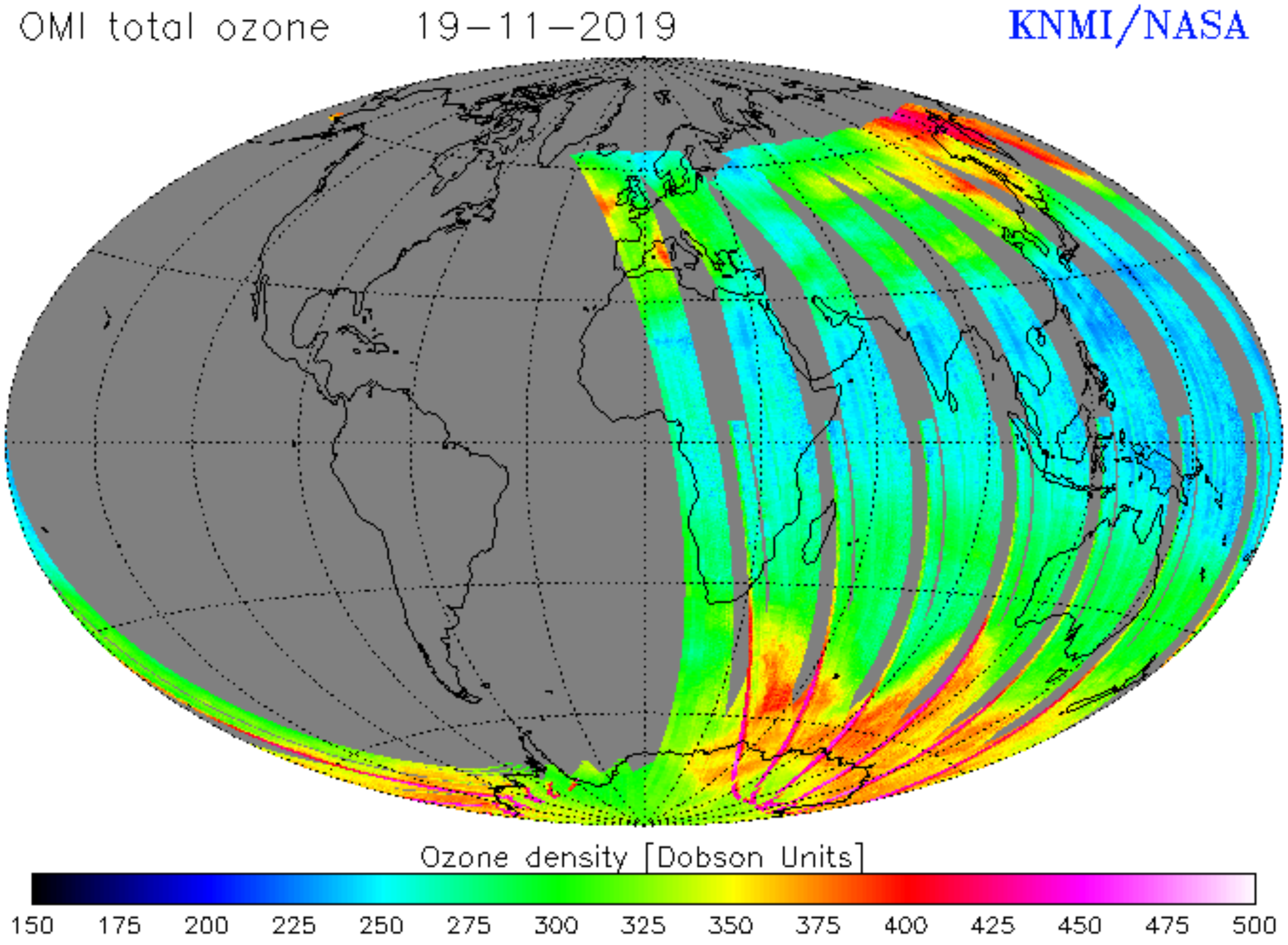
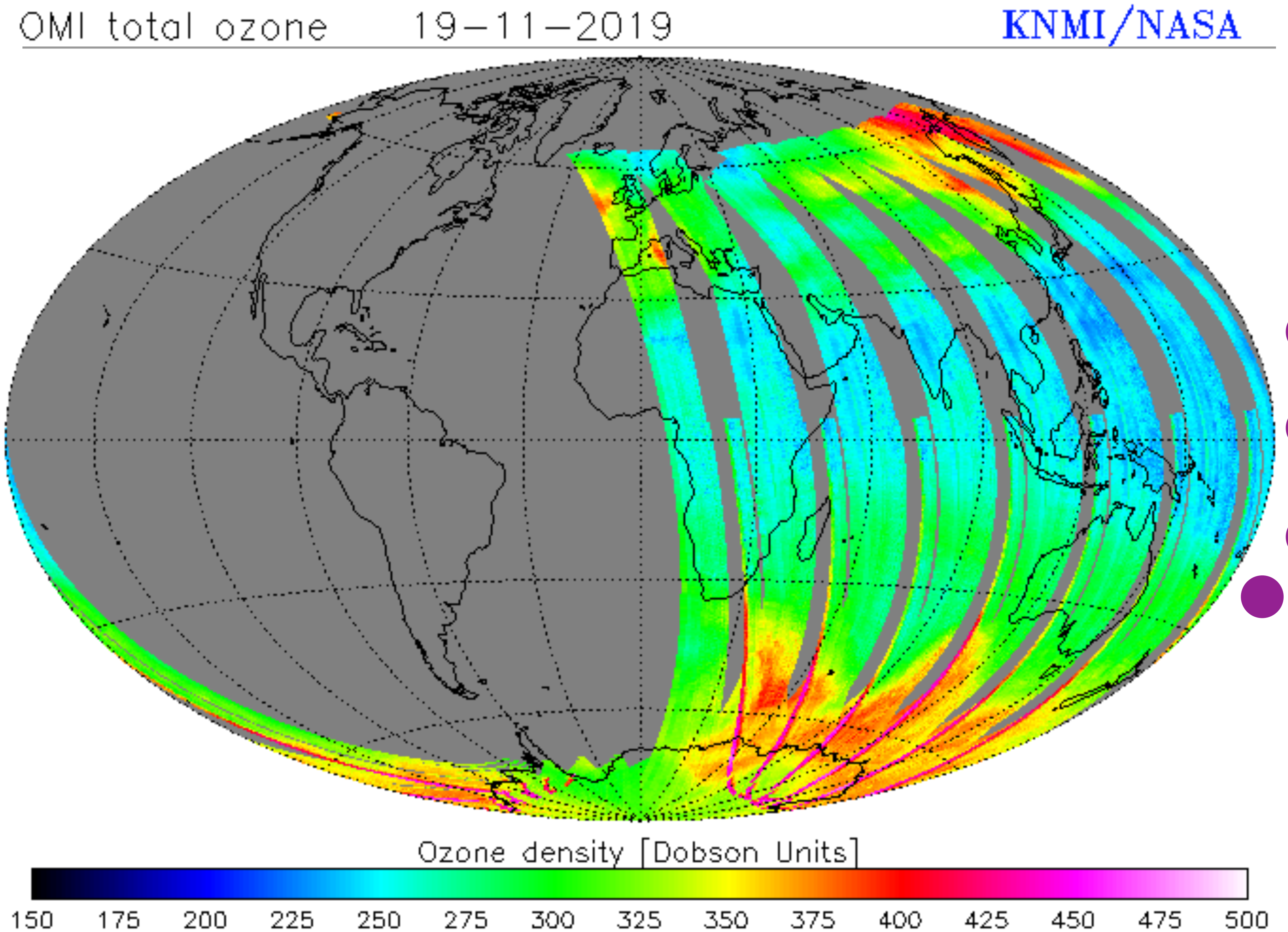
Trace Gas Transport in the Stratosphere: Opportunities and Challenges

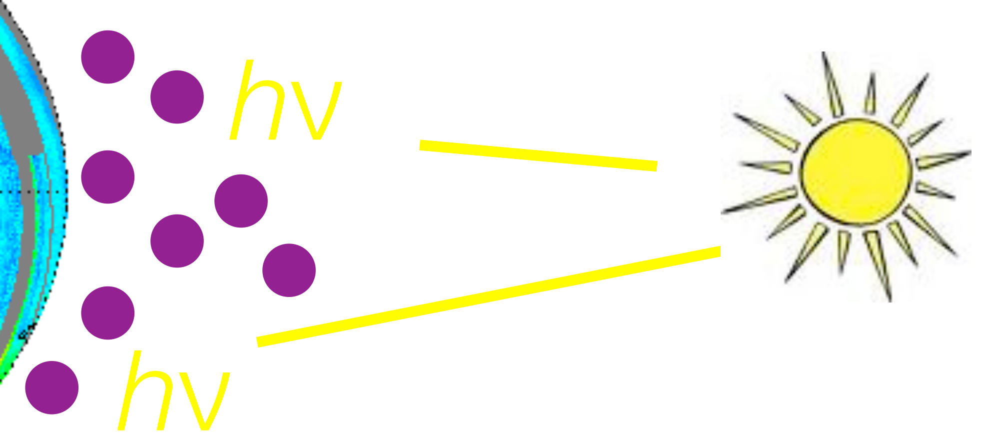
Edwin P. Gerber & Aman Gupta - Courant Institute of Mathematical Sciences
Marianna Linz - Harvard University
R. Alan Plumb - Massachusetts Institute of Technology

Today's Ozone



Today's Ozone: the Brewer-Dobson Circulation





Dobson, Harrison, and Lawrence [1929]

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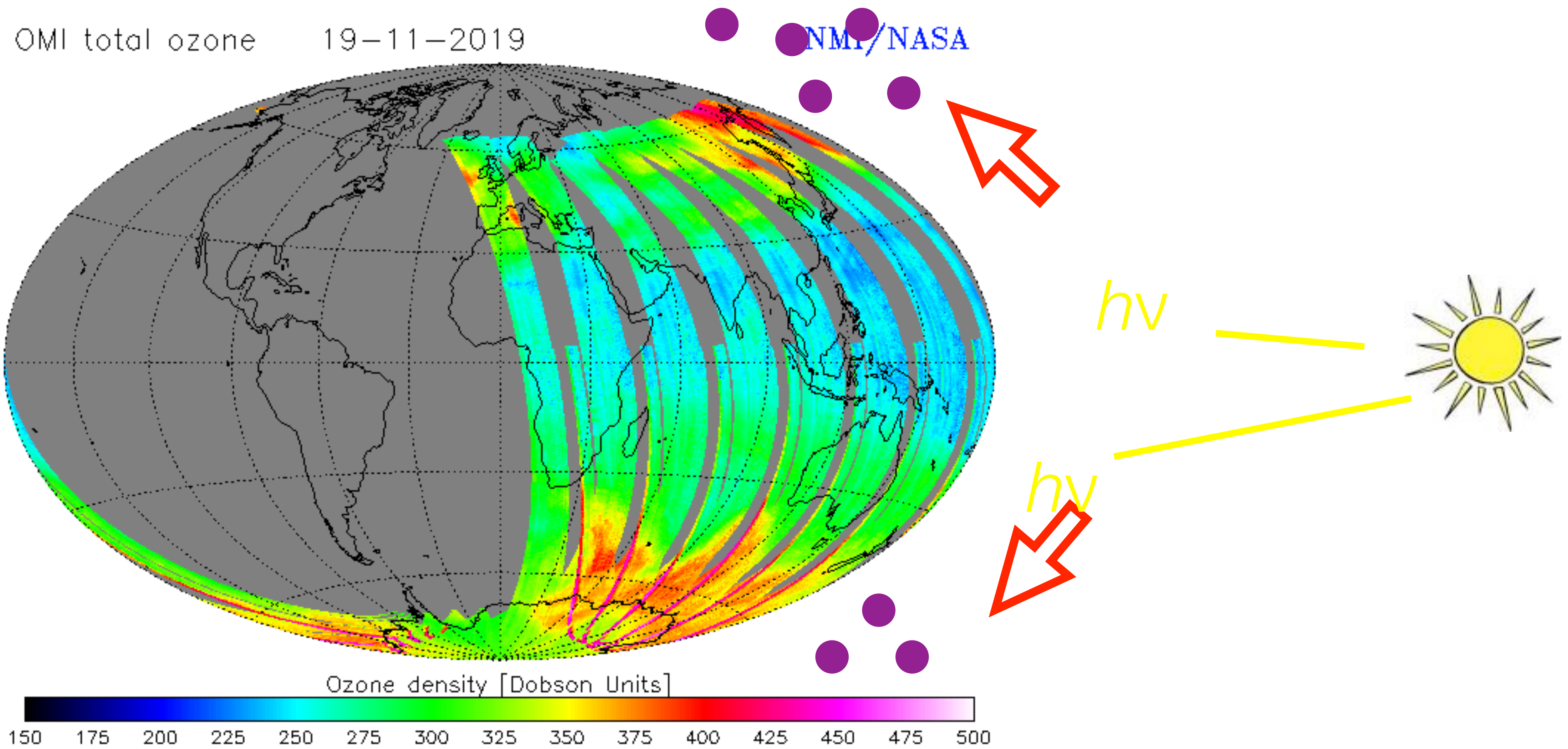

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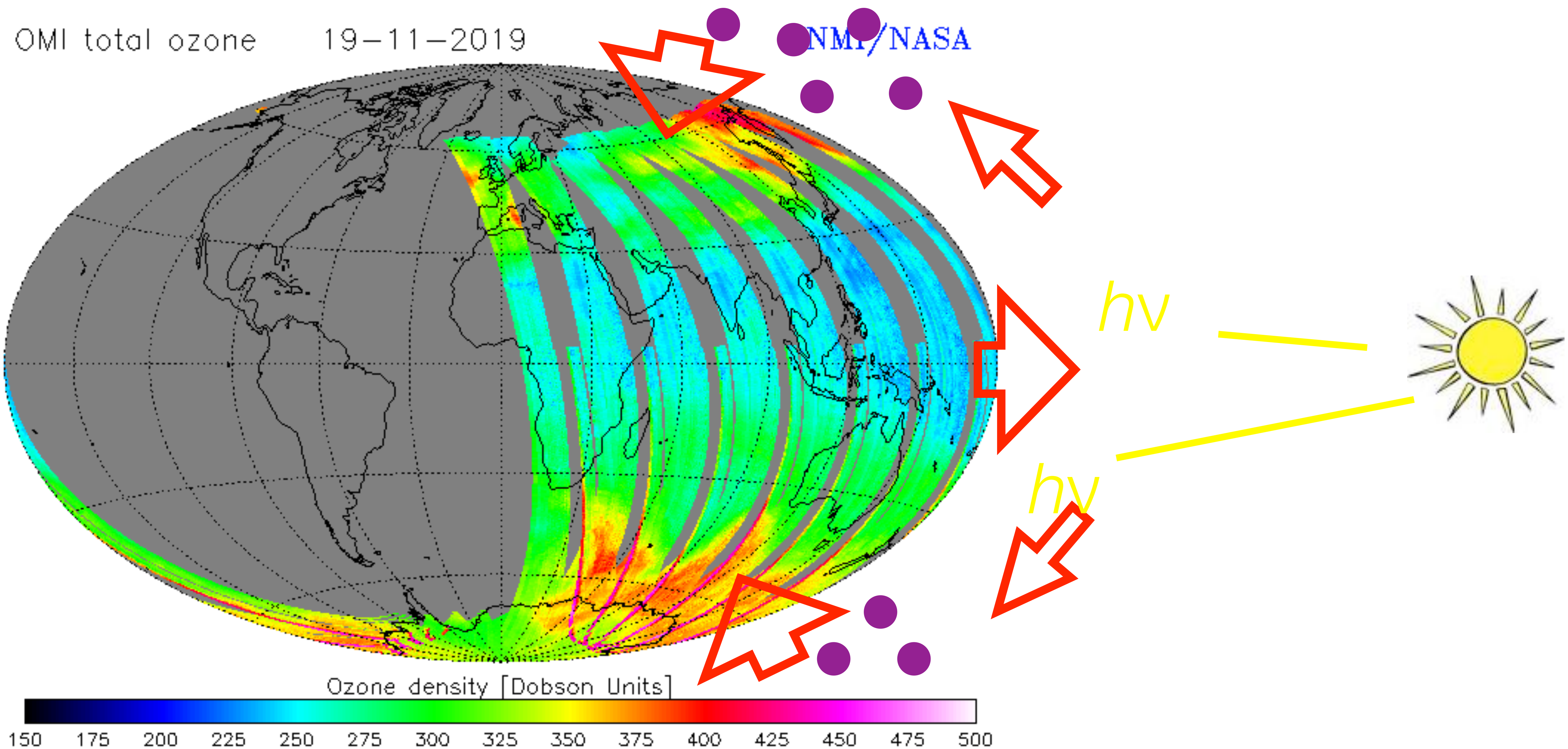

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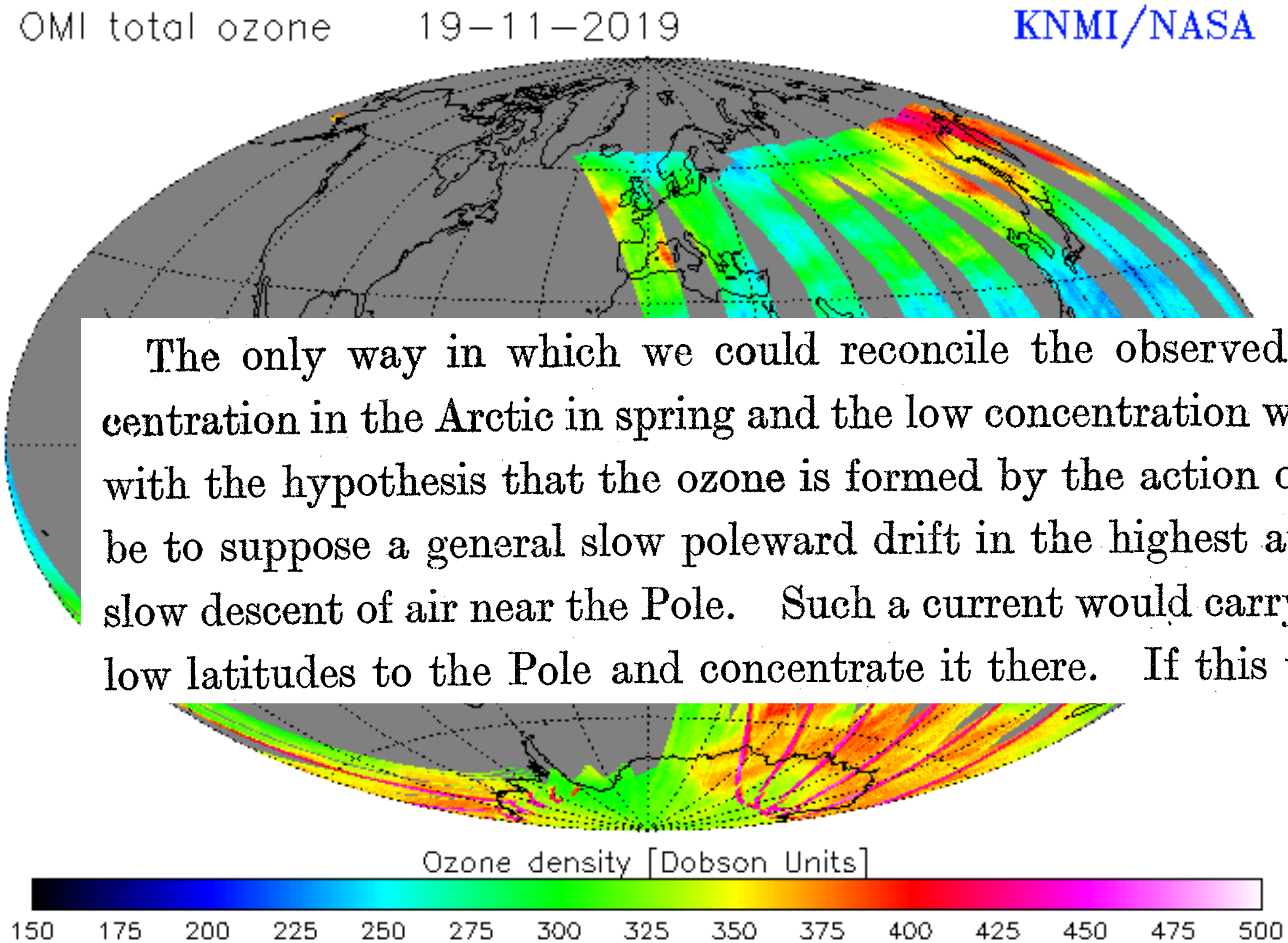

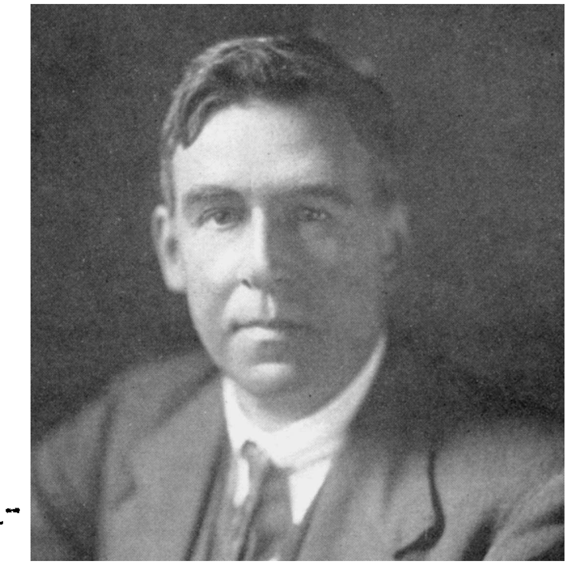

> The only way in which we could reconcile the observed high ozone concentration in the Arctic in spring and the low concentration within the Tropics, with the hypothesis that the ozone is formed by the action of sunlight, would be to suppose a general slow poleward drift in the highest atmosphere with a slow descent of air near the Pole. Such a current would carry ozone formed in low latitudes to the Pole and concentrate it there. If this were the case the

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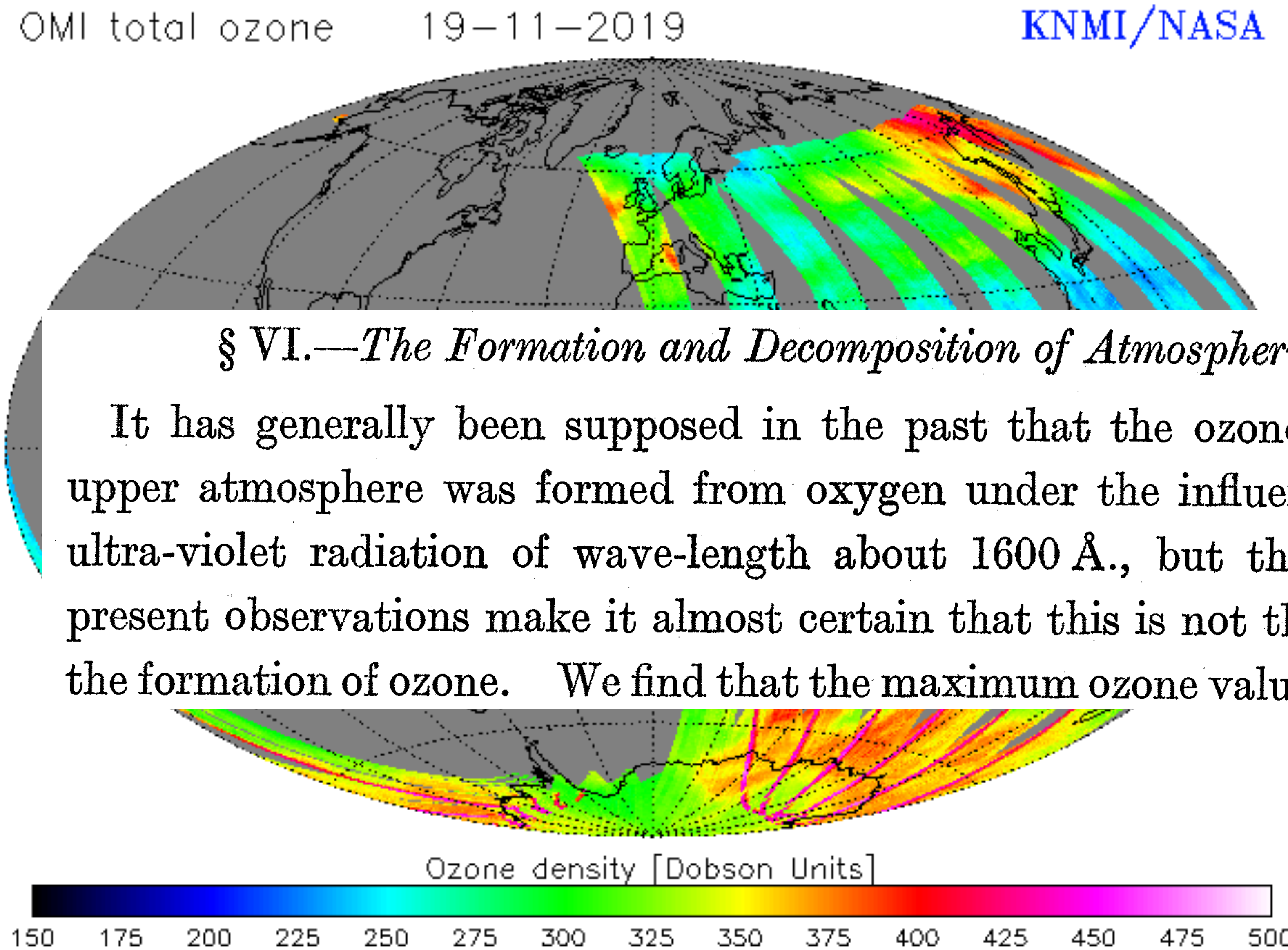
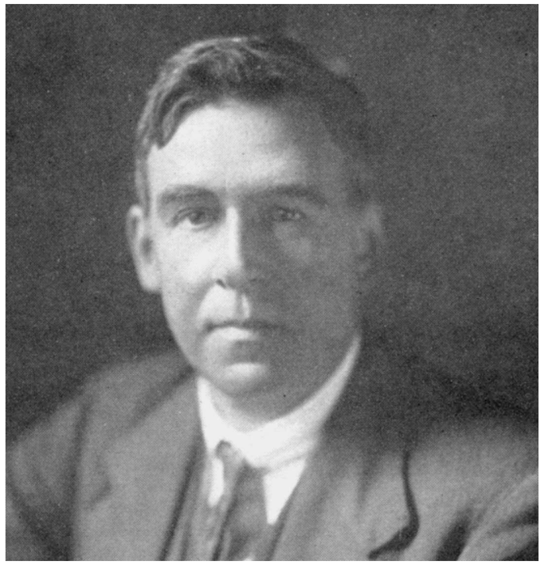
Today’s Ozone: the Brewer-Dobson Circulation



§ VI.—*The Formation and Decomposition of Atmospheric Ozone.*

It has generally been supposed in the past that the ozone present in the upper atmosphere was formed from oxygen under the influence of the sun’s ultra-violet radiation of wave-length about 1600 Å., but the results of the present observations make it almost certain that this is not the chief cause of the formation of ozone. We find that the maximum ozone values are associated



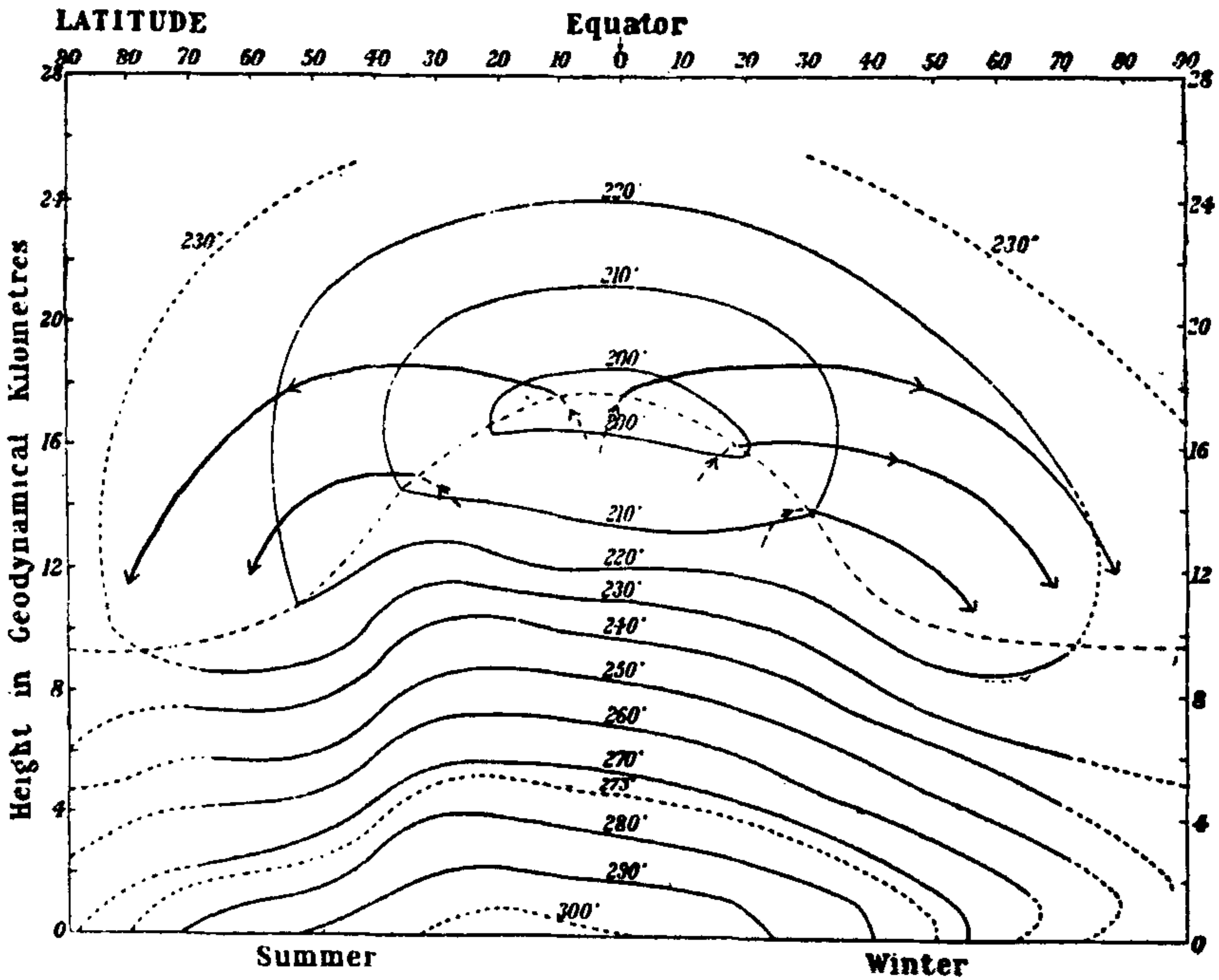
Dobson, Harrison, and Lawrence [1929]

551·510.5

EVIDENCE FOR A WORLD CIRCULATION PROVIDED BY THE MEASUREMENTS OF HELIUM AND WATER VAPOUR DISTRIBUTION IN THE STRATOSPHERE

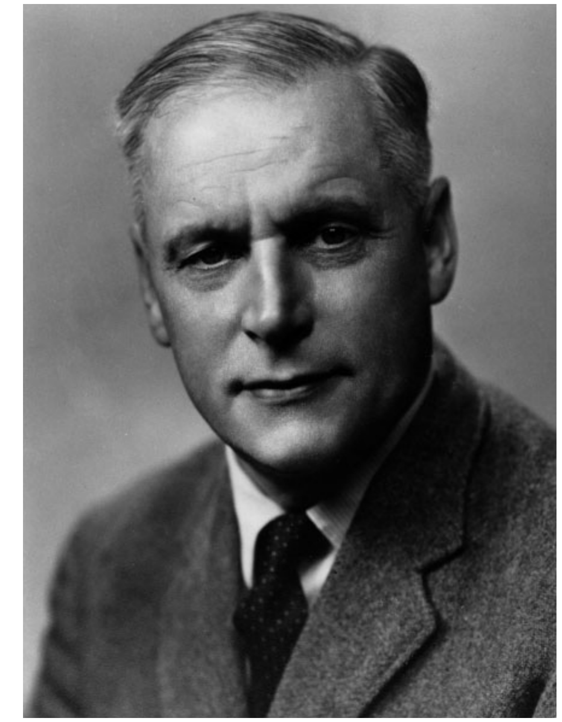
By A. W. BREWER, M.Sc., A.Inst.P.

(Manuscript received 23 February 1949)



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.



Trace gases in the stratosphere
Opportunities and Challenges

- Trace gas observations can *still* help us better understand the circulation of the stratosphere

- Trace gas transport is a challenge for climate prediction

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  - The “age-of-air” can be used to connect trace gas measurements to the overturning circulation
  - Modern reanalyses struggle with the overturning circulation; could assimilation of trace gases help?
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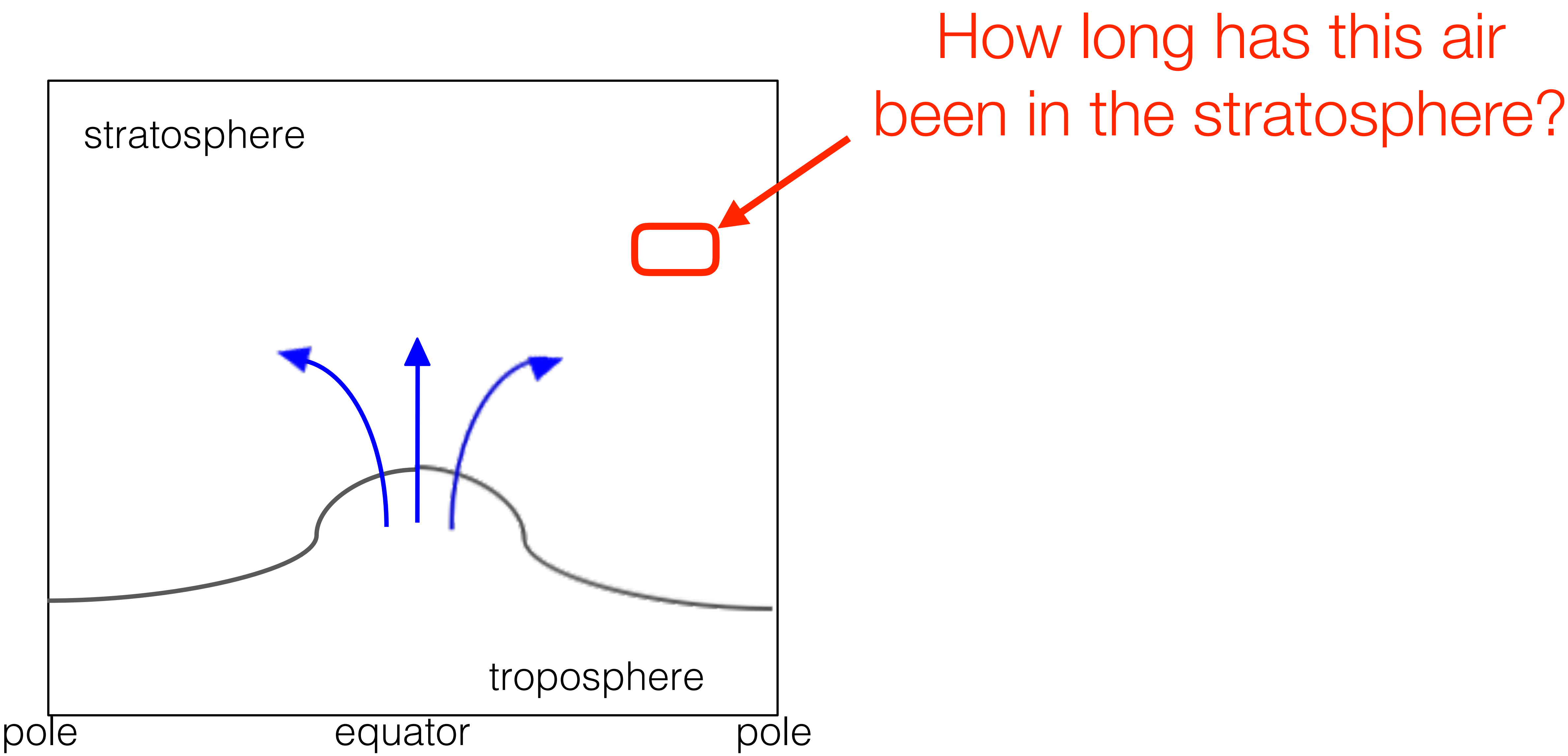
- Trace gas transport is a challenge for climate prediction
  - Ozone recovery projections vary considerably due to differences in transport
  - Transport depends critically on the numerical formulation and resolution; modern atmospheric model cores exhibit significant differences

Age-of-air: an idealized tracer that measures the mean elapsed time since air left the surface



[Linz et al. 2016]

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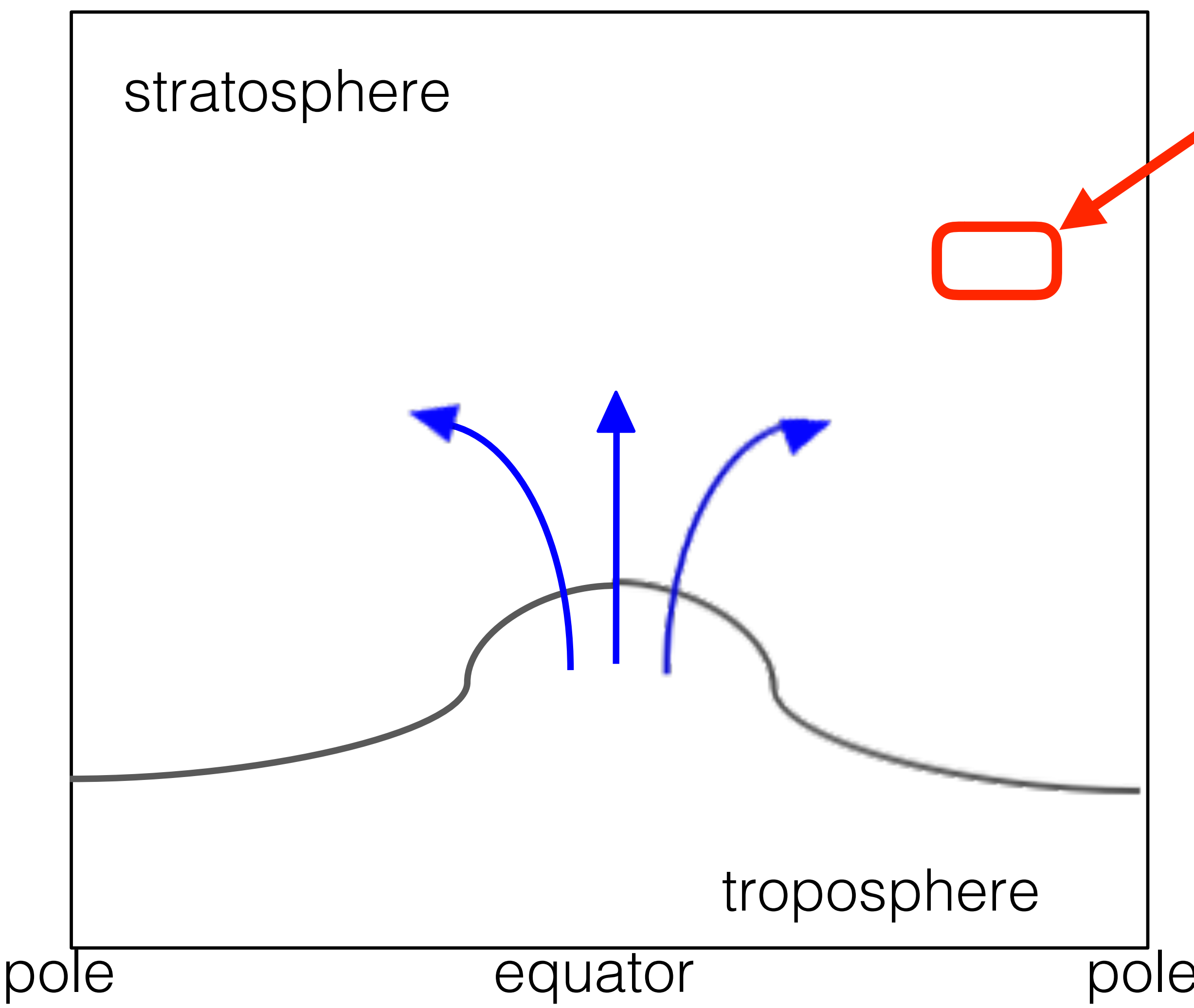

How long has this air been in the stratosphere?

rate of change in age	+	transport of newer/ older air	=	"aging" (1 yr/yr)

$$\frac{\partial \Gamma}{\partial t} + \frac{1}{\rho}\vec{v} \cdot \nabla \Gamma = 1$$

[Linz et al. 2016]

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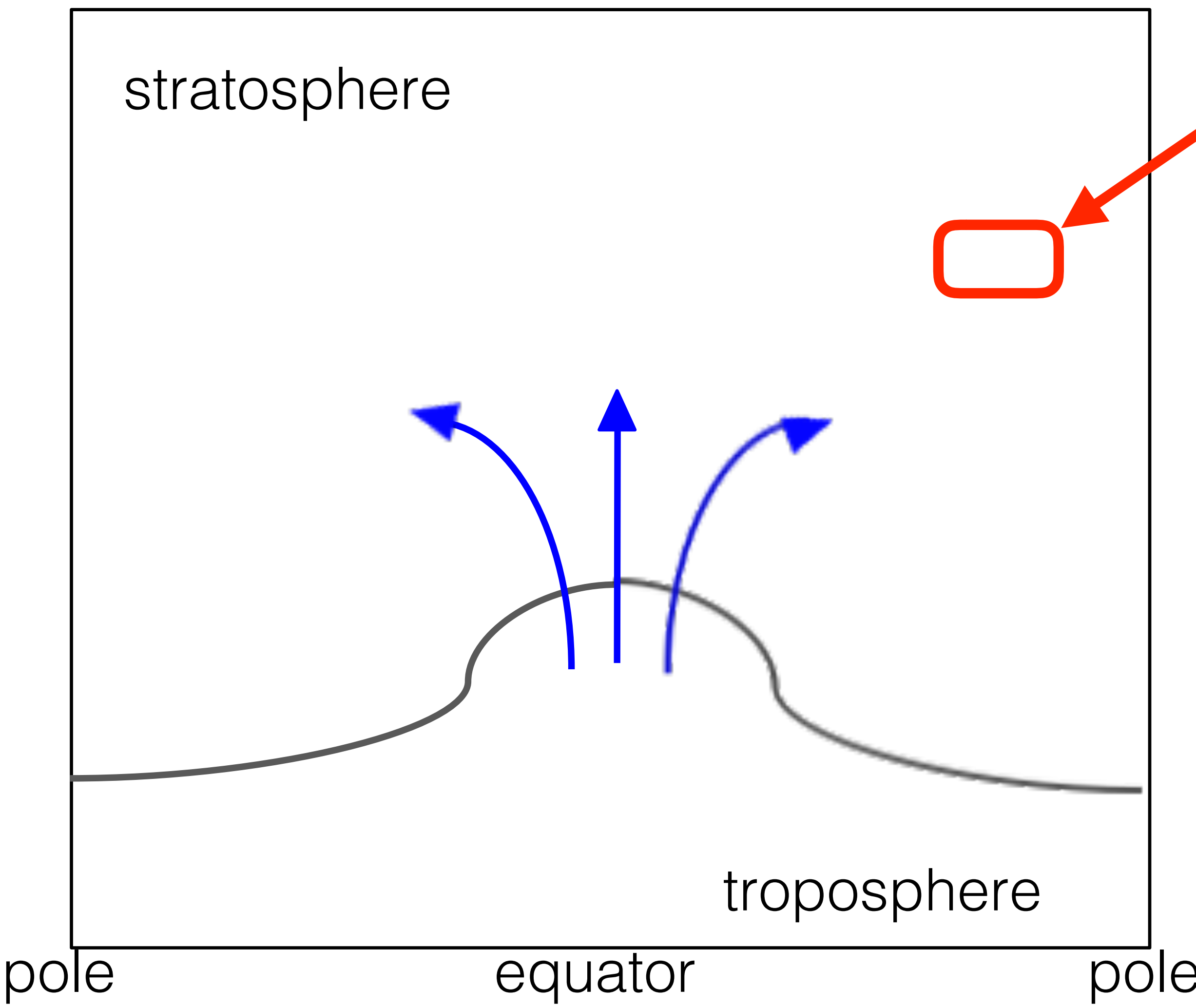

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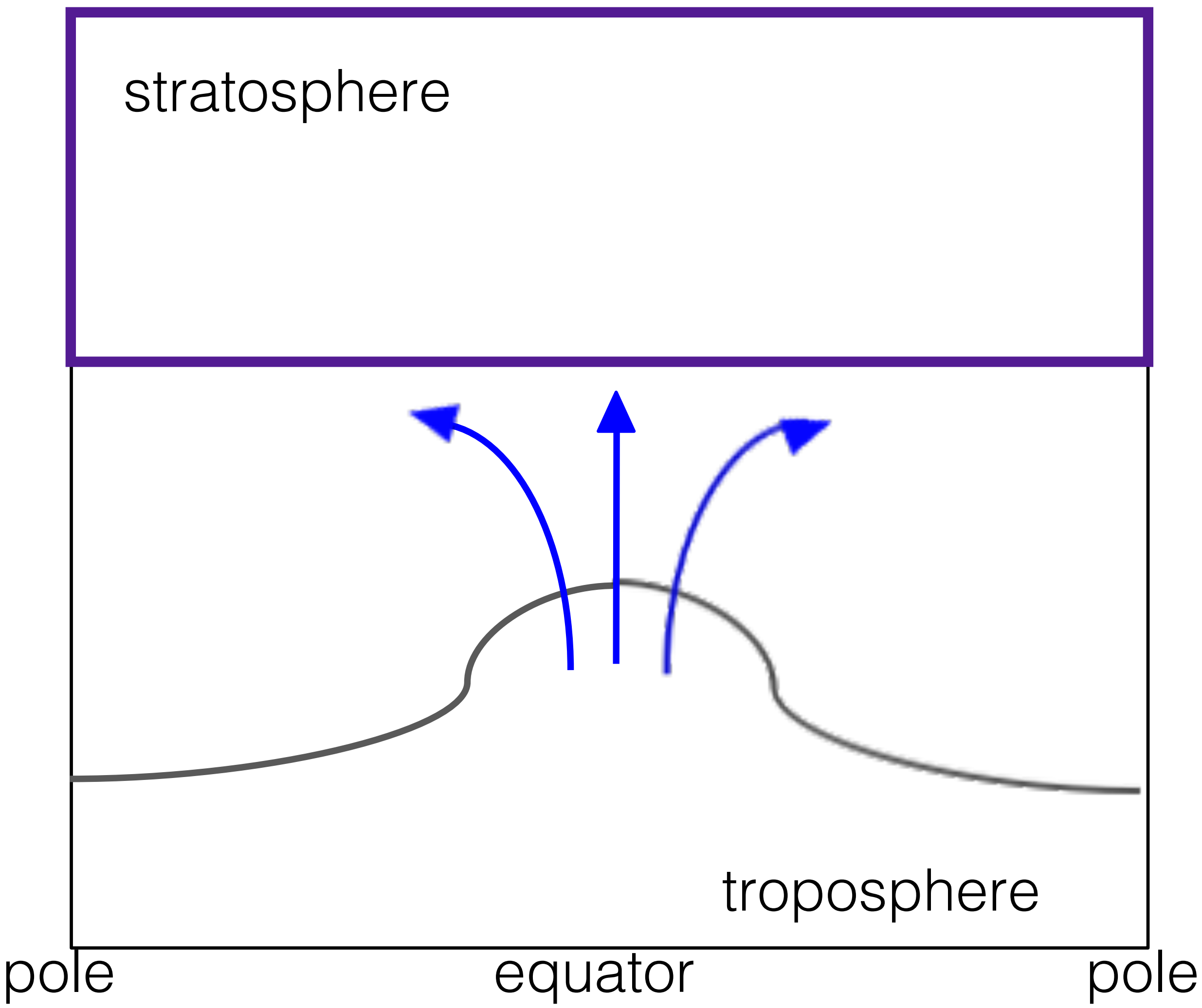
In steady state, transport balances local aging:

$$\frac{1}{\rho}\vec{v} \cdot \nabla \Gamma = 1$$

[Linz et al. 2016]

Age flux across an isentropic surface must equal the mass above the surface in steady state



In a steady state:

$$\vec{v} \cdot \nabla \Gamma = \rho$$

Integrate over the volume above an isentropic surface

[Linz et al. 2016]

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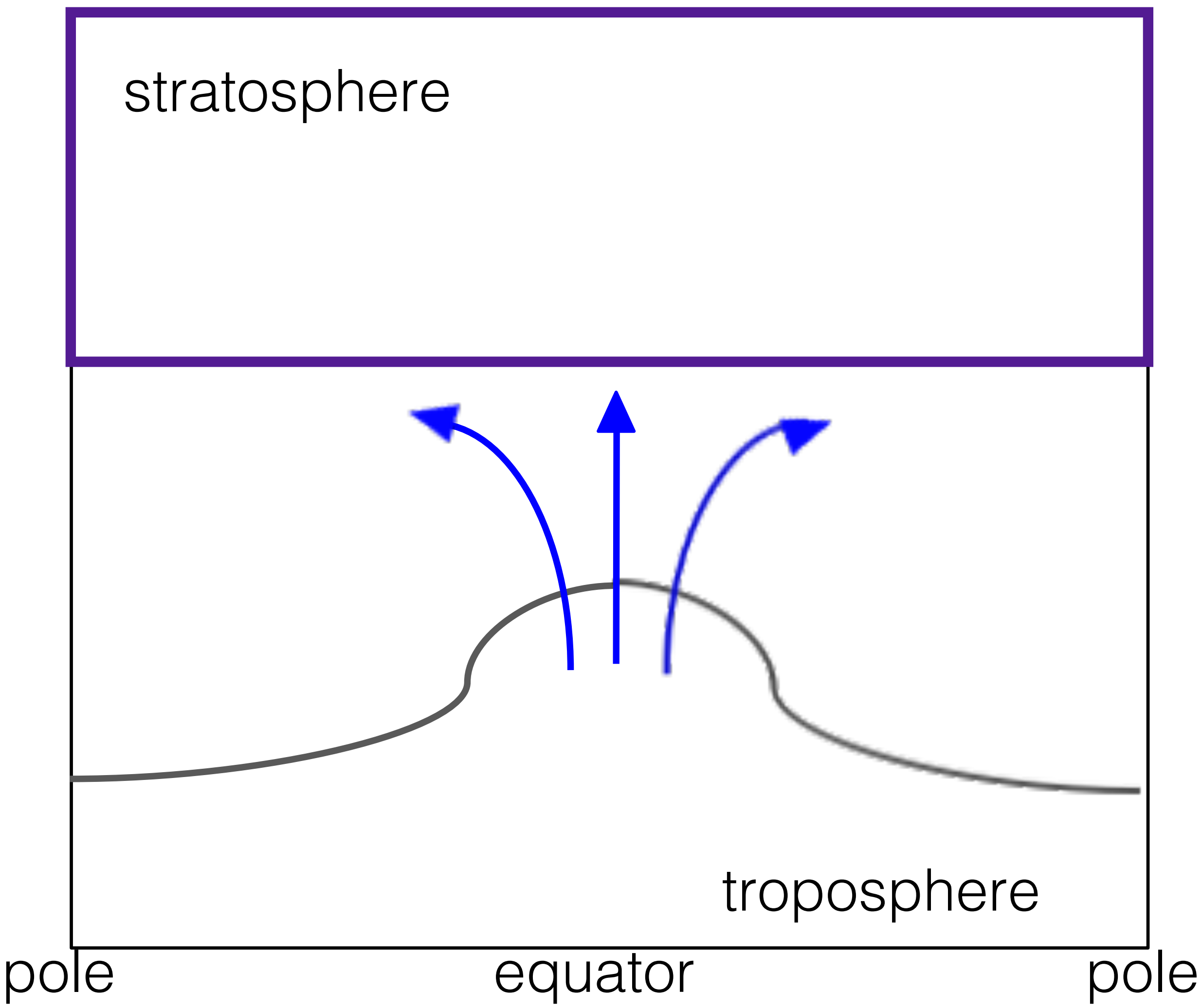


In a steady state:

$$\vec{v} \cdot \nabla \Gamma = \rho$$

Integrate over the volume above an isentropic surface

age flux across surface = mass above the surface

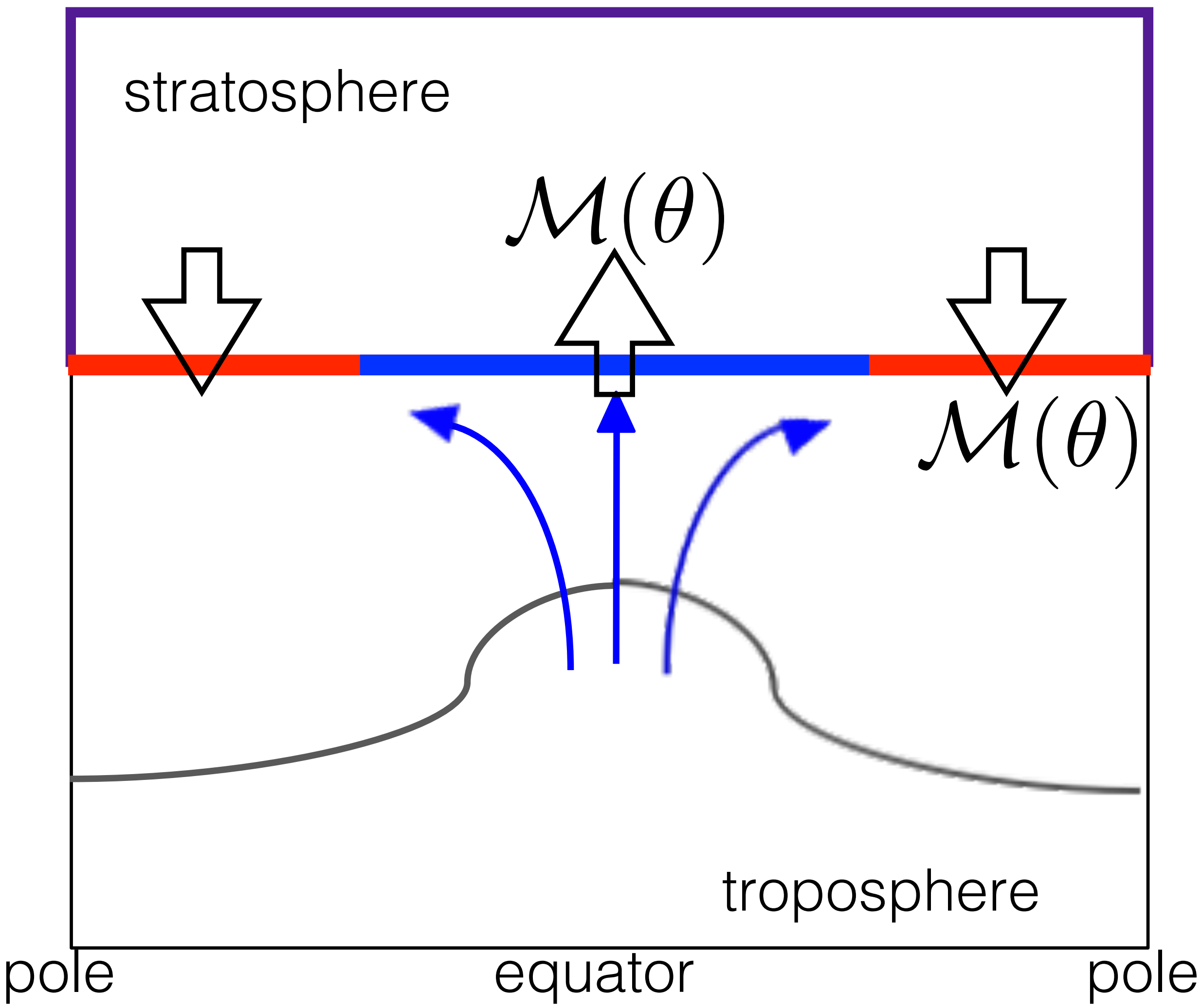
$$-\int_{\theta} \sigma \dot{\theta} \Gamma dA = M(\theta)$$

isentropic density

vertical velocity in isentropic coordinates

[Linz et al. 2016]

Age flux can be linked to mean overturning by considering the gross age gradient



what goes up must come down

$$\int_{up} \sigma \dot{\theta} dA = - \int_{down} \sigma \dot{\theta} dA = \mathcal{M}(\theta)$$

[Linz et al. 2016]

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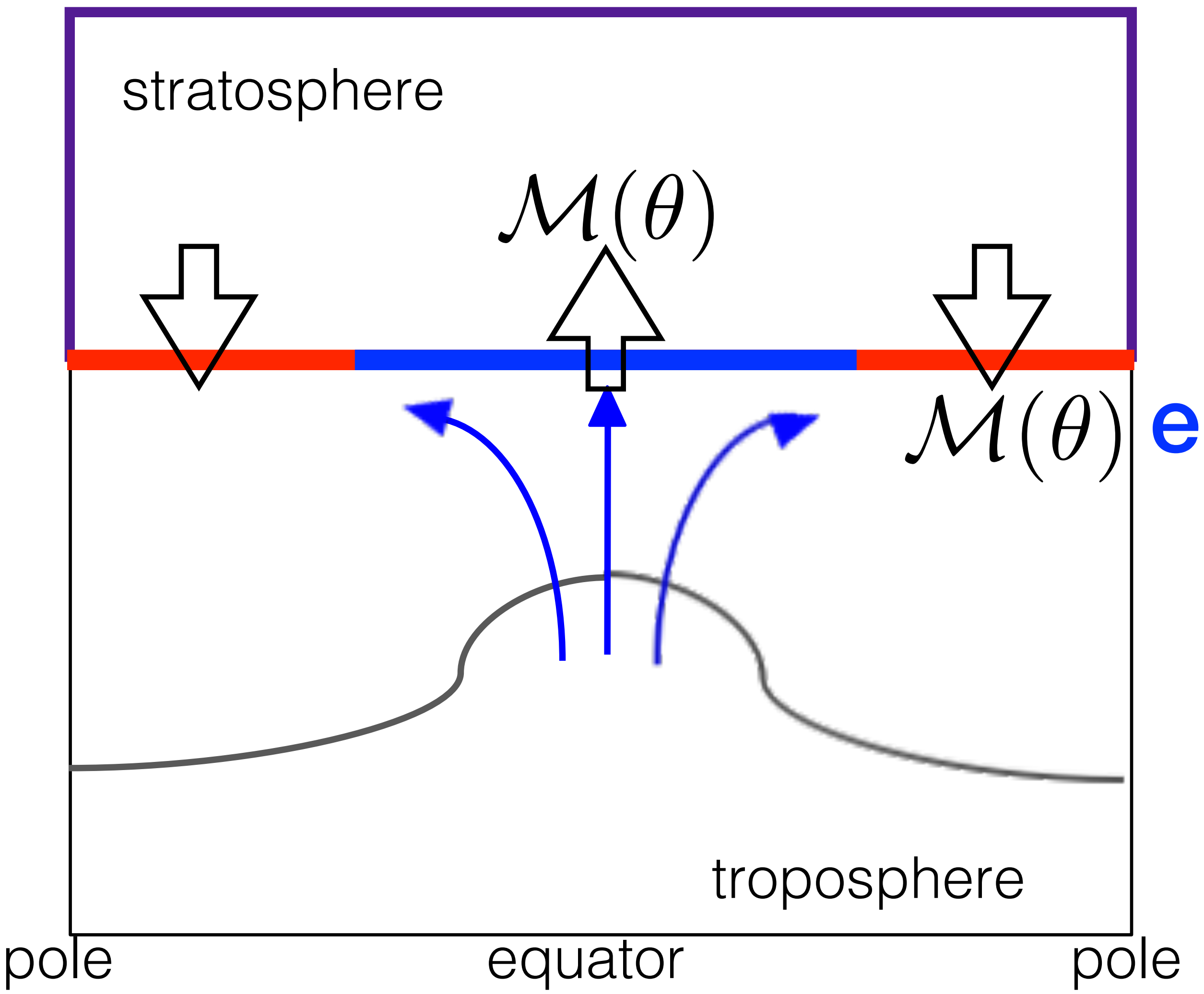


what goes up must come down

age flux related to mean age **entering** and **leaving** stratosphere

$$\int_\theta \sigma\dot{\theta}\Gamma dA = \Gamma_u \mathcal{M}(\theta) - \Gamma_d \mathcal{M}(\theta)$$

mean upwelling age

mean downwelling age

$$\int_{up} \sigma\dot{\theta} dA = -\int_{down} \sigma\dot{\theta} dA = \mathcal{M}(\theta)$$

[Linz et al. 2016]

(key: define mean upwelling/downwelling age as a mass weighted average)

Putting all together

$$-\int_\theta \sigma\dot{\theta}\Gamma dA = M(\theta)$$

$$\int_\theta \sigma\dot{\theta}\Gamma dA = \Gamma_u \mathcal{M}(\theta) - \Gamma_d \mathcal{M}(\theta)$$

↘ ↙

$$\Gamma_d - \Gamma_u = \frac{M(\theta)}{\mathcal{M}(\theta)}$$

gross age difference = mean residence time

[Linz et al. 2016]

Putting all together

$$-\int_\theta \sigma\dot{\theta}\Gamma dA = M(\theta) \qquad \int_\theta \sigma\dot{\theta}\Gamma dA = \Gamma_u \mathcal{M}(\theta) - \Gamma_d \mathcal{M}(\theta)$$

↘ ↙

$$\Gamma_d - \Gamma_u = \frac{M(\theta)}{\mathcal{M}(\theta)}$$

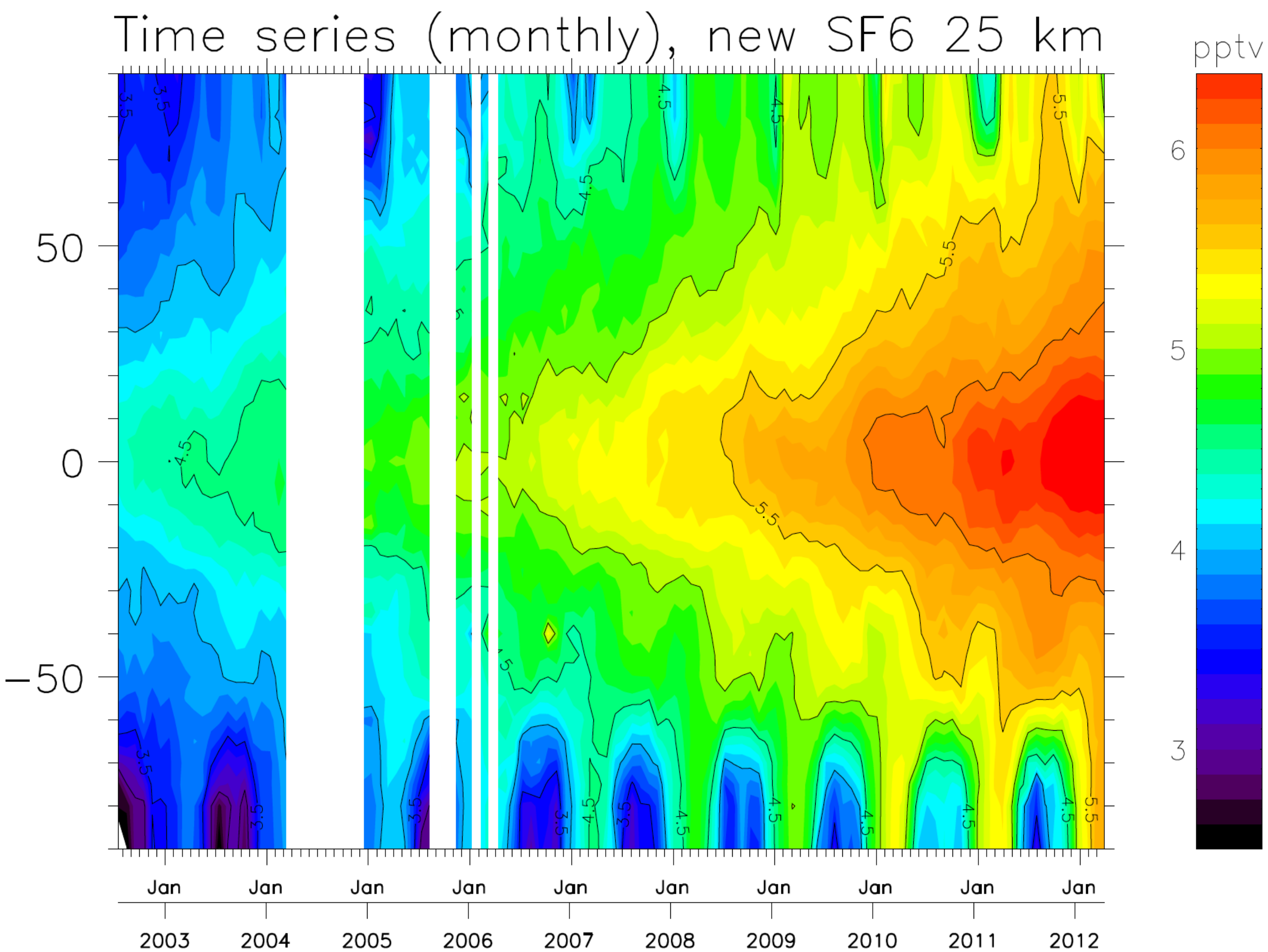
gross age difference = mean residence time

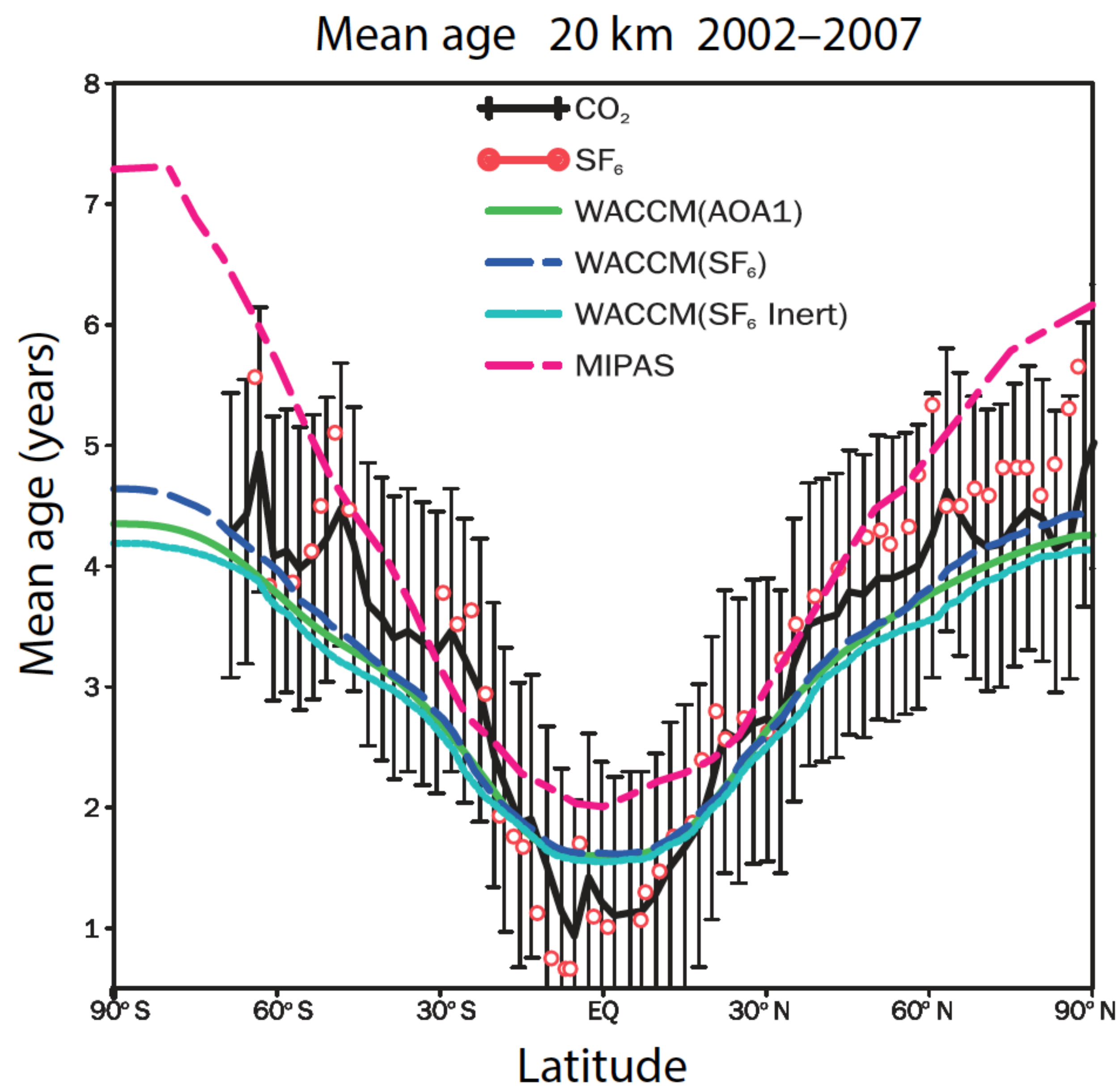
mean overturning relates directly to age difference
not necessarily the age itself

$$\mathcal{M}(\theta) = \frac{M(\theta)}{\Gamma_d - \Gamma_u}$$

[Linz et al. 2016]

Age from satellite SF_6 measurements by MIPAS



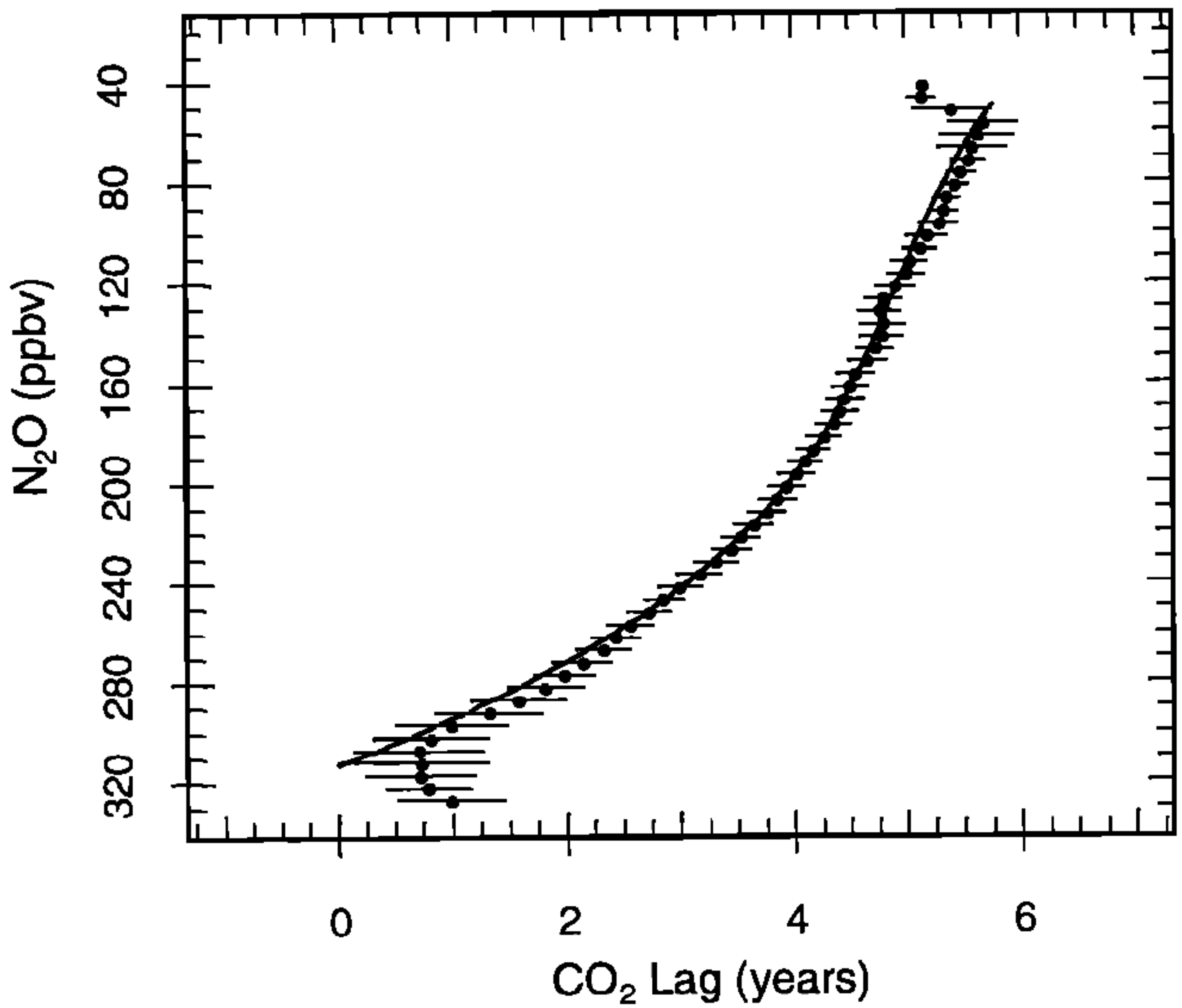


[Haenel et al. 2015]

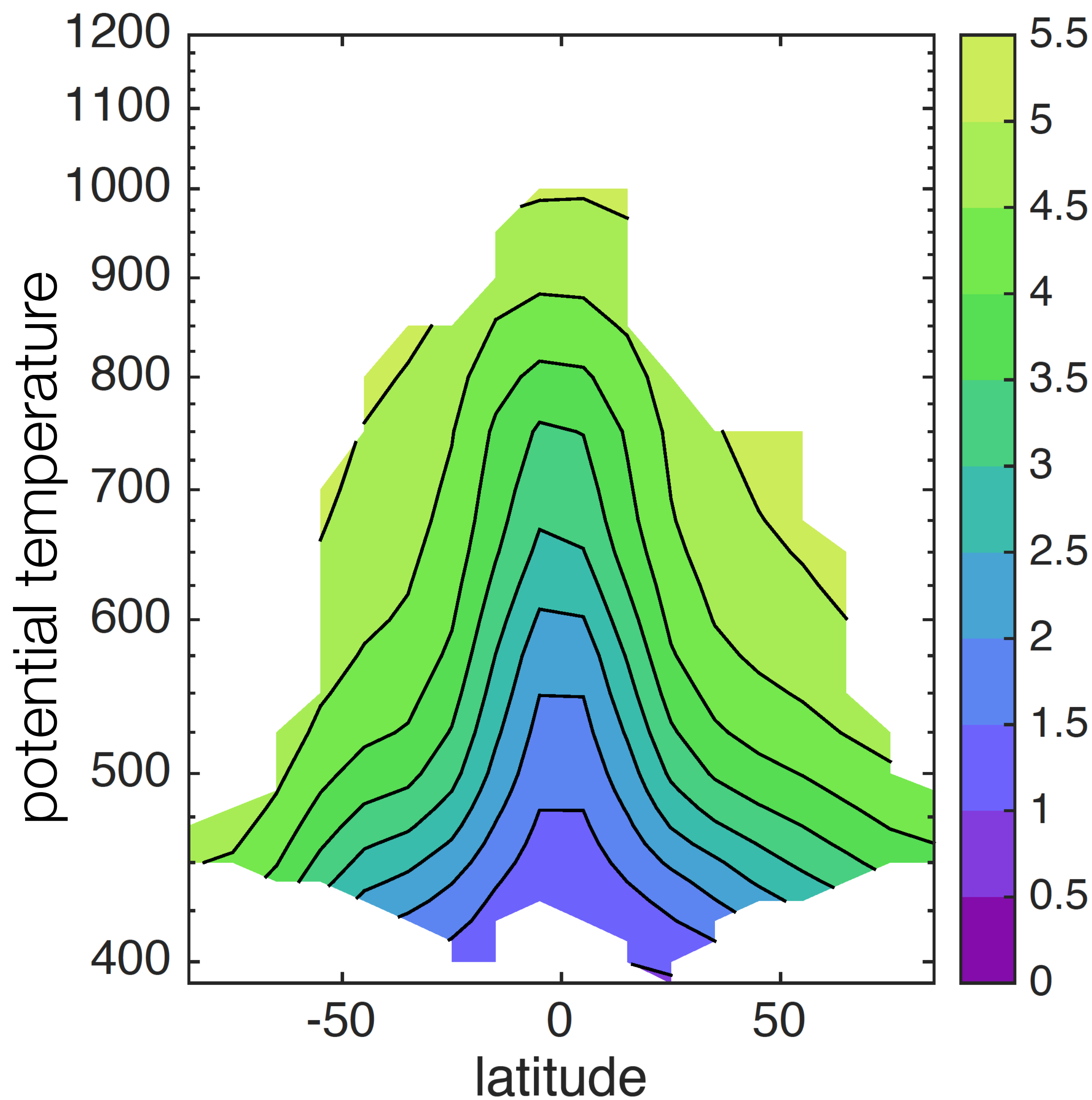
[Kovacs et al. 2017]

Age can also be estimated from N_2O due to it's compact relationship with CO_2

Balloon + aircraft measurements from 1990s



Age from satellite N_2O, using Andrews cubic

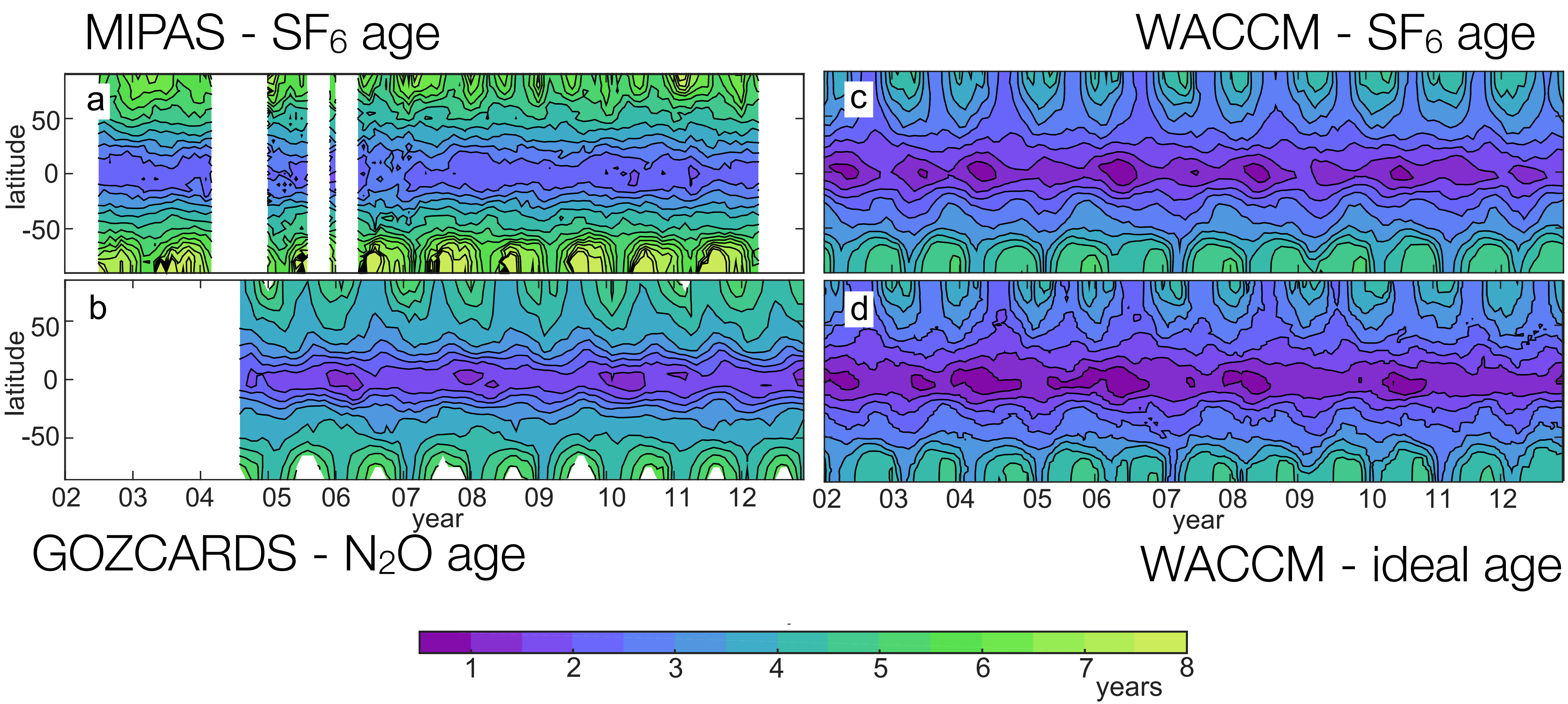


$$\Gamma_{LAG}(N_2O) = 0.0581(313 - N_2O) - 0.000254(313 - N_2O)^2 + 4.41 \times 10^{-7}(313 - N_2O)^3$$

[Andrews et al. 2001, Linz et al. 2017]

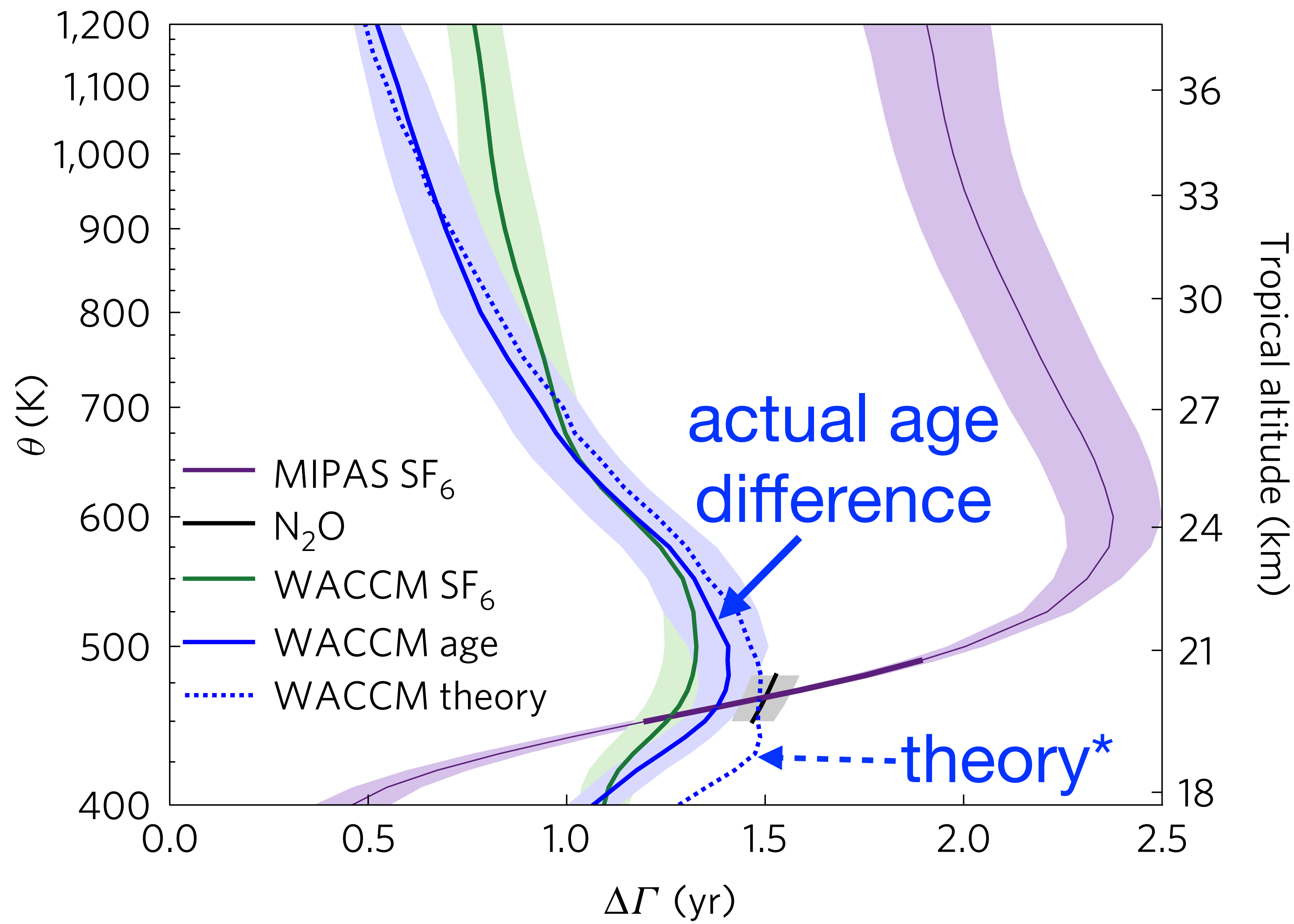
Age from SF_6, N_2O, and models vary a lot

Age on the 500 K isentrope (c. 21 km)



[Linz et al. 2017]

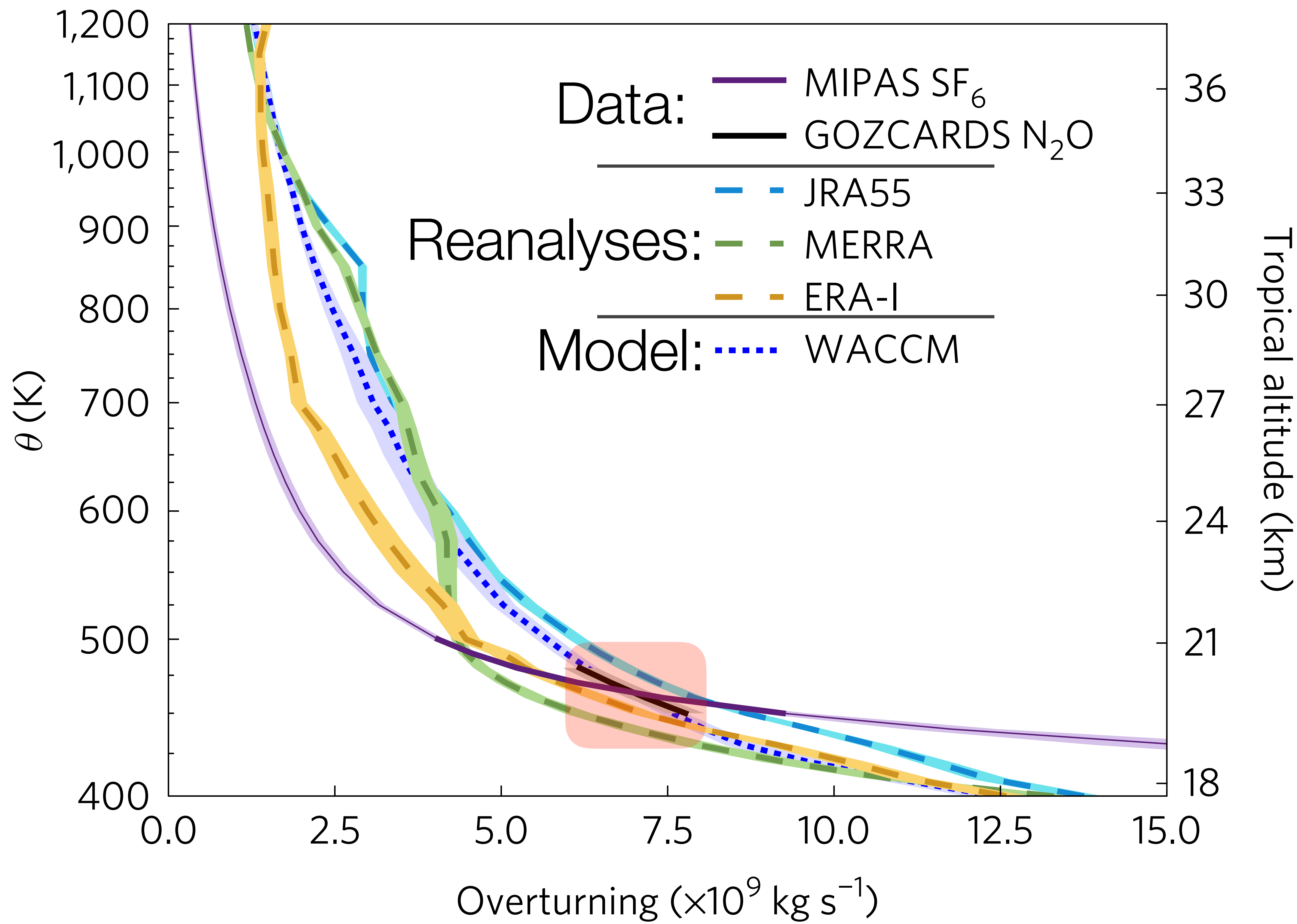
Theory holds well in a model (WACCM) allowing us to test assumptions



$$\Delta\Gamma(\theta) = \Gamma_d(\theta) - \Gamma_u(\theta) = \frac{M(\theta)}{\mathcal{M}(\theta)}.$$

[Linz et al. 2017]

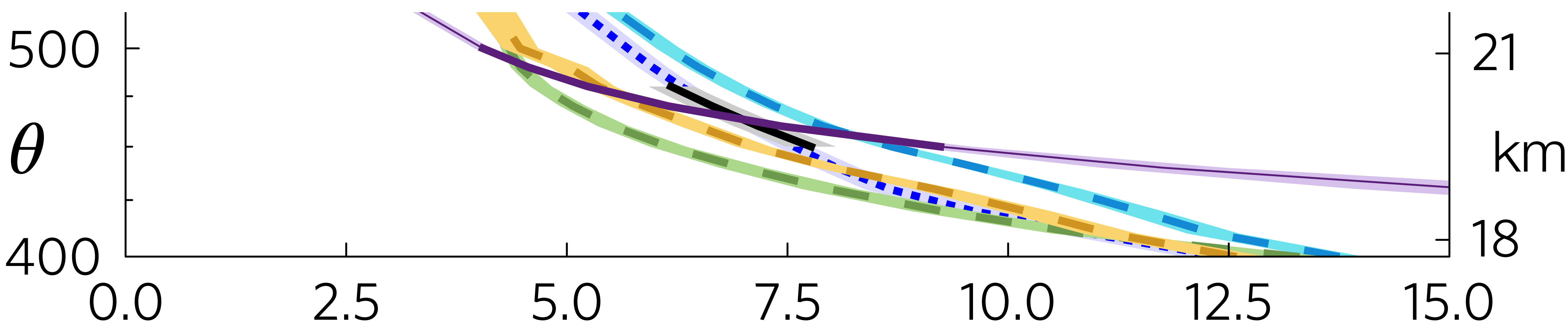
The Overturning Circulation: Two observational sets agree (where they both exist)



The Overturning Circulation: Significant disagreement with modern reanalyses

Overturning (10^9 kg/s) at 460 K

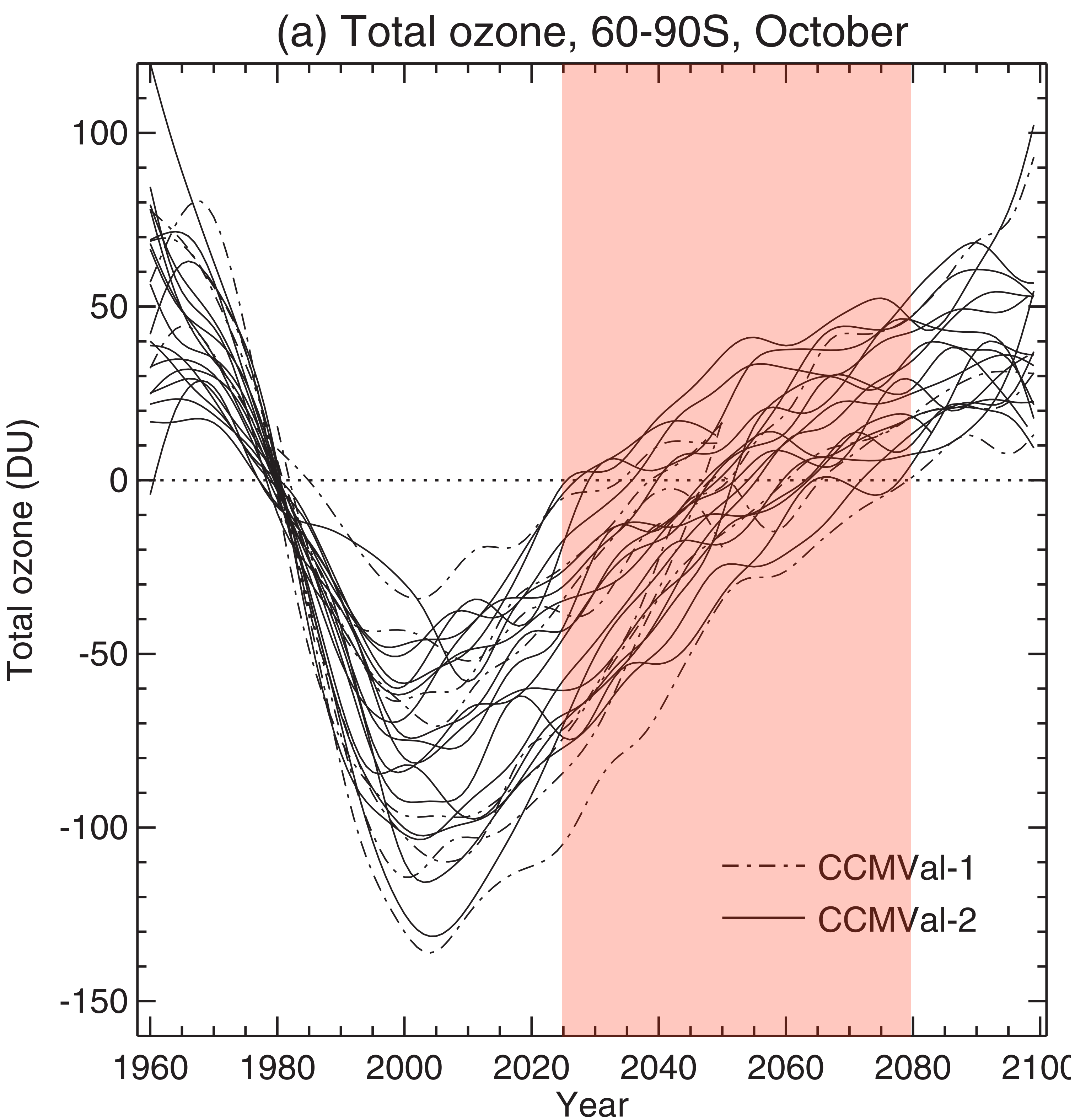
Dataset	Overturning	
MIPAS SF_6	7.4	6.3 - 7.6 (uncertainty)
GOZCARDS N_2O	7.2	
JRA55	7.9	
MERRA	5.5	
ERA-I	6.5	
WACCM	7.1	



Quantifying the Brewer-Dobson Circulation
is a challenge

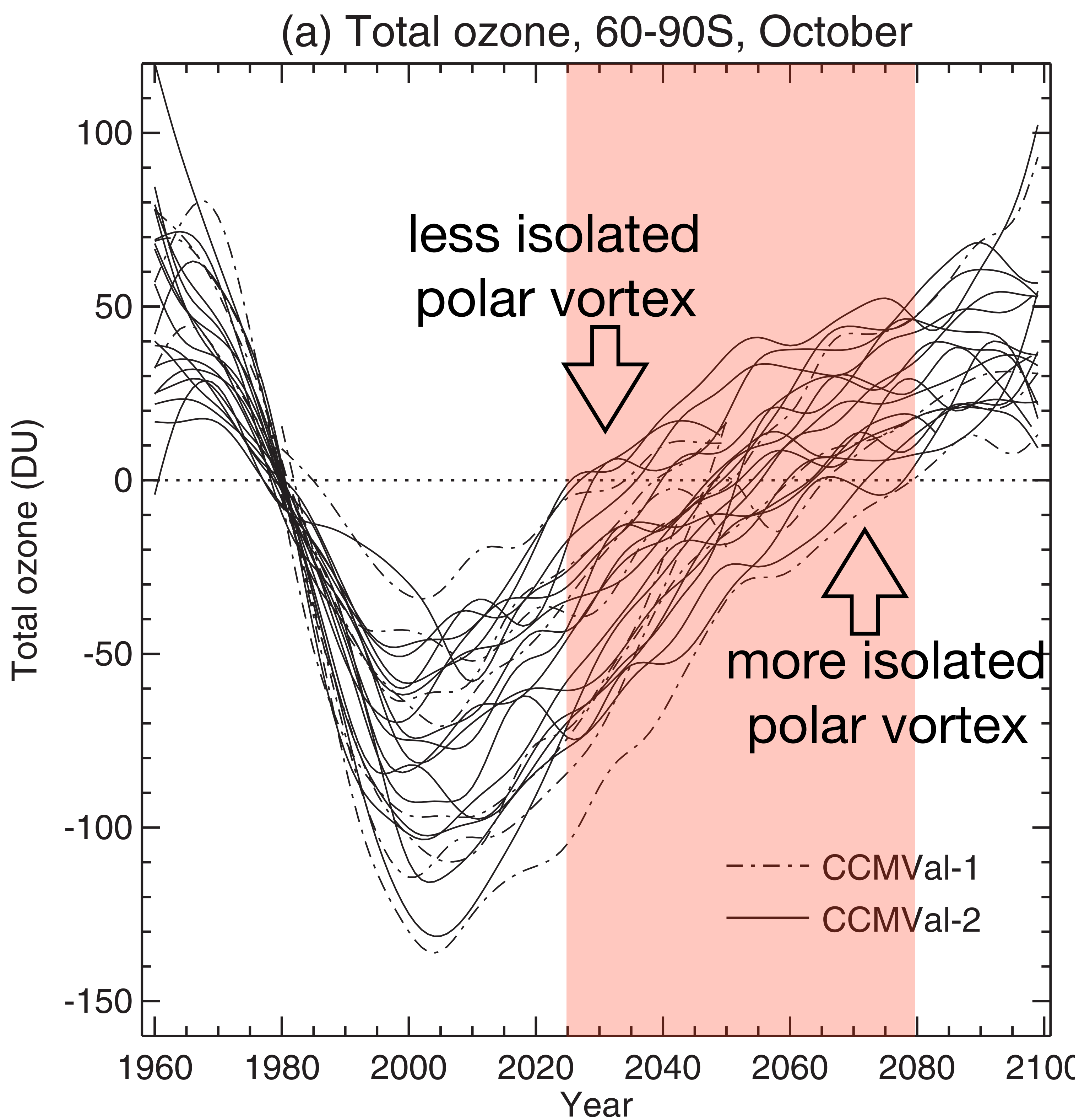
And it matters for future climate projections…

Tracer transport important for climate prediction: When will the ozone hole heal?

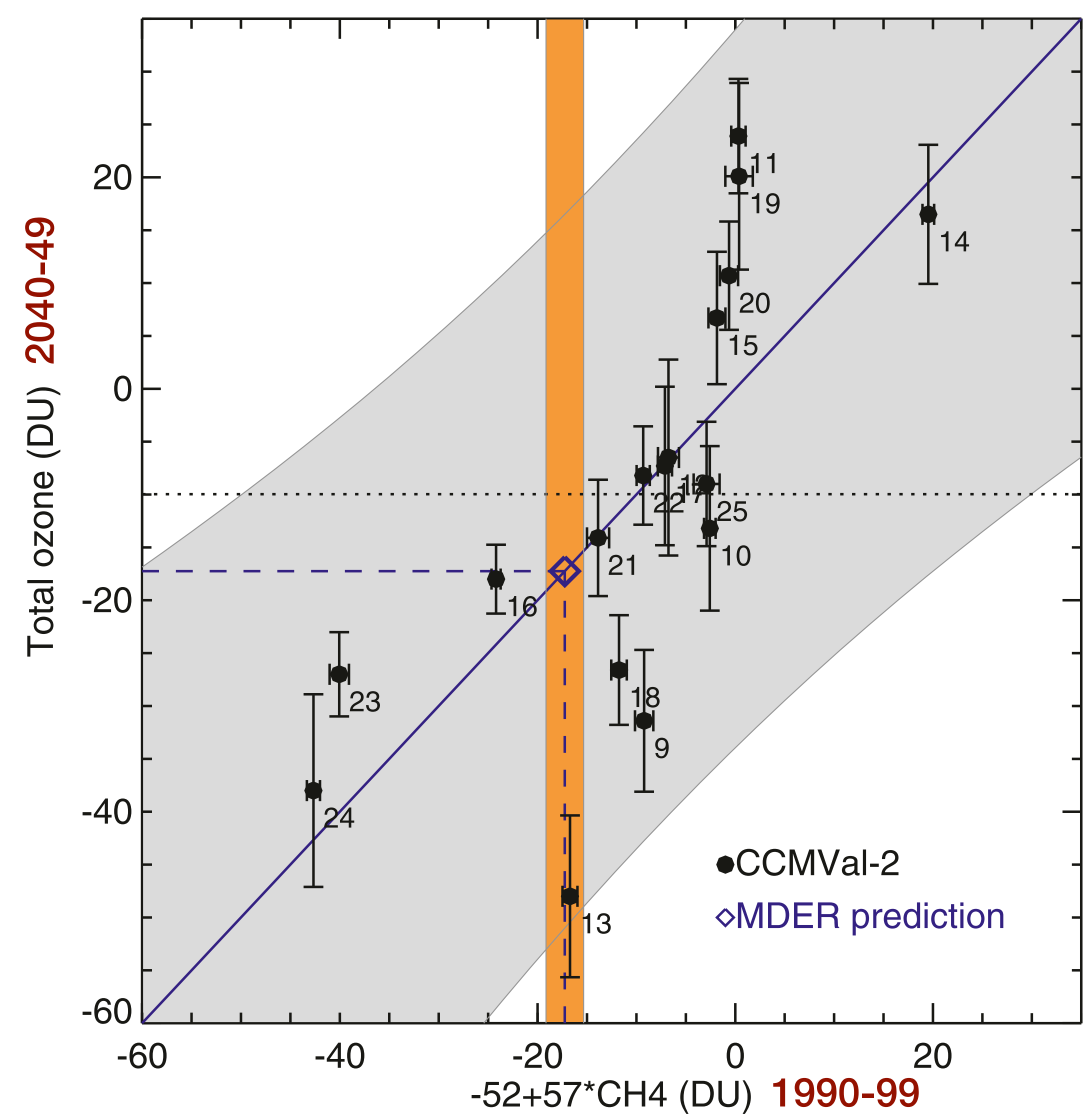


[Karpechko et al. 2013]

Tracer transport important for climate prediction: Ozone recovery



Karpechko et al. 2013: spread between models most strongly correlates with transport



Numerics and Transport

- *Karpechko et al. (2013)*: uncertainty in ozone recovery due more to transport than chemistry or climatology
- *Kent et al. (2014)* establish short term test of transport by dynamical cores, the numerical heart of an AGCM
- Today: an update of the *Held and Suarez (1994)* test to assess the climatological properties of transport (and stratosphere-troposphere coupling more generally)

[Gupta et al. (in review)]

A Proposal for the Intercomparison of the Dynamical Cores of Atmospheric General Circulation Models v2.0

Isaac M. Held*
and Max J. Suarez**

- In the last 25 years, growing awareness of importance of strat-trop coupling + chemistry

$$\frac{\partial v}{\partial t} = \cdots - k_v(\sigma) v$$

$$\frac{\partial T}{\partial t} = \cdots - k_T(\phi,\sigma)\left[T - T_{eq}(\phi,p)\right]$$

$$T_{eq} = \max\left\{200\text{K}, \left[315\text{K} - (\Delta T)_y \sin^2\phi - (\Delta\theta)_z \log\left(\frac{p}{p_0}\right)\cos^2\phi\right]\left(\frac{p}{p_0}\right)^{\kappa}\right\}$$

$$k_T = k_a + (k_s - k_a)\max\left(0, \frac{\sigma - \sigma_b}{1-\sigma_b}\right)\cos^4\phi$$

$$k_v = k_f \max\left(0, \frac{\sigma - \sigma_b}{1-\sigma_b}\right)$$

$\sigma_b = 0.7$ $\quad$ $k_f = 1\ \text{day}^{-1}$,

$k_a = 1/40\ \text{day}^{-1}$ $\quad$ $k_s = 1/4\ \text{day}^{-1}$

$(\Delta T)_y = 60\text{K}$ $\quad$ $(\Delta\theta)_z = 10\text{K}$

$p_0 = 1000\ \text{mb}$ $\quad$ $\kappa = \frac{R}{c_p} = \frac{2}{7}$ $\quad$ $c_p = 1004\ \text{J kg}^{-1}\ \text{K}^{-1}$

$\Omega = 7.292 \times 10^{-5}\ \text{s}^{-1}$ $\quad$ $g = 9.8\ \text{m s}^{-2}$ $\quad$ $a_e = 6.371 \times 10^6\ \text{m}.$

[Gupta et al. (in review)]

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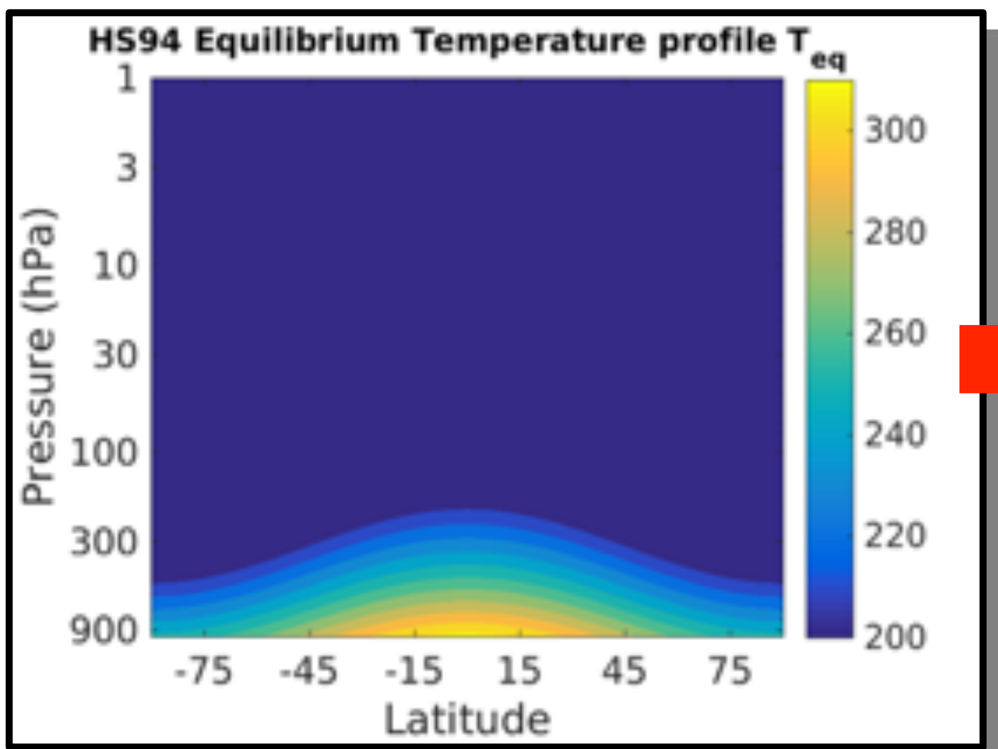

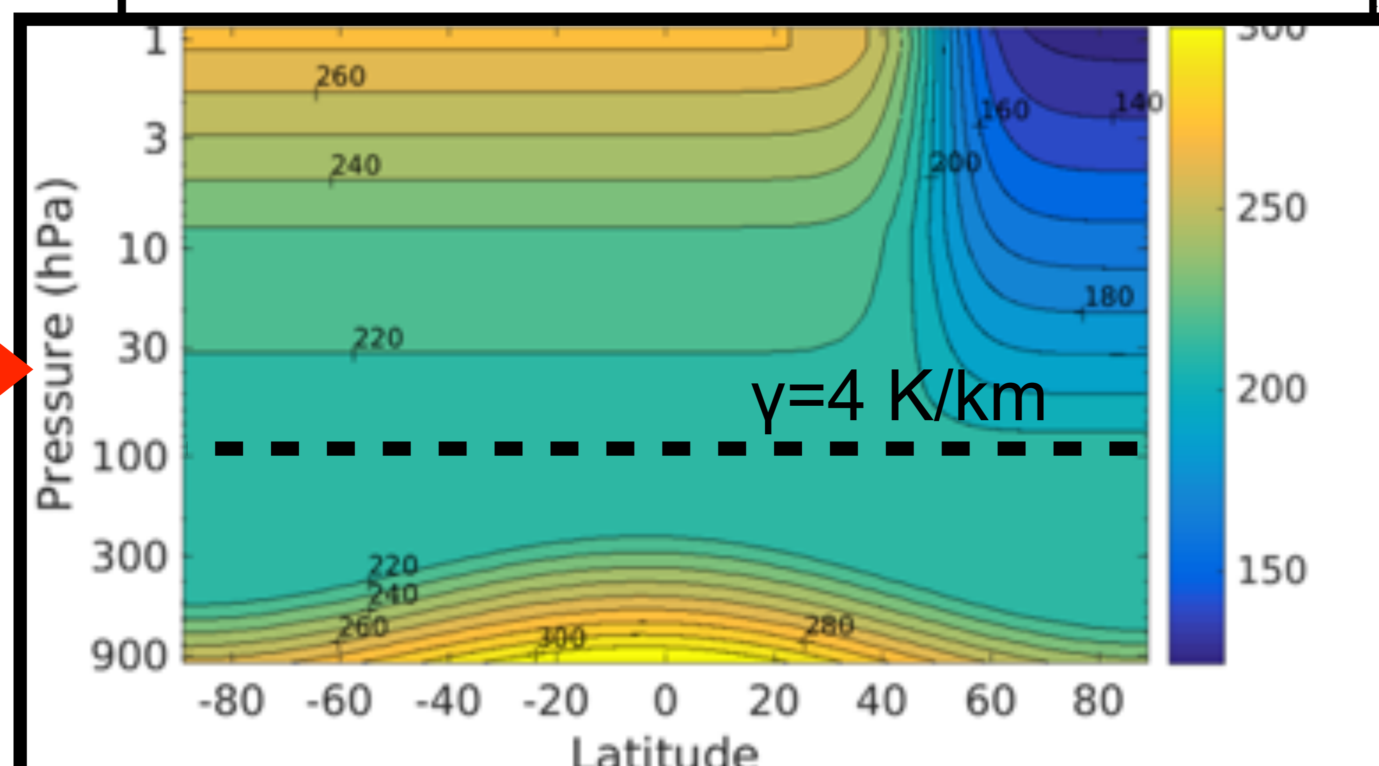

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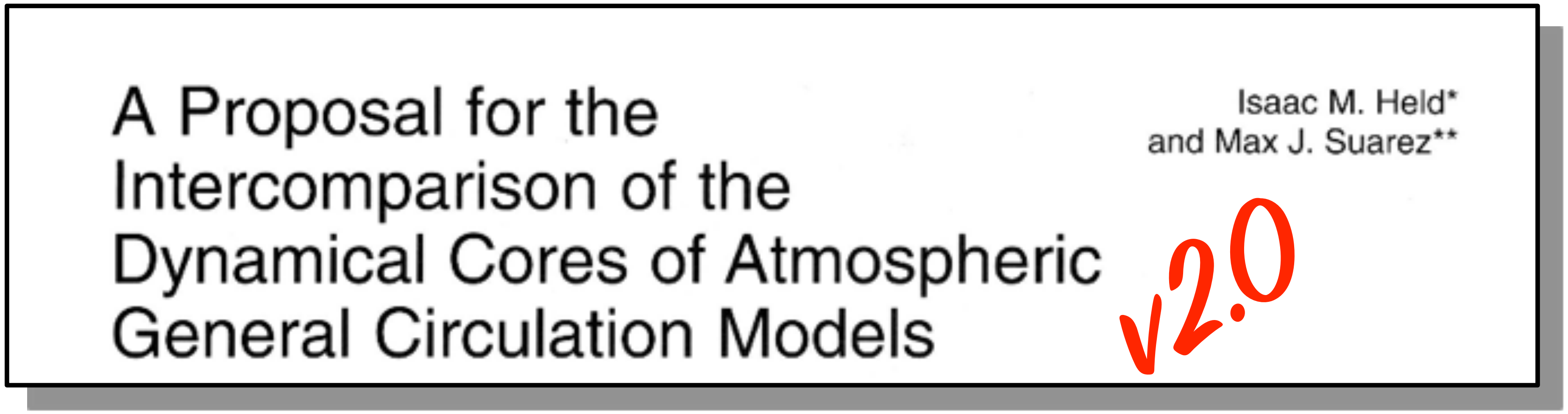
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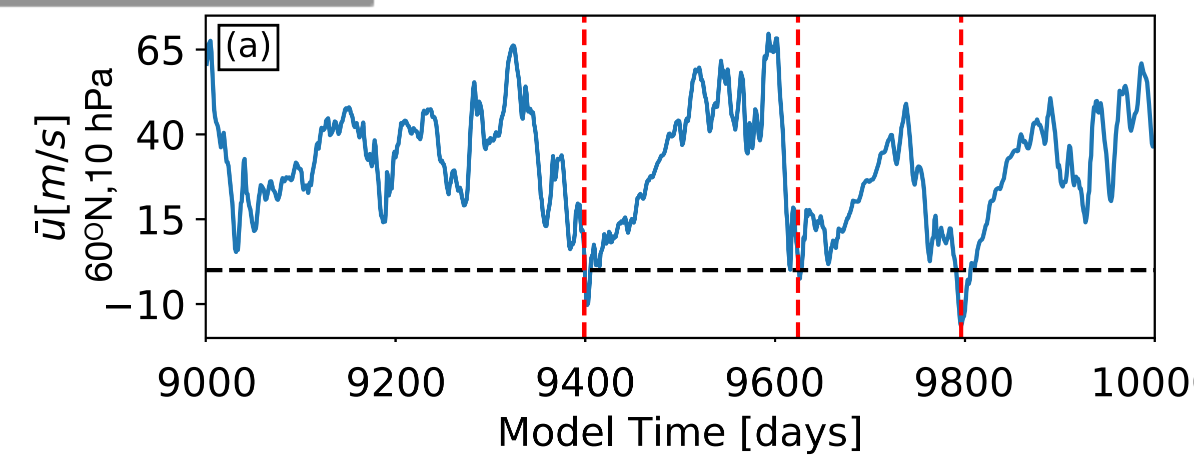
- Topography to stimulate SSWs *[Gerber and Polvani 2009]*



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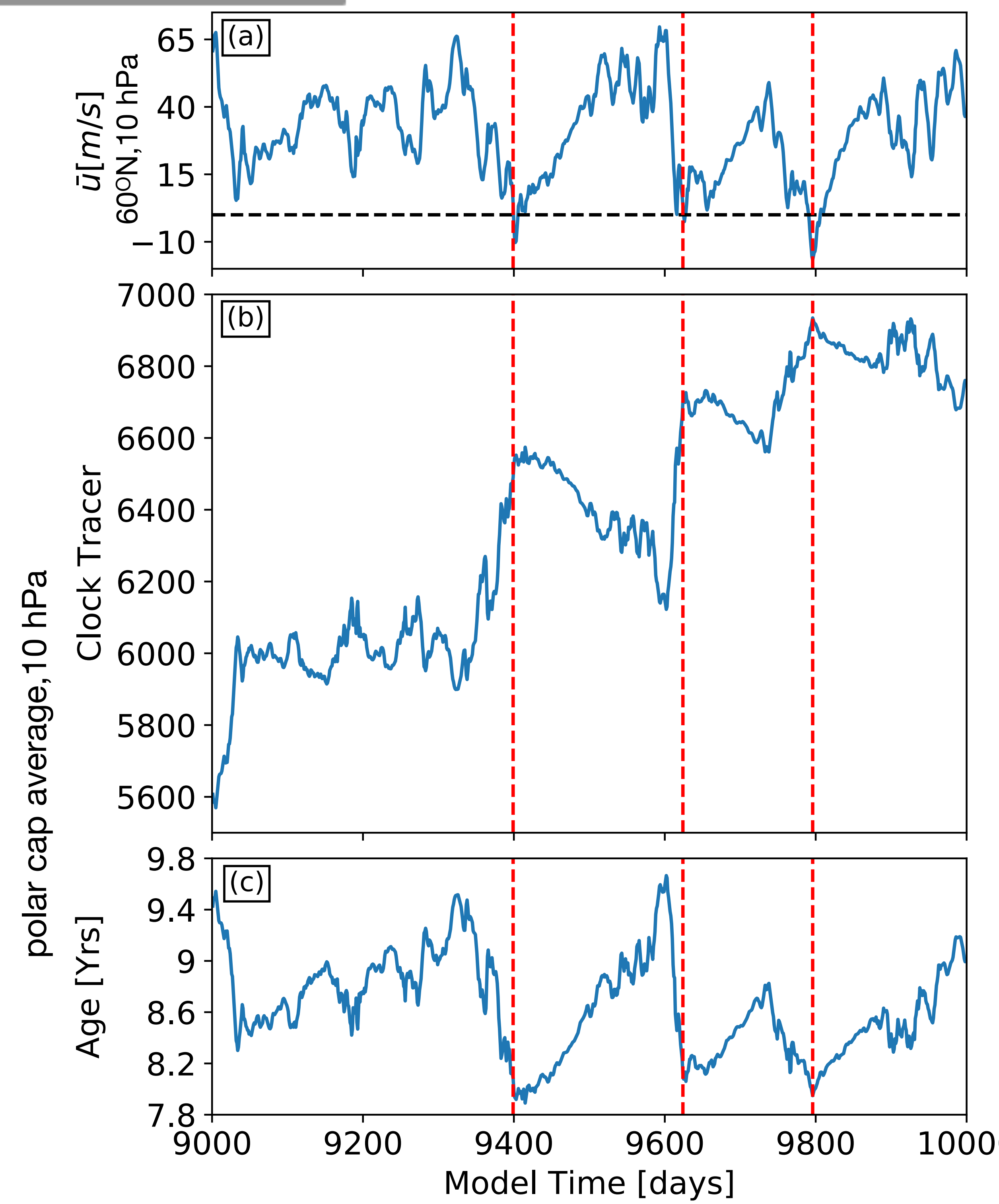
- Add clock tracer to evaluate age-of-air

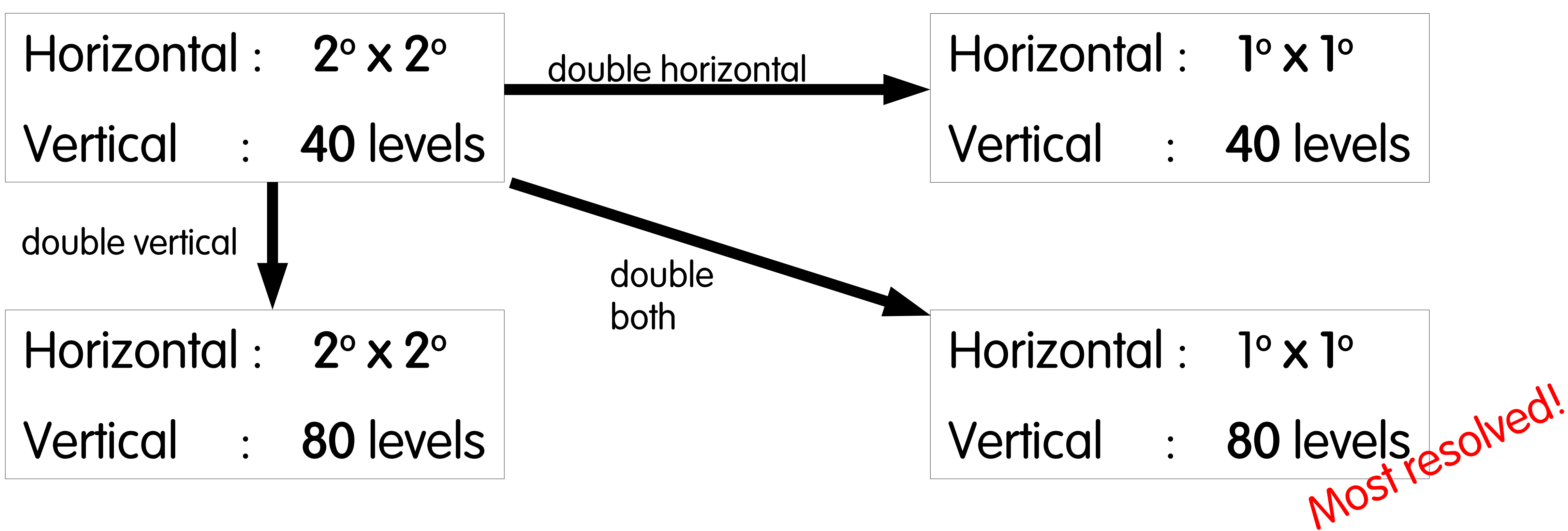


[Gupta et al. (in review)]

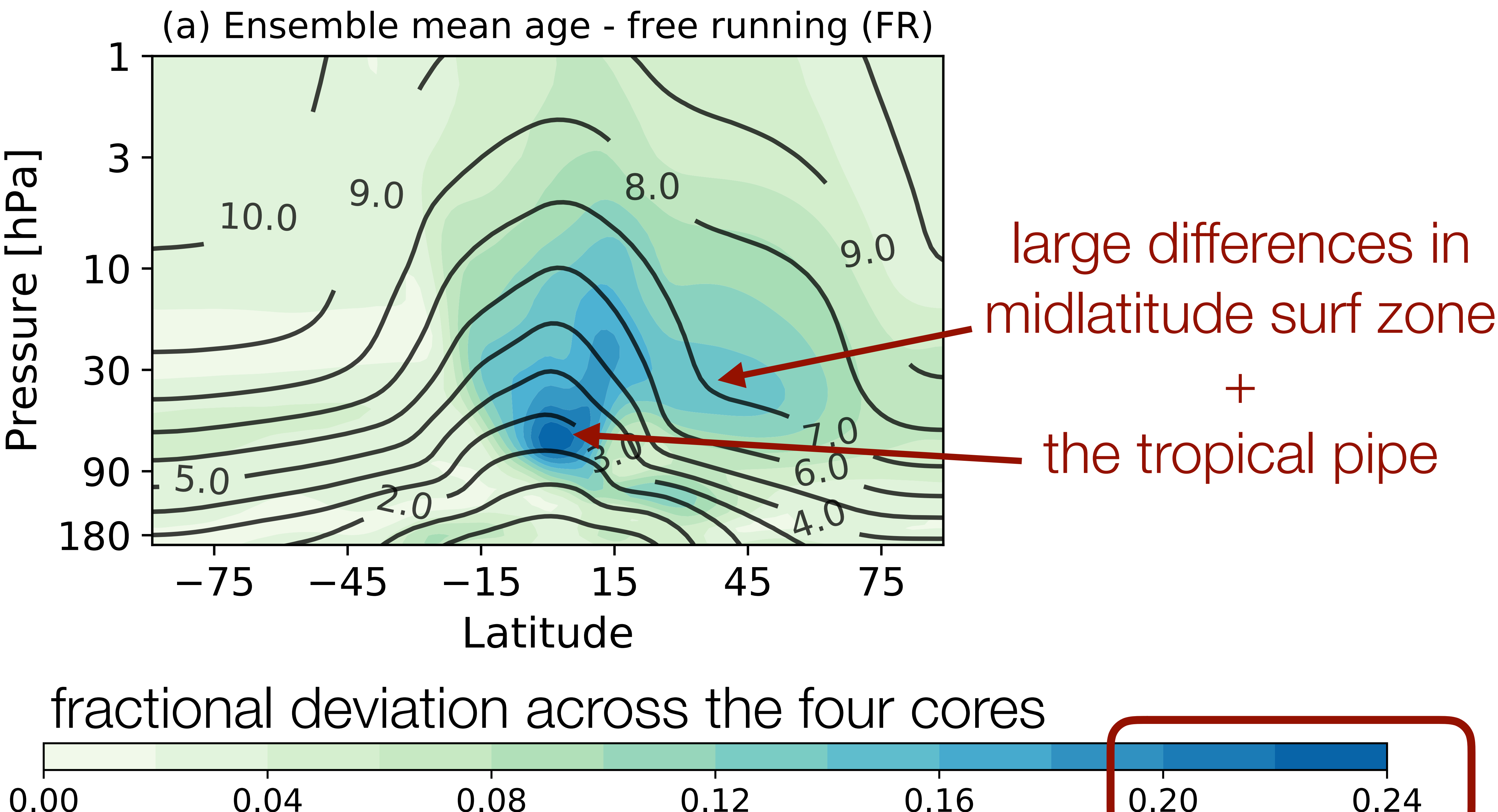
Compare 4 dynamical cores

GFDL-PS PSEUDOSPECTRAL	**GFDL-FV3** ← (new core of fvGFS) CUBED SPHERE FINITE VOLUME
CAM-SE ← (NCAR's CESM2 core) CAM SPECTRAL ELEMENT	**CAM-FV** CAM FINITE VOLUME (CAM-FV)

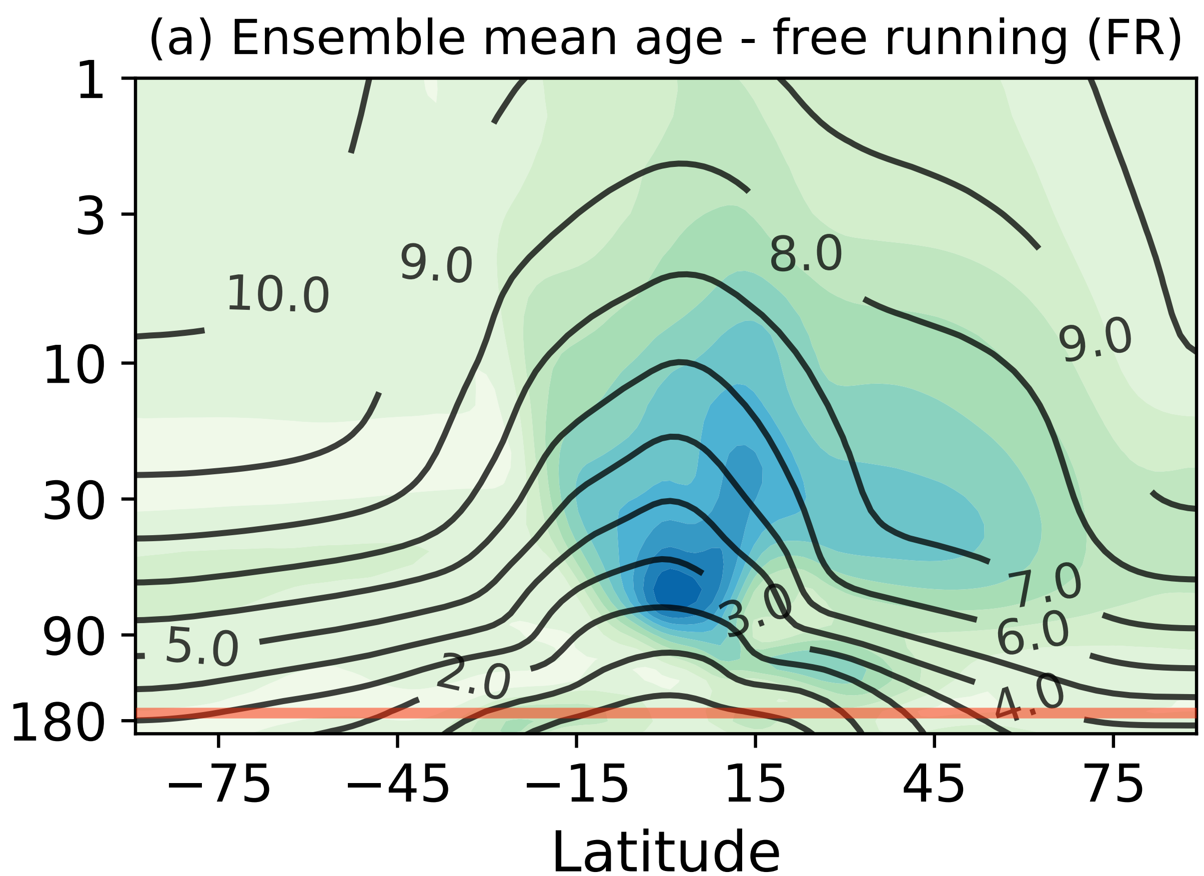
··· and their robustness to changing resolution

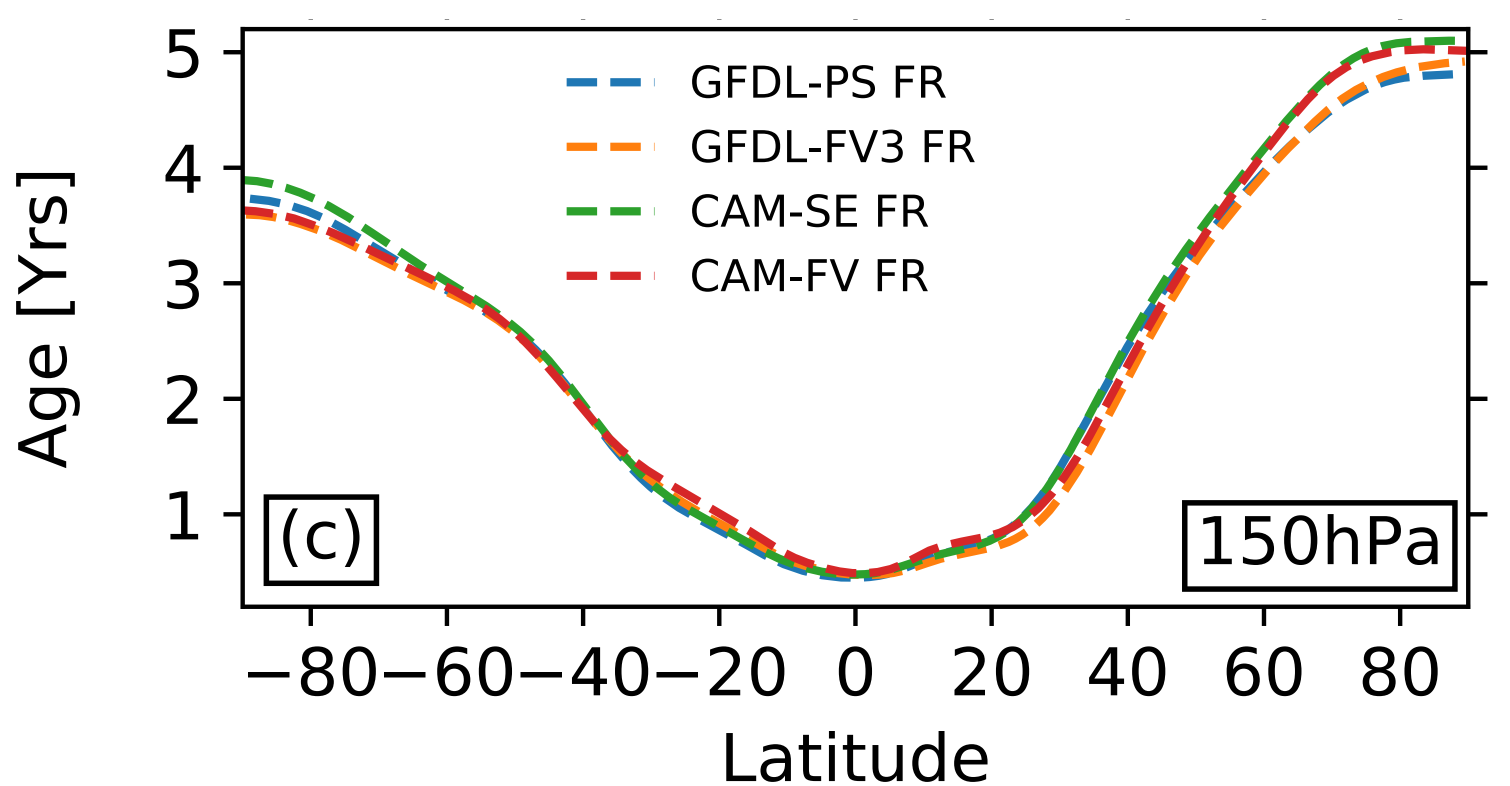


Initial Results: Large spread between models (in layman's terms, a real mess!)



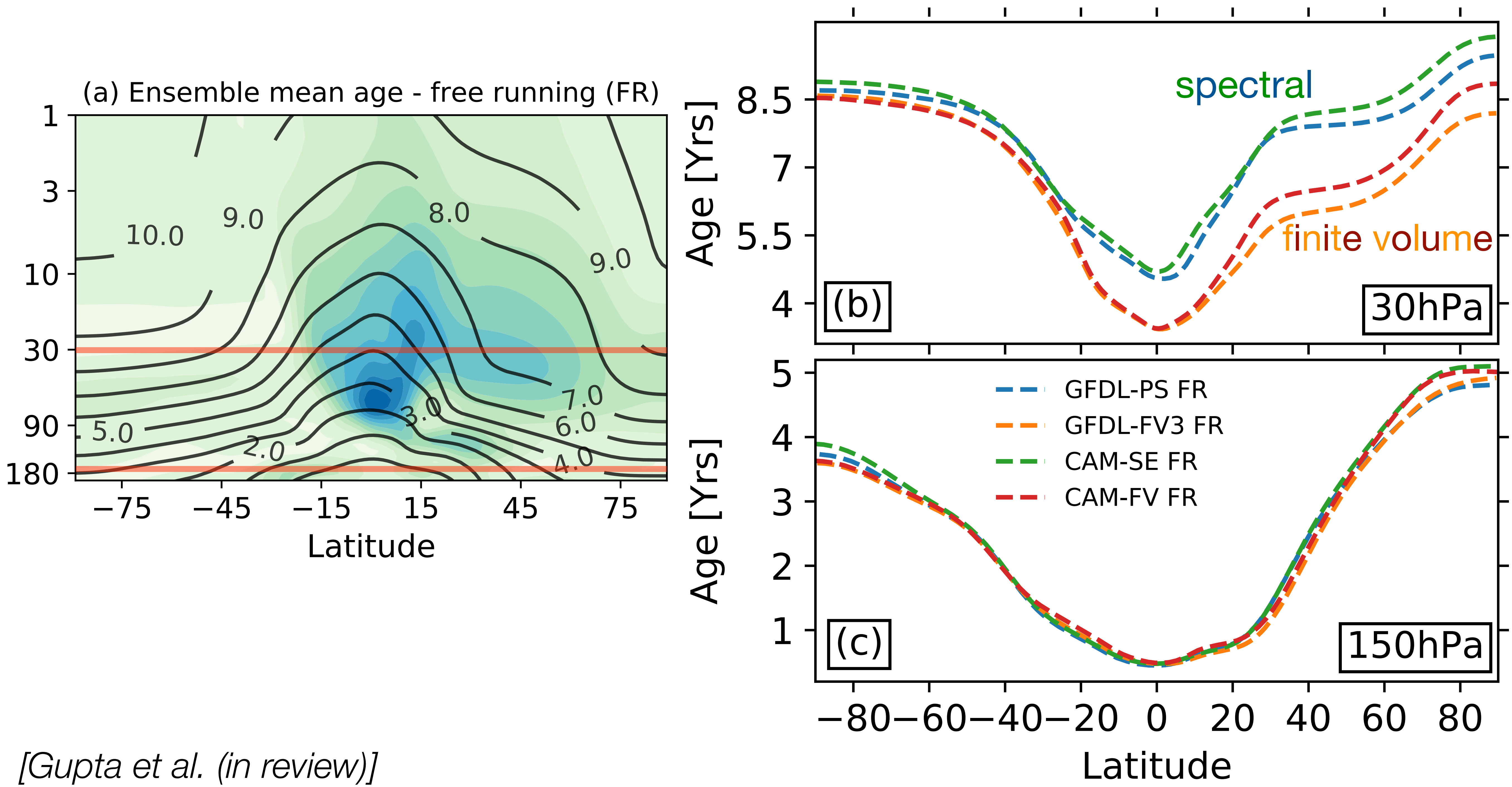
Differences are stratospheric in origin





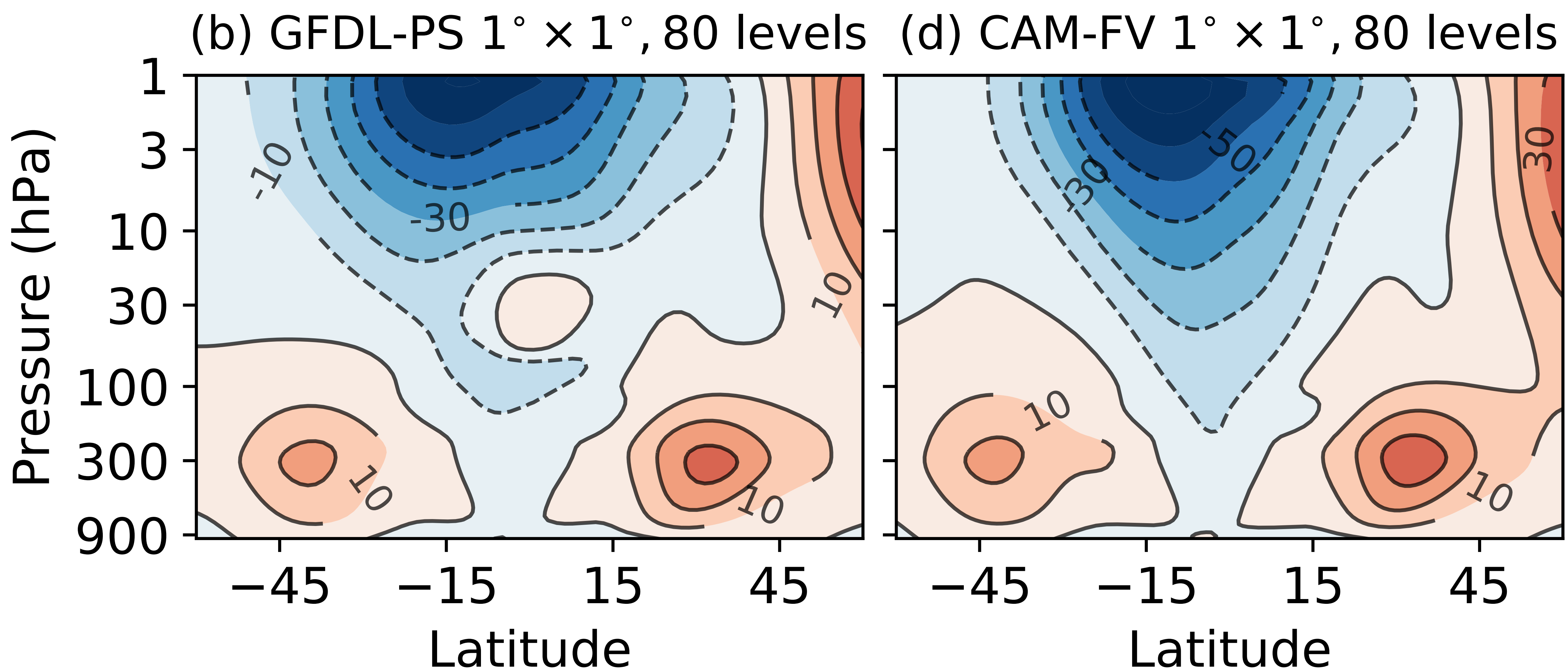
[Gupta et al. (in review)]

Differences are stratospheric in origin reflecting a split between spectral and FV cores



[Gupta et al. (in review)]

Key is divergence of tropical winds: spectral models develop westerly jets

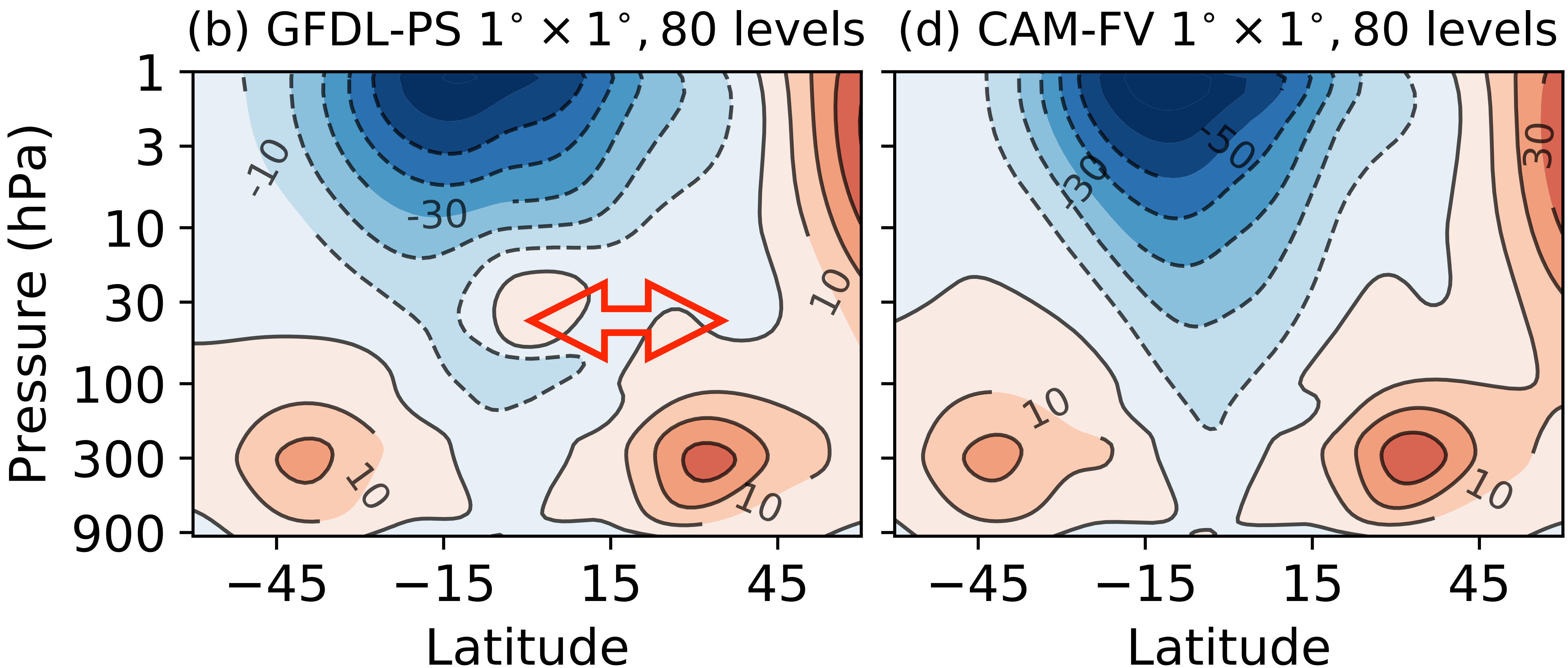


[cf. Yao and Jablonowski 2015]

[Gupta et al. (in review)]

Key is divergence of tropical winds: spectral models develop westerly jets

westerlies permit enhanced mixing into tropics



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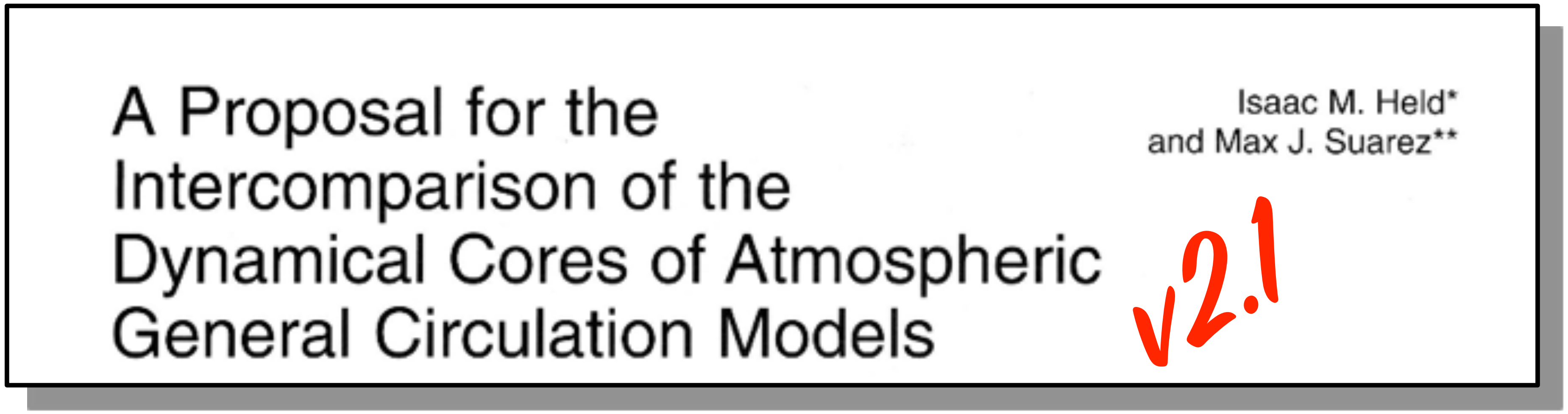
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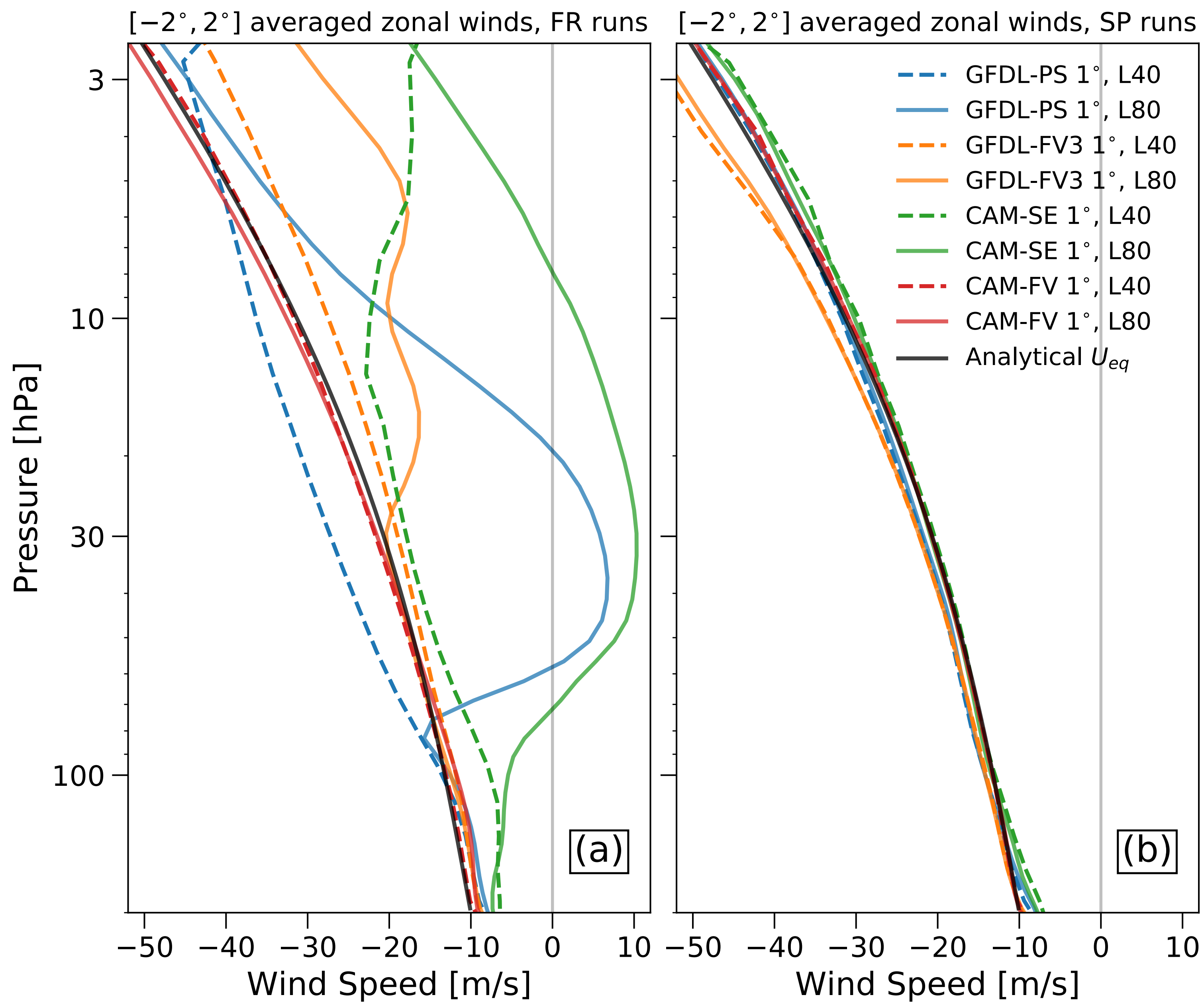
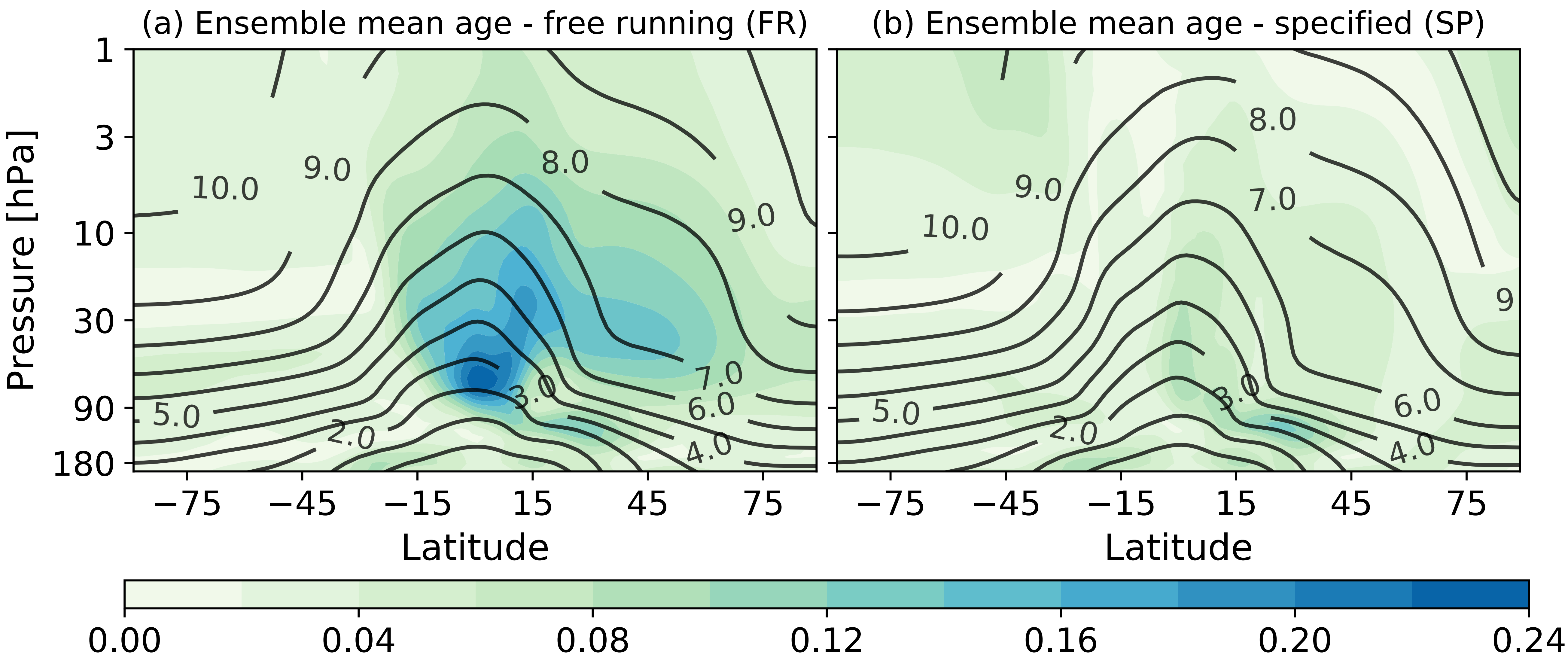
[Gupta et al. (in review)]

- In the last 25 years, growing awareness of importance of strat-trop coupling + chemistry
- Update T_{eq} to *Polvani and Kushner (2002)*: polar night jet (perpetual January)
- Topography to stimulate SSWs *[Gerber and Polvani 2009]*
- Add clock tracer to evaluate age-of-air
- Specify winds in the tropics (i.e., constrain QBO region)

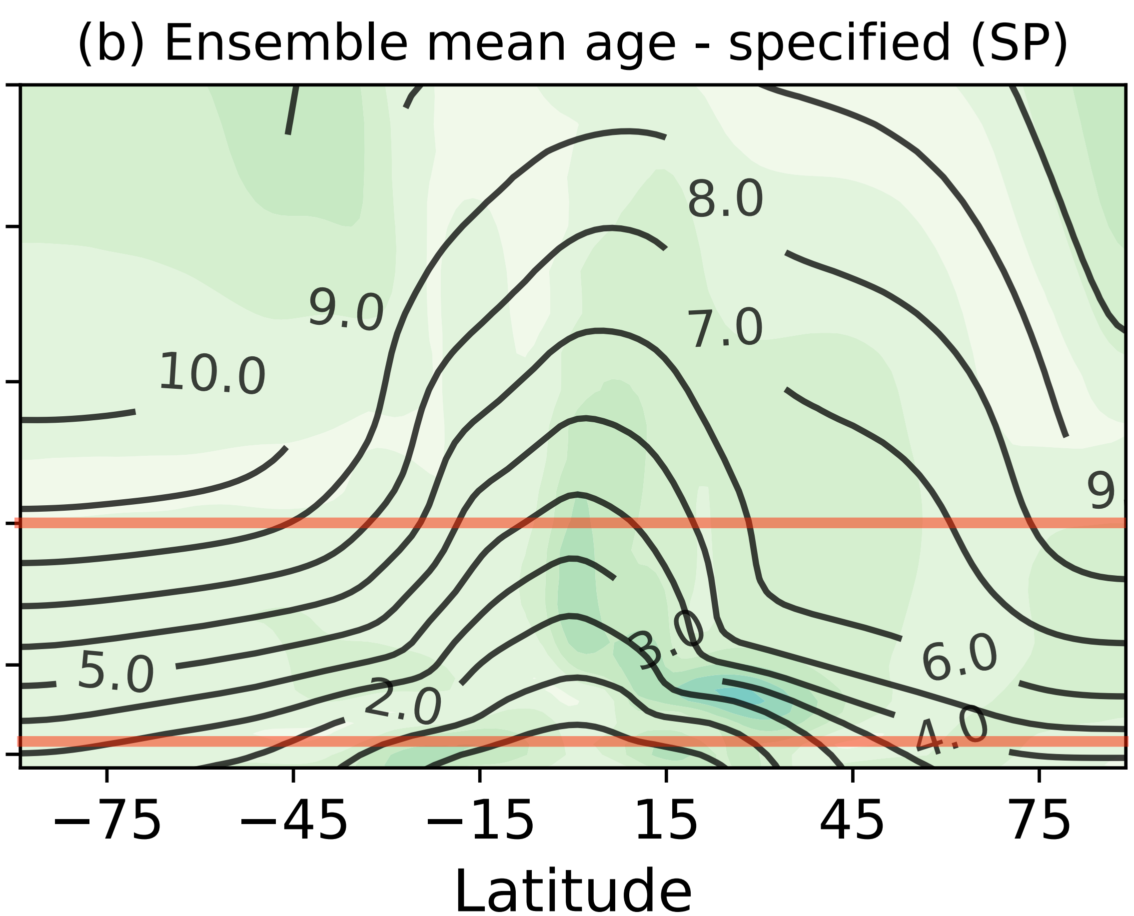


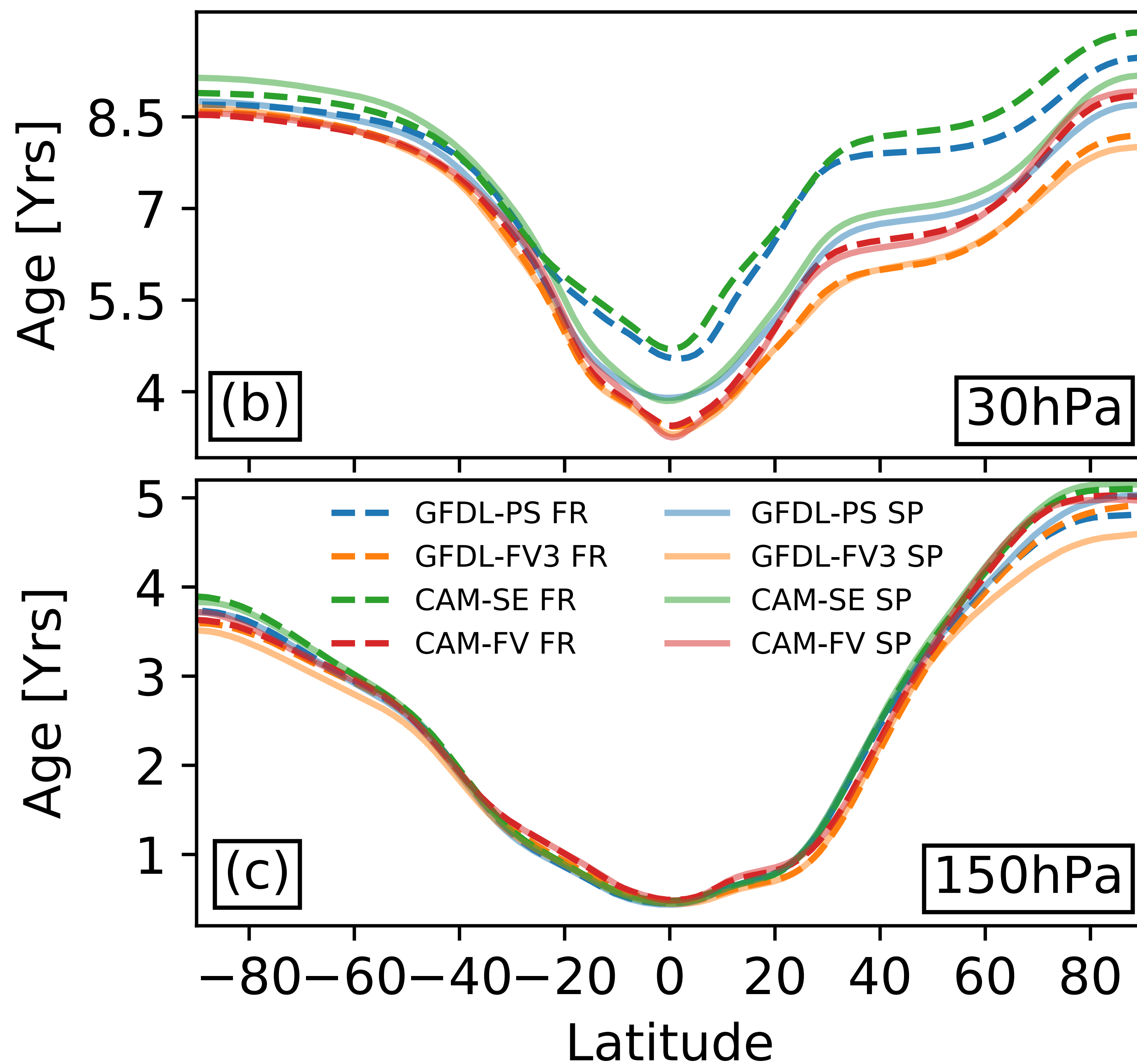
Greater agreement amongst cores but differences persist



[Gupta et al. (in review)]

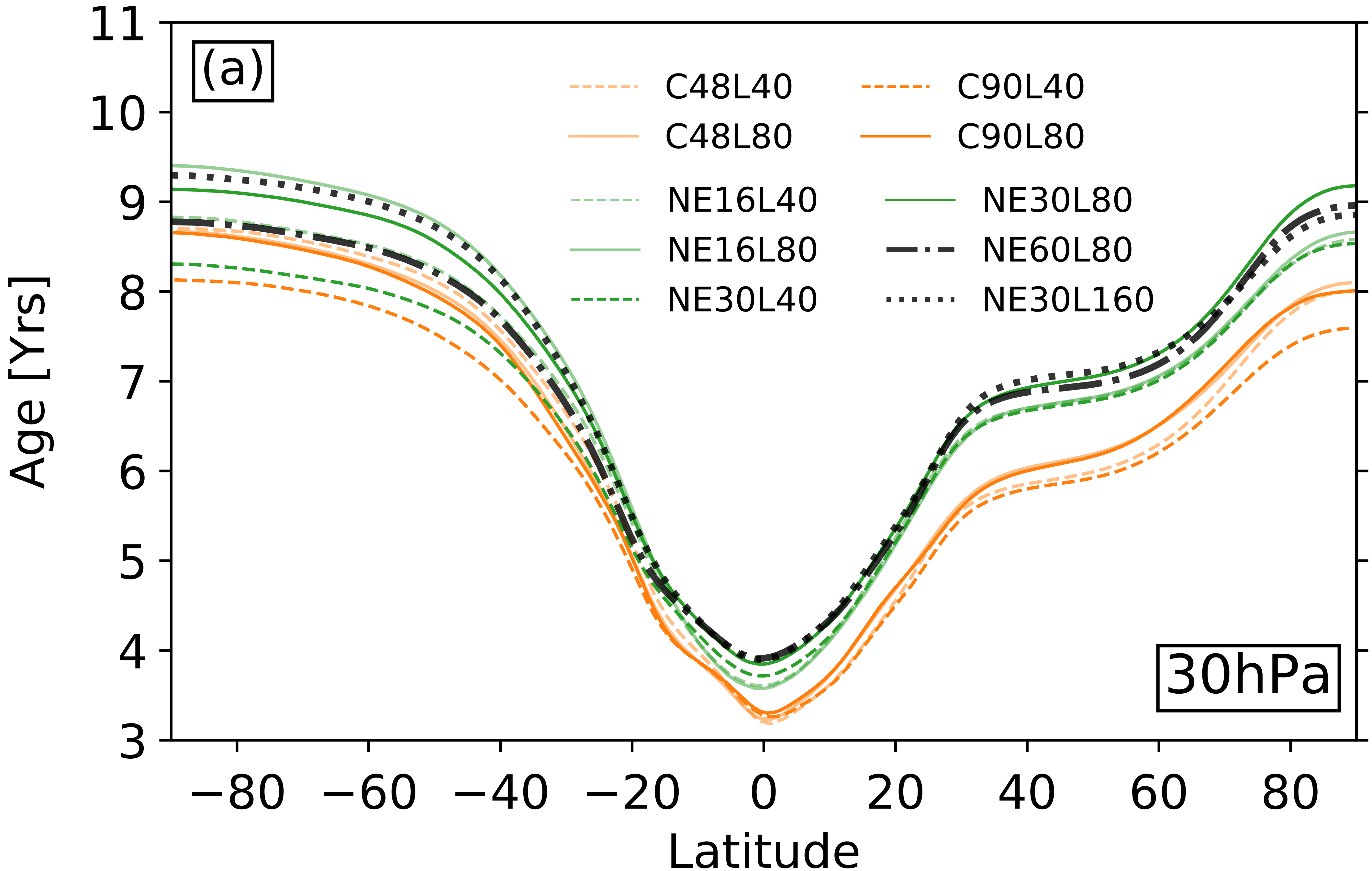
Greater agreement amongst cores, but differences persist between spectral and FV





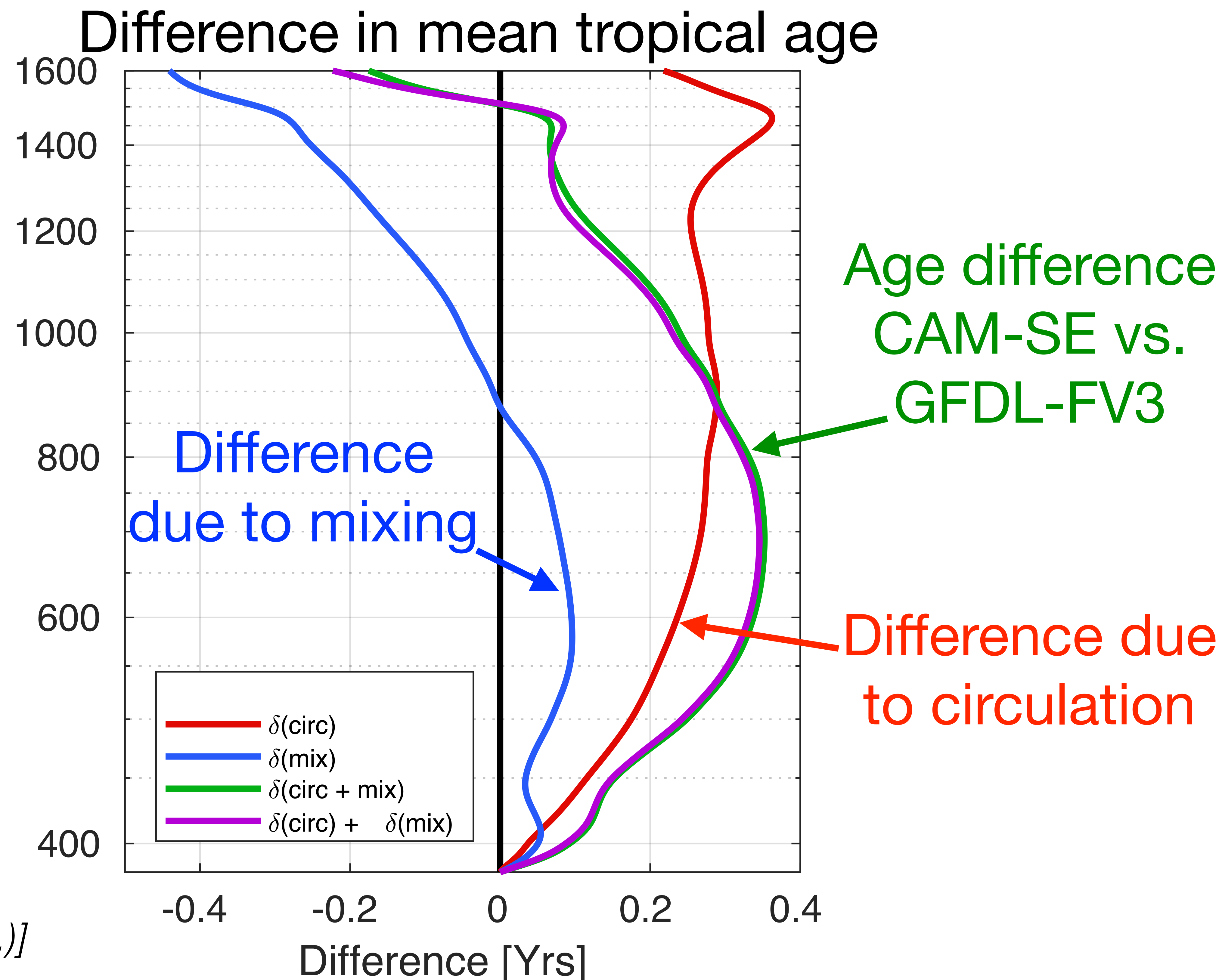
[Gupta et al. (in review)]

CAM-SE and GFDL-FV3 Converge towards different solutions!



[Gupta et al. (in review)]

Uncertainty in diabatic circulation dominates difference between CESM-SE and GFDL-FV3



[Gupta et al. (in prep.)]

Opportunities and Challenges

- Trace gas observations can *still* help us better understand the circulation of the stratosphere
  - The "age-of-air" can be used to connect trace gas measurements to the overturning circulation
  - Modern reanalyses struggle with the overturning circulation; could assimilation of trace gases help?
- Trace gas transport is a challenge for climate prediction
  - Ozone recovery projections vary considerably due to differences in transport
  - Transport depends critically on the numerical formulation and resolution; modern atmospheric model cores exhibit significant differences