Gravity wave forcing and the SH cold pole bias in WACCM

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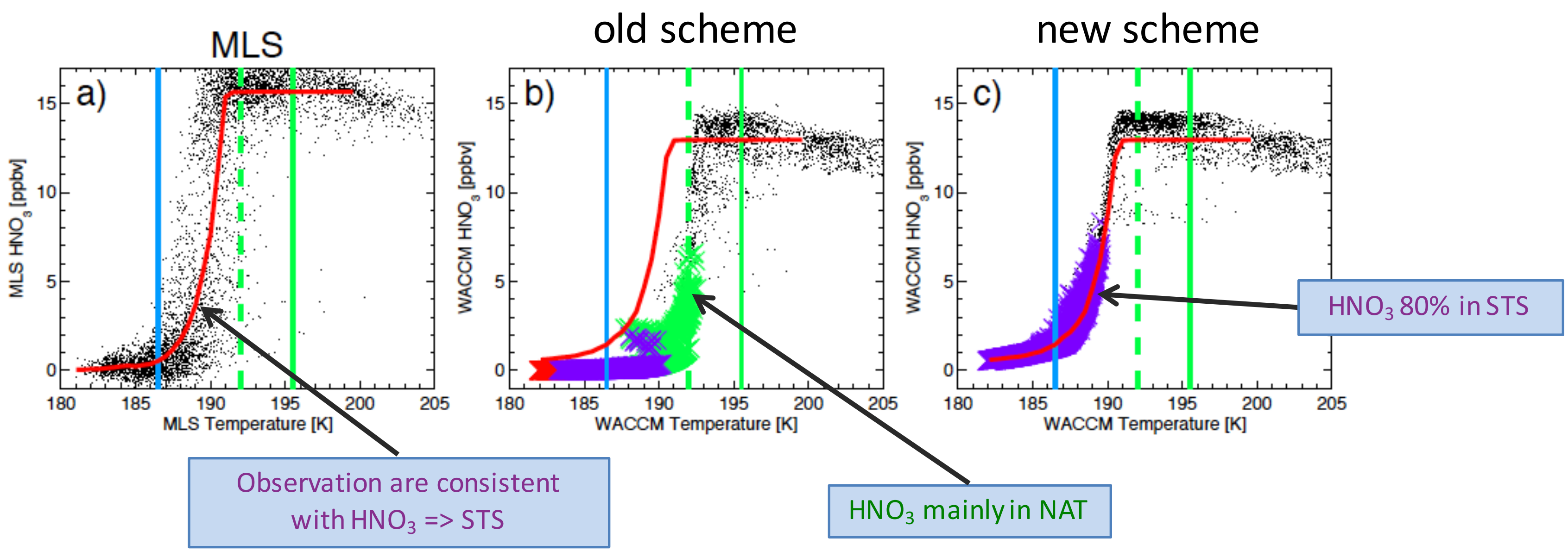
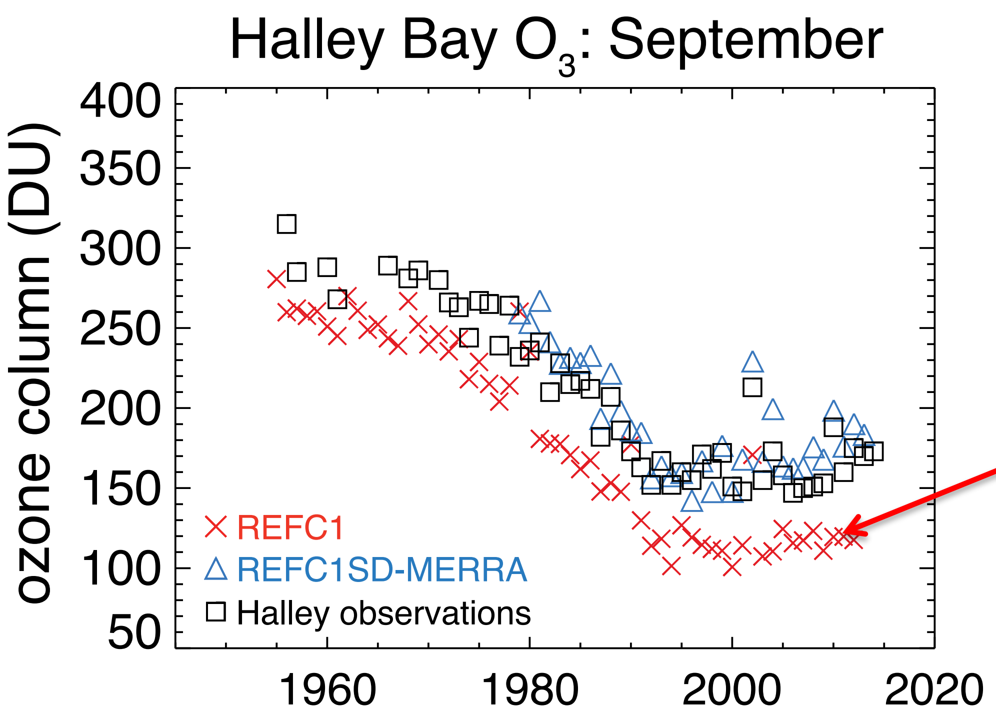
motivation: polar heterogeneous chemistry

Updated heterogeneous chemistry changes partitioning of condensed-phase HNO_3 between **Nitric Acid Tri-hydrate (NAT)** and **Supercooled Ternary Solution (STS)** [Wegner et al., *JGR*, 2013; Solomon et al, 2015]



- Updated chemistry reduces irreversible denitrification by decreasing NAT and increasing STS
- Allows reformation of $ClONO_2$ and heterogeneous halogen activation in Spring
- Halogen activation rate on STS is strongly sensitive to temperature (colder → faster)
- **Requires accurate representation of SH polar temperature in the lower stratosphere**

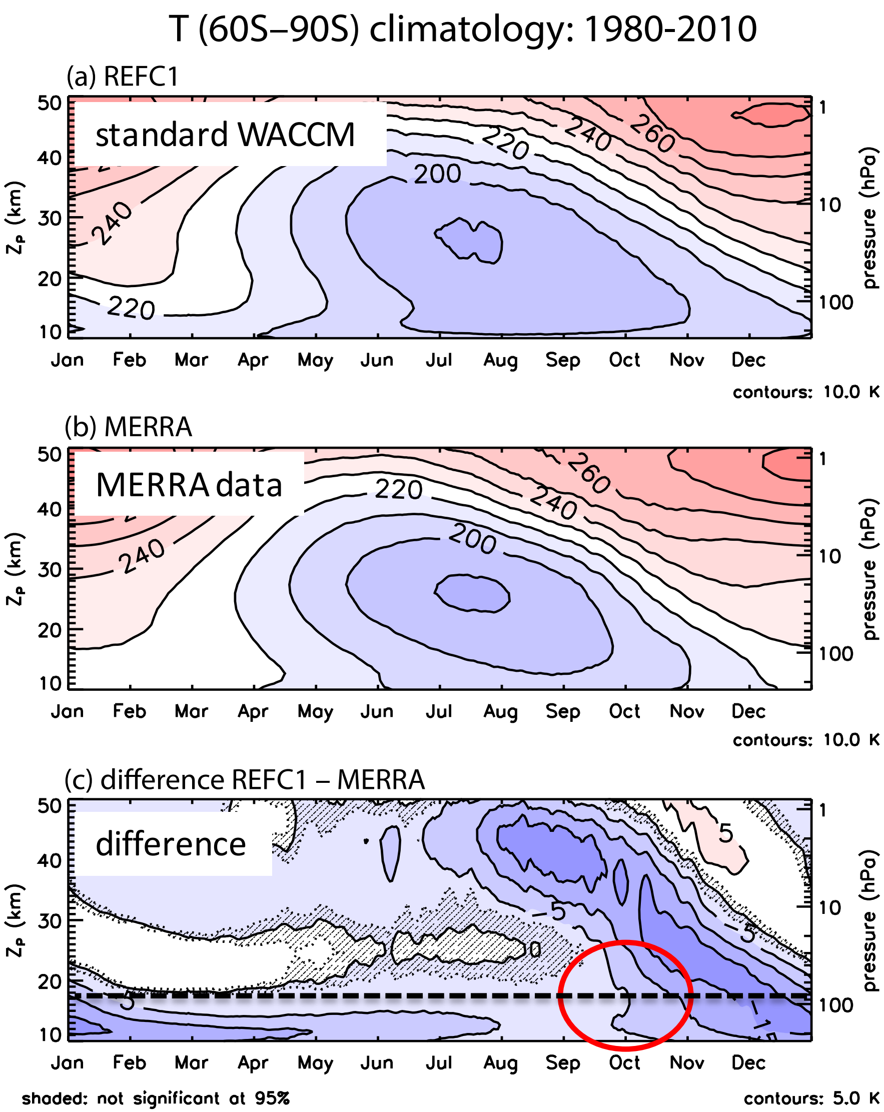
this leads to a problem: ozone column at Halley Bay (75S, 26W)



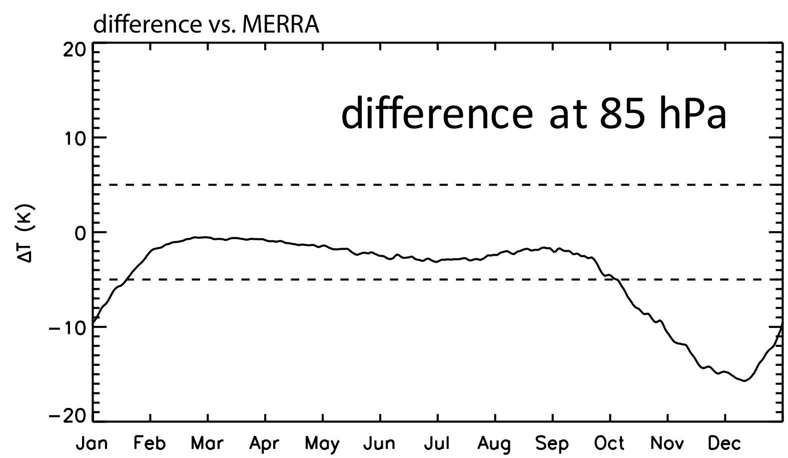
Calculated September O_3 column is ~40-50 DU lower than observed…

…but a simulation using T from MERRA reproduces well the observations

Polar cap (60-90 S) T climatology



- Low ozone is ultimately due to the large "cold pole bias" in WACCM
- T in ozone hole region/season is 5-10 K colder than observed



a possible solution

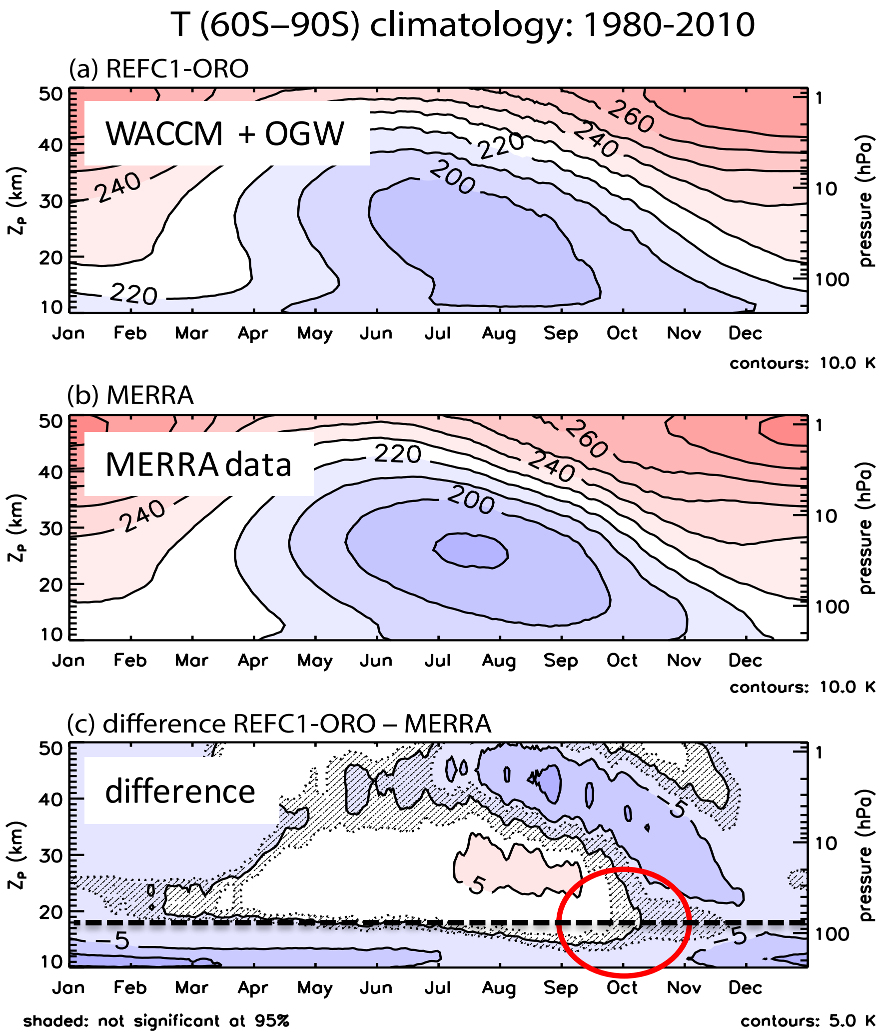
- polar temperatures are sensitive to wave-induced downwelling
  → wave forcing too weak in the SH

- resolved (Rossby) wave amplitudes and dissipation are not easily adjustable

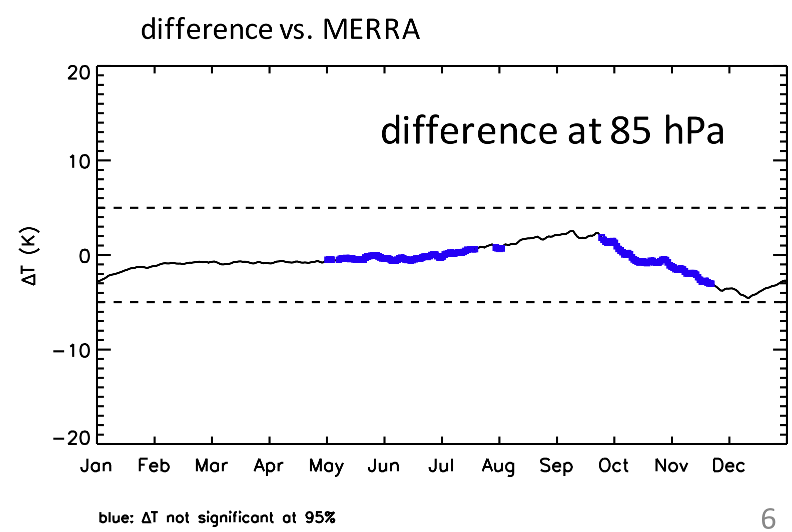
- but GW forcing can be increased by increasing the source flux of parameterized orographic GW, preferentially in the SH

- “tuning” the GW parameterization must be done carefully, such that the overall simulation is not degraded

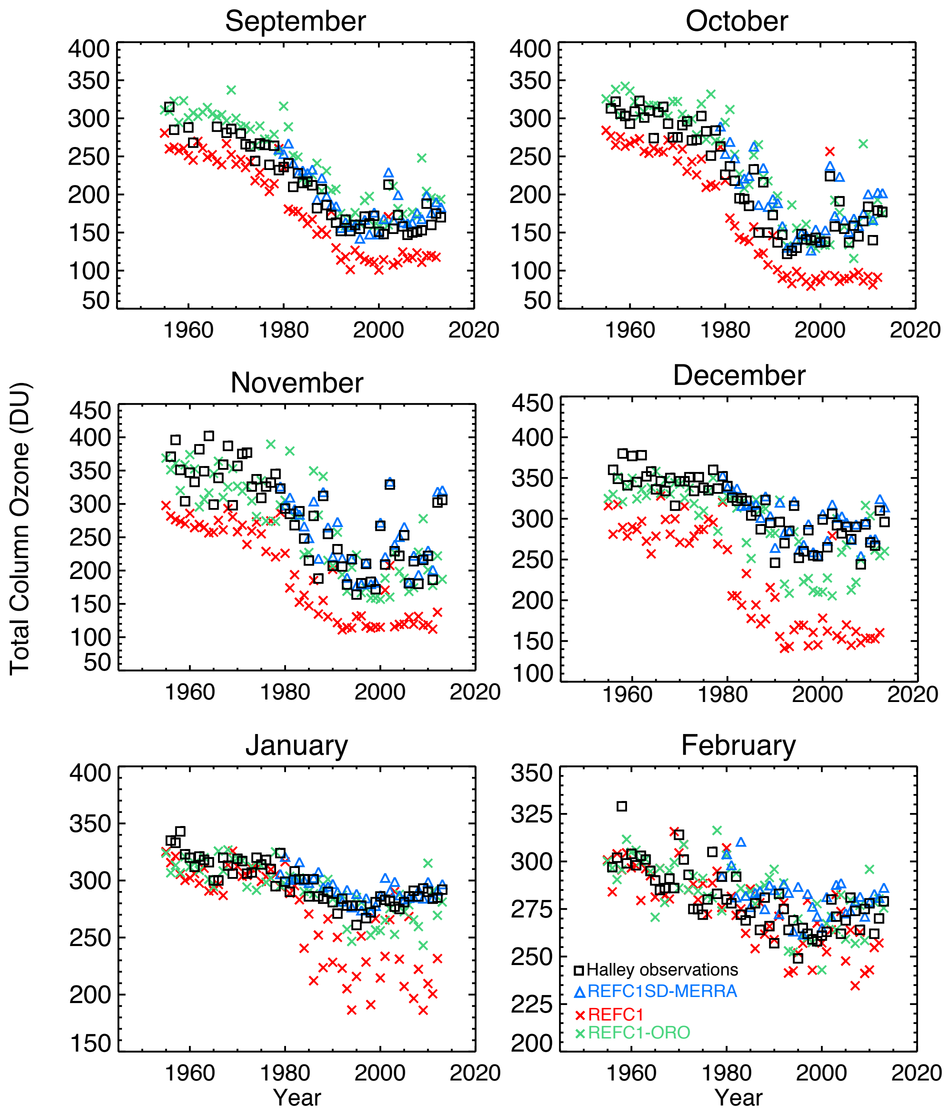
Polar cap T (60-90°S) climatology with enhanced orographic GW forcing



- T in ozone hole region in SH spring is much warmer with enhanced orographic GW forcing
- In the lower stratospere, T is now within 5K of MERRA climatology



Ozone column at Halley Bay



ozone responds favorably to warmer polar-cap T

black: Halley Bay ozone sondes

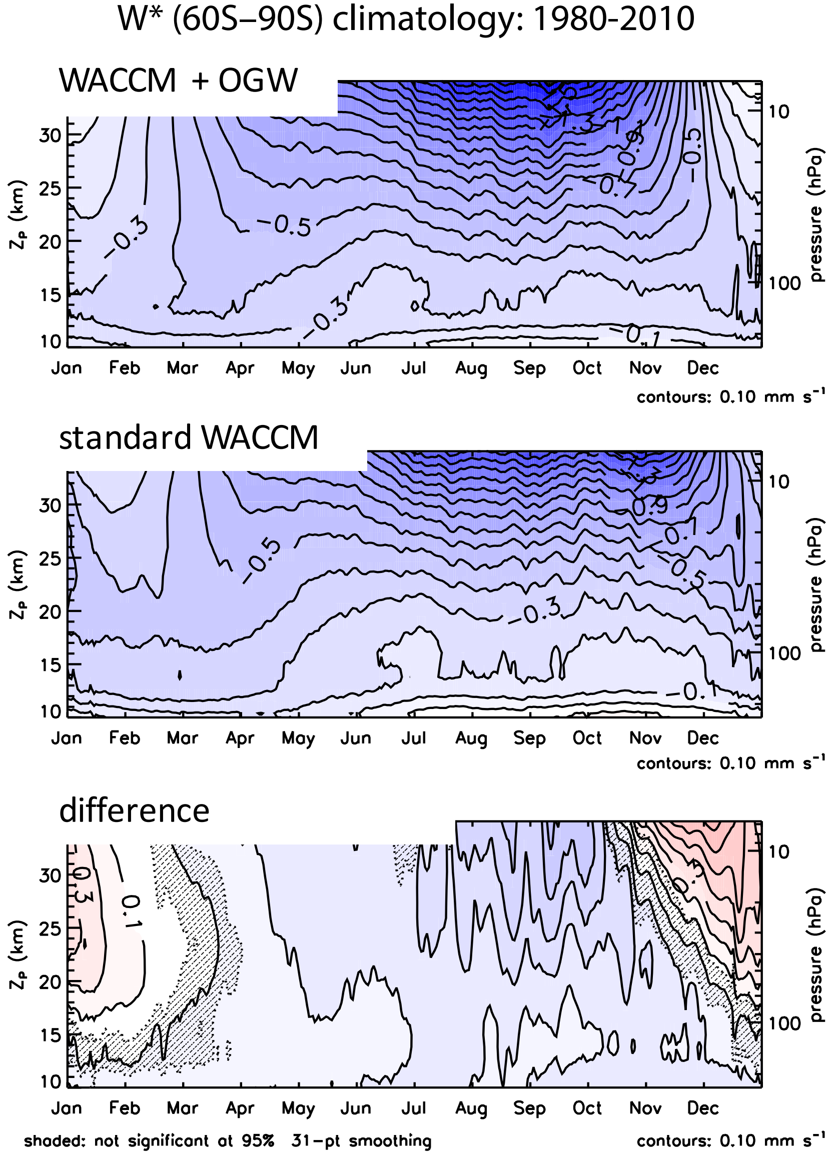
blue: WACCM driven with MERRA T

red: Standard free-running WACCM

green: Enhanced orographic GW forcing

- other desirable features of the model's climatology, e.g., SSW frequency, are preserved

acceleration of polar downwelling



- model with enhanced orographic GW fluxes produces stronger polar cap downwelling most of the year
- stronger downwelling reduces the cold pole bias
- downwelling change is smooth throughout the polar cap even though OGWD varies strongly with latitude (southern Andes, Palmer Peninsula)

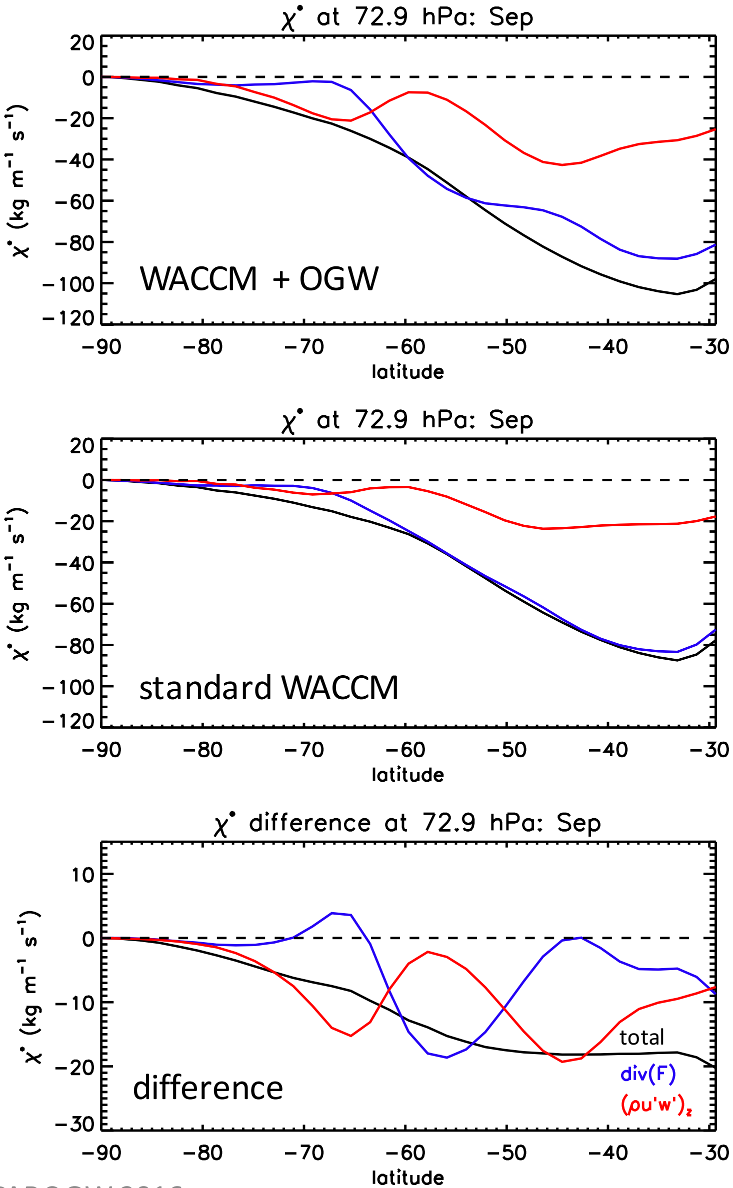
attribution

A Downward Control (DC) principle streamfunction may be obtained from the steady-state TEM angular momentum equation (Haynes et al, 1991):

$$\chi_d^*(\theta, z) = \int_z^{\infty} \frac{\rho\, a^2 \cos^2\theta \left[(\rho a \cos\theta)^{-1}\ \nabla \cdot \mathbb{F} + \rho^{-1}(\rho\overline{u'w'})_z\right]}{\bar{m}_\theta}\, dz'$$

It allows formal attribution of the mean-meridional streamfunction to forcing by planetary waves, $\nabla \cdot \boldsymbol{F}$, and gravity waves, $(\rho u'w')_z$.

DC streamfunction at 72 hPa, September



attributed to forcing by:

resolved Rossby waves

parameterized gravity waves

total forcing by all waves

- with enhanced orographic GW fluxes, the forcing due to GW drag increases ~ 2 X
- there is a GW forcing "gap" at 60°S, where there is no land to force orographic waves
- however, forcing due to Rossby waves changes, partly compensating the GW changes
- total forcing and total change in forcing remain smooth functions of latitude because of this compensation
- cf. Cohen et al. (2013); McLandress et al. (2012); Sigmond and Shepherd, (2014);

DC polar cap mean downwelling

The DC streamfunction

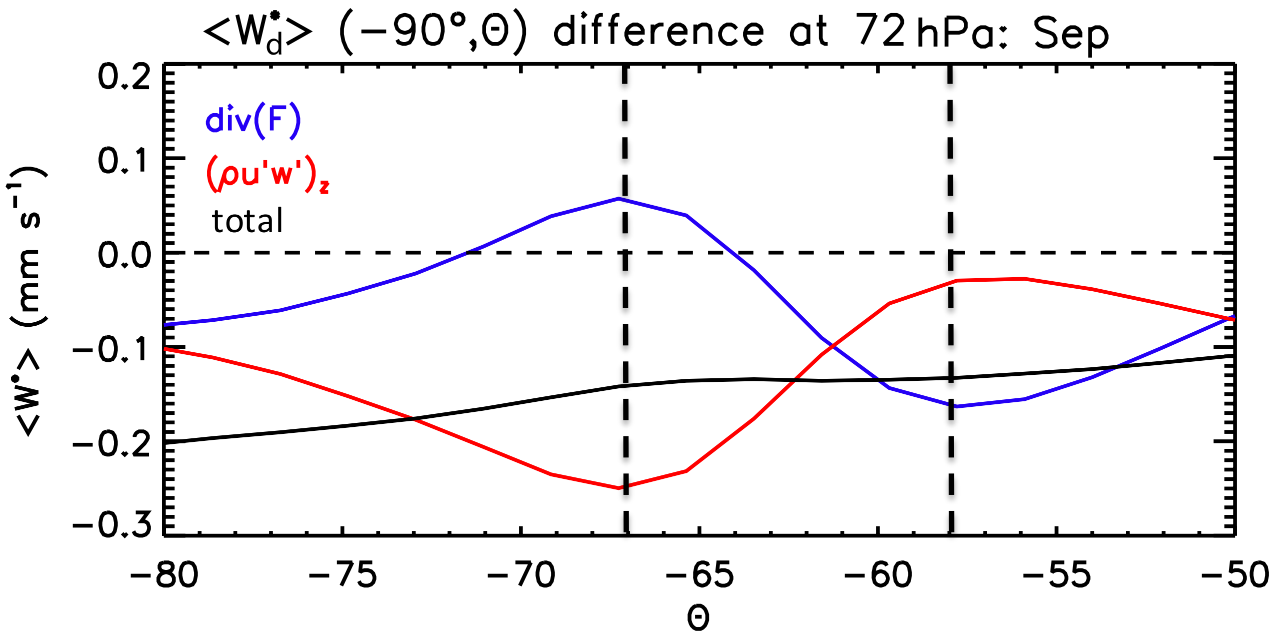
$$\chi_d^*(\theta, z) = \int_z^\infty \frac{\rho\, a^2 \cos^2\theta\, [(\rho a \cos\theta)^{-1}\ \nabla \cdot \mathbb{F} + \rho^{-1}(\rho \overline{u'w'})_z]}{\overline{m}_\theta}\, dz'$$

may be used to calculate the cosine-weighted downwelling over the polar cap:

$$\langle w_d^*(z) \rangle = \frac{1}{\rho(z)} \int_{-\pi/2}^{\theta} \frac{1}{a} \frac{\partial \chi_d^*}{\partial \theta} d\theta' \Big/ \int_{-\pi/2}^{\theta} \cos\theta' d\theta' = \frac{\chi_d^*\ (\theta, z)}{\rho(z)\ a\ \ (\sin\theta + 1)}$$

which depends on χ_d^* at the latitude, θ, that defines the edge of the polar cap

attribution of polar cap downwelling



$\langle W_d^* \rangle$ difference

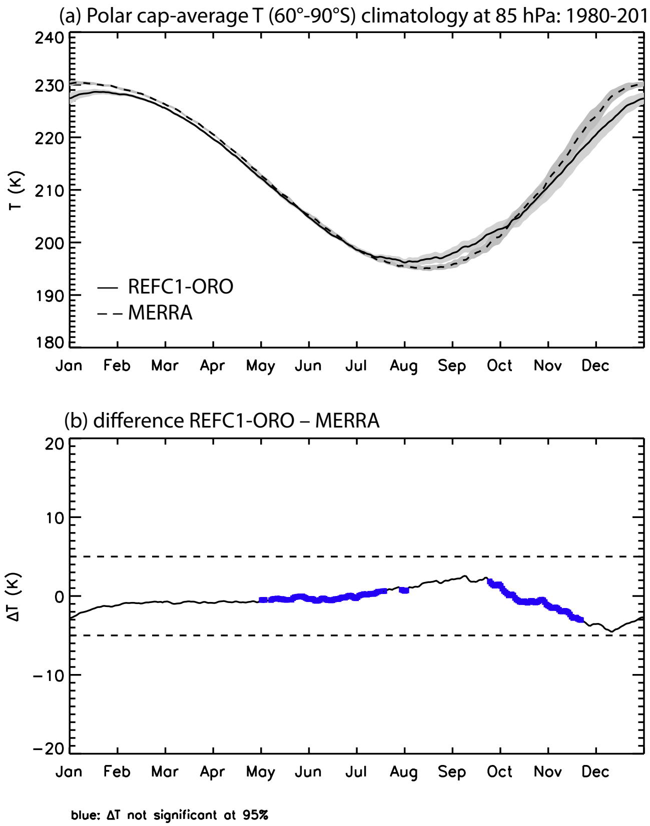
72 hPa

September

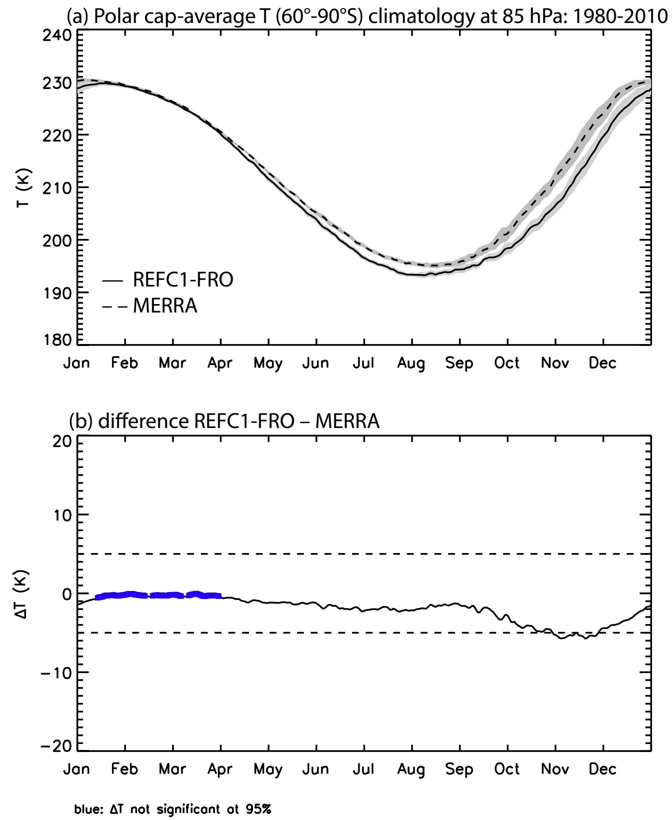
- figure shows the difference in $\langle W_d^* \rangle$ averaged from latitude θ to the pole in standard WACCM vs. WACCM with enhanced orographic GW
- attribution of the difference varies depending on the choice of θ
- DCP cannot independently determine causation–it is a diagnostic relationship

solution of cold pole bias is not unique

T(85 hPa): enhanced orographic GW



T(85 hPa): enhanced non-orographic GW



seasonal cycle vs. MERRA data, with 2-sigma errors

seasonal cycle difference vs. MERRA data

left: the enhanced orographic GW simulation discussed thus far
right: a simulation with enhanced non-orographic GW drag
both simulations produce T in the lower stratosphere within 5 K of observations

conclusions

- adding orographic GW forcing improves the SH cold pole problem
- warmer T allows realistic simulation of Antarctic ozone
- the simulation with enhanced orographic GW preserves desirable climatological features of the standard simulation
- attribution of changes in W* via DCP is ambiguous because of compensation between GW and Rossby wave forcing
- solution is not unique and interpretation is complicated by the compensation phenomenon; needs observational justification