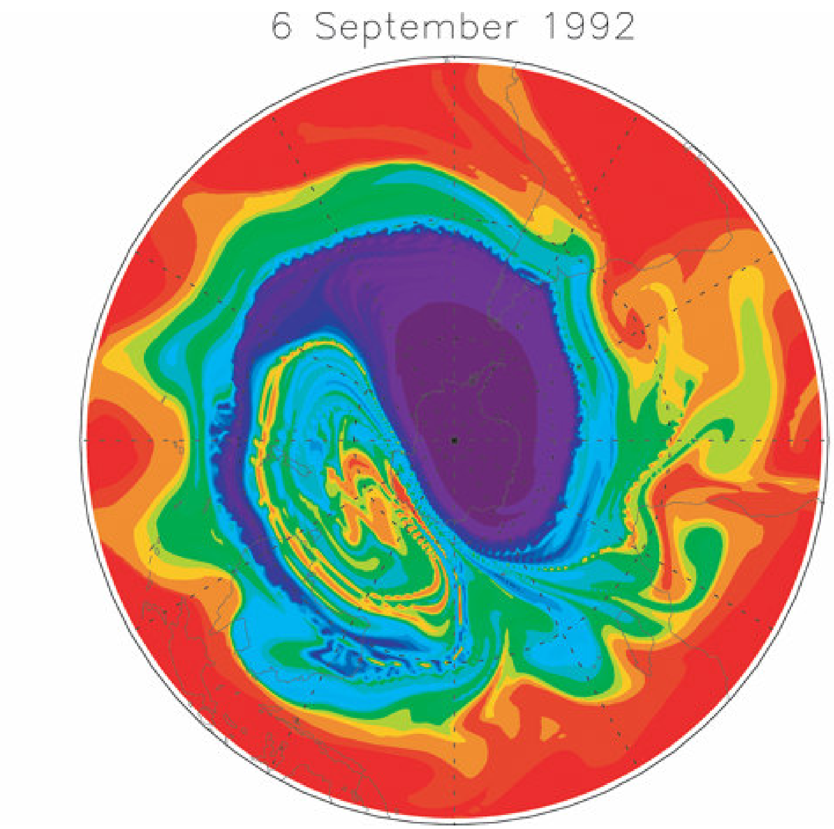
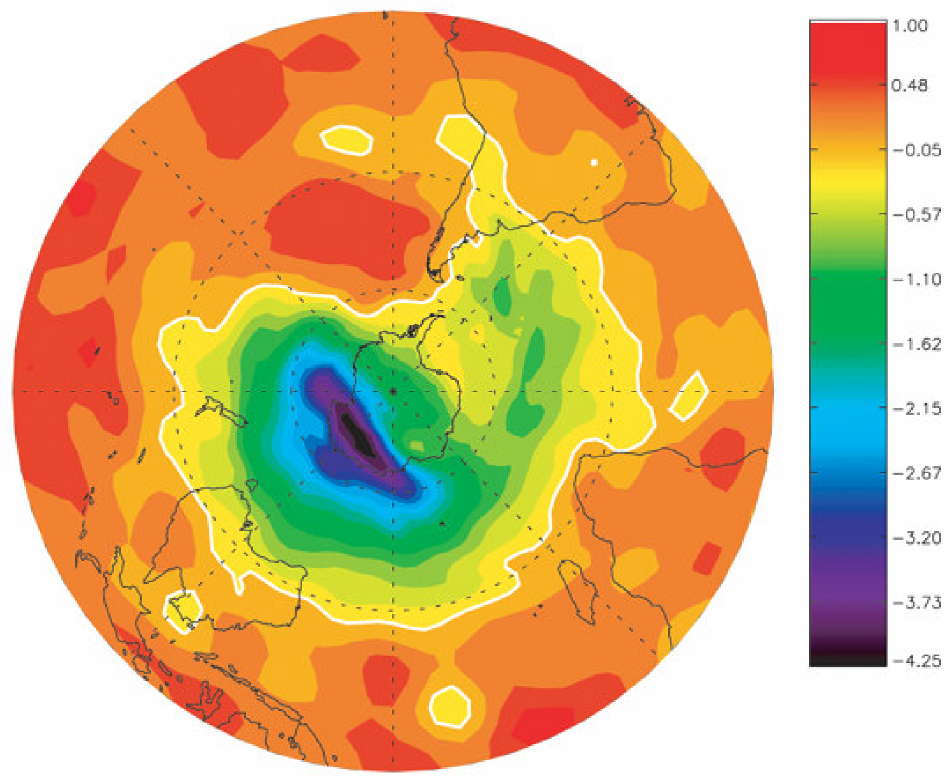
Lecture 4:
Stratospheric Transport

(i) Quantifying transport rates: Effective diffusivity
(ii) Quantifying transport rates: Age
(iii) Stratospheric trace gases:
Global structure and tracer-tracer relationships

FDEPS 2010
Alan Plumb, MIT
Nov 2010



stirring

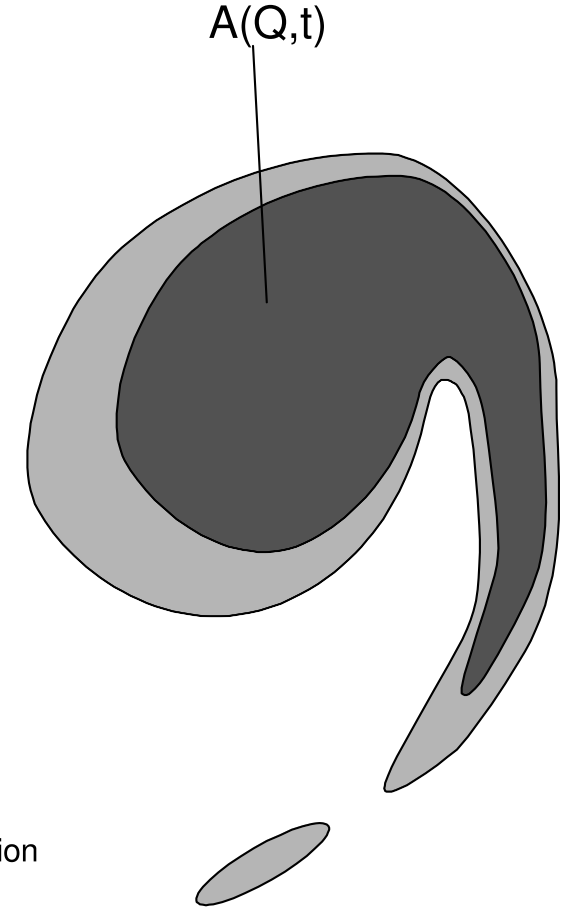


diabatic motion

Plumb et al (2007)

(i) Quantifying transport rates: Effective diffusivity

“Effective diffusivity”
[Nakamura, *J Atmos Sci*, 1996]



$$\frac{\partial q}{\partial t} + \mathbf{u} \cdot \nabla q = \kappa \nabla^2 q$$

$$\widehat{X} = \oint X \frac{dl}{|\nabla q|} \Big/ \oint \frac{dl}{|\nabla q|}$$

$$\widehat{\frac{\partial q}{\partial t}} = \left(\frac{\partial Q}{\partial t}\right)_A$$

$$\widehat{\mathbf{u} \cdot \nabla q} = 0$$

$$\widehat{\kappa \nabla^2 q} = \left(\frac{\partial A}{\partial Q}\right)^{-1} \frac{\partial}{\partial Q}\left[\kappa \frac{\partial A}{\partial Q}\left(\widehat{|\nabla q|^2}\right)\right]$$

$$\frac{\partial Q}{\partial t} = \frac{1}{a^2 \cos\phi_e} \frac{\partial}{\partial \phi_e}\left[K_{eff} \cos\phi_e \frac{\partial Q}{\partial \phi_e}\right]$$

diffusion equation

$$K_{eff} = \kappa \frac{L_e^2}{4\pi^2 a^2 \cos^2\phi_e} = \kappa \frac{L_e^2}{L^2(\phi_e)}$$

effective diffusivity

$$L_e(Q) = \sqrt{\left(\oint |\nabla q| \, dl\right)\left(\oint \frac{dl}{|\nabla q|}\right)}$$

equiivalent length

"Effective diffusivity"
[Nakamura, *J Atmos Sci*, 1996]

$$\frac{\partial q}{\partial t} + \mathbf{u} \cdot \nabla q = \kappa \nabla^2 q$$

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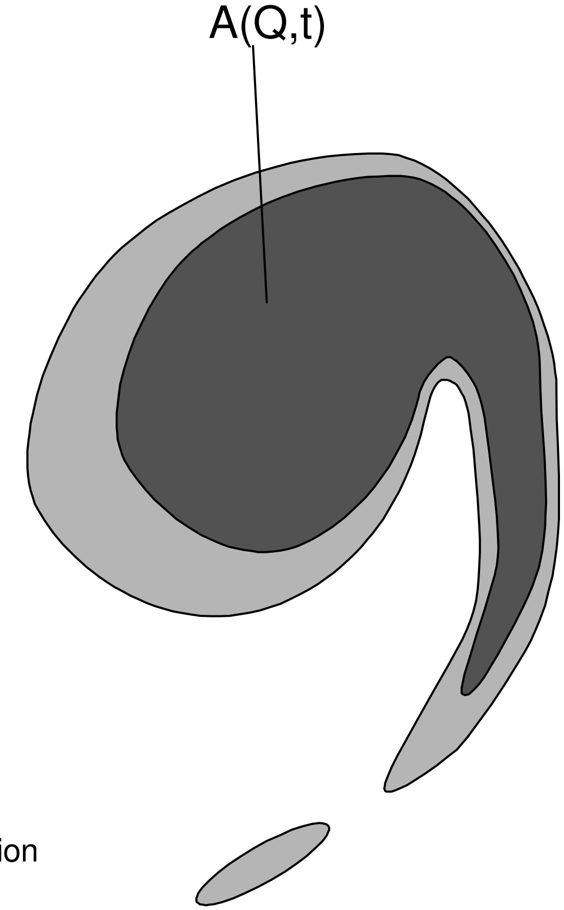
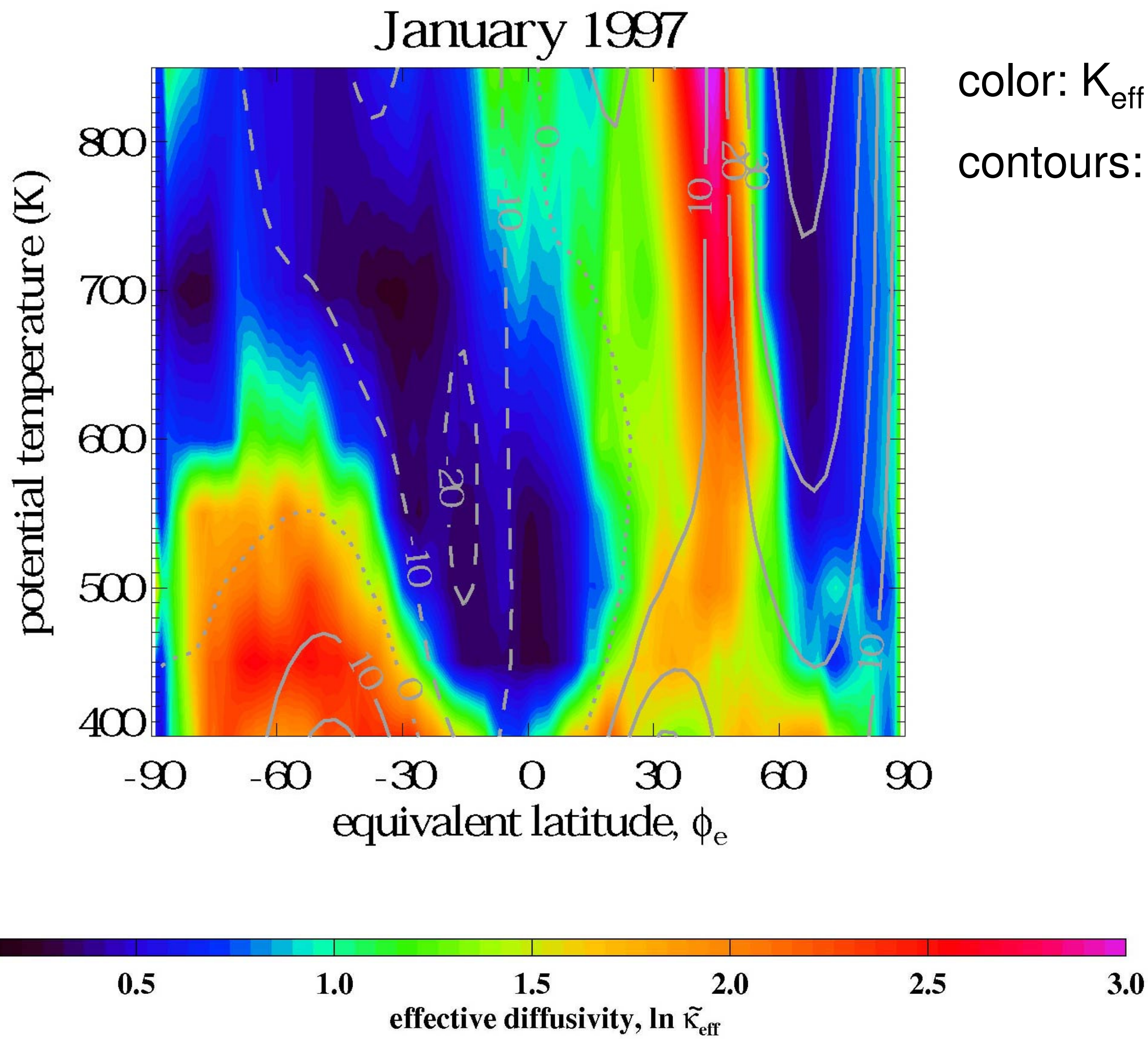


$$\frac{\partial Q}{\partial t} = \frac{1}{a^2 \cos\phi_e} \frac{\partial}{\partial \phi_e}\left[K_{eff} \cos\phi_e \frac{\partial Q}{\partial \phi_e}\right]$$ diffusion equation

$$K_{eff} = \kappa \frac{L_e^2}{4\pi^2 a^2 \cos^2\phi_e} = \kappa \frac{L_e^2}{L^2(\phi_e)}$$ effective diffusivity

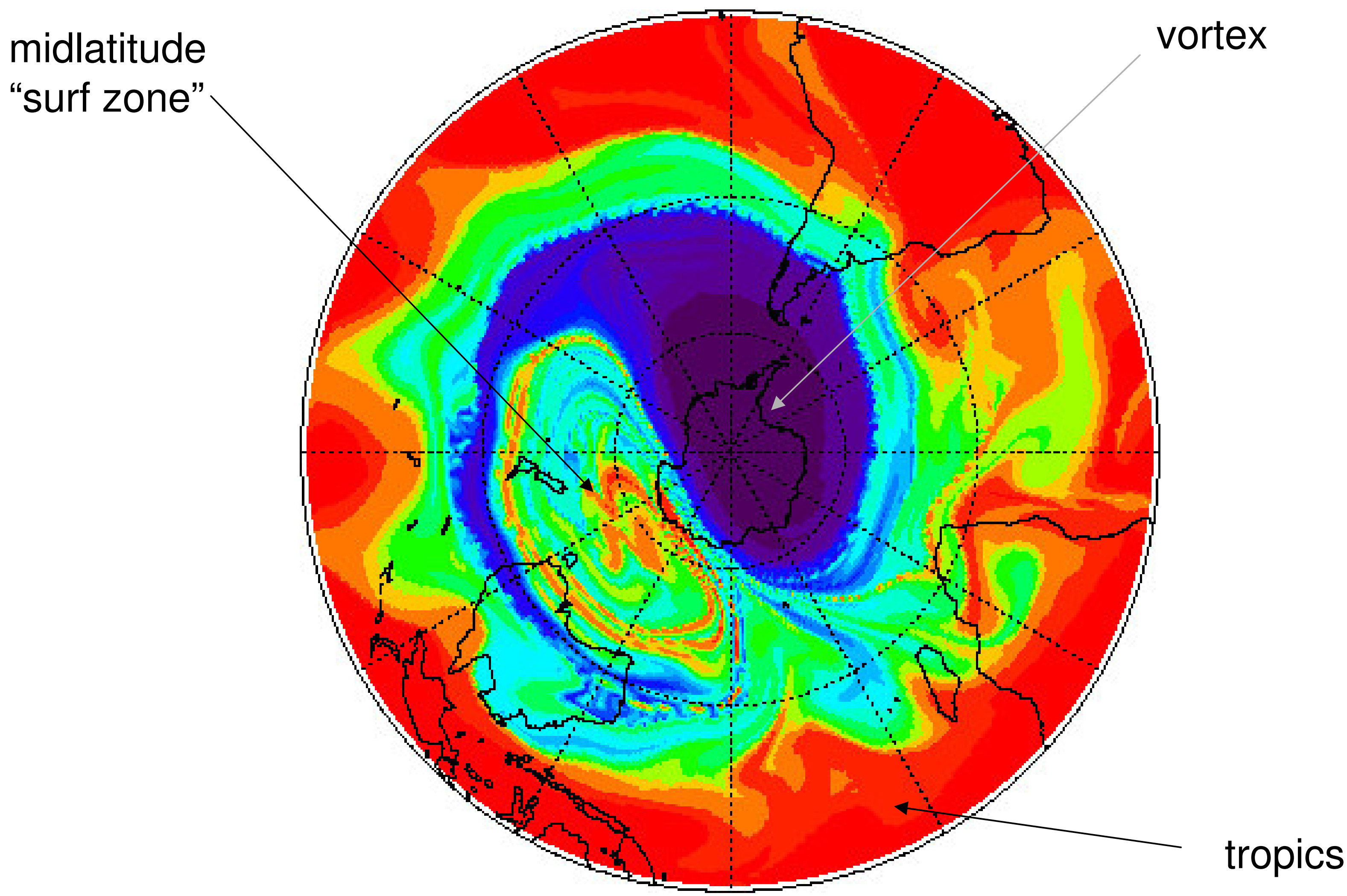
$$L_e(Q) = \sqrt{\left(\oint |\nabla q|\, dl\right)\left(\oint \frac{dl}{|\nabla q|}\right)}$$ equiivalent length



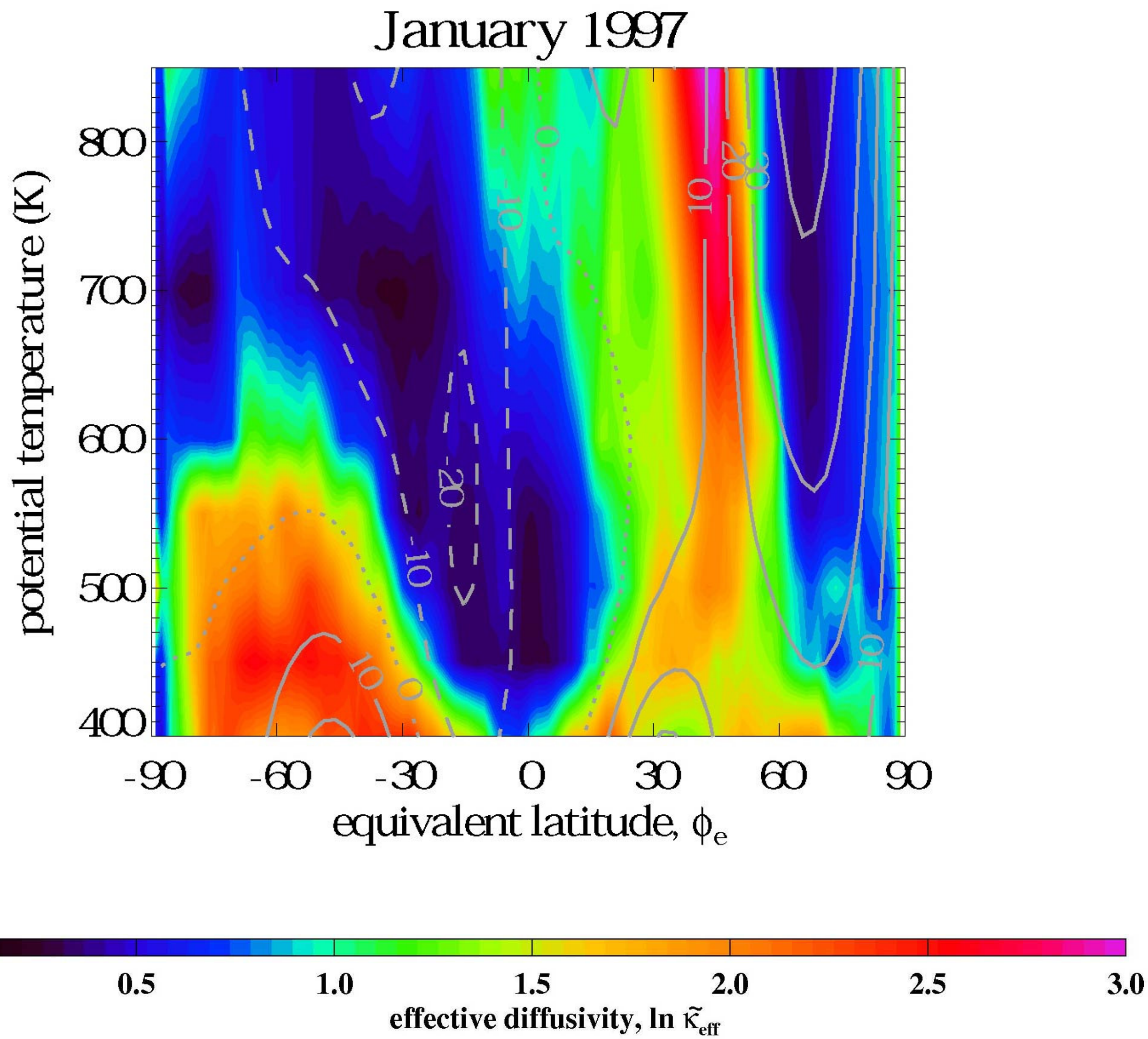
color: K_{eff}

contours: zonal wind

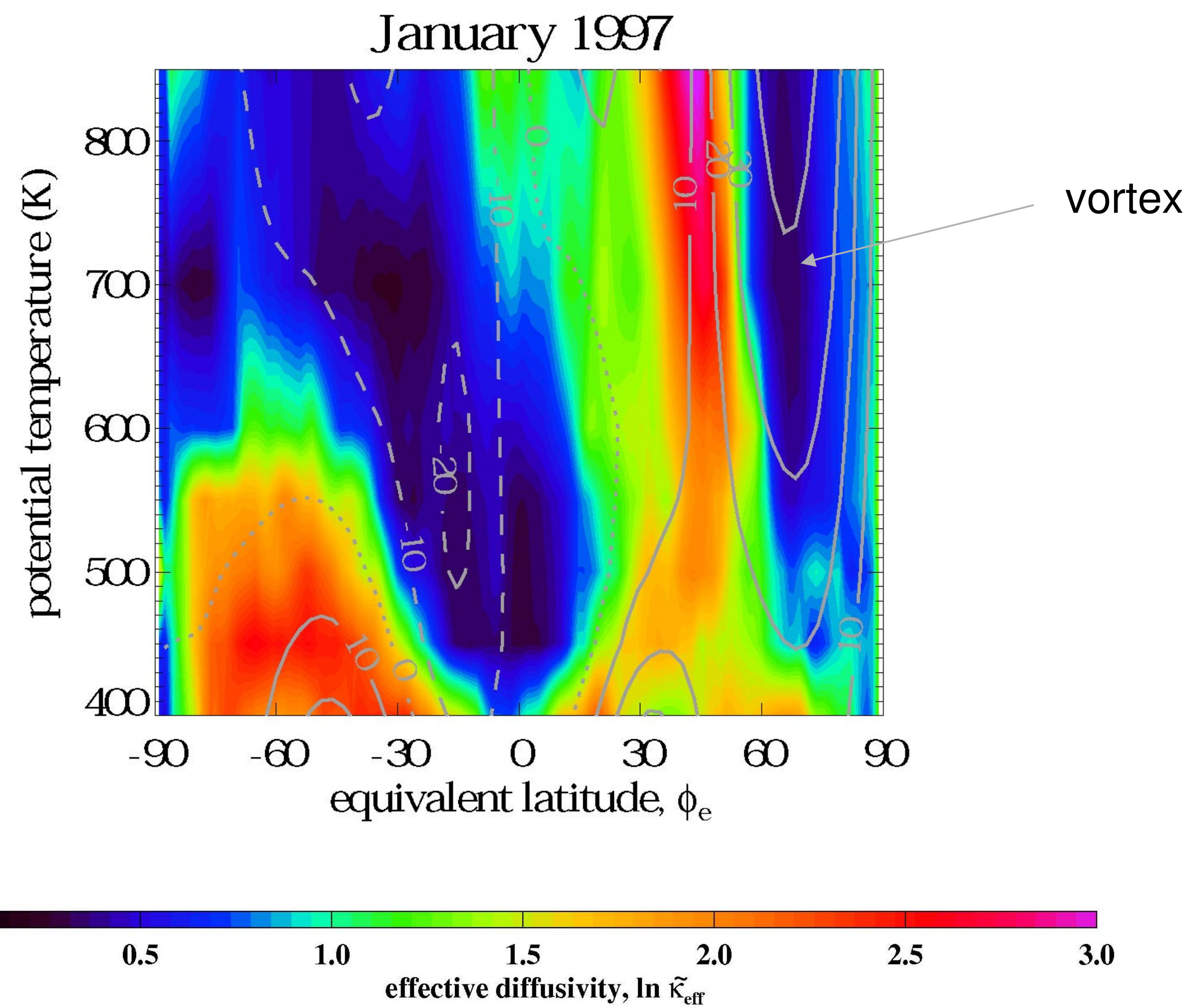
[Haynes & Shuckburgh, *J Atmos* Sci,2002]



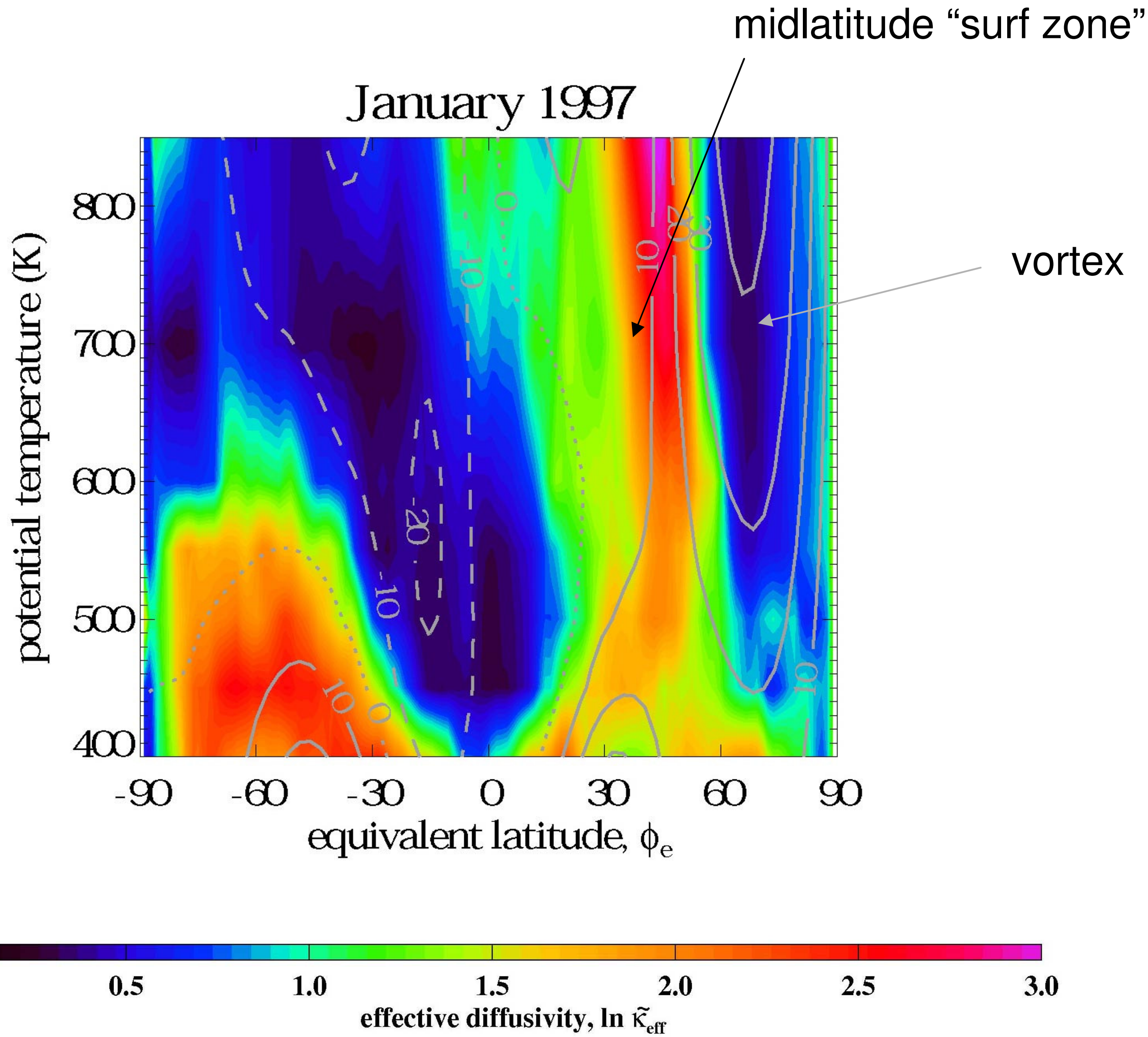
Plumb et al (2007)



Haynes & Shuckburgh, J Atmos Sci, 2002



Haynes & Shuckburgh, J Atmos Sci, 2002



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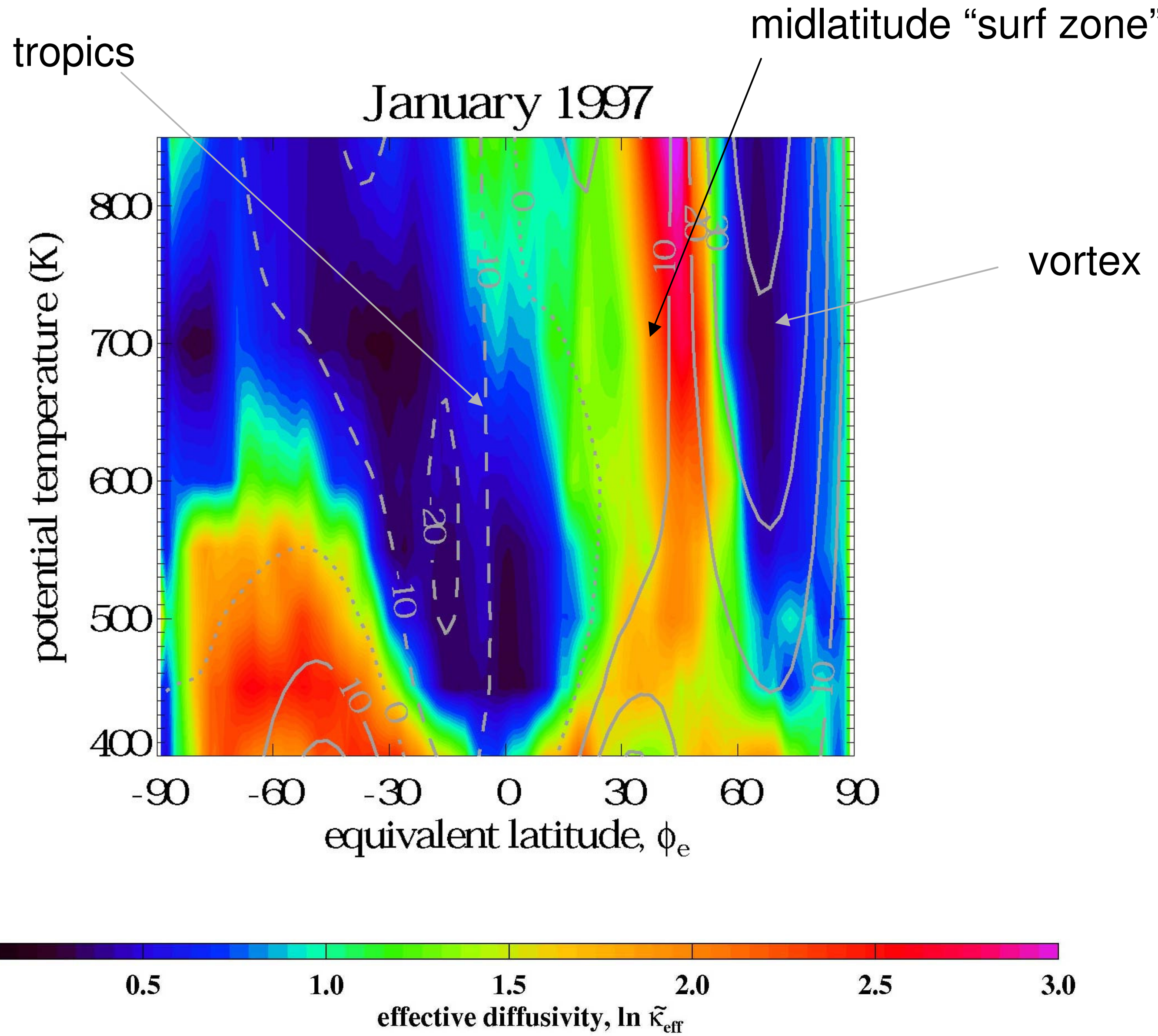
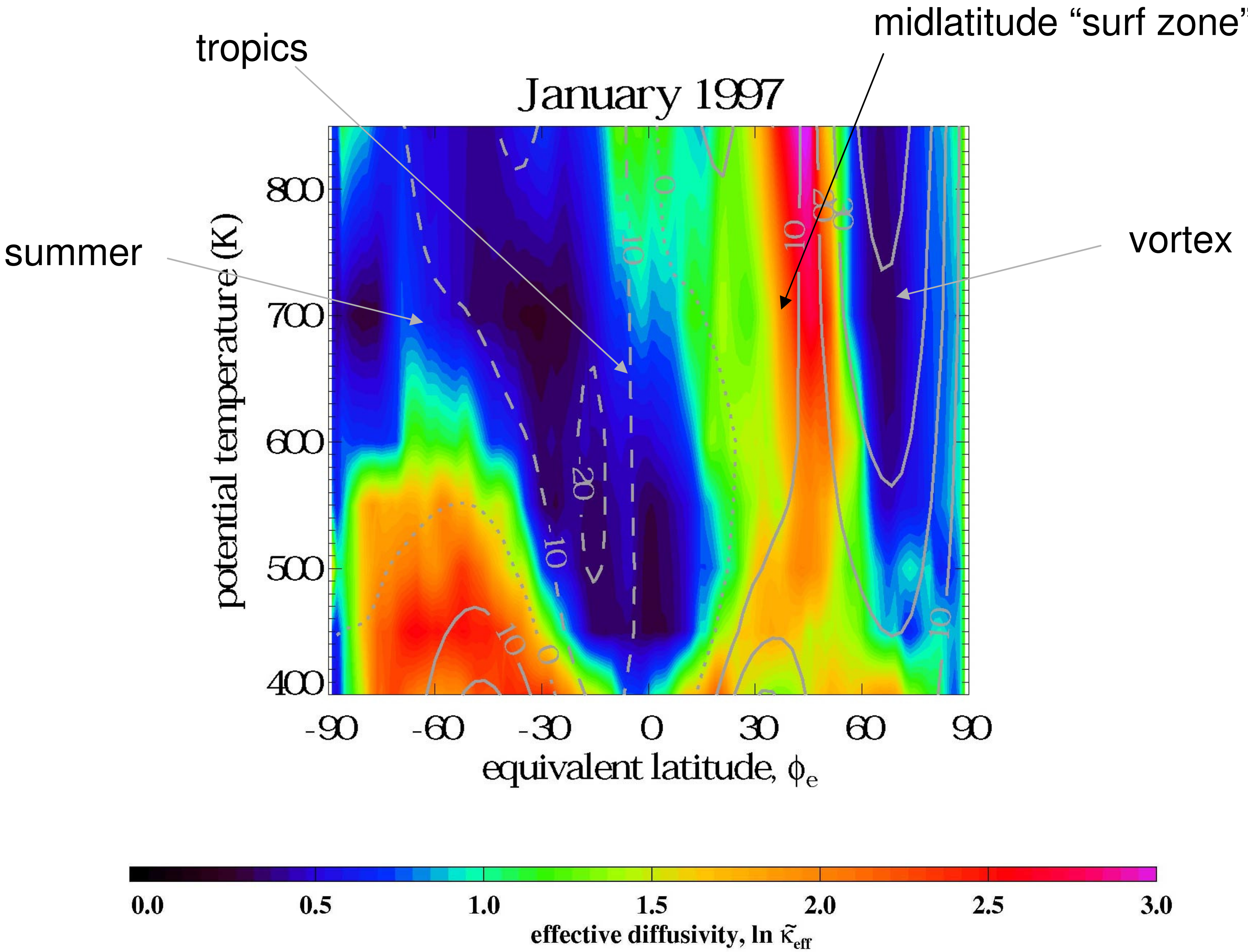


Haynes & Shuckburgh, J Atmos Sci, 2002



Haynes & Shuckburgh, J Atmos Sci, 2002

Transport rates

In "surf zone",

$$K_{eff} \sim 3 \times 10^6 \mathrm{m}^2\mathrm{s}^{-1}$$

mixing time across $L = 3000\mathrm{km}$:

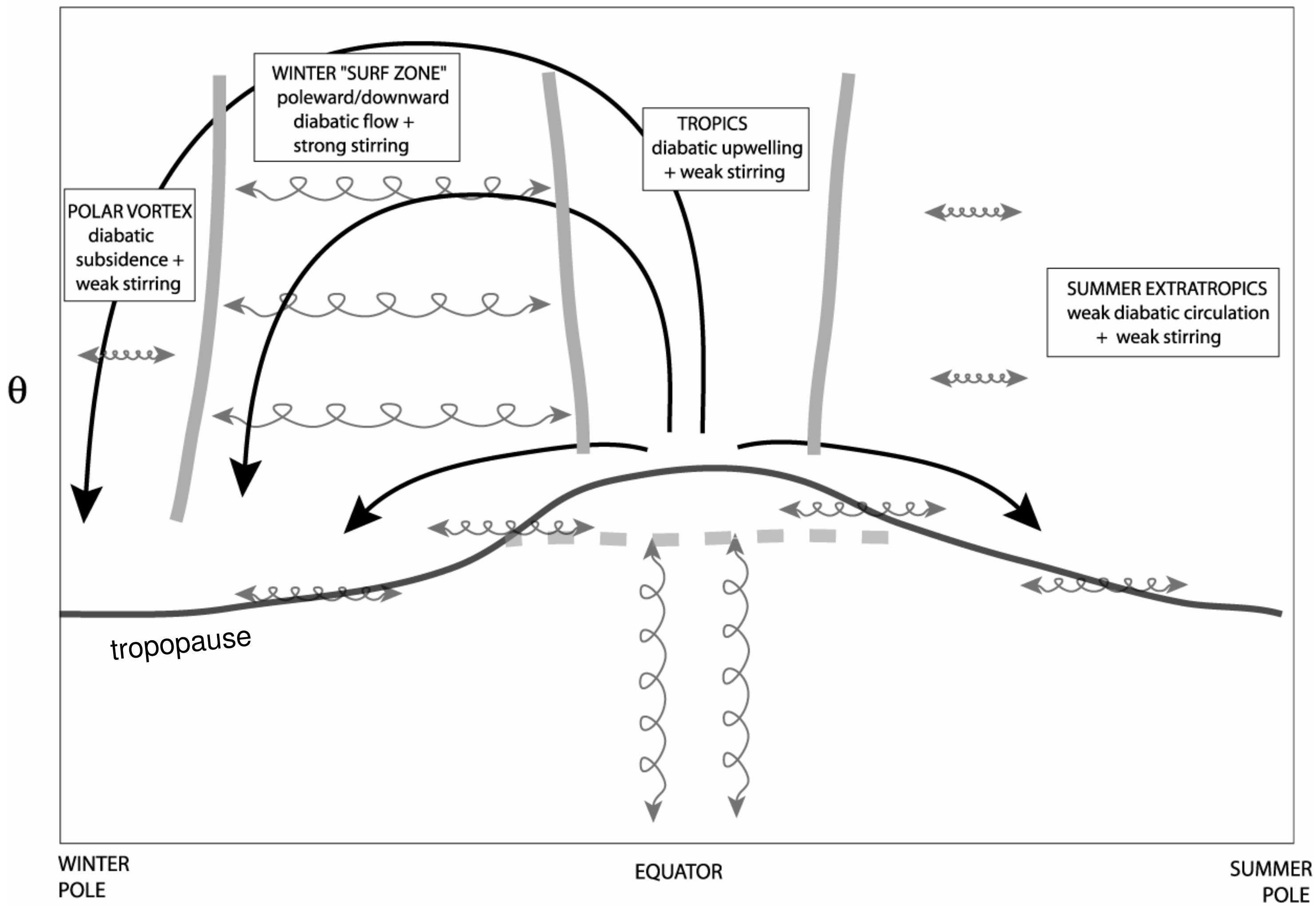
$$\tau_{mix} \sim \frac{L^2}{K_{eff}} \sim \frac{(3 \times 10^6)^2}{3 \times 10^6} \sim 3 \times 10^6 \mathrm{~s} \sim 35 \text{ days}$$

Time scale for residual advection across surf zone ($\bar{v}_* \sim 0.1\mathrm{ms}^{-1}$):

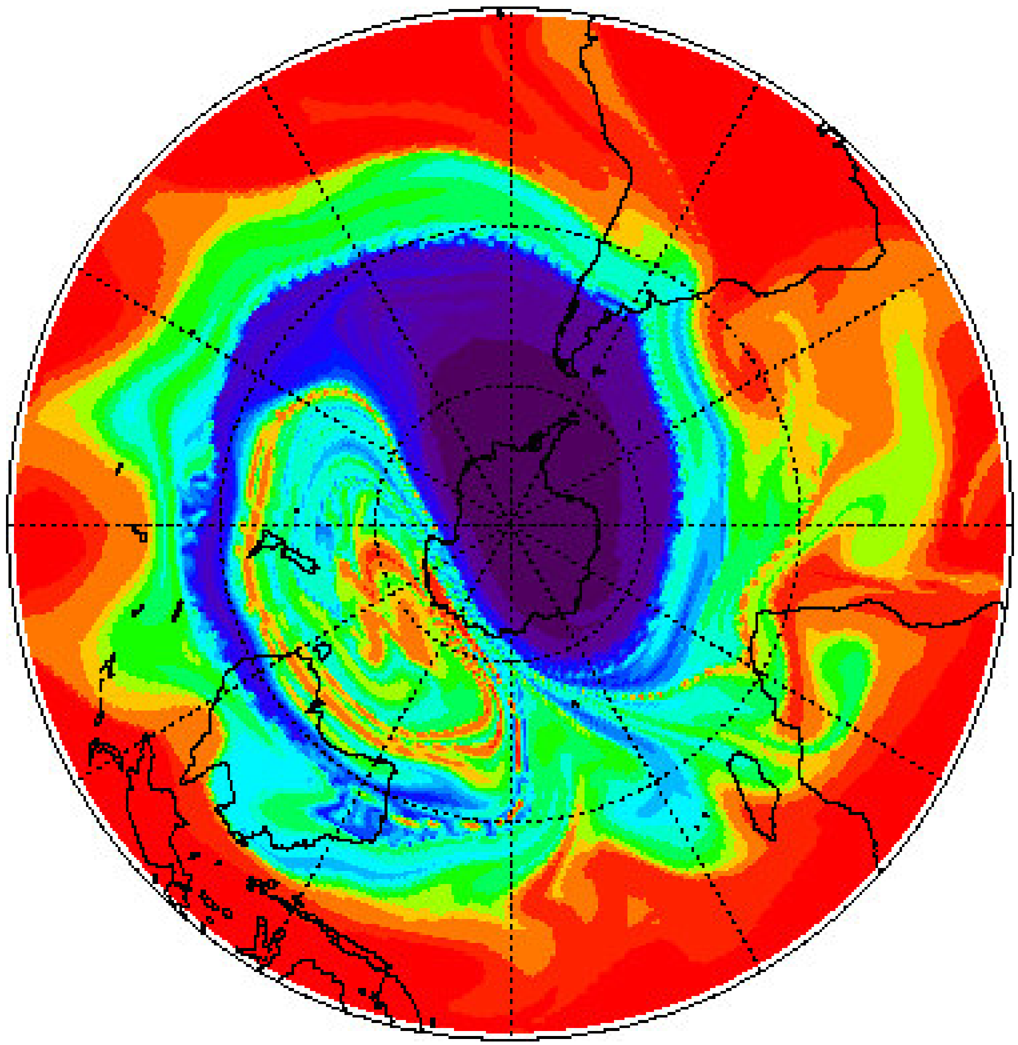
$$\tau_{adv} \sim \frac{L}{\bar{v}_*} \sim 3 \times 10^7 \mathrm{s} \sim 1 \text{ year}$$

$$\boxed{\tau_{mix} \ll \tau_{adv}}$$

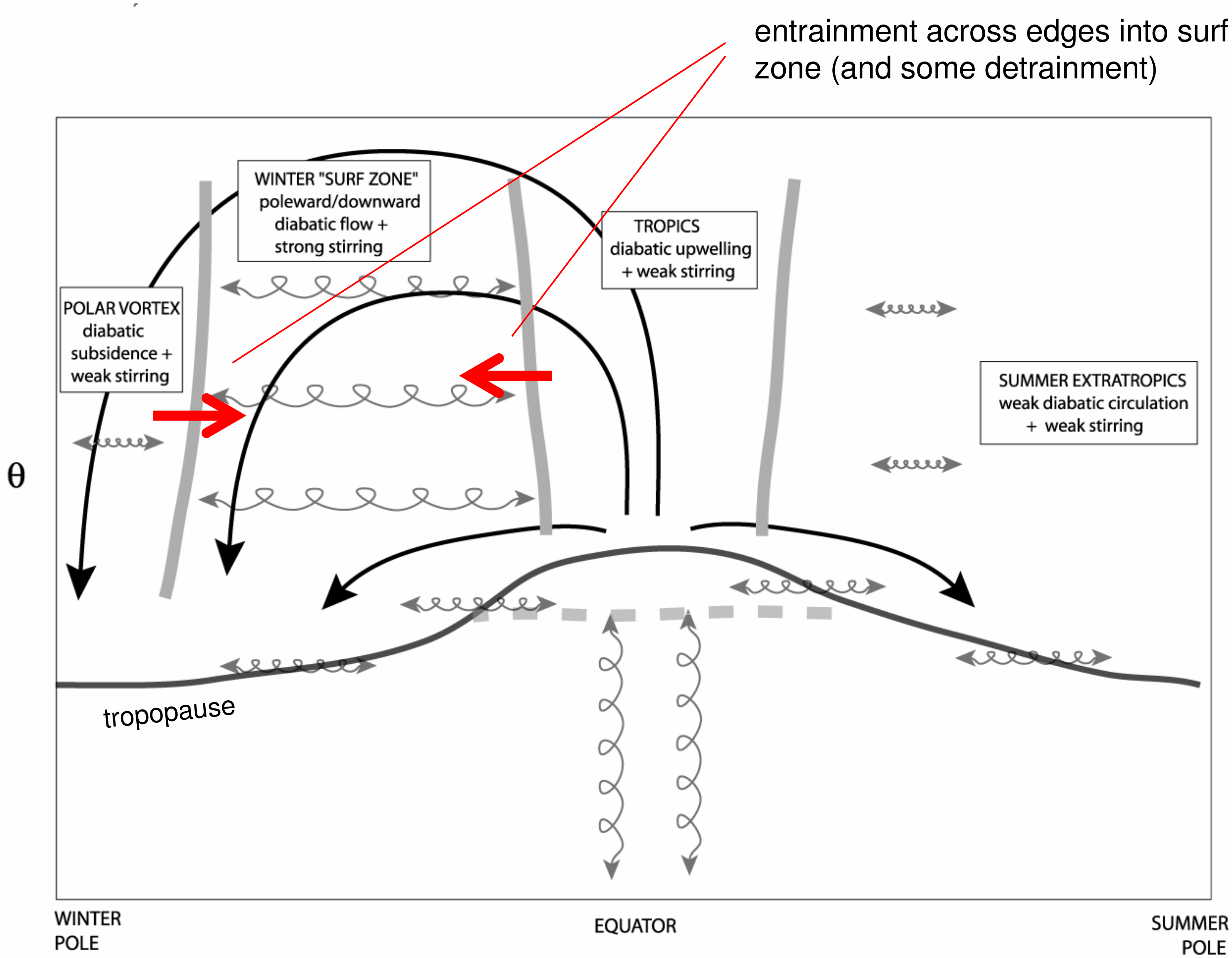
→ Stirring and mixing is the dominant poleward transport process



Plumb et al (2007)



Plumb et al (2007)

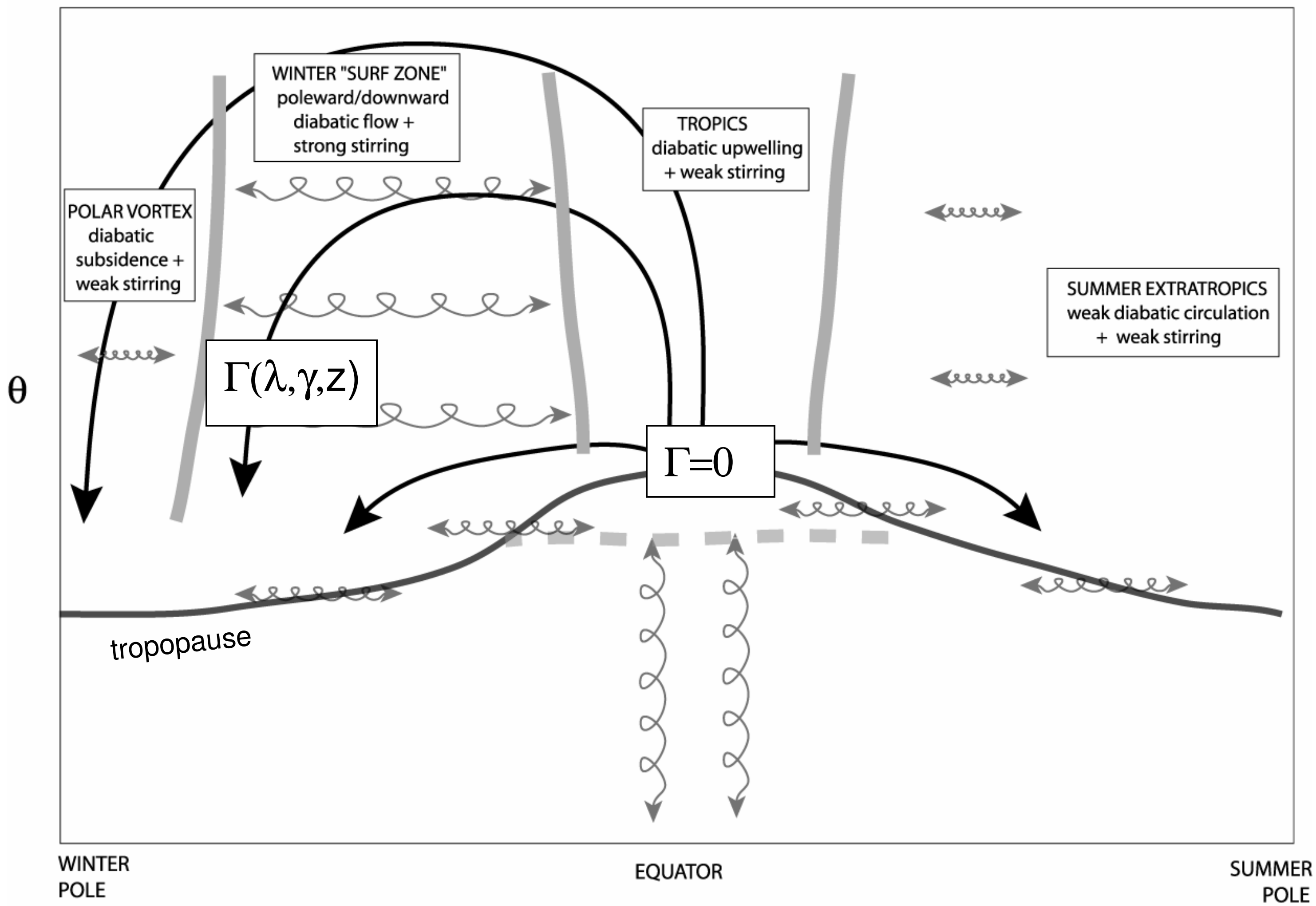


Plumb et al (2007)

(ii) Quantifying transport rates: Age

a stratospheric clock

Plumb et al (2007)



conserved tracer: $$\frac{\partial q}{\partial t} + \mathbf{u} \cdot \nabla q - \kappa \nabla^2 q = \frac{\partial q}{\partial t} + \mathcal{T}(q) = 0$$

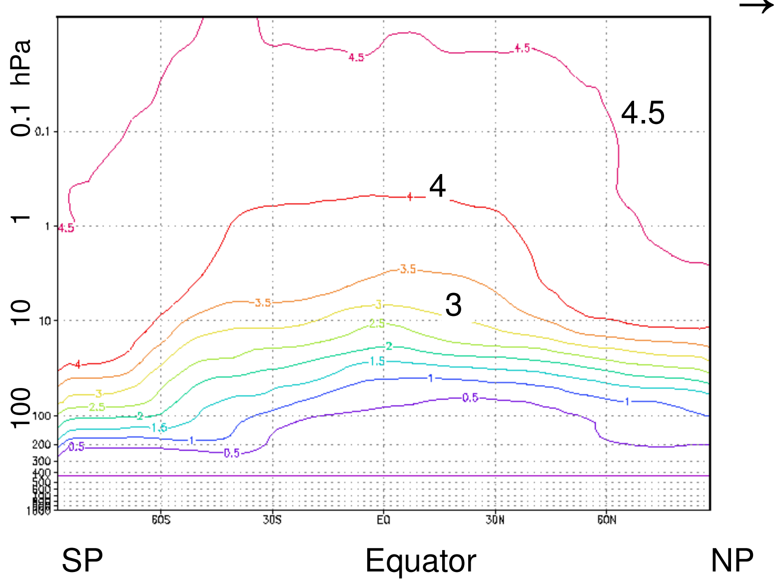
age: $$\frac{\partial \Gamma}{\partial t} + \mathcal{T}(\Gamma) = 1$$

Theoretical (ideal) age:

$$\frac{\partial \Gamma}{\partial t} + \mathcal{T}(\Gamma) = 1$$

steady equilibrium: $\mathcal{T}(\Gamma) = 1 \rightarrow \Gamma(\varphi, z) = \mathcal{T}^{-1}(1) \; ; \quad \Gamma_0 = 0$

Modeled age (annual mean; yrs)



Age from observed tracers:

linearly growing tracer $q_0(t) = Q_0 + \Lambda t$

$\rightarrow$ in equilibrium $q(\varphi, z, t) = Q(\varphi, z) + \Lambda t$

$$\frac{\partial q}{\partial t} + \mathcal{T}(q) = \Lambda + \mathcal{T}(Q) = 0$$

$$\rightarrow Q(\varphi, z) = -\mathcal{T}^{-1}(\Lambda) \; ; \quad Q(\varphi_0, z_0) = Q_0$$

$$\rightarrow Q - Q_0 = -\Lambda\Gamma$$

$$\rightarrow q(\varphi, z, t) = Q_0 + \Lambda(t - \Gamma)$$

$$= q_0(t - \Gamma)$$

Lines are smoothed surface values delayed by 4, 4.5, 5 years

Age from observed tracers:

linearly growing tracer $q_0(t) = Q_0 + \Lambda t$

$\rightarrow$ in equilibrium $q(\varphi, z, t) = Q(\varphi, z) + \Lambda t$

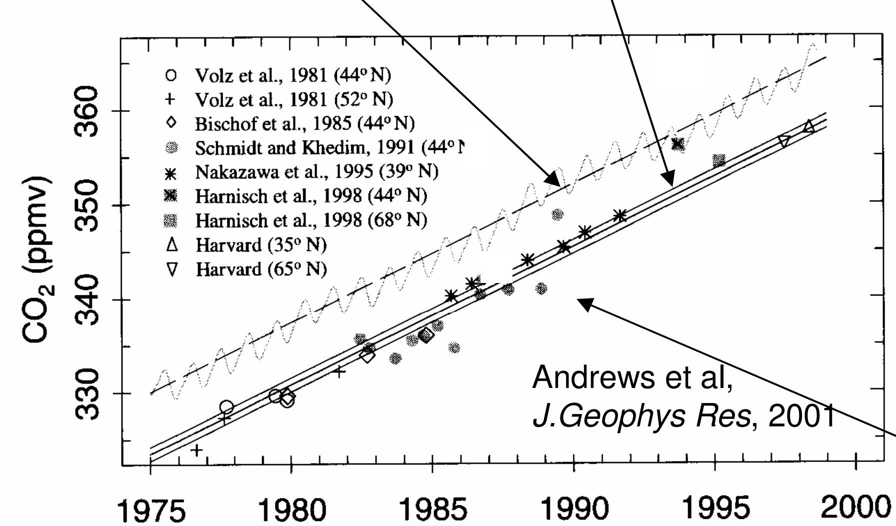
$$\frac{\partial q}{\partial t} + \mathcal{T}(q) = \Lambda + \mathcal{T}(Q) = 0$$

$$\rightarrow Q(\varphi, z) = -\mathcal{T}^{-1}(\Lambda) \quad ; \quad Q(\varphi_0, z_0) = Q_0$$

$$\rightarrow Q - Q_0 = -\Lambda\Gamma$$

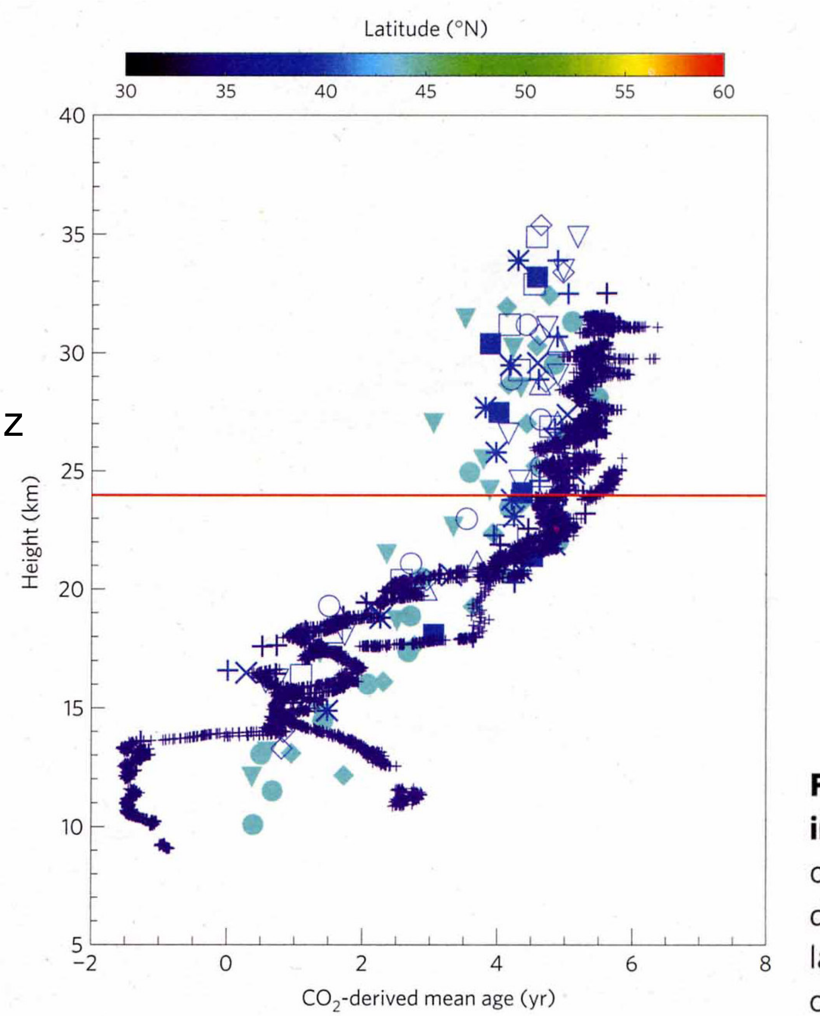
$$\rightarrow q(\varphi, z, t) = Q_0 + \Lambda(t - \Gamma) = q_0(t - \Gamma)$$

Surface values



balloon measurements

z



CO_2 – derived age (yr)

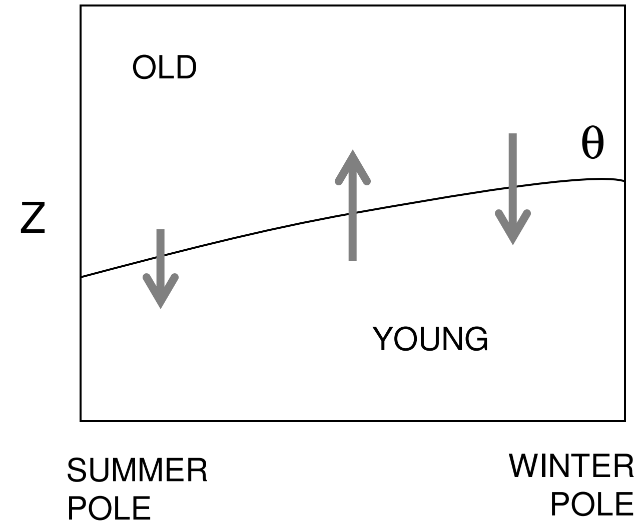
[Engel et al, *Nature Geoscience*, 2008]

Figure 2 | Vertical profiles of mean age derived from the CO_2 data shown in Fig. 3. The mean age is derived in the same way from the CO_2 observations, as explained in Engel *et al.*[20] using the reference tropospheric data set as discussed in the text. The colour code shows the (northern) latitude of the measurements. The red line shows the 24 km level, which corresponds to the 30 hPa level chosen as the lower pressure altitude limit of data included in this analysis. The uncertainty due to analytical error is of the order of 0.1 years. Systematic uncertainties are discussed in Supplementary Information.

Global flux of age

$$\frac{\partial \Gamma}{\partial t} + \mathcal{T}(\Gamma) = \frac{\partial \Gamma}{\partial t} + \frac{1}{\rho}\nabla \cdot \mathbf{F}_\Gamma = 1$$

$$\text{in equilibrium} \qquad \frac{1}{\rho}\nabla \cdot \mathbf{F}_\Gamma = 1$$



Integrate over volume above surface $\theta = \Theta$:

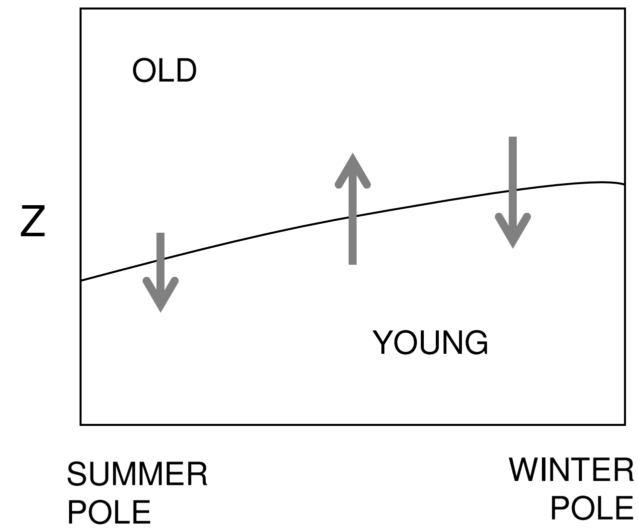
$$\rightarrow \iiint_{\theta>\Theta} \nabla \cdot \mathbf{F}_\Gamma \, dV = \iiint_{\theta>\Theta_0} \rho \, dV = M(\Theta)$$

$$\iiint_{\theta>\Theta} \nabla \cdot \mathbf{F}_\Gamma \, dV = \iint_{\theta=\Theta} \mathbf{F}_\Gamma \cdot \mathbf{n} \, dA$$

$$\rightarrow \iint_{\theta=\Theta} \mathbf{F}_\Gamma \cdot \mathbf{n} \, dA = M(\Theta)$$

→ so we know the net flux of age through any surface if we know the mass above that surface (which we do if we know p along the surface)

$$\rightarrow \iint_{\theta=\Theta} \mathbf{F}_\Gamma \cdot \mathbf{n}\, dA = M(\Theta)$$



If diabatic diffusion is negligible (K_{zz} weak in stratosphere), flux through θ surface is purely advective:

$$\mathbf{F}_\Gamma = \rho w_d \Gamma$$

$$\rightarrow \iint_{\theta=\Theta} \mathbf{F}_\Gamma \cdot \mathbf{n}\, dA = \iint_{\theta=\Theta} \rho w_d \Gamma dA$$

$$= \iint_{up} \rho w_d \Gamma dA + \iint_{down} \rho w_d \Gamma dA$$

$$= -\mathcal{M}\left[\langle\Gamma\rangle_{down} - \langle\Gamma\rangle_{up}\right]$$

where

$$\mathcal{M} = \iint_{up} \rho w_d dA = -\iint_{down} \rho w_d dA$$ overturning mass flux

$$\langle\Gamma\rangle_{down} = -\frac{1}{\mathcal{M}} \iint_{down} \rho w_d \Gamma dA \;\; ; \;\; \langle\Gamma\rangle_{up} = \frac{1}{\mathcal{M}} \iint_{up} \rho w_d \Gamma dA$$

$$\Delta\Gamma(\Theta) = \langle\Gamma\rangle_{down} - \langle\Gamma\rangle_{up} = \frac{M(\Theta)}{\mathcal{M}(\Theta)}$$

Age trends from WACCM

age (yr)

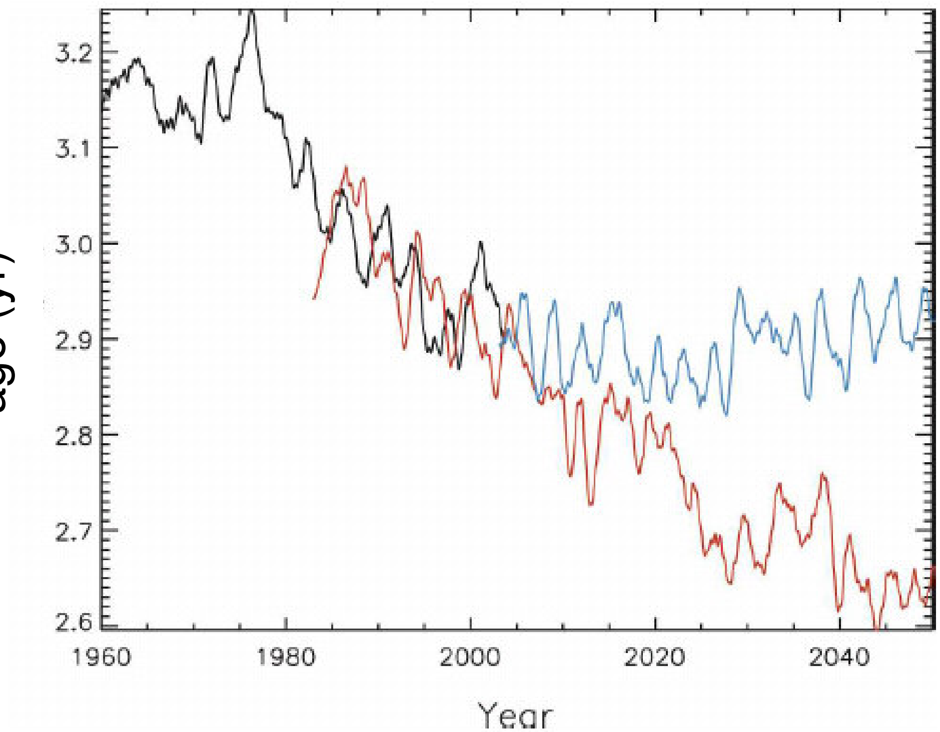
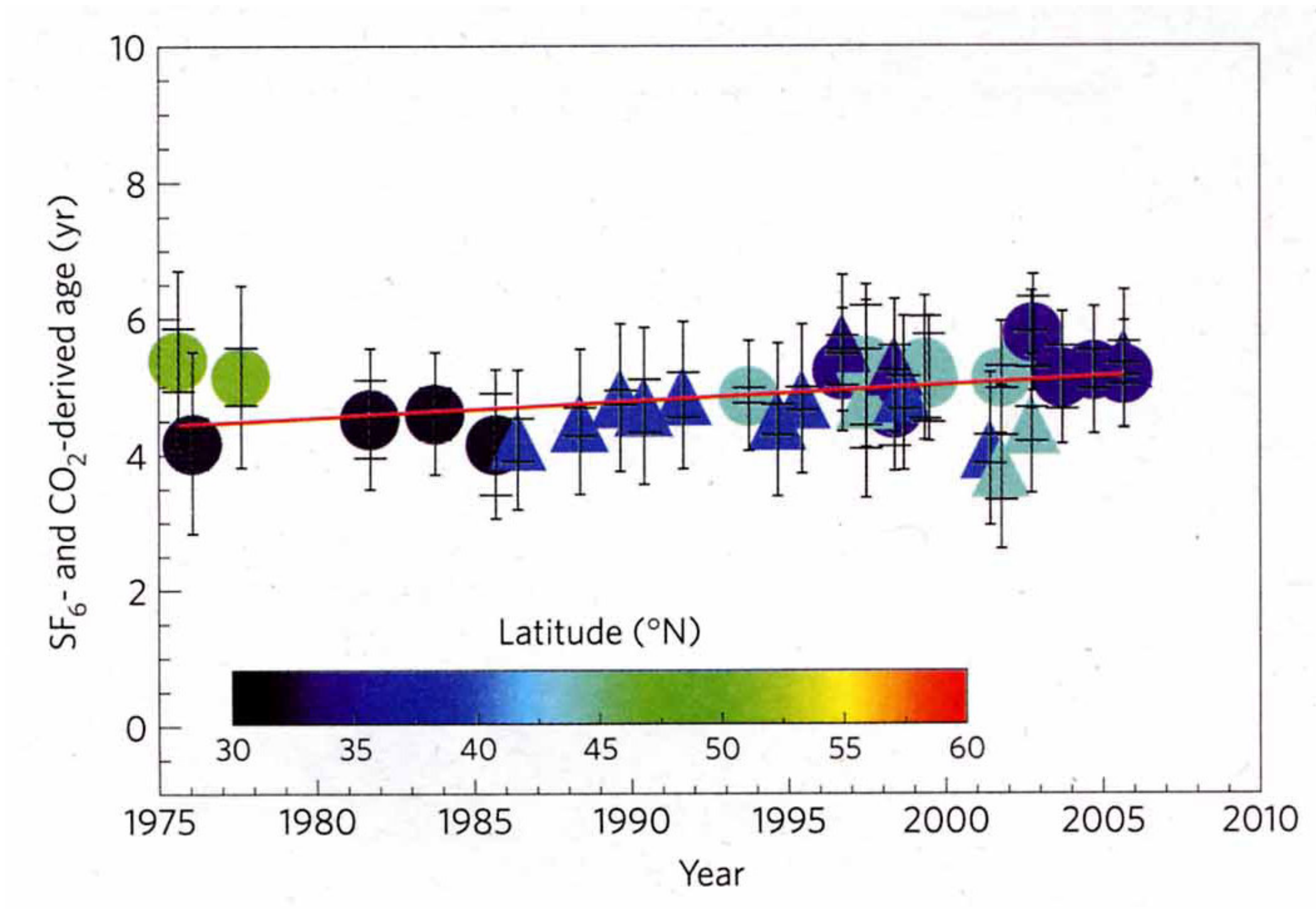


FIG. 1. Evolution of the age of air near 10 hPa averaged over ±22° [months $(10\ \text{yr})^{-1}$] for three-member ensemble simulations of the climate of the twentieth century (REF1; black curve); the climate of the twenty-first century under increasing loading of GHG (REF2; red); and the climate of the twenty-first century with GHG held constant at 1995 values (NCC; blue). See text for details.

[Garcia & Randel, *J Atmos Sci,* 2008]

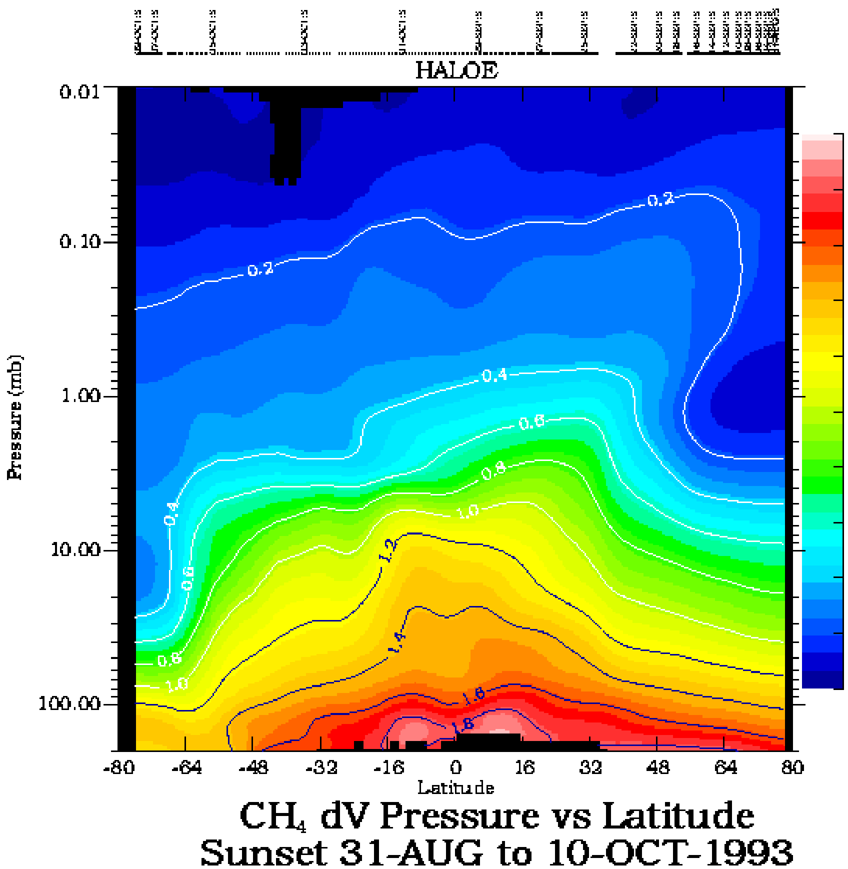


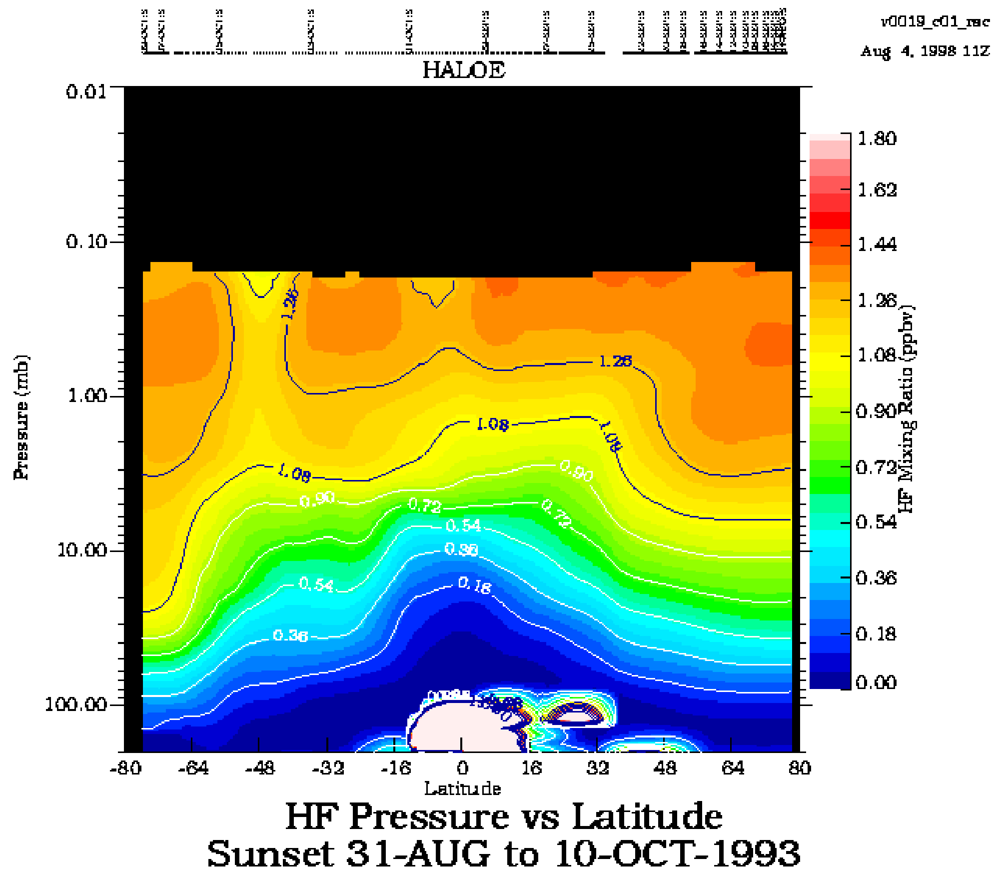
[Engel et al, *Nature Geoscience*, 2008]

(iii) Stratospheric trace gases:
Global structure and tracer-tracer relationships

HALOE data

[Russell et al, *J Geophys Res*, 1993]





CH_4

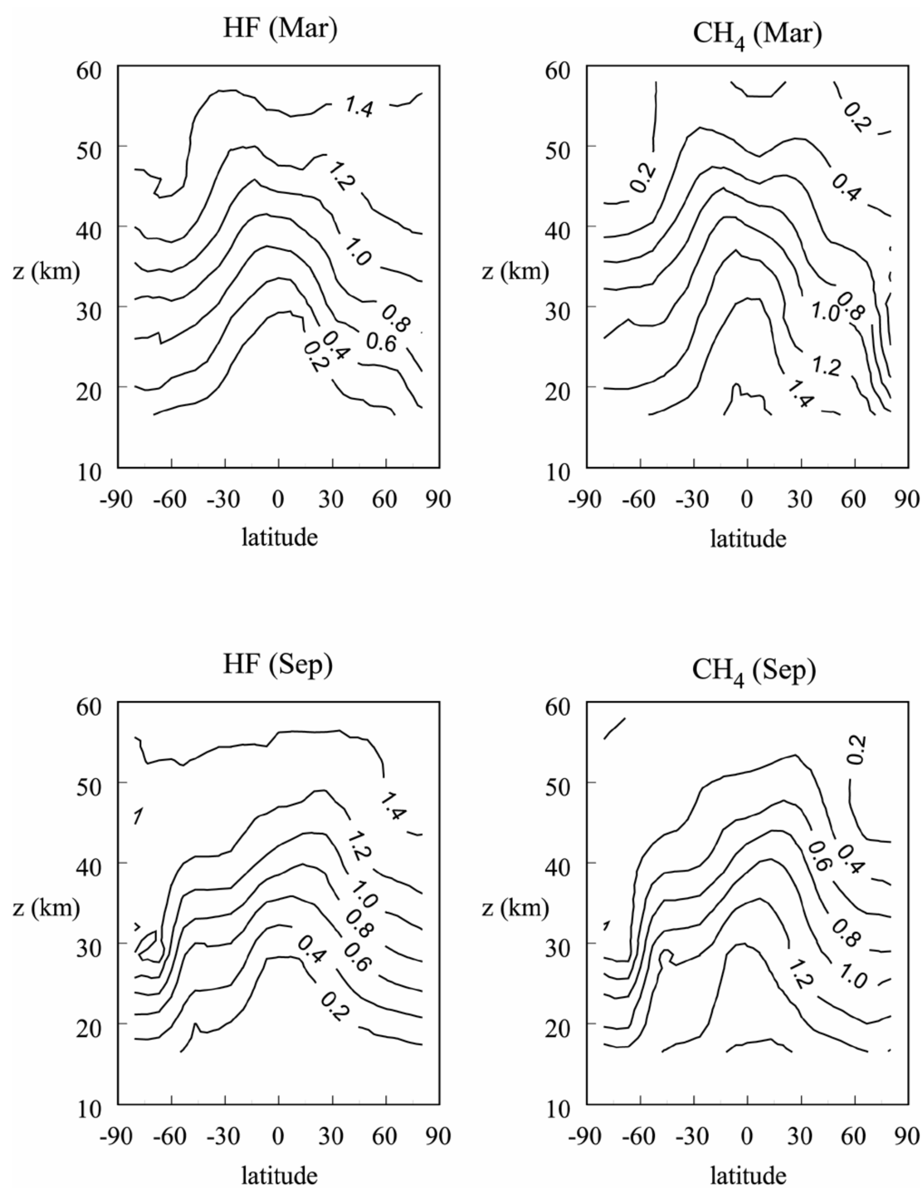
tropospheric source
stratospheric sink

HF

stratospheric source
tropospheric sink

CH_4 : HF comparison

(HALOE data)



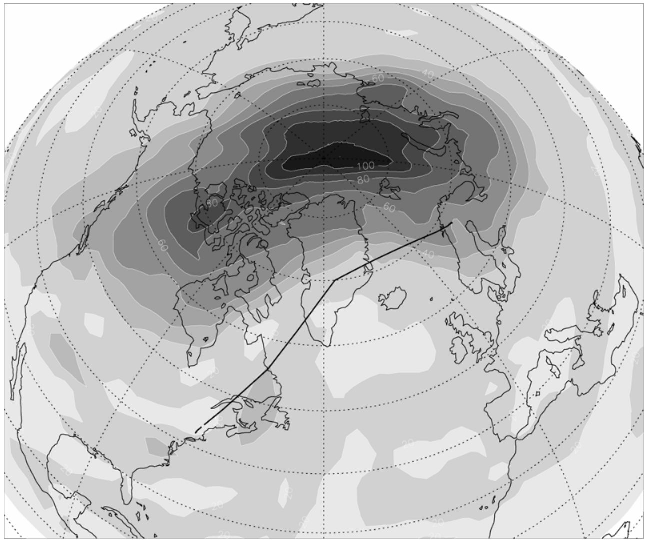
→ Similar isopleth shapes, despite different locations of sources and sinks

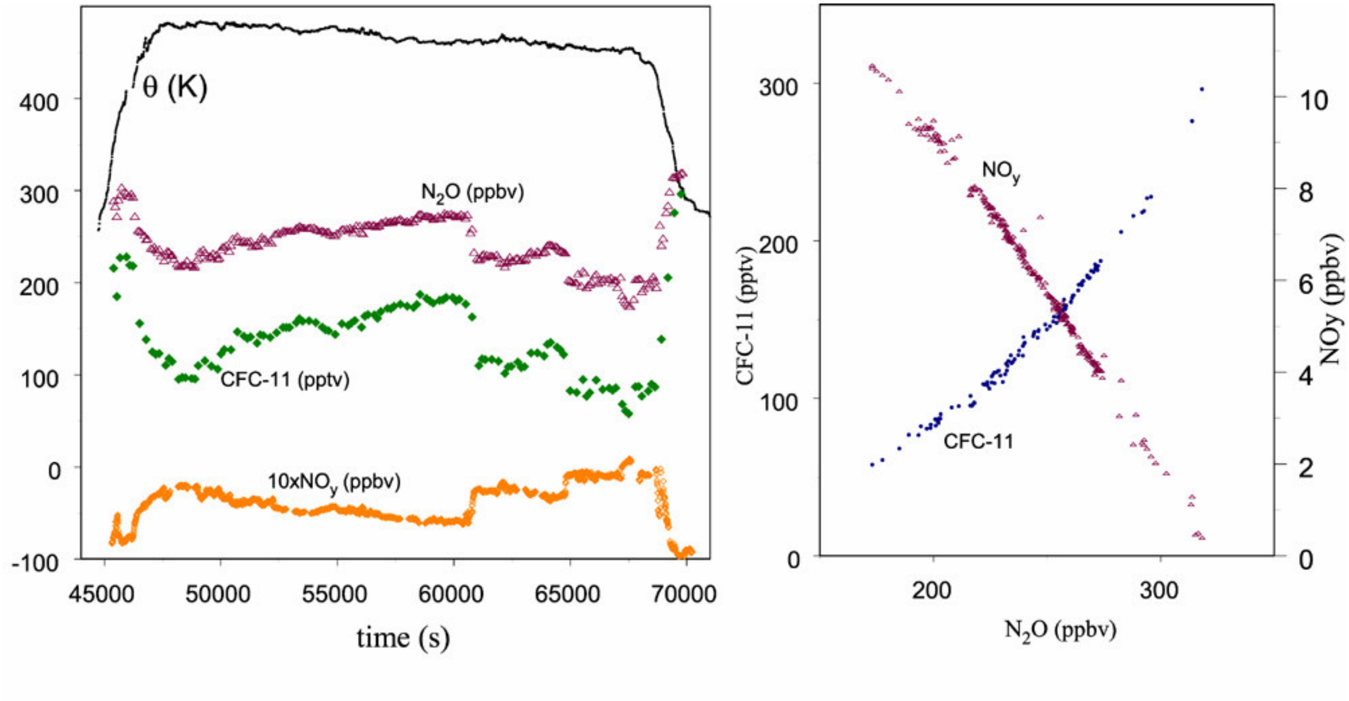
Plumb Haynes & Shuckburgh, J Atmos Sci,2002et al (2

In situ data

(SOLVE experiment 2000)

Ertel PV, 480K



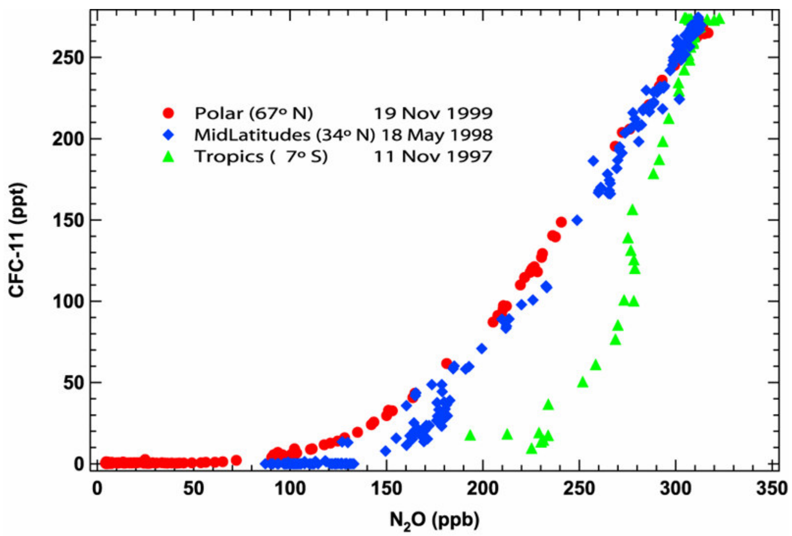


Plumb et al (2002)

Compact tracer-tracer relationships

Different relationships in different regions

In situ balloon data (LACE, Elkins/Moore)
CFC-11 : N_2O



[Plumb, *Rev Geophys*, 2007]

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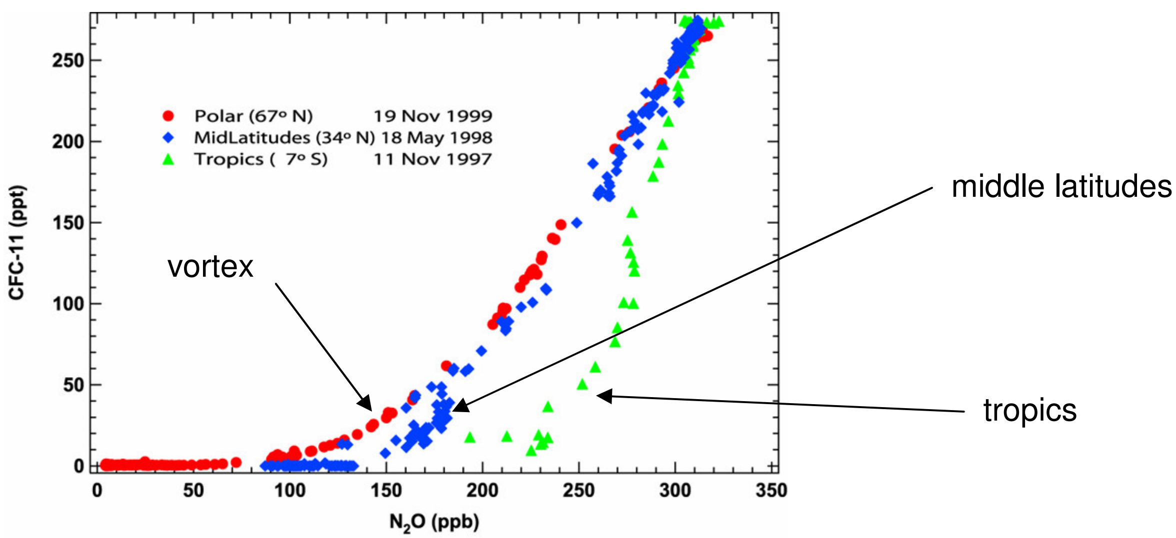
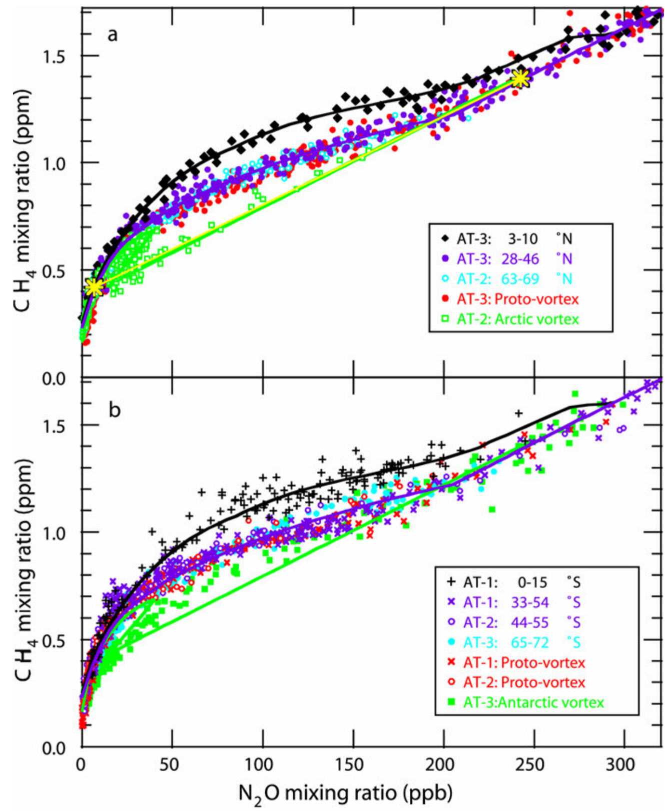


[Plumb, *Rev Geophys*, 2007]

Different relationships in different regions

Space-based data (ATMOS)
CH_4 : N2O



Michelsen et al, *J Geophys Res*, 1998]

Different relationships in different regions

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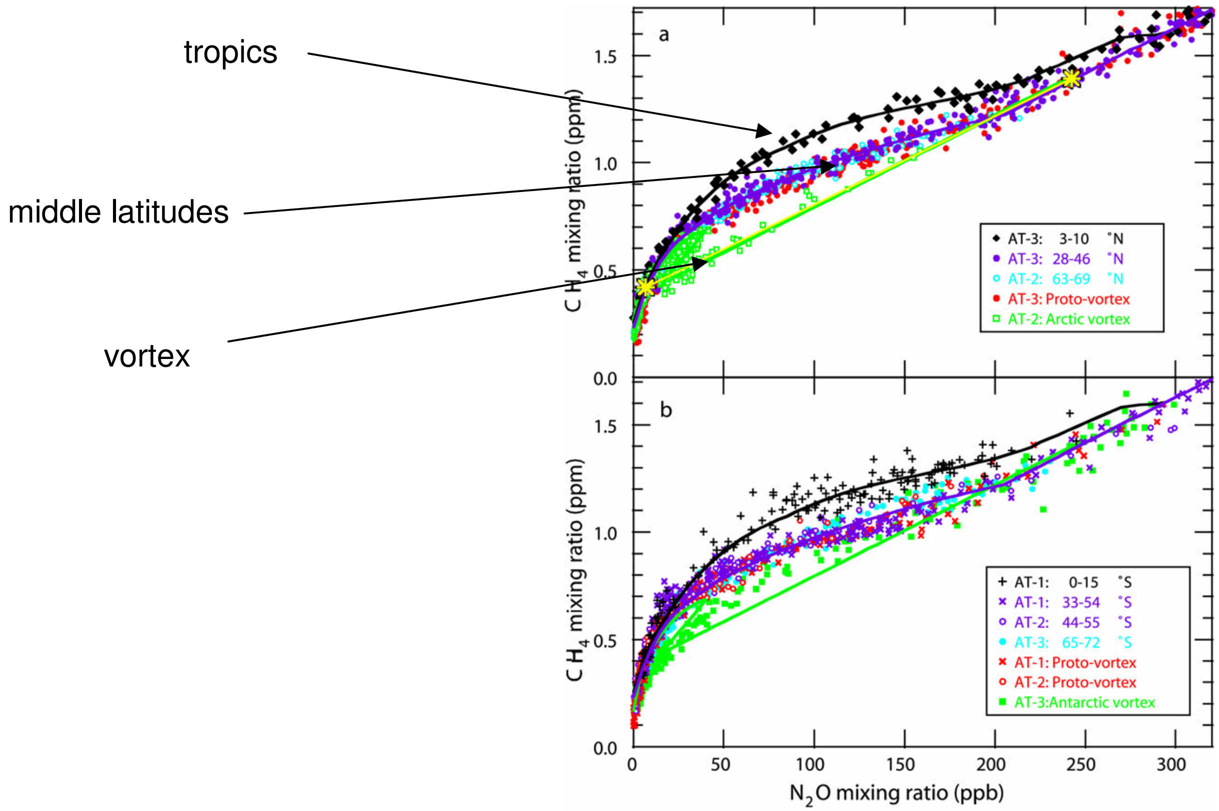

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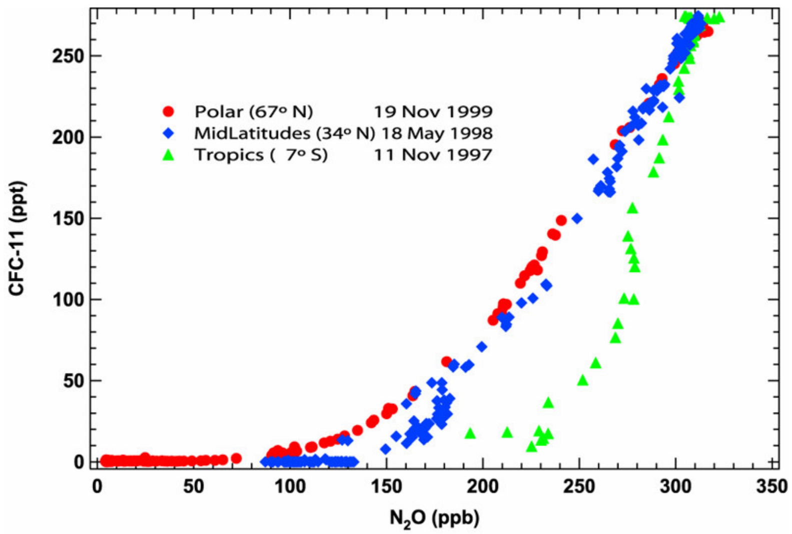

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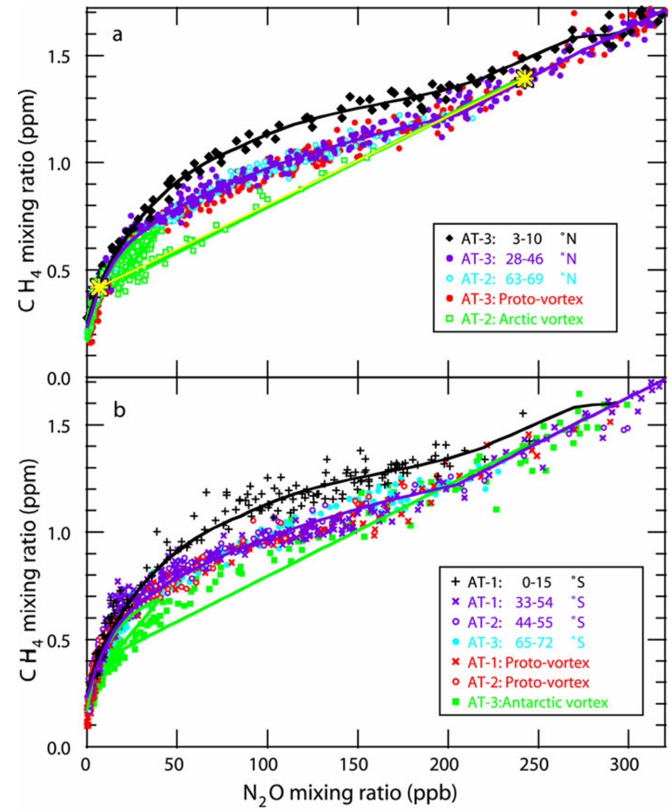
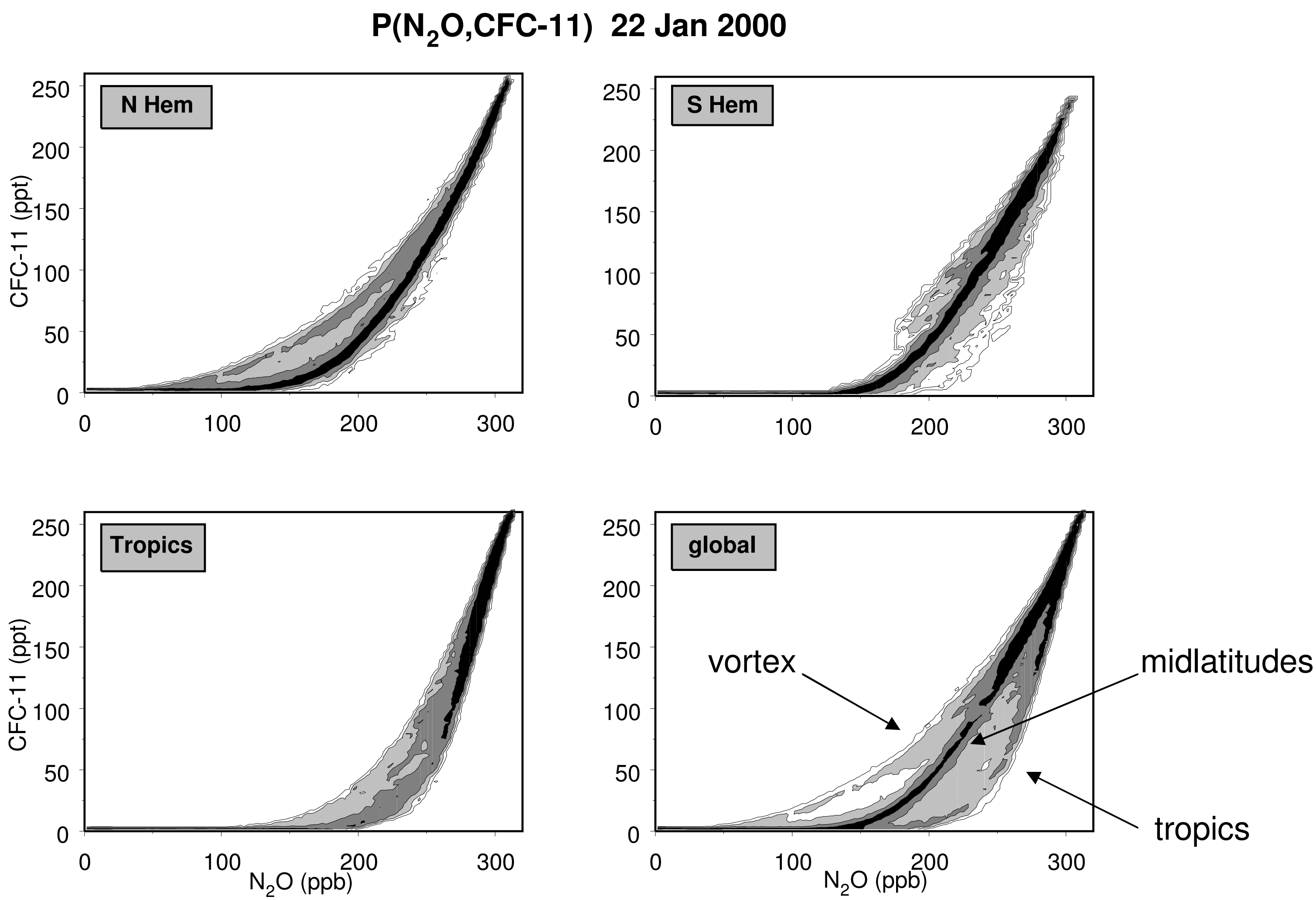


Michelsen et al, *J Geophys Res*, 1998]

from chemical transport model
[Plumb et al., *J Geophys Res*, 2002]



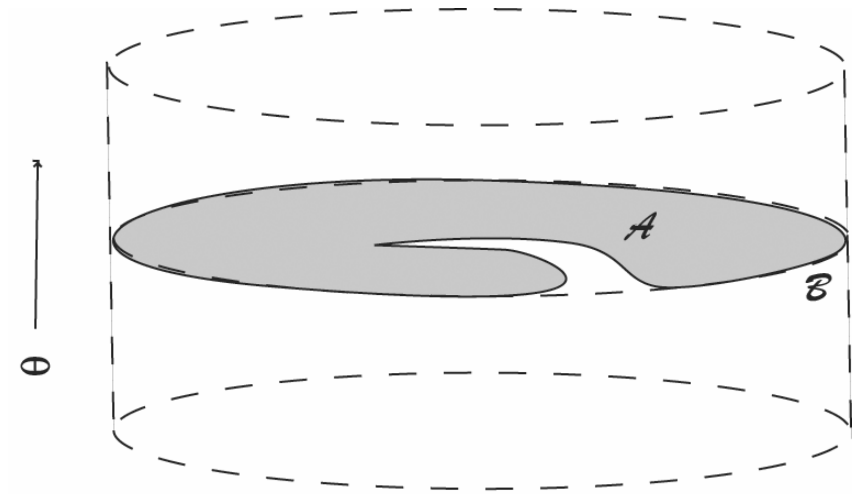
Theory: $\tau_{mix} \ll \tau_{adv}$

[Plumb, *Rev Geophys*, 2007]

$$\frac{\partial \chi}{\partial t} + \mathbf{u} \cdot \nabla \chi - \kappa \nabla^2 \chi = S$$

tracer mixing ratio

sources and sinks



Theory: $\tau_{mix} \ll \tau_{adv}$

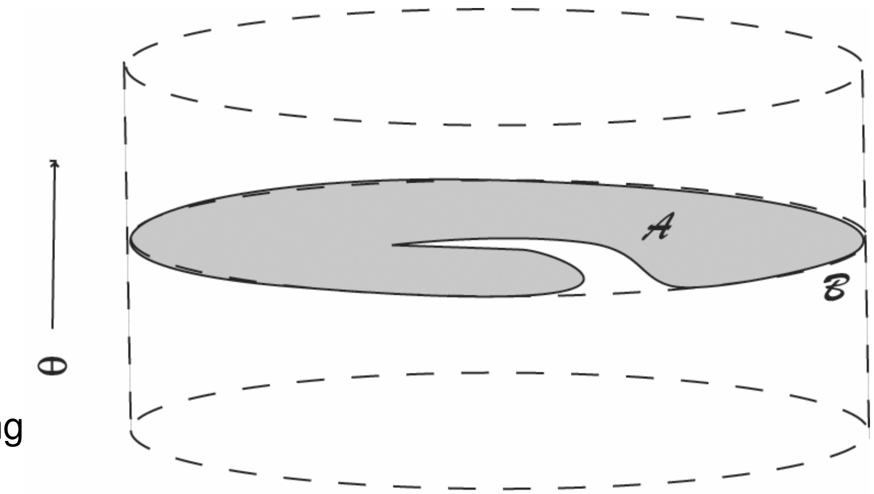
$$\frac{\partial \chi}{\partial t} + \mathbf{u} \cdot \nabla \chi - \kappa \nabla^2 \chi = S$$

$$\frac{\partial \chi}{\partial t} + \mathbf{u}_d \cdot \nabla \chi + \dot{\theta} \frac{\partial \chi}{\partial \theta} + \mathcal{H}(\chi) = S$$

slow diabatic transport

rapid isentropic stirring / mixing

Plumb (2007)



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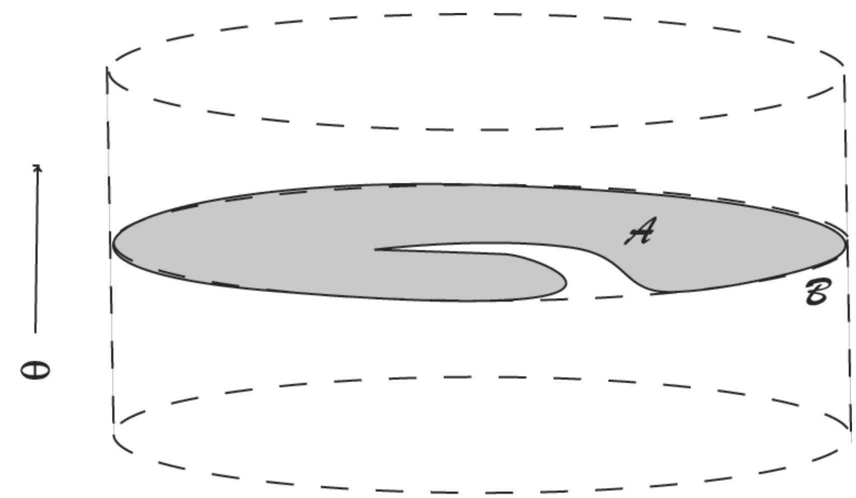
$$\frac{\partial \chi}{\partial t} + \mathbf{u} \cdot \nabla \chi - \kappa \nabla^2 \chi = S$$

$$\frac{\partial \chi}{\partial t} + \mathbf{u}_d \cdot \nabla \chi + \dot{\theta} \frac{\partial \chi}{\partial \theta} + \mathcal{H}(\chi) = S$$

$$\frac{\partial \sigma}{\partial t} + \nabla \cdot (\sigma \mathbf{u}_d) + \frac{\partial}{\partial \theta}(\sigma \dot{\theta}) = 0$$

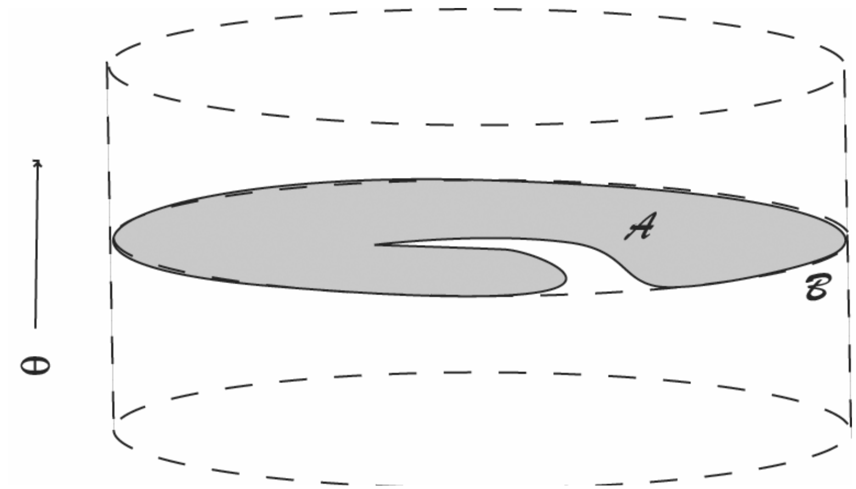
$\sigma = -g^{-1} \dfrac{\partial p}{\partial \theta}$ is density in θ – coordinates

Plumb (2007)



Theory: $\tau_{mix} \ll \tau_{adv}$

Plumb (2007)



$$\frac{\partial \chi}{\partial t} + \mathbf{u}_d \cdot \nabla \chi + \dot{\theta}\frac{\partial \chi}{\partial \theta} + \mathcal{H}(\chi) = S$$

Properties of $\mathcal{H}$:

- only acts on isentropic gradients: $\mathcal{H}[f(\theta, t)] = 0$
- it is linear: $\mathcal{H}(\chi + \phi) = \mathcal{H}(\chi) + \mathcal{H}(\phi)$ and $\mathcal{H}[f(\theta, t)\chi] = f(\theta, t)\mathcal{H}(\chi)$
- redistribution operator (does not create or destroy tracer)

$$\iint \sigma \mathcal{H}(\chi)\, dA = \text{boundary fluxes}$$

- it is uniquely invertible; solution to

$$\mathcal{H}(\chi) = X$$

subject to zero net boundary flux, has solution

$$\chi = \mathcal{H}^{-1}(X)$$

(solvability condition:

$$\bar{X} = \left[\iint \sigma\, dA\right]^{-1} \iint \sigma X\, dA = 0 \;\;)$$

Theory: $\tau_{mix} \ll \tau_{adv}$

$$\frac{\partial \chi}{\partial t} + \mathbf{u}_d \cdot \nabla \chi + \dot{\theta}\frac{\partial \chi}{\partial \theta} + \mathcal{H}(\chi) = S$$

$$T_{mixing} \ll T_{diabatic}, T_t \ll T_{chem}$$

$$\dot{\theta} = \varepsilon(\dot{\theta}_0 + \varepsilon\dot{\theta}_1) \ ,$$

$$\frac{\partial}{\partial t} = \varepsilon\left(\frac{\partial}{\partial t} + \varepsilon\frac{\partial}{\partial \tau}\right)$$

$$S = \varepsilon^2 S_0$$

$$\chi = \chi_0 + \varepsilon\chi_1 + \varepsilon^2\chi_2 + \ldots\ldots\ldots\ldots\ldots$$

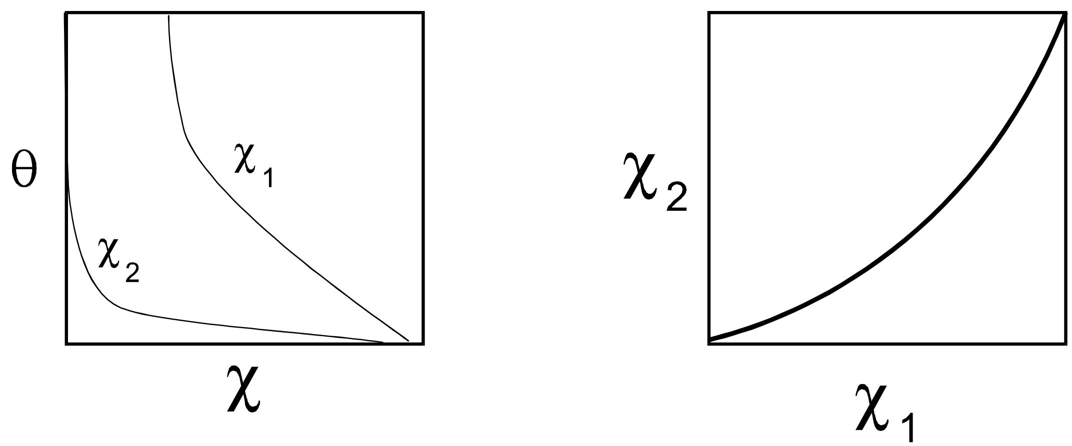
At leading order ε⁰,

$$\frac{\partial \chi}{\partial t} + \mathbf{u}_d \cdot \nabla \chi + \dot{\theta}\frac{\partial \chi}{\partial \theta} + \mathcal{H}(\chi) = S$$

$$\mathcal{H}(\chi_0) = 0$$

$$\rightarrow \chi_0 = \chi_0(\theta, t)$$

$\rightarrow$ complete isentropic homogenization



$$\chi_0^{(n)} = \chi_0^{(n)}(\theta, t) \quad \rightarrow \quad f(\chi_0^{(1)}, \chi_0^{(2)}, t) = 0 \text{ , trivially}$$

At order ε^1,

$$\frac{\partial \chi}{\partial t} + \mathbf{u}_d \cdot \nabla \chi + \dot{\theta} \frac{\partial \chi}{\partial \theta} + \mathcal{H}(\chi) = S$$

$$\mathcal{H}(\chi_1) = S - \frac{\partial \chi_0}{\partial t} - \mathbf{u}_d \cdot \nabla \chi_0 - \dot{\theta} \frac{\partial \chi_0}{\partial \theta}$$

solvability condition ⟶

advection by *average* vertical motion

mixing ratio of entrained tropical air

$$\boxed{\frac{\partial \chi_0}{\partial t} + \bar{\dot{\theta}} \frac{\partial \chi_0}{\partial \theta} = \bar{S} + \frac{1}{\tau_e}(\chi_T - \chi_0)\,,}$$

where $\tau_e = \iint \sigma \, dA \,/\, \oint \sigma V \, dl$

time for entrained air to fill surf zone

entrainment velocity

At order ε^1,

$$\frac{\partial \chi}{\partial t} + \mathbf{u}_d \cdot \nabla \chi + \dot{\theta}\frac{\partial \chi}{\partial \theta} + \mathcal{H}(\chi) = S$$

$$\mathcal{H}(\chi_1) = S - \frac{\partial \chi_0}{\partial t} - \mathbf{u}_d \cdot \nabla \chi_0 - \dot{\theta}\frac{\partial \chi_0}{\partial \theta}$$

distribution of entrained air

$$\chi_1 = \mathcal{H}^{-1}\left(S' - \dot{\theta}' \frac{\partial \chi_0}{\partial \theta}\right) + \tau_e \phi\{\sigma V\}\left(\bar{S} - \bar{\dot{\theta}}\frac{\partial \chi_0}{\partial \theta} - \frac{\partial \chi_0}{\partial t}\right)$$

if χ_0 steady, and $\bar{S}$ negligible,

$$\chi_1^{(n)} = -\zeta \frac{\partial \chi_0^{(n)}}{\partial \theta} \quad , \quad \text{where}$$

$$\zeta = \mathcal{H}^{-1}(\dot{\theta}') - \bar{\dot{\theta}}\tau_e \phi\{\sigma V\}$$

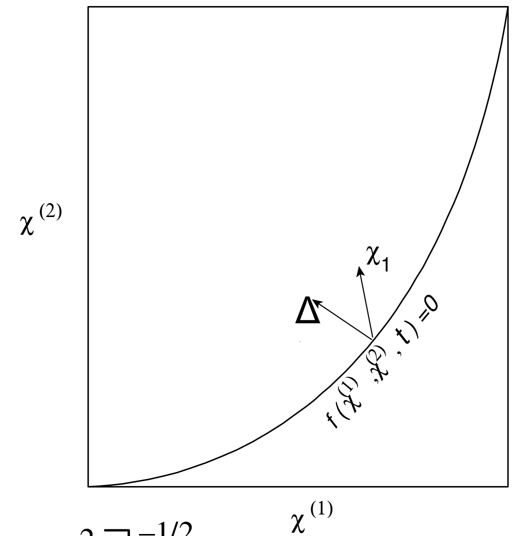
$\zeta(\lambda, \varphi, t)$ is the vertical displacement of tracer isopleths
it is *purely kinematic*: same for all tracers

$$\chi_1^{(n)} = -\zeta \frac{\partial \chi_0^{(n)}}{\partial \theta} \quad ,$$

$$\zeta = \mathcal{H}^{-1}(\dot{\theta}') - \bar{\dot{\theta}} \tau_e \phi\{\sigma V\}$$

→ all (long-lived) tracrs have the same isopleth shapes
→ "equilibrium slopes" [Ehhalt et al. 1983; Mahlman et al, 1986; Holton 1986]

Plumb (2007)



In tracer-tracer space:

The $O(\varepsilon)$ departure from the canonical curve $f(\chi_0^{(1)}, \chi_0^{(2)}, t) = 0$ is

$$\Delta = \varepsilon\left(\chi_1^{(1)}, \chi_1^{(2)}\right) \bullet \left(\frac{\partial \chi_0^{(2)}}{\partial \theta}, -\frac{\partial \chi_0^{(1)}}{\partial \theta}\right)\left[\left(\frac{\partial \chi_0^{(1)}}{\partial \theta}\right)^2 + \left(\frac{\partial \chi_0^{(1)}}{\partial \theta}\right)^2\right]^{-1/2}$$

$$= -\varepsilon\left(\zeta \frac{\partial \chi_0^{(1)}}{\partial \theta} + \zeta \frac{\partial \chi_0^{(2)}}{\partial \theta}\right) \bullet \left(\frac{\partial \chi_0^{(2)}}{\partial \theta}, -\frac{\partial \chi_0^{(1)}}{\partial \theta}\right)\left[\left(\frac{\partial \chi_0^{(1)}}{\partial \theta}\right)^2 + \left(\frac{\partial \chi_0^{(1)}}{\partial \theta}\right)^2\right]^{-1/2}$$

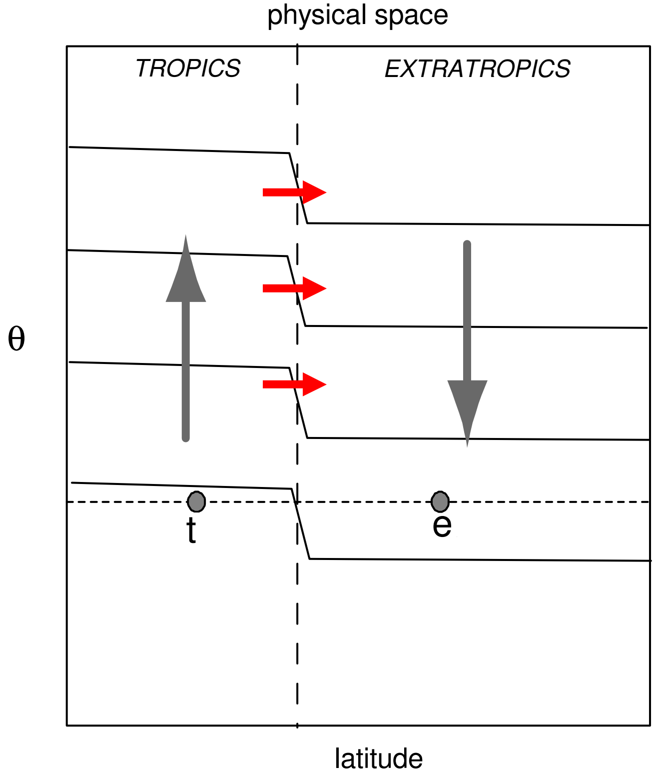
$$= 0$$

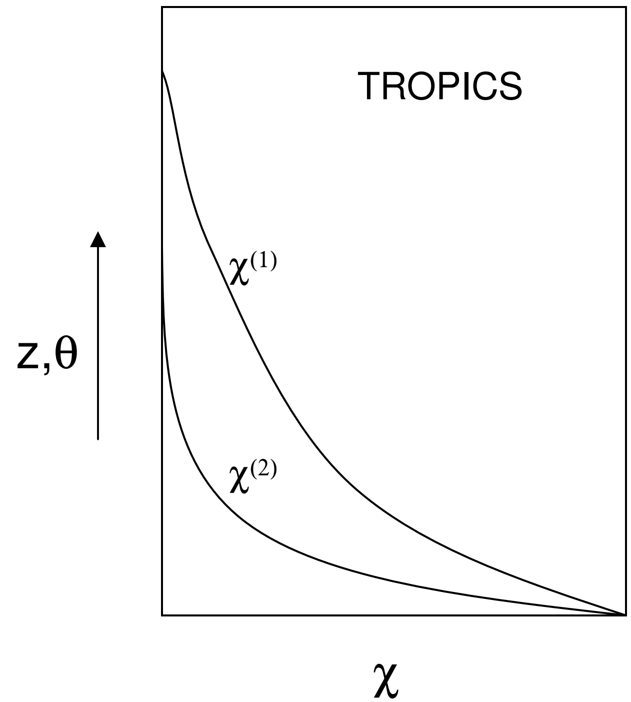
→ the $O(\varepsilon)$ correction lies *along* the canonical curve, so

$$f(\chi^{(1)}, \chi^{(2)}, t) = 0$$

remains valid at this order: non-trivial *compact relationships*

Creation of tropical relationships

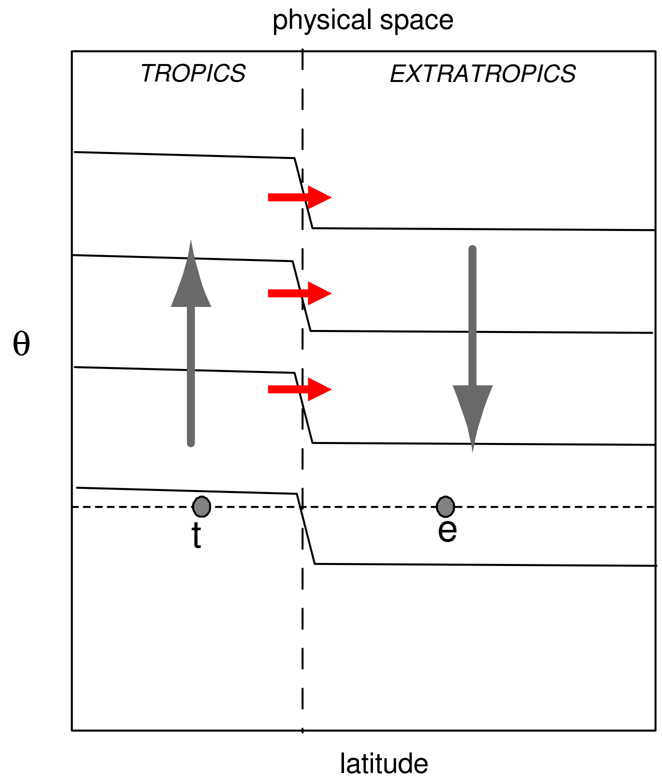


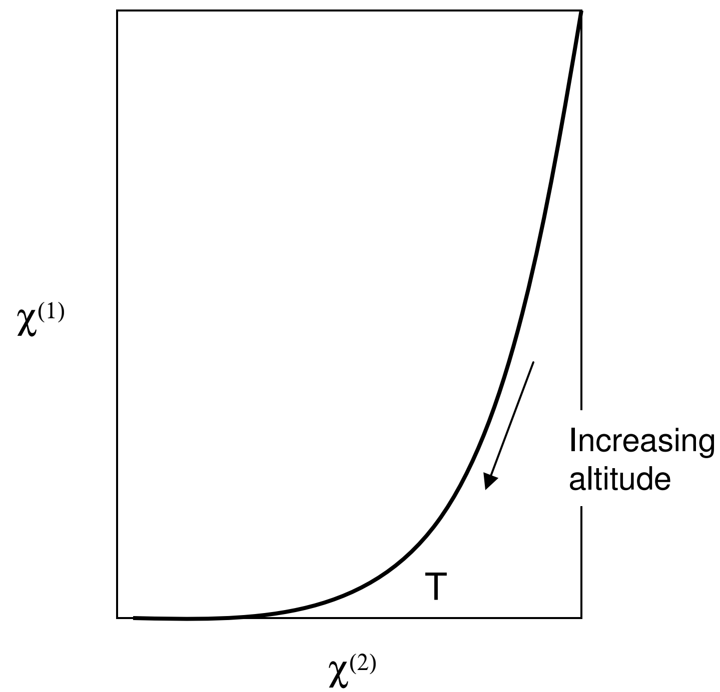


2 tropospheric source gases, destroyed in tropical stratosphere

tracer 2 has shorter lifetime than tracer 1 → tracer-tracer relation in tropics is curved as shown (T)

Creation of tropical relationships





2 tropospheric source gases, destroyed in tropical stratosphere

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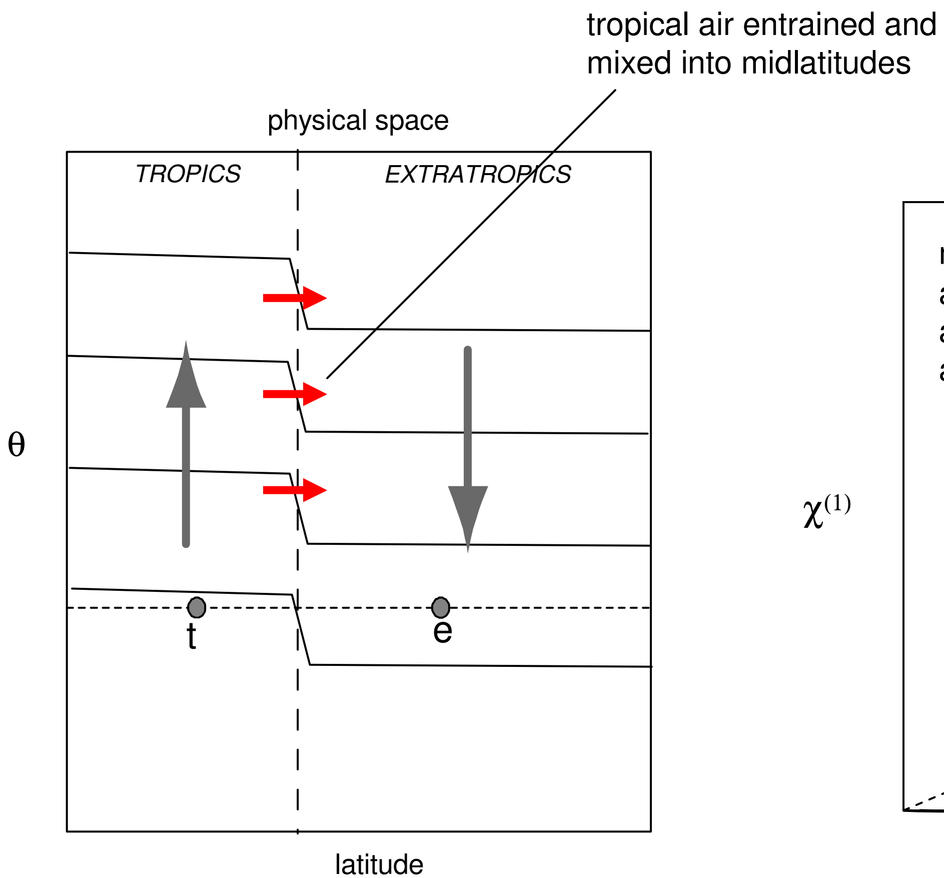
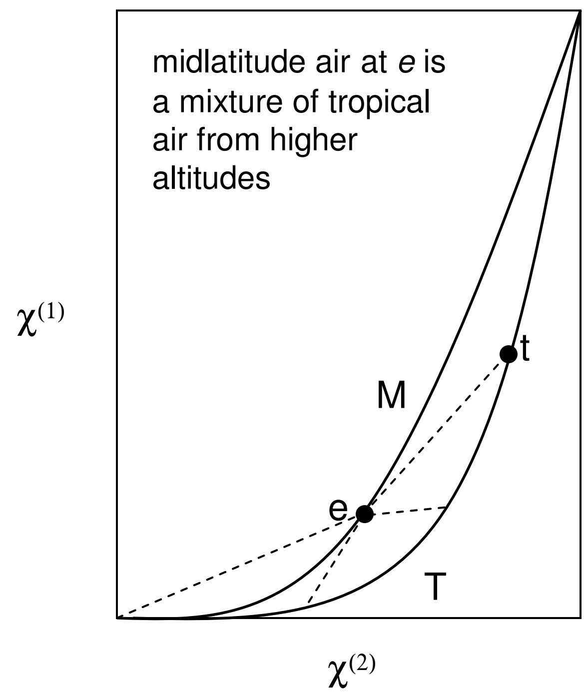
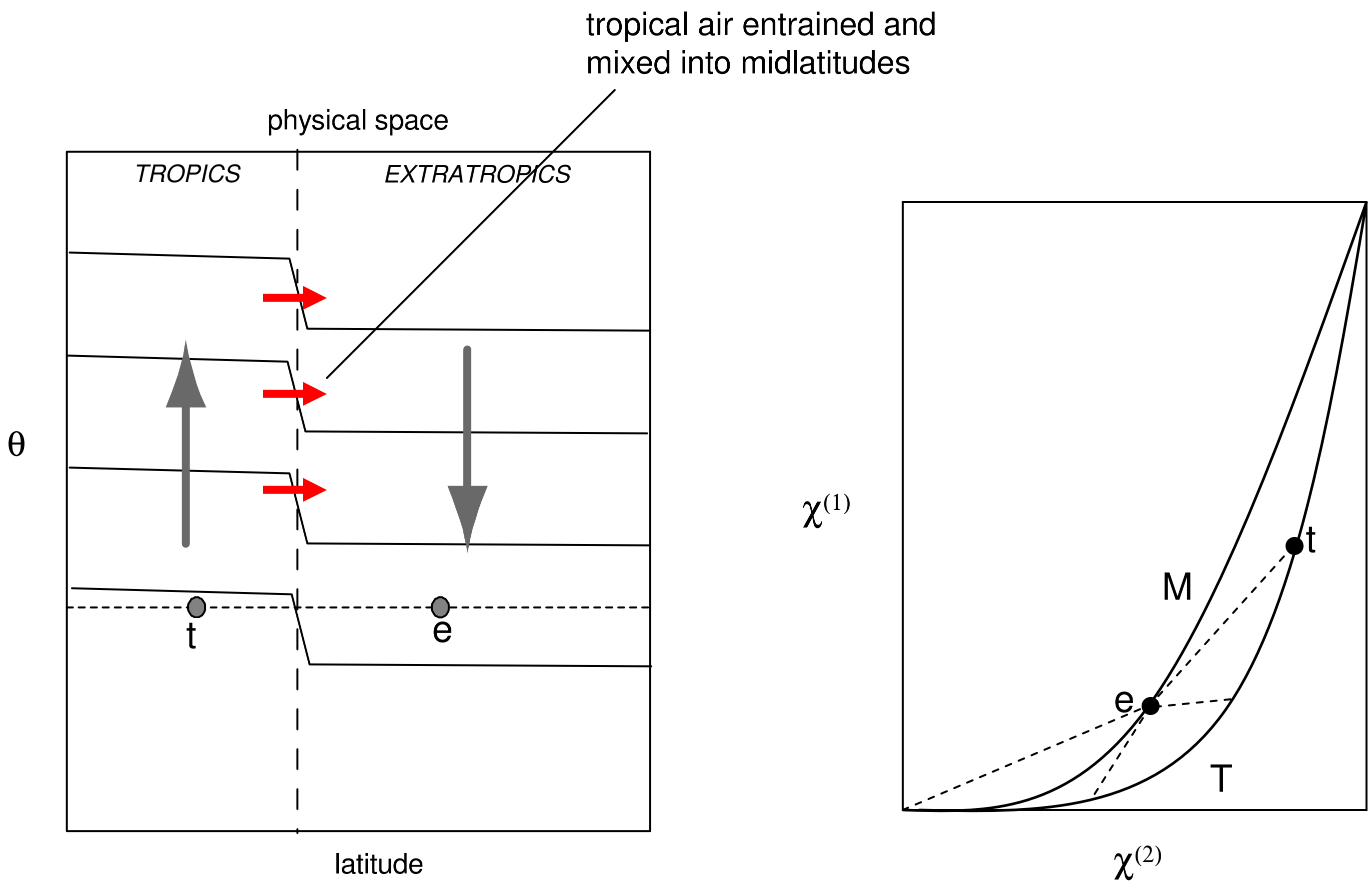
Creation of midlatitude relationships



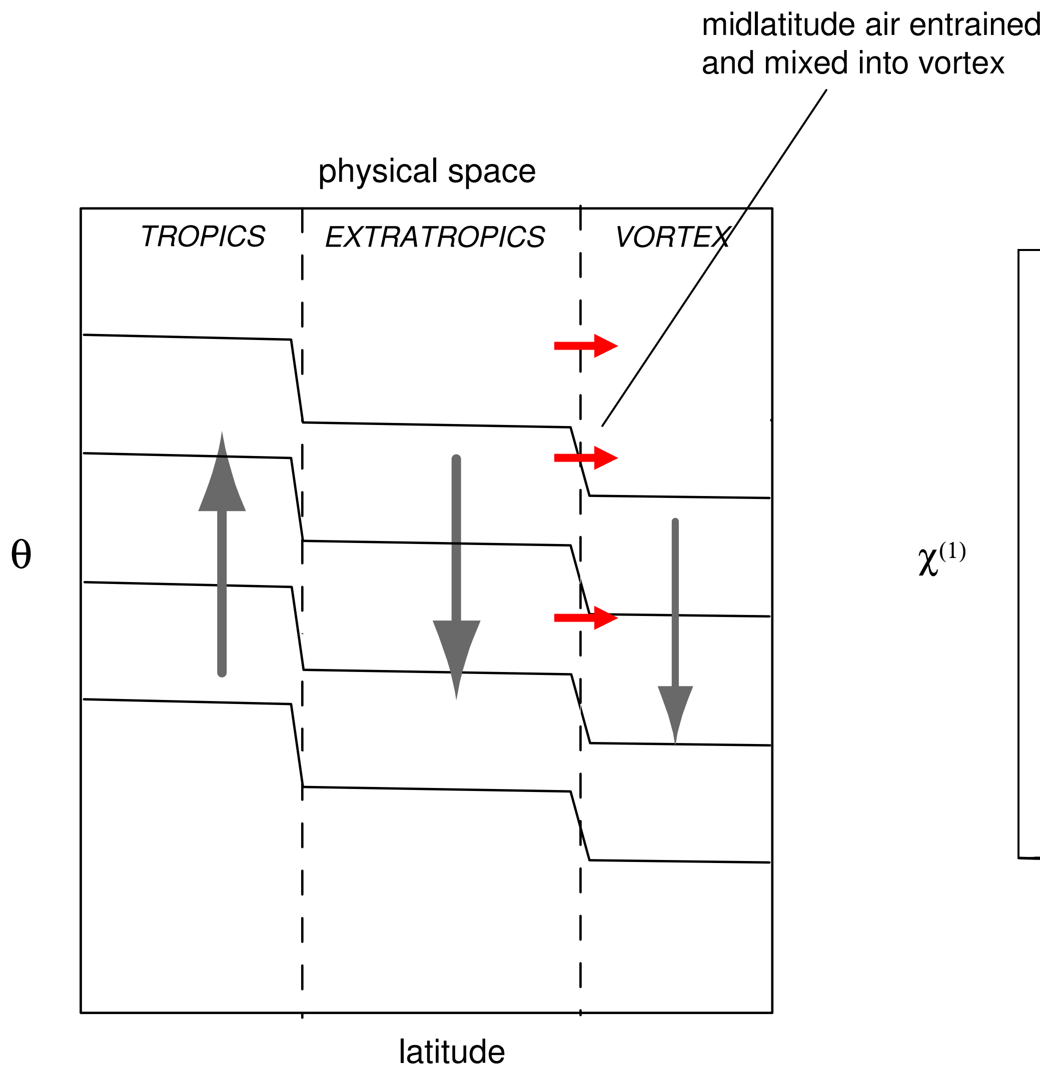


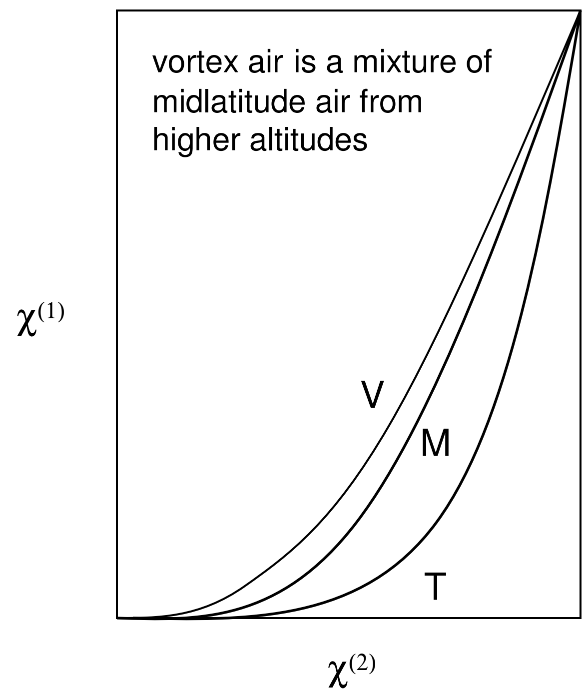
Creation of midlatitude relationships



→ midlatitude curve lies on concave side of tropical curve

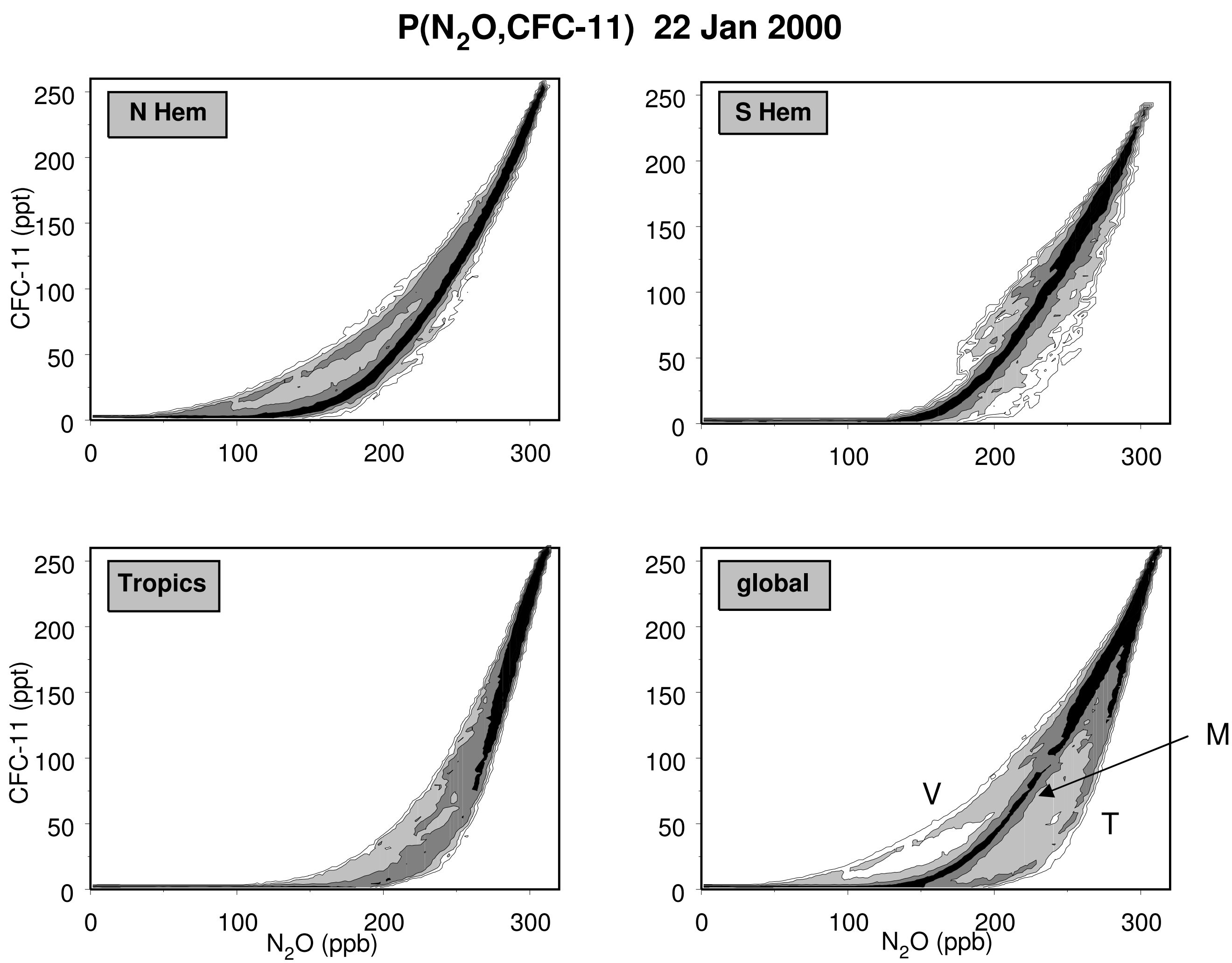
Creation of vortex relationships





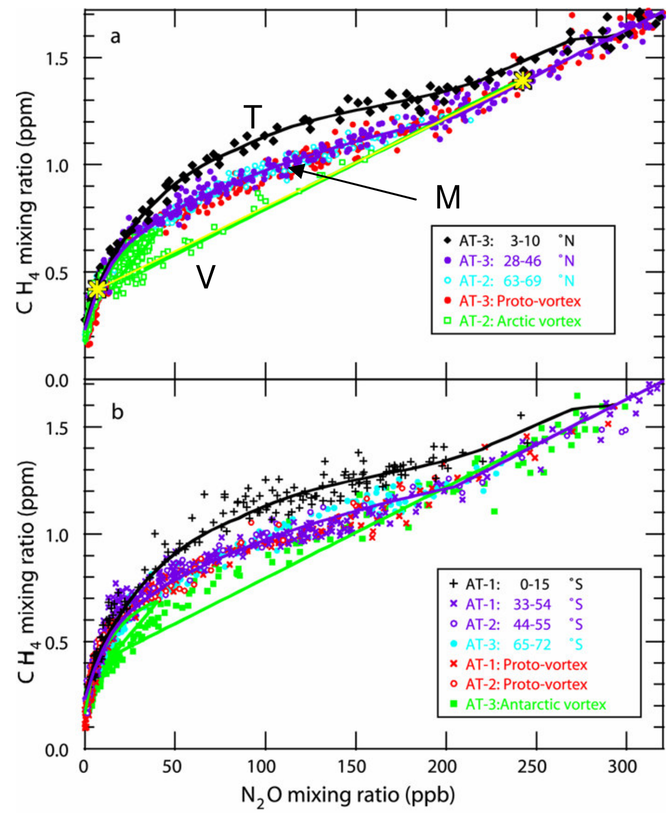
→ vortex curve lies on concave side of midlatitude curve

from chemical transport model
[Plumb et al., *J Geophys Res*, 2002]



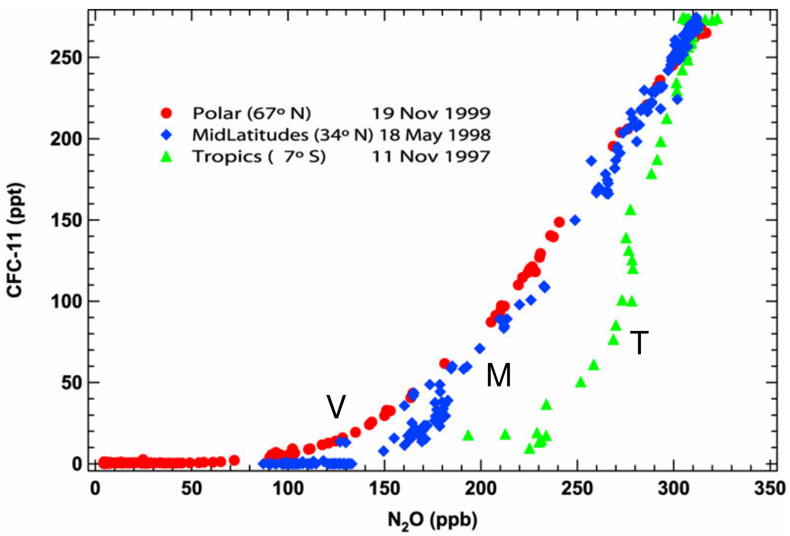
Different relationships in different regions

Space-based data (ATMOS)
CH_4 : N2O



Michelsen et al, *J Geophys Res*, 1998]

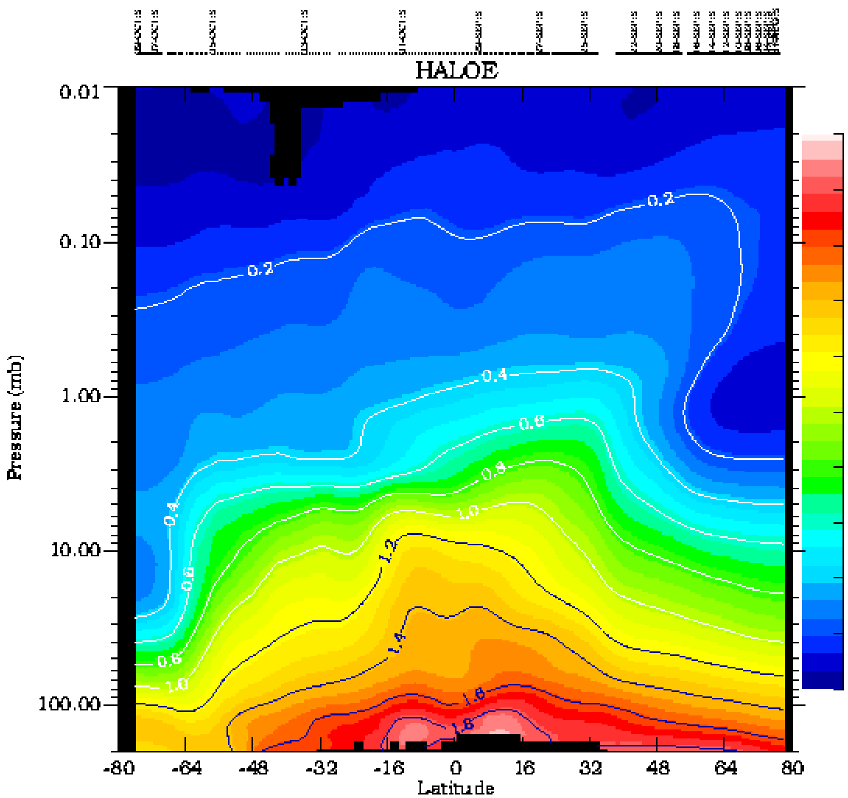
In situ balloon data (LACE, Elkins/Moore)
CFC-11 : N_2O



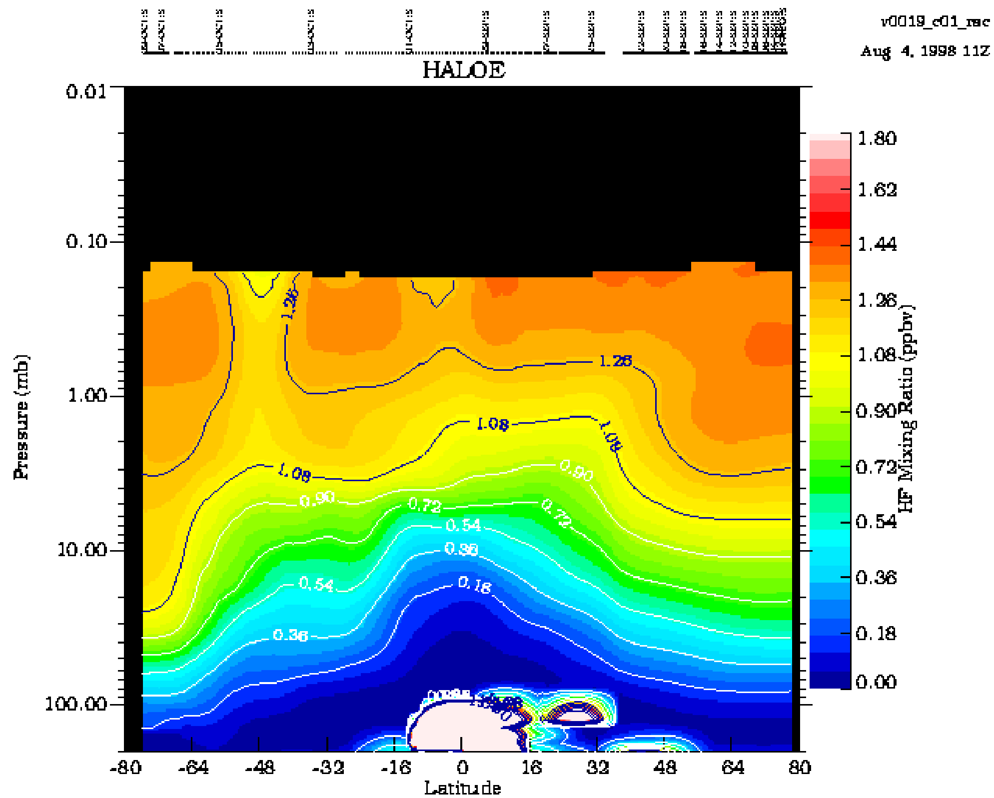
[Plumb, *Rev Geophys*, 2007]

HALOE data

[Russell et al, *J Geophys Res*, 1993]



CH_4 dV Pressure vs Latitude
Sunset 31-AUG to 10-OCT-1993



HF Pressure vs Latitude
Sunset 31-AUG to 10-OCT-1993

CH_4

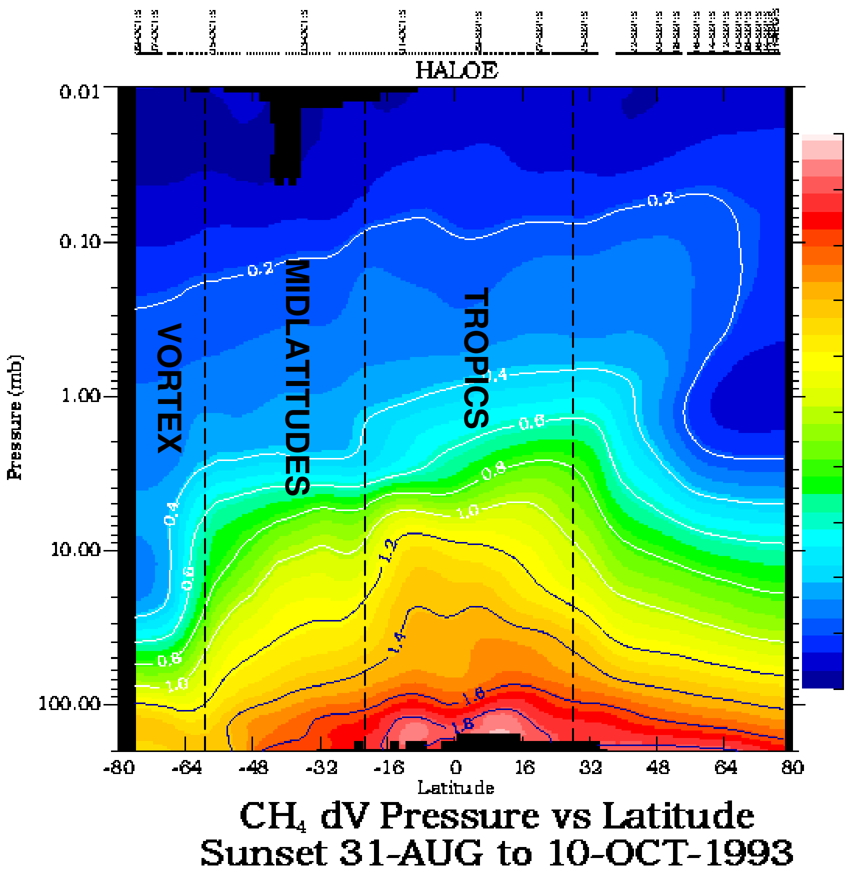
tropospheric source
stratospheric sink

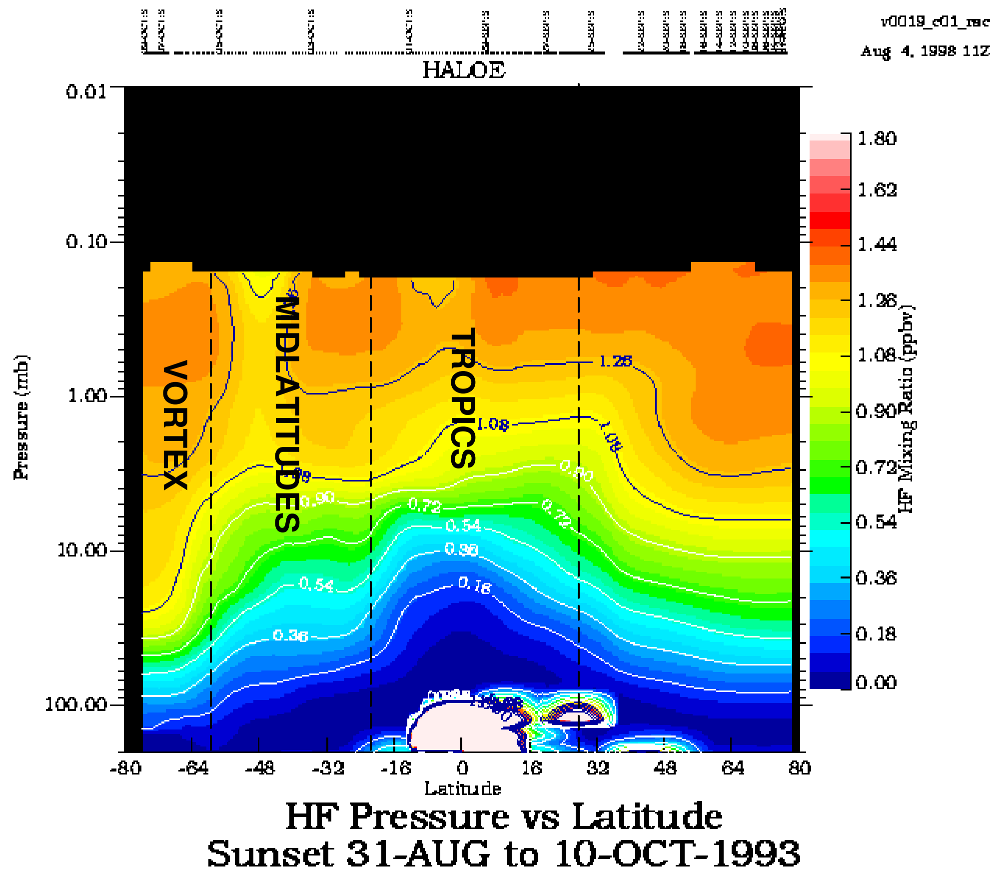
HF

stratospheric source
tropospheric sink

HALOE data

[Russell et al, *J Geophys Res*, 1993]





CH_4

tropospheric source
stratospheric sink

HF

stratospheric source
tropospheric sink

References

- Andrews et al, 2001: Mean ages of stratospheric air derived from in situ observations of CO2, CH4, and N2O, J.Geophys Res, 106, 32295-32314
- Engel et al, 2008: Age of stratospheric air unchanged within uncertainties over the past 30 years,
- N. Geosci., 14, 28-31
- Garcia and Randel, 2008: Acceleration of the Brewer?Dobson Circulation due to Increases in Greenhouse Gases, J. Atmos. Sci., 65, 2731-2739.
- Haynes and Shuckburgh, 2002: Effective diffusivity as a diagnostic of atmospherictransport 1. Stratosphere, J. Atmos. Sci., 105, 22777-22794.
- Michelsen et al, 1998: Correlations of stratospheric abundances of NOy, 03, NO, and CH 4 derived from ATMOS measurements, J. Geophys. Res., 03, 28347-28359.

References

- Russell et al,1993: THE HALOGEN OCCULTATION EXPERIMENT, J. Geophys. Res., 98, 10777-10797
- Plumb et al., 2002: Global tracer modeling during SOLVE: High-latitude descent and mixing, J. Geophys. Res., 108, 14 pp.
- Plumb, R. A., 2007: Tracer interrelationships in the stratosphere, Rev. Geophys., 45, 33 pp.
- NCEP, http://www.ncep.noaa.gov/