Overview: Focus on three dimensional global models → two types

1. Climate models, i.e. WACCM
   (Whole Atmosphere Community Climate Model)

2. Weather models, i.e. the NRL NOGAPS-ALPHA model
   (Navy Operational Global Atmospheric Prediction System)
   a. Extension of the Navy’s weather model to include middle atm.
   b. Case studies of specific events, Sept 2002 (for the stratosphere),
      Jan/Feb 2005 vs. 2006 (for the mesosphere)
   c. Comparison with observations
   d. What can this teach us about the atmosphere?
### Summary of 3D models
(which both include and care about the mesosphere)

<table>
<thead>
<tr>
<th>NAME</th>
<th>DOMAIN</th>
<th>RECENT REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMAM</td>
<td>71 levels, 0 to .0006 hPa</td>
<td>Fomichev et al., JGR, 2004</td>
</tr>
<tr>
<td>HAMMONIA</td>
<td>67 levels, 0 to 250 km</td>
<td>Schmidt et al., J. Clim, 2006</td>
</tr>
<tr>
<td>LIMA</td>
<td>150 levels, 30-150 km</td>
<td>Berger and Lubken, GRL, 2006</td>
</tr>
<tr>
<td>NOGAPS-ALPHA</td>
<td>60-74 levels, 0 to .005-.0005 hPa</td>
<td>Siskind et al., GRL, 2007</td>
</tr>
<tr>
<td>ROSE</td>
<td>64 levels, 90 hPa to 188 km</td>
<td>Smith and Marsh, JGR, 2005</td>
</tr>
<tr>
<td>TIMEGCM</td>
<td>45 levels, 30 to ~500 km</td>
<td>Liu and Roble, JGR, 2002</td>
</tr>
<tr>
<td>WACCM</td>
<td>66 levels, 0 to 4.5e-6 hPa</td>
<td>Garcia et al., JGR, 2007</td>
</tr>
<tr>
<td>SMLTM</td>
<td>16 km – 200 km (1/2 scale ht res.)</td>
<td>Akmaev et al., JASTP, 2006</td>
</tr>
<tr>
<td>IDEA (NOAA/CU)</td>
<td>0-600 km</td>
<td>none yet?</td>
</tr>
</tbody>
</table>

See Eyring et al., JGR, 2006 for long list of models which may have tops at .01 hPa, but don’t really consider the mesosphere.
### Comparing a climate with a weather model

<table>
<thead>
<tr>
<th>Parameter/Model</th>
<th>WACCM</th>
<th>NOGAPS-ALPHA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Vertical Domain</strong></td>
<td>Slightly greater vertical domain 0 - 115 km vertical res: 0.5 – 2 km</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 - ~145 km, vertical res: 1 – 3.5 km</td>
<td></td>
</tr>
<tr>
<td><strong>Horizontal Domain</strong></td>
<td>Either 1.9 x 2.5 or 4 x 5 degrees</td>
<td></td>
</tr>
<tr>
<td></td>
<td>greater spatial resolution either 1.5 or 0.5 deg (T79 or T239 spectral)</td>
<td></td>
</tr>
<tr>
<td><strong>Physics/chemistry</strong></td>
<td>MOZART (complete ozone chemistry) Molecular diffusion Complete SW heating (EUV, FUV and UV) NLTE LW cooling above 65 km (CO2,NO) Auroral processes (ion drag, joule heating) Parameterized gravity waves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Parameterized (and operational O₃) NLTE cooling above 75 km New: WACCM GW param Future: SW and chemical heating</td>
<td></td>
</tr>
<tr>
<td><strong>Forcing</strong></td>
<td>Tropospheric values of chemical tracers Monthly SSTs F107-based solar flux All going back to 1950</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Temps every 6 hours from NAVDAS assimilation (only up to 10 mb, merge to CIRA above that level) Daily SST, ice, snow fields O₃ from Goddard assim.</td>
<td></td>
</tr>
</tbody>
</table>

CEDAR Tutorial #2, June 07

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WACCM: Simulation of secular trends in the middle atmosphere, 1950-2003 (Garcia et al)
Summary

Temp, ozone trends generally are consistent with observations.

Water vapor trends are not possibly due to missing low frequency variations from the QBO, volcanoes, and El Nino which confound trend studies unless 50 years of data are used (which we don’t have)

Combination of T and H\textsubscript{2}O trends will be able to drive a PMC parameterization to look at PMC trends over the last 50 years (although the implication is that interpreting decadal trends is much more complicated)
**Nomenclature: NOGAPS and NOGAPS-ALPHA**

**ANALYSIS**

“Best” Estimate of the Current Global Atmospheric State

**Global Forecast Model**

**Short Term (0-6 hour) Forecasts**

**Longer Term Forecasts**

- +1 day
- +2 days
- +3 days....

**NOGAPS-ALPHA development**

**Global Observations come in over the next 0-6 hours**

**Statistical Global “Data Assimilation” System (NAVDAS)**

**Short Term Forecast Error Estimates**

**Data Quality Control & Errors/Biases**

**FNMOC: <20 min per forecast day**

Global Observations come in over the next 0-6 hours
- new hybrid $\sigma$-$p$ vertical coordinate specified to maintain smooth vertical layer thickness profiles over all topography; increased vertical domain
- better vertical resolution in middle atmosphere
- new physics packages (short wave (MUV) heating, prognostic ozone)
- non-LTE cooling (Fomichev) extends model to 110-115 km (74 levels)
- non-zero phase speed gravity waves (shown for the 1\textsuperscript{st} time here)
Stratospheric Weather Forecasting: Analysis of 10 mb Temperature on 26 September 2002

Impact on Weather Forecasting
Skill Scores: Geopotential Height Anomaly Correlation


A improved tropospheric forecast!
CHEM2D-OPP: A fast Linear O3 parameterization
(from 2D model with complete chemistry)

The **current operational ozone** scheme in NCEP/GFS (as of 8/22/06)
(also transitioned to FNMOC for creating fully prognostic ozone in NOGAPS)

Tested in several different global ozone assimilation systems:

1. NRL’s new Global Ozone Assimilation & Testing System (GOATS) . **Coy et al., ACPD, 2006**

2. Univ. of Reading Data Assimilation Research Centre (DARC) system, **Geer et al., ACPD, 2006.**

3. NCEP/GFS, JCSDA newsletter June 2006

4. Developmental CHEM2D-OPP versions consistently outperform existing “fast ozone” schemes of the ECMWF, NASA Goddard, & UC Irvine, **McCormack et al, ACP, 2006**

Recommended as the preferred ozone scheme in the UKMO/DARC model
[Geer et al., QJRMS, 2006]
Ozone Data Assimilation Tests Using NOGAPS-ALPHA with CHEM2D-OPP and ECMWF Chemistry

ECMWF Chemistry underestimates high total ozone. CHEM2D-OPP does substantially better.
 Operational in the National Weather Service GFS, 8/22/06

New NRL Photochemistry Model Improves NCEP Ozone Forecasts

Total Ozone Zonal Mean Error

29 Day Period Ending 5/14/2006

NCEP/GFS

-24 -21 -18 -15 -12 -9 -6 -3 0 3 6 9 12 15 18 21 24 Dobson Units

NCEP/PRY

Latitude

0 1 2 3 4 5

Forecast Length (Days)

EQ

-90 -60 -30 0 60 90
Mesospheric Interannual Variability
from SABER IR instrument on NASA/TIMED satellite

Normal years (215-220K at 75 km)

Anomalous years (240-250K at 75 km)

FEB 15, 2003
FEB 11, 2004
FEB 11, 2005
FEB 11, 2006
Unusual NOx enhancements - descent from above

HALOE profiles
(Natarajan et al., GRL, 2004)

3 Years of NO and CO from ACE
(Randall et al., GRL 2006)
Can NOGAPS explain this unusual temperature structure? Can the model provide a link between this structure and the descent of thermospheric NO into the stratosphere?

Cold start initialization: Jan 31, 2005 and 2006. Free running GCM for 2 weeks, T79 resolution 1.5° resolution, L74. Also some T239 calculations (0.5° resolution)

Three GW drag approaches

1) Test three orographic (mountain wave) parameterizations
   a) Nothing: Usually least realistic. Zonal winds generally become unacceptably large
   b) Rayleigh friction: forces drag on zonal wind to mimic gravity waves—usually better than nothing, (except here)
   c) A realistic orographic scheme (Palmer et al): Accounts for location of mountain wave sources and filtering by zonal winds, state of the art for tropospheric systems 10-15 years ago

The above results were recently published in GRL (Siskind et al., May 07)

2) High resolution without parameterization
3) WACCM scheme for non-orographic waves
   effects of spectral width, efficiency, flux
Some background on mountain waves
(Eckermann and Preusse, Science, 1999)

- the Cryogenic Infrared Spectrometers and Telescopes for the Atmosphere (CRISTA) and NRL’s MAHRSI instrument were deployed into orbit on the Shuttle Pallet Satellite (SPAS) by Atlantis during STS-66 (November, 1994).
- this is shown in photo in panel A, taken over southern South America (see panel C) on Nov 4, 1994. Banded wave clouds can be seen downstream of the Andean Ridge
- Two days later (Nov 6, 1994) CRISTA acquired sequence of stratospheric temperature profiles over this region (labeled 1,2,3 in panels B and C)
- various tests prove the oscillations in measured temperatures panel B are mountain waves: e.g.,

\[
(\lambda_z)_{\text{theory}} = \frac{2\pi \bar{U}}{N}
\]

At 42°S, \(\bar{U} \sim 20-23\) m s\(^{-1}\), \(N \sim 0.02\) rad s\(^{-1}\) (see panel D)

\[
(\lambda_z)_{\text{theory}} \sim 6-7\) km
\]

Measured CRISTA \(T'(z)\) Perturbations from inspection of panel B

\(\lambda_z \sim 6.5\) km

CEDAR Tutorial #2, June 07
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Spectral Terrain for Orographic Parameterization
#1. Results of 6 simulations:
3 parameterizations x 2 years

Experiment 3: Realistic OGWD
Experiment 2: Invariant GWD
Experiment 1: Control (no GWD)

Suggests “anomalous” 2006 due to heavily suppressed mesospheric OGWD
Test Hypothesis: Zonal Mean GWD

Much weaker GWD in 2006 occurs (and ~15 km higher than in 2005) → no lower mesospheric drag poleward of 60N

Why?
Zonal mean winds

In 2005, Rayleigh friction is better than doing nothing, (Palmer et al drag is best)
In 2006, doing nothing is better than Rayleigh friction- unusual!
This suggests an absence of mountain waves in 2006

Mean zonal winds from model

Weak winds, gravity waves (actually mountain waves with zero phase speed) will encounter lots of critical lines. Absence of drag allows strong upper level vortex to develop at 0.1 mb (65 km)
Calculated net tracer Descent:
Greater in 2006 than in 2005

NOGAPS CH$_4$ is Initialized with the dashed lines.
("pseudo-CH$_4$": like CH$_4$ in distribution and chemistry, but initialized only with 2D climatology)

.01 ppmv contour:
  descends 10 km in 2006
  only 4 km in 2005

.05 ppmv contour
  descends 6 km in 2006
  only 2 km in 2005
#2. A high resolution view of gravity waves (65 km)

Resolved waves in T239 simulation to compare with T79 parameterization

Gravity waves suppressed poleward of 60N in 2006, by weak stratospheric winds
At the higher altitudes, it appears that there are more waves in 2006. Why? non-orographic waves?
#2. Zonal mean temps: T239 simulation vs. SABER (no GWD parameterization- only whatever the model resolves)

1. Displaced Stratopause is reproduced at correct altitude (still ~ 15K too cold)
2. Hints of a cold summer mesopause, but not well defined.
3. Summer/low-lat stratopause discrepancy → initial conditions?
Resolved waves capture the interannual variability. The 2005 simulation remains too cold in the lowermost stratosphere and too warm at the stratopause. Also neither simulation shows a well defined cold summer mesopause.
A gravity wave spectrum can be included by setting the number of waves to be greater than zero. In that case,

\[ \tau_s(c_\ell) = \tau_0 \exp \left[ -\left( \frac{c_\ell}{30} \right)^2 \right] \]

\[ c_\ell \in [0, \pm10, \pm20, ...] \]. \hfill (4.e.19)

As we’ll see, the wide spectrum is needed to generate a cold summer mesopause.
(bkgnd) Propagation of different phase speed waves
(Siskind et al., JGR, 2003)

Saturation amplitude depends upon (c-u) which is different for each wave.

Mountain waves hit critical line in summer, pass through in winter.

Eastward waves pass through in summer to upper mesosphere.
#3. WACCM Source Spectrum (Garcia)

Seasonally dependent, max in winter, equatorial minimum (other resolved waves important there); (based upon diagnosis by Charron and Manzini (2002))

This forcing can be scaled a couple of different ways. Here we use an efficiency (or intermittancy) factor. Also Garcia suggests scaling a source magnitude scaling ($\tau$)
#3. Two week calculation with WACCM MGWD param. (T79)

T\text{\_min} \text{ drops to 95K in 1 week}

Stratopause at 0.1 mb (too low in altitude)

Both summer and winter suggest \text{too much gravity wave drag}
#3. With GWD efficiency cut by factor of 2.5

Tmin now 117 K

Stratopause now at .03 mb, closer to observed alt
Conclusion: Reducing the efficiency improves the agreement with SABER in both hemispheres. There is still some slack to further reduce the efficiency or possibly the source flux.
#3. Finally with a narrow spectrum
(no waves > 40 m/sec)

Summer mesopause largely disappears, displaced stratopause in winter becomes much weaker \(\rightarrow\) conclusion: need fast waves for the cold summer mesopause and for the wintertime displaced stratopause
Fast eastward waves responsible for wind reversal above the mesopause
Conclusions (specific)

Unusual temperature structure in the mesosphere in 2006 result from changes in gravity wave filtering in the stratosphere.

Normally, the warm winter stratopause is sensitive to orographic waves; in 2006, non-zero phase speed waves were more important as orographic waves were absent.

The high resolution NOGAPS captures a lot of the winter structure, but does not get much of the cold summer mesopause. To simulate the summer mesopause, fast eastward waves must be postulated.

The WACCM GWD parameterization works well in NOGAPS-ALPHA with some evidence for different tuning required.
Conclusions (philosophical)

Both climate (WACCM) and weather (NOGAPS ALPHA) models can yield information about the physics of the middle atmosphere. In the case of NOGAPS-ALPHA, we do this by performing case studies up to 80-85 km. These case studies have shed light on GW effects and how they vary in response to meteorological changes.

**Coupling between the stratosphere and thermosphere:**
Can suggest why some years are favored. In 2004 and 2006, it’s the filtering of gravity waves by a disturbed stratosphere (we think)

Solar-terrestrial science needs to consider meteorological forcing by waves from the troposphere as much as solar/geomagnetic cycles

**Future research**
Improve physics of MLT region (above 80 km) → chemical heating, FUV heating

Support AIM and SHIMMER measurements of PMC/summer mesopause

**ONR/DTRA initiative**
pass these waves up into USU T-I system →
link ionospheric forecasts to tropospheric/middle atmosphere forecasts
Back to NOGAPS-ALPHA: Period of simulation
(rising temp at .02 mb in 2006, falling at 9 mb)

The period covered by the simulation is between the vertical red lines.
Note: SABER data is not synoptic, so we can’t directly compare model geopotential with observations.
Forcing from the troposphere
(proportional to upward component of Pwave activity)

Polvani and Waugh (J. Clim, 2004) identify this quantity as best indicator of AO index at 10 mb. Thus weather forced from troposphere is as important (more so?) than the solar cycle in coupling thermospheric NO to stratospheric NOx!
Why Less Vortex Disturbance in the Longer Range Forecasts?

Strong blocking feature in South Atlantic

Blocking ridge (anticyclone) radiates strong Rossby wave fluxes into the stratosphere

Less 500 hPa ridging in +4 day forecast → less Rossby wave EP flux → less disturbed vortex

500 hPa values of vertical component of 3D EP-Flux (Plumb, 1986)

100 hPa values of vertical component of 3D EP-Flux
Effect of refining mesospheric ozone inputs

Ozone is lower in the day in mesosphere. Diurnal average climatologies will overestimate the heating!

Model-data comparison of temps with new ozone heating

Blue: with old ozone
Red: with new ozone

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