Modeling the Stratosphere: Chemistry, Dynamics, and Tropospheric Coupling

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CM3 Coupled Climate Model

**AM3**
Atmospheric Model

- **Forcing**
  - Solar Radiation
  - Volcanic Aerosols
  - WMGGs (CO₂, CH₄, N₂O)
  - ODSs (CFC-11, CFC-12, CFC-113, HCFC-22)

- **CH₄, N₂O, ODSs** (as model lower boundary condition)

- **Short-lived Pollutant Emissions**
  - Anthropogenic, ships, biomass burning, natural, & aircraft

**Designed to address:**

- **Chemistry-climate feedbacks**
- **Stratosphere-troposphere chemical and dynamical coupling (high model top)**
- **Aerosol-cloud interactions**

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- Donner et al. (2011)
- Austin et al. (2013)
- Naik et al. (2013)

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**Modular Ocean Model version 4 (MOM4) & Sea Ice Model**

**Atmospheric Dynamics & Physics**
- Radiation, Convection (includes wet deposition of tropospheric species), Clouds, Vertical diffusion, and Gravity waves

**Atmospheric Chemistry**
- 86 km
  - Stratosphere
    - O₃, HOₓ, NOₓ, Clₐ, Brₐ, and Polar Clouds
  - Troposphere
    - Gases (O₃, CO, CH₄, NOₓ, VOCs)
    - Aerosols (sulfate, carbonaceous, mineral dust, sea salt, SOA)

**Aerosol-Cloud Interactions**
- Dry Deposition
- 0 km

**Land Model version 3**
- (soil physics, canopy physics, vegetation dynamics, disturbance and land use)
Stratospheric ozone distributions and trends are generally well simulated.

Ozone Column

Development of Antarctic Ozone Hole

Eyring et al., JGR (2013)
Stratospheric ozone and temperature respond strongly to volcanic eruptions

**Ozone Column**

- Total column (DU)

- Month relative to the eruption start

- Sign of ozone response to volcanic aerosols depends on atmospheric chlorine loading

**Temperature**

- Temperature anomaly (K)

- Year

- Post-volcanic warming and long-term cooling in stratosphere are well simulated by CM3

Austin et al., J.Clim. (2013); WMO (2014)
Deep stratospheric ozone intrusion

AM3 simulation of deep stratospheric O₃ intrusion over California
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AM3 simulation using:
- C180 horizontal resolution (~50x50 km²)
- Full stratospheric and tropospheric chemistry
- Winds nudged to GFS analysis

Isentropic transport of stratospheric ozone to lower troposphere during event sampled by NOAA CalNex 2010

Meiyun Lin et al., JGR (2012)
Deep stratospheric ozone intrusions captured by AM3

NOAA CalNex 2010 field campaign:
AM3 compared with ozonesonde observations

Case Study: May 28, 2010

Balloon observations  AM3 (~50x50km²)  AM3 (~200x200km²)

Altitude (km)

Sonde sites in California, north → south

O₃ [ppbv]

Stratospheric ozone penetrates to lower troposphere over southern California

Meiyun Lin et al., JGR (2012)
Stratospheric sources contribute episodically to high-ozone events above the health-based threshold.
Stratospheric influence on interannual variability of surface $O_3$ over Western U.S. during April-May

Emissions held constant
Nudged to "real" winds

$r^2 (OBS, AM3) = 0.56$
$r^2 (OBS, O_3S) = 0.43$
$r^2 (AM3, O_3S) = 0.74$

Meiyun Lin et al., in review (2015)
Wave-like jet stream under La Niña conditions ➞ Deep tropopause folds and injection of stratospheric O₃

Meiyun Lin et al., in review (2015)
Diagnosing the Brewer-Dobson Circulation (BDC)

**Annual Mean TEM Stream Function**

**Climatological Strength**

(10^9 kg/s)

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<thead>
<tr>
<th></th>
<th>ERA-i</th>
<th>GFDL CM3</th>
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<tbody>
<tr>
<td>30 hPa</td>
<td>1.73</td>
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<td>1.44</td>
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**TEM = Transformed Eulerian Mean**

Pu Lin and Q. Fu, *JGR* (2013)
BDC versus tropical surface T: decadal to multi-decadal variations

Shallow BDC well correlated with tropical surface temperatures, for internal (unforced) variability and various external forcings

Pu Lin et al., GRL (2015)
Shallow BDC versus tropical surface T: similar correlations across timescales and forcings

Pu Lin et al., GRL (2015)
BDC versus tropical surface T: internannual variability in recent decades

Shallow Branch

Deep Branch

AM3 captures correlation of shallow BDC with tropical surface temperatures

Pu Lin et al., GRL (2015)
Mechanism: critical layer control

Stronger subtropical jet leads to more wave dissipation in lower stratosphere and stronger shallow branch of BDC.

(Garcia and Randel, 2008, Shepherd and McLandress, 2011)
Response to surface warming

Regression of T and U upon tropical surface T

Shading: T
Black Contours: U
Gray Contours: U climatology (PI Control)

Regression of wave forcing and U upon tropical surface T

Shading: wave forcing
Black Contours: U

Pu Lin et al., GRL (2015)
Dramatic impact of non-hydrostatic dynamics

- QBO is difficult to simulate in free-running GCMs (with or without convective GWD)
- QBO impacts sudden warmings, stratospheric ozone, and (possibly) hurricanes & winter storms

S.-J. Lin and Lucas Harris
- Kelvin waves are better simulated with non-hydrostatic dynamics (all else equal)
- No QBOs if the Kelvin waves are too weak
Conclusions

• AM3/CM3 chemistry-climate model successfully simulates major features of stratospheric climate, ozone, and trends

• Response of ozone to volcanic eruptions highly sensitive to stratospheric chemical regime (halogens)

• Deep stratospheric intrusions can episodically elevate surface ozone (particularly in La Niña years over WUS)

• Tropical surface temperatures drive strength of lower branch of BDC, through modulation of wave forcing

• New non-hydrostatic cubed sphere dynamical core allows greatly improved simulation of QBO