Vertical mixing and the temperature and wind structure of the tropical tropopause layer

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Introduction

The tropical tropopause layer (TTL) is an important region of the atmosphere. For example, it controls stratospheric water vapour, which must enter through this region. Vertical mixing has been observed to occur in the TTL (see for example Fujiwara et al. 2001, 2003) and is parametrised by models.

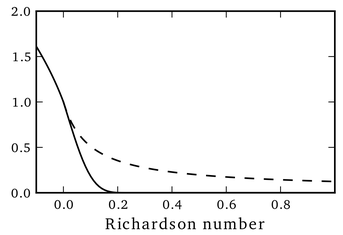

Figure 1 : Dependency of mixing scheme diffusivity on Richardson number normalised by value at $Ri = 0$ for MO scheme (solid) and rL scheme (dashed).

We consider two schemes:
- rL scheme: used in ERA-Interim.
- MO scheme: used in more recent IFS versions from IFS Cy33 onwards.
- **These schemes are very different**.

This study addresses:
- Can mixing schemes have a significant impact on the TTL?
- These schemes are very different – what are the associated uncertainties for the TTL?

1. Mixing schemes have different impact on TTL

- Mixing is computed offline using ERA-Interim data.
- Validated by comparing results with the diabatic terms in ERA-Interim.
- We focus on forcing terms – **zonal acceleration** and **diabatic heating**.

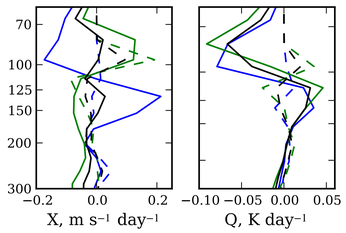

Figure 2 : Climatological mean profiles (1989–2009) averaged over 10°N–10°S of zonal mean zonal acceleration and zonal mean temperature tendency.

- **rL (solid)** and **MO (dashed)** schemes give very different forcing profiles.
- Annual cycle: different profiles for **DJF (green)**, **JJA (blue)** and the **annual average (black)**.
- Dipole structures centred at 104 hPa common for both MO and rL schemes.
- Forcing terms largest with rL scheme, so **we focus on the rL scheme**.

2. Mixing in ERA-Interim (rL scheme)

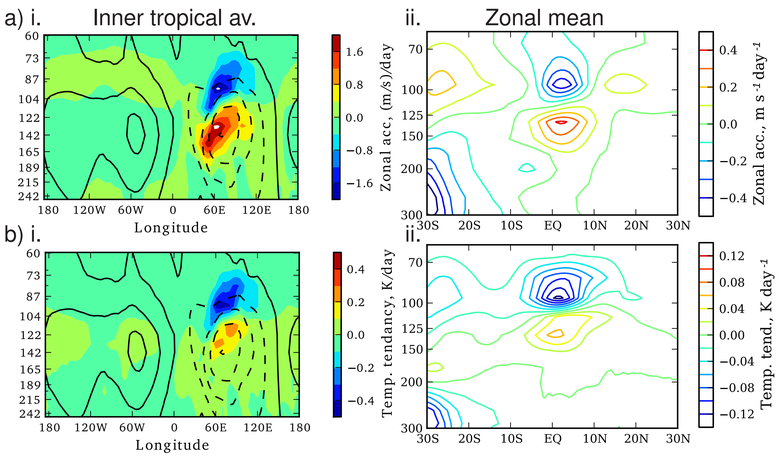

Figure 3 : Climatological a) zonal acceleration and b) temperature tendency for JJA computed using the rL scheme applied to ERA-Interim data from 1989 to 2009. i) shows the 10°N–10°S average, and ii) shows the zonal average.

- Forcing confined to 10°N–10°S.
- Strongly localised – forcing strongest is over the Indian Ocean/Maritime Continent.

3. Model Setup

We use a **T42 resolution dynamical core** (the GFDL FMS model) with 60 vertical levels (approximately **800 m resolution**) with a sponge above 1 hPa. We force the model with **diabatic heating** and **zonal acceleration** with a dipole structure:

$$F \propto \begin{cases} \cos\left(\frac{\pi x}{2L_x}\right)\cos\left(\frac{\pi y}{2L_y}\right)\sin\left(\frac{\pi(z_0-z)}{L_z}\right) & \text{where } |x|<L_x, |y|<L_y, |z-z_0|<L_z, \\ 0 & \text{otherwise.} \end{cases}$$

Parameters are chosen to give a similar structure to the dipole structure observed over the Indian Ocean/Maritime Continent, so

$L_x = 30°$ $L_y = 10°$ $L_z = 0.5H \approx 3.5$ km $z_0 = 2.2H \approx 15$ km

4. Modelling Results

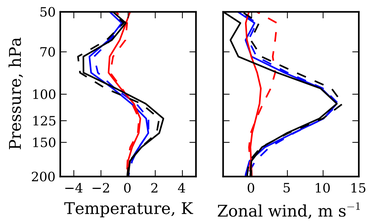

Figure 4 : Zonal average response to zonally symmetric forcings (solid) and localized forcings (dashed) averaged over 10°N–10°S.

- Responses for **zonally symmetric forcings (solid)** and **localised forcings (dashed)** similar.
- Temperature response for both **diabatic heating (red)** and **zonal acceleration (blue)**.
- Large wind response only for zonal acceleration forcing.
- **Both forcings (black)** approx. linear combination of the two seperate responses.

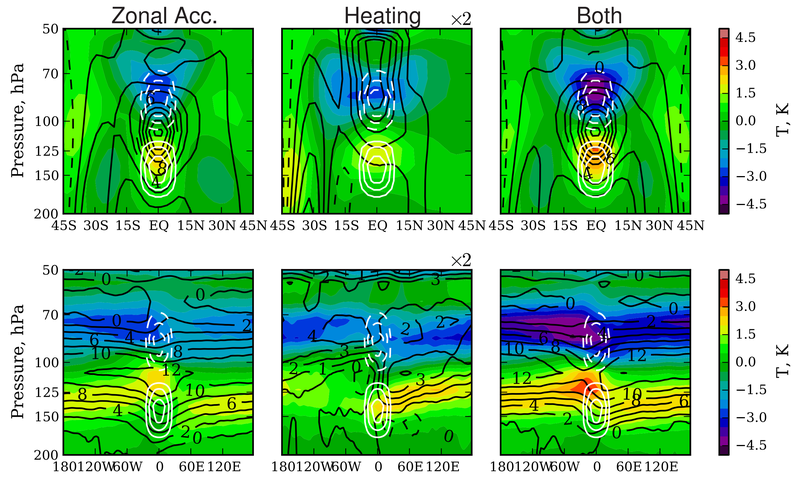

Figure 5 : Zonal mean (top) and inner tropical mean (bottom) temperature response (colors) and wind response (black contours; contour spacing 2 m s^{-1}). Response doubled for heating so as to use the same colour scale. White contours show the structure of the forcing.

- Response confined to inner tropics.
- **Response $\sim$ 12 m s^{-1} and 4 K.**
- Remarkably zonally symmetric.
- Standing wave in heating response.

Conclusions

- Vertical mixing is prevalent in the TTL in ERA-Interim. We show significant forcing terms are associated with this mixing.
- We show these forcings are very sensitive to parametrisation.
- Our modelling study shows significant potential impact in the TTL. Forcing similar to that in ERA-Interim leads to temperature perturbations of 4 K and zonal wind perturbations of 12 m s^{-1}.

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5. Analysis of Model Response

$$a^{-1}\overline{v}\frac{\partial\overline{\theta}}{\partial\phi}+\overline{w}\frac{\partial\overline{\theta}}{\partial z}=-\tau^{-1}(\overline{\theta}-\theta_{eq})+e^{\kappa z/H}F_Q^{\text{sym}}-\frac{1}{a\cos\phi}\frac{\partial(\overline{\theta'v'}\cos\phi)}{\partial\phi}-\frac{1}{\rho_0}\frac{\partial(\rho_0\overline{\theta'w'})}{\partial z} \quad (1)$$

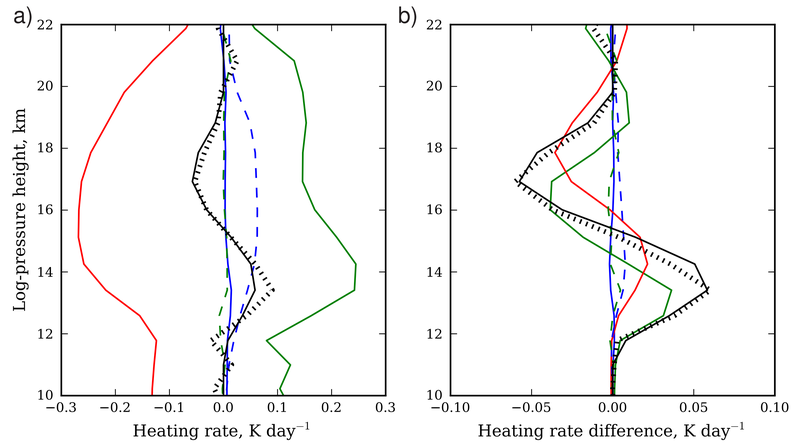

Figure 6 : a) Profiles of the terms in (1) averaged over ±10° for the run forced with zonally symmetric heating. Solid lines correspond to the boxed terms in (1). Dashed lines are the eddy terms (coloured in (1)). b) Profiles of the difference between the forced and unforced runs for each quantity shown in a).

$$\overline{v}\left[\frac{1}{a\cos\phi}\frac{\partial(\overline{u}\cos\phi)}{\partial\phi}-f\right]+\overline{w}\frac{\partial\overline{u}}{\partial z}=F_X^{\text{sym}}-\frac{1}{a\cos^2\phi}\frac{\partial(\overline{u'v'}\cos^2\phi)}{\partial\phi}-\frac{1}{\rho_0}\frac{\partial(\rho_0\overline{u'w'})}{\partial z} \quad (2)$$

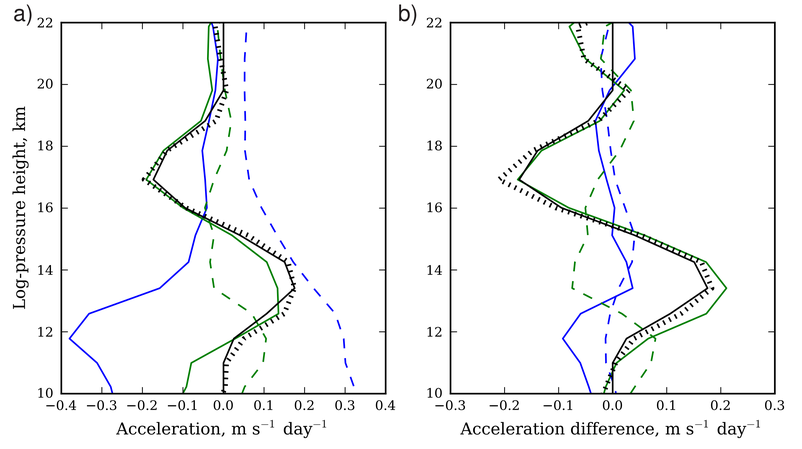

Figure 7 : a) Profiles of the terms in (2) averaged over ±10° for the run forced with zonally symmetric zonal acceleration forcing. Solid lines correspond to the boxed terms in (2). Dashed lines are the eddy terms (coloured in (2)). b) Profiles of the difference between the forced and unforced runs for each quantity shown in a).

In both cases, the **vertical advection** term dominates the response (the subplots 6b and 7b). Response to background w_0 is most of this. So

$$\delta u \sim F_X / w_0$$

Radiative damping also important for temperature response.

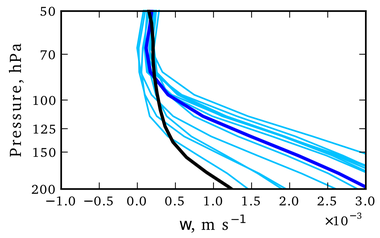

Figure 8 : Mean vertical velocity $\overline{w}$ averaged over 10°N to 10°S for the model run and for ERA-Interim (blue lines, dark line is average, light lines are climatological monthly averages.)

Model has reasonable upwelling compared with ERA-Interim above 100 hPa (ERA-Interim may have too much upwelling).