The strength of the diabatic circulation of the stratosphere

Ed Gerber

October 25, 2017

S-RIP and SPARC-DA workshop

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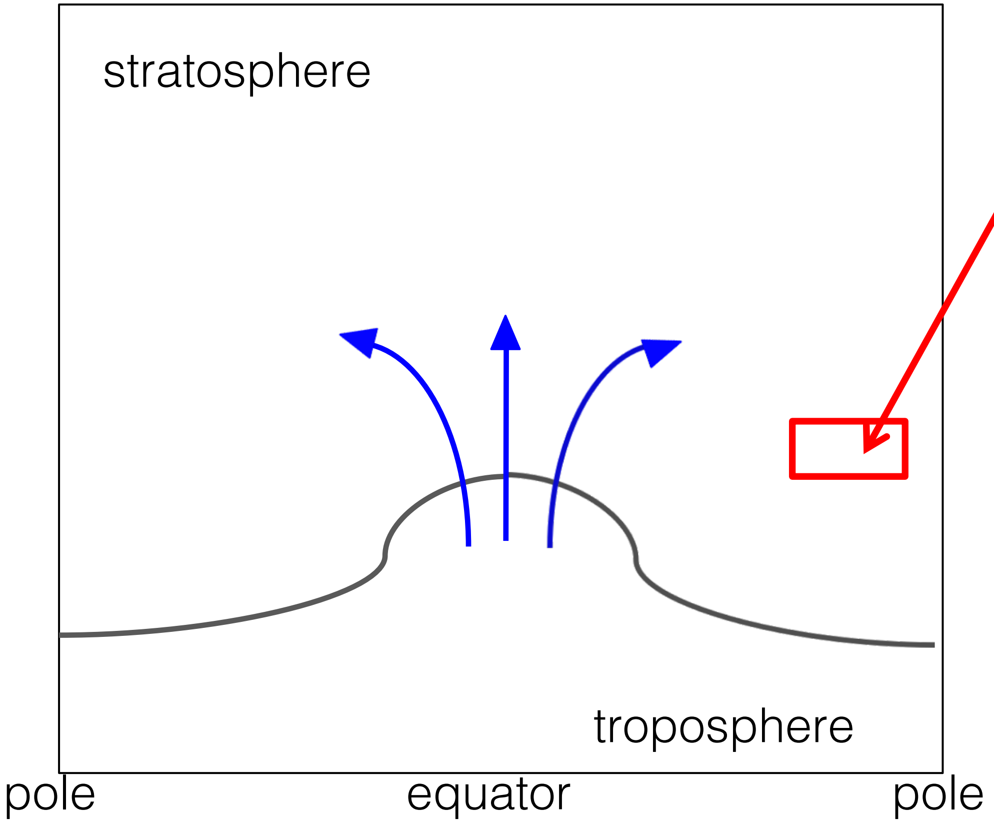
The idealized tracer "age" of air is used as a proxy for the overturning circulation



How long has this air been in the stratosphere?

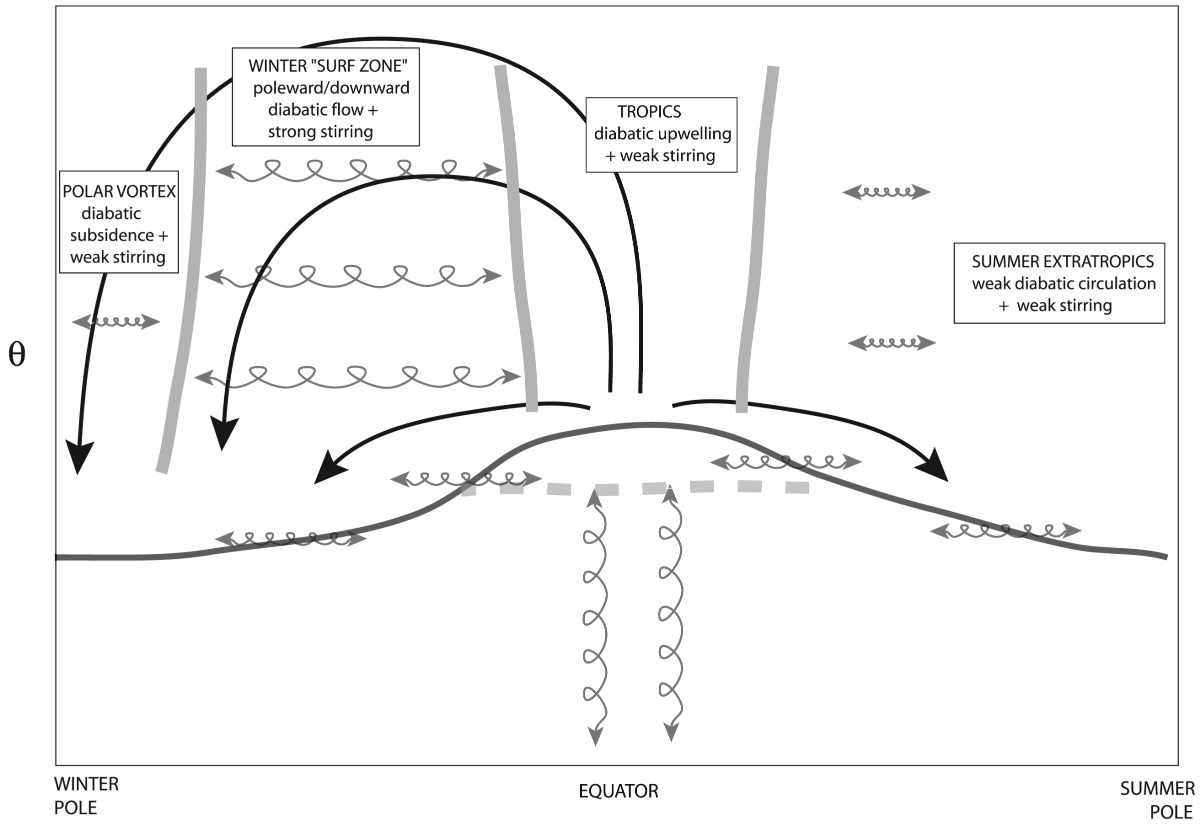
Rate of change of age + Transport = Source: 1yr/yr

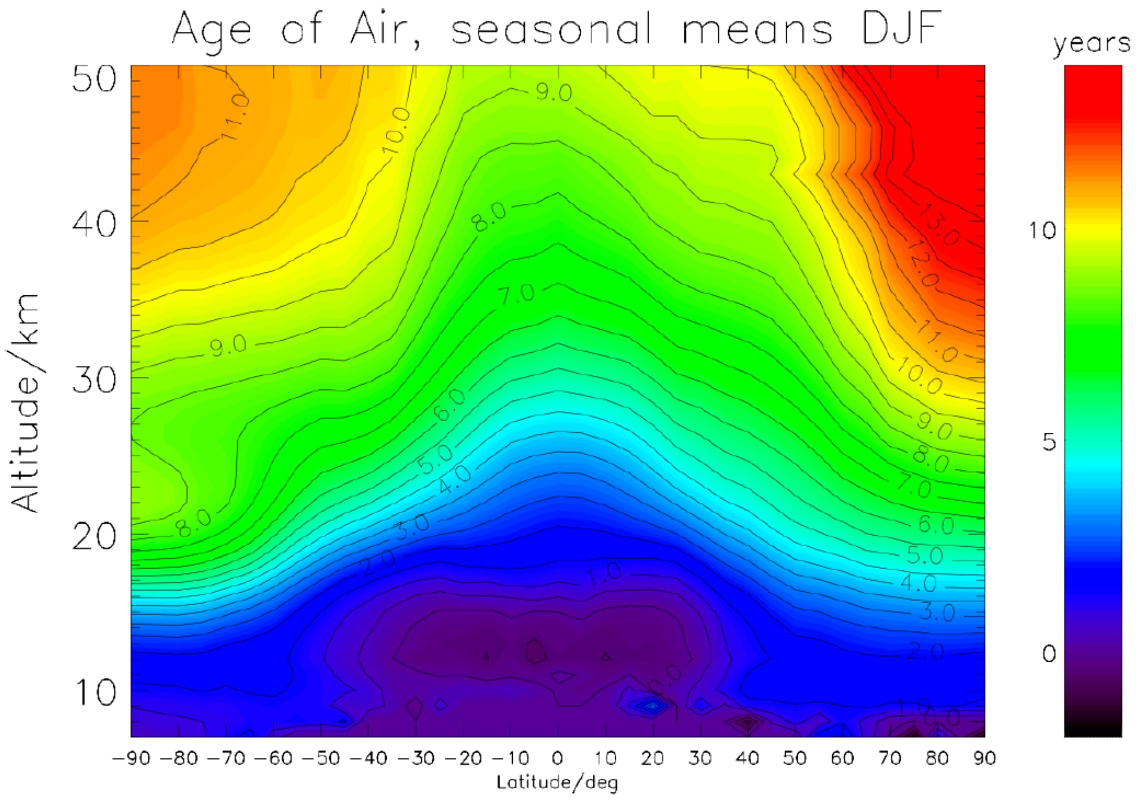
$$\frac{\partial \Gamma_i}{\partial t} + \mathcal{L}(\Gamma_i) = 1$$

In steady state, $\mathcal{L}(\Gamma_i) = 1$

Mean age roughly reflects the pattern of circulation

BDC Schematic

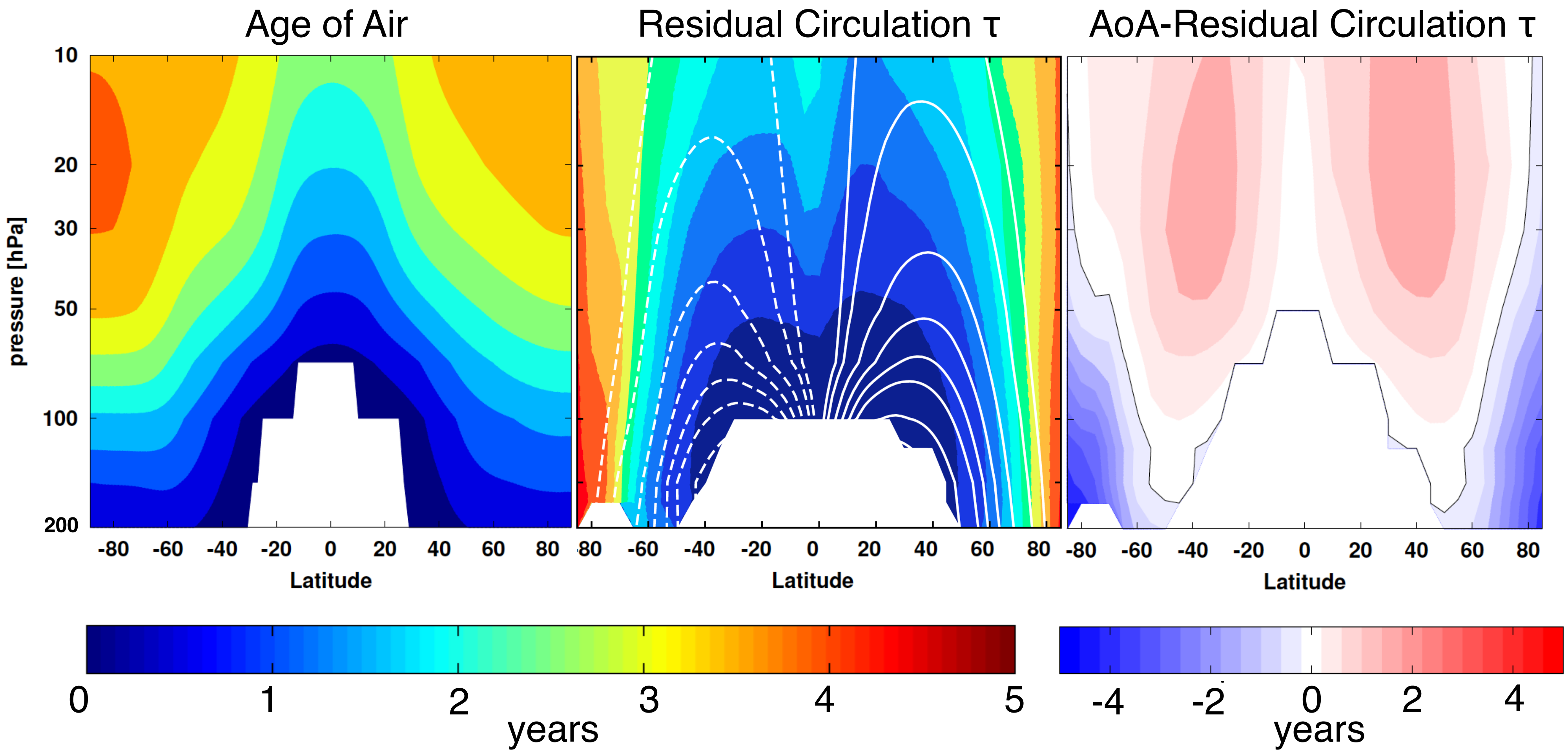




Plumb 2007

Haenel et al. 2015

Age and the overturning circulation are only qualitatively similar



Modified from Garny et al. 2014

Insight from the "Leaky Pipe" of Neu and Plumb 1999: Diabatic circulation is related to the *latitudinal gradient* in age.

Isentropic mixing between upward and downward branches of circulation increases *vertical gradient*, but leaves gross *horizontal gradient* unchanged!

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Key idea today:

(1) Extend "leaky pipe" to 3-D diabatic circulation
(2) Use satellite-based age measurements to quantify the circulation

Consider the steady-state case

Statistical equilibrium:

$$\frac{\partial \Gamma}{\partial t} + \frac{1}{\rho}\nabla \cdot F^{\Gamma} = 1$$

Integrate over the volume above an isentropic surface*:

$$F^{\Gamma}(\theta) = \int_{\theta} \sigma \dot{\theta} \Gamma dA = -M(\theta) \qquad (1)$$

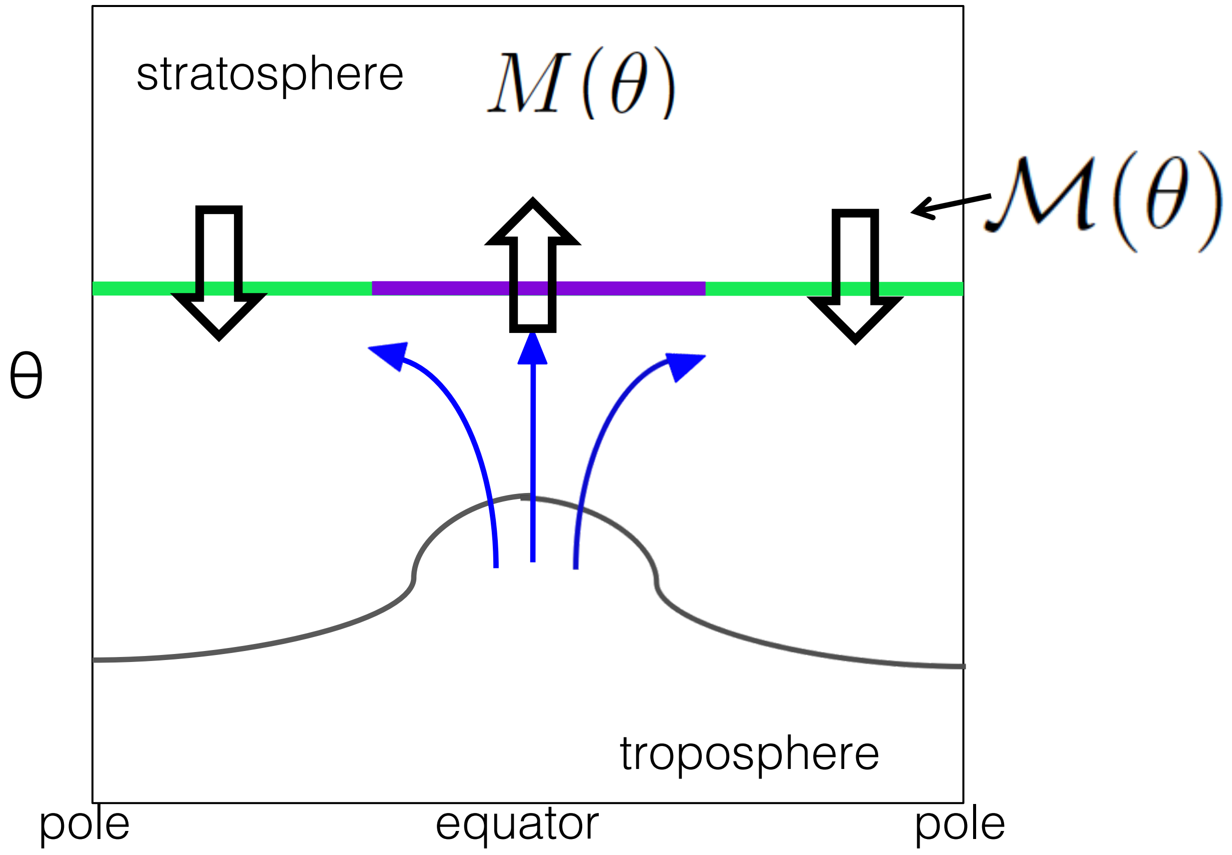
Age flux

Isentropic density

Total mass

*neglecting diabatic diffusion

Divide the surface into upwelling and downwelling regions



The mass flux, $\mathcal{M}(\theta)$ through each of these two regions must be equal.

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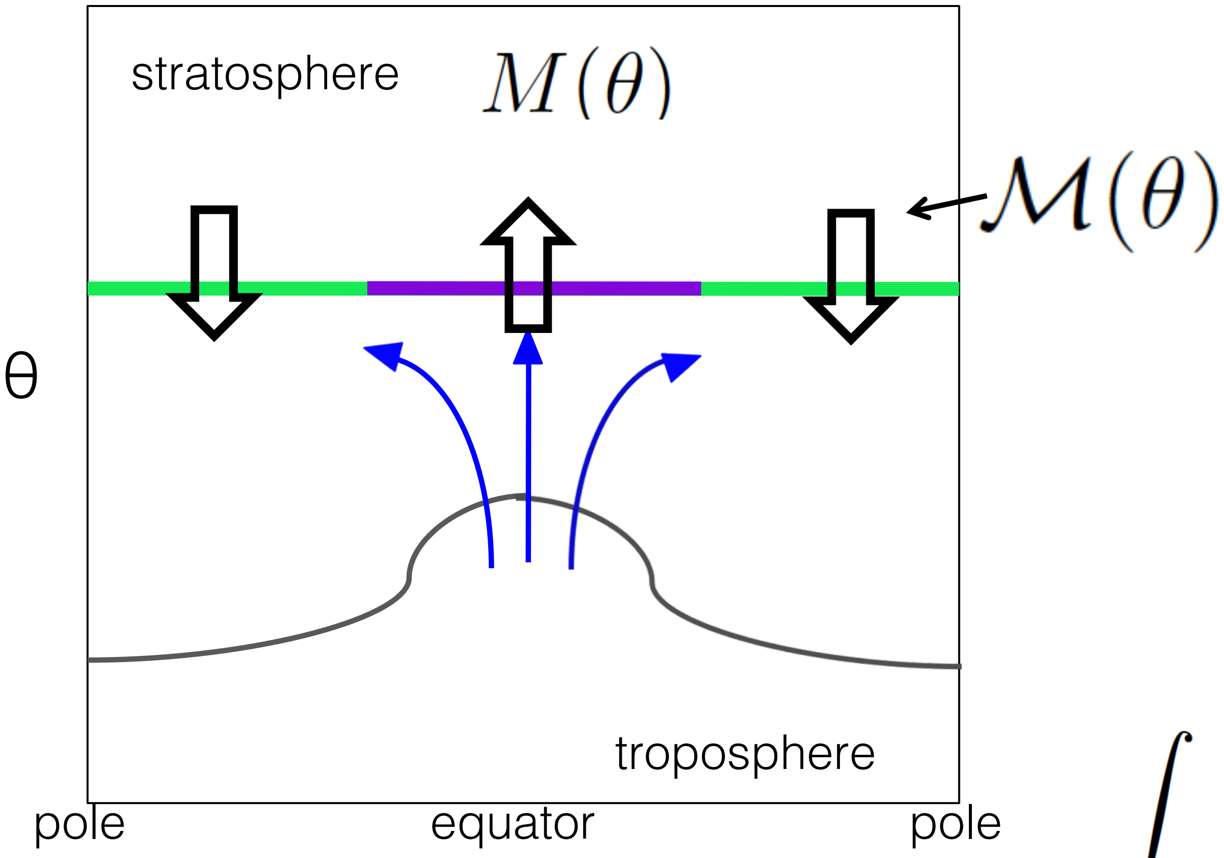

The mass flux, $\mathcal{M}(\theta)$ through each of these two regions must be equal.

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

Upwelling mass flux

Downwelling mass flux

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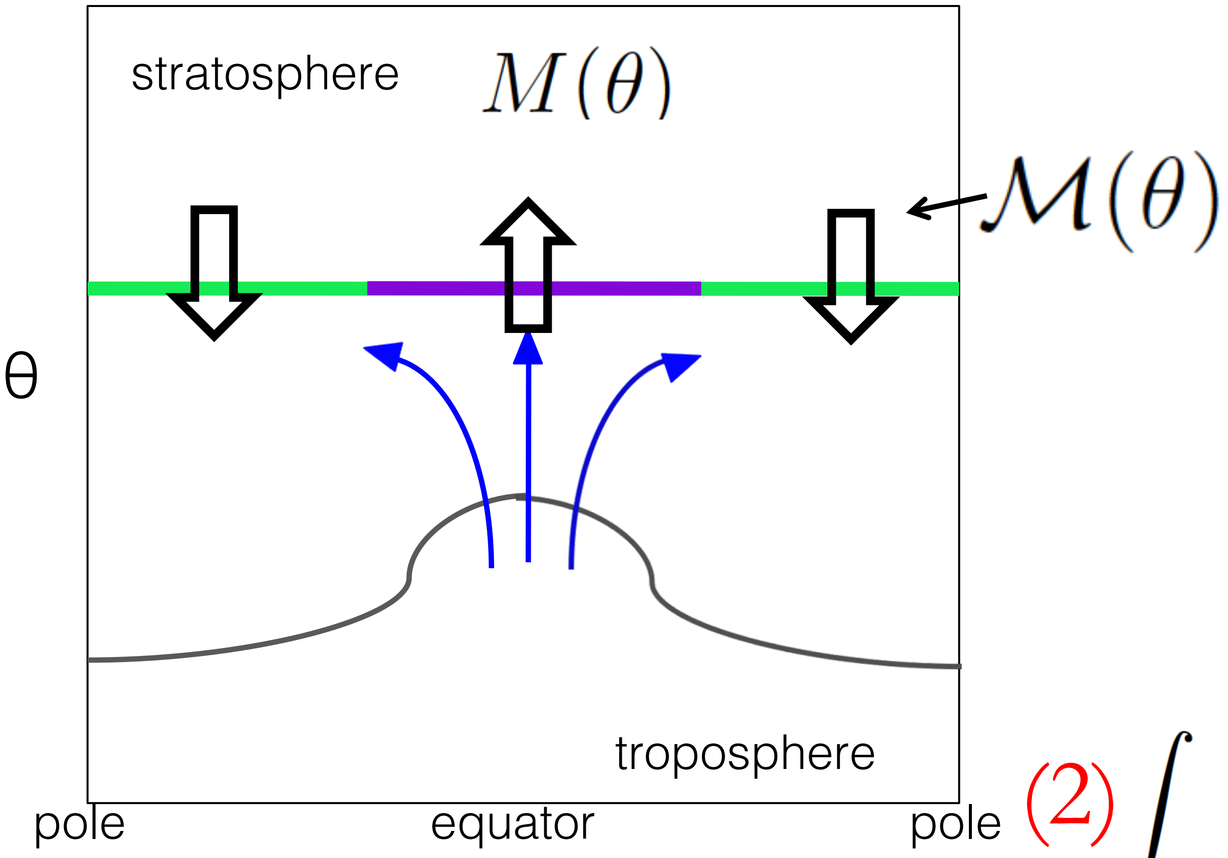


The mass flux, $\mathcal{M}(\theta)$ through each of these two regions must be equal.

$$(2) \int_{up} \sigma \dot{\theta} dA = -\int_{down} \sigma \dot{\theta} dA = \mathcal{M}(\theta)$$

Upwelling mass flux

Downwelling mass flux

Combine equations (1) and (2)

$$F^{\Gamma}(\theta) = \int_{\theta} \sigma\dot{\theta}\Gamma dA = -M(\theta) \quad (1)$$

$$\int_{up} \sigma\dot{\theta} dA = -\int_{down} \sigma\dot{\theta} dA = \mathcal{M}(\theta) \quad (2)$$

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

Upwelling age   Downwelling age

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

Linz et al. JAS 2016

The age difference is inversely proportional to the circulation strength

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

(Age down – Age up) = total mass above Θ / Total overturning flux through Θ

Linz et al. JAS 2016

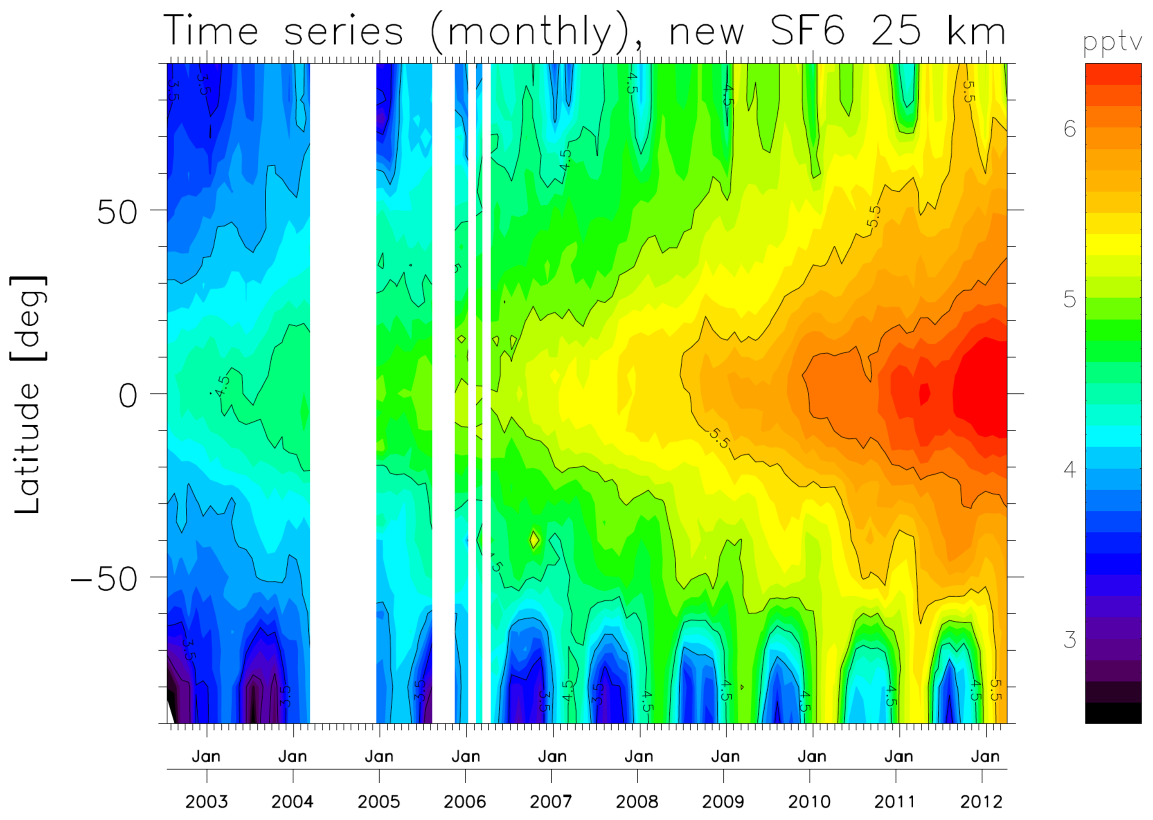
The age difference is inversely proportional to the circulation strength

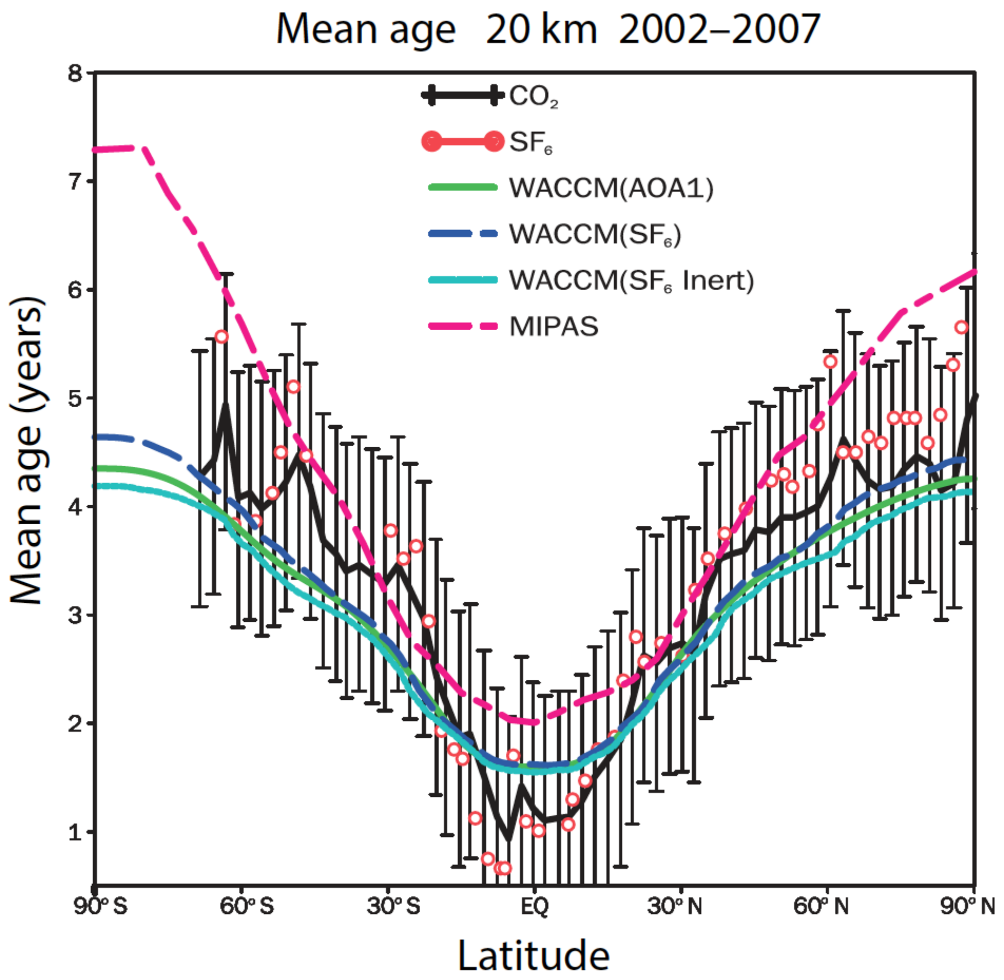
$$\Delta\Gamma(\theta) = \Gamma_d(\theta) - \Gamma_u(\theta) = \frac{M(\theta)}{\mathcal{M}(\theta)}.$$

Age difference on a surface depends only on the strength of the mean circulation through that surface.

Linz et al. JAS 2016

Ages from satellite SF_6 measurements from MIPAS



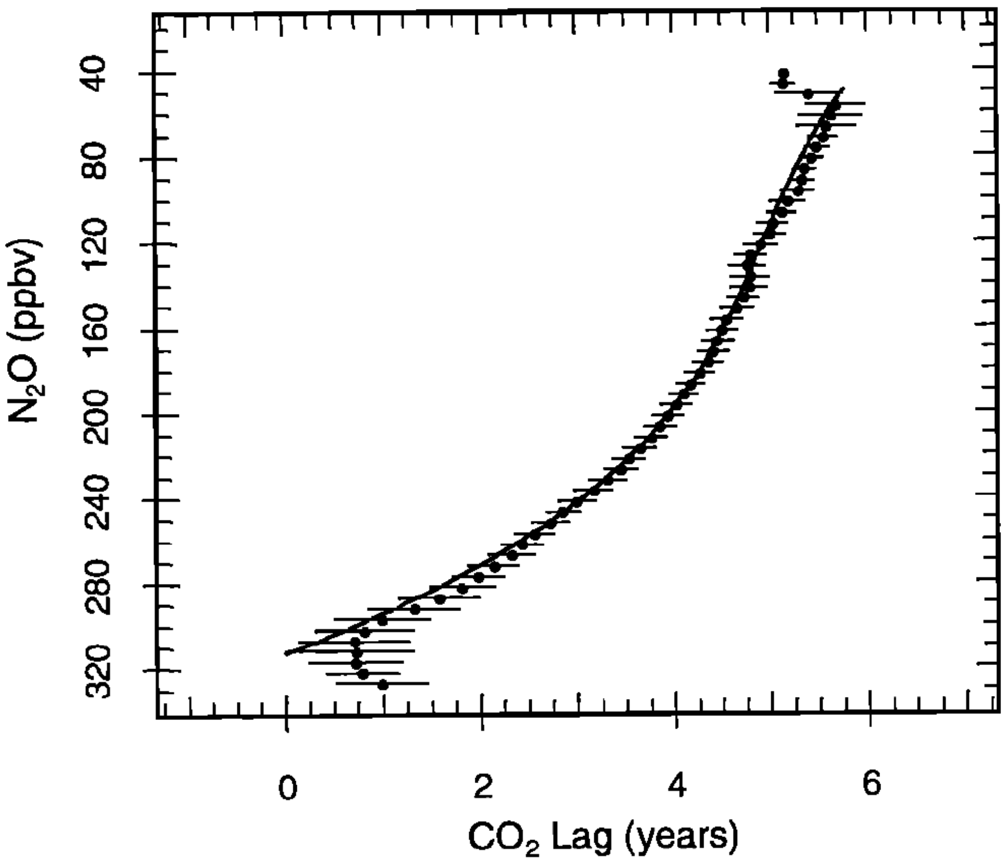


Haenel et al. 2015

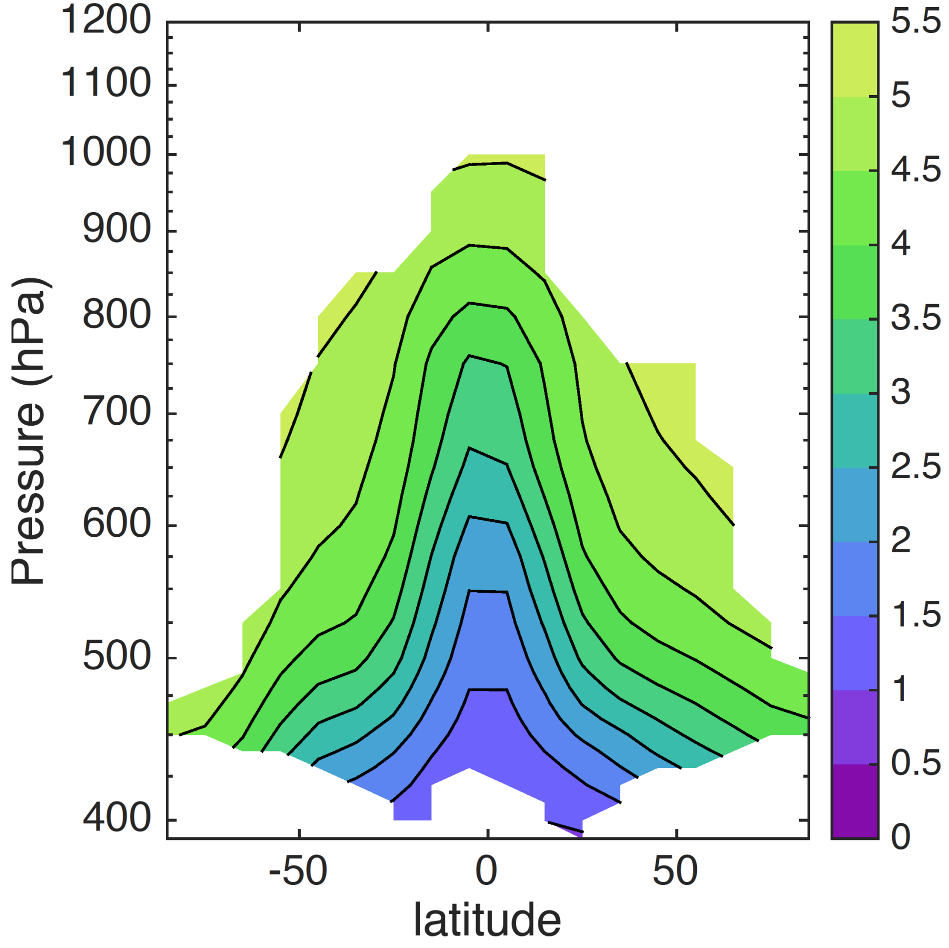
Kovacs et al. 2017

N_2O shows a compact relationship with age of air

Balloon and aircraft measurements from 1990s



Age from satellite N_2O, using Andrews cubic

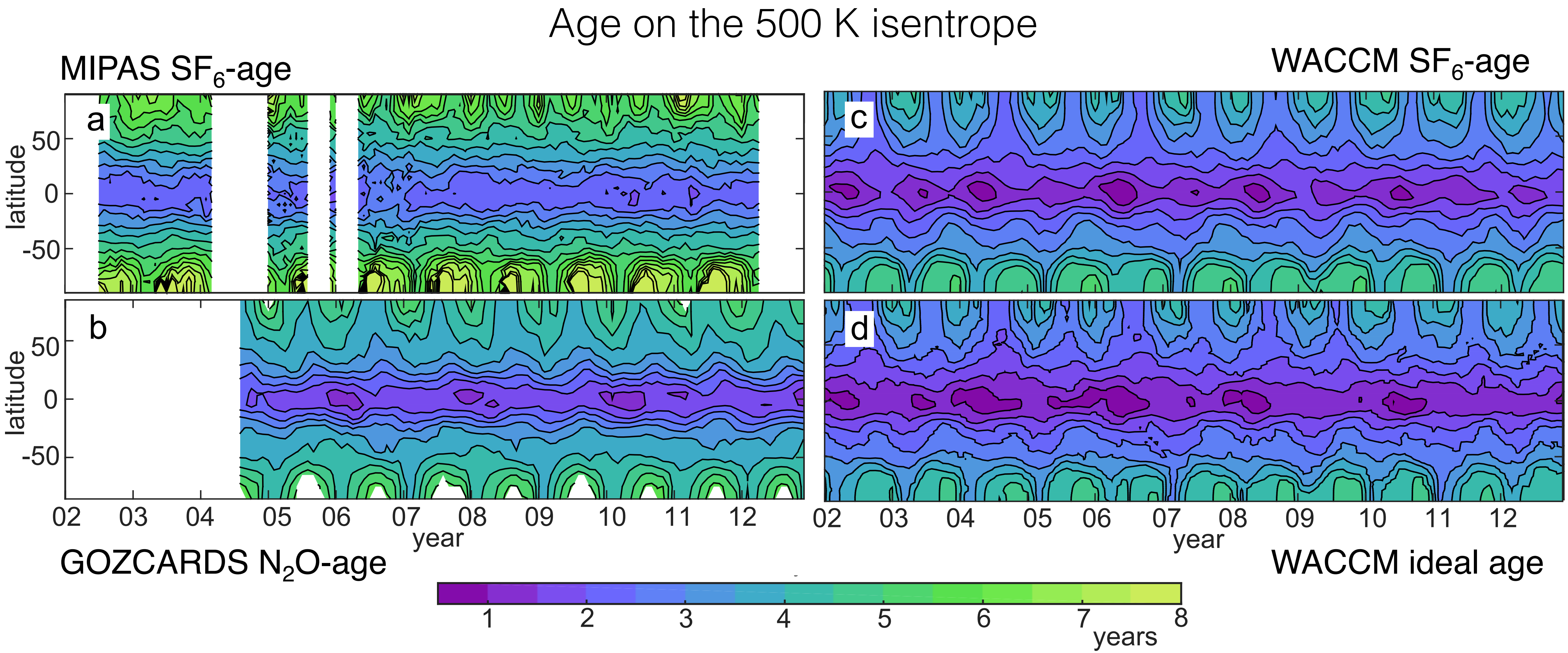


$$\Gamma_{LAG}(N_2O) = 0.0581(313 - N_2O) - 0.000254(313 - N_2O)^2 + 4.41 \times 10^{-7}(313 - N_2O)^3$$

Andrews et al. 2001

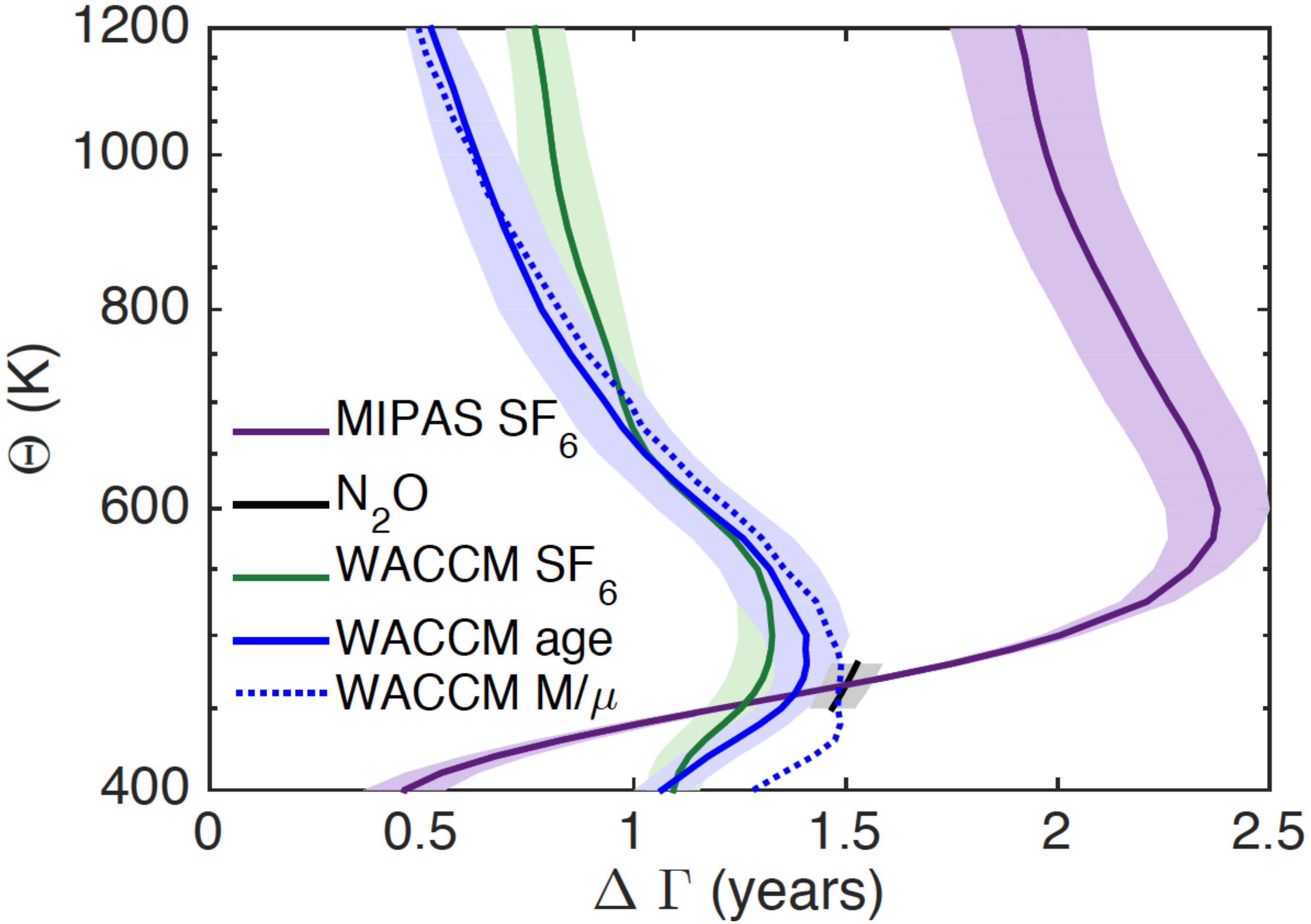
Linz et al. Nat. Geo. 2017

Age from SF_6, N_2O, and model are quite different



Linz et al. Nat. Geo. 2017

Age difference shows that the theory holds in a realistic model



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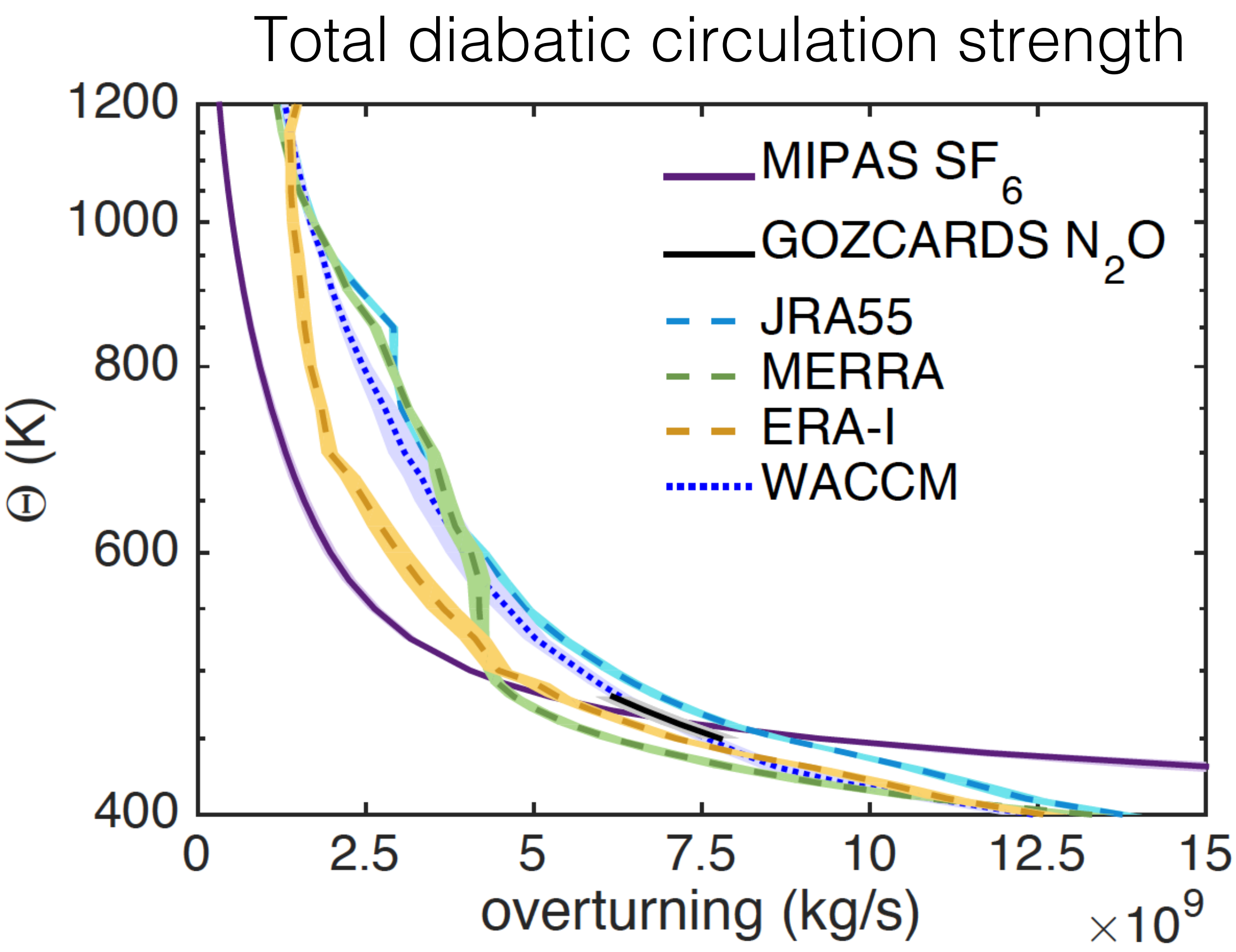
Linz et al. Nat. Geo. 2017

The two data calculations agree closely where they both exist



Linz et al. Nat. Geo. 2017

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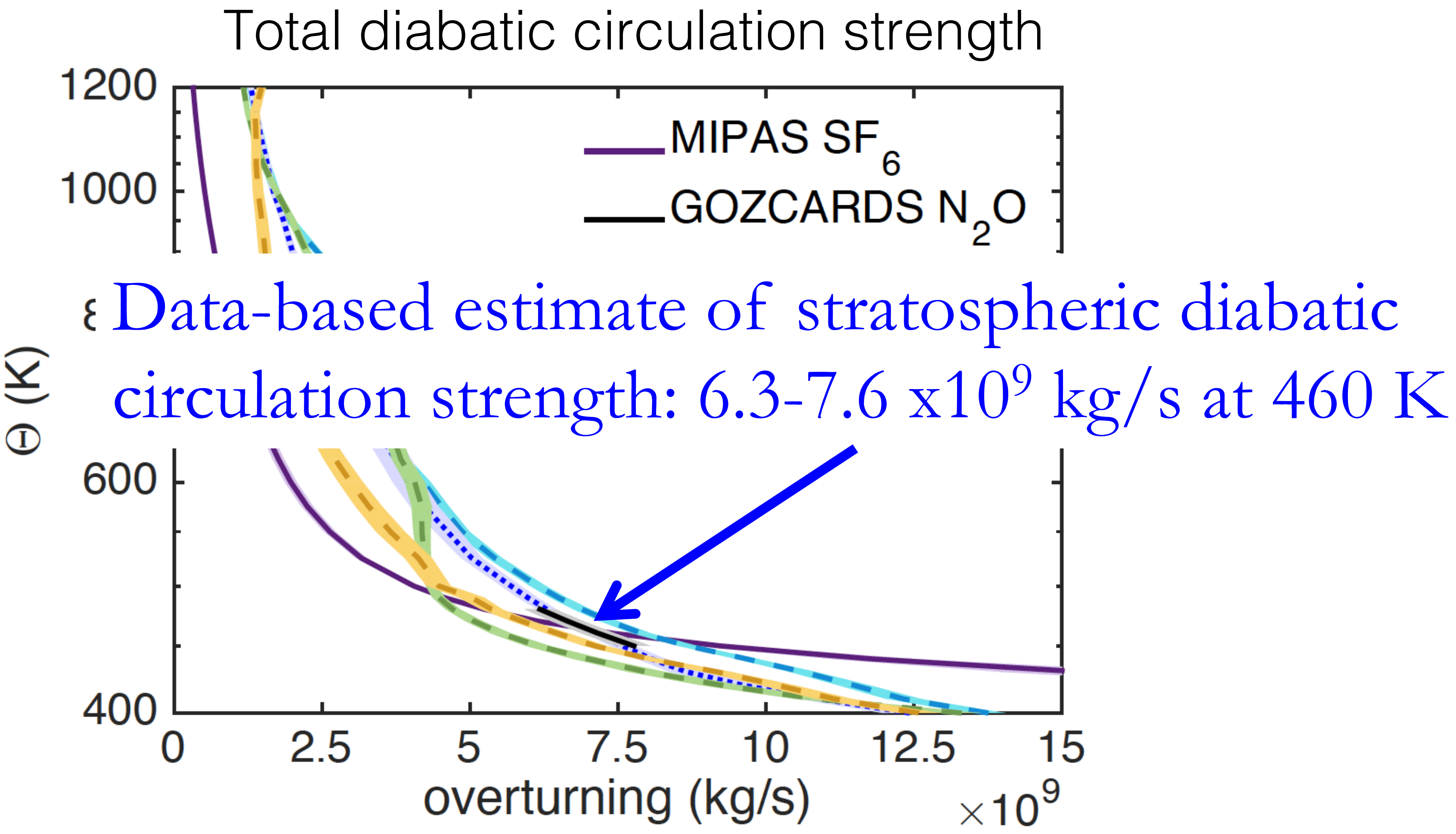
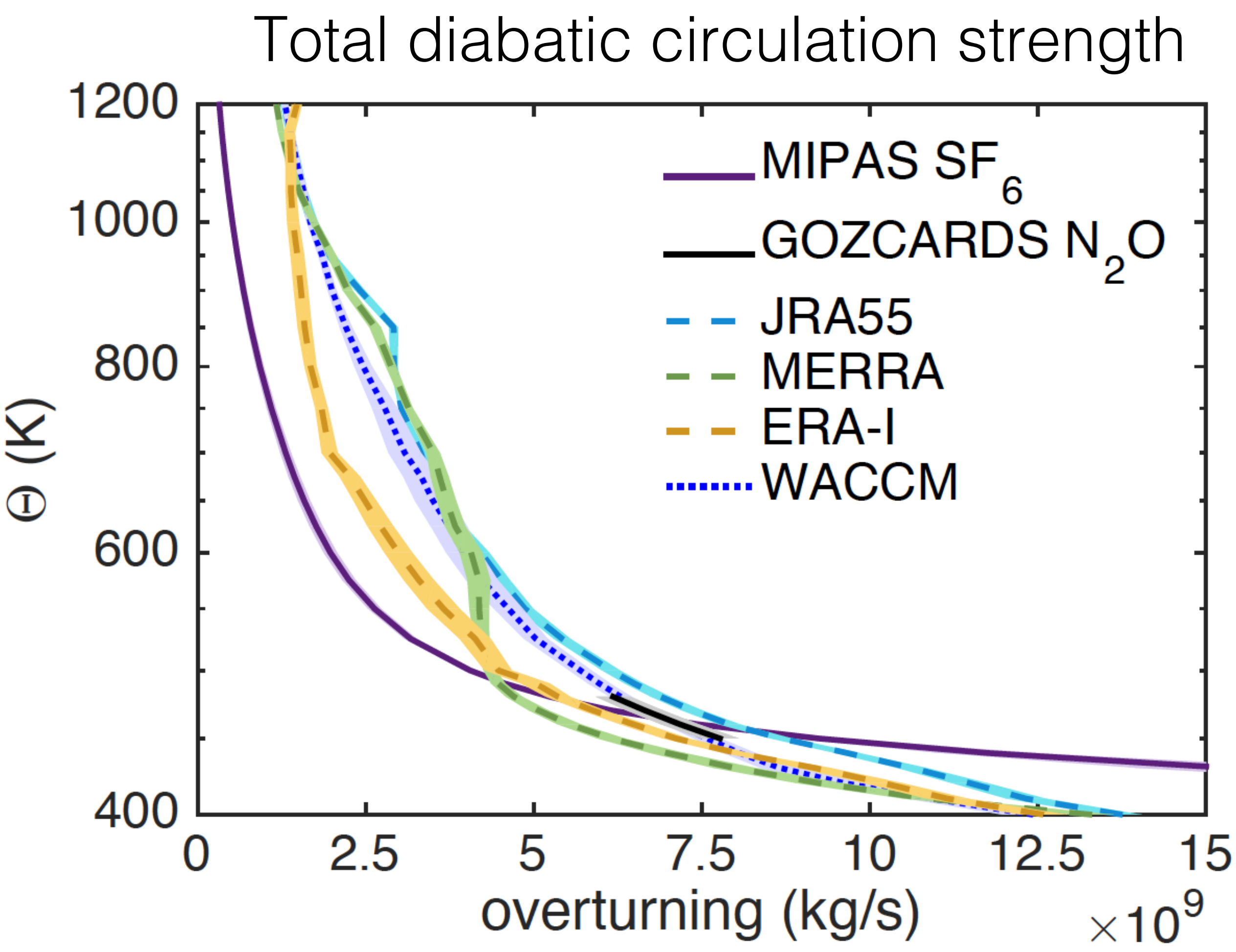


Linz et al. Nat. Geo. 2017

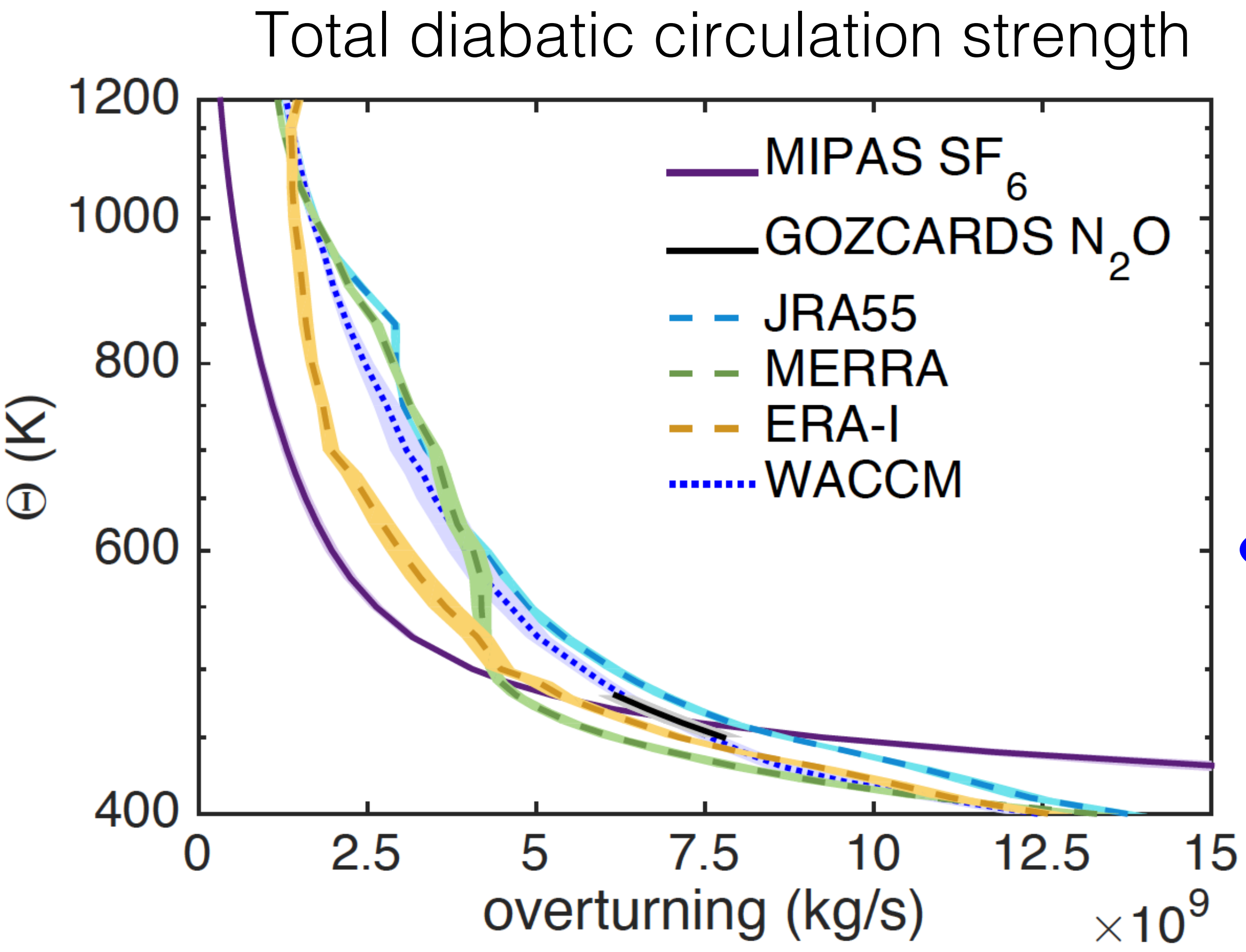
The two data calculations agree closely where they both exist, while reanalysis products vary



Data set	**460 K overturning ($\times 10^9$ kg/s)**
MIPAS SF_6-age	7.43
GOZCARDS N_2O	7.17
WACCM	7.11
ERA-Interim	6.48
JRA 55	7.90
MERRA	5.52

Linz et al. Nat. Geo. 2017

Because of potential high bias in the method, ERA-Interim is in the range calculated from the data



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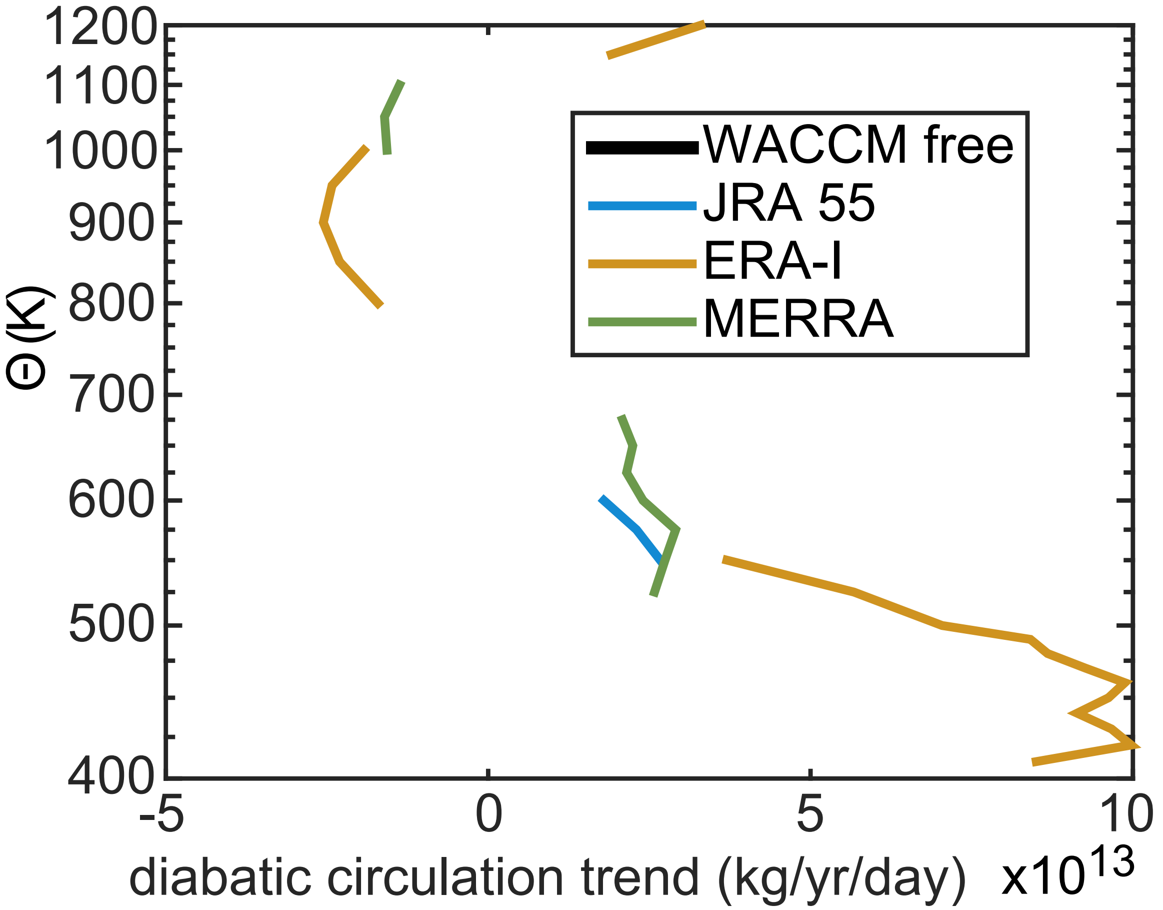
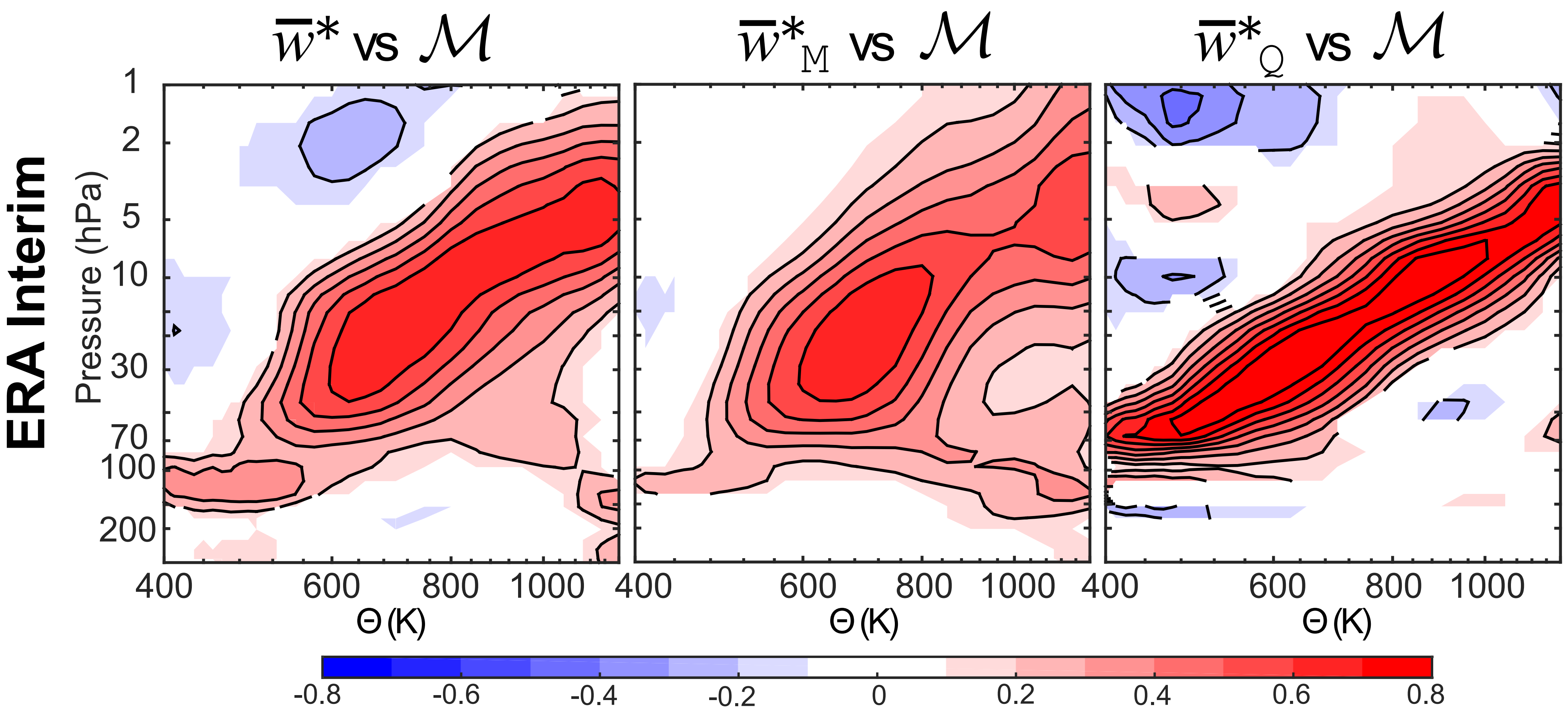
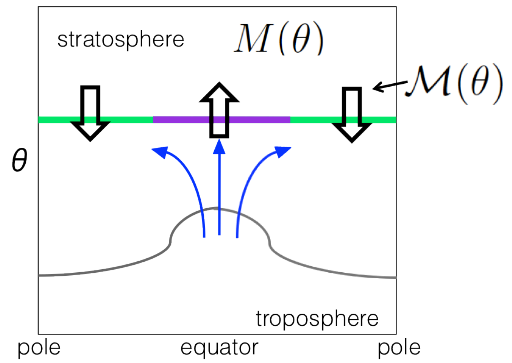
Trends in the diabatic circulation are less significant than trends in other measures



Correlations of the interannual variability show that the diabatic circulation is more closely related to one metric



Summary



Latitudinal age difference on isentropes is directly related to the diabatic circulation strength.

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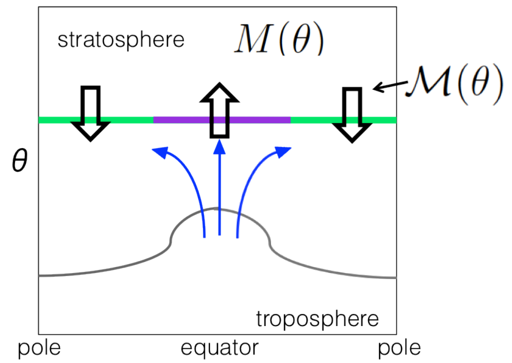
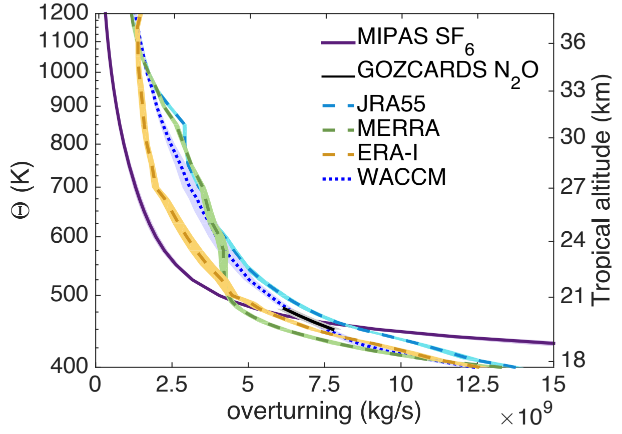


Strength of the circulation has been characterized from data. ERA-Interim plausible; JRA 55 and MERRA are outside confidence interval!



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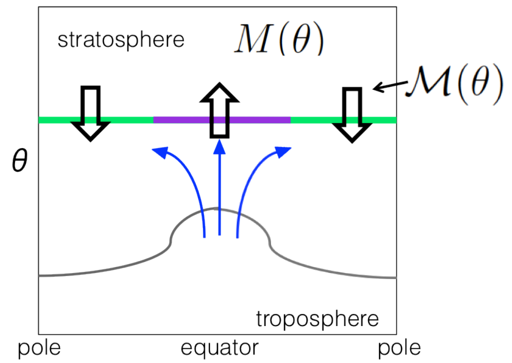

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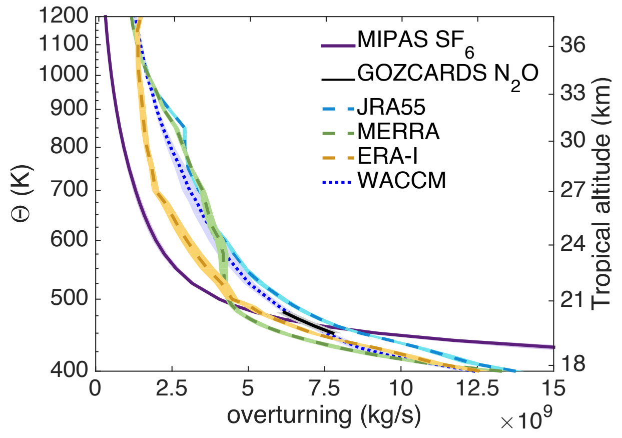

The diabatic circulation behaves differently than the traditional residual vertical velocity, including in vertical structure and in trends