On the Permeability of the Extratropical Tropopause

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Contents

- Introduction
- MLS CO in “tropopause coordinates”
- The subtropical jet
- Static stability
- Averaging kernel effect
- Summary

Introduction: Tropopause definitions

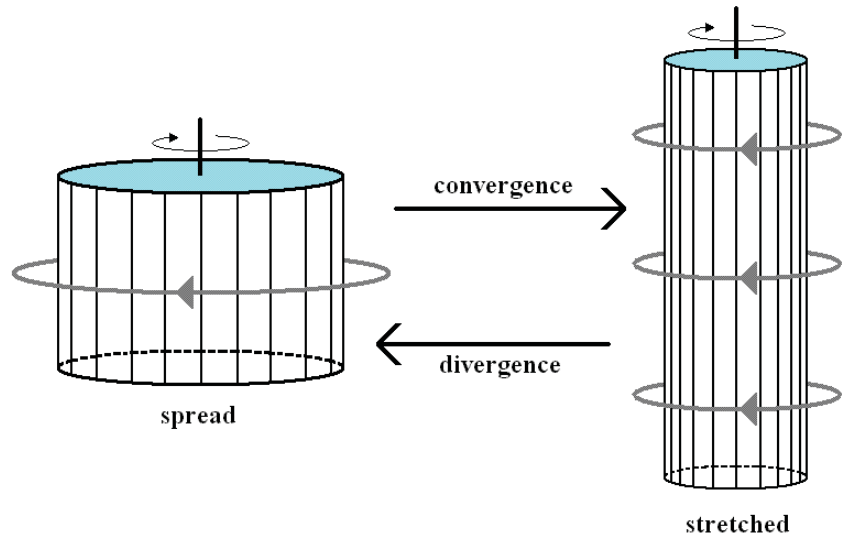
- **Traditional definitions**
  - Thermal tropopause: The lowest level at which the lapse rate decreases to 2 °C/km or less, provided that the average lapse rate between this level and all higher levels within 2 km does not exceed 2 °C/km (WMO).
  - Dynamical tropopause (Potential verticity, i.e. 2 PVU, or 3.5 PVU;

    1 PVU = 10^{-6} K m^2 kg^{-1} s^{-1})
  - Chemical tropopause: 200 ppbv ozone surface.
- **New definitions**
  - PV gradient tropopause (Kunz et al., 2011): the equivalent latitude of maximum PV gradient on an isentropic surface.
  - Chemical tracer e90 (Prather et al., 2011): An artificial model tracer with surface sources and 90 day decay time, as the tropopause.
  - *Subtropical and polar jet coordinates (Manney et al., 2011)*: Re-locate obs. relative to jet latitude and altitude.

PV and Equivalent Latitudes

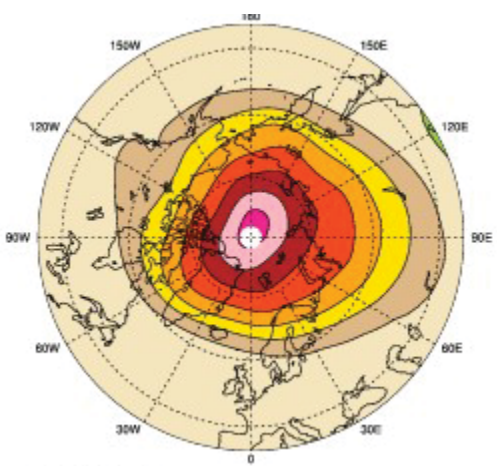
Potential Vorticity (PV), conserved in adiabatic and frictionless process.

$$\mathrm{PV} = \frac{1}{\rho}\zeta^{a} \cdot \nabla\theta$$

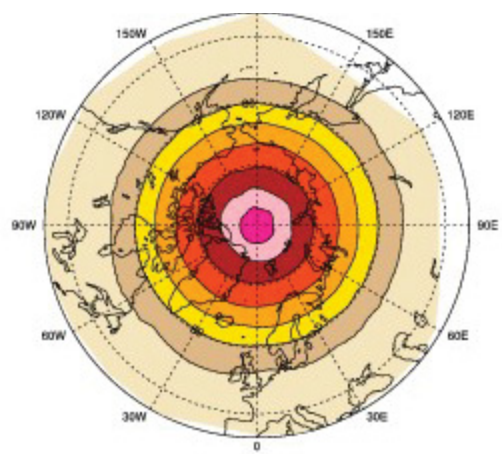


(From Wiki)

PV in geographical Lat at 600 K.

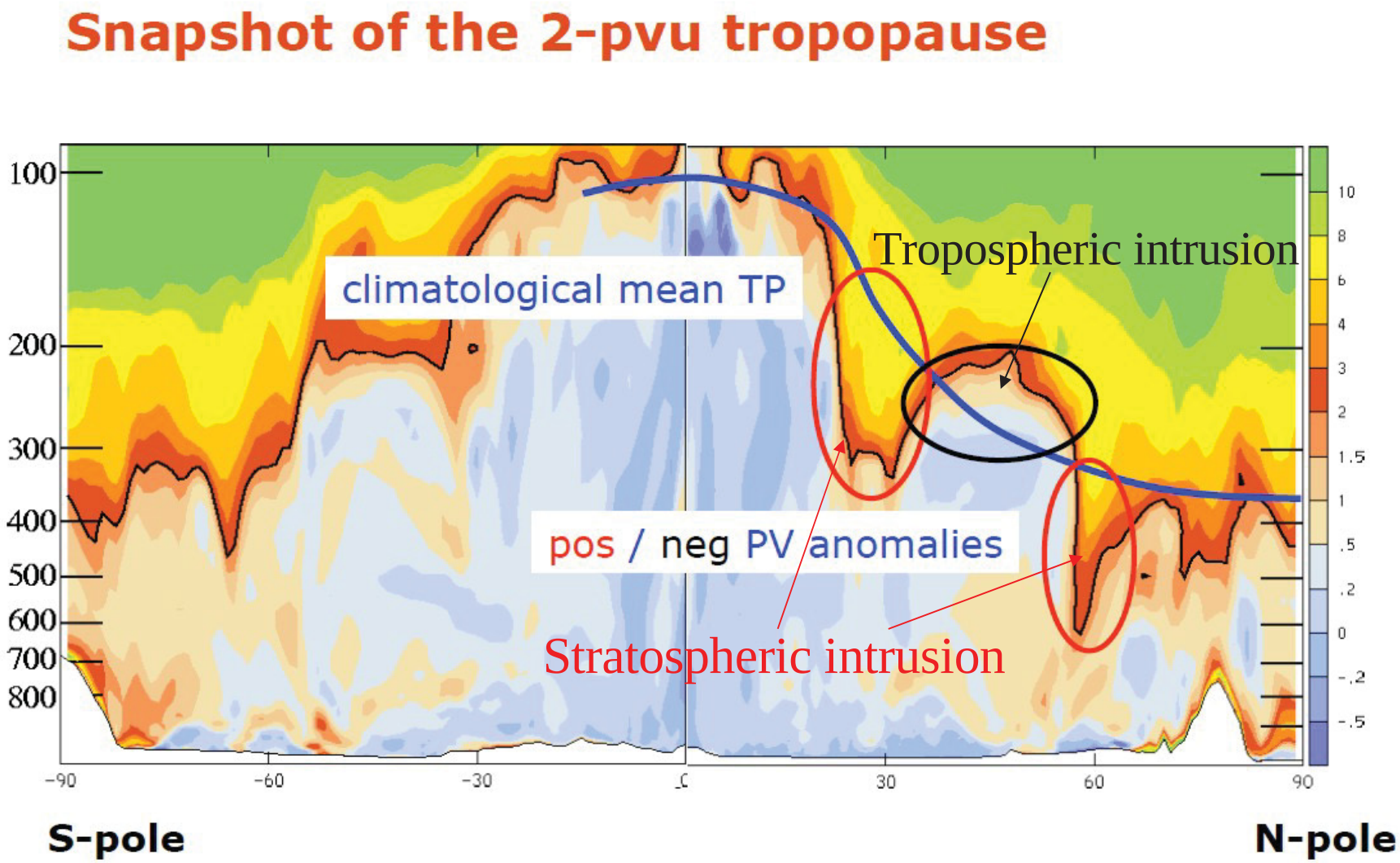


PV in Equivalent Lat (EqL) at 600 K



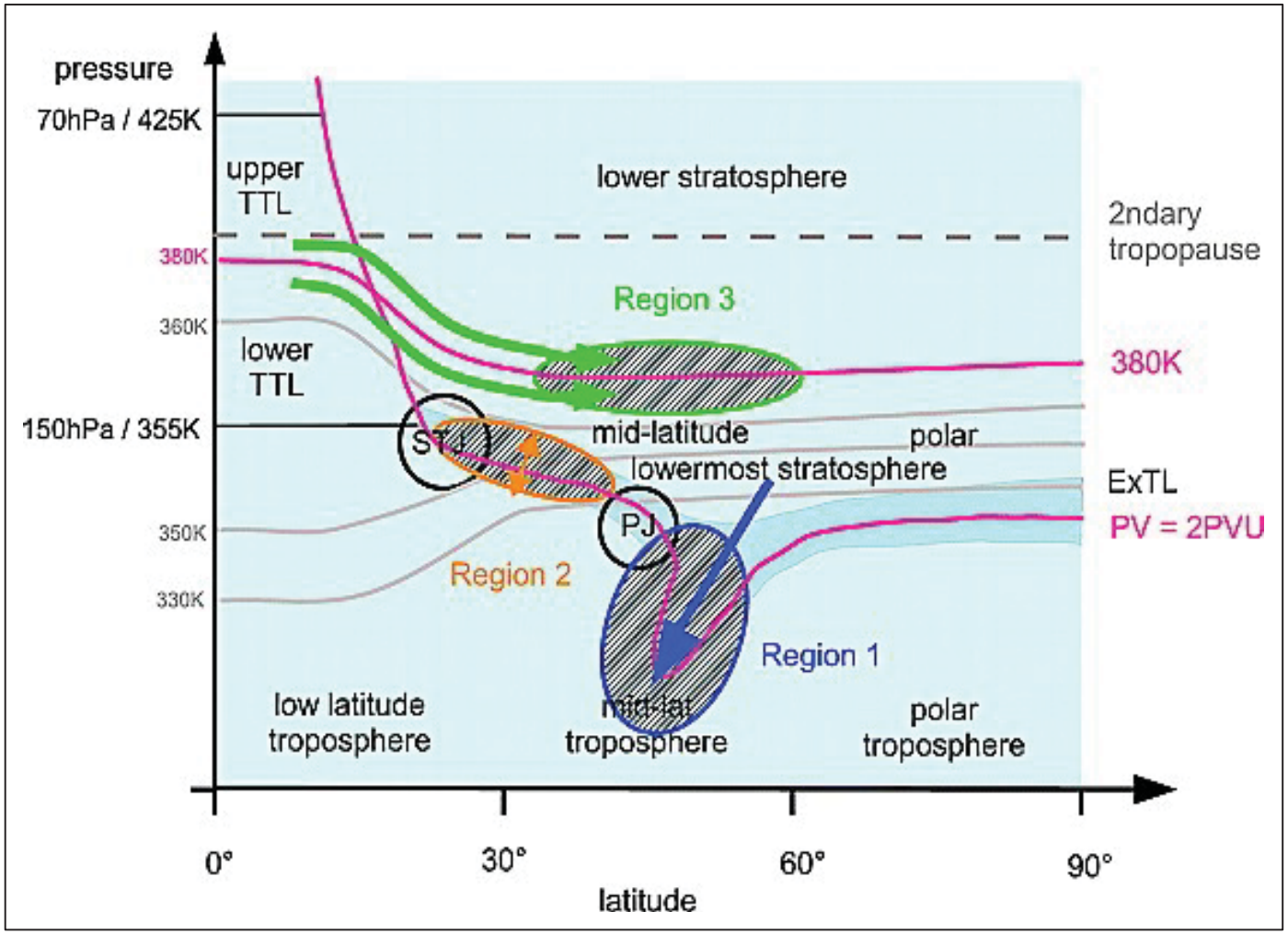
(http://www.ncl.ucar.edu/Applications/equiv_lat.shtml)

Introduction: PV and tropopause



(Courtesy of Heini Wernli, ETH, 2005)

Introduction: STE processes

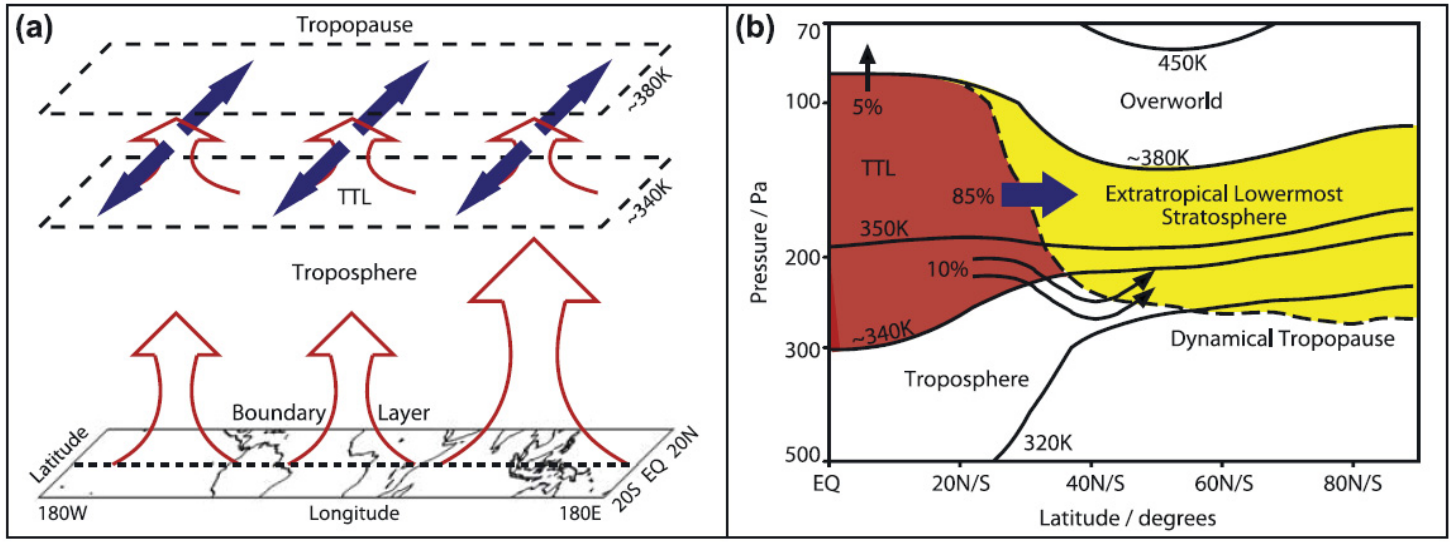


(Vogel, B., et al., 2011, JGR)

Introduction: Current studies

- Many studies have shown there is a “mixing layer” at the tropopause.
- Aircraft and ozonesonde measurements show there is a sharp vertical gradient of chemical species' (i.e. O3 and CO) VMRs at the tropopause.
- SPURT campaign measurements show strong meridional gradient of the VMRs at the tropopause.
- However, studies also demonstrated horizontal or isentropical Stratosphere-Troposphere Exchange (STE) and the seasonal variation of it.
  - A few studies also show tropospheric air pollution tracers (i.e, CO) is transported along isentropical surface into the lower-most stratosphere (LMS).

Troposphere-towards-Stratosphere Transport (TST)



(Levine et al., 2007, JGR)

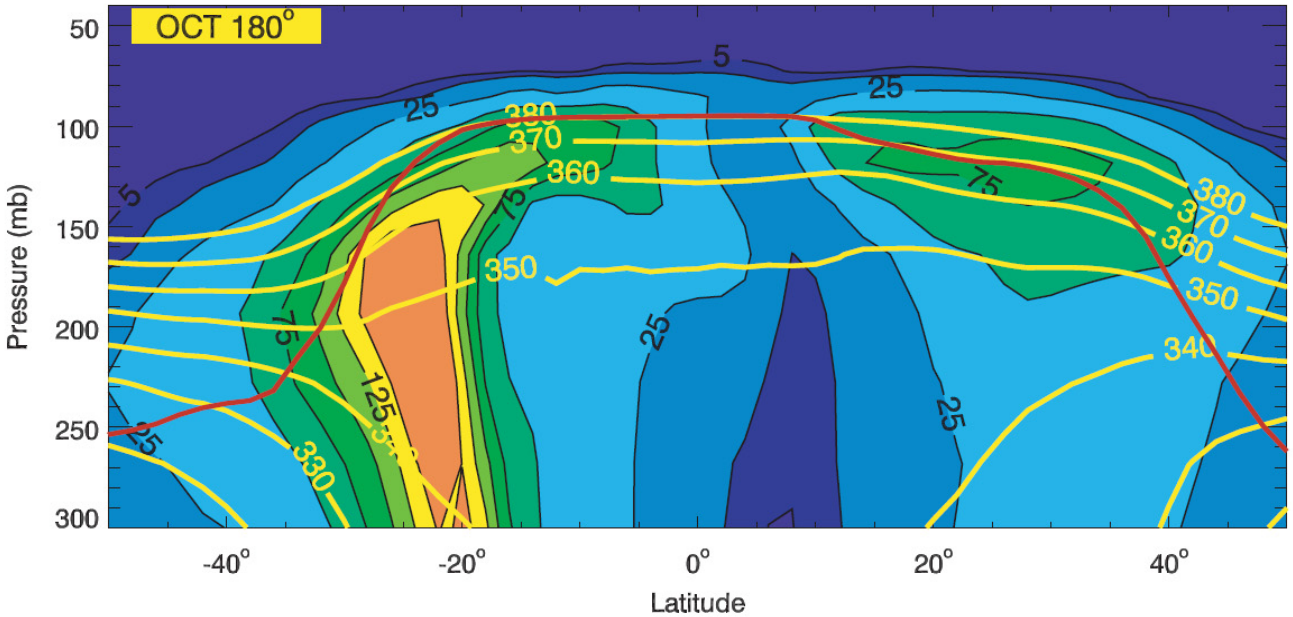
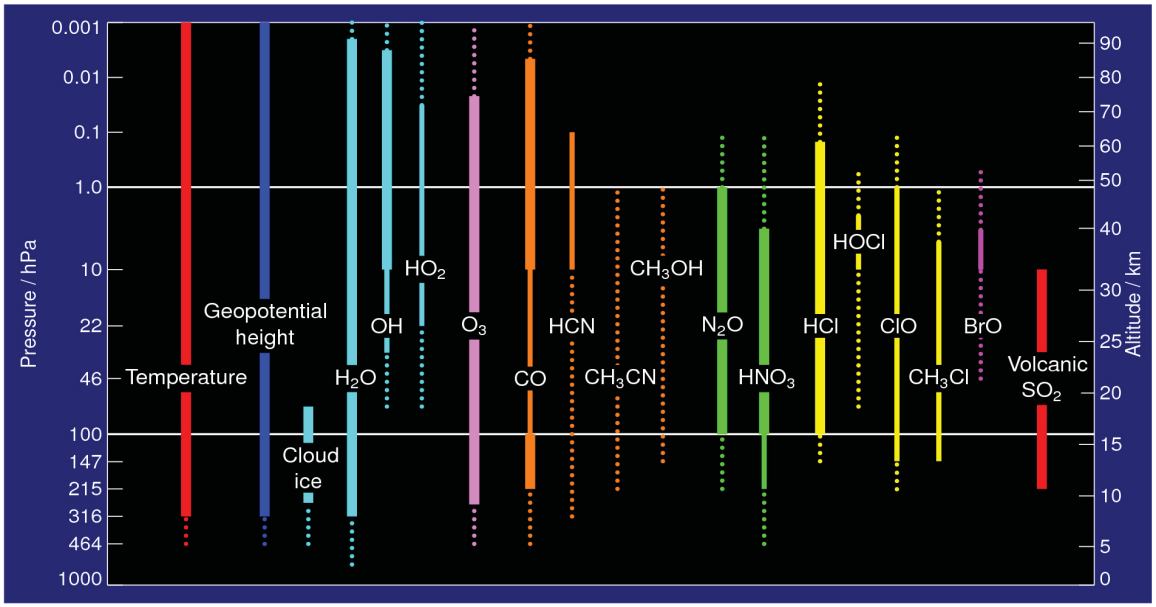


Fig. 8. The monthly-averaged CO perturbation (%) at 180° longitude in October 1997 caused by the Indonesian fires. Potential temperatures (K) are shown as yellow lines. The monthly-averaged tropopause is shown as a red line. The contours are 5, 10, 25, 50, 75, 100, 125, and 150%.

(Duncan et al., 2007, ACP)

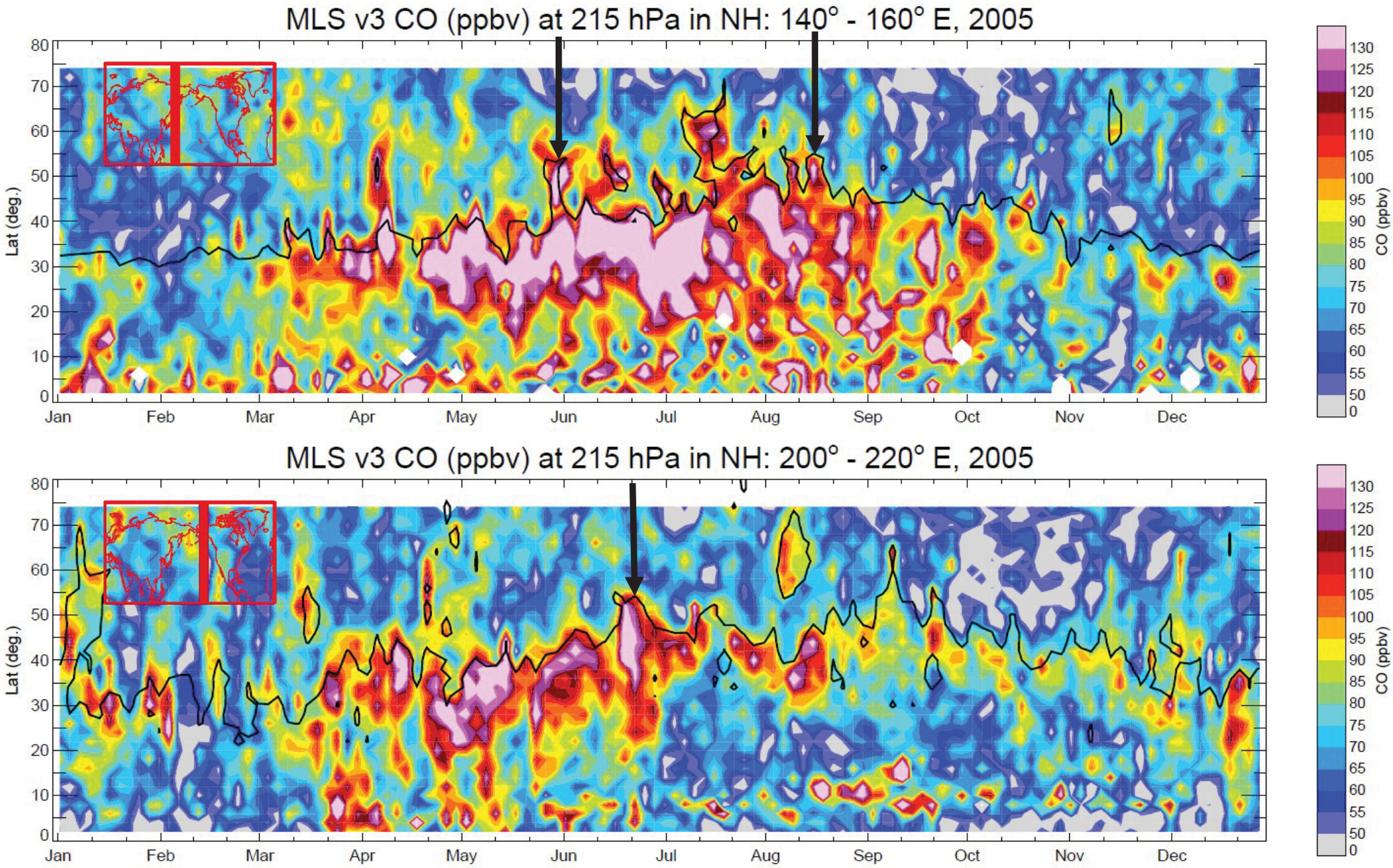
Introduction: MLS data

- MLS V3.3 carbon monoxide CO (chemical lifetime is ~ 2 months, so CO is a good tracer.)
- Tropopause – GMAO 3.5 PVU
- PV is taken from MLS (v3) Derived Meteorological Products (DMP) dataset

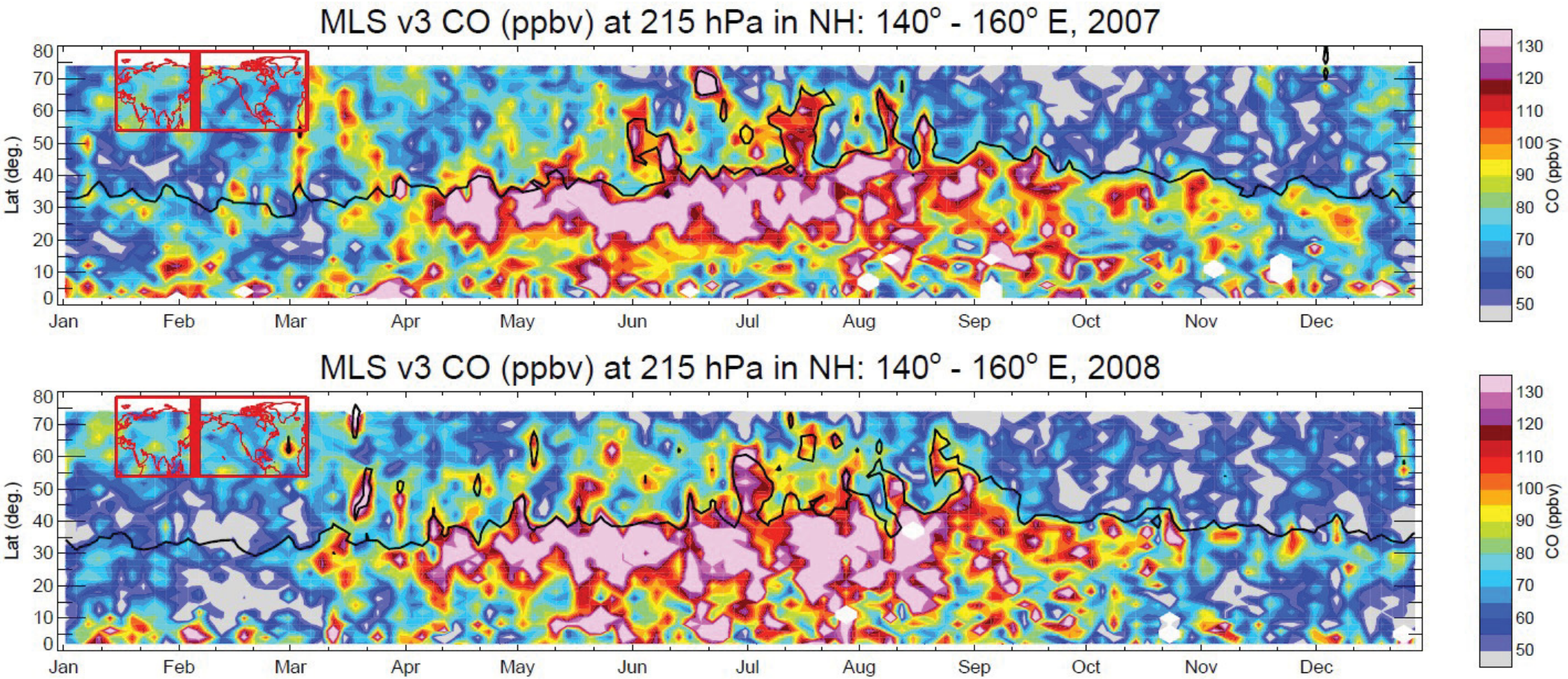


MLS CO, 2005

(tropopause (3.5 PVU) in black)



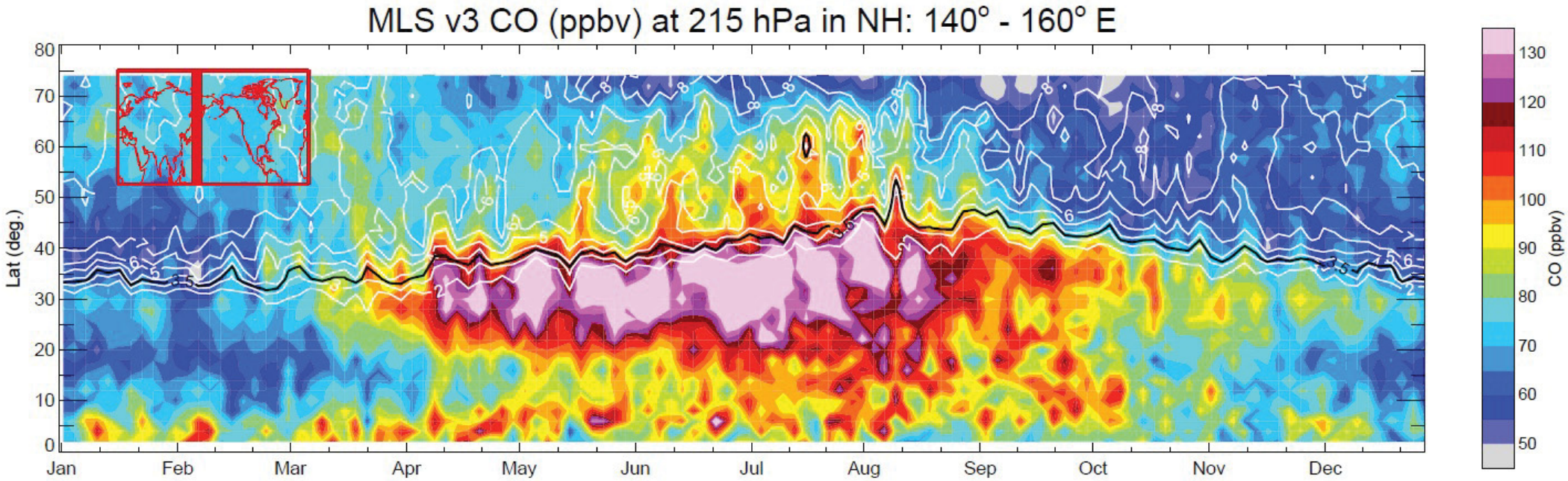
MLS CO at 140-160E in 2007 and 2008

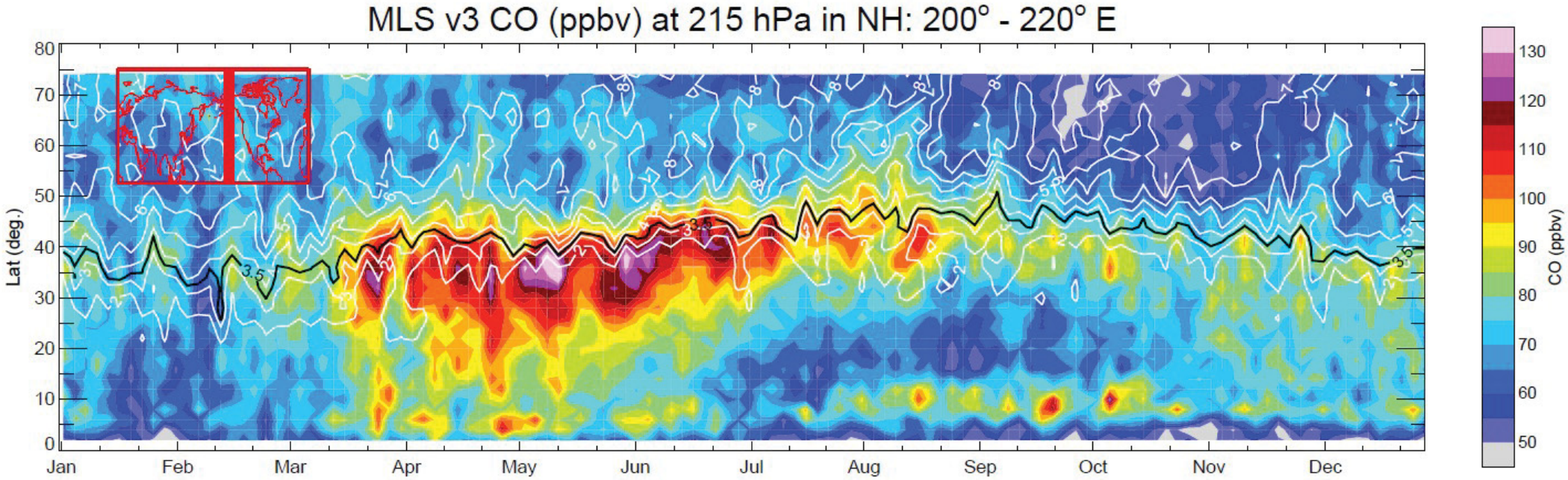


- Common feature of strong meridional gradient in MLS observations.

MLS CO, 2004-2010

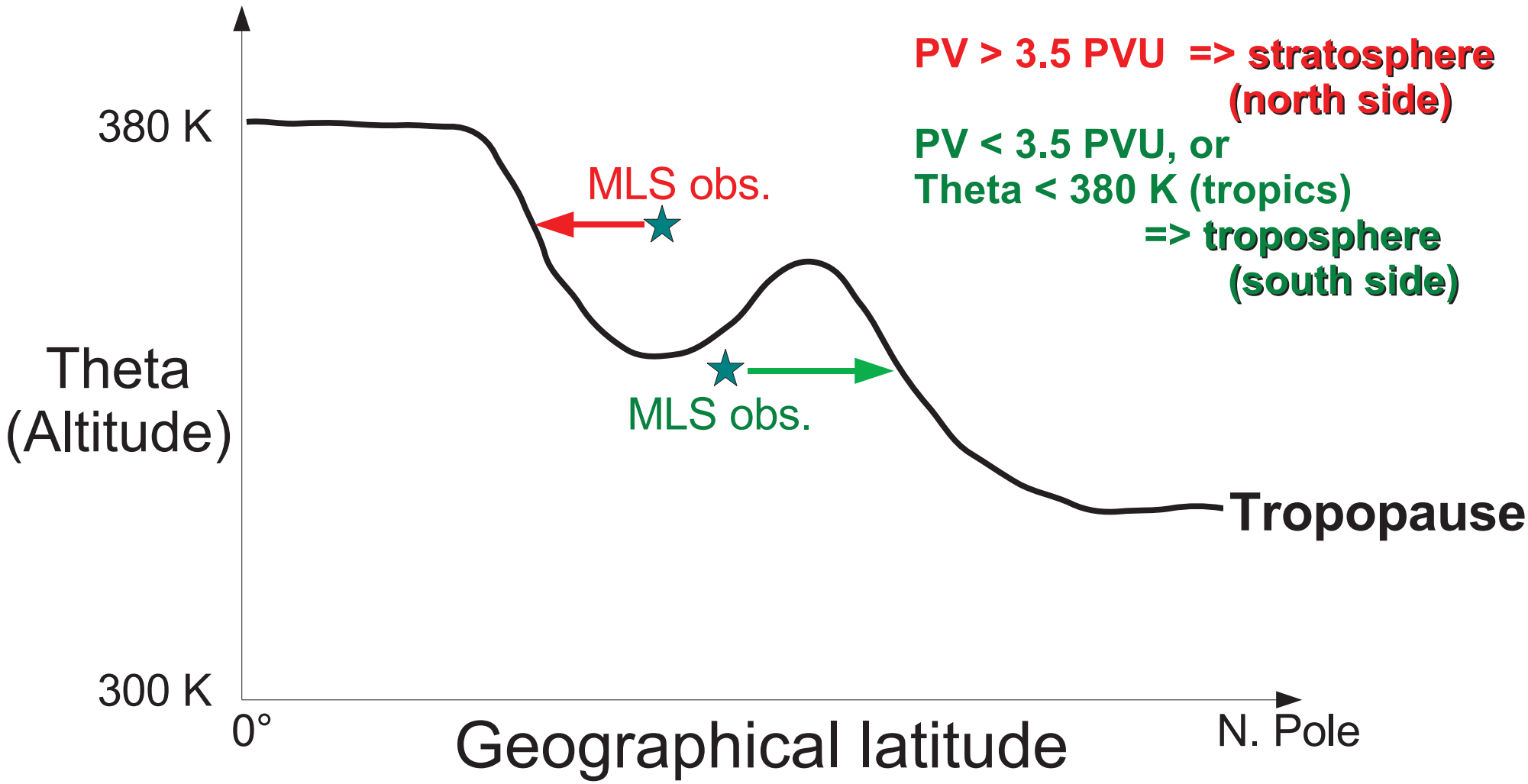
(PV in white, tropopause (3.5 PVU) in black)





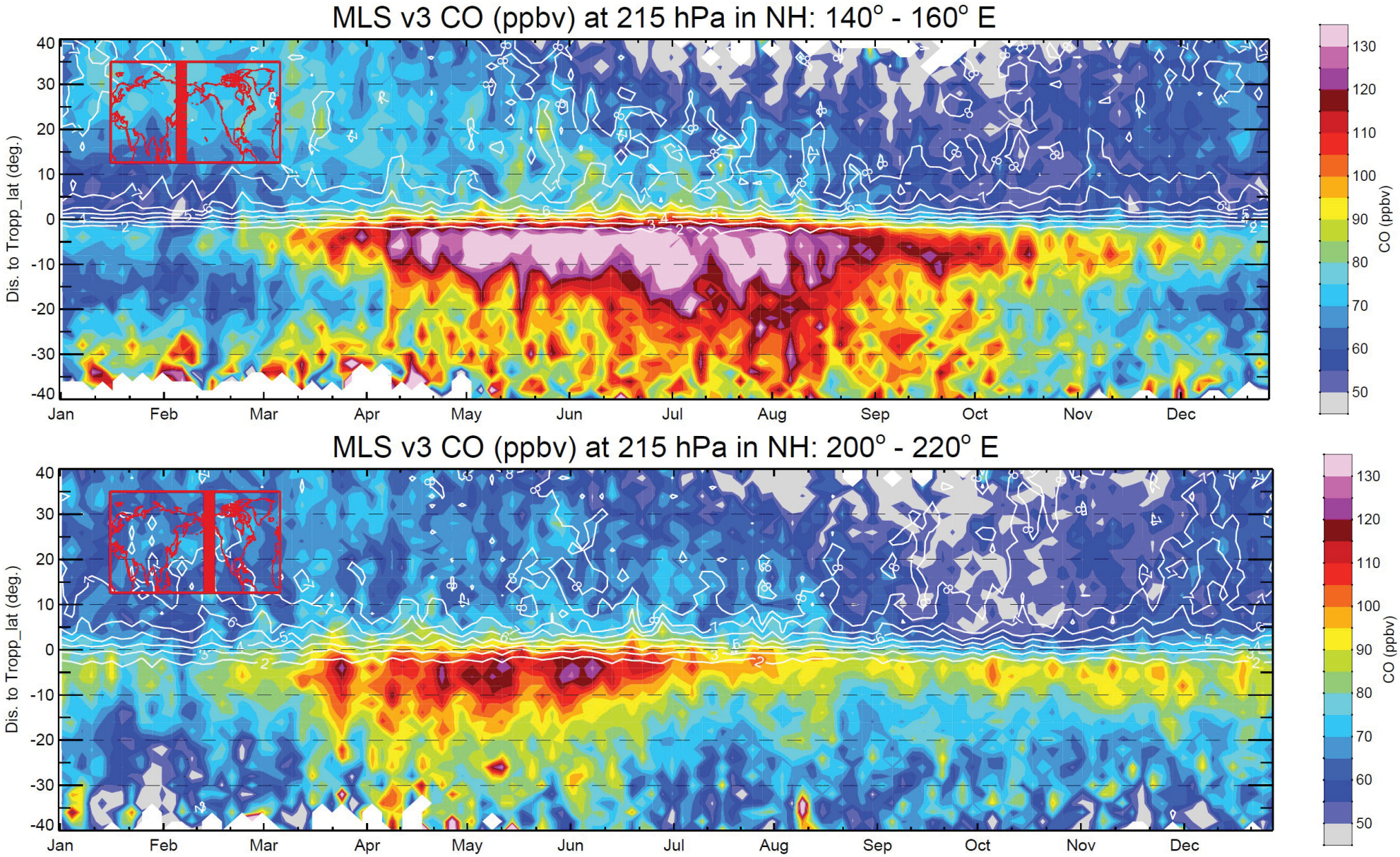
“Tropopause Coordinates”:

Relative distance to the latitude of the tropopause.



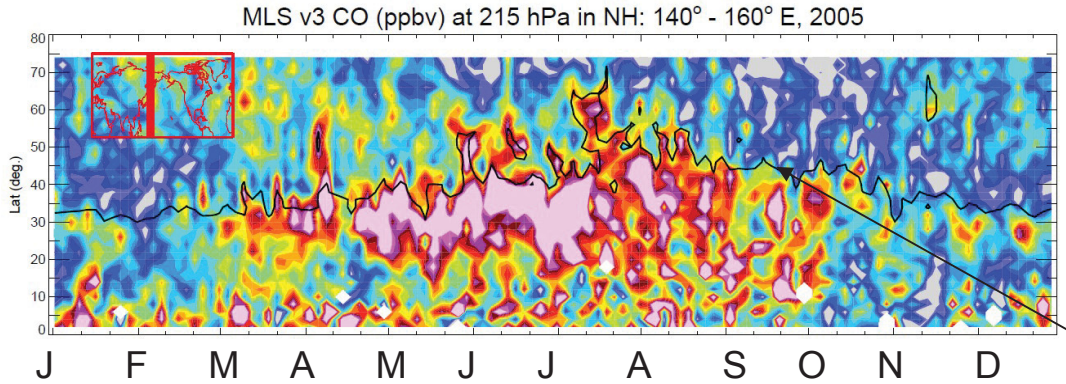
MLS CO in “tropopause coordinate” in NH

(PV in white; 2004-2010)

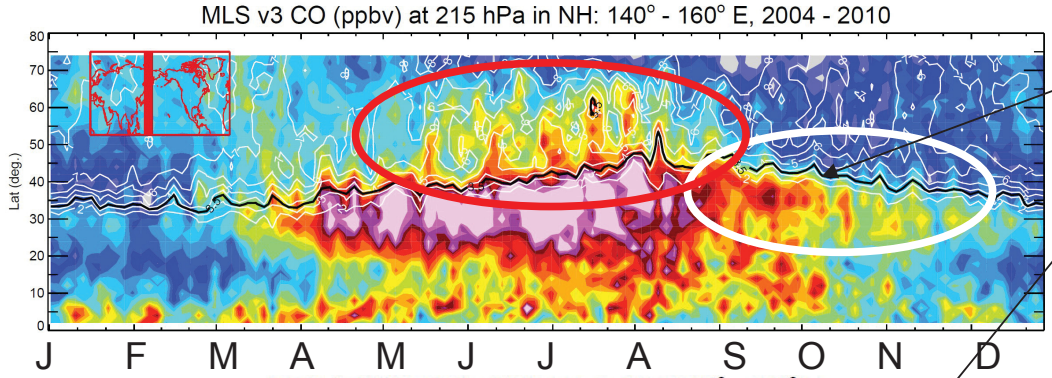


MLS v3 CO at 215 hPa at ~150° E in NH

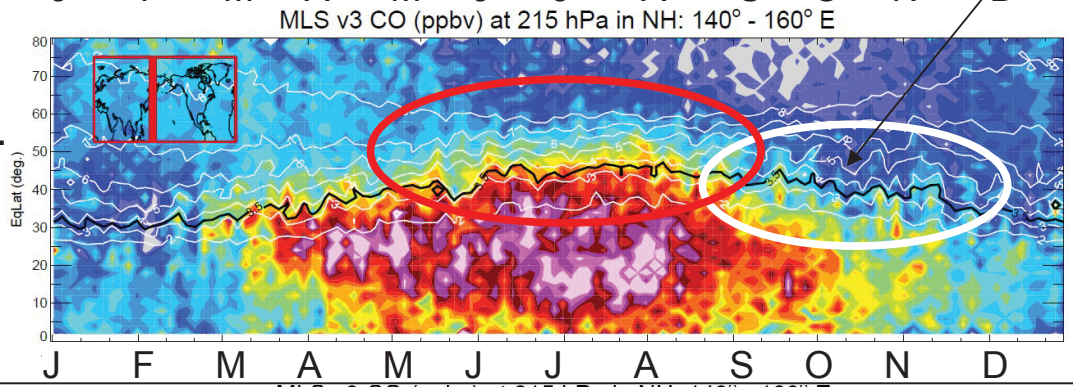
Lat. (0~90° N) 2006



Lat. (0~90° N) 2004-2010



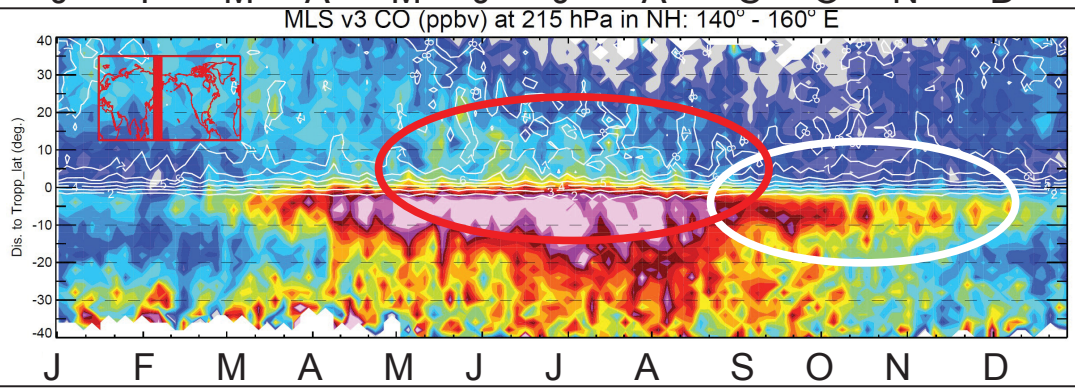
Equivalent Lat. (0~90° N) 2004-2010



Black: 3.5 PVU tropopause

White, potential vorticity (PV) contours, which controls transport and is a dynamical tracer.

"Tropopause coordinate" (-40°~ 40°, Lat) 2004-2010



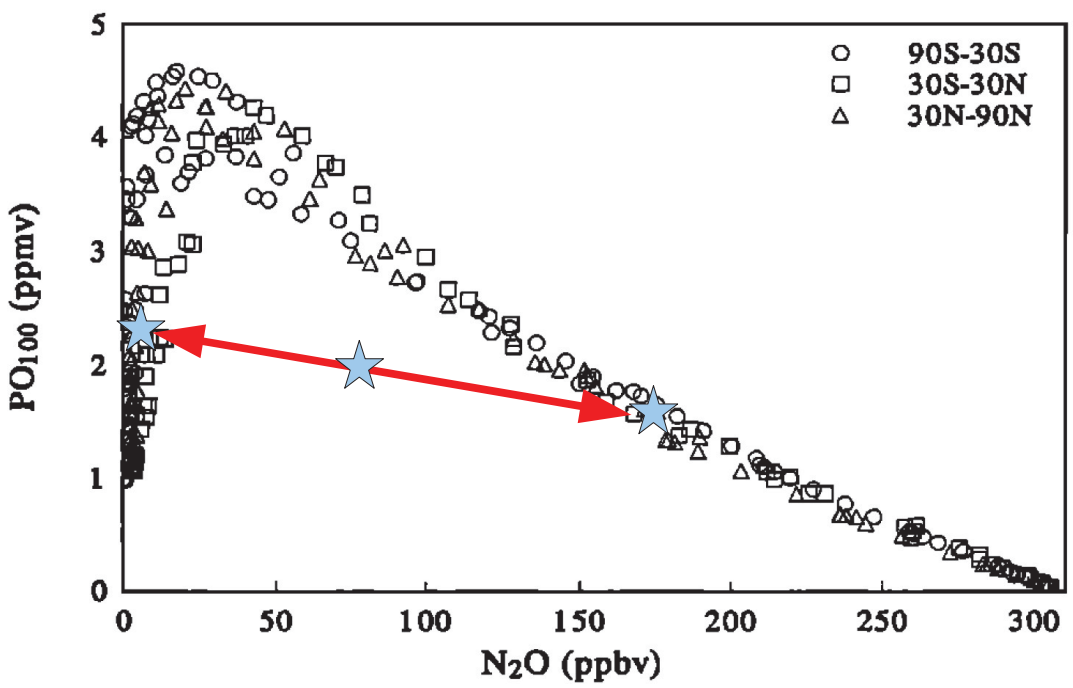
Tropopause => 0°, Lat

PV > 3.5 PVU => stratosphere (north side)

PV < 3.5 PVU, or Theta < 380 K (20° S – 20° N) => troposphere (south side)

Why is the "popular" EqLat not a good tool here?

- Explanation-1: The EqLat for the tropopause does not change with longitudes, but changes with time.
- *Explanation-2: Regarding PV (EqLat) as a conservative dynamical tracer, the correlation between PV and CO changes after mixing (averaging) because of their non-linear relation. (Note, Sine PV is not conserved tracer in UT, this is not a correct explanation. JJJ, June 13, 2011).*

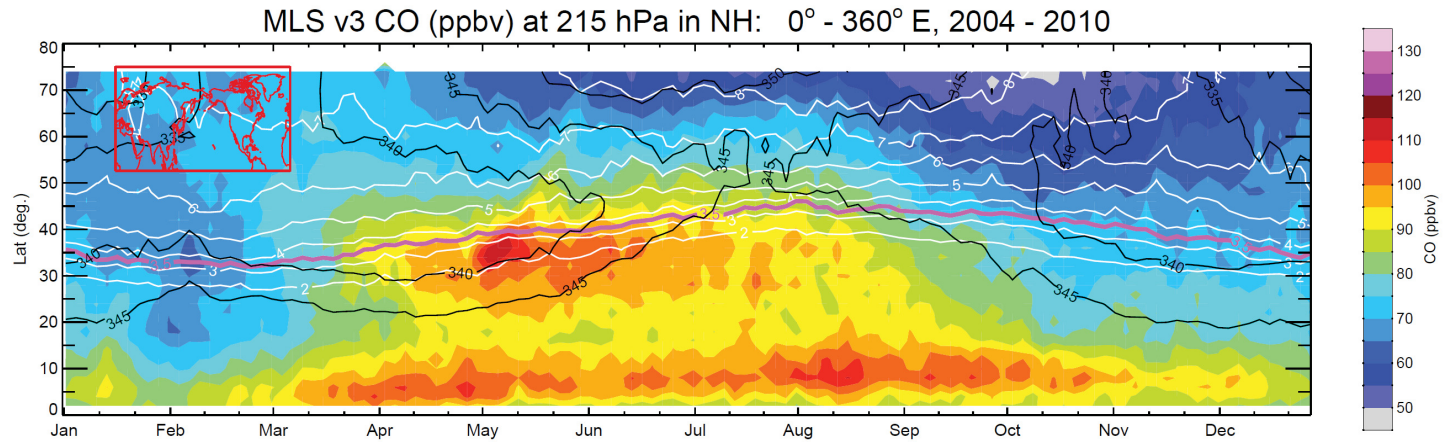


(Plumb and Ko, 1992, JGR)

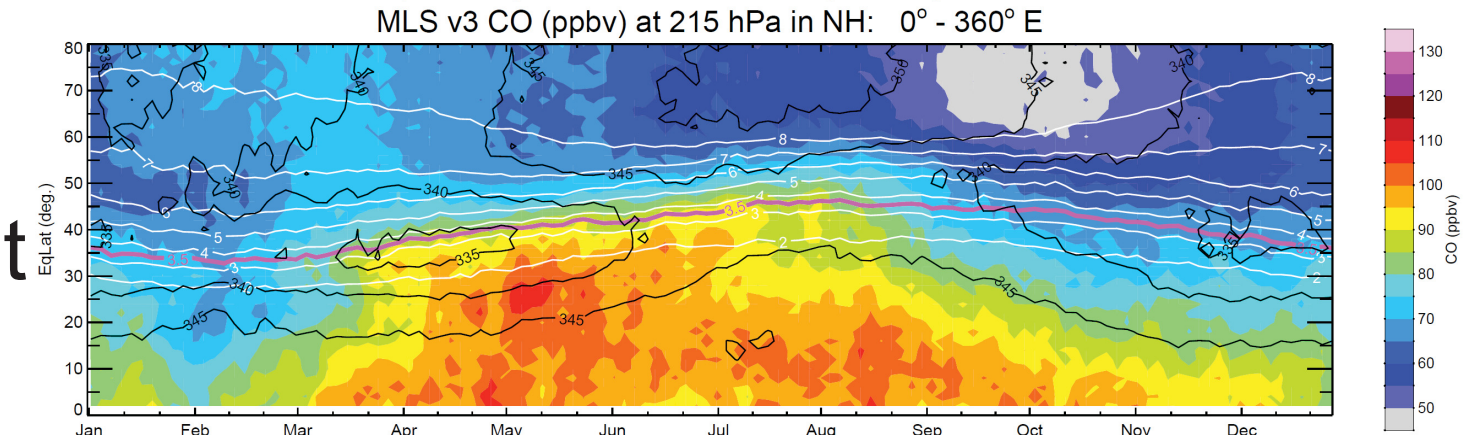
NH Zonal mean, 2004-2010

(tropopause in thick pink, PV in white, theta (K) in black)

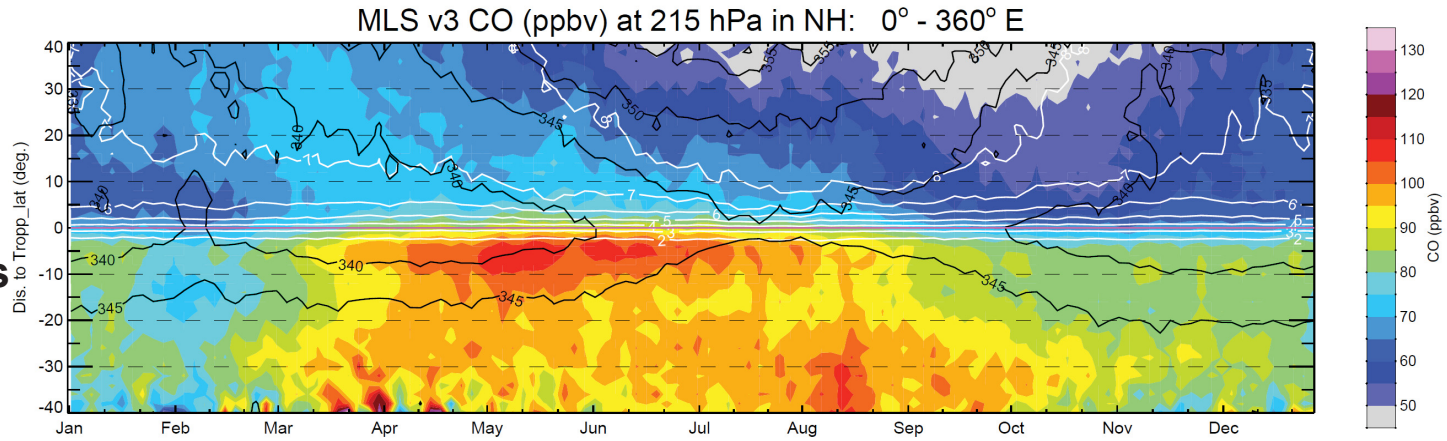
Lat



EqLat



Tropopause coordinates



Vertical distribution of CO made at 215-147 hPa

Zonal mean

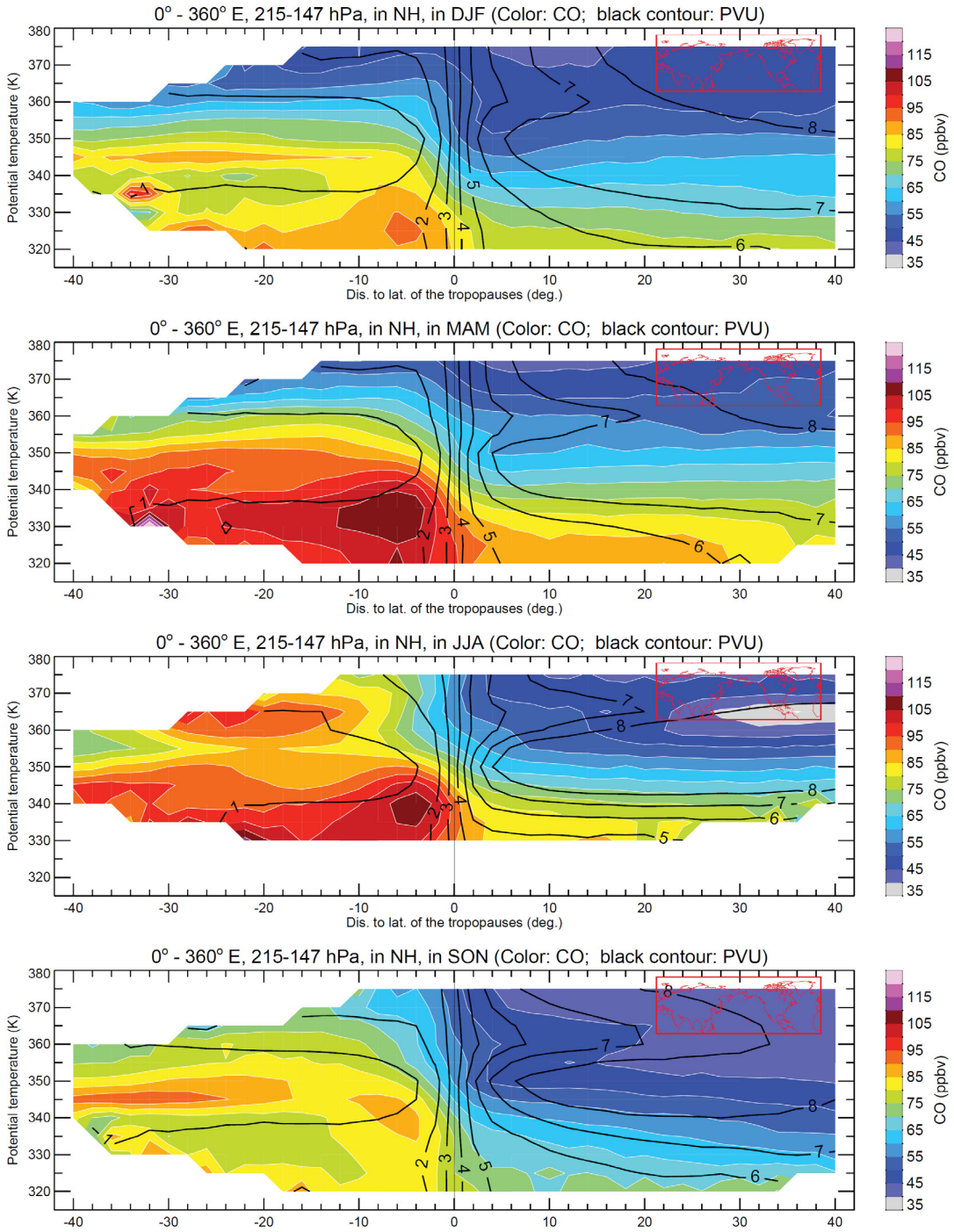
DJF

MAM

JJA

SON

Potential Temperature (K)



Black contours, PV

Strong CO and PV horizontal gradients are between 330 – 350 K.

Distance to the Lat of tropopause (deg)

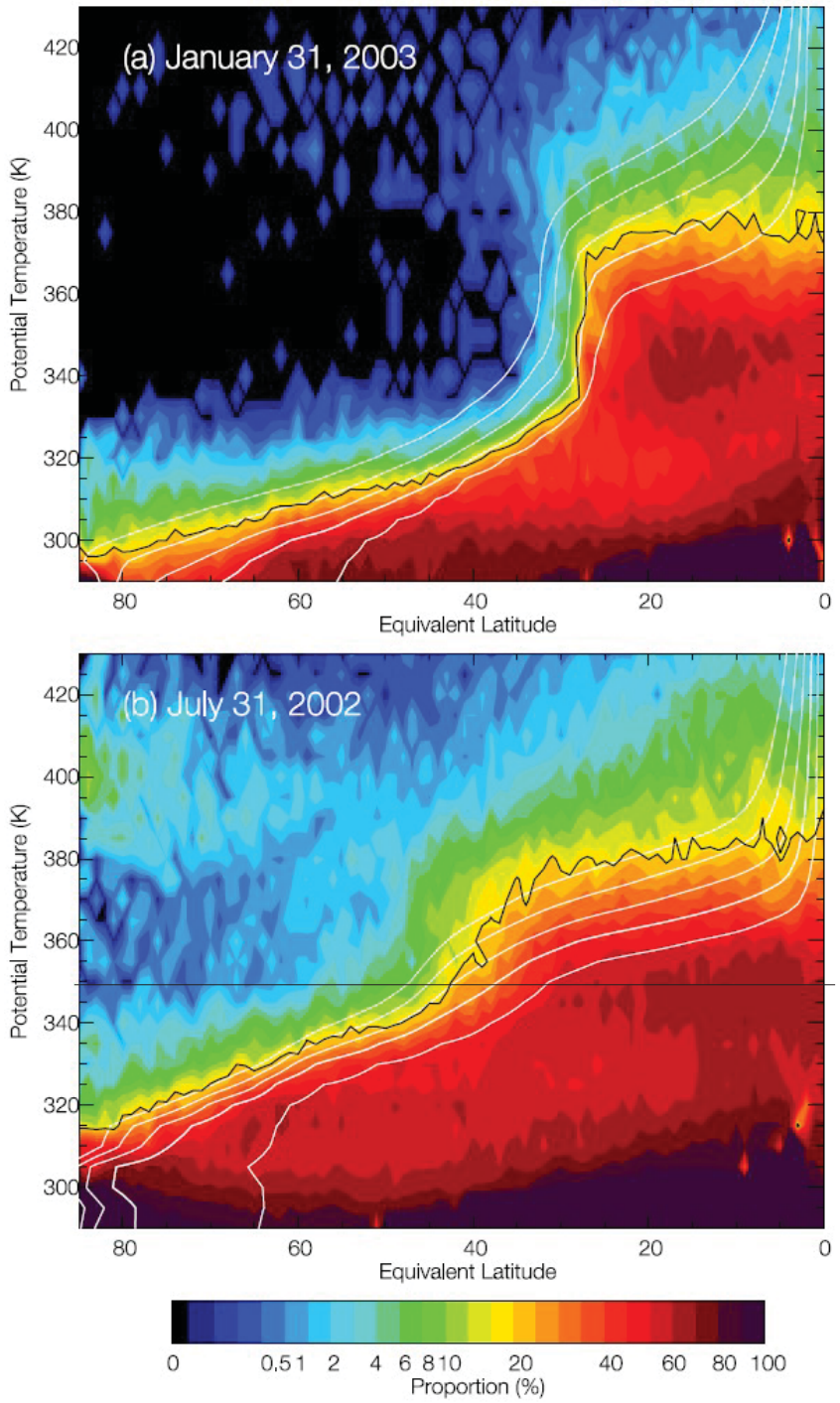


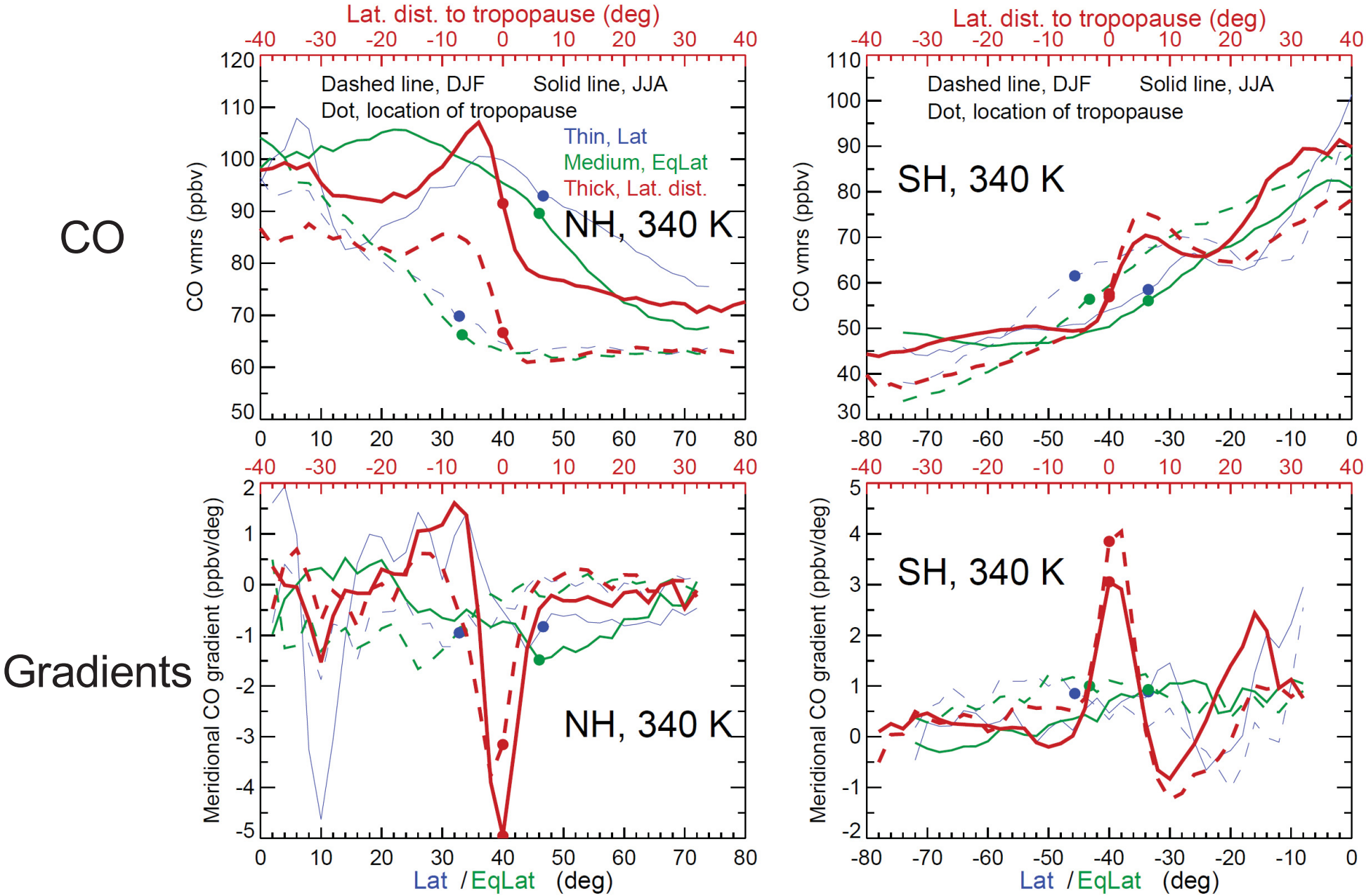
Figure 2. Color contour plot of $X_{BL}(\varphi_e, \theta)$, the proportion of trajectories arriving at a given equivalent latitude φe and potential temperature θ location that have encountered the boundary layer ($z^* < 1$ km) within the previous 30 days. For comparison, potential vorticity is also contoured (white curves) at values 1, 2, 4, 8 and 12 PVU with the 2 PVU contour in bold, and the X_{BL} = 20% contour is plotted in black.

(Berthet et al., 2007, JGR)

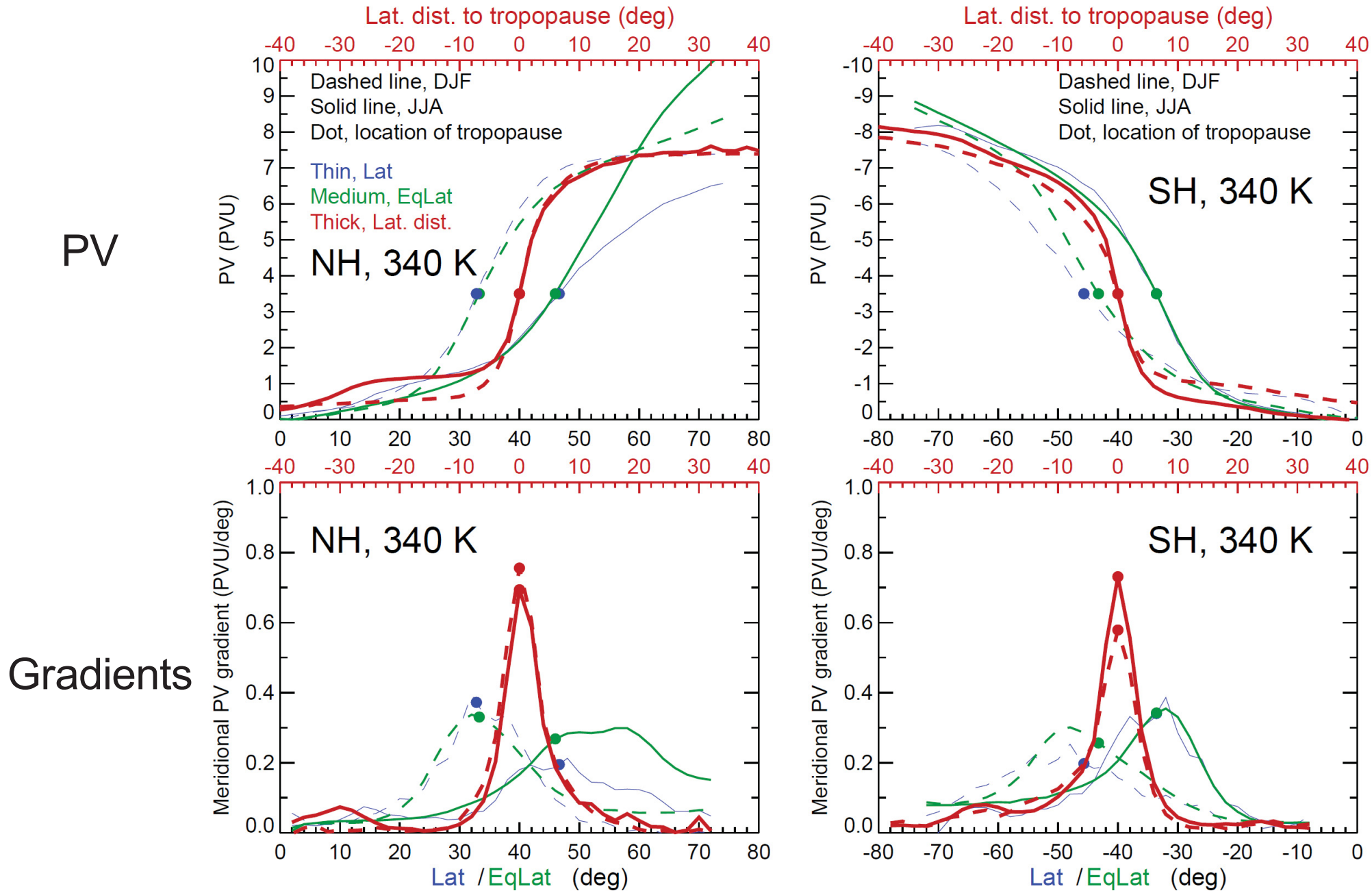
Previous trajectory model simulation show the seasonal variation above 370 K, but strong "barrier" below it.

Note: EqL is used in the figure.

Zonal mean CO (upper panels), and its meridional gradients (bottom panels)

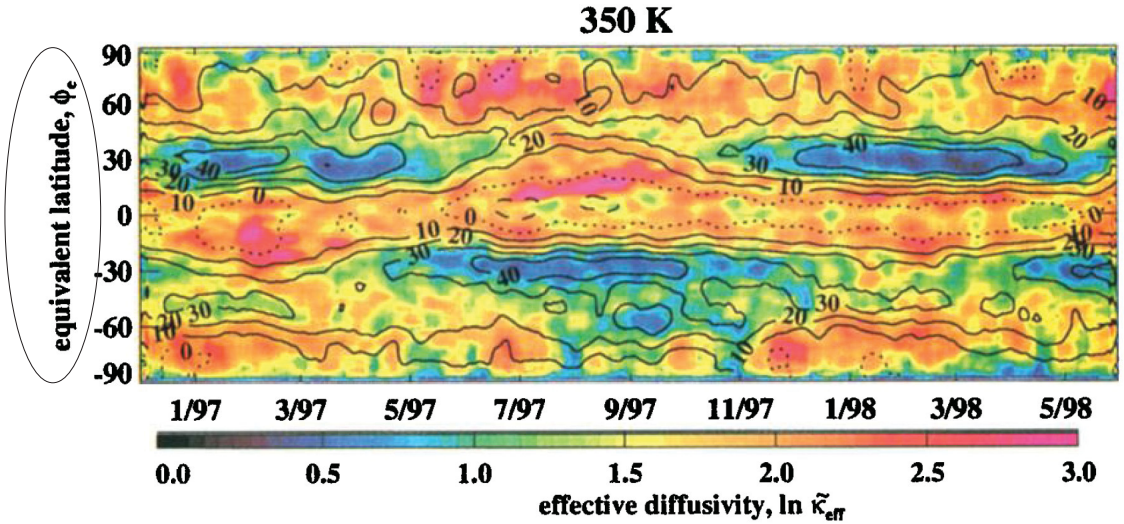


Zonal mean PV (upper panels), and its meridional gradients (bottom panels)



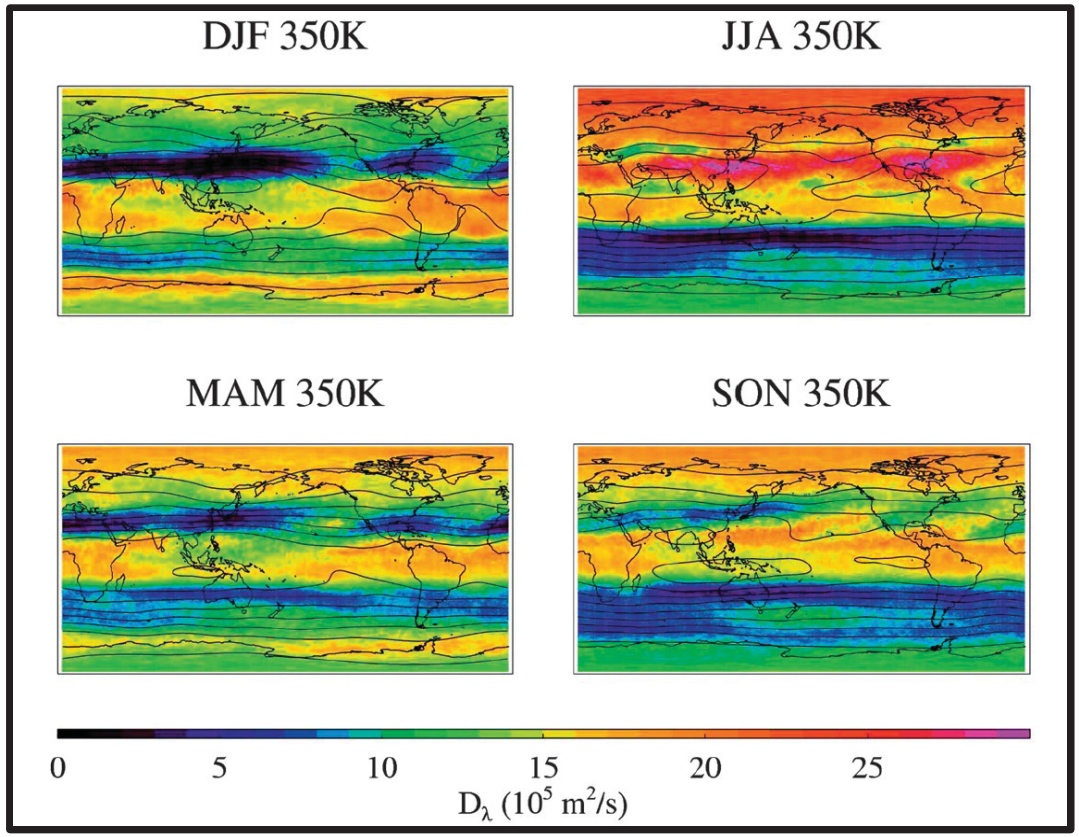
Previous studies, generally based on EqLat.

EqLat



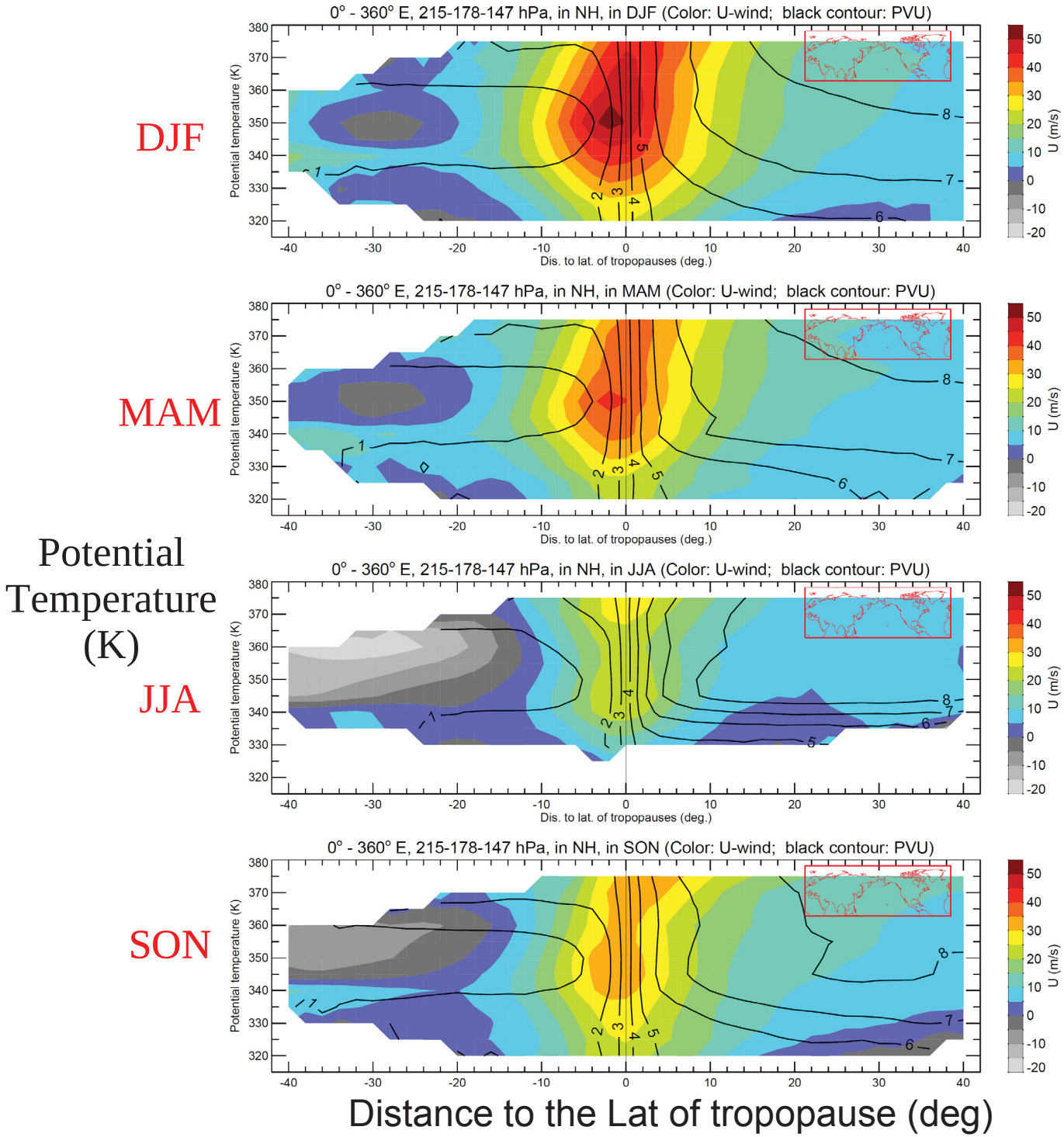
Effective difusivity and U wind

(Haynes and Schuckburgh, 2000, JGR)



Seasonal cycle of the Lyapunov diffusivity (color), with time-mean streamlines overplotted as black contours.
(Schuckburgh et al., 2009, JAS)

Subtropical Jet



Vertical distribution of U velocity at 215 – 178 – 147 hPa

0 – 360 E (zonal mean)

Black contours, PV

Strong seasonal variation of U, but always maximum U wind at the tropopause.

Static stability

$$N^2 = \frac{g}{\theta}\frac{\partial\theta}{\partial z}.$$

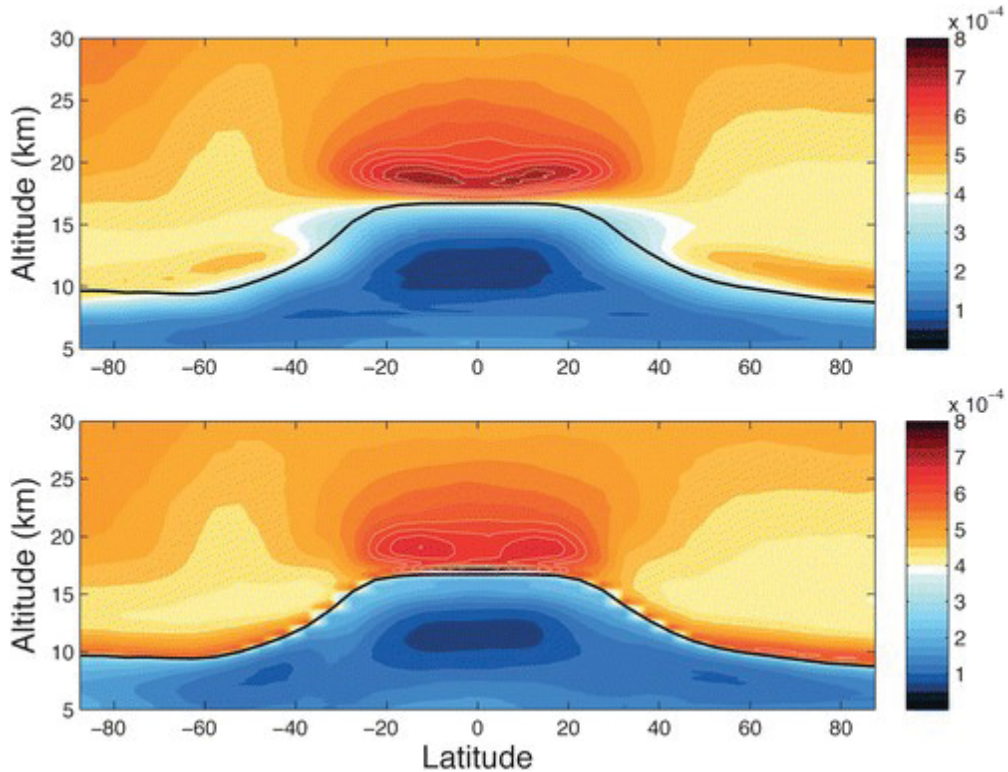
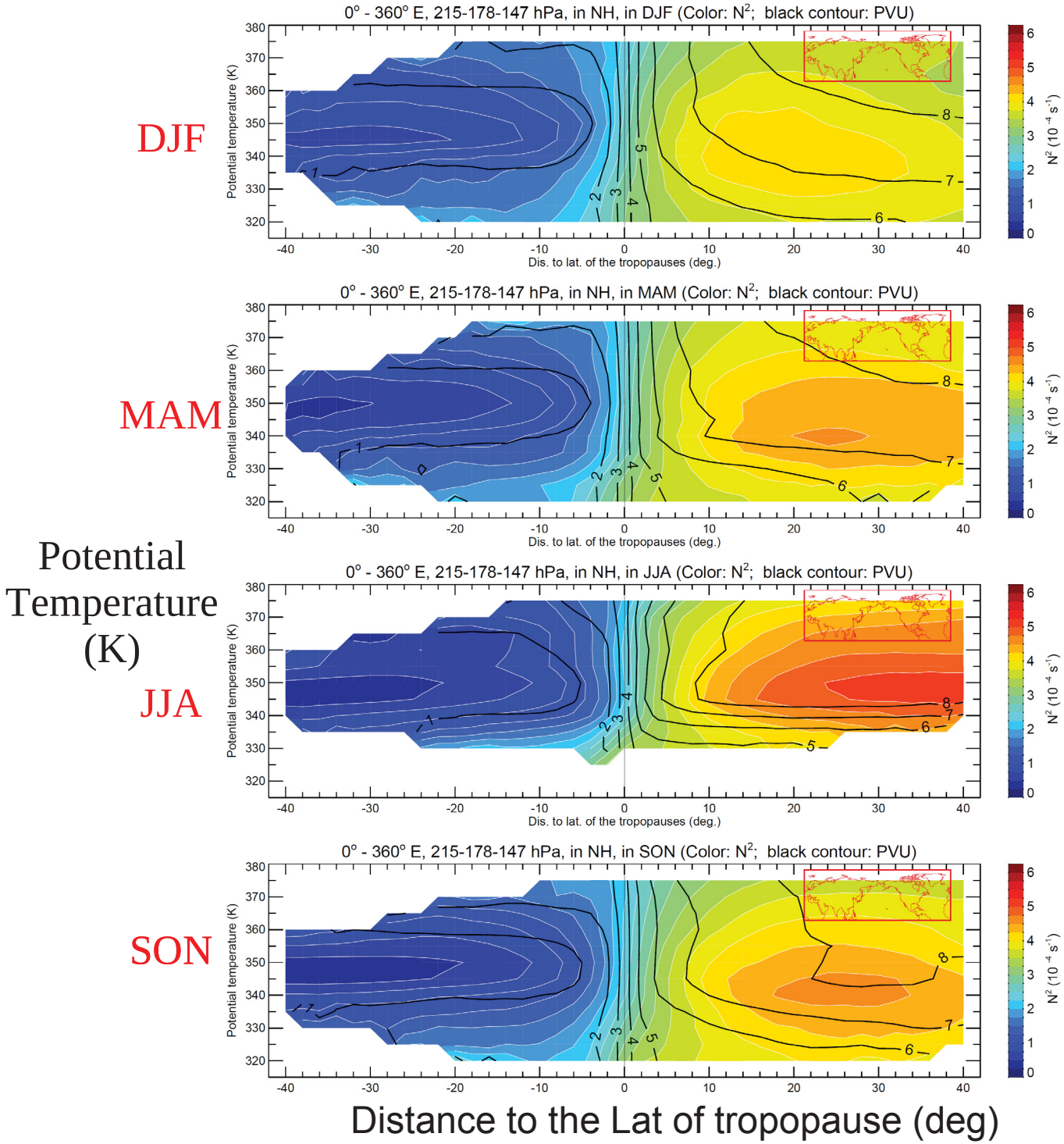


Fig. 1. Annual-mean, zonal-mean static stability (N2) in (top) conventional vertical coordinates and (bottom) tropopause-relative vertical coordinates. The shading interval is 2.5 × 10−5 s−2. The thick solid black line is the annual-mean, zonal-mean thermal tropopause height. The thin white contours highlight the shading intervals for values greater than or equal to 6.0 × 10−4 s−2. The annual mean is based on data averaged over April 2002–March 2008. In all figures, static stability is calculated using the GPS temperature profiles from the CHAMP satellite. (Grise et al., 2010, J. Climate)

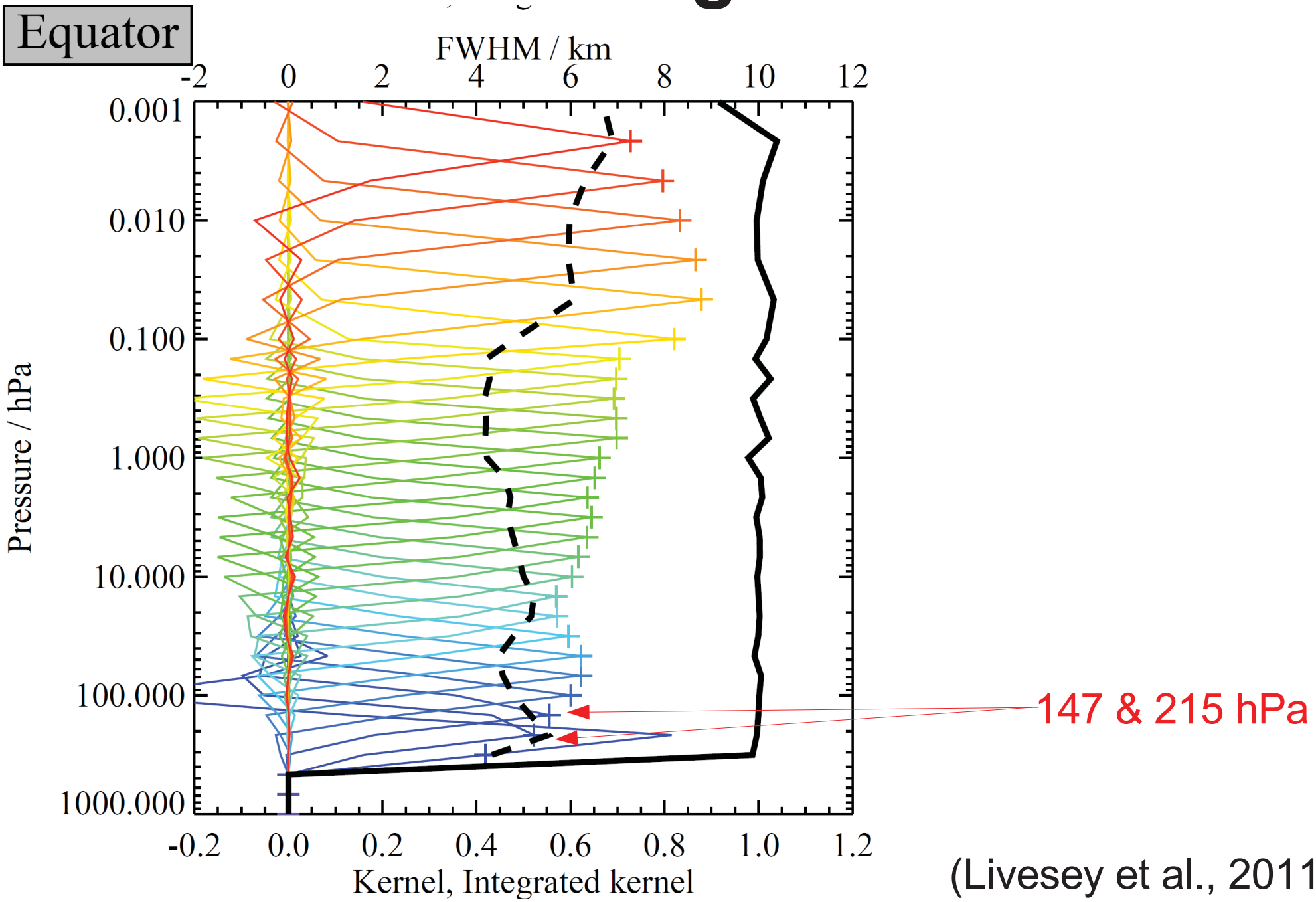
Static stability at 215–178–147 hPa



The static stability is larger in the LS than in the UT;

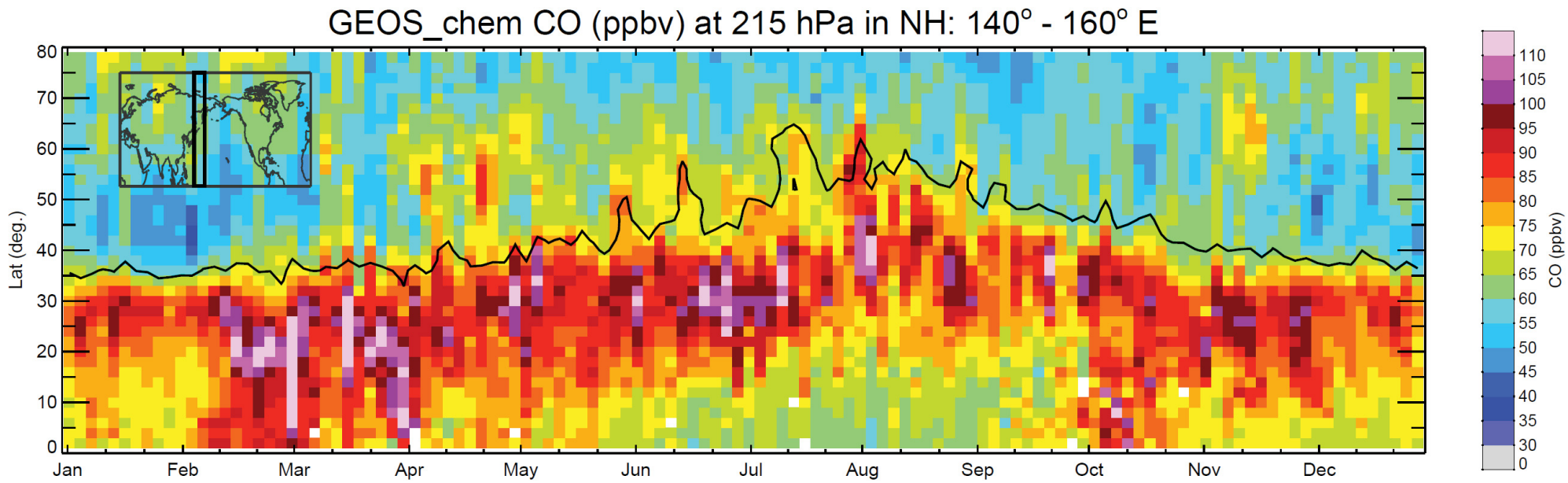
It is the largest in JJA and the smallest in DJF.

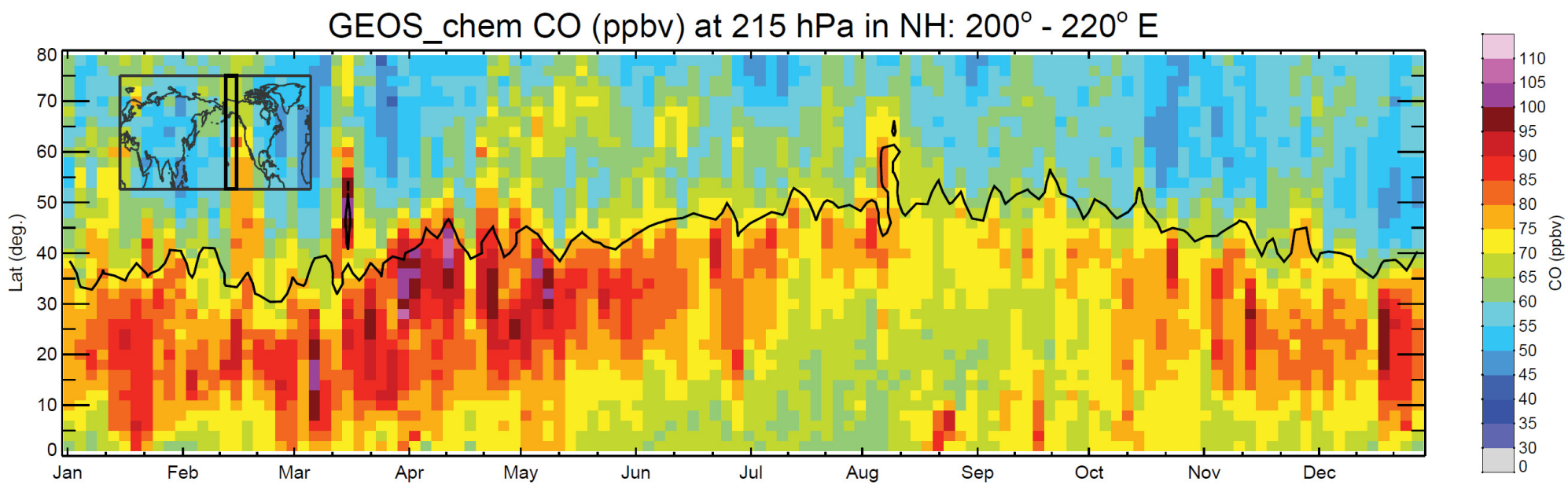
MLS v3 CO average kernel



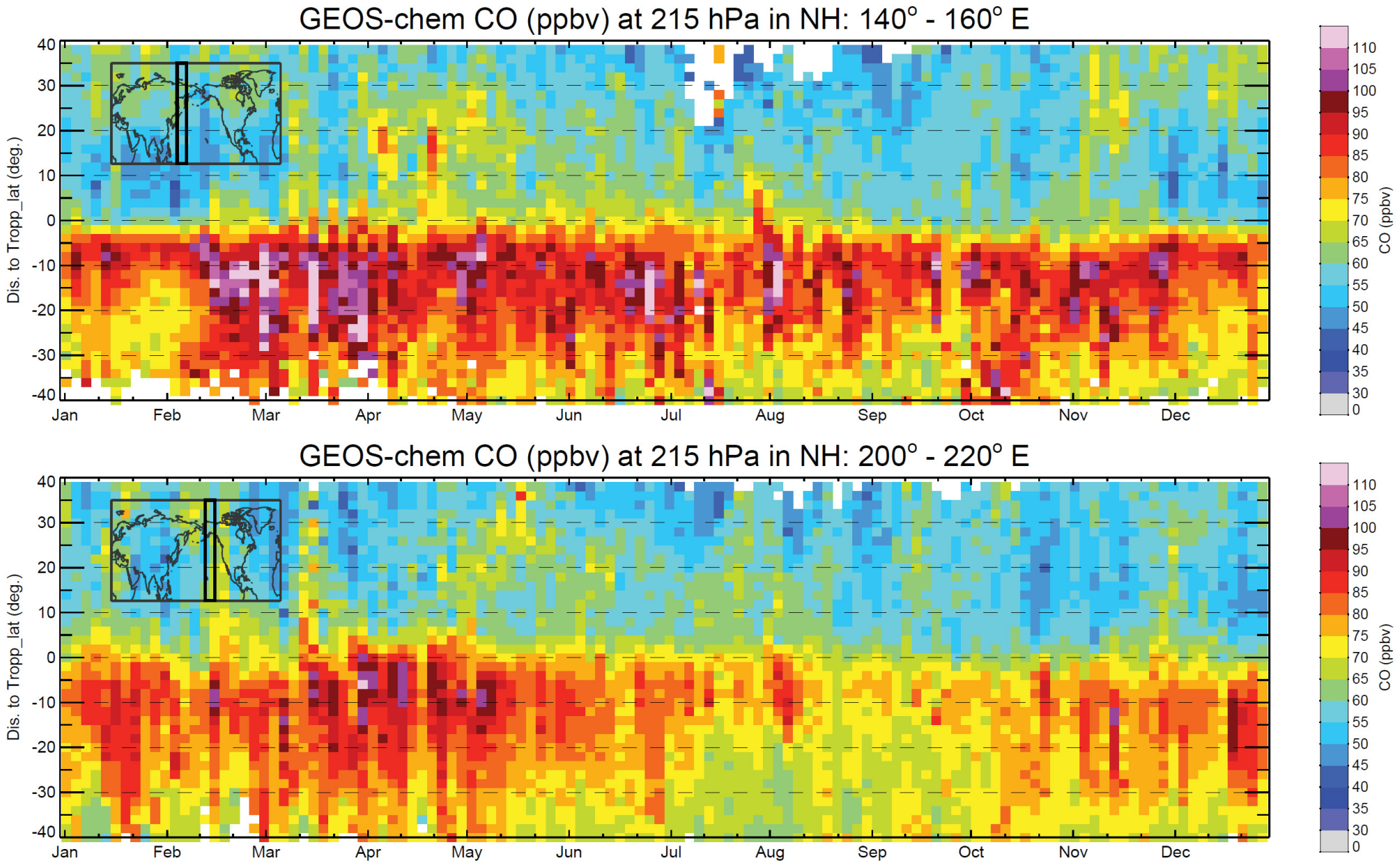
(Livesey et al., 2011)

GEOS-Chem simulations in 2005-2006

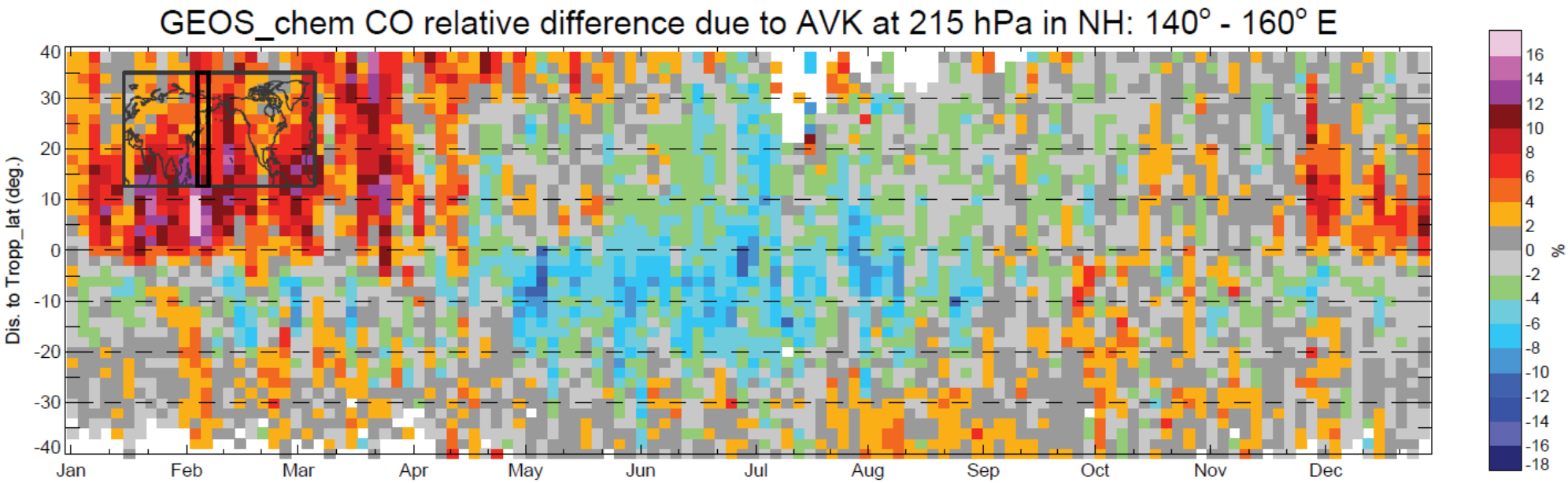


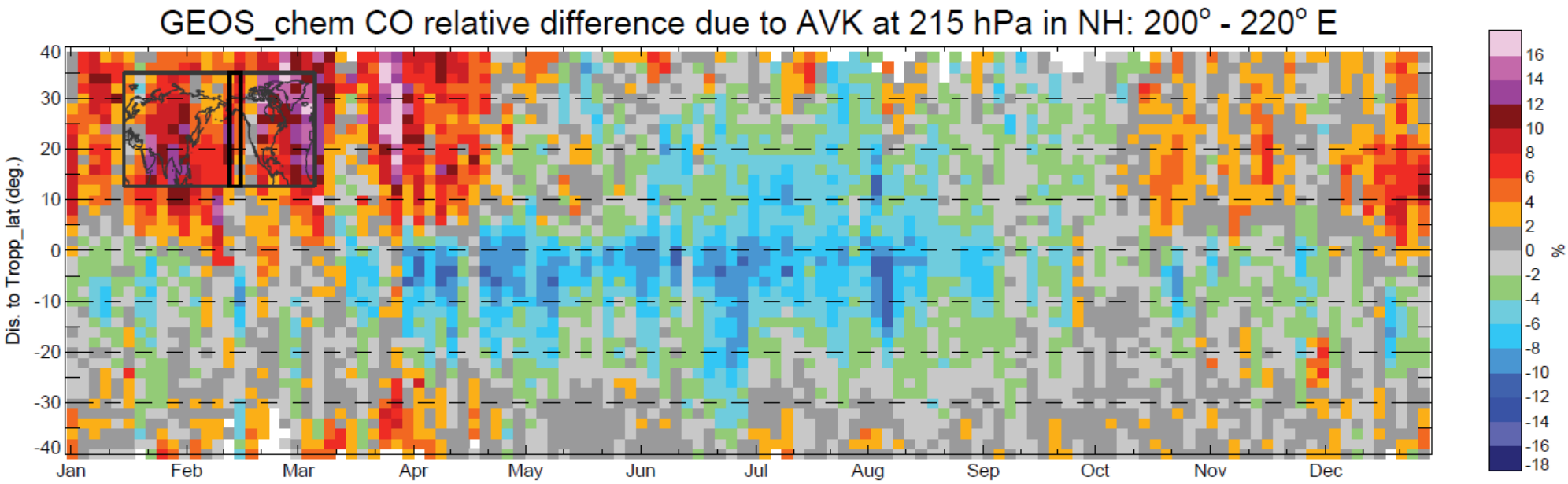


GEOS-Chem simulations in 2005-2006



Relative difference (%) due to average kernel (MLS v2)





Summary

- **MLS observations are useful for STE studies** even though they have a coarse vertical resolution. Aircraft observations have high precision and spacial resolution, but usually do not show the ultimate fate of the STE processes.
- The CO meridional gradients in real atmosphere **should be even slightly larger** than shown by MLS observation (averaging kernel effect).
- The analysis shows **no indication of strong seasonal variation** in permeability of the extratropical tropopause (shown by CO and PV distribution and meridional gradients).
- Previous studies of STE based on **climatological** tropopause in **geographical or EqLat coordinates may be biased.**
- **Dynamical coordinates such as the "tropopause coordinates"** are more appropriate for a climatological view of STE.

Thank you!

Effective difusivity (Haynes and Schuckburgh, 2000, JGR)

Both *Nakamura* [1996] and *Winters and D'Asaro* [1996] have introduced a quantity, "effective diffusivity," for the consideration of the evolution of a conservative chemical tracer with concentration $c(\mathbf{x}, t)$ according to a two-dimensional advection-diffusion equation

$$\frac{\partial c}{\partial t} + \mathbf{u} \cdot \nabla c = \nabla \cdot (\kappa \nabla c) \ , \qquad (1)$$

where $\mathbf{u}(\mathbf{x}, t)$ is the velocity field and κ is a constant diffusivity. For each value C of the concentration, the function $A(C, t)$ may be defined as the area of the region for which the tracer concentration $c(\mathbf{x}, t)$ is greater than or equal to C [*Butchart and Remsberg*, 1986]. By definition, $A(C, t)$ is a monotonic function of C, and there is therefore a unique inverse function $C(A, t)$ such that $C(A(\tilde{C}, t), t) = \tilde{C}$. In considering advection-diffusion on a sphere of radius r, it is convenient to replace the area A by an "equivalent latitude" ϕ_e defined by $A = 2\pi r^2(1 - \sin\phi_e)$. Then C may be regarded as a function of ϕ_e and t.

Nakamura [1996] showed that, providing the velocity field $\mathbf{u}(\mathbf{x}, t)$ is nondivergent, the function $C(\phi_e, t)$ satisfies the diffusion-only equation

$$\frac{\partial C(\phi_e, t)}{\partial t} = \frac{1}{r^2 \cos\phi_e} \frac{\partial}{\partial \phi_e} \left[\kappa_{\text{eff}}(\phi_e, t) \cos\phi_e \frac{\partial C(\phi_e, t)}{\partial \phi_e} \right] , \qquad (2)$$

where κ_{eff}, the effective diffusivity, is defined by

$$\kappa_{\text{eff}}(\phi_e, t) = \kappa r^2 \frac{\langle\ |\nabla c|^2\ \rangle}{(\partial C / \partial \phi_e)^2} = \frac{\kappa L_{\text{eq}}^2(\phi_e, t)}{(2\pi r \cos\phi_e)^2} \ . \qquad (3)$$

Here $\langle(\cdot)\rangle$ denotes the average over the area between adjacent tracer contours and is defined by

$$\langle(\cdot)\rangle = \frac{\oint (\cdot) \frac{dl}{|\nabla c|}}{\oint \frac{dl}{|\nabla c|}} \ ,$$

where the integrals are around a contour of c. The quantity $L_{\text{eq}}(\phi_e, t)$, defined by the second equality in (3), is known as the "equivalent length." The transformation to ϕ_e as an independent variable removes the advective terms from the evolution equation for the tracer concentration, and consequently, equation (3) simply describes the diffusion of tracer relative to contours of ϕ_e. The equivalent length $L_{\text{eq}}(\phi_e, t)$

$$x_{rtv} = x_a + A(x_{true} - x_a) = Ax_{true} + (I - A)x_a$$

where x_{true} is the true profile, A is the averaging kernel matrix, and I is the identity matrix. Xa is a priori profile.