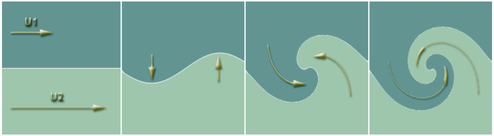
The Climatology of Vertical Mixing in the Tropical Tropopause Layer

Thomas Flannaghan and Stephan Fueglistaler
Atmosphere Ocean Sciences/Geosciences, Princeton University

Vertical Mixing in the Tropical Tropopause Layer

- Vertical mixing – Kelvin Helmholtz instability



- A shear instability
- Occurs when Richardson number $Ri < 0.25$

$$Ri = \frac{N^2}{|\partial \vec{u} / \partial z|^2}$$

A balance between static stability and vertical wind shear

Motivation

- ERA Interim diabatic budget is not fully explained by convection, clouds and radiation [Fueglistaler et al., 2009b]
- Points to significant diabatic forcing arising from vertical mixing
- Diabatic terms provide connection between Hadley cell and Brewer-Dobson circulation
- Also, observations show large strat-trop exchange of ozone across the TTL associated with vertical mixing [Fujiwara and Takahashi, 2001, Fujiwara, 2003]

- The diabatic terms and vertical mixing in TTL are important

Vertical mixing parametrisations

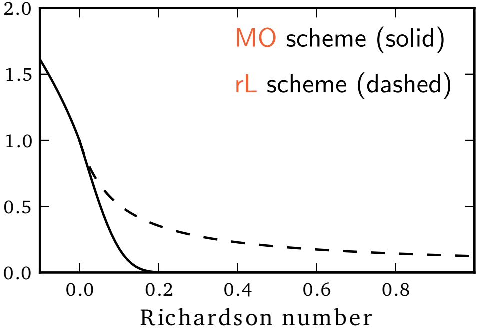
- Vertical mixing cannot be resolved by GCMs
- Therefore, we parametrise vertical mixing
- Most schemes use a diffusivity approximation:

$$\rho \frac{\partial \phi}{\partial t} = \frac{\partial}{\partial z}\left(\rho K(z) \frac{\partial \phi}{\partial z}\right)$$

  ϕ is generic quantity to be mixed:
  - Dry static energy when computing temperature tendency
  - Wind when computing momentum forcing
- Schemes typically give K as a function of u, v, T profiles

Two very different schemes

Most schemes define K as a function of Ri. These are two very different schemes:



- Monin-Obukhov-type (MO) scheme has cut off at $Ri = 0.25$
- Revised Louis (rL) scheme has long tail as $Ri \to \infty$

Two very different schemes

- Monin-Obukhov-type (MO) scheme has cut off at $Ri = 0.25$
- Revised Louis (rL) scheme has long tail as $Ri \to \infty$

- ERA Interim using the rL scheme
- More recent ECMWF forecast models use MO scheme
- Other forecast models typically use schemes similar to MO scheme
- See Flannaghan and Fueglistaler [2011]

Two very different schemes

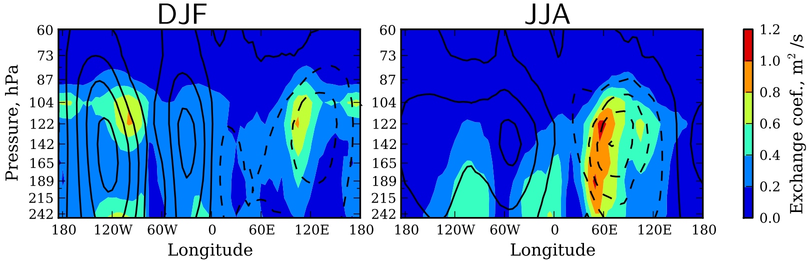
- Monin-Obukhov-type (MO) scheme has cut off at $Ri = 0.25$
- Revised Louis (rL) scheme has long tail as $Ri \to \infty$

- ERA Interim using the rL scheme
- More recent ECMWF forecast models use MO scheme
- Other forecast models typically use schemes similar to MO scheme
- See Flannaghan and Fueglistaler [2011]

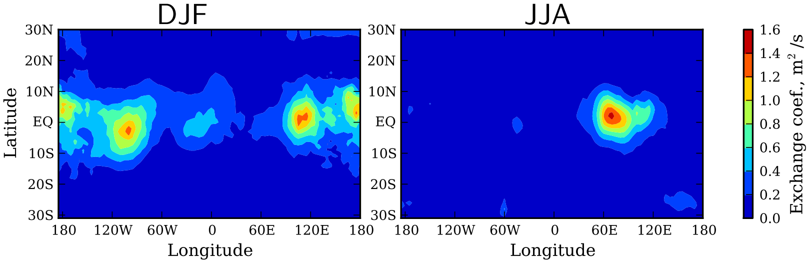
We do not state which scheme is better: MO *seems* most physical but in absence of resolved gravity waves, is it a good idea to have Ri cut off at 0.25?

ERA Interim Climatology (rL scheme)

Exchange coefficient K climatology averaged over $\pm 10°$:

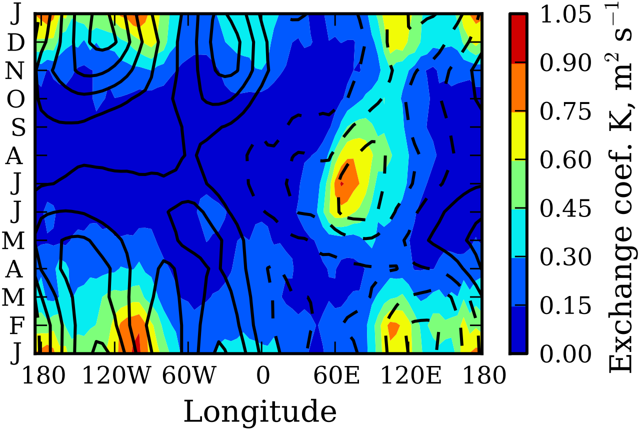


K climatology at 104 hPa:



ERA Interim Climatology (rL scheme)

K climatology at 104 hPa averaged over 10°N–10°S:

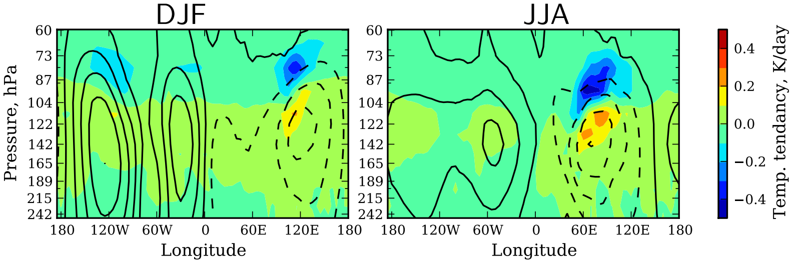


Most mixing in regions of high shear

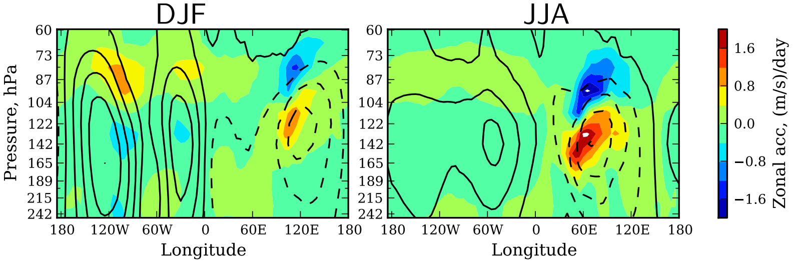
ERA Interim Climatology (rL scheme)

What do K results mean for diabatic forcing?

Temperature tendency (dT/dt):

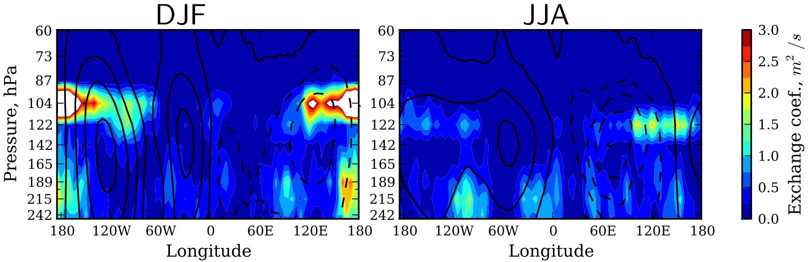


Zonal acceleration (du/dt):



ERA Interim Climatology using MO scheme

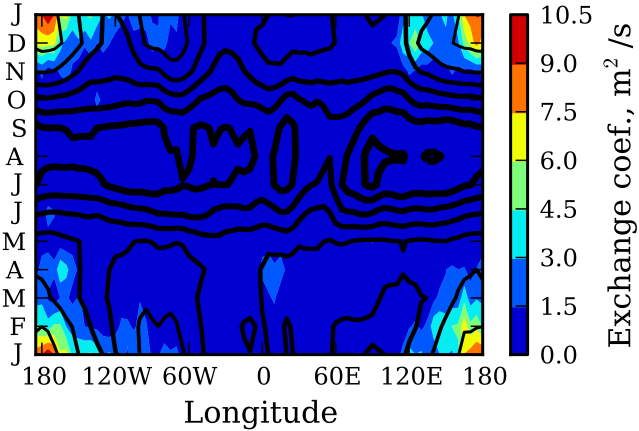
What happens to K if we apply MO scheme to ERA Interim data?



- Very high values in DJF Western Pacific (around 180°)
- Low values over Indian Ocean (where rL scheme mixed most)
- Average K similar – a tuning parameter was used

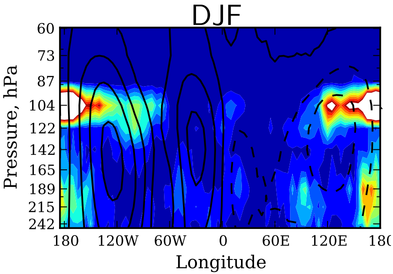
ERA Interim Climatology using MO scheme

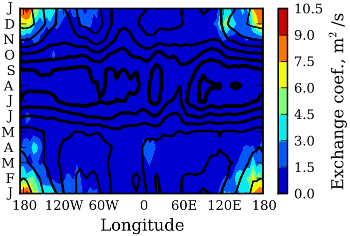
K climatology at 104 hPa averaged over 10°N–10°S:



- Most mixing in regions of low N^2 (contours are N^2)
- No contribution from regions of high shear

ERA Interim Climatology using MO scheme





What effect does this have on diabatic terms?

- MO scheme mixes in regions where background stability very low
- $\implies$ average temperature tendency is much smaller
- MO scheme mixes in regions where background wind shear very low
- $\implies$ average zonal acceleration is much smaller

Modelling the Impact of Diabatic Terms

- We have seen that there are significant diabatic terms caused by mixing in ERA Interim
- Diabatic terms very sensitive to scheme
- Therefore, could cause significant bias to ERA Interim

Here we model the response to these diabatic terms to get estimate of potential impact

Model

- Held and Suarez [1994] forcing
- Horizontal resolution is T42
- 800 m vertical resolution in TTL (60 levels)
- 4000 day spin-up (unforced) then 4000 day forced run
- Idealised forcing of form

$$A\cos^2\left(\frac{\pi x}{L_x}\right)\cos^2\left(\frac{\pi y}{L_y}\right)\sin\left(\frac{\pi(z_0 - z)}{L_z}\right),$$

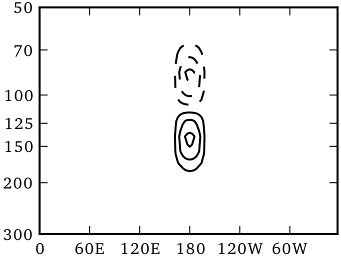
where $|x| < L_x$, $|y| < L_y$ and $|z| < L_z$

Model

- Held and Suarez [1994] forcing
- Horizontal resolution is T42
- 800 m vertical resolution in TTL (60 levels)
- 4000 day spin-up (unforced) then 4000 day forced run
- Idealised forcing of form

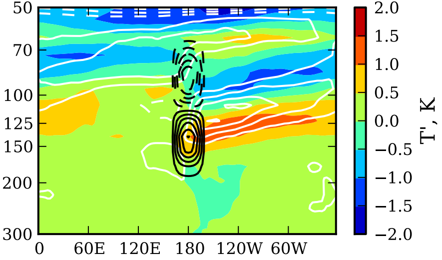
$$A\cos^2\left(\frac{\pi x}{L_x}\right)\cos^2\left(\frac{\pi y}{L_y}\right)\sin\left(\frac{\pi(z_0 - z)}{L_z}\right),$$

where $|x| < L_x$, $|y| < L_y$ and $|z| < L_z$

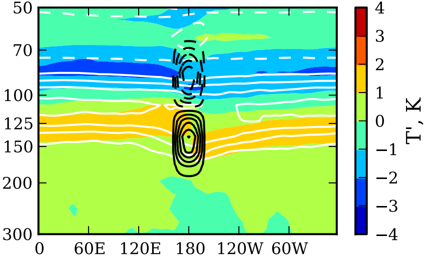


L_x	20°longitude
L_y	10°latitude
L_z	0.5 scale heights ≈ 3 km
z_0	2.2 scale heights

Results

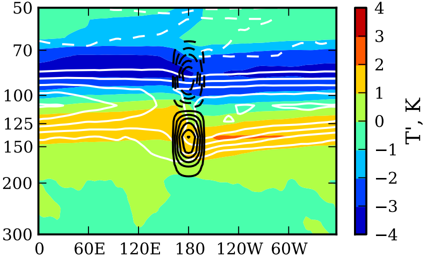


- Temperature tendency term only
- Amplitude $A = 0.5\ \mathrm{K\,day^{-1}}$
- Response of order 1.5 K, $3\ \mathrm{m\,s^{-1}}$



- Zonal acceleration term only
- Amplitude $A = 2\ \mathrm{m\,s^{-1}\,day^{-1}}$
- Response of order 3 K, $8\ \mathrm{m\,s^{-1}}$
- Very zonally symmetric
- Results similar in nature to Shaw and Boos [2012]

Results

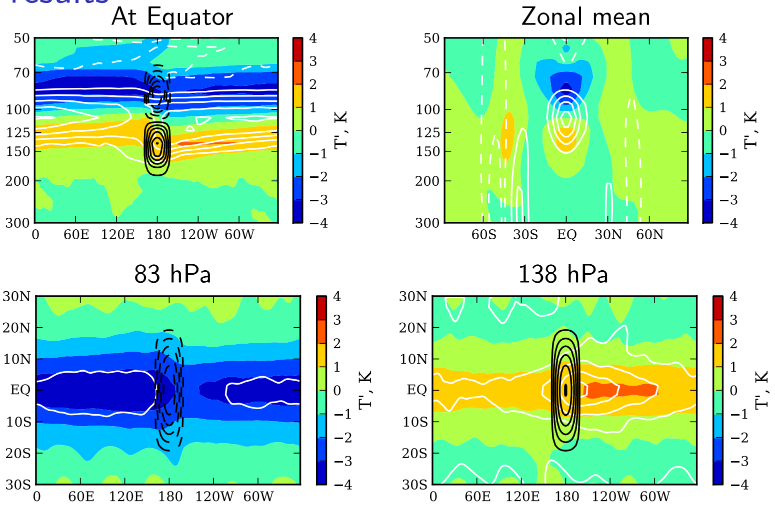


- Both diabatic terms
- Zonal Acc. 2 $\mathrm{m\,s^{-1}\,day^{-1}}$
- Temp. Tend. 0.5 $\mathrm{K\,day^{-1}}$
- Response of order 4 K, 8 $\mathrm{m\,s^{-1}}$

- Dominated by zonal acceleration forcing
- Solution is very similar to linear combination of separate solutions

This result is a significant cooling of 4 K at around 90 hPa

More results



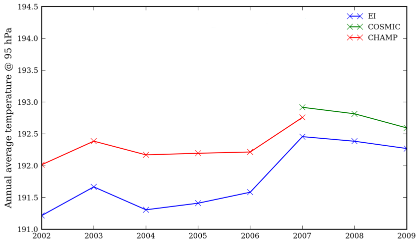
- Results similar in nature to Shaw and Boos [2012]
- Response confined to inner tropics $\sim \pm 15^\circ$ latitude

Analysis

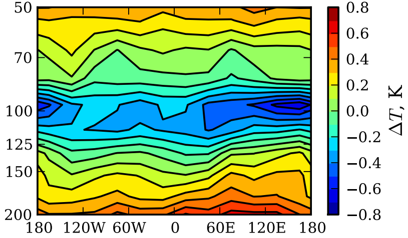
- These results are consistent with balance between radiative cooling and the diabatic forcing
- $\implies$ magnitude of response prop. to radiative timescale τ
- $\tau = 40$ days in the Held-Suarez model
- But radiative transfer model applied to temperature response gives $\tau \approx 10$ days to 15 days
- This *suggests* real magnitude of response of order 1 K, 2 $\mathrm{m\,s^{-1}}$
- ... but this is still a significant cooling at the tropopause

Bias in TTL in ERA Interim

- ERA Interim is consistently cold when compared to COSMIC and CHAMP at 95 hPa
- 0.8 K too cold vs. CHAMP
- 0.4 K too cold vs. COSMIC
- COSMIC assimilated – reduces error



ERA - COSMIC, 2007 – 2012



Summary

- Vertical mixing gives rise to significant diabatic terms in ERA Interim
- Terms are localised and seasonally varying
- Other mixing schemes (i.e. MO) give rise to much smaller diabatic terms – therefore somewhat uncertain
- Modelling suggests that diabatic terms arrising from mixing in ERA Interim can make order 1 K difference around 90 hPa
- Could account for difference between ERA Interim and COSMIC

Thanks for listening!