

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_2O , CH_4)
 - dynamical variability
 - migrating and nonmigrating tides
 - SSW
 - momentum forcing and eddy diffusion due to gravity waves

coupling questions

Q: Does externally forced variability of the thermosphere affect the middle and lower atmosphere?

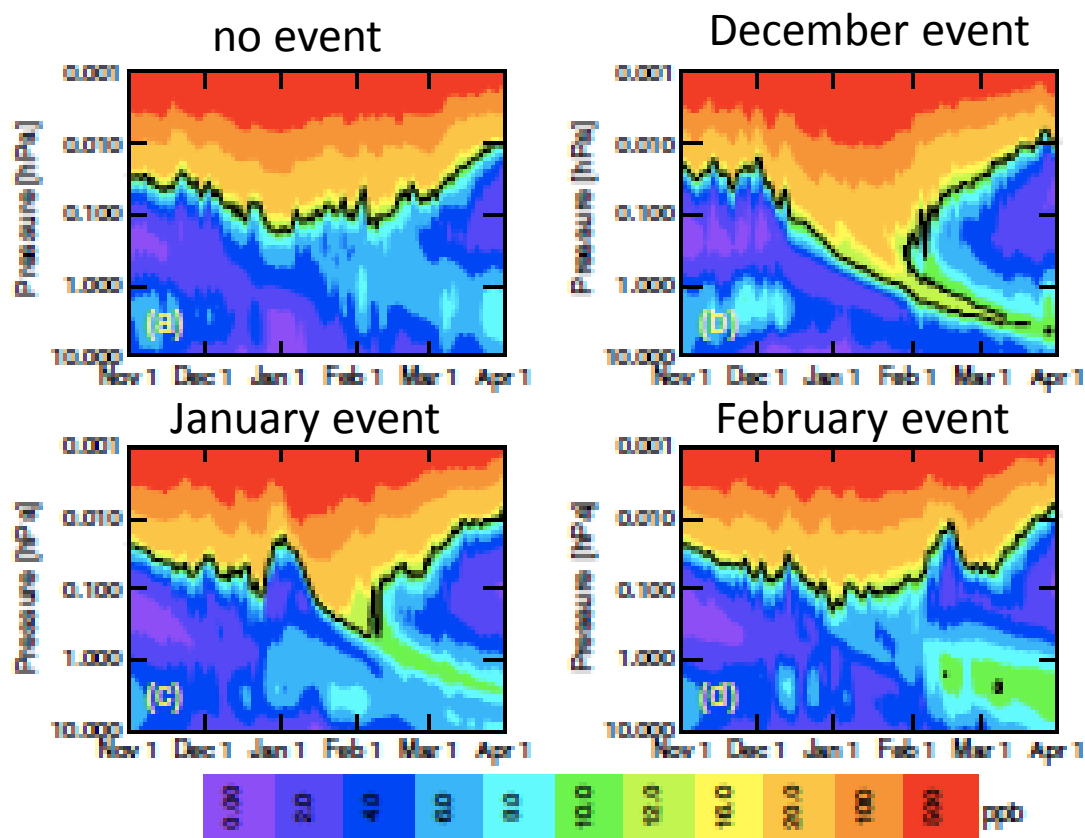
Q: Excluding external forcing, are the upper mesosphere and lower thermosphere “slave” to the lower atmosphere?

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

NO_x transport in WACCM – highest when SSW and/or elevated stratopause occur in December



event = SSW and/or elevated stratopause

Downward penetration of NO_x highest when event occurs during December.

WACCM underestimates NO_x 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.

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?

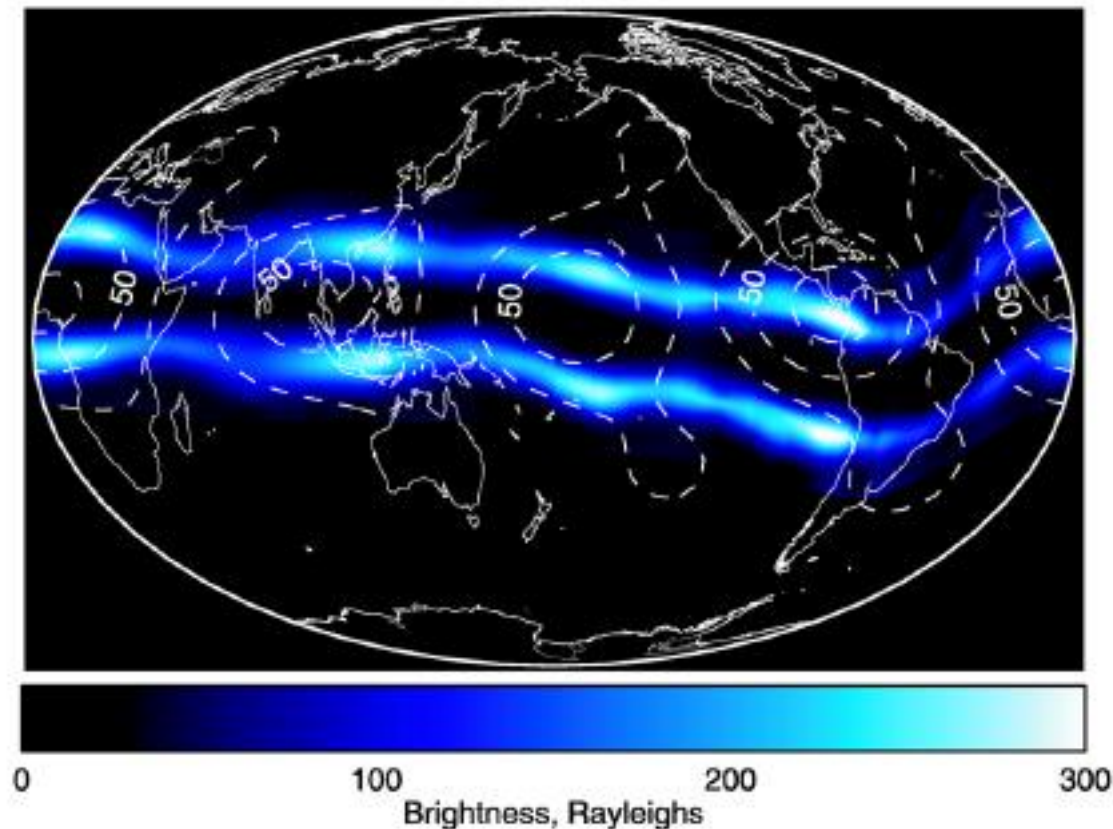
These topics will not be addressed:

- 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

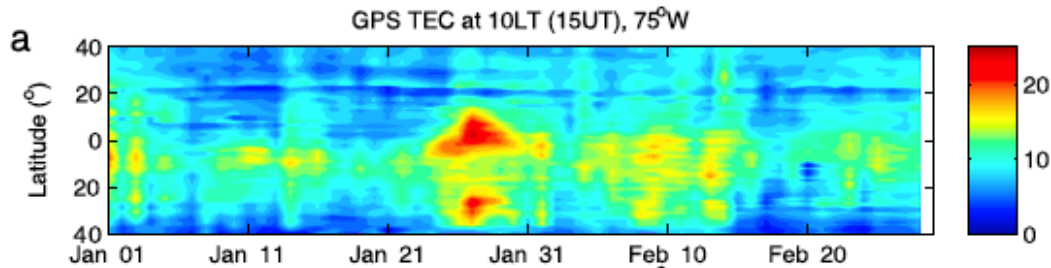
Ionospheric emission from IMAGE satellite



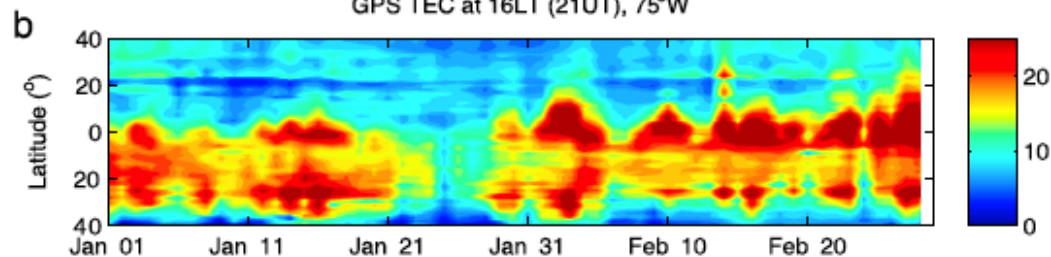
DE3 tide (a tide with 24-hour period, zonal wavenumber 3, propagating eastward) is excited by latent heat release in the tropical troposphere

Observational investigations of impact of lower-middle atmosphere on thermosphere/ionosphere

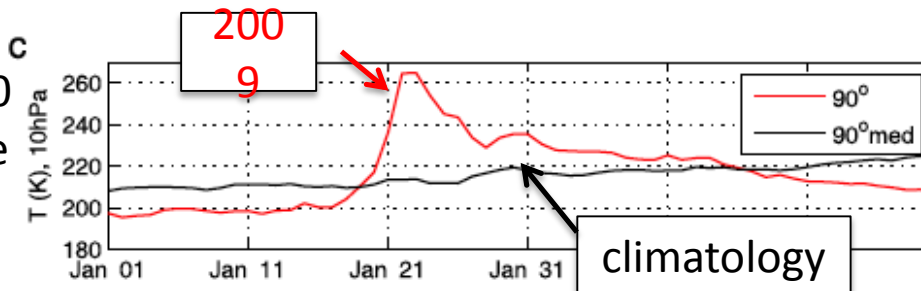
total electron
content 10 LT



total electron
content 21 LT



temperature 10
hPa, North Pole



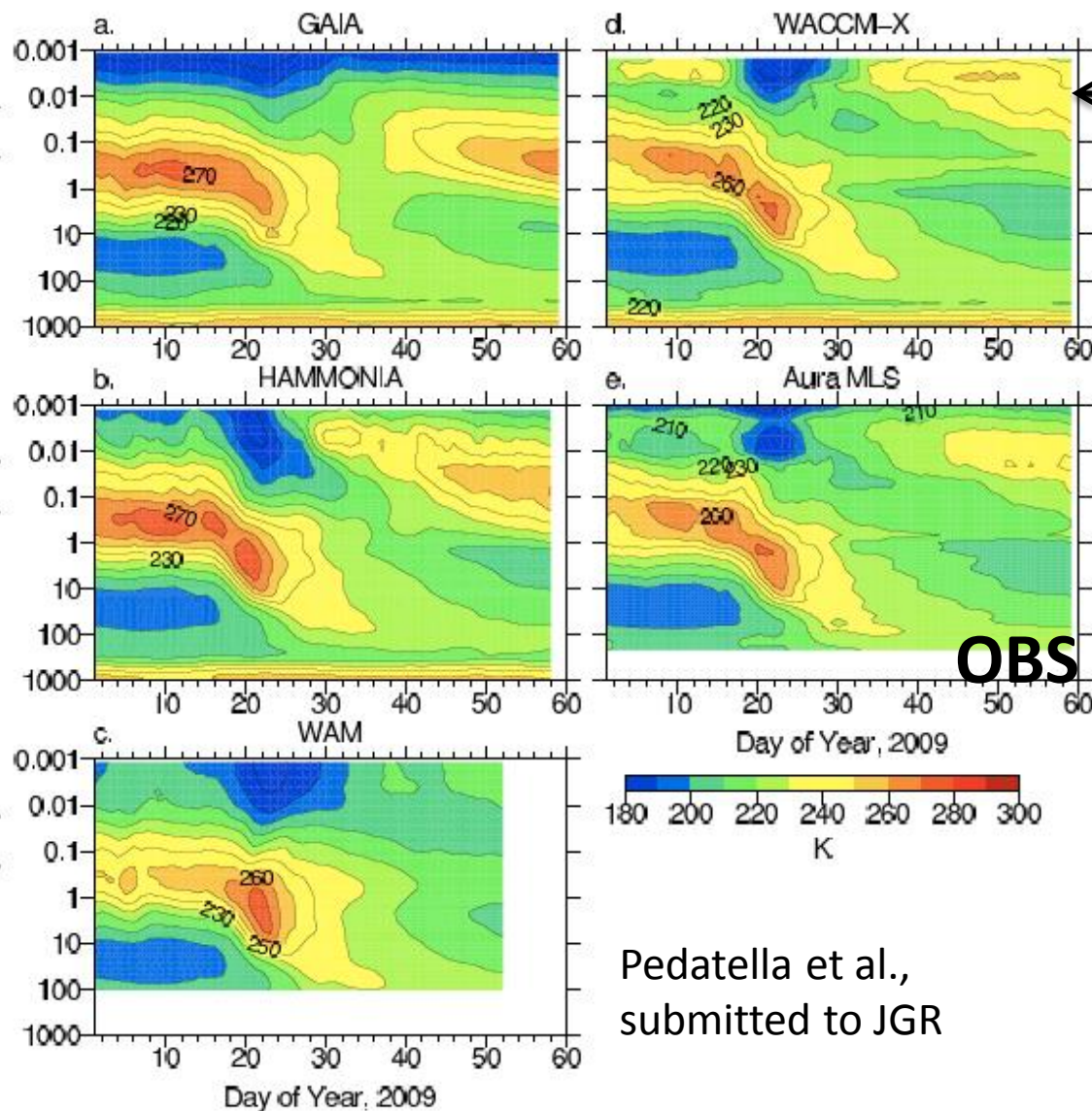
Changes to diurnal
variation (tides) in
ionosphere during
2009 SSW

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



Temperature 70°-80°N

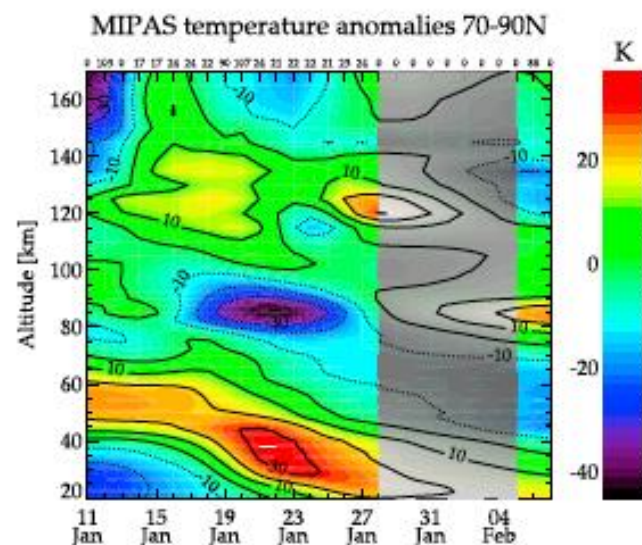
GAIA – nudged, surface to 15 hPa

HAMMONIA – nudged 850-1 hPa

WAM – assimilates meteorological data

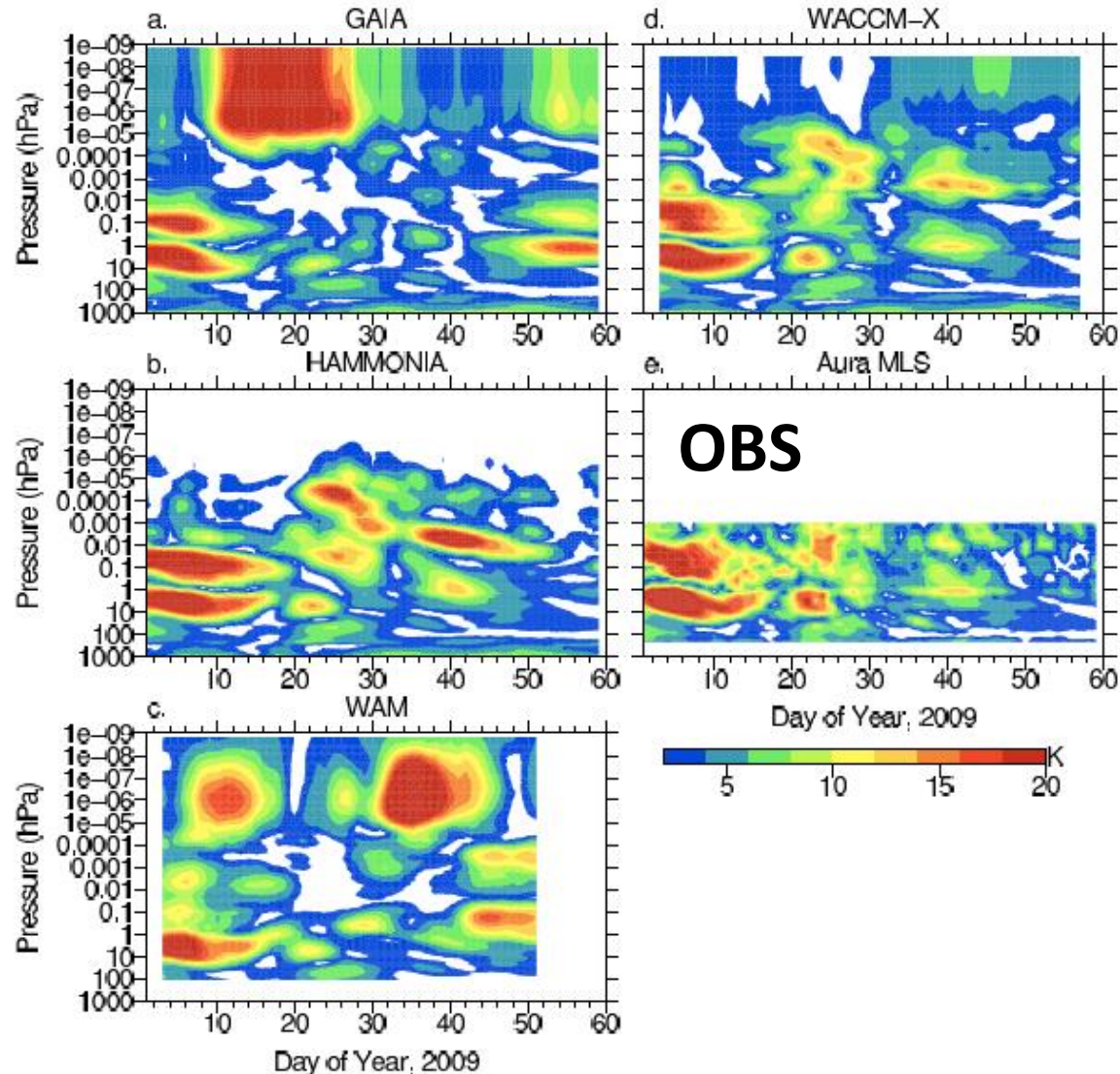
WACCM-X – nudged, surface to 0.002 hPa using fields from NOGAPS

MIPAS T (Funke et al., GRL, 2010)



Pedatella et al.,
submitted to JGR

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

nudging process

$$T_{predicted} = T_{n-1} + DT_{advection} + DT_{diabatic} + DT_{adiabatic} + DT_{diffusion}$$

free running: $T = T_{predicted}$

nudged: $T = (1 - a)T_{predicted} + aT_{met}$ applied every timestep over certain vertical range

Linear interpolation in time is used to get T_{met} at every timestep

VARIATIONS IN NUDGING

- altitude range where nudging is applied
- frequency that T_{met} is available
- strength of α
- 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.

WACCM runs

Advantages of this setup

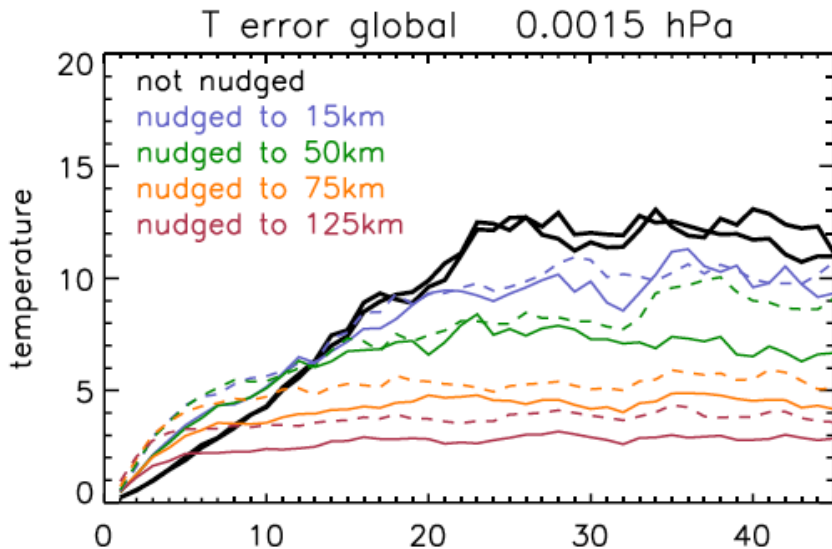
- “true” atmosphere is known (=BASE case)
- model physics agrees perfectly with meteorological data
- external forcing (due to e.g. solar or composition changes) is identical in all cases
- meteorology fields for nudging are perfect; no interpolation onto a different horizontal grid is needed
- allows control over data frequency and vertical range for nudging

free running (FR) and nudging (SD) runs

name	type	nudge region*	frequency of met data	relaxation time	comments
BASE	FR				used for all “met” fields
DIFF1	FR				perturbed initial u
DIFF2	FR				perturbed initial u
15km 1 hr	SD	nudge <15 km	1 hr	50 hrs	
15km 6 hr	SD	nudge <15 km	6 hr	50 hrs	
50km 1 hr	SD	nudge <50 km	1 hr	50 hrs	
50km 6 hr	SD	nudge <50 km	6 hr	50 hrs	standard for SD-WACCM
75km 1 hr	SD	nudge <75 km	1 hr	50 hrs	
75km 6 hr	SD	nudge <75 km	6 hr	50 hrs	
125km 1 hr	SD	nudge <125 km	1 hr	50 hrs	
125km 6 hr	SD	nudge <125 km	6 hr	50 hrs	
25 hr relax	SD	nudge <125 km	1 hr	25 hrs	
6 hr relax	SD	nudge <125 km	1 hr	6 hrs	
1 hr relax	SD	nudge <125 km	1 hr	1 hrs	

* nudging tapers off over 10 km region above this level

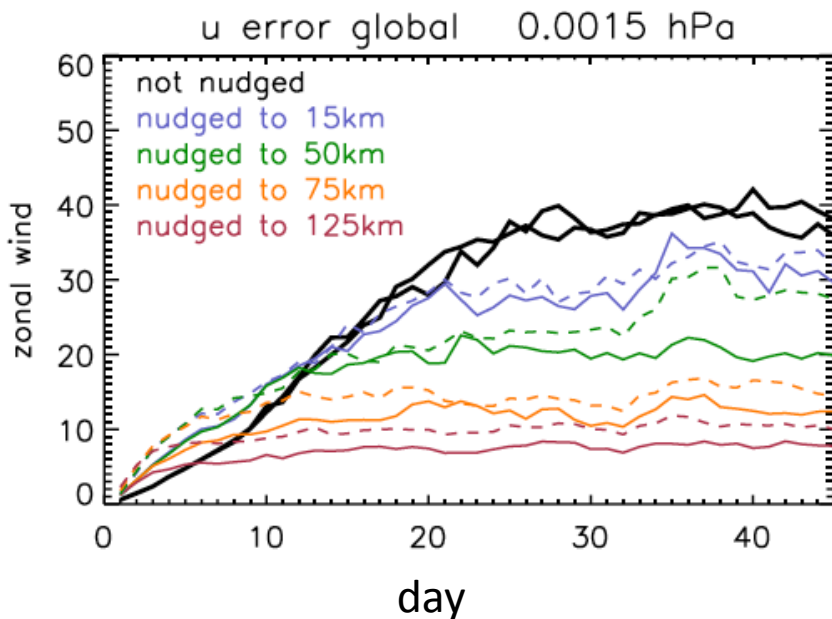
RMS error growth in the MLT



~90 km

RMS using data at every
longitude & hour

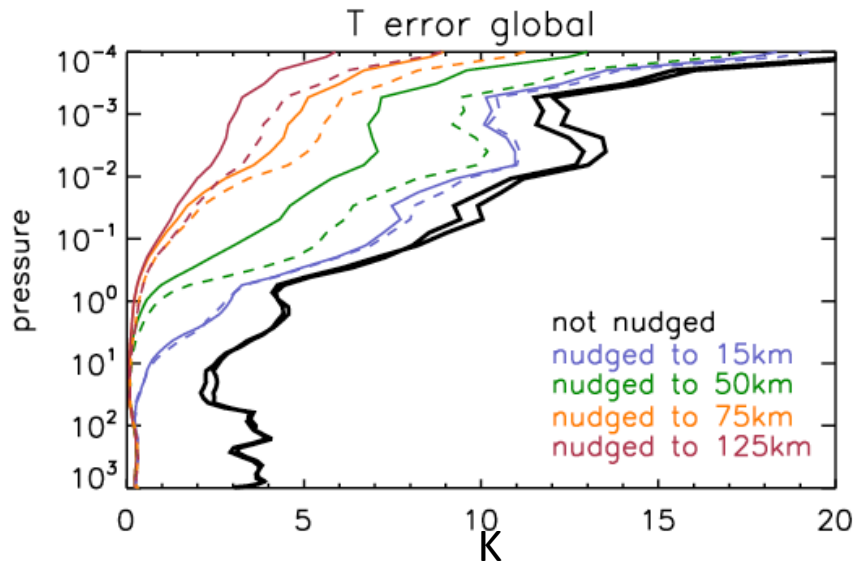
solid: met data updated every hour
dashed: met data updated every 6 hours



initial error growth is
faster for nudged runs

RMS error plateaus after
10-25 days

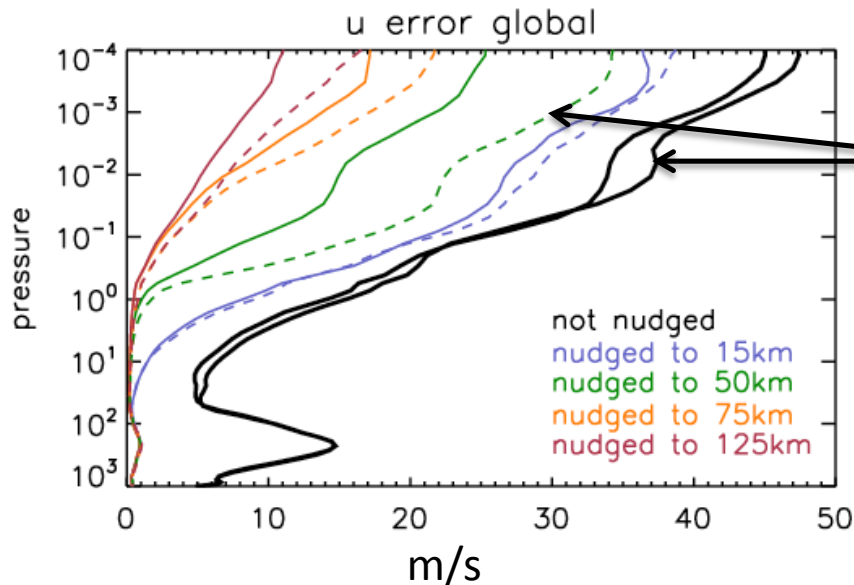
RMS error growth versus pressure



solid: met data available every hour
dashed: met data available every 6 hours

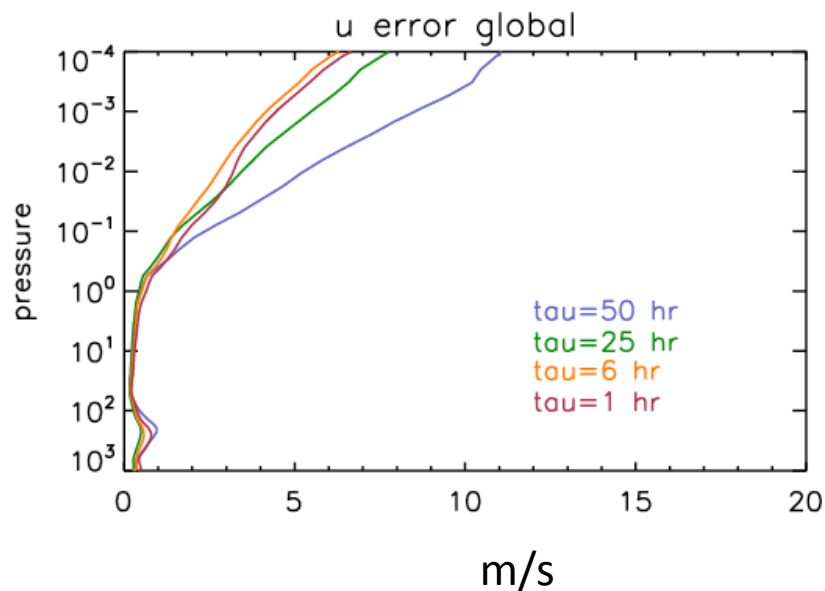
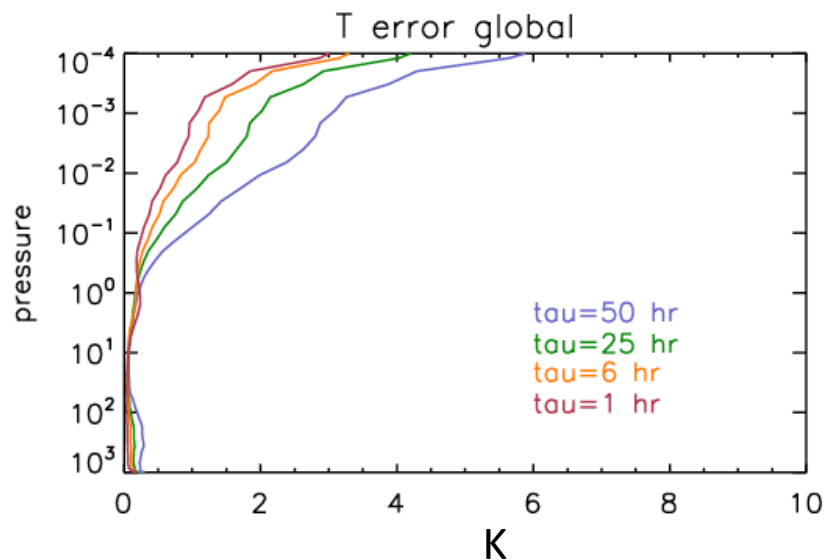
error from last 10 days of each run

error grows above ~1hPa even when the temperature and horizontal winds are nudged there



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

RMS error growth for different τ



τ 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

RMS error declines slowly as nudging becomes tighter

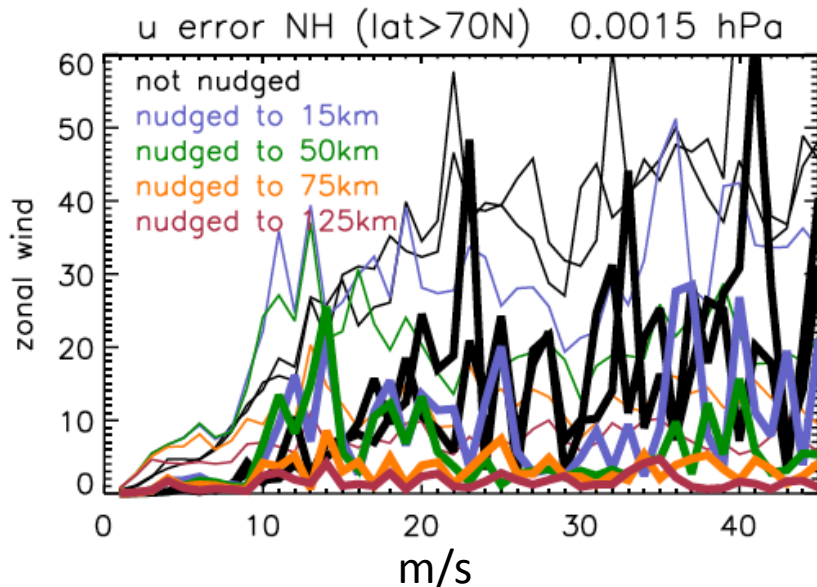
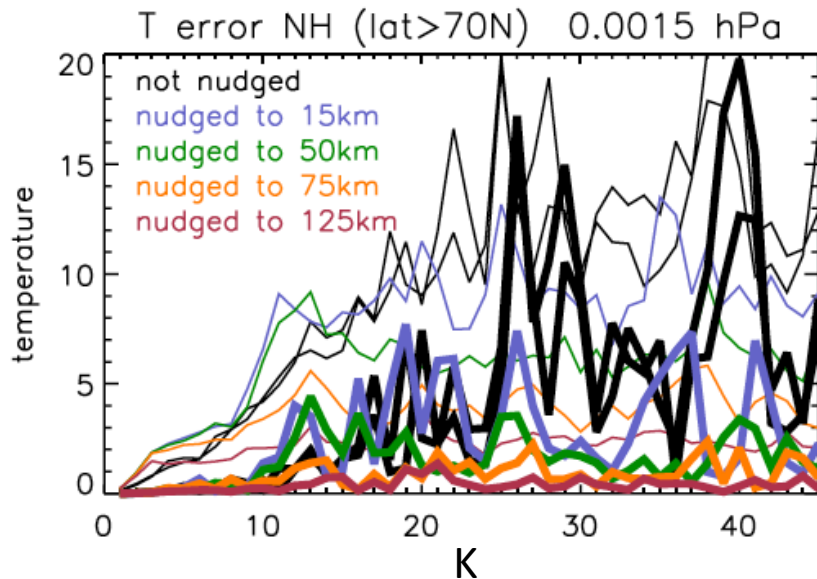
Why does RMS error persist for tight constraint to “perfect” data?

free running: $T = T_{predicted}$

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

- inherent lag in nudging process
- formulation of dynamical equations is different

Error for zonal daily mean - NH winter

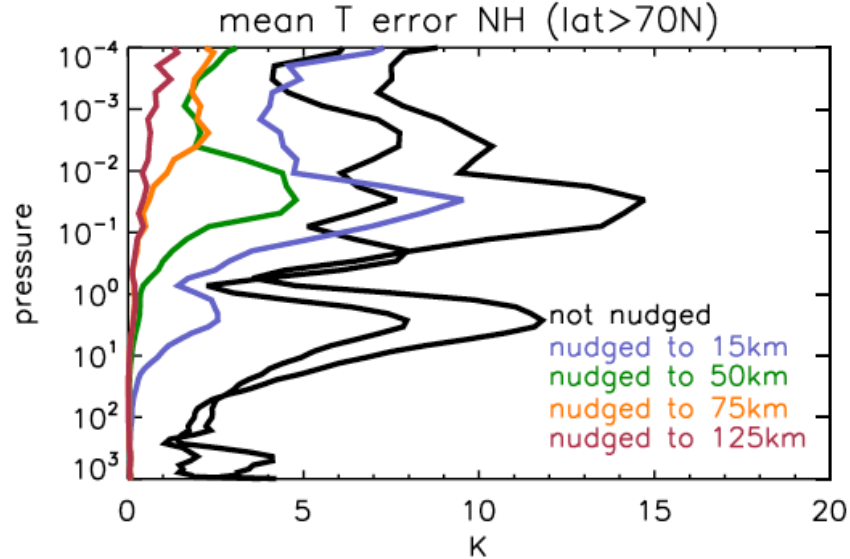


Thin lines: RMS error at ~90 km, 70°-90°N

Thick lines: RMS error for daily zonal averages
(all cases use 1-hr met data)

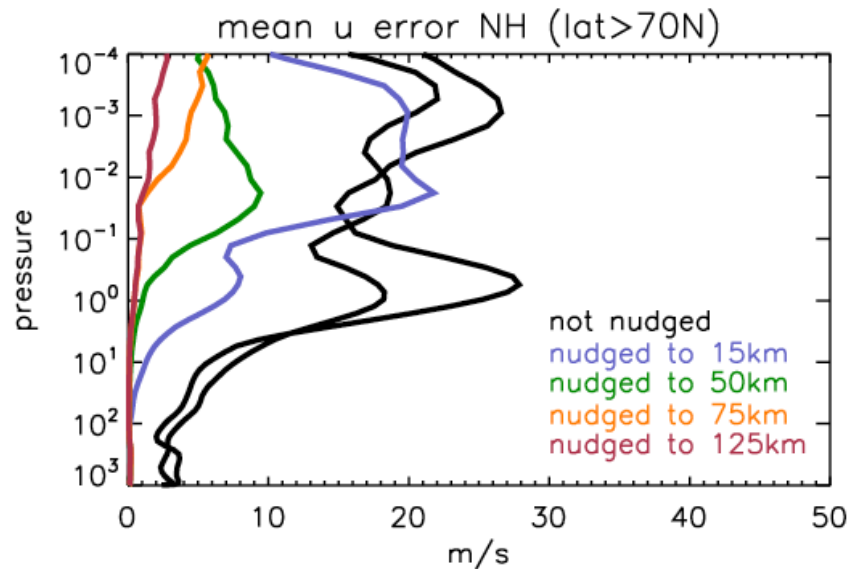
Nudging is somewhat successful in keeping mean state close to basic atmosphere during variable NH winter conditions.

Pressure variation of daily mean error - NH winter



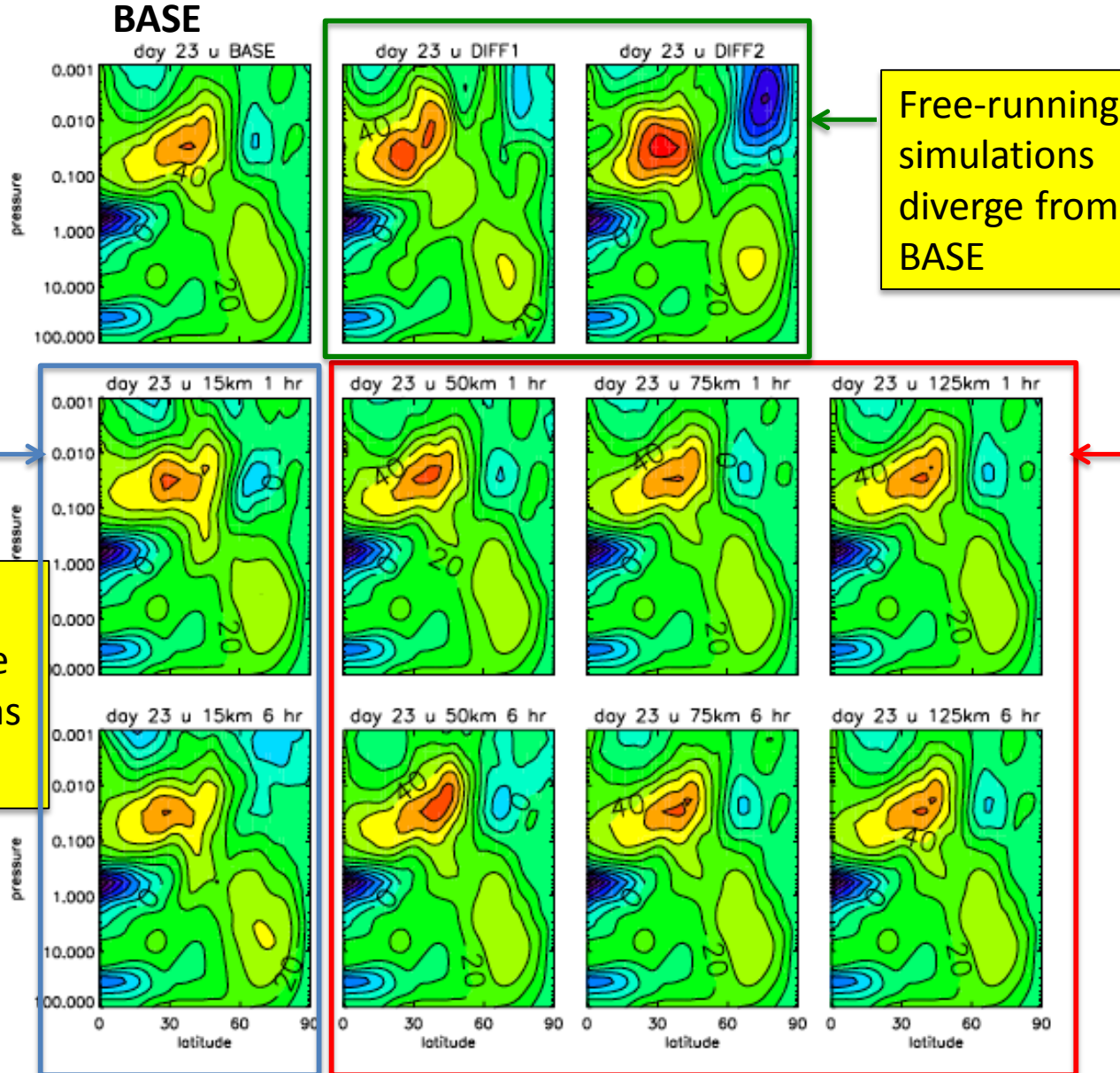
RMS error for daily zonal averages

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



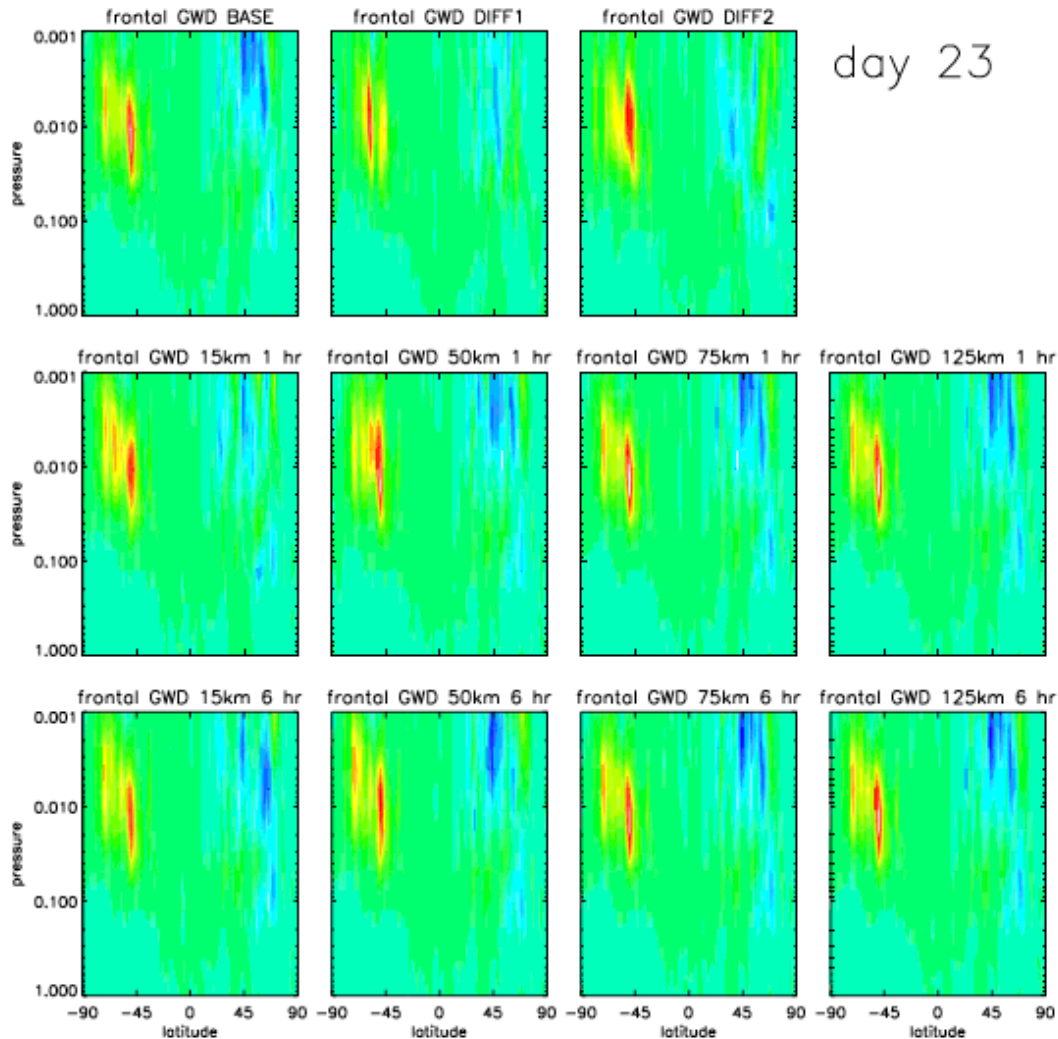
Nudging the troposphere only has similar mean errors to the free-running (no nudging) simulations.

Zonal daily mean wind for a typical individual day



Gravity wave drag generated by fronts (same day as shown in previous slide)

BASE

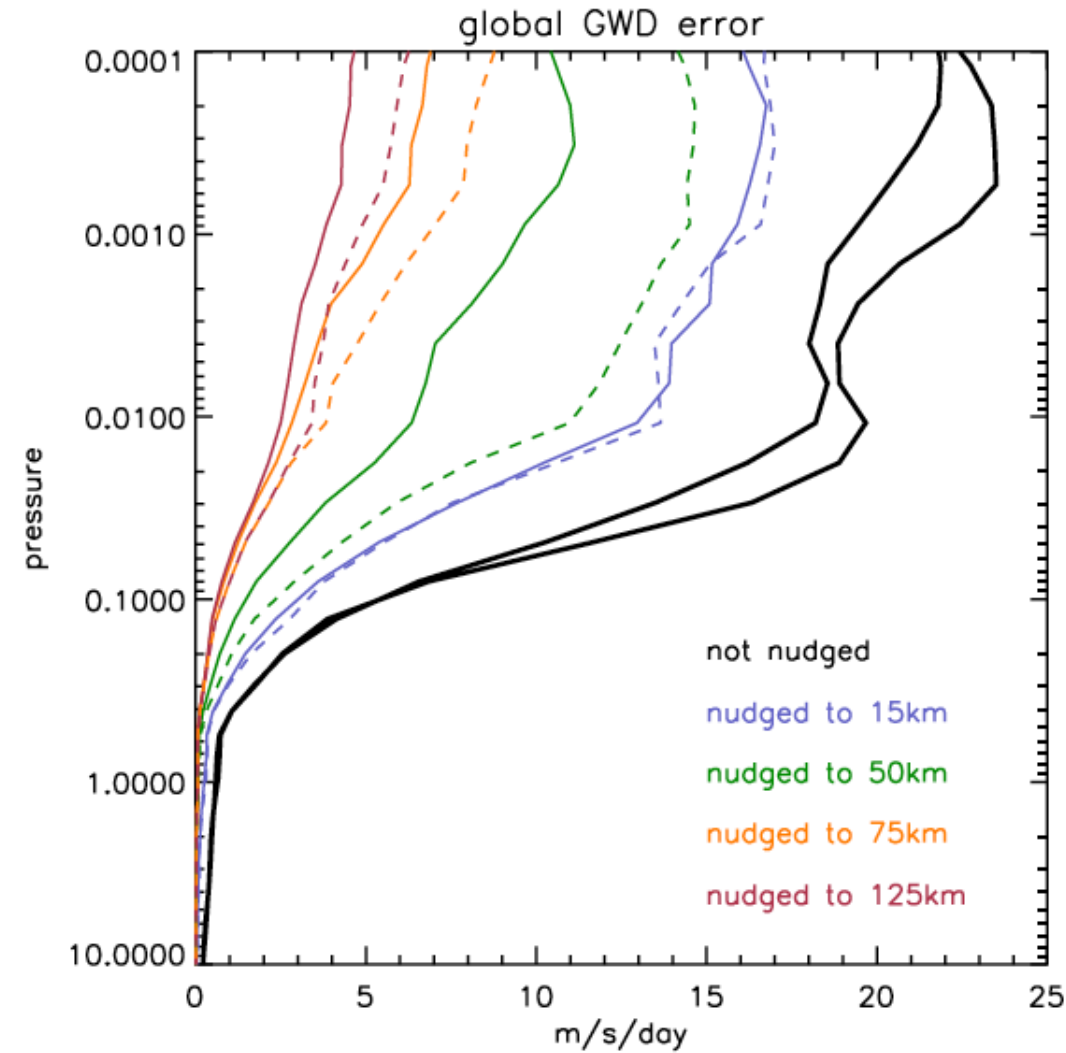


WACCM has parameterized GW from

- fronts
- convection
- orography

apparent differences from BASE
in both hemispheres

Differences in gravity wave drag (all sources)

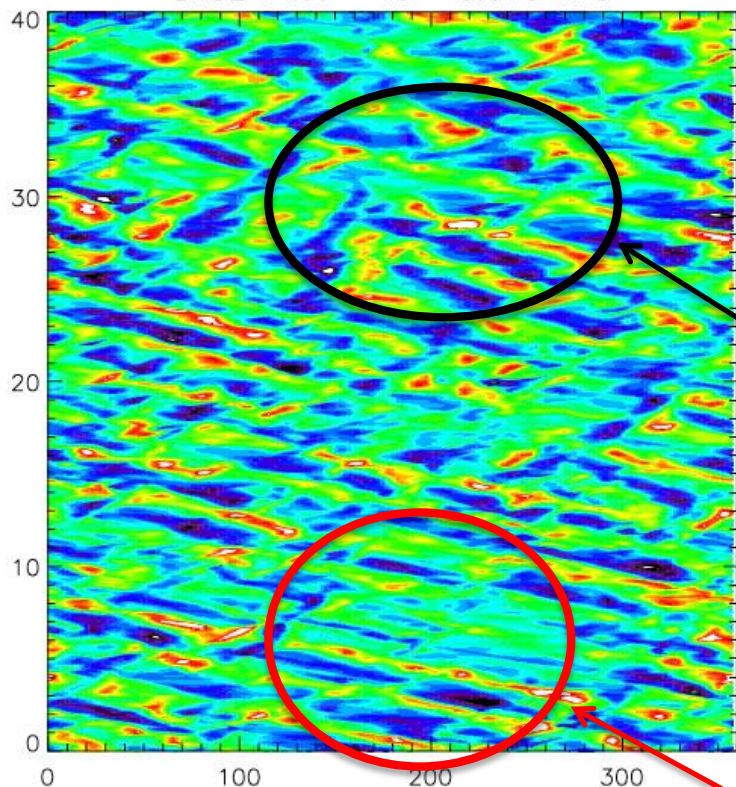


Errors in GWD
consistent with errors
in T and u above the
stratopause.

Q2D wave in simulation nudged to 15km

BASE

BASE v lat=-46 0.018 hPa

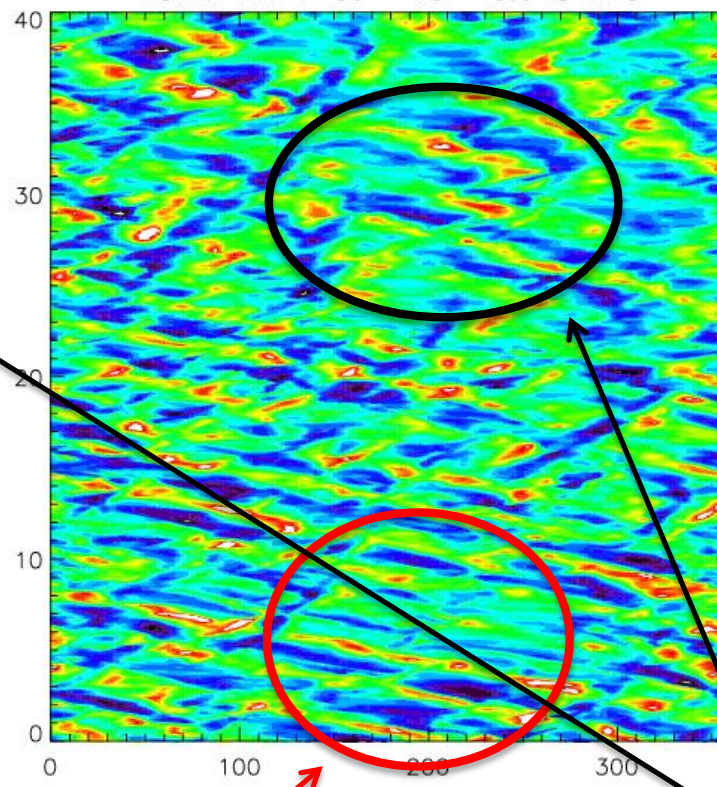


longitude

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

Nudged up to 15 km

15km 1hr v lat=-46 0.018 hPa

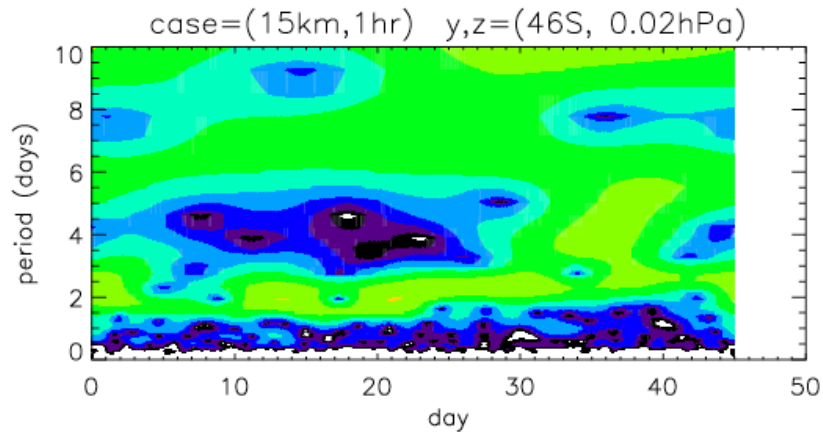
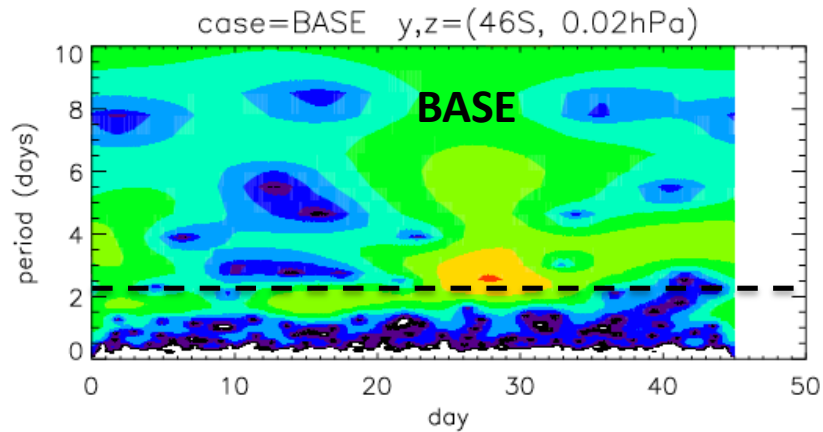


details similar
in early days

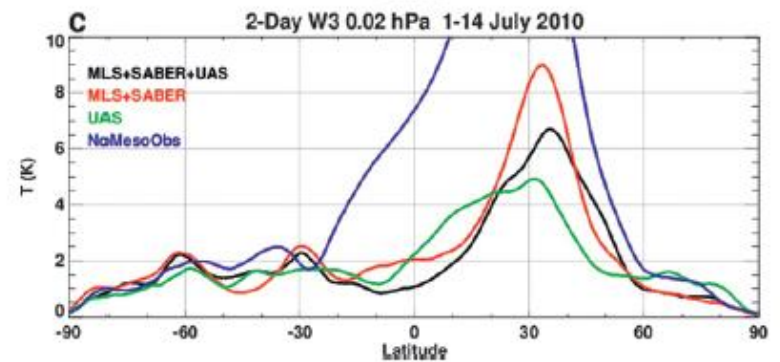
details and phase
different in later days

Q2D wave comparisons

Wavelet analysis of wavenumber 4



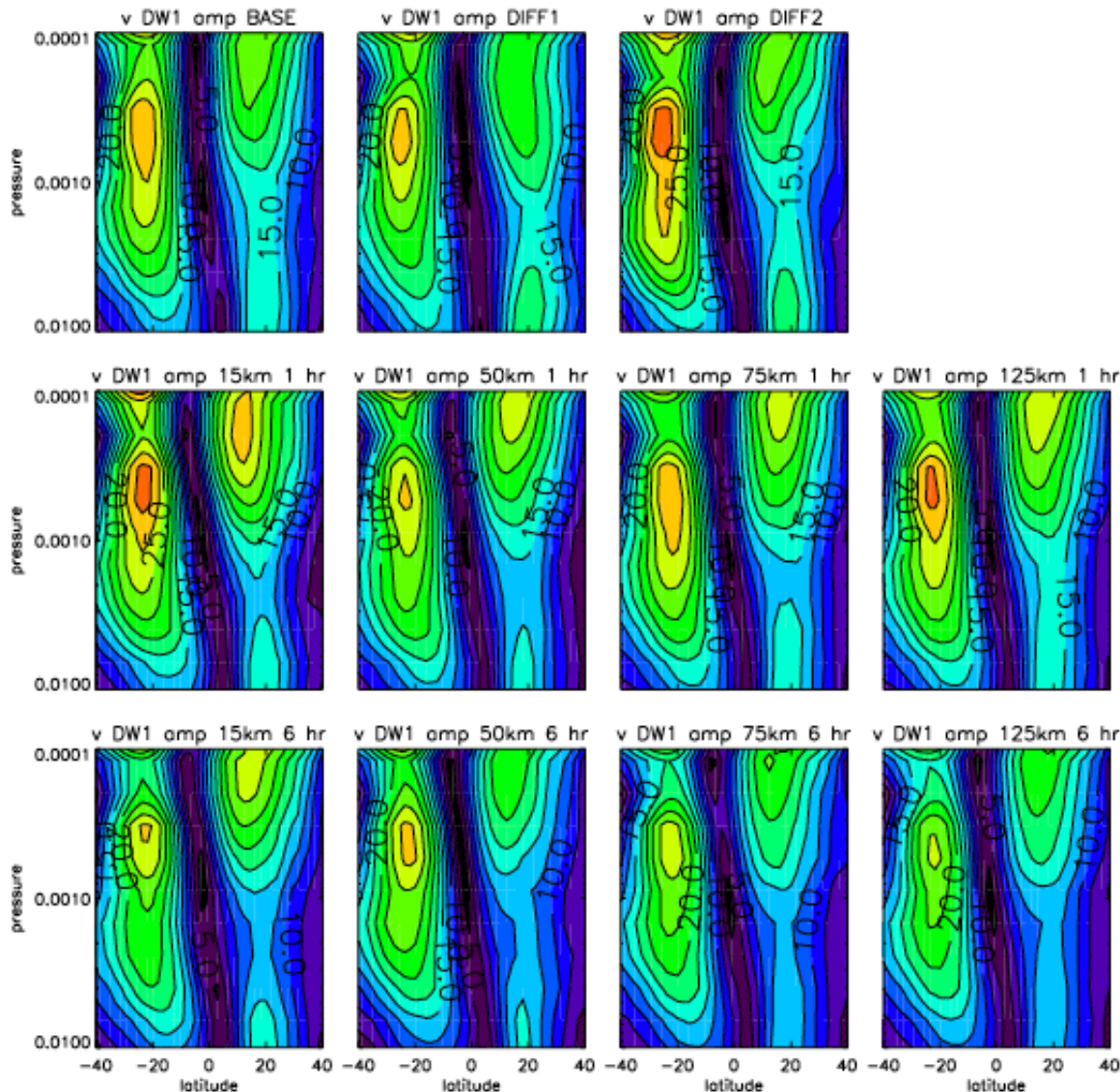
T amplitude in NAVGEM model with or without assimilated mesospheric data



Hoppel et al., MWR, 2013

migrating diurnal (24 hr) tide

BASE



TIDE IN MERIDIONAL WIND

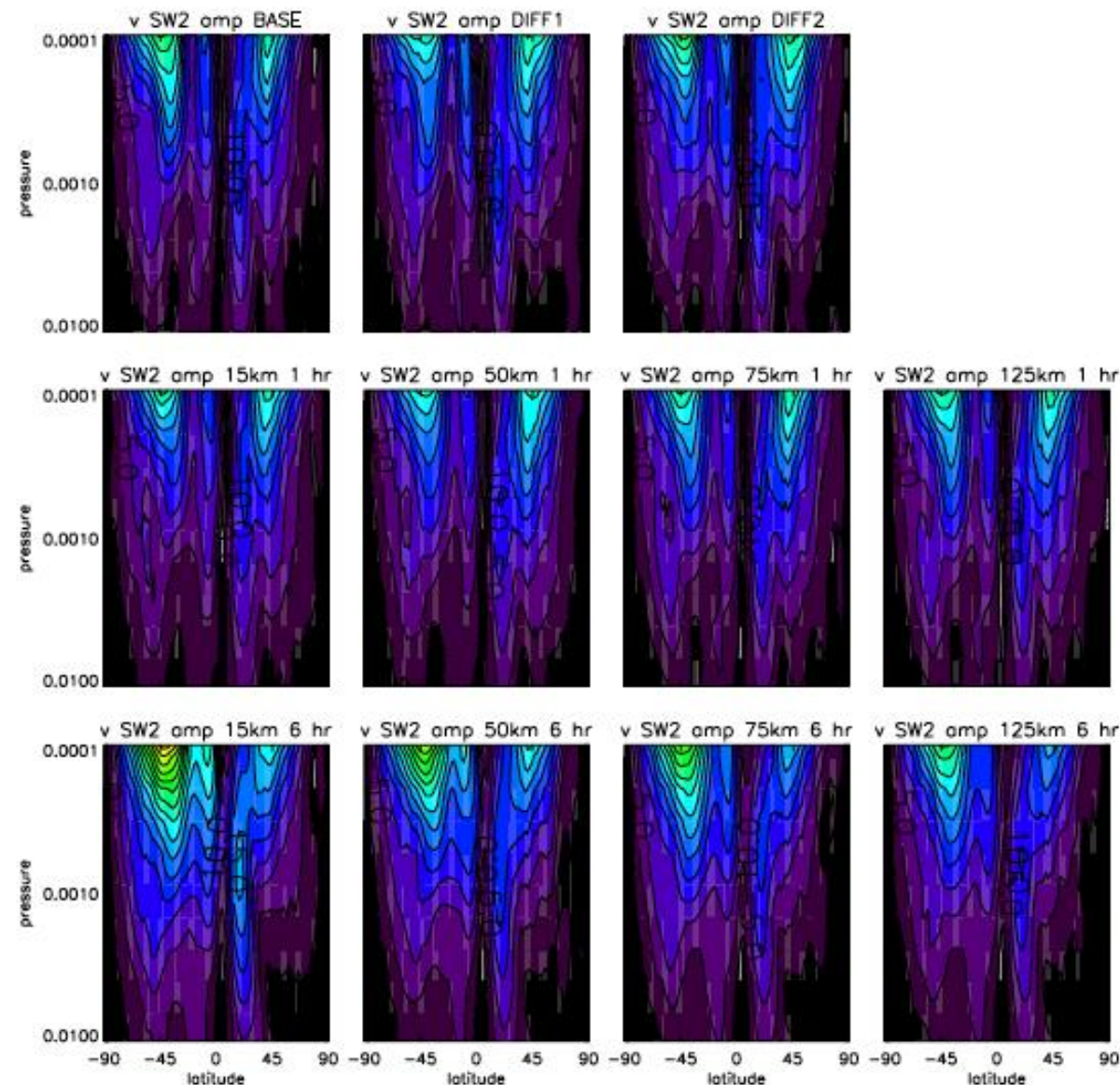
Tide structure is similar in all cases (FR as well as nudged).

← amplitudes ~similar to base
with 1 hr met data

← lower amplitude with
6 hr met data

migrating semidiurnal (12 hr) tide

BASE



Tide in meridional wind:

← amplitude ~ similar to base with 1 hr met data

← *higher* amplitude with 6 hr met data

Conclusions: lower or middle atmosphere control of the dynamical variability of the MLT

- 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.