Diagnosing the impact of numerics on transport in GCMs using the Leaky Pipe model of Stratospheric Transport

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Disagreement in transport among climate models

- A spread of over 60 years in ozone recovery times among Chemistry Climate Models (CCMs).
- Differences correlated more strongly with differences in transport than with differences in chemistry (Karpechko et al. 2013)
- Uncertainty in ozone recovery largely a transport problem!

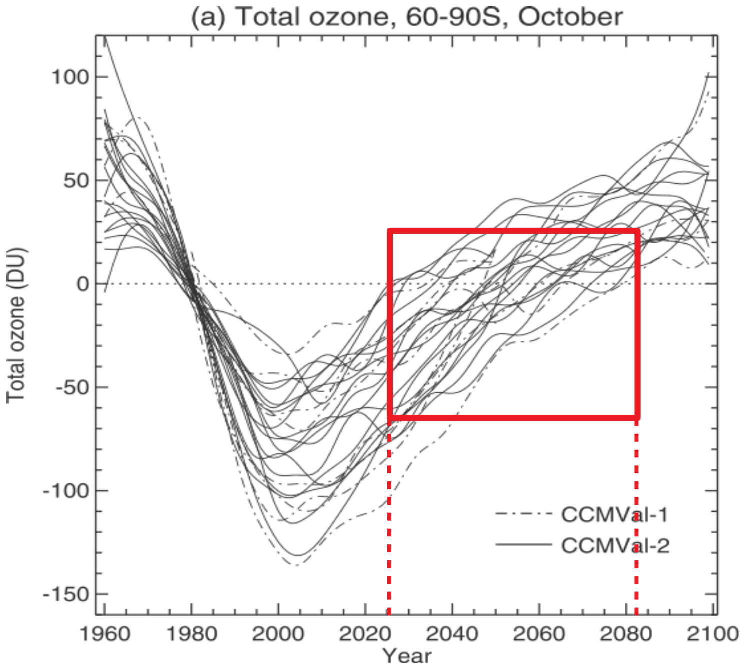


Fig : Model projections of ozone recovery (taken from Karpechko et al. 2013)

Stratospheric transport is strongly coupled with dynamics

- Besides chemistry, the large-scale circulation also plays a dominant role in determining the large-scale stratospheric tracer distribution
- We focus on the impact of the circulation on tracer distributions using the age-of-air, a measure of transport time scales
- In models, both differences in numerical advection and resolved dynamics can lead to differences in transport.

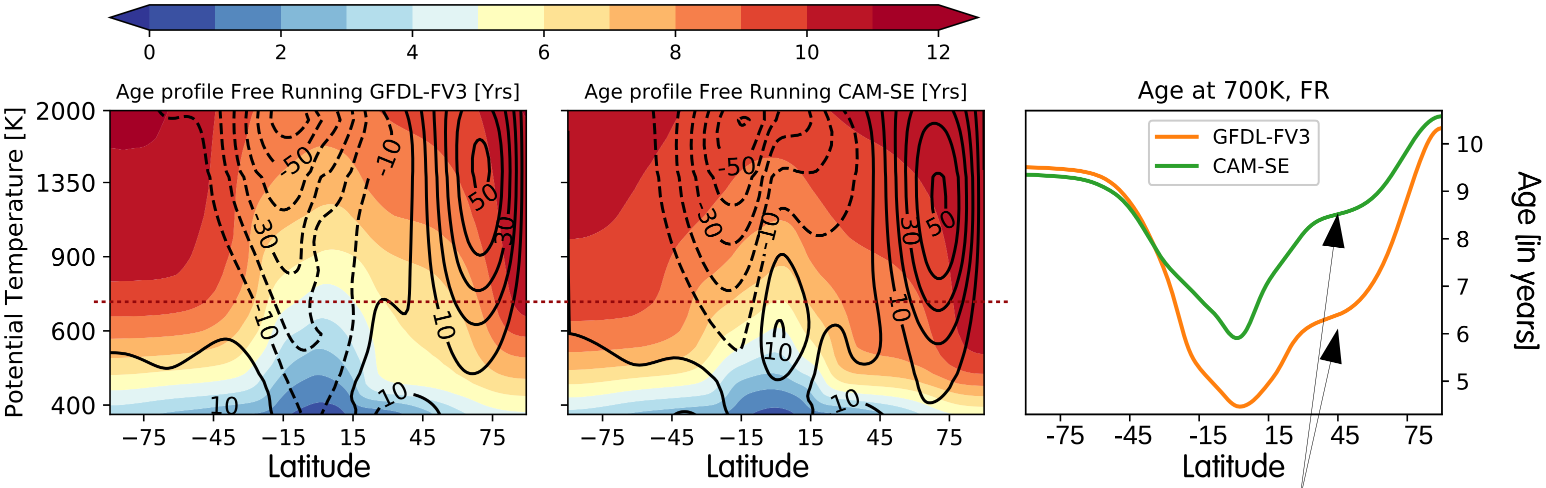
Strikingly different age-of-air in modern dynamical cores

CAM-SE

CAM SPECTRAL ELEMENT

GFDL-FV3

CUBED SPHERE
FINITE VOLUME

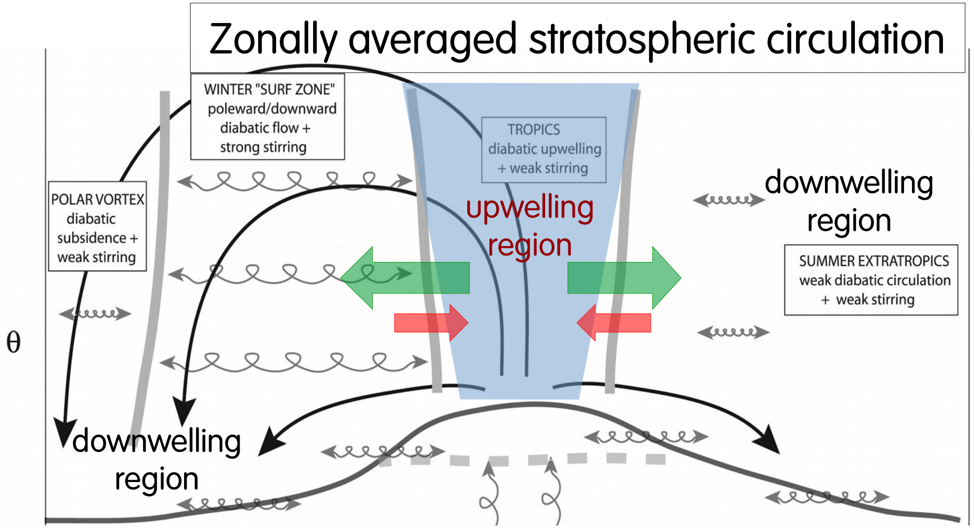


Age of air with superimposed zonal wind profiles

Age of air in SE is 40% older than FV3

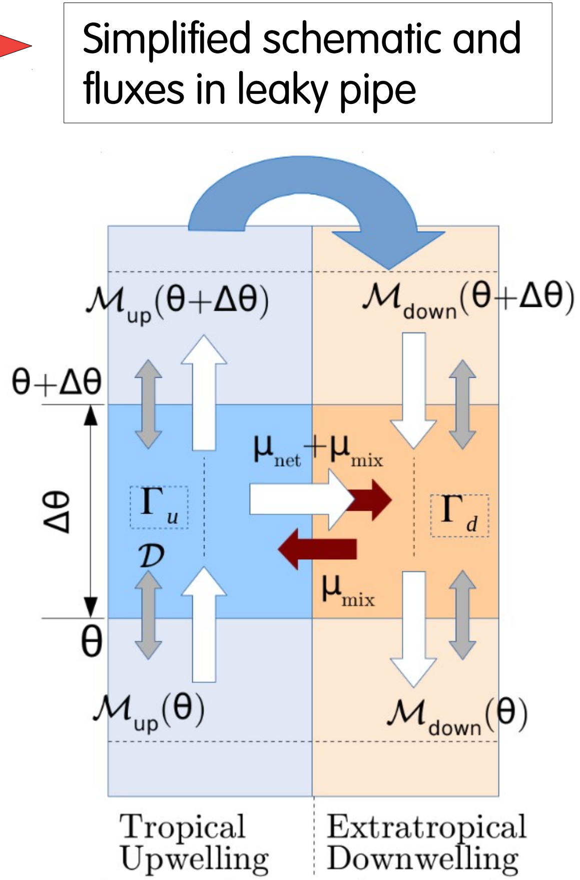
- 2 state-of-the-art dynamical cores, forced with identical idealized diabatic forcing (Held-Suarez + Polvani-Kushner) : Integrated for 10,000 days. Age computed using a clock tracer near surface.
- The 2 cores develop strikingly different age-of-air profiles in the stratosphere. Why?
- We investigate the role of differences in dynamics, unresolved diabatic fluxes and numerical diffusion

Using the Leaky Pipe to understand model transport differences



(Figure credits : Dr. Marianna Linz)

horizontally integrating



- The theoretical leaky pipe model (Neu and Plumb '99) integrates and divides the stratosphere into 2 regions of upwelling (u) and downwelling (d).
- The net and mixing fluxes b/w the two regions are specified as a function of height.
- Following Linz et al. 2016, we map the 3-D model circulation and transport (age) onto the leaky pipe to diagnose the net and mixing fluxes.

Transport metrics using isentropic analysis of age of air

1. Full model transport and 1D leaky pipe connected using diabatic mass-flux weighted ages (Linz et al. 2016, JAS)

$$\boxed{\Gamma_u(\theta) = \frac{\int_u \rho_\theta \dot{\theta}\Gamma \, dA}{\int_u \rho_\theta \dot{\theta} \, dA} \quad , \quad \Gamma_d(\theta) = \frac{\int_d \rho_\theta \dot{\theta}\Gamma \, dA}{\int_d \rho_\theta \dot{\theta} \, dA}}$$

$\Gamma_u(\theta)$: mass-flux wtd upwelling age

$\Gamma_d(\theta)$: mass-flux wtd downwelling age

2. The vertical gradient of these quantities allow quantifying the mixing fluxes across the subtropical barrier (Linz et al. *in prep*)

Vertical gradient :

$$\boxed{\frac{\partial \Gamma_u}{\partial \theta} = \frac{\sigma}{\mathcal{M}} + \frac{\mu_{mix} \Delta\Gamma}{\mathcal{M}}}$$

$\mathcal{M}(\theta)$: diabatic mass flux

$\sigma(\theta)$: horizontally avgd density

$\mu_{mix}(\theta)$: ET $\rightarrow$ T mixing flux

We compute the weighted age Γ_u and Γ_d and μ_{mix} from the model data

Creating parallelism between full model transport and 1D theoretical Leaky Pipe model

- The original leaky pipe formulation uses constant vertical velocity and mixing efficiency. While it makes the problem analytically solvable, it prevents a direct connection between models and theory.

- **We allow vertical variations of all the leaky pipe parameters** and reformulate it in isentropic coordinates, for a more accurate model-to-theory connection.

- These equations are numerically integrated with ascent rate, mixing efficiency and mass distribution determined using model data

Theoretical leaky pipe formulation

$$-K_M\frac{\partial^2\Gamma_M}{\partial Z^2}+\left(\frac{K_M}{H}-\alpha W_T\right)\frac{\partial\Gamma_M}{\partial Z}-(1+\epsilon)\lambda(\Gamma_T-\Gamma_M)=1$$

$$-K_T\frac{\partial^2\Gamma_T}{\partial Z^2}+\left(\frac{K_T}{H}+W_T\right)\frac{\partial\Gamma_T}{\partial Z}+\frac{\epsilon\lambda}{\alpha}(\Gamma_T-\Gamma_M)=1$$

diffusion

ascent rate

mixing efficiency

Stratospheric mass distribution

$$W_T=0.3mm\ s^{-1}\qquad \alpha=1/2\qquad \epsilon=1$$

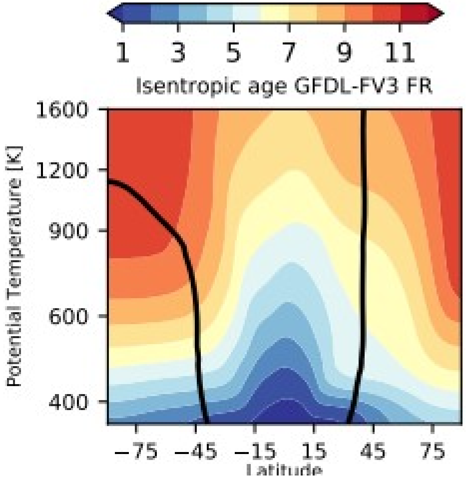
$$W_T\rightarrow W_T(Z)\qquad \alpha\rightarrow\alpha(Z)\qquad \epsilon\rightarrow\epsilon(Z)$$

Computed from full model data

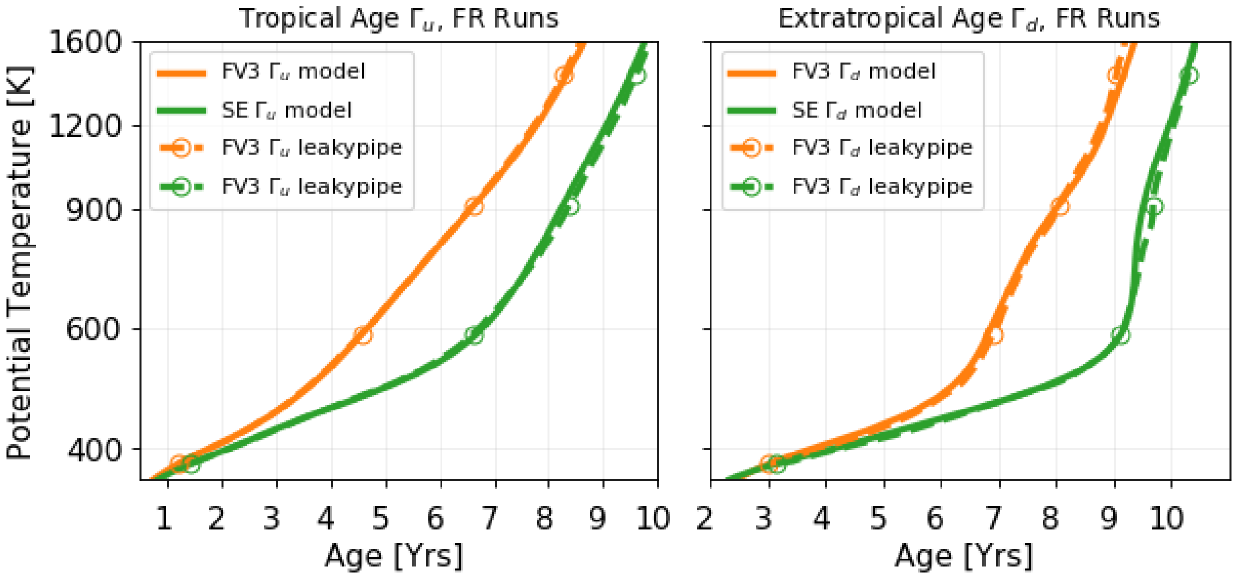
$$-K_M\frac{\partial^2\Gamma_M}{\partial Z^2}+\left(\frac{K_M}{H}-\alpha(Z)W_T(Z)\right)\frac{\partial\Gamma_M}{\partial Z}-(1+\epsilon(Z))\lambda(Z)(\Gamma_T-\Gamma_M)=1$$

$$-K_T\frac{\partial^2\Gamma_T}{\partial Z^2}+\left(\frac{K_T}{H}+W_T(Z)\right)\frac{\partial\Gamma_T}{\partial Z}+\frac{\epsilon(Z)\lambda(Z)}{\alpha(Z)}(\Gamma_T-\Gamma_M)=1$$

Comparing the model age and the leaky pipe “fit”



Dimensional reduction
from full model age

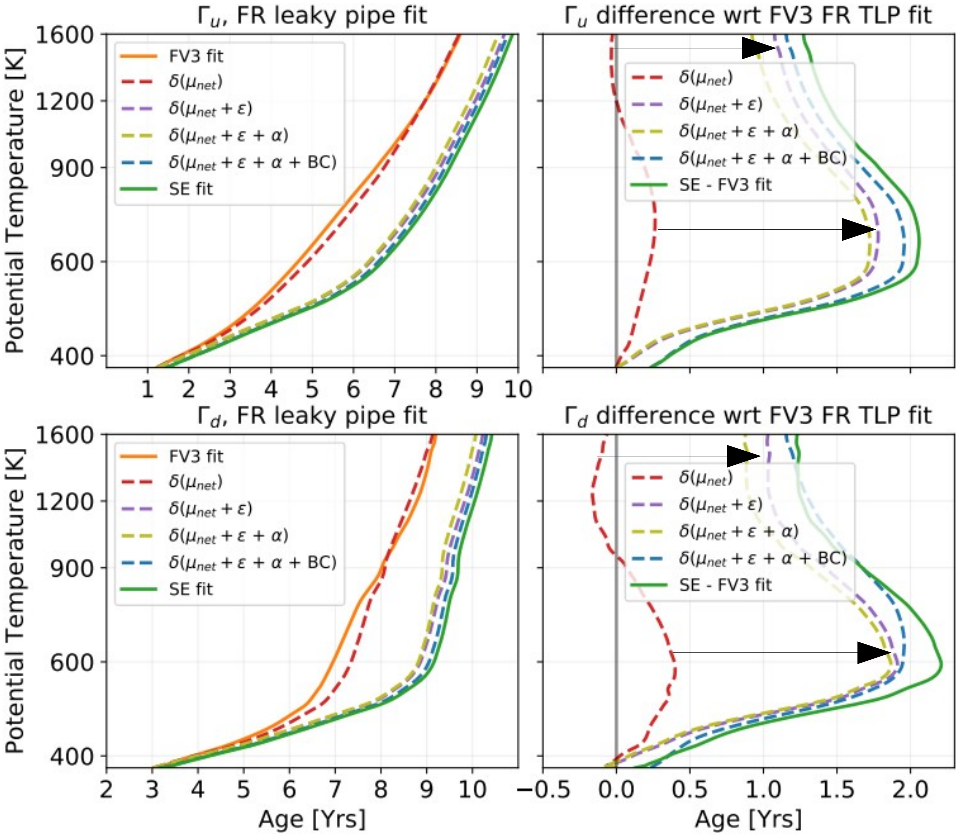


A good fit is obtained between integrated age from models and the age from vertically varying leaky pipe formulation in both the regions.

Isolating the contribution of different factors to transport

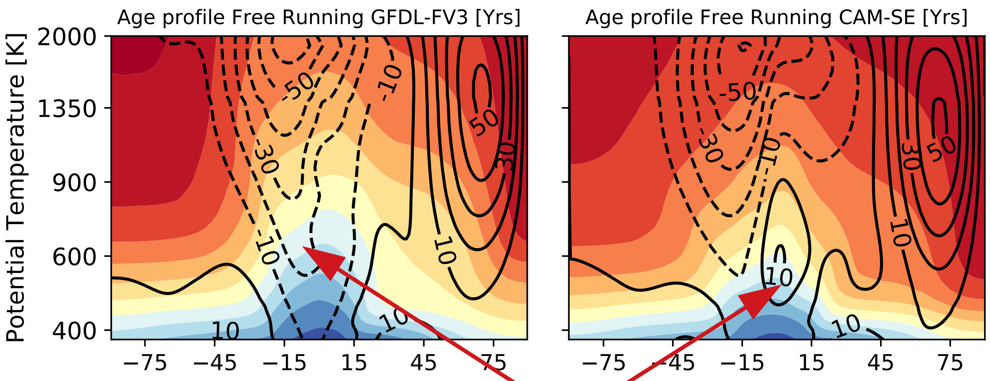
$$\Gamma_{SE} - \Gamma_{FV3} = \delta(W_T) + \delta(\mu_{mix}) + \delta(\alpha) + \delta(\text{diffusion}) + \delta(\text{tropopause boun. cond.})$$

i.e. mixing efficiency

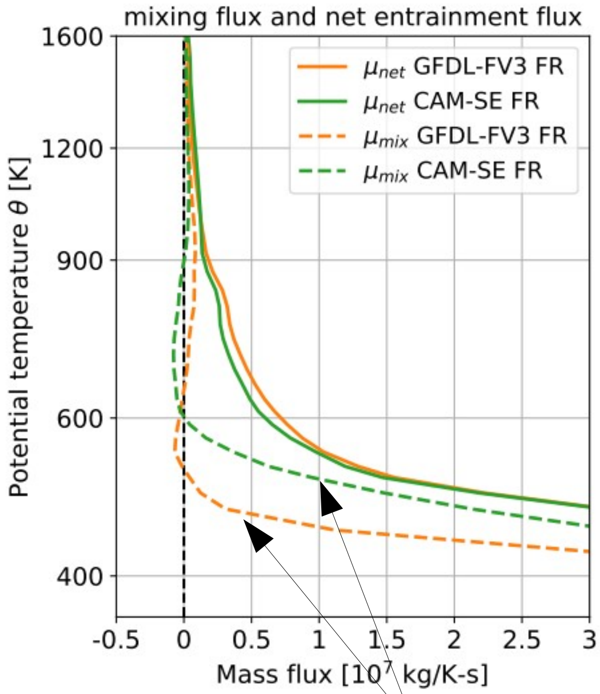


- We start with leaky pipe fit of FV3 climate model (in orange) and *incrementally* force the leaky pipe model with the parameters of SE model (in green).
- Difference in mixing between the models accounts for 3/4th of the difference in age (red → violet curve).
- The residual difference (between solid green and dashed blue) represents differences due to numerical diffusion

The extratropical-tropical mixing fluxes are different indeed!



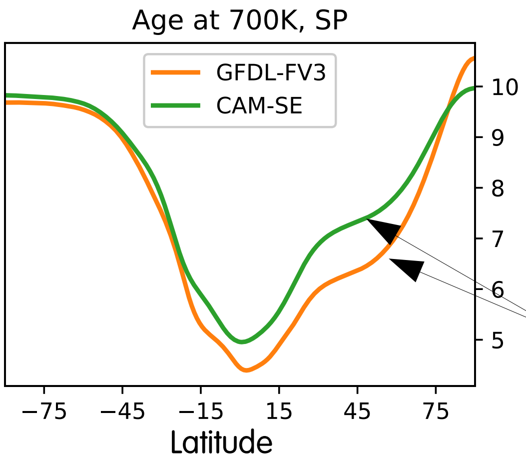
Very different tropical climatology among the two models



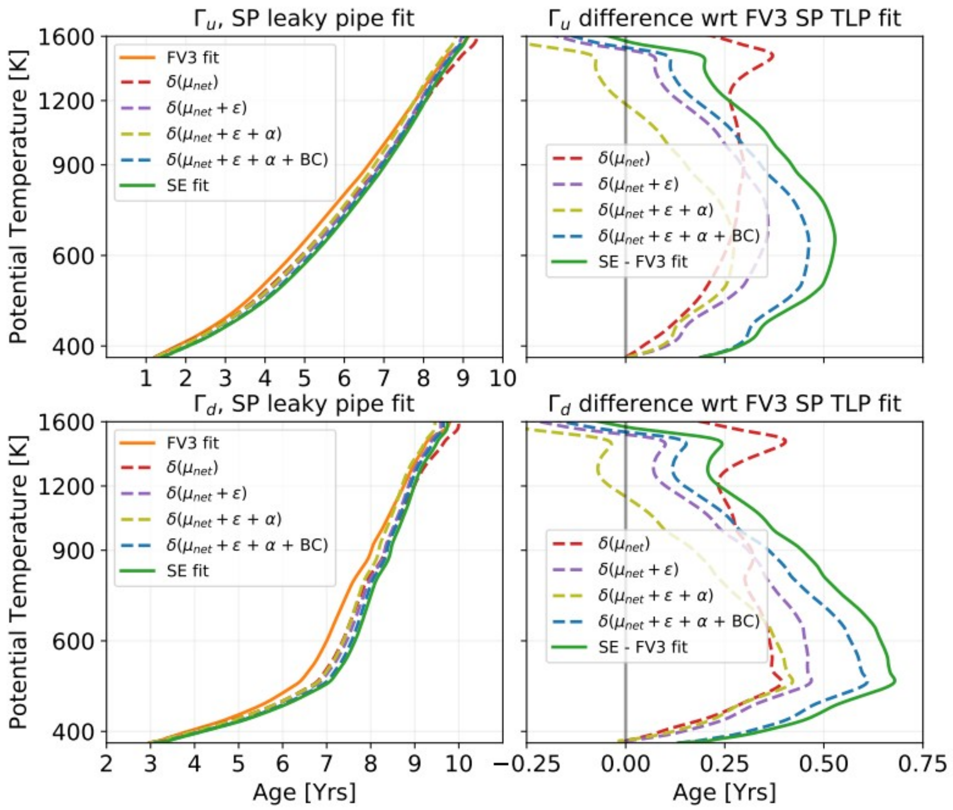
Higher mixing flux in SE as compared to FV3

- The tropical winds in the two models have different phases. Akin to different phases of the QBO.
- Westerlies induce more mixing between the two regions by allowing the midlatitude mixing fluxes deeper into the tropics (critical line theory)

Does constraining the tropical winds resolve the issue?



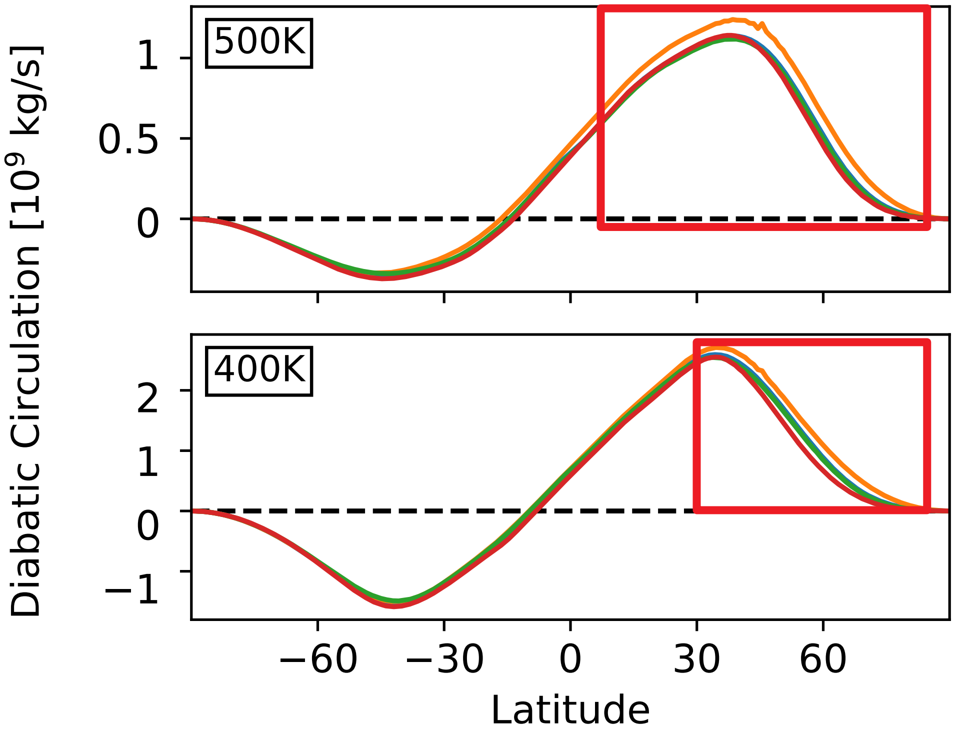
Constraining tropical winds to be identical among models drastically reduces the age difference. Some difference still remains.



- In this case, analysis shows that most of the age difference can now be explained due to differences in diabatic circulation (red dashed curve).
- Differences in mixing have small contribution (red vs violet dashed curve) in the lower and mid stratosphere.

The diabatic circulation is noticeably different indeed!

- Figure shows the diabatic mass streamfunction at two different isentropes.
- The FV3 model (in orange) develops a slightly higher diabatic circulation as compared to the SE model (in green), when the tropical winds are constrained.
- A faster circulation results in a younger age.



References

- Gupta, Aman, Edwin P. Gerber, and Peter H. Lauritzen: "Numerical impacts on tracer transport: A proposed intercomparison test of Atmospheric General Circulation Models", *Quart. J. Roy. Meteor. Soc.*, under revision.

- Gupta, Aman, Edwin P. Gerber, R. Alan Plumb, Olivier Pauluis and Peter H. Lauritzen: "Numerical impacts on tracer transport : Understanding biases in dynamical cores with the leaky pipe framework.", *J. Atmos. Sci.*, in prep.

- Linz, Marianna, R. Alan Plumb, Edwin P. Gerber, Douglas E. Kinnison, and Aman Gupta: "Stratospheric adiabatic mixing rate derived from the vertical age gradient", in prep.