being tested)
- Reduced divergence damping -> improved tides (being tested)
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Thermospheric Zonal Mean Temperature (January)

- Ion/electron energetics added
- Thermal electron heating results in higher thermospheric temperature
- Improvement when compared to TIE-GCM
Recent Progress on WACCM-X

– Ion and electron energetics implemented
  • Thermal electron heating -> neutral temperature increase
– Improvements in thermosphere
  • Time dependent solar EUV input, \(^{3}\Pi\) cooling, H escape flux, helium as a minor species (being tested)
– Parallel equatorial electrodynamo added using geomagnetic coordinates
– Ionospheric dynamics installed
  • Vertical diffusion ("ambipolar diffusion") of \(\text{O}^{+}\)
  • Horizontal transport of \(\text{O}^{+}\) in the upper ionosphere
– \(\text{O}^{+}(^{2}\Pi)\) and \(\text{O}^{+}(^{2}\Delta)\) included in ion chemistry and energetics
– Bug fixes
  • Nighttime E-region ionization rate, EUV heating, \(\text{CO}_2\) cooling
– Model domain vertically extended to \(4 \times 10^{-10}\) hPa, with \(\frac{1}{4}\) scale height resolution
– Dynamical core now includes species dependent specific heat and gas constant (being tested)
– Reduced divergence damping -> improved tides (being tested)
Interactive ionospheric electric wind dynamo produces plasma drifts

Vertical and horizontal plasma drifts in good agreement with climatology and TIE-GCM

Vertical drifts upward during day, downward at night, and a clear pre-reversal enhancement
WACCM-X Equatorial ExB Drifts: Model and Radar Observations (Solar Maximum)

January WACCM-X Vertical Drift

January WACCM-X Zonal Drift

Scherliess and Fejer, 1999

Fejer et al., 2005

NOV-FEB
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Zonal Mean Electron Number Density

WACCM-X

• With ionospheric dynamics, now get equatorial ionospheric anomaly pattern similar to TIE-GCM
WACCM-X Ionosphere at ~250 km

- Electrodynamo and Ion transport
- Includes ambipolar diffusion, field-aligned transport, and ExB drifts
- A well-defined equatorial ionospheric anomaly is produced by the model.
Recent Progress on WACCM-X

- Ion and electron energetics implemented
  - Thermal electron heating -> neutral temperature increase
- Improvements in thermosphere
  - Time dependent solar EUV input, $O(^3P)$ cooling, H escape flux, helium as a minor species (being tested)
- Parallel equatorial electrodynamo added using geomagnetic coordinates
- Ionospheric dynamics installed
  - Vertical diffusion ("ambipolar diffusion") of $O^+$
  - Horizontal transport of $O^+$ in the upper ionosphere
- $O^+(^{2}P)$ and $O^+(^{2}D)$ included in ion chemistry and energetics
- Bug fixes
  - Nighttime E-region ionization rate, EUV heating, CO$_2$ cooling
- Model domain vertically extended to $4 \times 10^{-10}$ hPa, with $\frac{1}{4}$ scale height resolution
- Dynamical core now includes species dependent specific heat and gas constant (being tested)
- Reduced divergence damping -> improved tides (being tested)
In CAM, divergence damping set to a default value
- Results in lower amplitude and less variability of diurnal tides propagating through the atmosphere
- In WACCM/WACCM-X this has a significant impact in the mesosphere/thermosphere
- Optimum value for most realistic tides and stability still being investigated
Ionospheric Variability: Total Electron Content (TEC)

**Default Divergence Damping**

**Reduced Divergence Damping**

- Reduced divergence damping increases TEC variability (dashed)
Next Step: Implementing an Ionosphere-Plasmasphere Model in WACCM-X

— Geomagnetic coordinate system
— Interhemispheric coupling
— Auroral-equatorial coupling of electrodynamics
— Field-aligned current approach to solving the global electric potential
— Capability for coupling to magnetospheric model

Continuing Development

— Clean up the code to be ready for inclusion in CAM trunk and CESM2
— Testing: helium as minor species, divergence damping, and species dependent specific heat and gas constant in dynamical core
— General verification/validation against observations and empirical models
— Perform SD-WACCM-X runs for targeted time periods with many available thermosphere and ionosphere observations (2009 and/or 2013 SSW periods) for further validation
— WACCM-X+DART for whole atmosphere data assimilation
  (HAO/DA Postdoctoral Fellow and Nick’s talk)