Variability of stratospheric mean age of air linked to residual circulation and eddy mixing

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Motivation

Mean age: average time elapsed since crossing tropopause

$\Rightarrow$ commonly used measure for residual circulation (mass flux)

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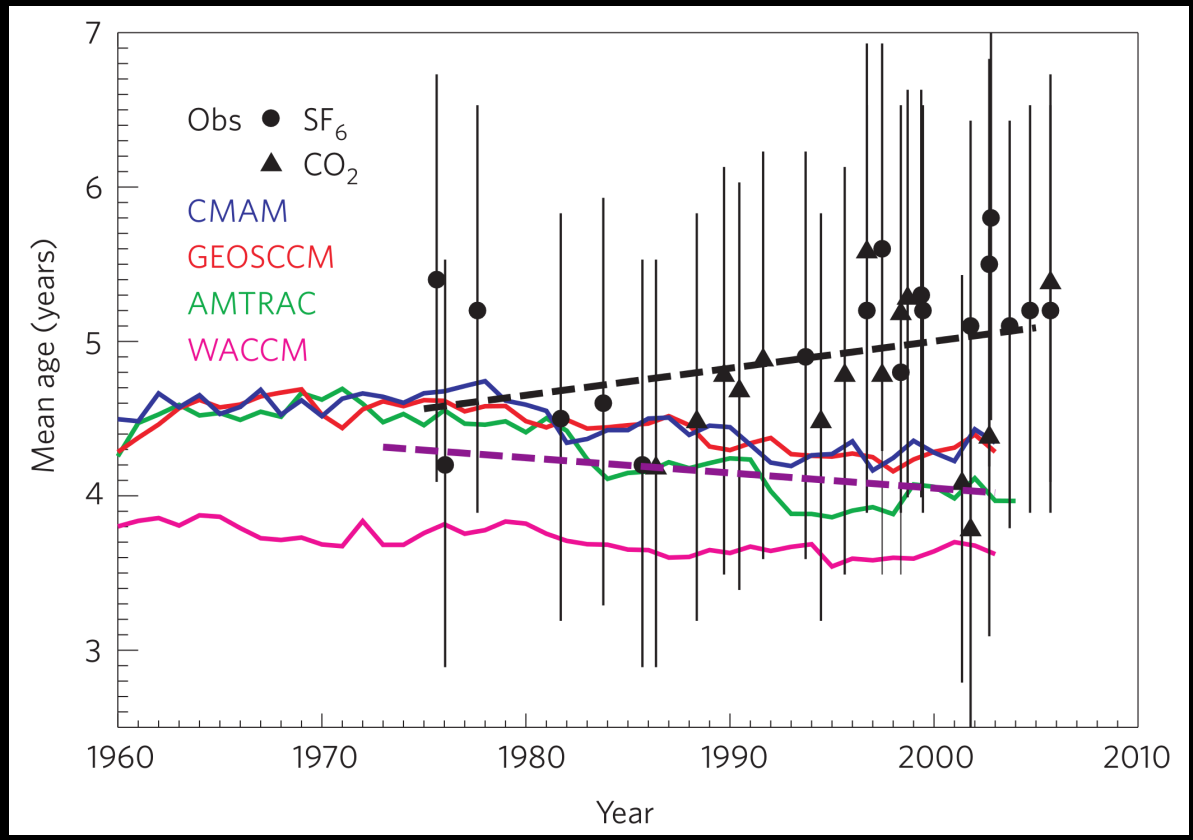


[Waugh,2009]

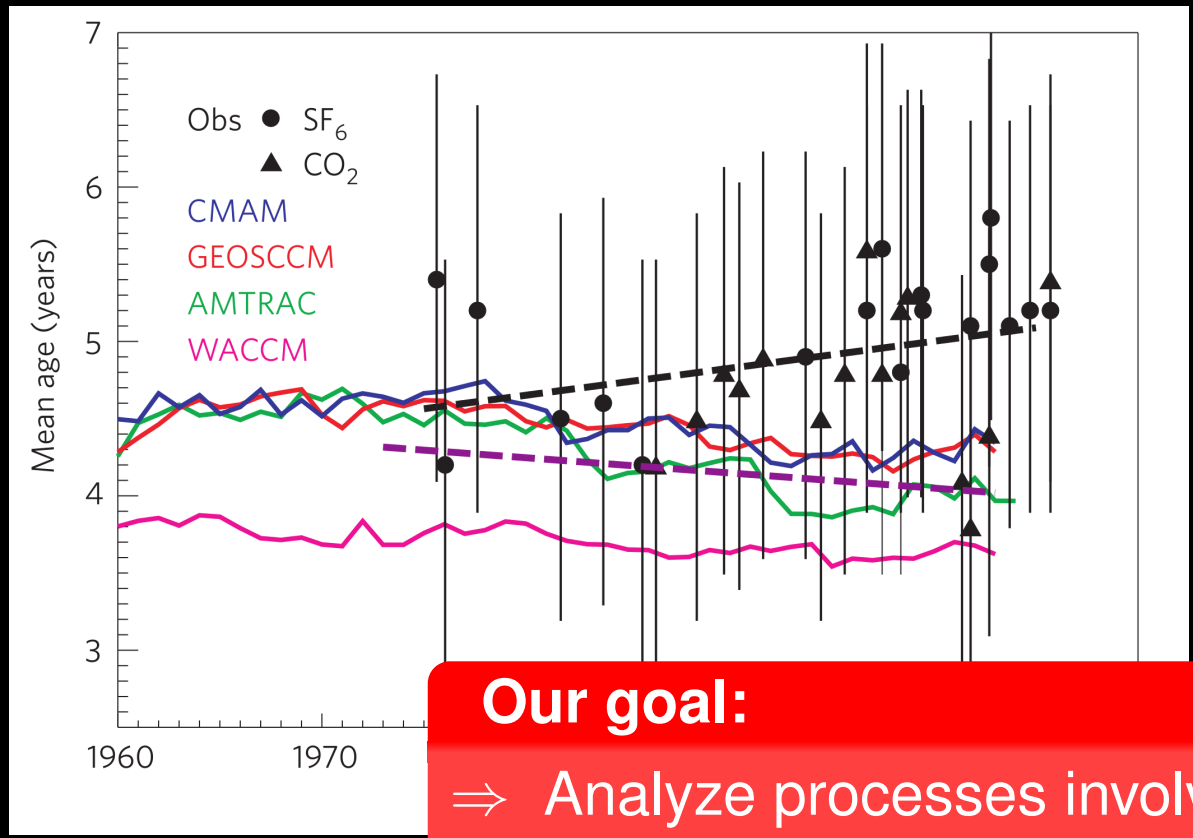
★ **Change of stratospheric Brewer-Dobson circulation???**

$\Rightarrow$ discrepancy observations $\leftrightarrow$ models! [e.g., Engel et al.,2009; Butchart et al.,2010]

Motivation

Mean age: average time elapsed since crossing tropopause

$\Rightarrow$ commonly used measure for residual circulation (mass flux)



Our goal:

$\Rightarrow$ Analyze processes involved!

- residual circulation & mixing
- their impact on mean age

h,2009]

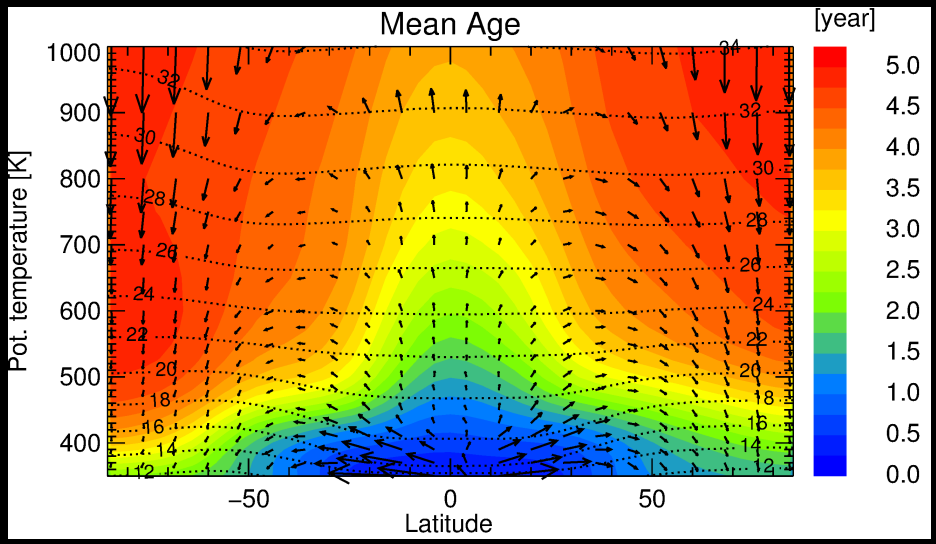
★ **Change of stratosphe ??**

$\Rightarrow$ discrepancy observations ←

Mean age and trend 1988–2012

- Lagrangian chemistry transport model CLaMS
  (ERA-Interim / diabatic heating rates / ‘clock-tracer’ age)

- Simulation of mean age 1988–2012



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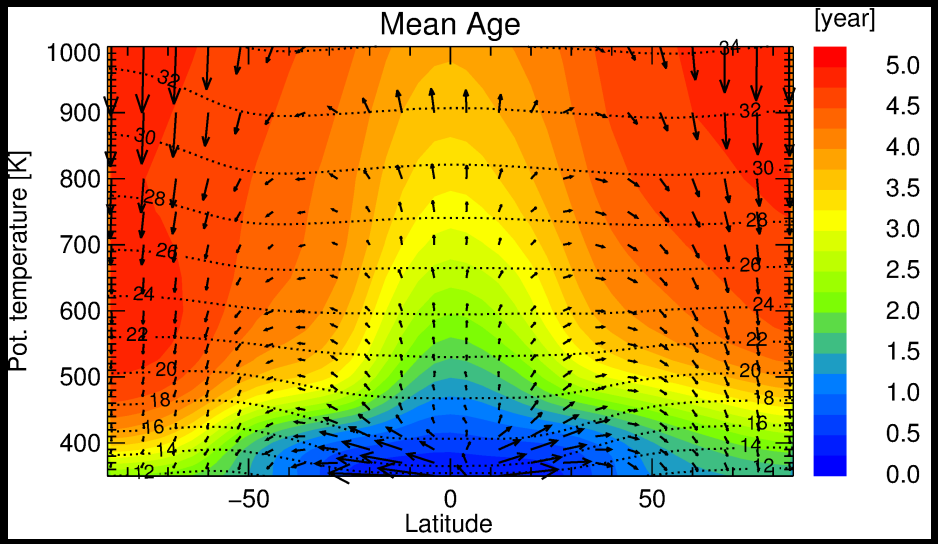
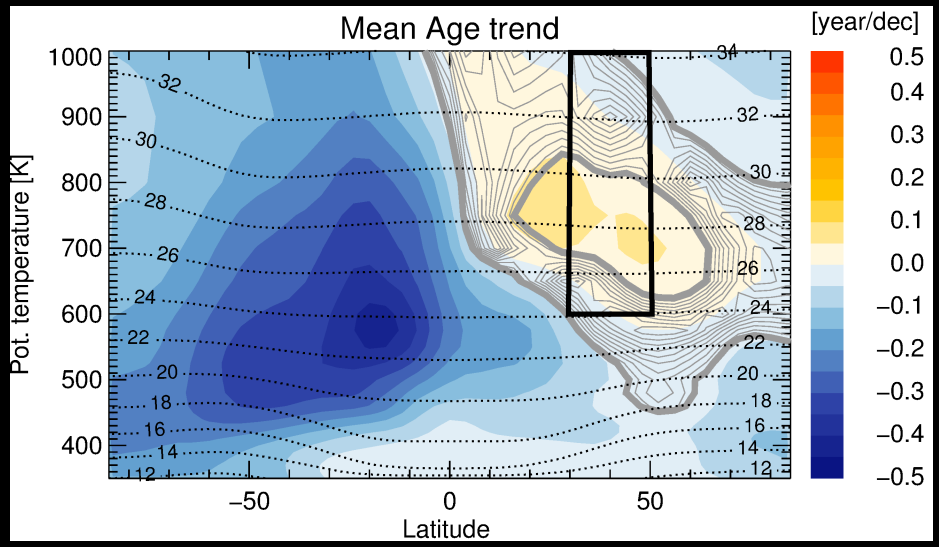
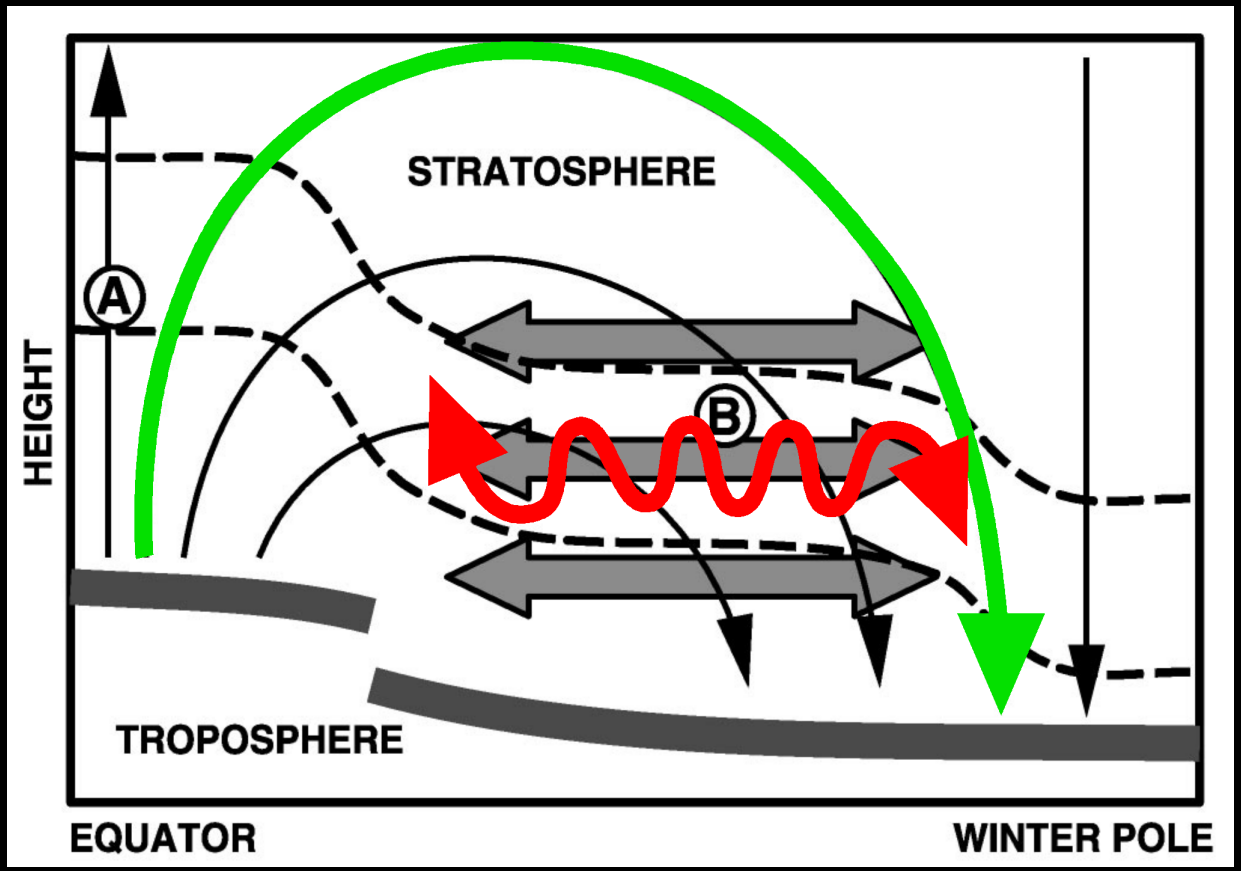




Mean age trend:

- mainly negative
- positive in NH subtropics

Stratospheric transport

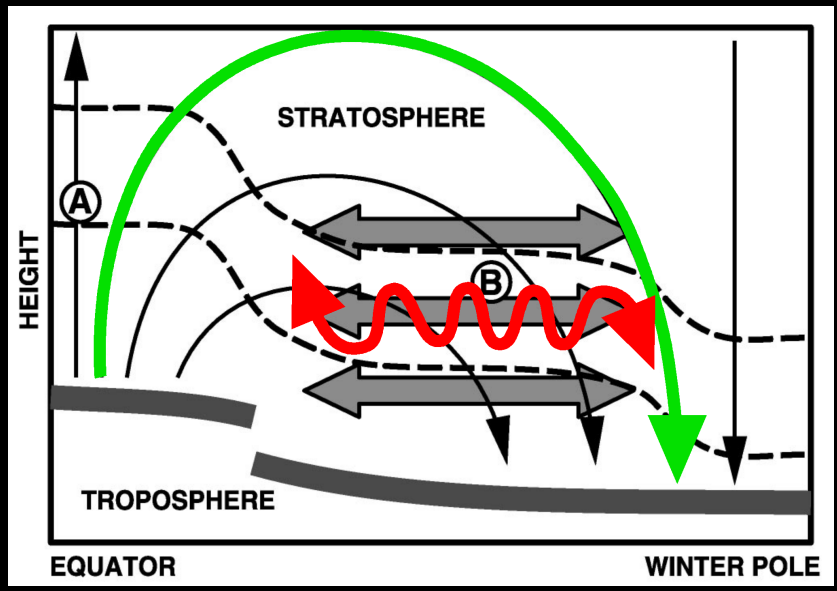


[Waugh&Hall, 2002]

★ Brewer-Dobson circulation: residual circulation (slow)
isentropic eddy mixing (fast)

Separate resid. circulation & eddy mixing effects

★ Separate circulation & mixing effects on mean age



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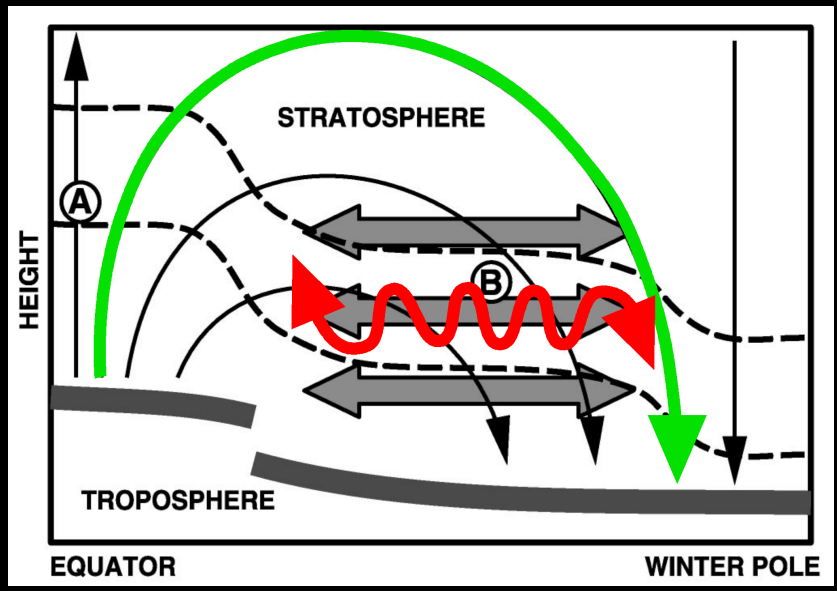


★ Isentropic zonal mean continuity eqn. for mean age Γ

$$\partial_t \overline{\Gamma} = -\overline{\mathbf{v}}^* \partial_y \overline{\Gamma} - \overline{\mathbf{Q}}^* \partial_\theta \overline{\Gamma} + \frac{1}{\sigma} \nabla \cdot \boldsymbol{M}_\Gamma - \frac{1}{\sigma} \partial_t (\overline{\sigma' \Gamma'}) + 1$$

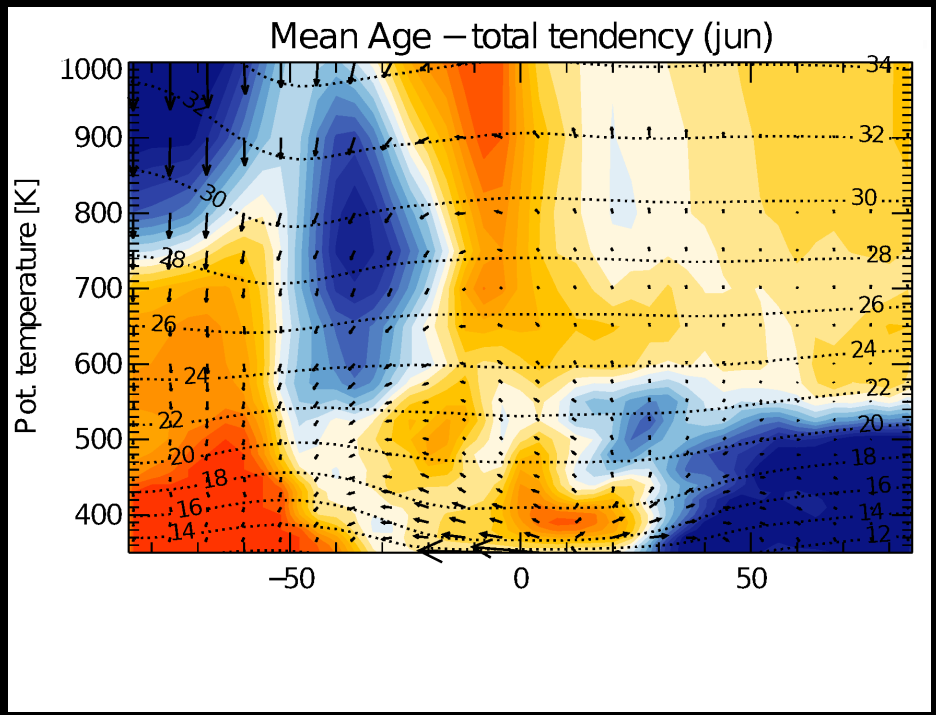
resid. circulation — eddy mixing

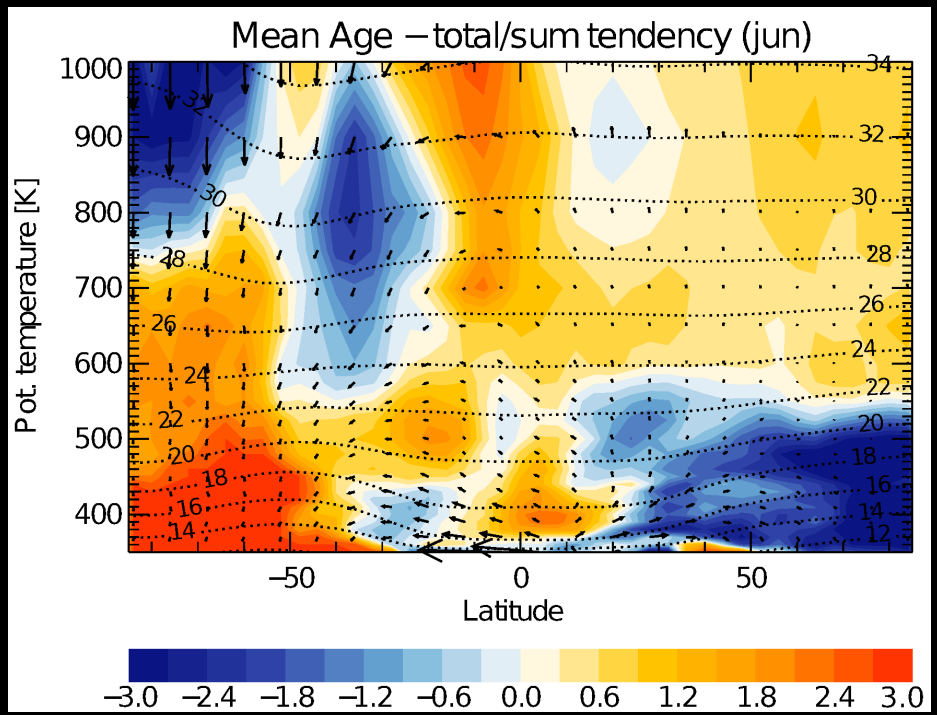
Age variability = circulation tendency + mixing tendency

Validity of isentropic zonal mean approach

★ Mean age tendency budget well closed!

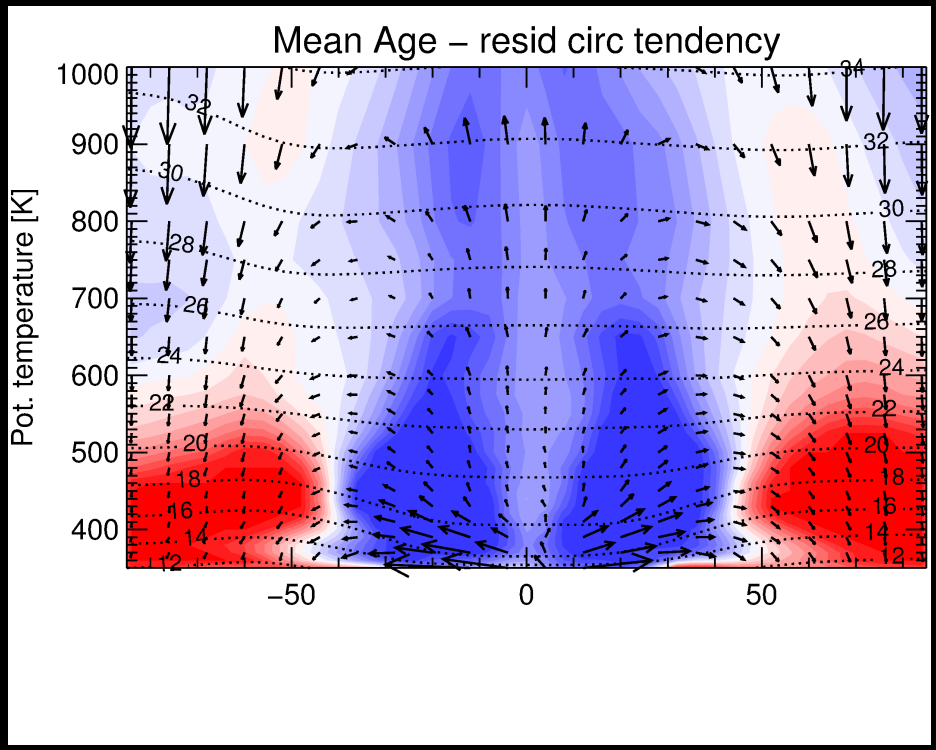
$$\partial_t \overline{\Gamma} = -\overline{v}^* \partial_y \overline{\Gamma} - \overline{Q}^* \partial_\theta \overline{\Gamma} + \frac{1}{\sigma} \nabla \cdot M_\Gamma - \frac{1}{\sigma} \partial_t (\overline{\sigma' \Gamma'}) + 1$$





Residual circulation vs. eddy mixing

Circulation



★ circulation ⇒ decreases age in tropics, increases in extratropics

Residual circulation vs. eddy mixing

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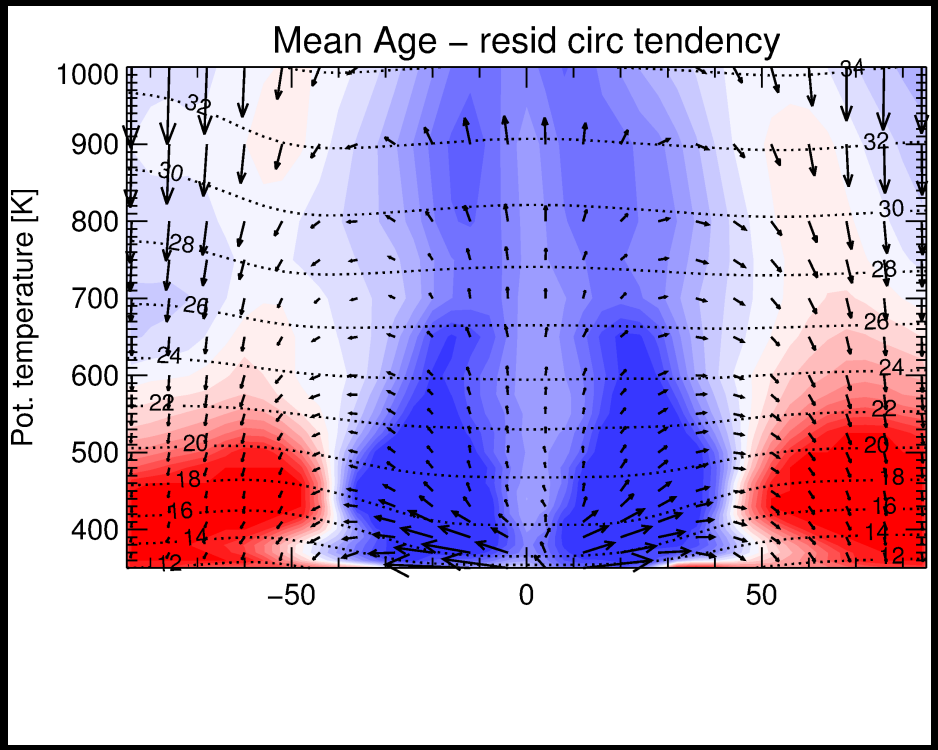
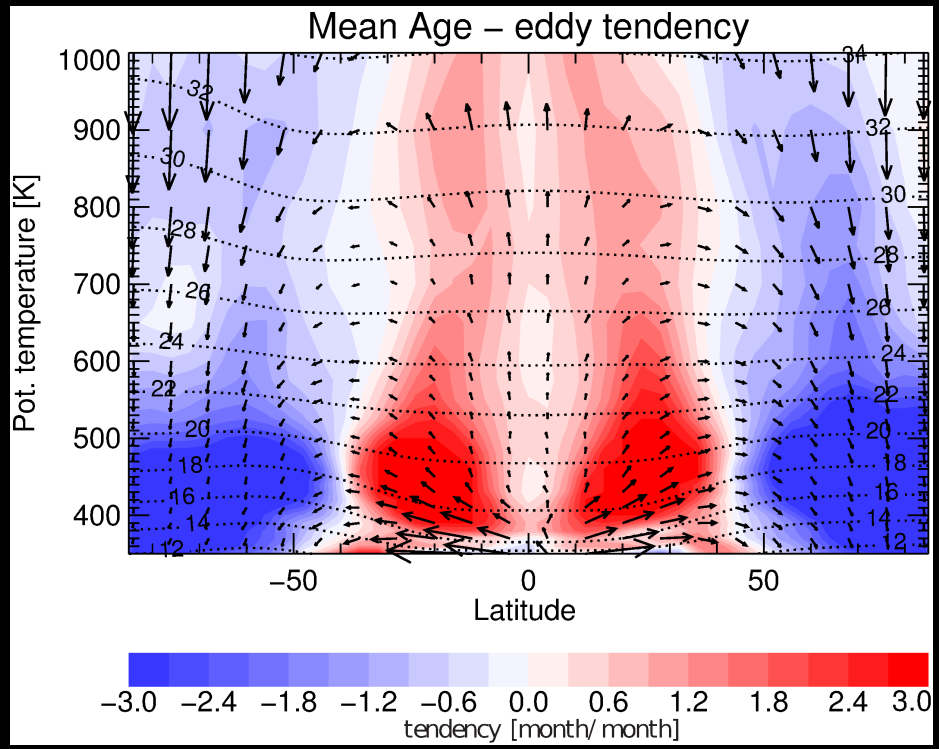


Mixing



★ circulation ⇒ decreases age in tropics, increases in extratropics

★ mixing ⇒ increases age in tropics, decreases in extratropics

Residual circulation vs. eddy mixing

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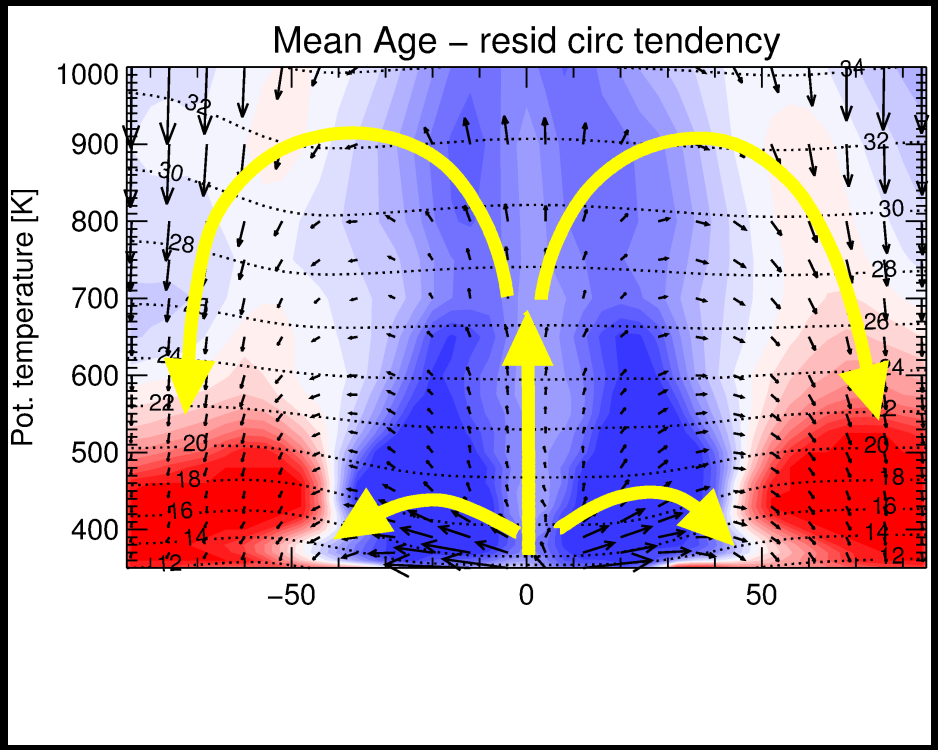
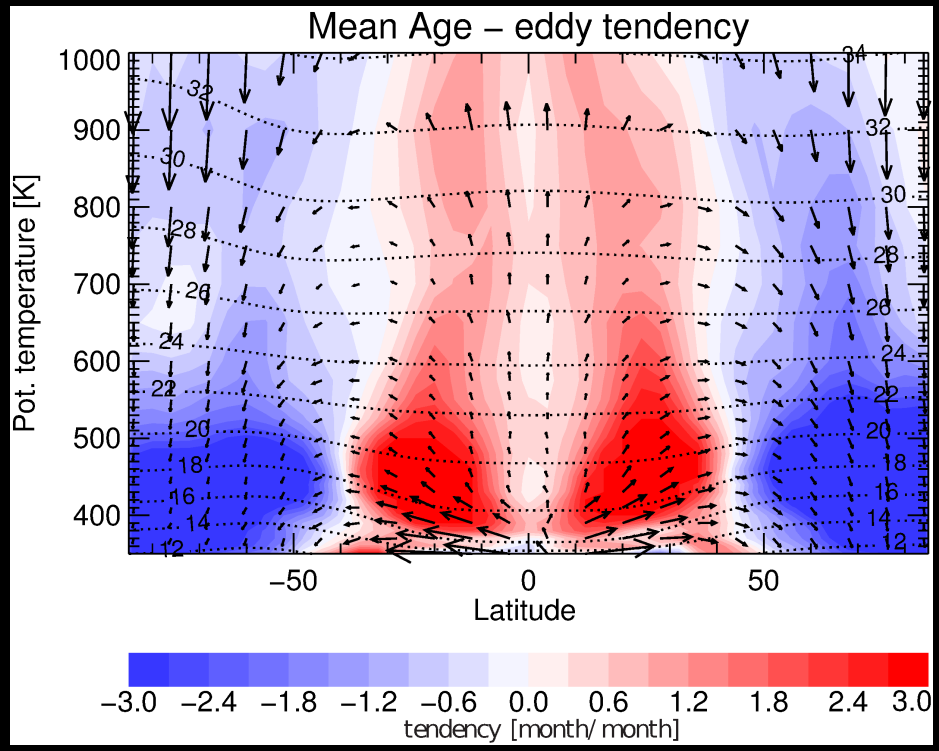


Mixing



★ circulation ⇒ decreas

★ mixing ⇒ increases a

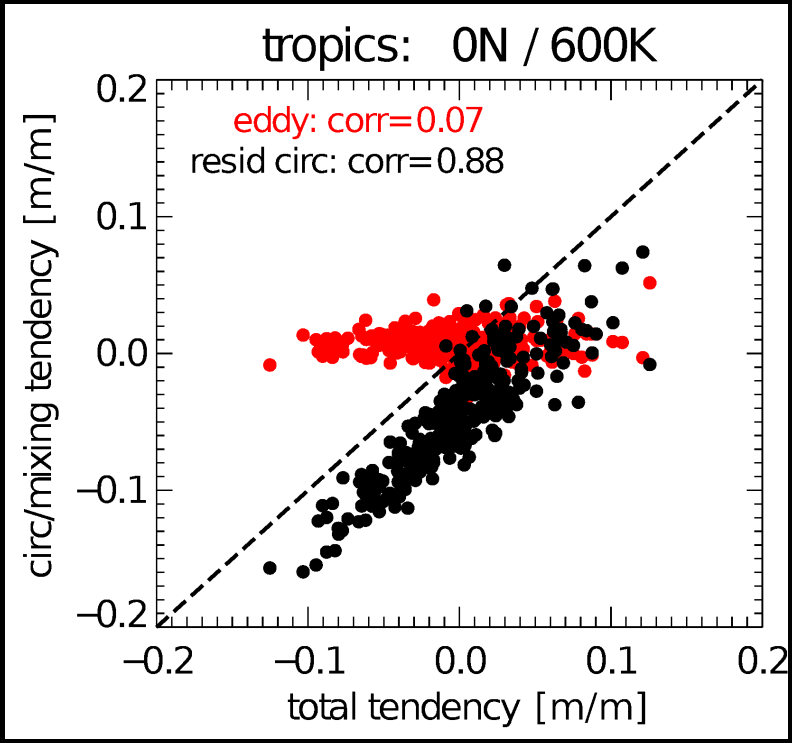
Circulation & mixing effects:

- shallow & deep circulation branches
- same order of magnitude, opposite!

⇒ **What controls age variability? – circulation?**

Control of mean age variability

★ correlation: mean age tendency (AoA) $\leftrightarrow$ circulation/mixing effect



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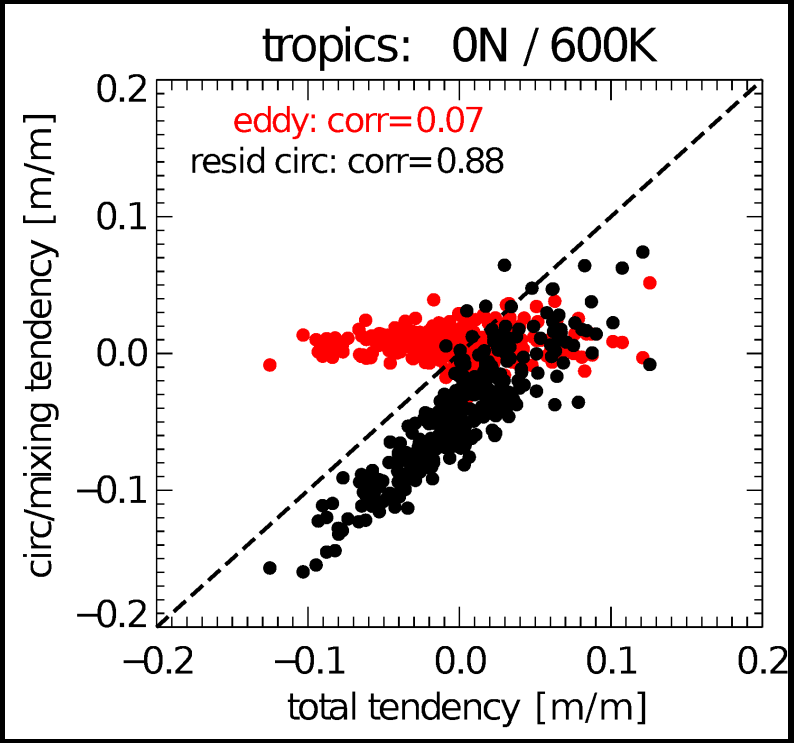

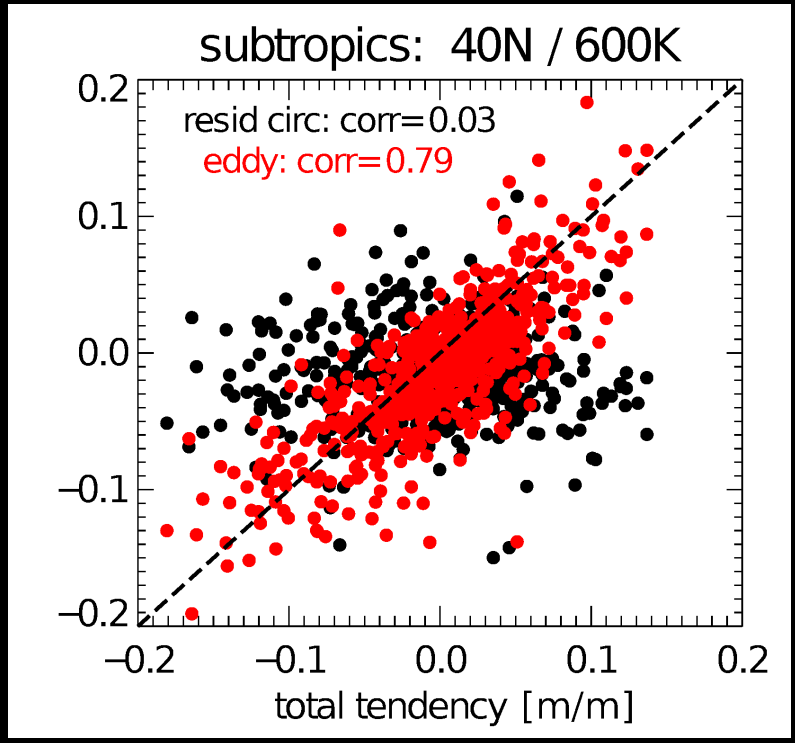

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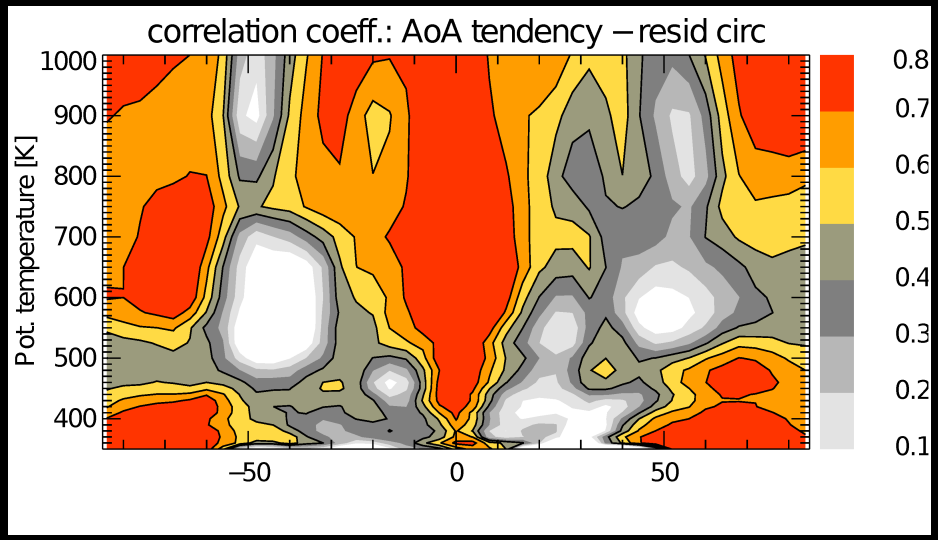
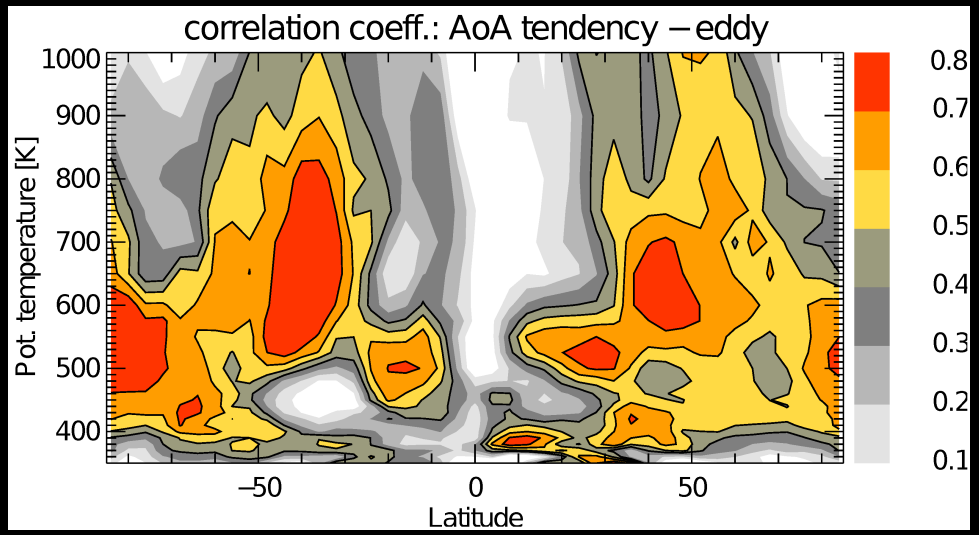


Mixing



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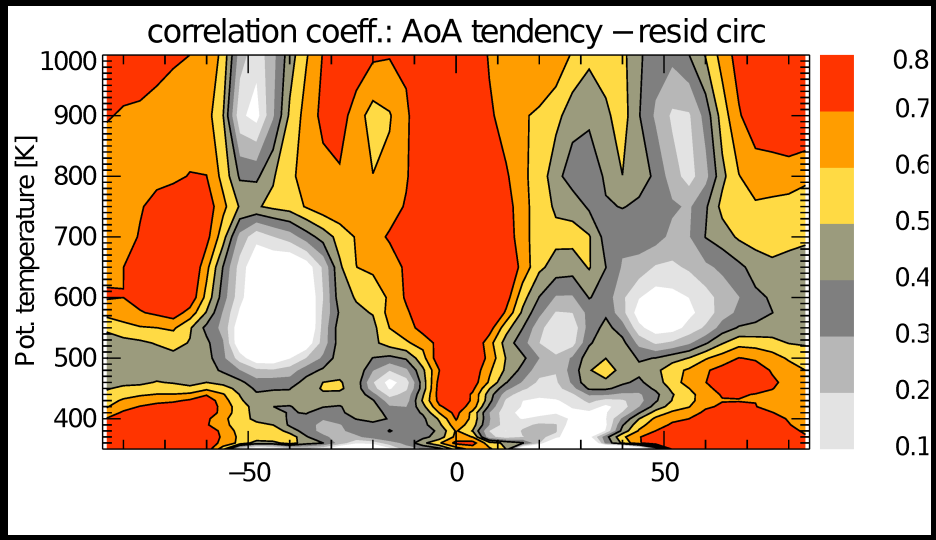

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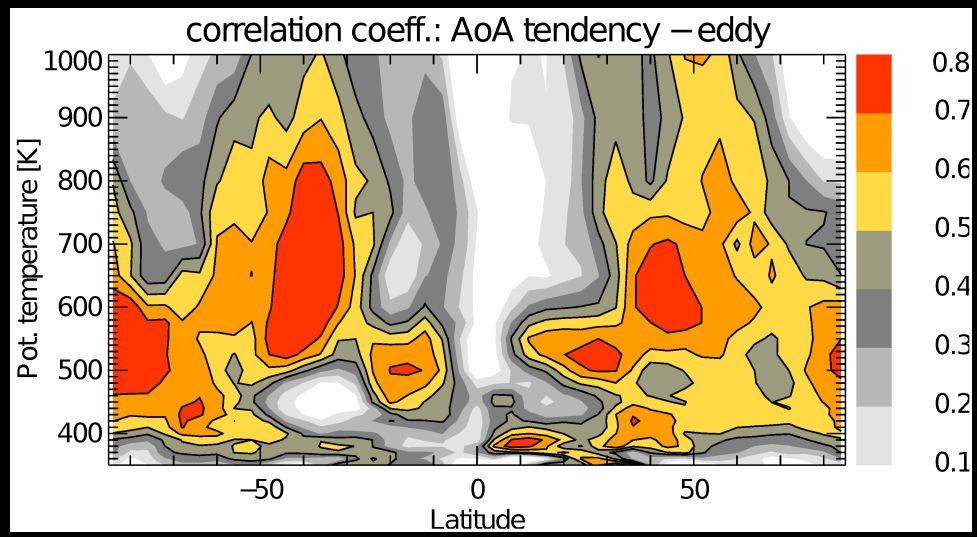


Mean age control:

⇒ circulation: tropics & high-lat upper stratosphere

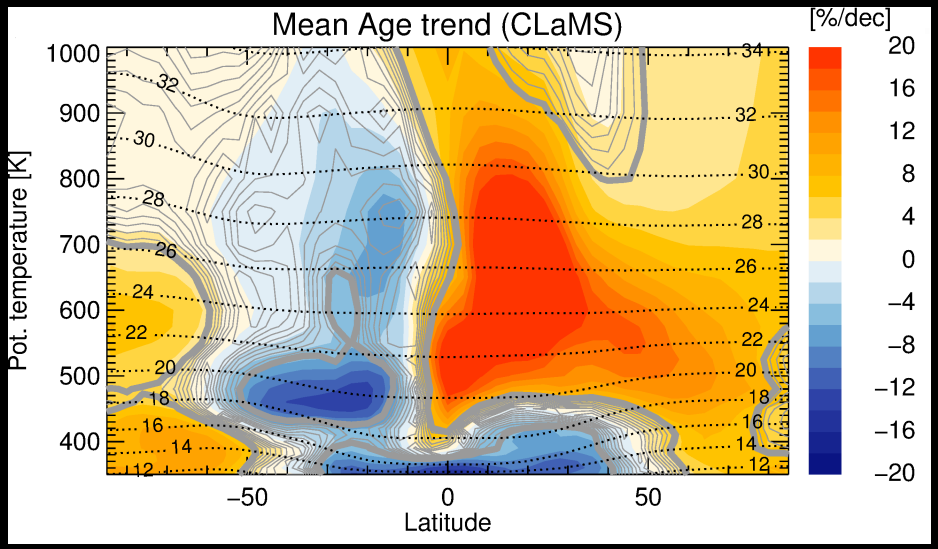
⇒ mixing: subtropics, mid-lat & polar vortex

⇒ **mean age no unique proxy for resid. circulation!!!**

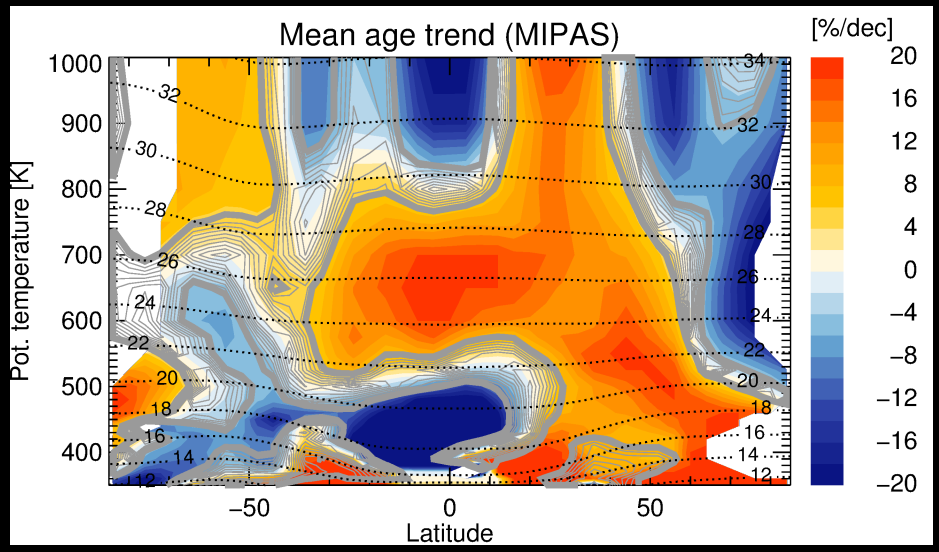
Comparison: CLaMS ↔ MIPAS observations

ts

CLaMS



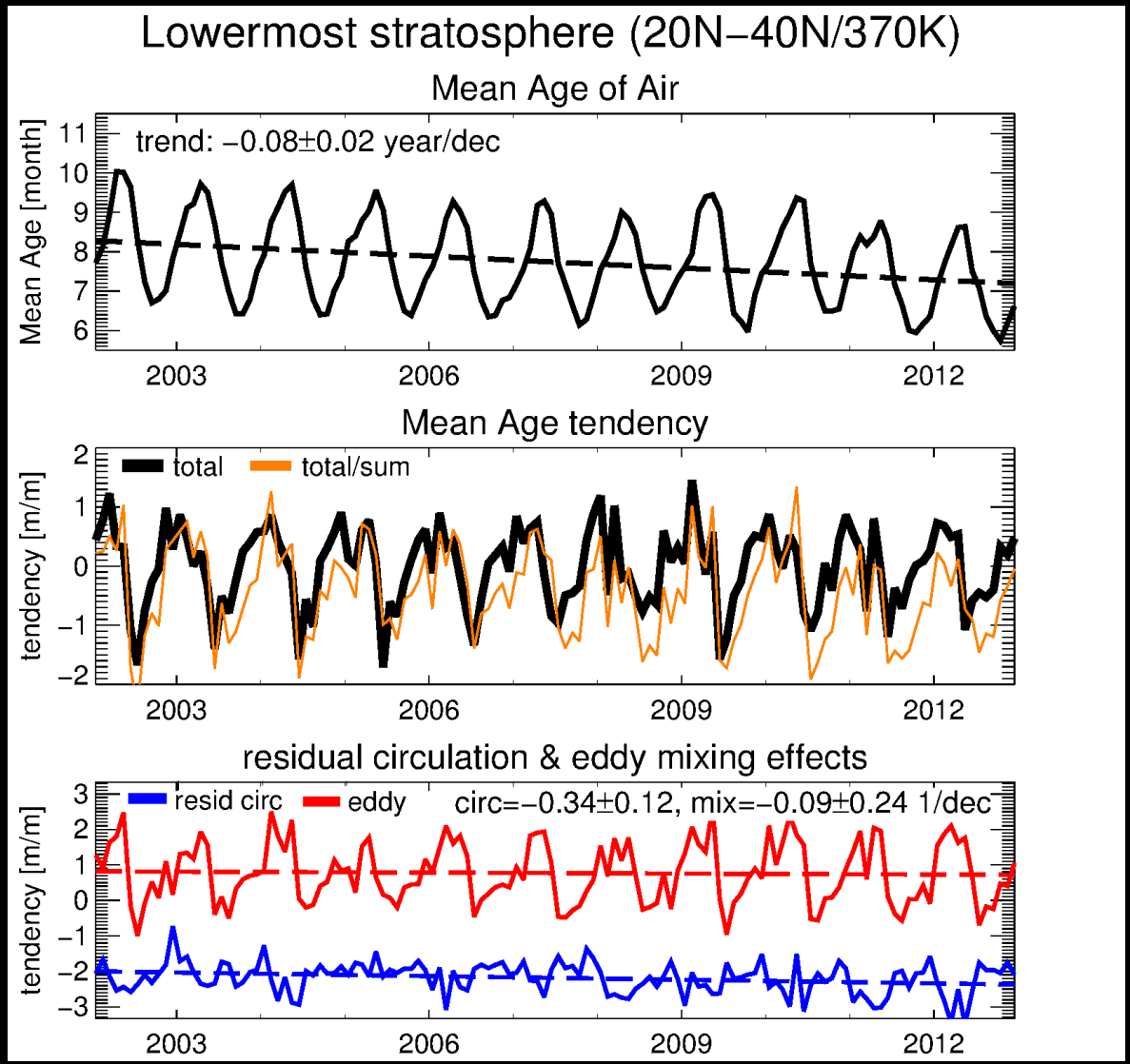
MIPAS



[Stiller et al.,2012]

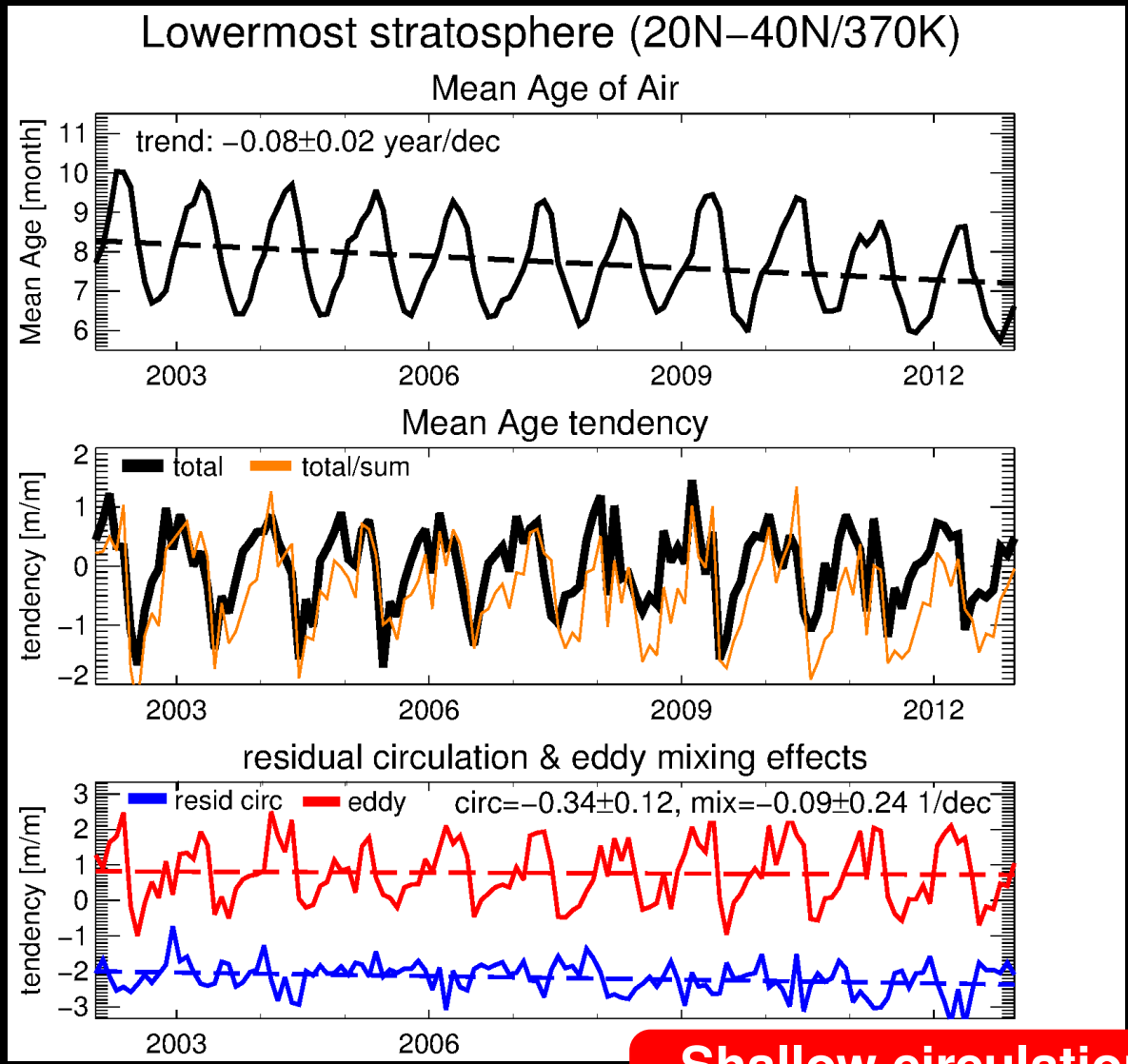
- ★ Significant age increase in NH (subtropics) for 2002–2010
- ★ Age decrease in lower stratosphere

Mean age variability: NH lower stratosphere



★ Strengthening circulation effect 2002–2012 (blue) ⇒ age decrease

Mean age variability: NH lower stratosphere

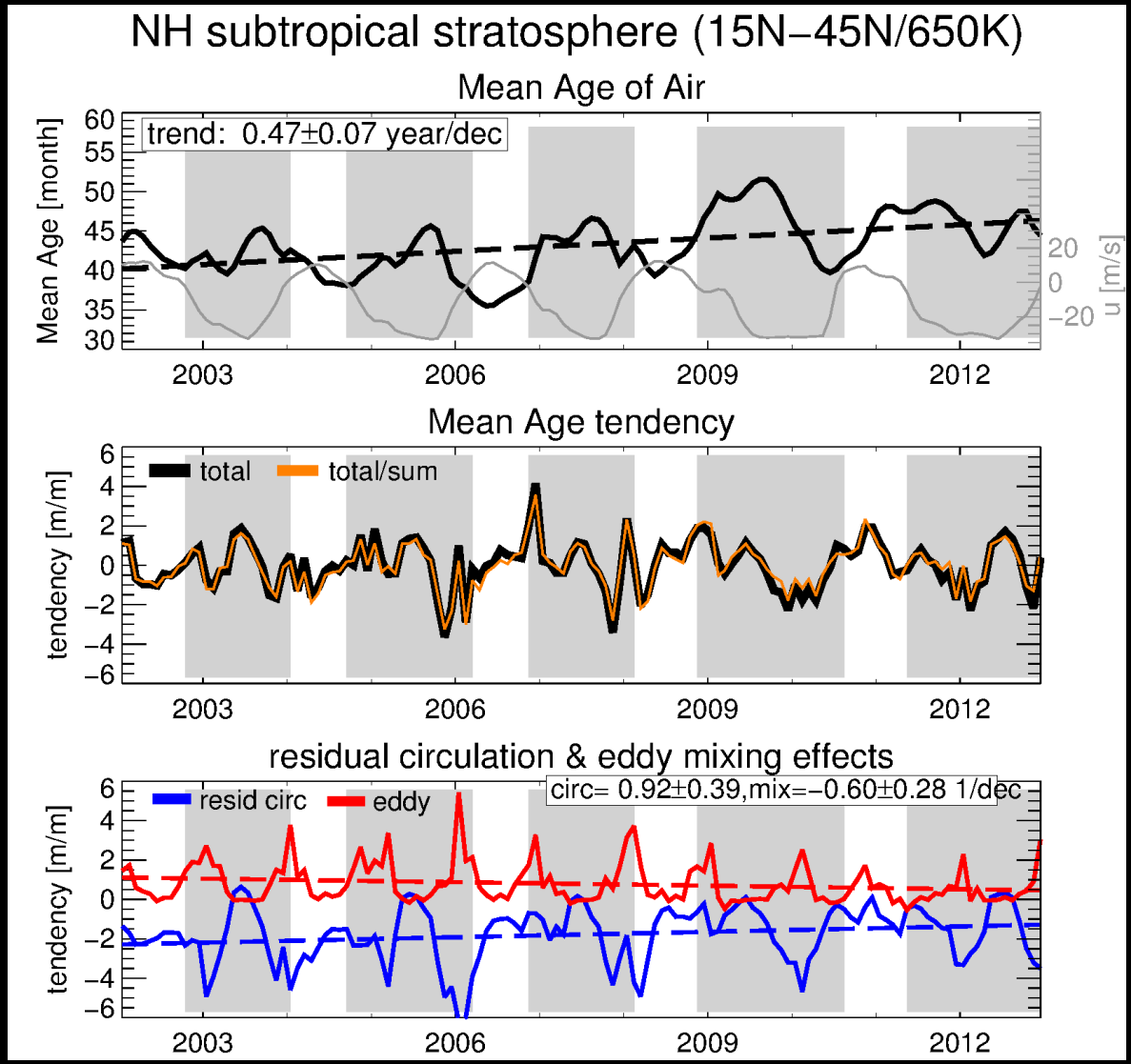


Shallow circulation branch:

⇒ strengthening (2002–2012)!

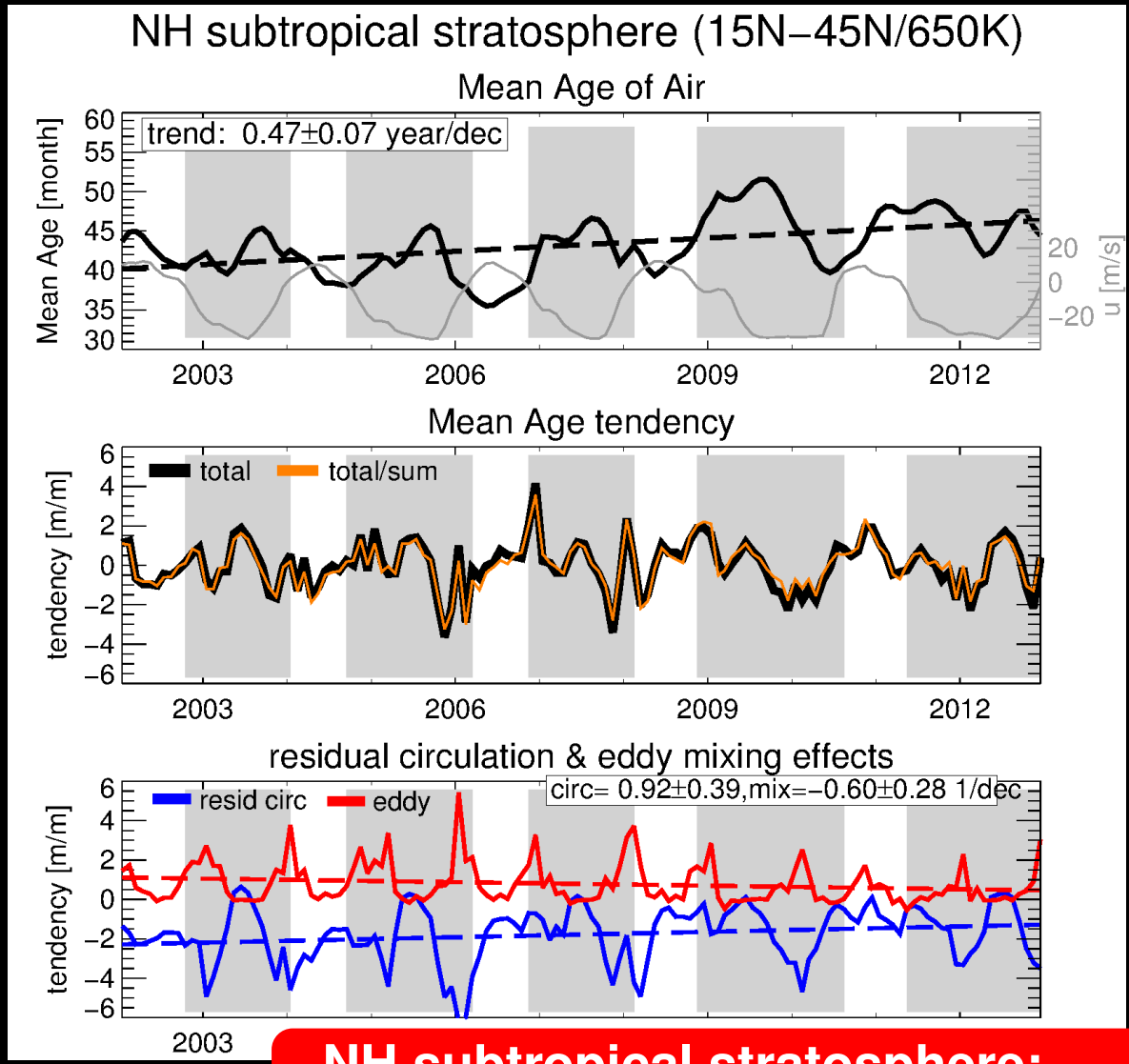
★ Strengthening circulation effect 2002–2

Mean age variability: NH subtropics



★ Weakening circulation & mixing 2002–2012 (blue & red) ⇒ age increase

Mean age variability: NH subtropics

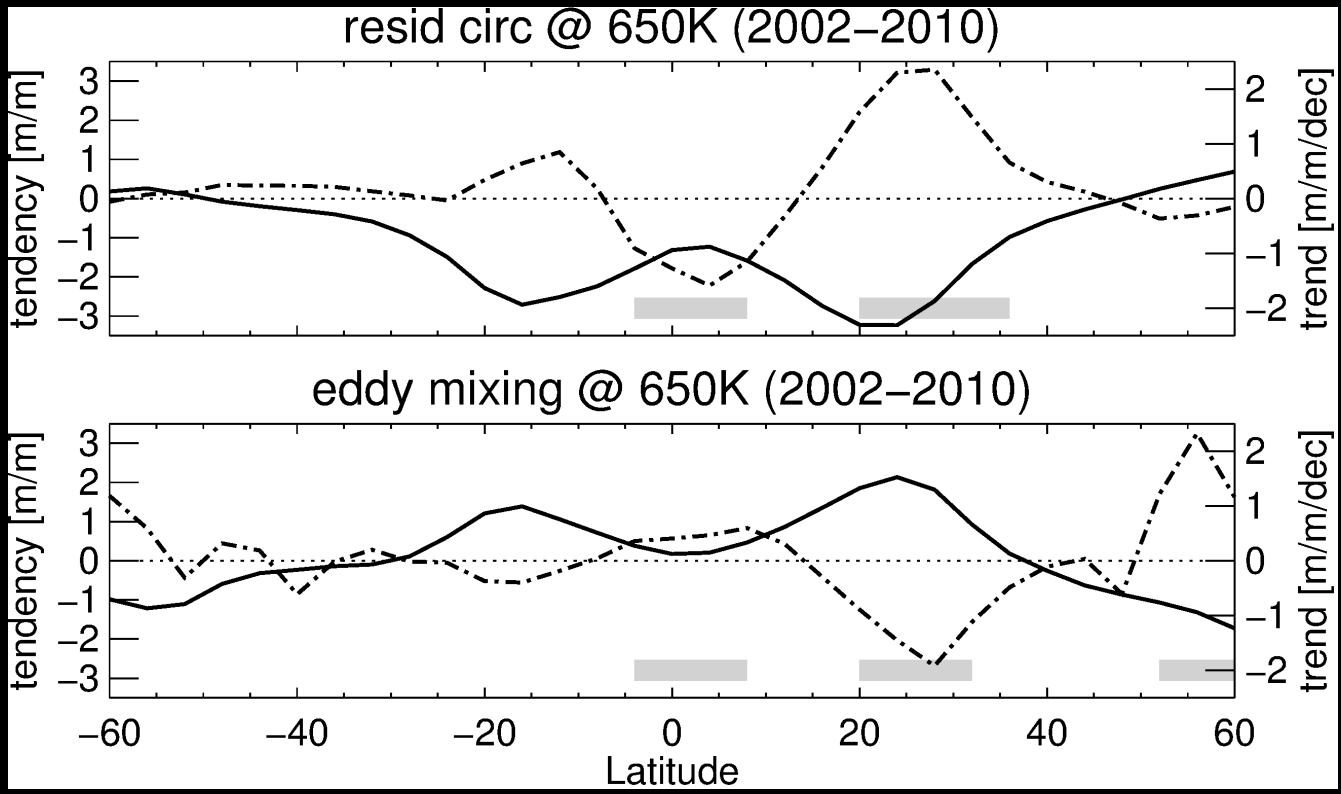


★ Weakening circulation

NH subtropical stratosphere:

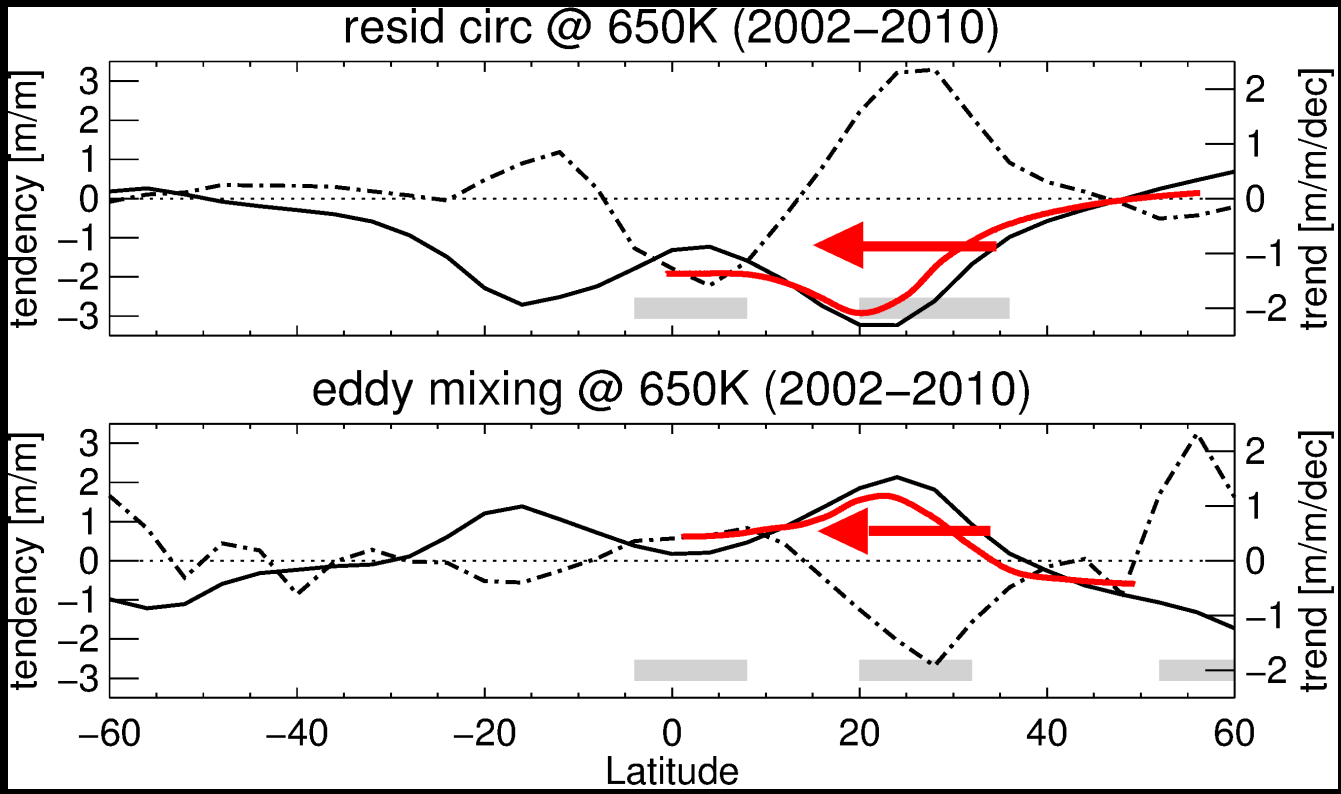
⇒ weakening circulation & mixing (2002–2012)!

Circulation & mixing changes 2002–2010 (650K)



- ★ circulation & mixing effects opposite (black) - even their trends (dashed)!
- ★ NH: trends opposite to mean effects ⇒ weakening circulation & mixing!

Circulation & mixing changes 2002–2010 (650K)



★ circulation & mixing effects opposite (black) - even their trends (dashed)!

★ NH: trends opposite to mean effects ⇒ weakening circulation & mixing!

Weakening circulation & mixing:

⇒ southward shift of circ/mix patterns?

⇒ shift of mixing barriers? [G. Stiller, in prep.]

Summary & conclusions

★ Separation of resid. circulation & mixing effects on mean age (continuity eqn.)

★ circulation & mixing effects opposite ('delicate balance')

$\Rightarrow$ **mean age no unique measure for resid. circulation!**

★ tropics: circulation controlled mean age variability

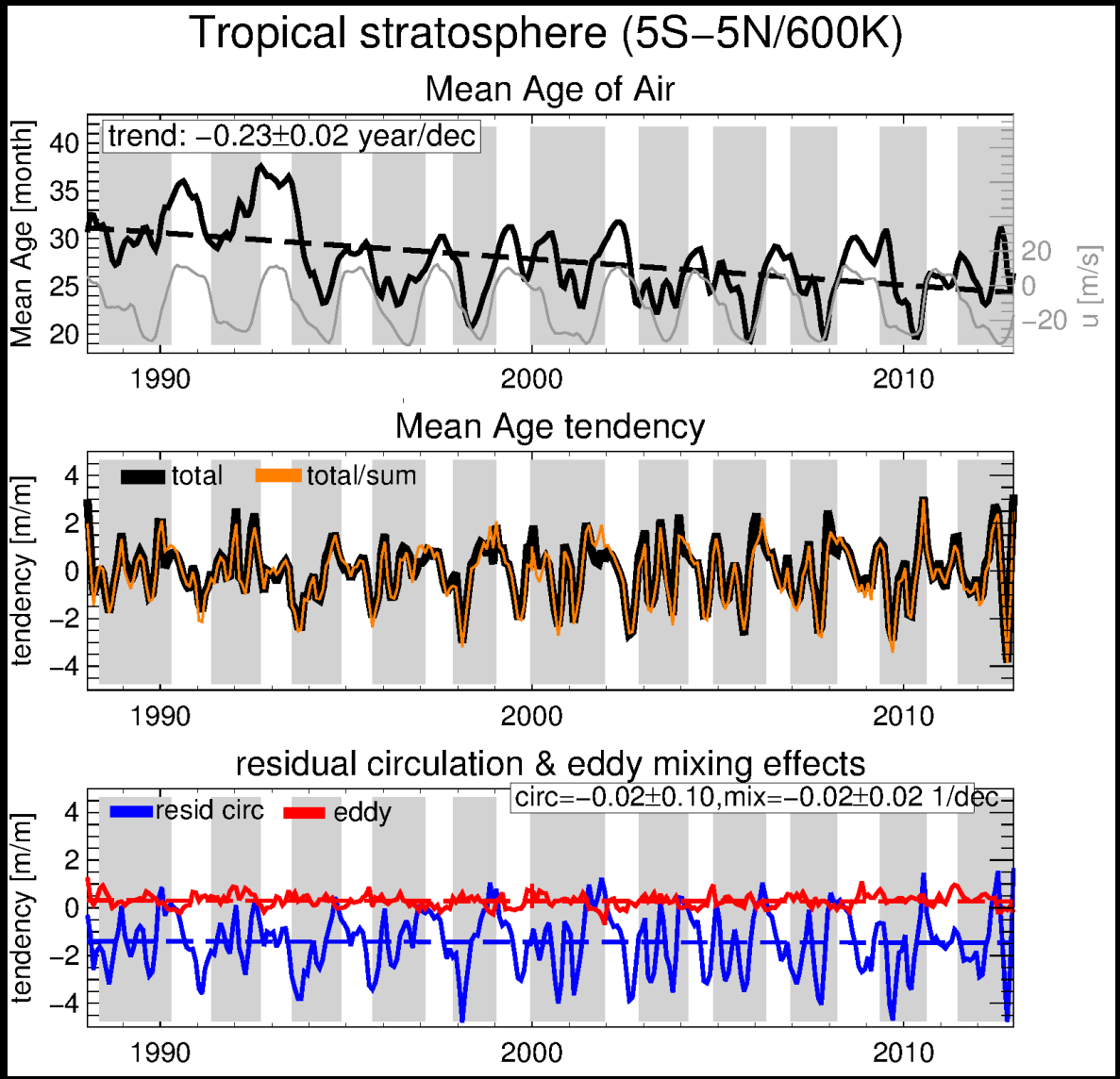
extratropics: mixing controlled!

★ age increase in **NH (2002–2010): weakening circulation & mixing** $\Rightarrow$ shift?

age decrease in lower stratosphere: strengthening shallow circulation branch

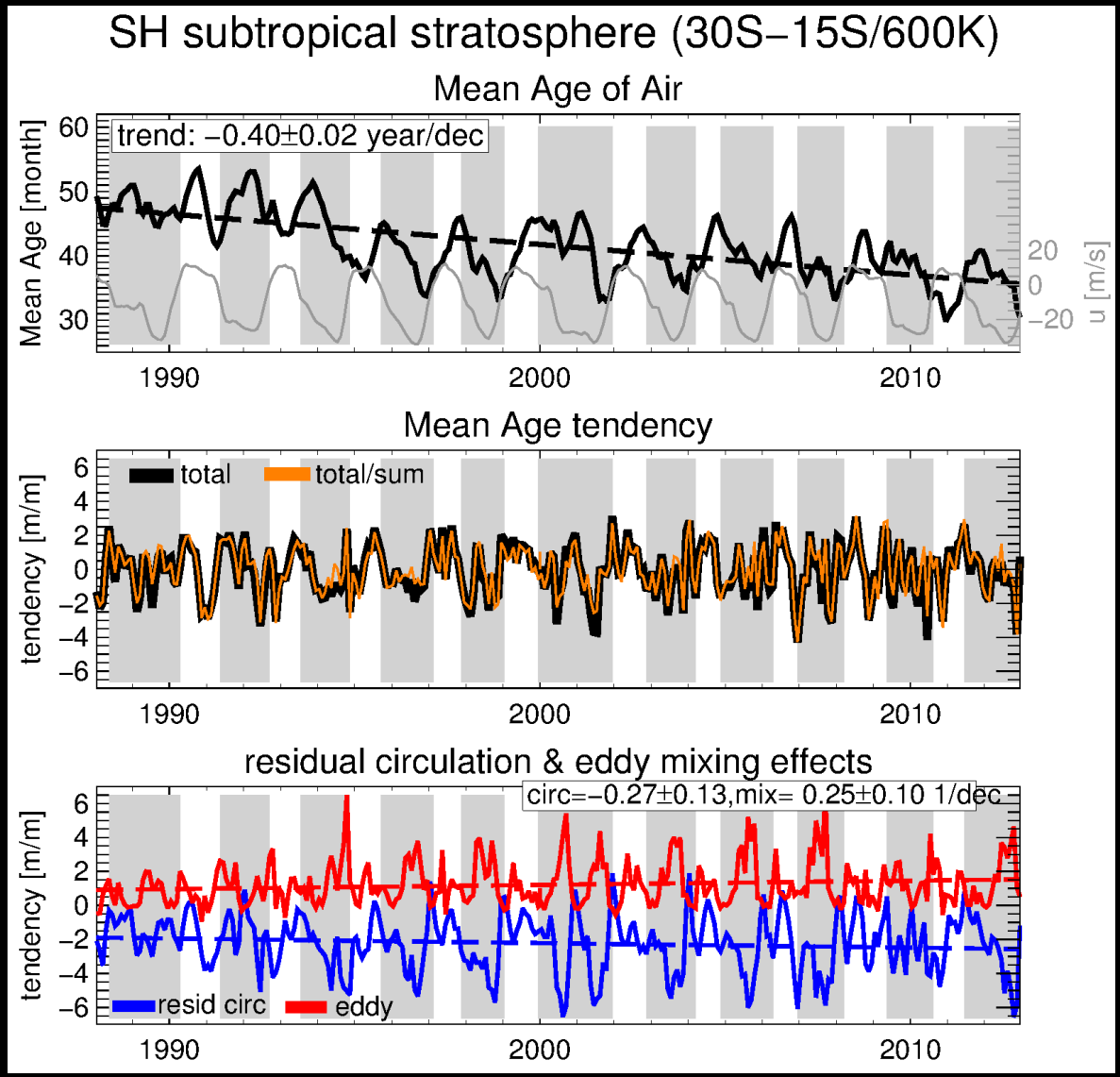
Appendix

Mean age variability: tropics



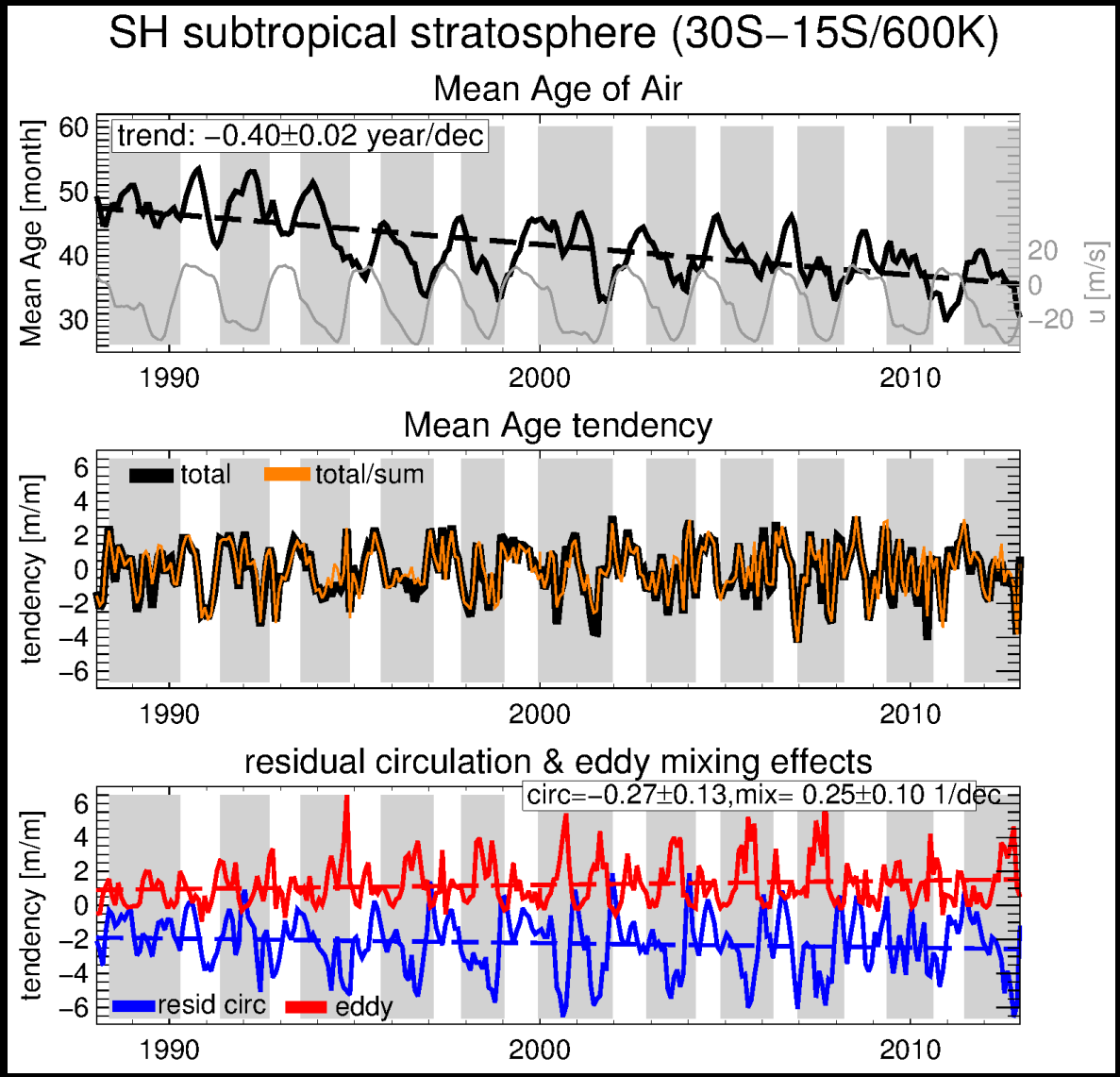
★ Age variability follows residual circulation variability

Mean age variability: SH subtropics



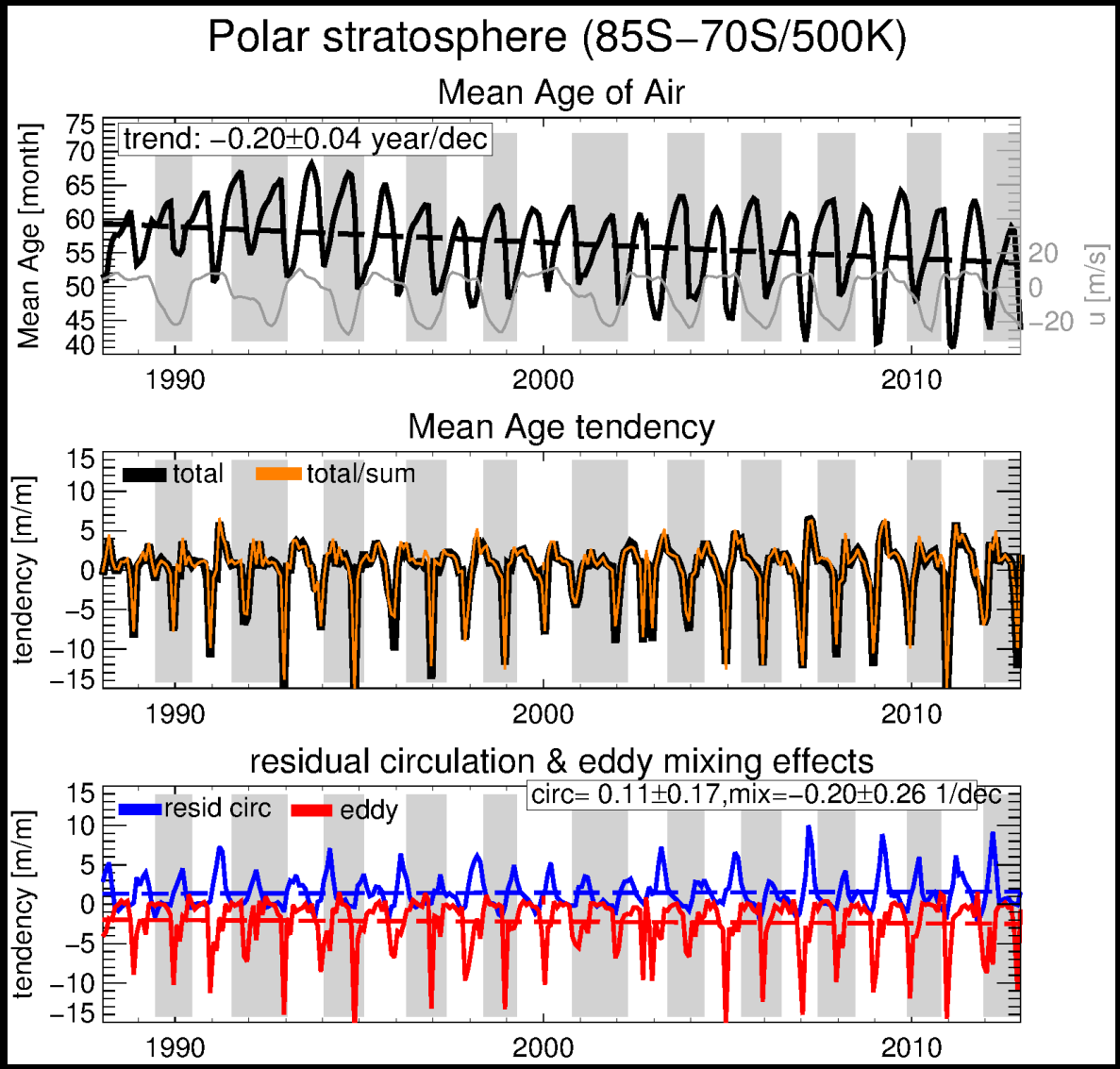
★ Strengthening circulation & mixing ⇒ age decrease

Mean age variability: NH subtropics



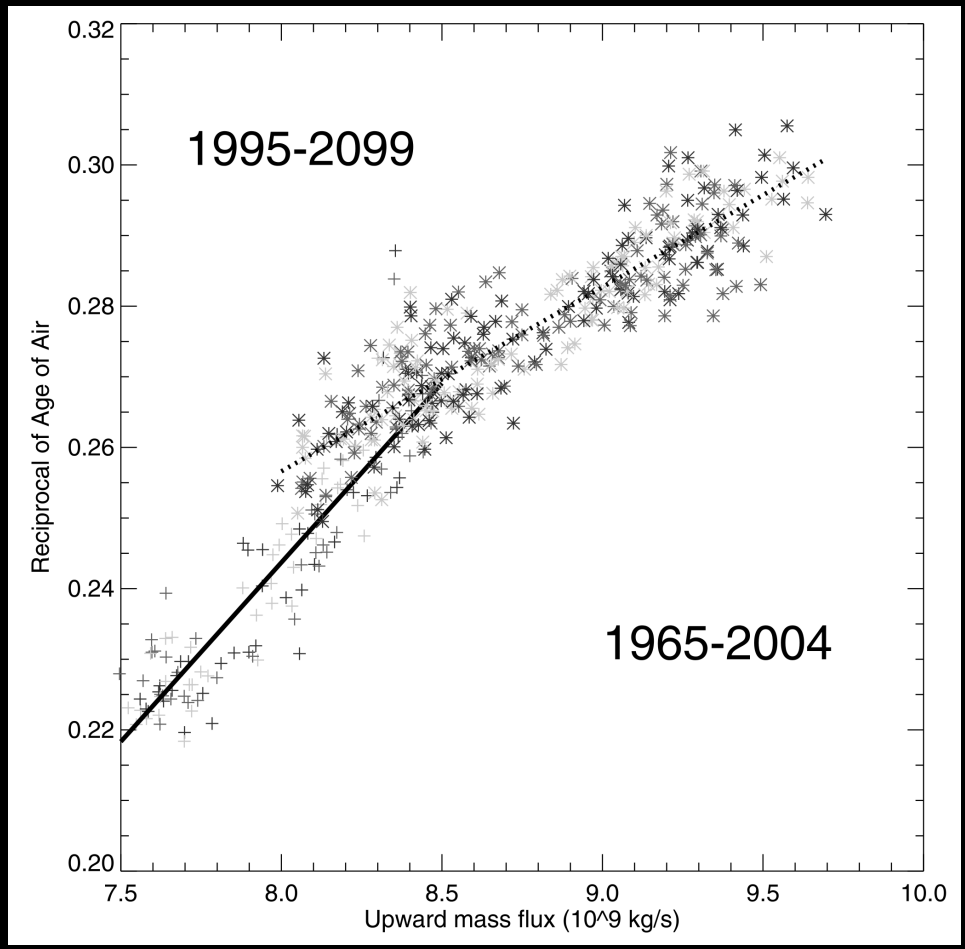
★ Weakening circulation & mixing ⇒ age increase

Mean age variability: SH polar vortex



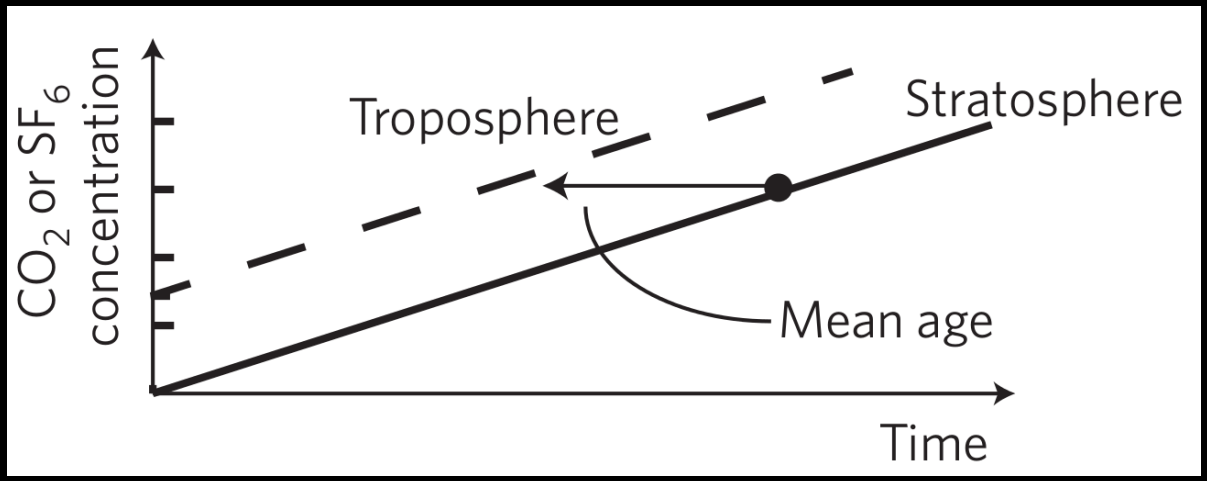
★ Strong mixing when vortex breaks up

Mean age as measure for BD-circulation?



★ Mean age linearly related to (residual) circulation strength [Austin&Li, 2006]

Mean age of air Γ



★ Models: 'clock-tracer' with linearly increasing mixing ratio in troposphere

$$\chi(\boldsymbol{x},t) = \chi^{trop}(t - \Gamma(\boldsymbol{x},t)) = \gamma(t - \Gamma)$$

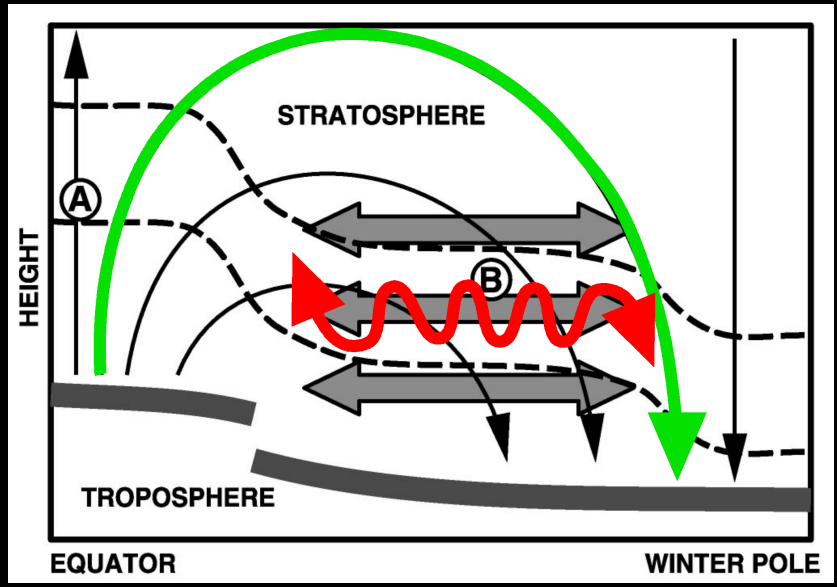
★ Observations: from SF_6, CO_2 mixing ratios...

Here:

model ⇒ mean age and trace gas data

Residual circulation vs. eddy mixing

★ Separate circulation & mixing effects on simulated trace gases/mean age



★ Isentropic zonal mean continuity eqn. for trace gas mixing ratio χ

$$\partial_t \overline{\chi} = -\overline{\mathbf{v}}^* \partial_y \overline{\chi} - \overline{\mathbf{Q}}^* \partial_\theta \overline{\chi} + \frac{1}{\sigma} \nabla \cdot \boldsymbol{M} - \frac{1}{\sigma} \partial_t (\overline{\sigma' \chi'})$$

resid. circulation eddy mixing

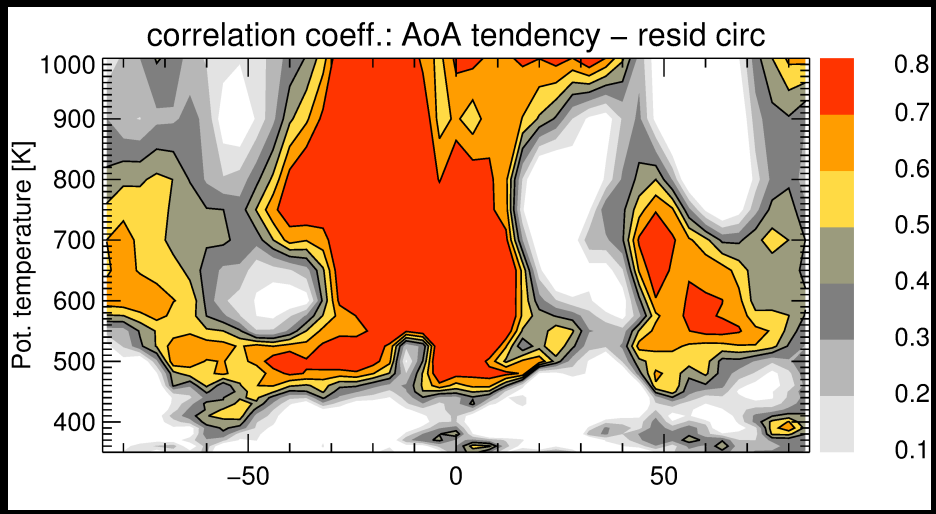
★ ... for mean age use $\chi = \gamma(t - \Gamma)$

$$\partial_t \overline{\Gamma} = -\overline{\mathbf{v}}^* \partial_y \overline{\Gamma} - \overline{\mathbf{Q}}^* \partial_\theta \overline{\Gamma} + \frac{1}{\sigma} \nabla \cdot \boldsymbol{M}_\Gamma - \frac{1}{\sigma} \partial_t (\overline{\sigma' \Gamma'}) + 1$$

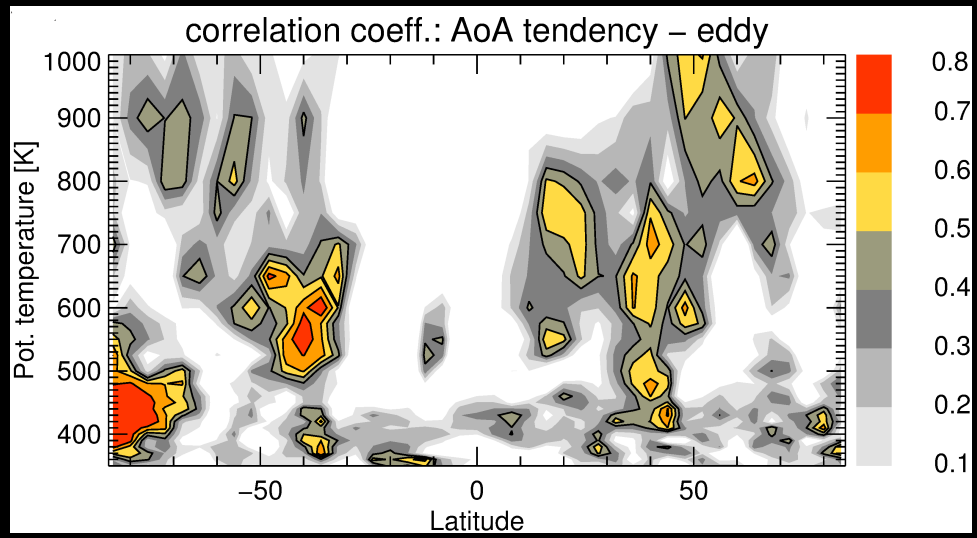
Control of mean age variability

★ correlation: age tendency ↔ circulation/mixing for annual averages

Circulation



Mixing



Mean age control:

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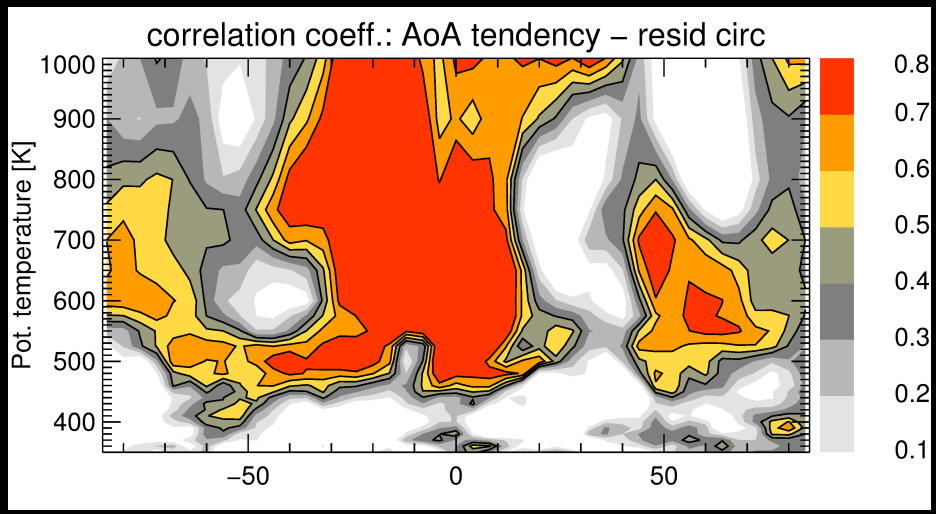
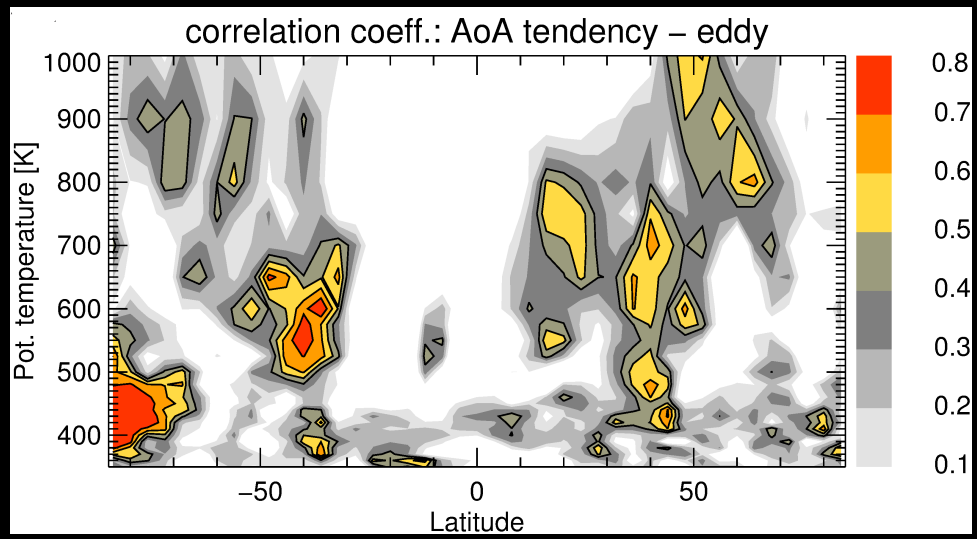


Mixing



Mean age control:

⇒ circulation: tropics & high-lat upper stratosphere

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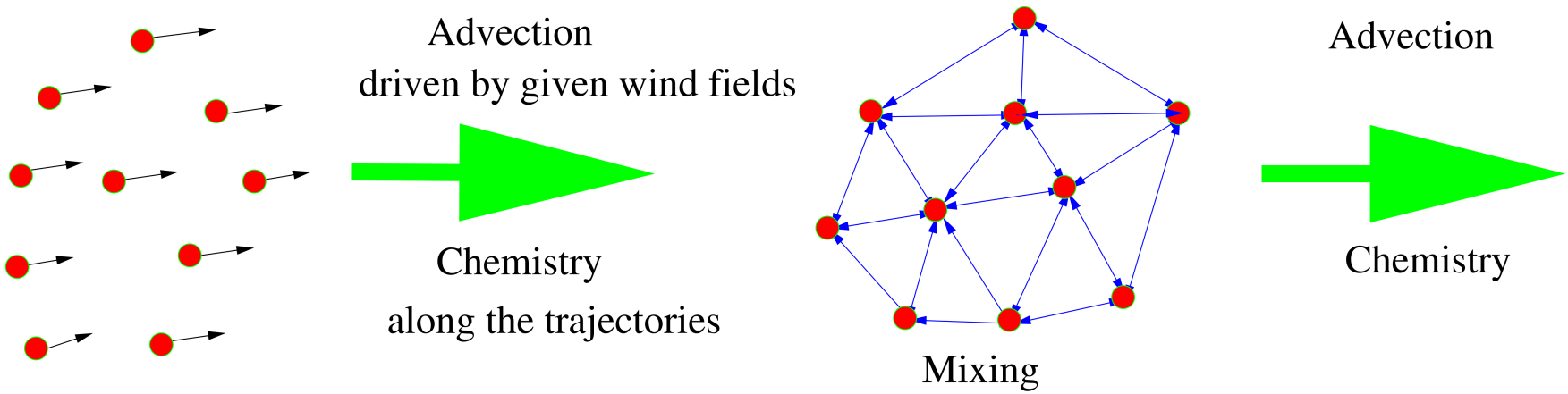
Our model tool CLaMS

★ **C**hemical **La**grangian **M**odel of the **S**tratosphere: a trajectory based CTM



Tracer transport = Advection (Trajectories) (reversible) + Mixing (Adaptive grid) (irreversible)

(courtesy of Paul Konopka)