Using gravity wave parameterizations to address WACCM discrepancies

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focus on the tropics & global mean

GW momentum forcing
- QBO
- SAO

GW heating and diffusion
- global mean mesopause temperature

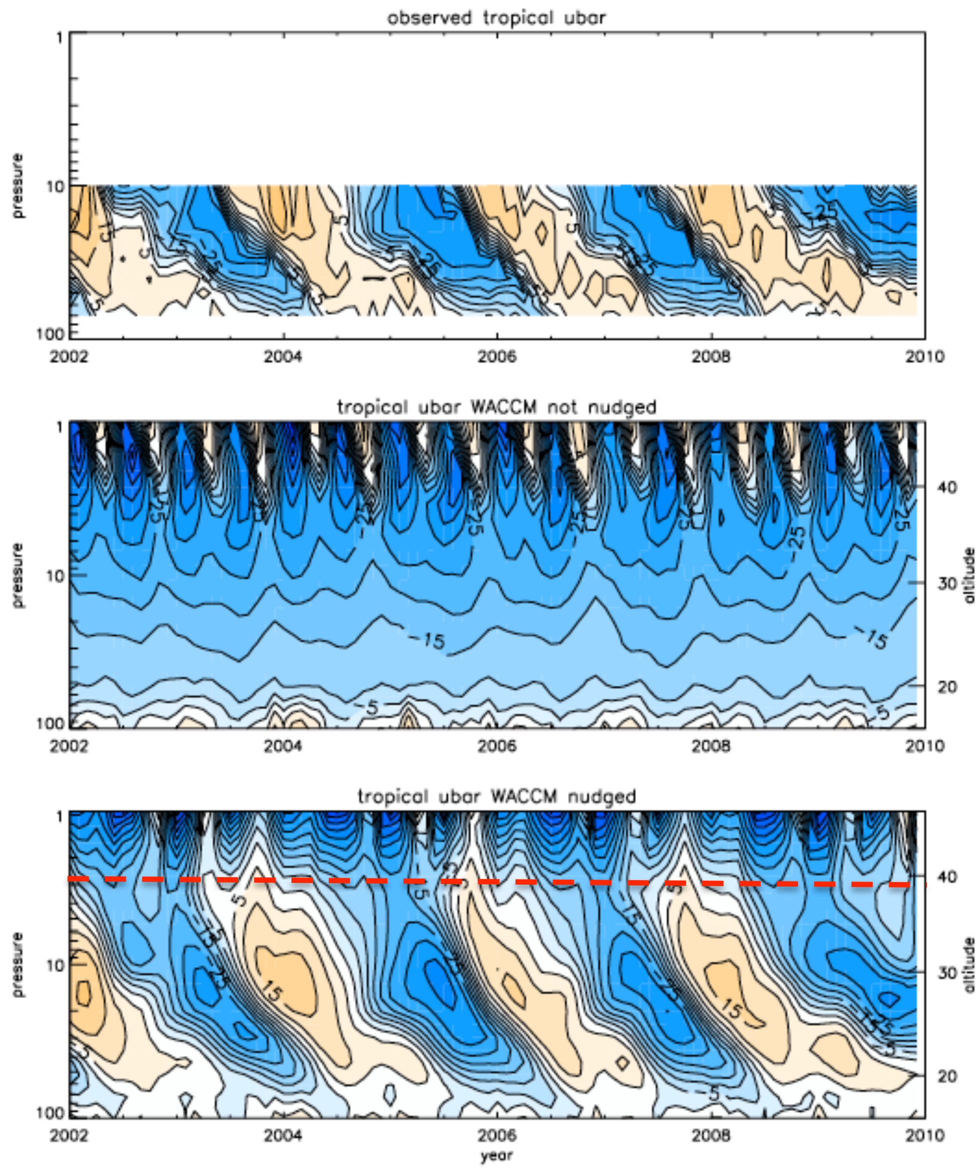
WACCM = Whole Atmosphere Community Climate Model
- Developed at NCAR
- Based on CESM/CAM
- Under continuous evaluation, with periodic new releases

WACCM4 (2x2 horizontal resolution)
WACCM5 (1x1 horizontal resolution; other changes)

QBO

QBO winds

- No QBO is generated in WACCM4 due to insufficient wave forcing and poor vertical resolution.
- A QBO is normally added by nudging to winds 90-0.3 hPa.
- The QBO nudging also affects the SAO near the stratopause.



observations from http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/

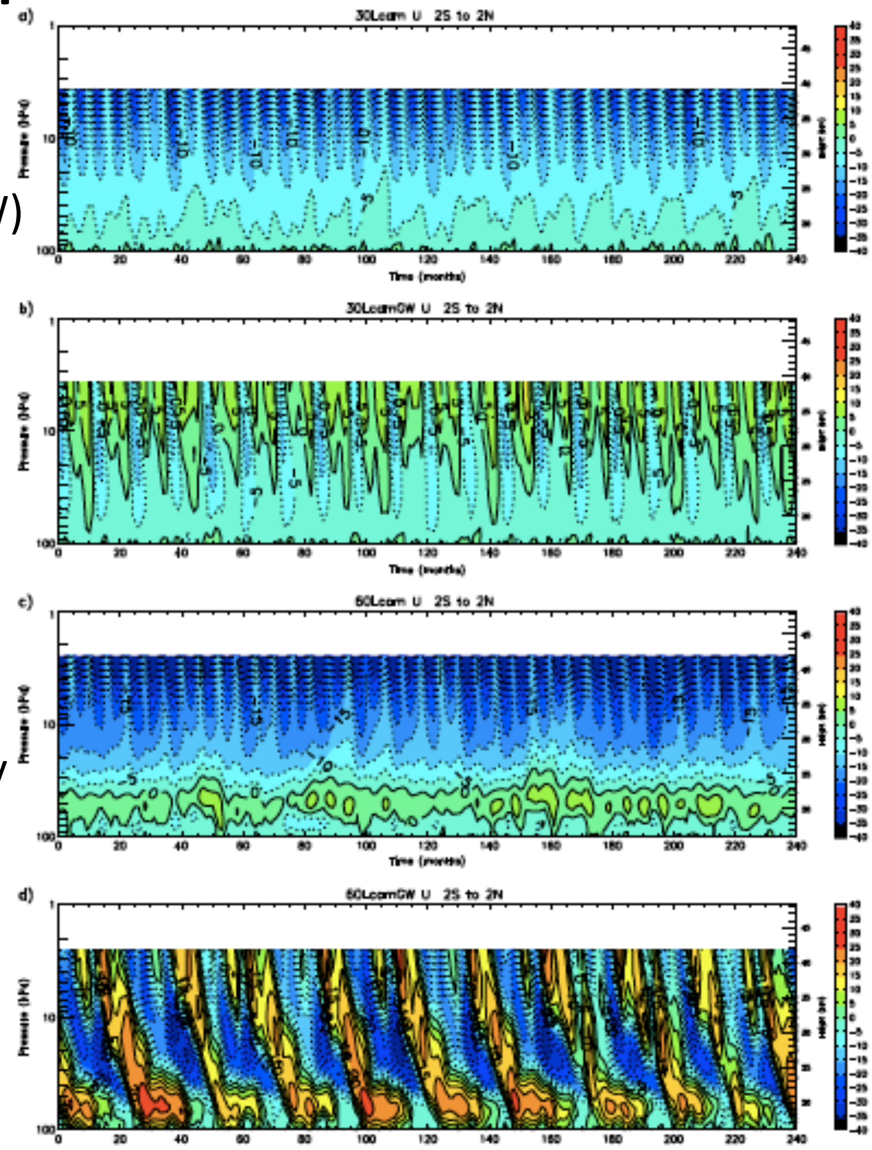
interactive QBO in CAM

low resolution
orographic GW only
(no non-orographic GW)

low resolution
GW changes *

high resolution
orographic GW only

high resolution
GW changes *



Richter et al, JGR, 2014

** GW changes*

- added non-orographic GW generated by convection and fronts
- increased "efficiency" of convectively generated GW

adapting interactive QBO to WACCM

GWs forced by orography and fronts are left as is (primarily affect middle and high latitudes)

GW forced by convection (Beres et al, JGR, 2005)

- GW source depend on
    - presence of convection
    - magnitude and depth of convective heating
    - background wind
- GW drag depends on
    - sources
    - interaction with background atmosphere
    - efficiency factor (less than 1)

Changes to WACCM GW

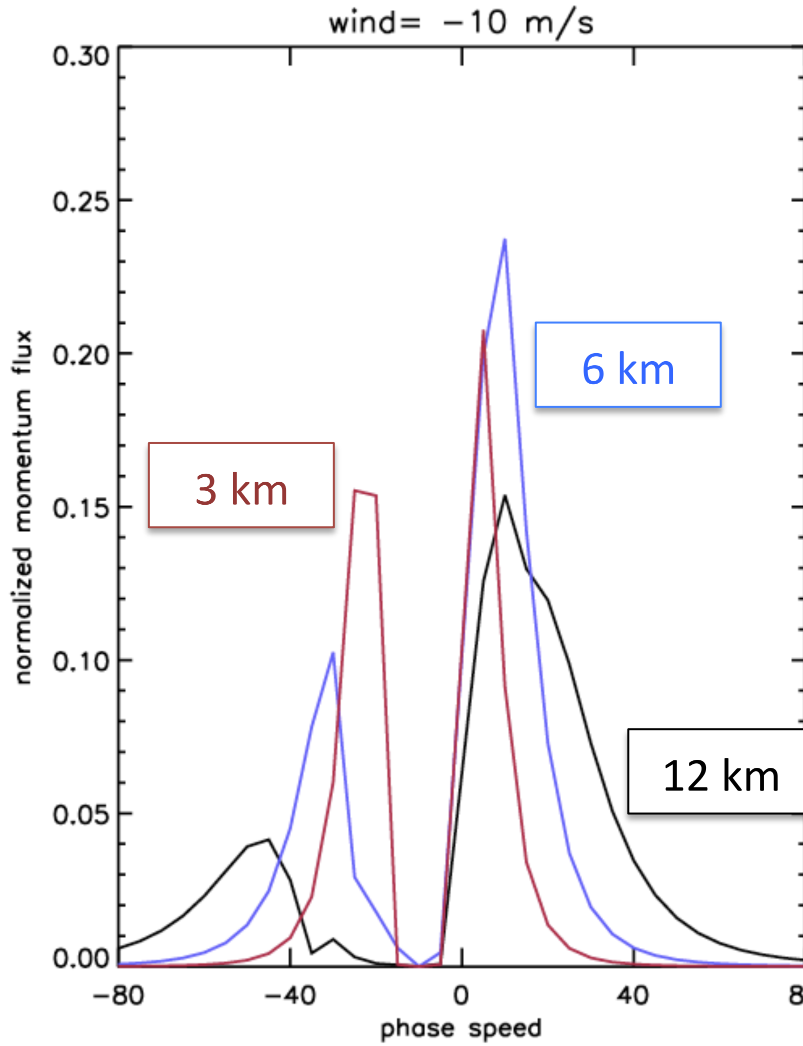
- increased "efficiency" of convectively generated GW (as in CAM)
- reduced the heating depth of convection (has impact of narrowing the phase speed spectrum of the waves generated)

dependence of GW spectrum on heating depth

Phase speed spectrum for each profile is computed from a look-up table with variables:

- background wind
- heating depth

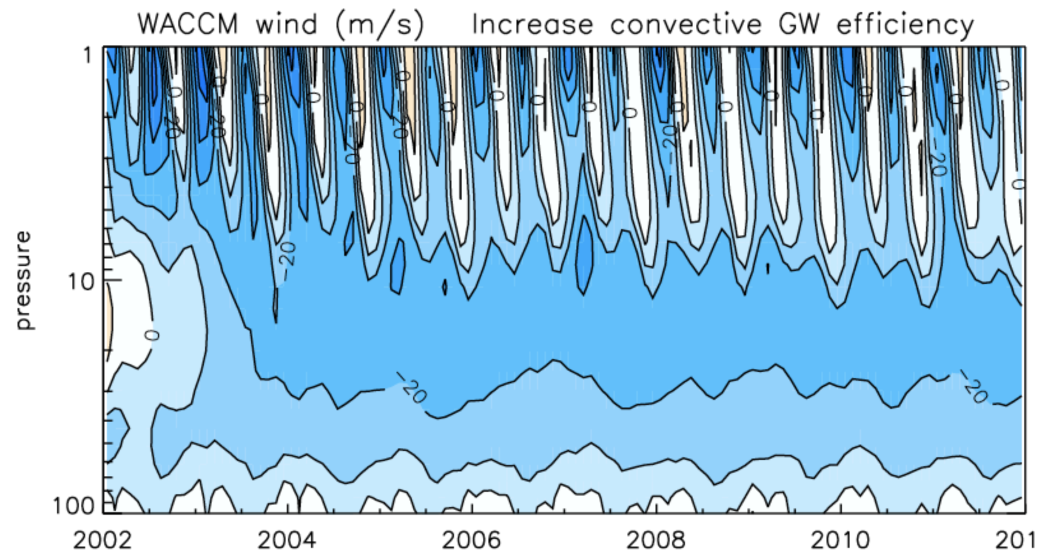
WACCM calculation probably overestimates heating depth and so its value is reduced in some simulations.



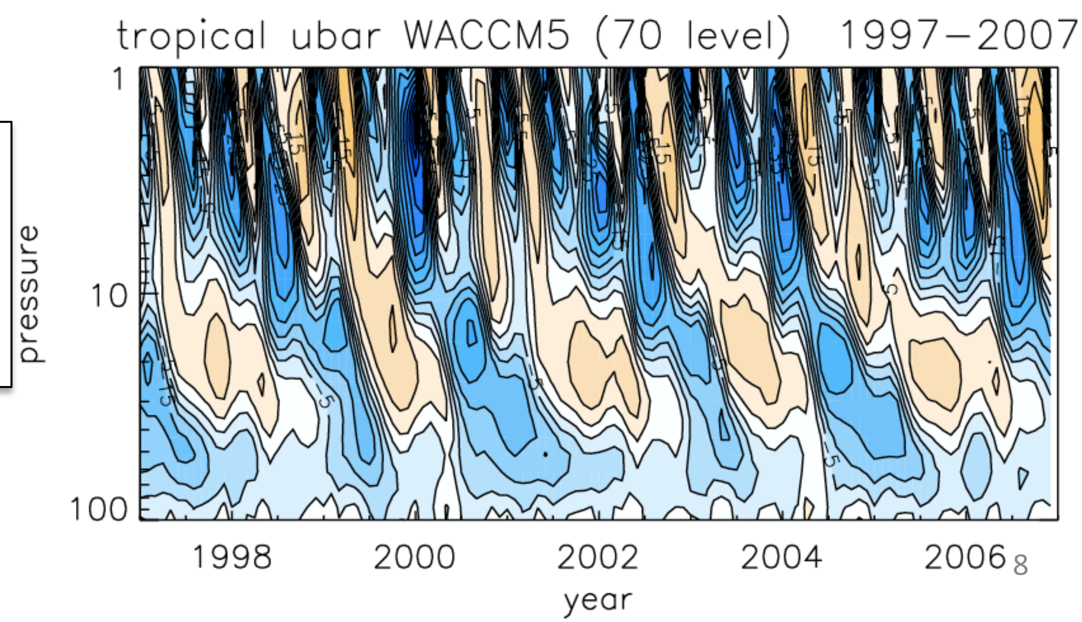
lookup table based on simulations by Beres et al., 2005

steps to simulating WACCM QBO

-> 2x2 horizontal resolution
-> low vertical resolution
-> decrease convective heating depth and increase efficiency



-> 1x1 horizontal resolution
-> low vertical resolution
-> decrease convective heating depth and increase efficiency



steps to simulating WACCM QBO

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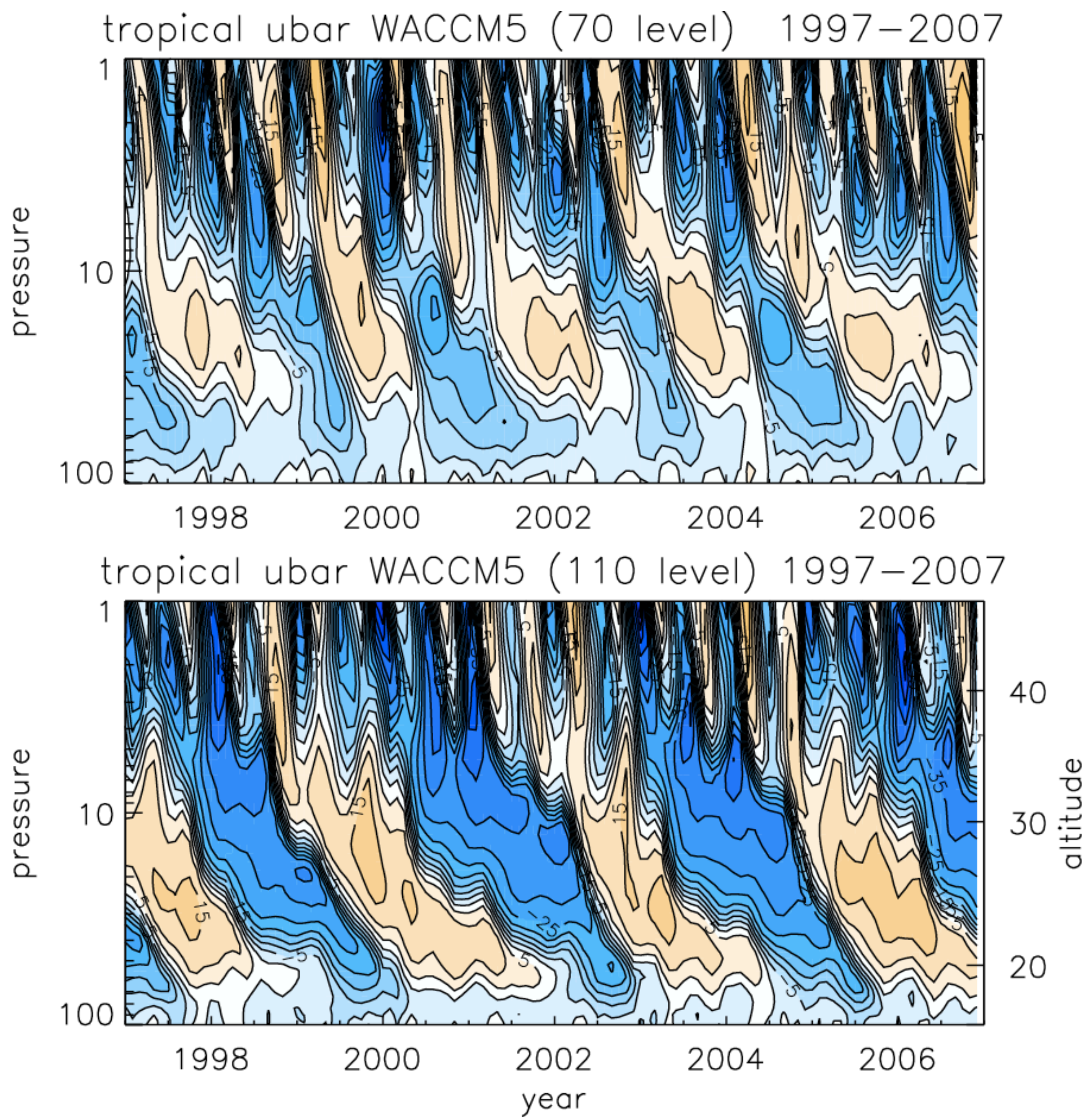
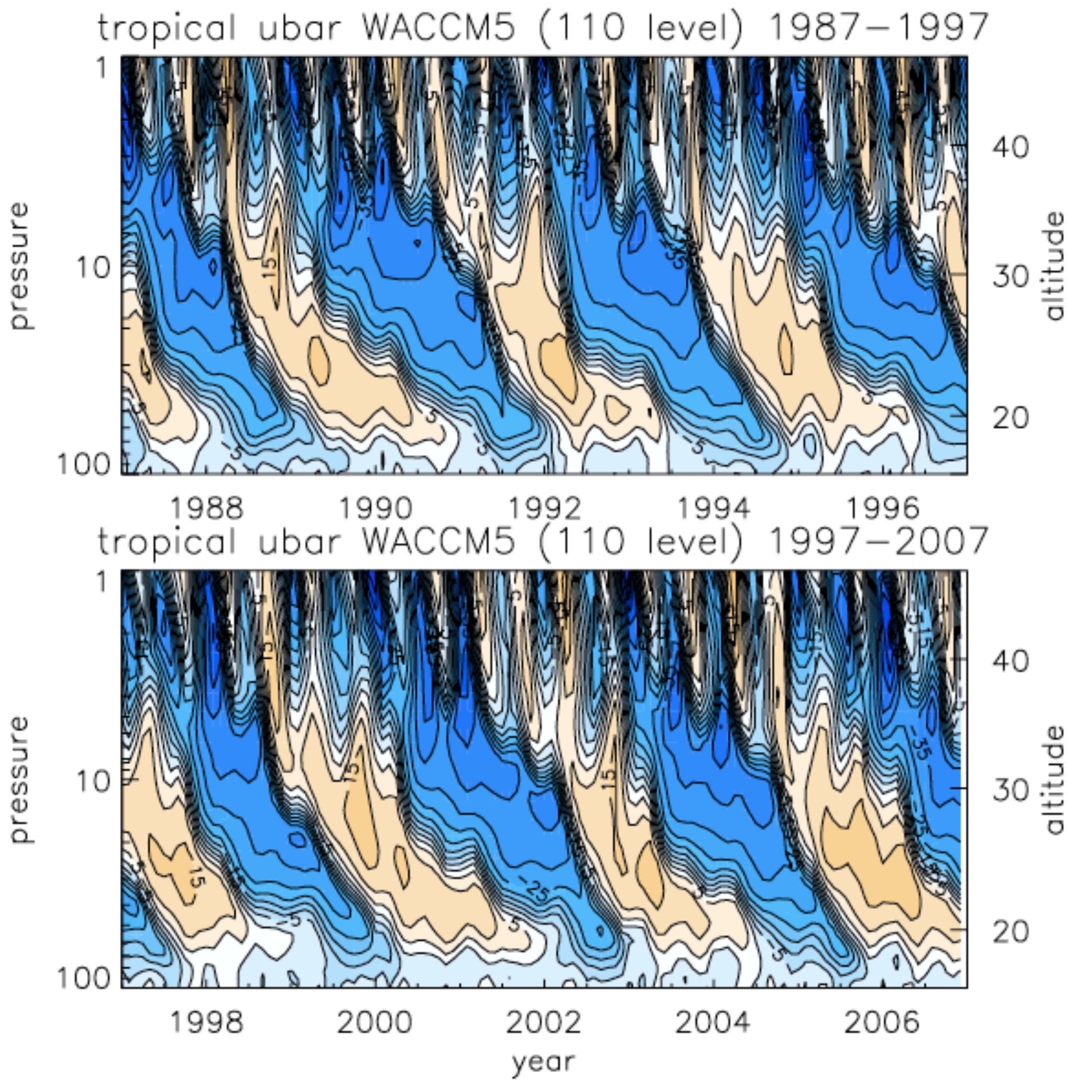


-> 1x1 horizontal resolution
-> high vertical resolution*
-> decrease convective heating depth and increase efficiency

*110 levels; dz=500m in upper troposphere & lower stratosphere

current WACCM5 QBO



Period is slightly too long (~31-32 months).

More tuning is needed (small increase in "efficiency" of convective waves) to reduce period to 28 months.

QBO: success

- WACCM5 generates a realistic QBO
- the primary forcing is from convectively generated GW
- resolved equatorial waves also contribute

CONCERN FOR USERS:

- If WACCM5 is run with lower horizontal and/or vertical resolution, it will not have a proper QBO.

WACCM is participating in the QBOi initiative: a model intercomparison project to explore interactive simulation of the QBO and its response to climate change.

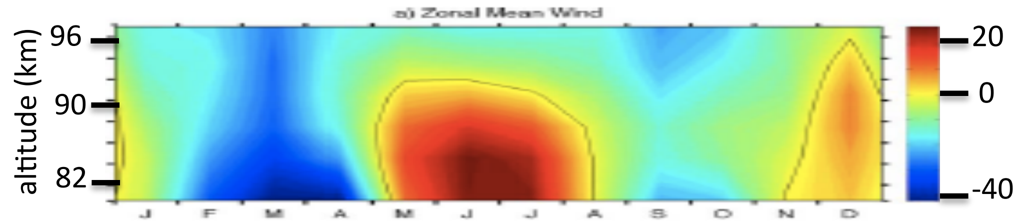
http://users.ox.ac.uk/~astr0092/QBOi.html

SAO

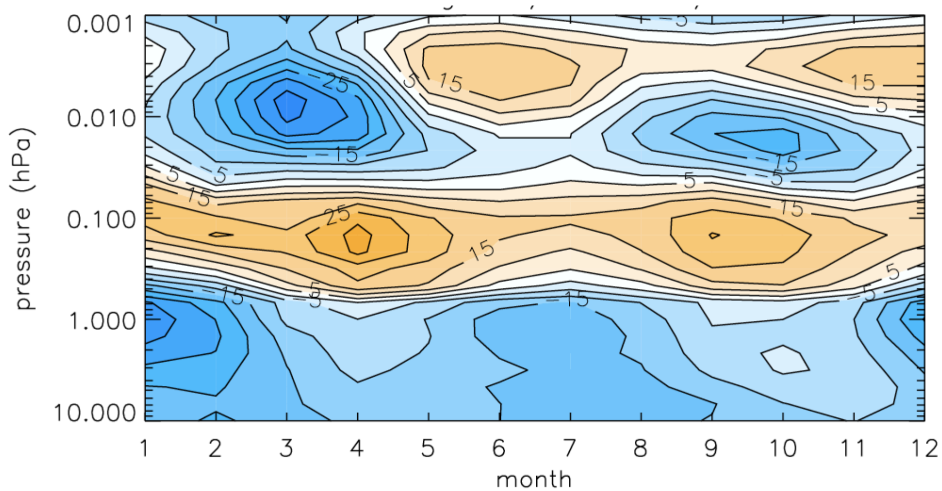
observed SAO winds

- Radar data have limited altitude range (80-96 km)
- URAP (direct wind observations) has gaps in altitude; the upper levels have contamination from the large semiannual variation in diurnal tide amplitude.
- SABER winds are derived from geopotential using balance wind formula and interpolated across tropics (12°S-12°N).

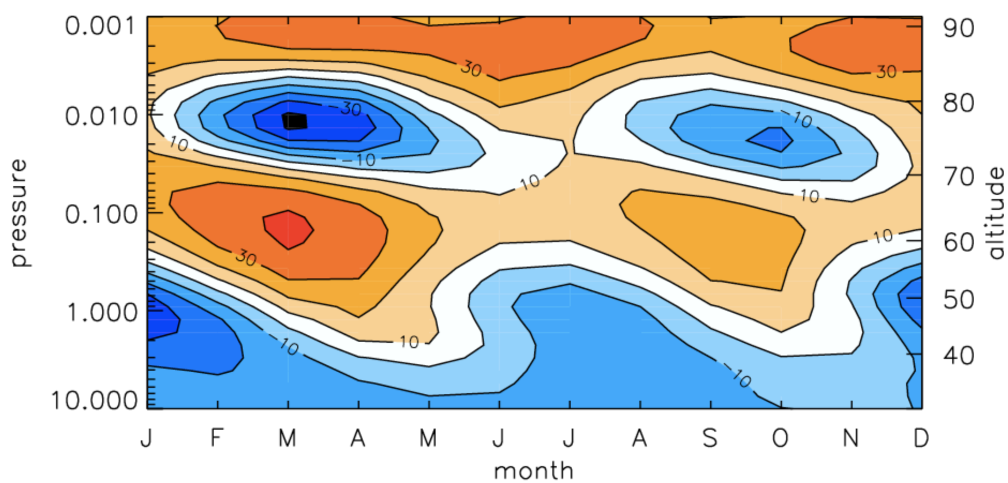
SAO observed by radar (Davis et al., ACP, 2013)



SAO from URAP (UARS obs & other obs/calculations)



SAO derived from SABER



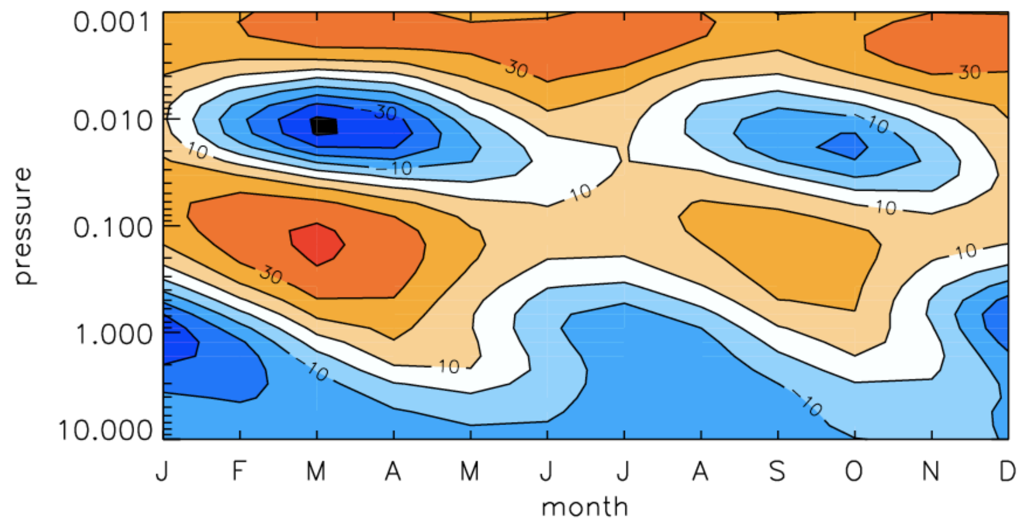
Mesospheric part of the SAO is wave-driven but not much is known about which waves.

- gravity waves?
- inertia gravity waves?
- fast Kelvin waves?

WACCM4 SAO winds

Observations do not give a strong indication of downward propagating wind max and min above 0.1 hPa as simulated in WACCM.

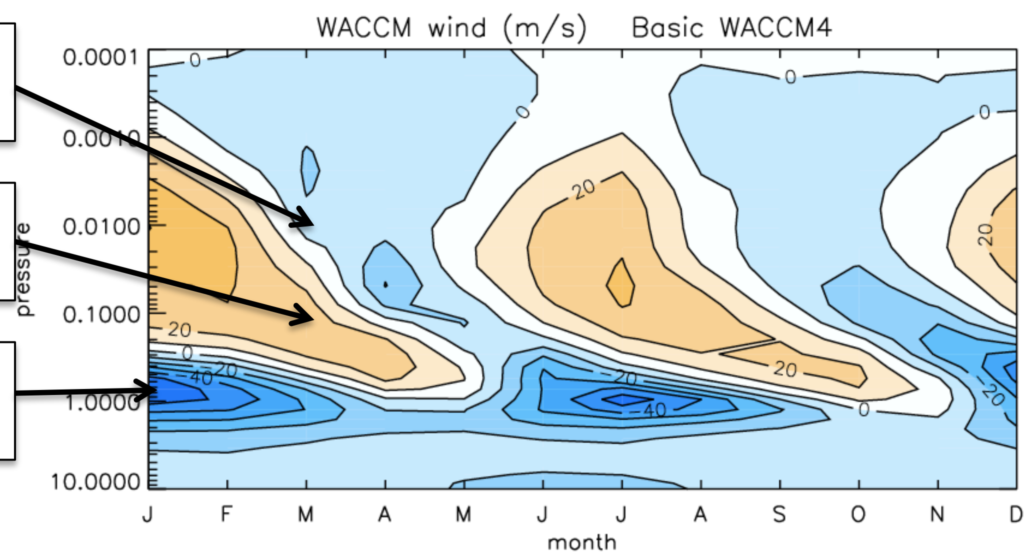
SAO derived from SABER



upper easterly max (equinox, ~80 km) is missing

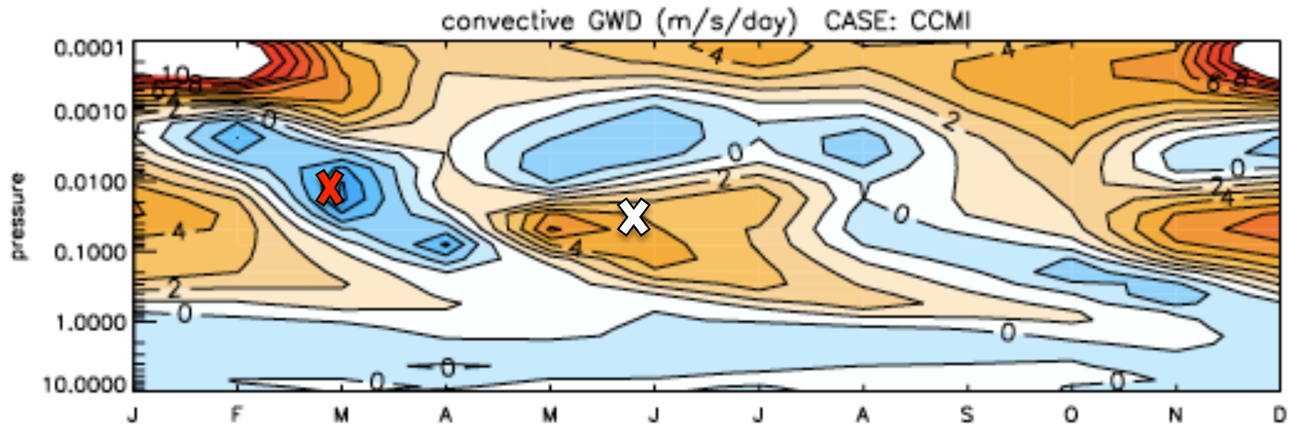
wrong timing, altitude & magnitude for westerly max

stratopause easterlies too strong, especially second max (June-July)

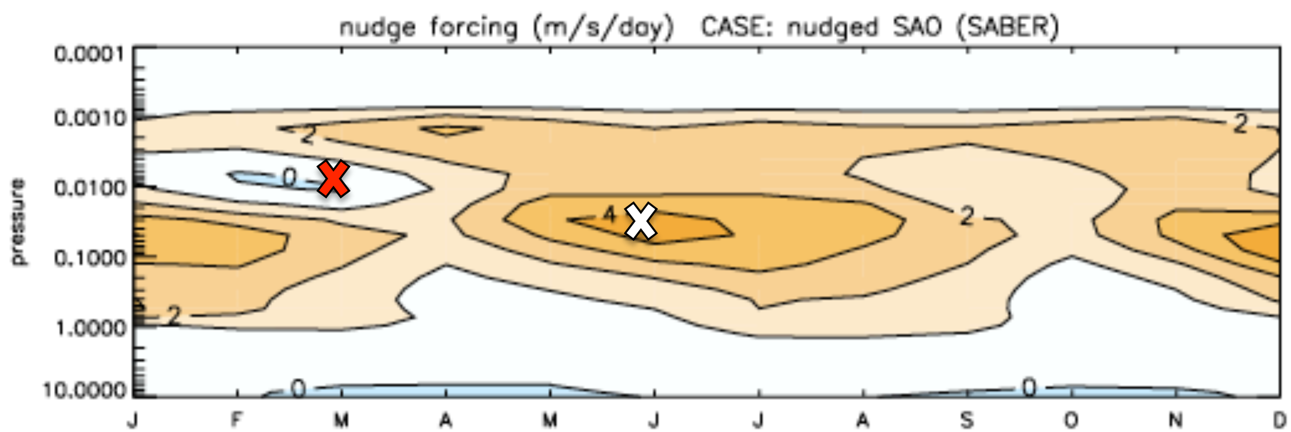


zonal momentum forcing in the tropics

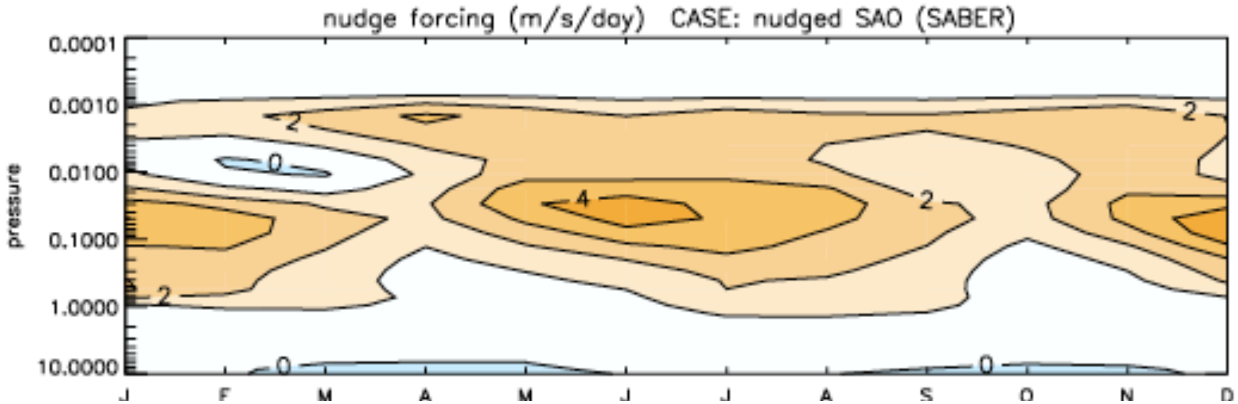
standard WACCM4 GWD from convection



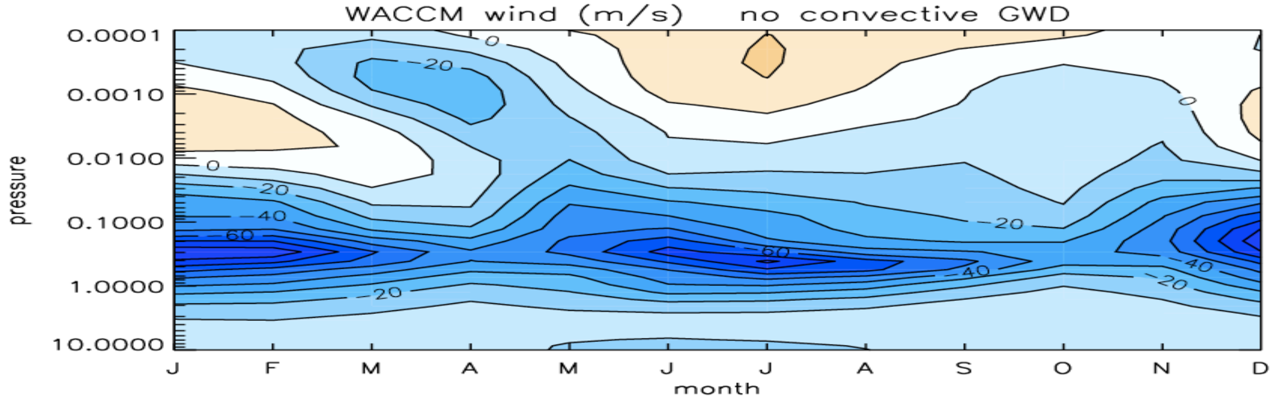
momentum forcing needed to constrain WACCM so that simulated SAO resembles observed



zonal momentum needed for SAO



momentum forcing needed to simulate observed SAO

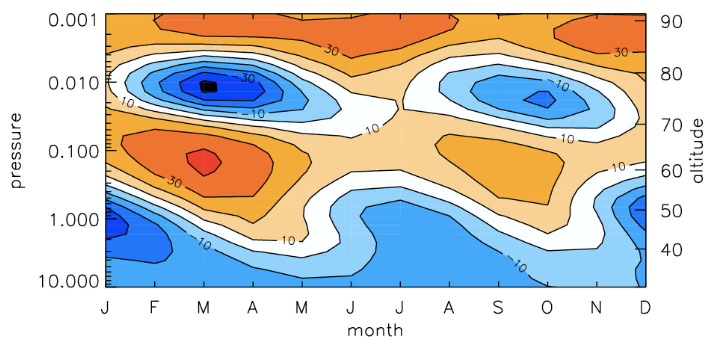


WACCM SAO with no convective GW

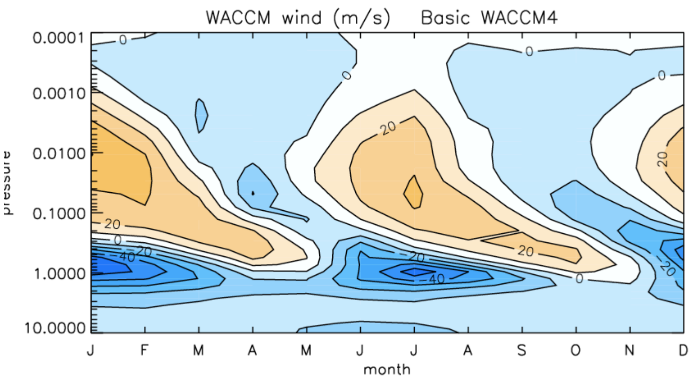
- tropical winds with no convective GW are strongly easterly (up to 80 m/s)
- “missing” forcing is mostly westerly
- westerly forcing could come from gravity waves
- westerly forcing could also come from Kelvin waves
- fast Kelvin waves have large horizontal & vertical scales that should be resolved (but may not be properly forced) in WACCM4 and WACCM5

WACCM5 SAO winds

SAO derived from SABER



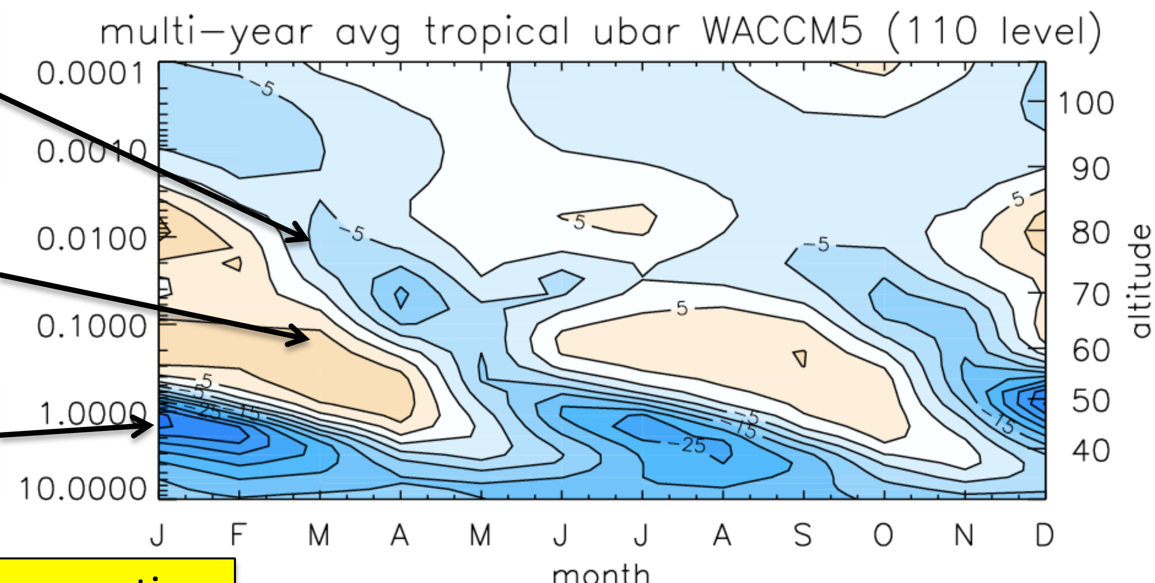
WACCM4 SAO



upper easterly max (equinox, ~80 km) is better but still too late, too weak

still with wrong timing, altitude & magnitude for westerly max

stratopause easterlies more realistic



WACCM still indicates downward propagation of easterly/westerly winds

SAO: under development

- Ongoing: we are using observations to determine the structure and interannual variability of the mesospheric SAO
- SAO near the stratopause is improved by having an interactive QBO (the "nudged" QBO introduces biases in the SAO)
- WACCM5 SAO is somewhat better than that in WACCM4 but far from satisfactory
- Tests indicate that the wave driving needed for the SAO is mostly westerly, with peaks around the solstices.

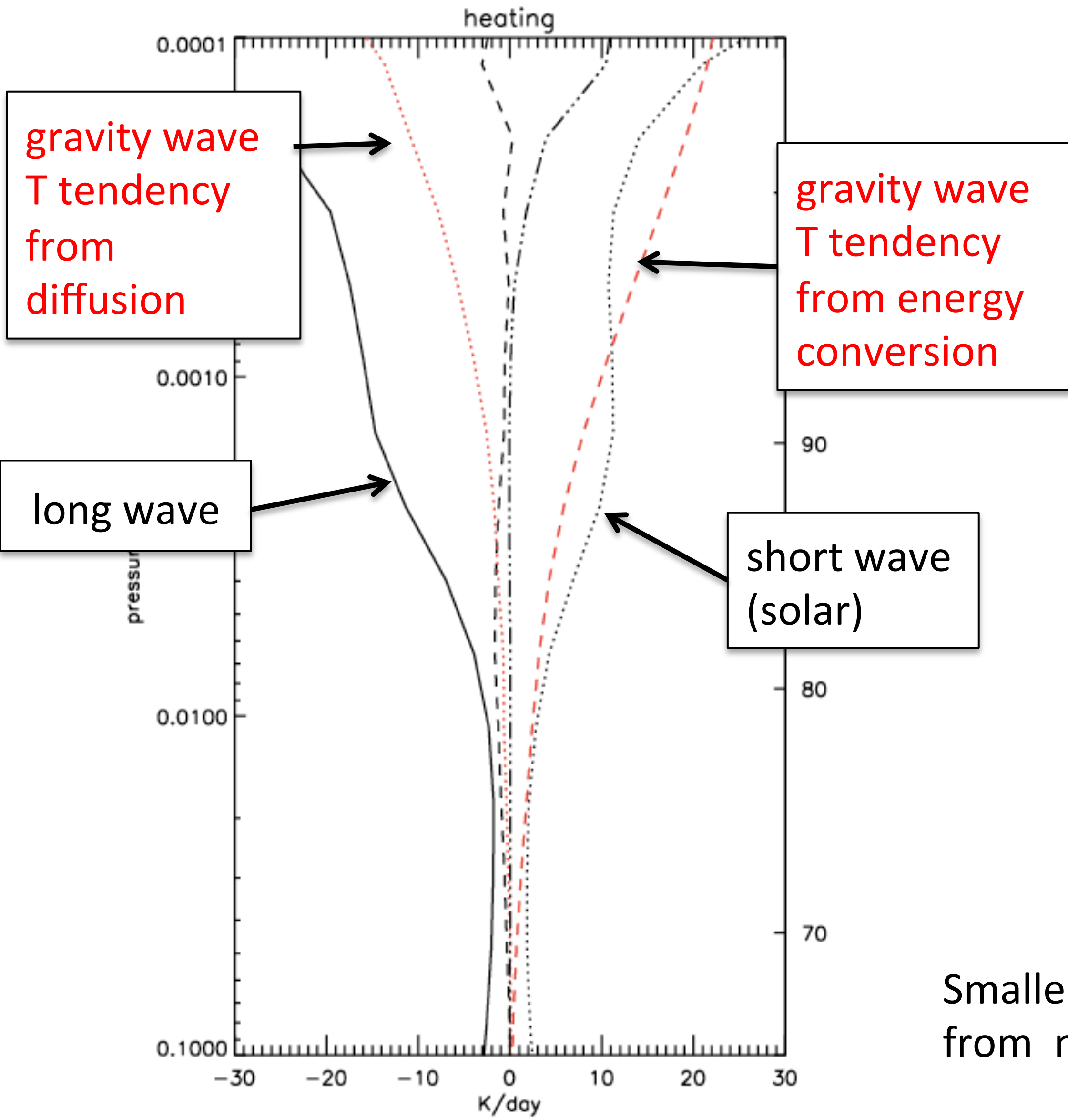
global mean temperature

Global impact of GW diffusion and heating

- WACCM GW parameterization is based on Lindzen (1981).
- The limit on wave growth at saturation gives an eddy heat flux that can be expressed using an eddy diffusion coefficient.
- Diffusion of heat acts to **cool** the mesosphere.
- Diffusion of trace species is important in simulating realistic composition.
- We also include a GW **heating** term which is determined from the net energy loss of the decaying wave.
- The Prandtl number affects the balance between cooling and heating but its range is constrained by need to simulate trace species (CO_2, CO, H_2O, NO, etc). Currently Pr=2.

- ***The net GW temperature tendency in the mesosphere from the WACCM GW parameterization is positive.***

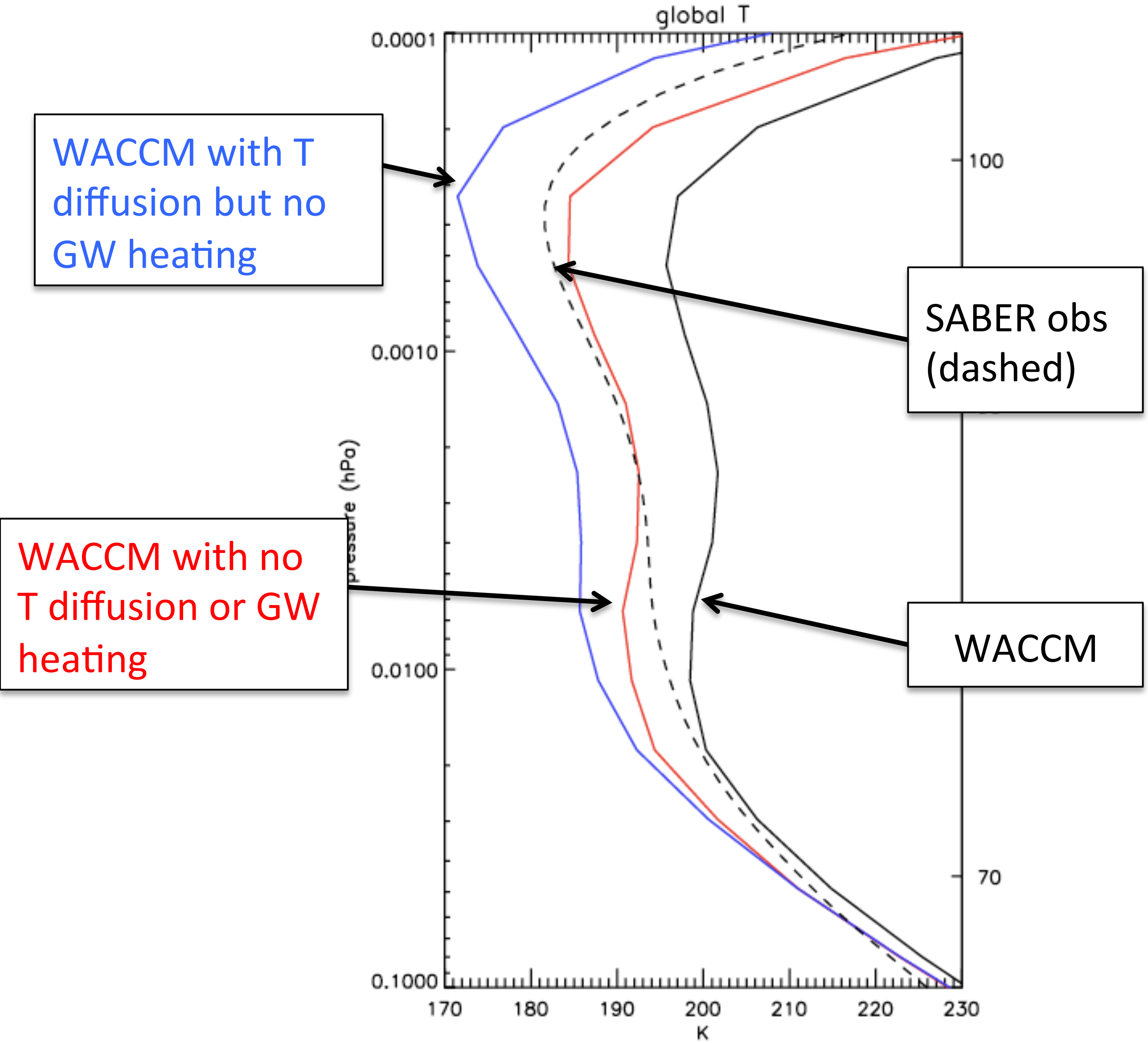
global mean heating/cooling in mesosphere



Sum of GW influences is a net global heating; the sum of heating is balanced by IR cooling

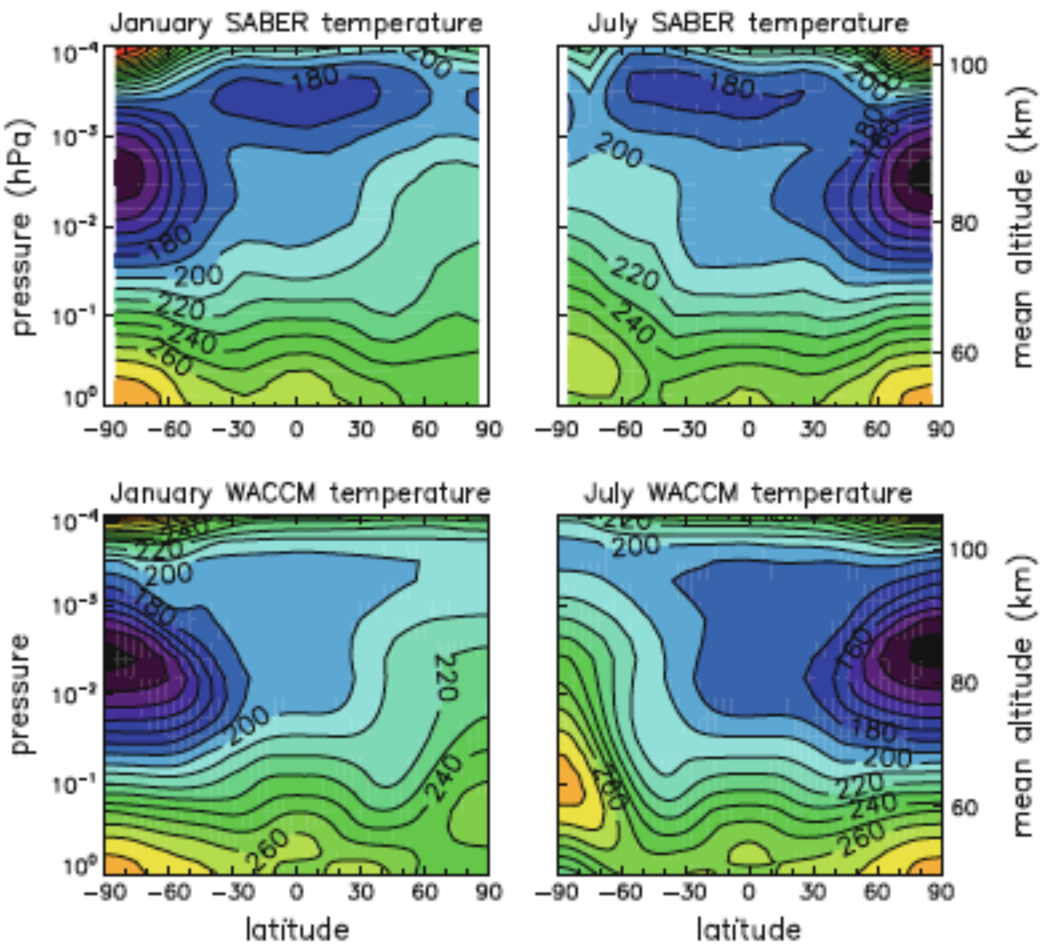
Smaller contributions (shown but not labeled) from molecular diffusion and dynamical core

global annual mean temperature in mesosphere



Best agreement with SABER when net GW temperature impact (diffusion plus energy deposition) is near zero.

mean temperature (latitude x pressure)



Temperature bias at mesopause affects:

- ozone concentration
- energy budget

The problem:
To simulate reasonable circulation (driven by momentum forcing), our parameterization generates too much heating.

The solution:
none so far (suggestions welcome)

global mean temperature: something is not right

- GW eddy diffusion cools mesosphere
- GW energy deposition warms mesosphere
- net impact: warming (temperatures are too high)
- changing the balance of cooling & heating by reducing the Prandtl number could improve the mesopause temperature but adversely affects the composition of trace species (H_2O, CO_2, O_3)

Conclusions: GW parameterization in WACCM

- Momentum forcing, primarily from parameterized gravity waves with convective sources, now successfully drives a QBO.
- More work is needed to use momentum forcing to give a realistic mesospheric SAO.
- Current formulation and/or implementation of gravity wave parameterization gives too much net heating and an unrealistic (warm) global mesopause.