Dynamical coupling between the middle atmosphere and lower thermosphere

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- Model runs performed at the NCAR-Wyoming Supercomputing Center
origin of variability in the MLT (mesosphere-lower thermosphere)

• solar
  – direct flux of radiation and particles
  – particles from magnetosphere

• lower or middle atmosphere
  – changes in radiatively active gases (CO$_2$, O$_3$, H$_2$O, CH$_4$)
  – dynamical variability
    • migrating and nonmigrating tides
    • SSW
  • momentum forcing and eddy diffusion due to gravity waves
Q: Does externally forced variability of the thermosphere affect the middle and lower atmosphere?

Q: Excluding external forcing, are the upper mesosphere and lower thermosphere “slave” to the lower atmosphere?
Does externally forced variability of the thermosphere affect the middle and lower atmosphere?

So far, there are only a few pathways that have identifiable physical mechanisms:

- changes in composition move downward by transport and diffusion
  
  *auroral NO transported into the polar winter stratosphere or lower mesosphere affects ozone & heating*

- change in thermal structure affects vertical structure and propagation or reflection of large-scale waves & tides
  
  *vertical structure of tides with long vertical wavelengths affected by solar cycle heating in mesosphere and lower thermosphere*
  
  ⇒ *also an issue for the upper lid of models*

- change in wave dissipation affects momentum deposition and can affect mean circulation below through downward control
  
  *gravity wave dissipation and breaking can vary depending on molecular diffusion, static stability*
NOx transport in WACCM – highest when SSW and/or elevated stratopause occur in December

- Event = SSW and/or elevated stratopause

Downward penetration of NOx highest when event occurs during December.

WACCM underestimates NOx penetration compared to observations.

Some of the variability (NO production) originates in the thermosphere.

Some of the variability (occurrence and timing of SSW) is driven from below.

Holt et al., JGR, 2013
Are the upper mesosphere and lower thermosphere “slave” to the lower atmosphere?

**Talk will address these topics:**
- Does all of the unpredictability of atmospheric dynamics originate in the lower atmosphere?
- What information from the lower & middle atmosphere is needed to predict the dynamics of the MLT?
- To what altitude is meteorological data needed in order to predict the dynamical variability above?

**These topics will not be addressed:**
- How important is the generation of additional gravity waves during breaking events?
- Is a global model with moderate resolution a sufficient tool to address the above?

**Tool used:** WACCM (Whole Atmosphere Community Climate Model)
Observational investigations of impact of lower-middle atmosphere on thermosphere

DE3 tide (a tide with 24-hour period, zonal wavenumber 3, propagating eastward) is excited by latent heat release in the tropical troposphere

Ionospheric emission from IMAGE satellite

Immel et al., GRL, 2006
Observational investigations of impact of lower-middle atmosphere on thermosphere/ionosphere

- Total electron content 10 LT
- Total electron content 21 LT
- Temperature 10 hPa, North Pole

Changes to diurnal variation (tides) in ionosphere during 2009 SSW

Gonchrenko et al., GRL, 2010
Recent investigations with high-top models

- **CMAM**
  - data assimilation: Polavarapu et al., 2005; Ren et al., JGR, 2011
  - dynamical control: McLandress et al., JAS, 2013
- **GAIA**
  - data assimilation: Jin et al., JGR, 2012
- **HAMMONIA**
  - nudging and error growth: Schmidt et al., in preparation
- **NAVGEM**
  - data assimilation: Hoppel et al., MWR, 2013
- **NOGAPS-ALPHA & WACCM-X**
  - data assimilation/nudging: Sassi et al., JGR, 2013
- **WACCM**
  - data assimilation: Pedatella et al., 2013; submitted
  - error growth: Liu et al., JGR, 2009
- **WAM**
  - data assimilation: Wang et al., JGR, 2011
Temperature from simulations of the 2009 SSW in several models with nudging or data assimilation

- GAIA – nudged, surface to 15 hPa
- HAMMONIA – nudged 850-1 hPa
- WAM – assimilates meteorological data
- WACCM-X – nudged, surface to 0.002 hPa using fields from NOGAPS

Pedatella et al., submitted to JGR

Temperature 70°-80°N:

- MIPAS T (Funke et al., GRL, 2010)
Wave 1 from simulations of the 2009 SSW in several models with nudging or data assimilation

Planetary wave 1 amplitude 60°N

GAIA – nudged, surface to 15 hPa
HAMMONIA – nudged 850-1 hPa
WAM – assimilates meteorological data
WACCM-X – nudged, surface to 0.002 hPa

Pedatella et al., submitted to JGR
T_{predicted} = T_{\text{n}} + T_{\text{advection}} + T_{\text{diabatic}} + T_{\text{adiabatic}} + T_{\text{diffusion}}

free running: \[ T = T_{predicted} \]

nudged: \[ T = (1 - a)T_{predicted} + aT_{\text{met}} \]

applied every timestep over certain vertical range

Linear interpolation in time is used to get \( T_{\text{met}} \) at every timestep

VARIATIONS IN NUDGING
- altitude range where nudging is applied
- frequency that \( T_{\text{met}} \) is available
- strength of \( \alpha \)
- fields that are nudged
WACCM runs

- **free-running (FR)**
  - 45-day base run, beginning January 1
  - two additional realizations with slight differences in initial
tropospheric zonal wind

- **nudged (SD=specified dynamics)**
  - nudge with meteorological fields from base run
    - temperature, horizontal winds, several surface variables
  - use initial conditions that are slightly different from “base”
  - several runs to test aspects of nudging
    - altitude range of meteorological data
    - frequency of meteorological data
    - relaxation timescale of nudging

NOTE: All SD runs here use output from another WACCM run; not actual reanalysis data.
Advantages of this setup

• “true” atmosphere is known (=BASE case)
• model physics agrees perfectly with meteorological data
• external forcing (due to e.g. solar or composition changes) is identical in all cases
• meteorology fields for nudging are perfect; no interpolation onto a different horizontal grid is needed
• allows control over data frequency and vertical range for nudging
<table>
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<th>name</th>
<th>type</th>
<th>nudge region*</th>
<th>frequency of met data</th>
<th>relaxation time</th>
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<tr>
<td>50km 6 hr</td>
<td>SD</td>
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<td>standard for SD-WACCM</td>
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<td>nudge &lt;125 km</td>
<td>1 hr</td>
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</table>

* nudging tapers off over 10 km region above this level
RMS error growth in the MLT

Initial error growth is faster for nudged runs.

RMS error plateaus after 10-25 days.

~90 km

RMS using data at every longitude & hour.

Solid: met data updated every hour.
Dashed: met data updated every 6 hours.

Initial error growth is faster for nudged runs.

RMS error plateaus after 10-25 days.
RMS error growth versus pressure

- solid: met data available every hour
- dashed: met data available every 6 hours
- error from last 10 days of each run

For RMS error, improvement of standard WACCM (green dashed line; nudged to 50 km with 6 hr met data) over free-running is less than a factor of 2

Error grows above ~1hPa even when the temperature and horizontal winds are nudged there.
RMS error growth for different $\tau$

$\tau$ is the relaxation time (inverse of strength of nudging; proportional to $1/\alpha$)

all cases shown have met data available every hour

all cases nudged to 125 km
Why does RMS error persist for tight constraint to “perfect” data?

free running:  \[ T = T_{predicted} \]

nudged:  \[ T = (1 - a)T_{predicted} + aT_{met} \]

• inherent lag in nudging process
• formulation of dynamical equations is different
Nudging is somewhat successful in keeping mean state close to basic atmosphere during variable NH winter conditions.

Thin lines: RMS error at ~90 km, 70°-90°N
Thick lines: RMS error for daily zonal averages
(all cases use 1-hr met data)
Pressure variation of daily mean error - NH winter

RMS error for daily zonal averages

All cases use 6-hr met data (green lines have the standard settings for WACCM)

Nudging the troposphere only has similar mean errors to the free-running (no nudging) simulations.
Zonal daily mean wind for a typical individual day

Free-running simulations diverge from BASE

Nudging at least to the stratopause gives reasonable agreement.

Nudging of troposphere only is not as good.
Gravity wave drag generated by fronts (same day as shown in previous slide)

WACCM has parameterized GW from:
- fronts
- convection
- orography

apparent differences from BASE in both hemispheres
Differences in gravity wave drag (all sources)

Errors in GWD consistent with errors in T and u above the stratopause.
Q2D wave in simulation nudged to 15km

Perturbation meridional wind (zonal mean removed) at 46°S, 0.18 hPa (~75 km)

BASE

Nudged up to 15 km

Details similar in early days

Details and phase different in later days
Q2D wave comparisons

Wavelet analysis of wavenumber 4

T amplitude in NAVGEM model with or without assimilated mesospheric data

Hoppel et al., MWR, 2013
migrating diurnal (24 hr) tide

TIDE IN MERIDIONAL WIND
Tide structure is similar in all cases (FR as well as nudged).

- amplitudes ~similar to base with 1 hr met data
- lower amplitude with 6 hr met data
migrating semidiurnal (12 hr) tide

Tide in meridional wind:

- amplitude ~ similar to base with 1 hr met data
- higher amplitude with 6 hr met data
Observations of various waves and tides in the thermosphere or ionosphere can be traced to the troposphere or stratosphere.

Models constrained to meteorological analyses can simulate observations better than unconstrained models.

Tests with nudged WACCM indicate that the system is not completely deterministic.

Potential sources of error (even if lower atmosphere is perfectly known):
- waves generated by instability (quasi-2 day wave; 5 day wave, etc)
- gravity waves, including parameterized
- stratosphere

RMS errors grow with height before or as soon as the constraint is removed. Expanding altitude range of constraint improves the prediction of MLT dynamics.

There is a modest reduction of error for more frequent meteorological data.

Continued MLT observations are needed.