# Transport and mixing in the extratropical tropopause region in a high vertical resolution GCM

**(Miyazaki et al. JAS 2010a,2010b)**


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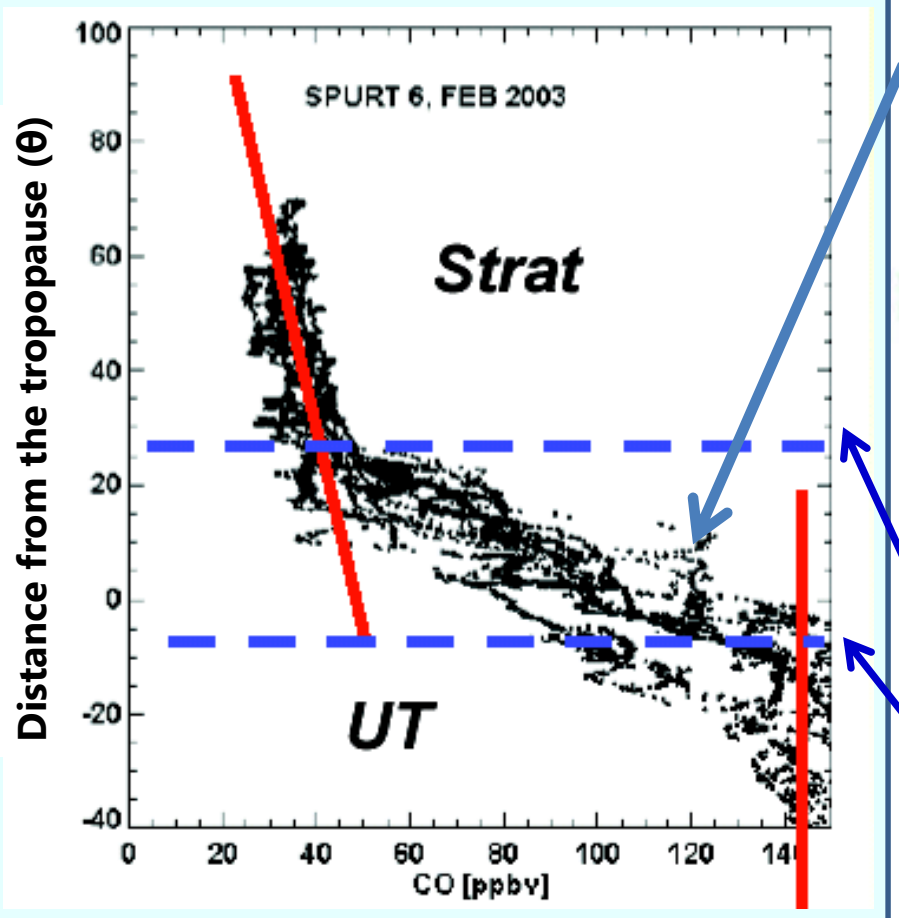
# Extratropical tropopause transition layer (ExTL)

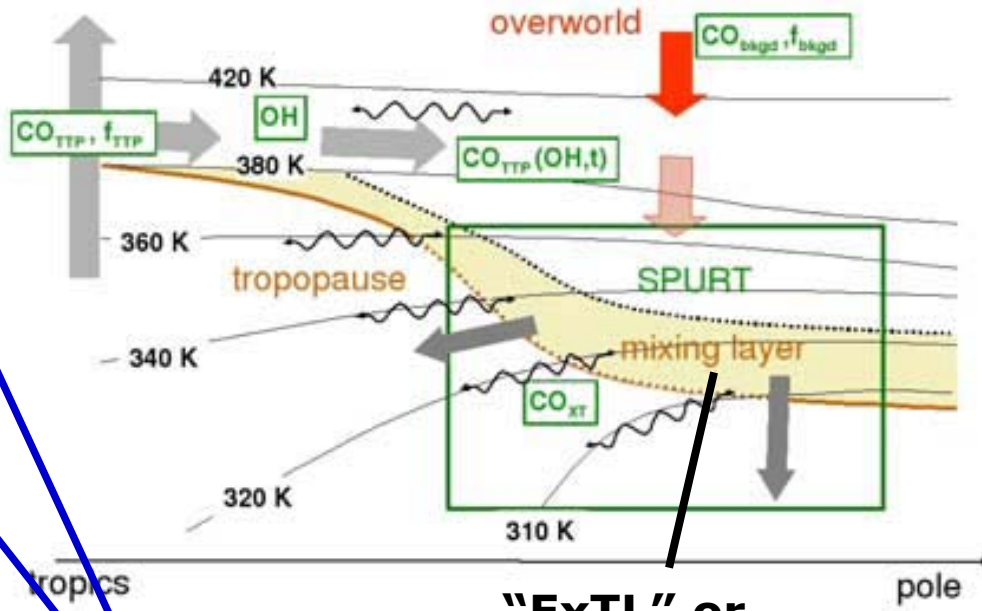



**CO profiles as a function of a distance from the tropopause**

**Transition layer**

**(thickness =2 km)**

**(Hoor et al., 2004)**

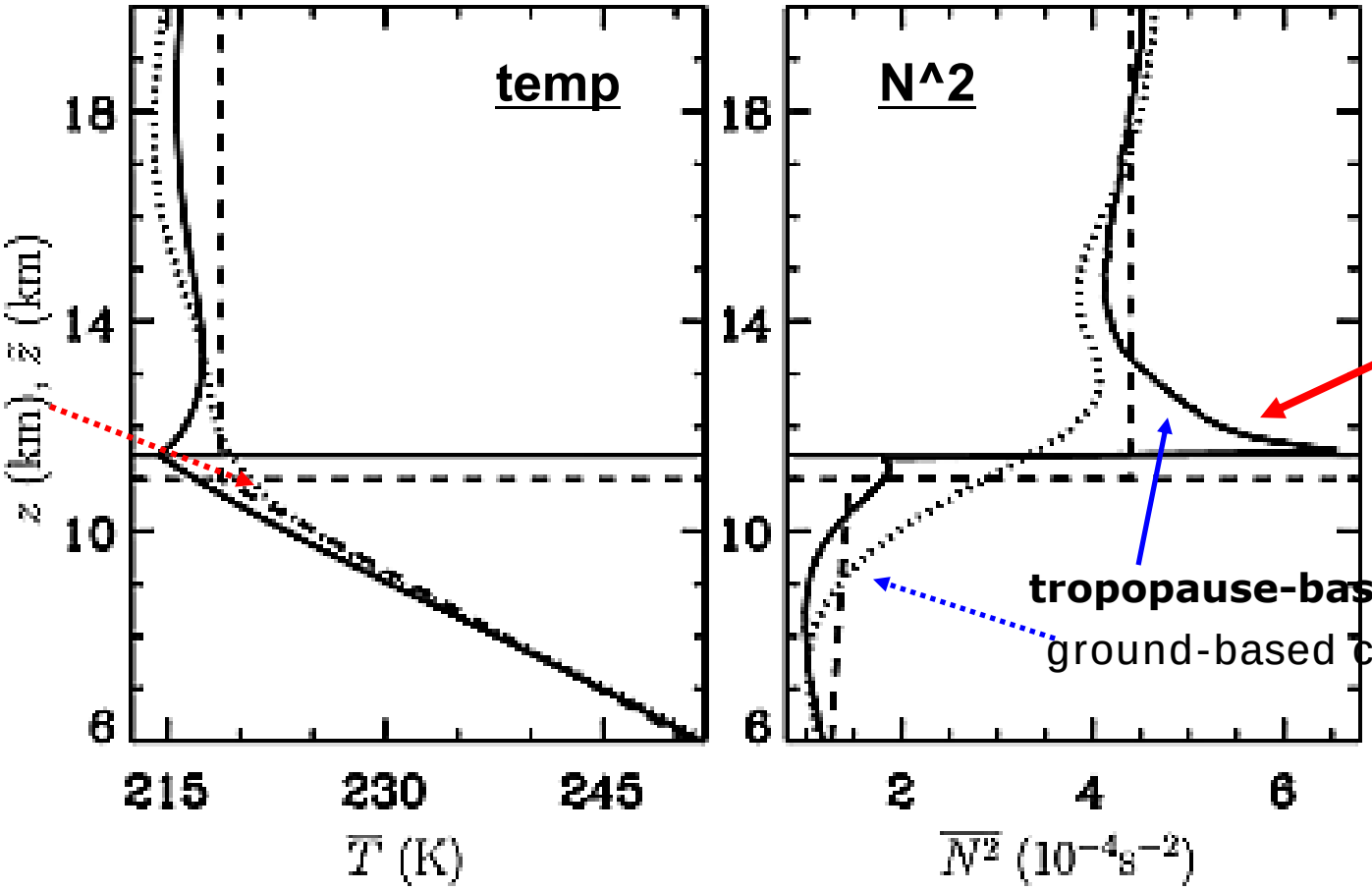



**"ExTL" or**
**"Tropopause mixing layer"**

**Transport barrier?**

**Chemical tracers have intermediate concentrations in the extratropical tropopause region.**

# Tropopause inversion layer (TIL)




(Birner et al., 2006; Randel et al., 2007)

**A large temperature gradient in the lowermost stratosphere forms a tropopause inversion layer (TIL) just above the extratropical tropopause**

-**The similar locations of the TIL and ExTL imply that the chemical and thermal structures interact with each other in the extratropical tropopause region (e.g., Randel et al., 2007).**

**- relationship between the mechanisms of formation of the TIL and the ExTL ?**

**- relative importance of transport processes at different scales ?**

**- current models do not fully succeed in simulating the location and depth of these layers (e.g., CCMval inter-comparisons).**

# KANTO project: A high vertical resolution GCM

**T213L256 GCM**:

**vertical resolution = 300 m**, top=85km

horizontal resolution = 0.5625°

**No gravity wave drag parameterization**

Watanabe et al., JGR2008, JGR2009, Tomikawa et al., JGR2008, Kawatani et al., JAS2010a & JAS2010b, Sato et al., GRL2009, Miyazaki et al., JAS2010a & JAS2010b

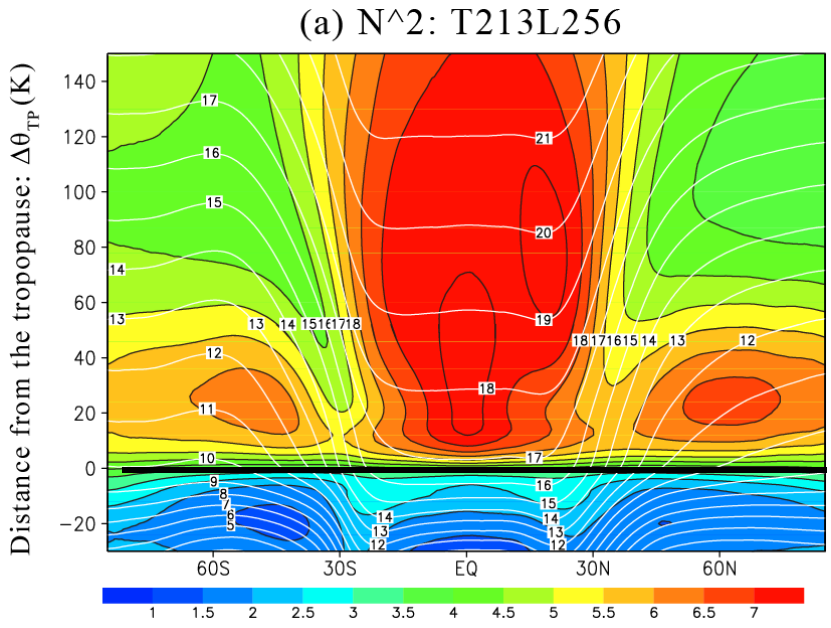
**·gravity wave propagations and the induced circulation**

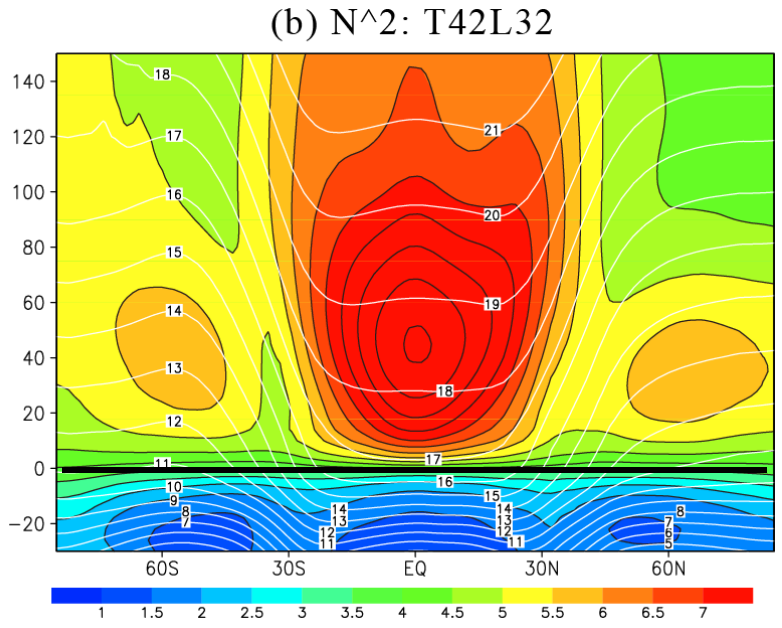
**·fine thermal/dynamical structure around the tropopause**

**· importance of variously scaled atmospheric processes**

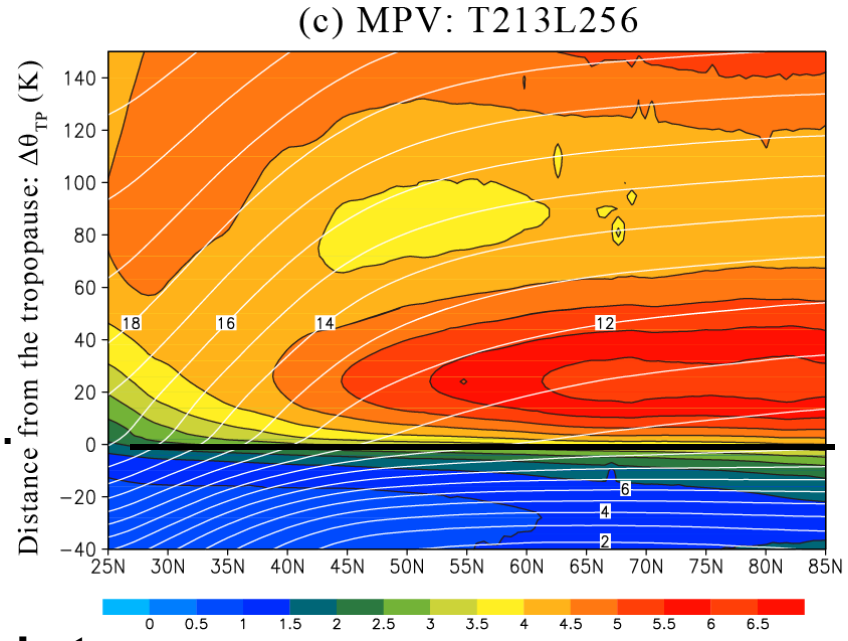
# Comparisons with a coarse-resolution GCM (Δz≒1km)

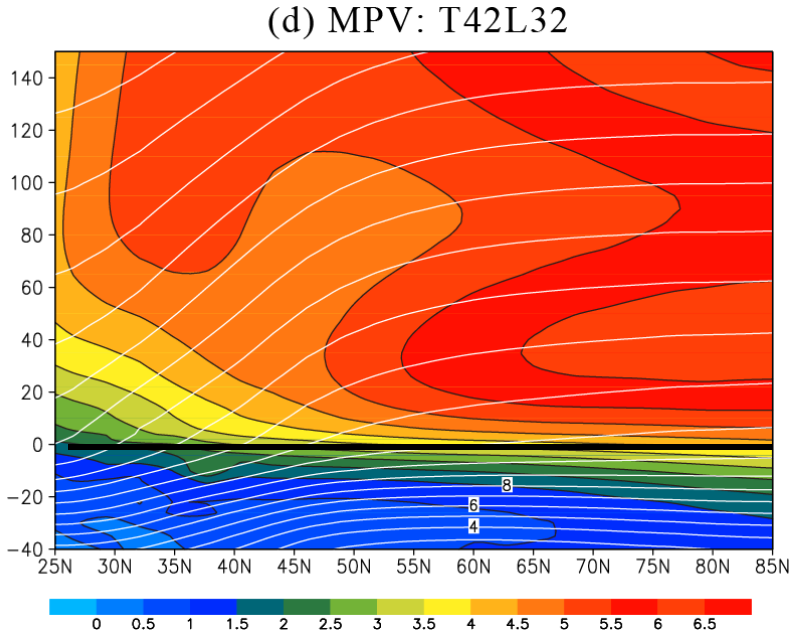
**N²**




**MPV**



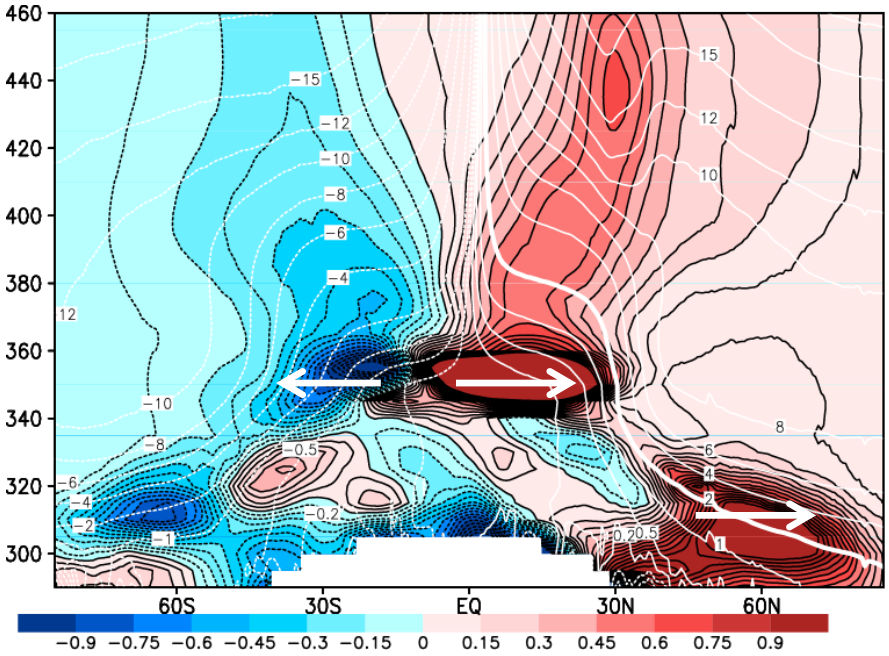




**θ tropopause based-coord.**

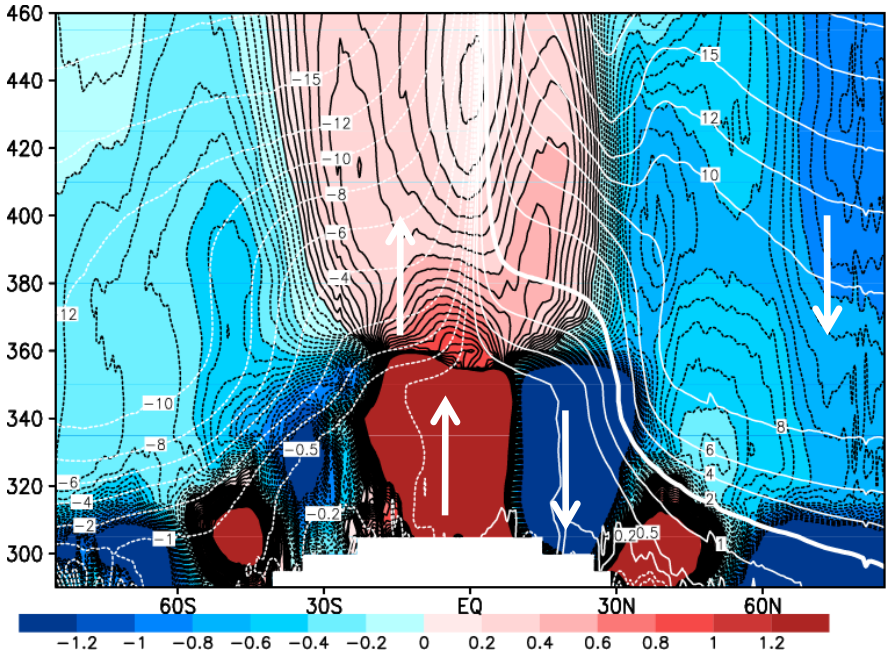
**Lat.**

# Mean-meridional circulation January

## Mean meridional wind V*




## Mean vertical wind W*




**Compared to coarse resolution models:**

- **stronger convergence of the mean downward velocity in the LS**
- **stronger and sharper meridional divergent flows in the UT**

The PV is a material invariant (i.e., passive tracer) under inviscid (frictionless) and adiabatic approximation (Hoskins, 1985).

Continuity equation of isentropic PV;

$$\frac{D_\theta q}{Dt} = \frac{\partial q}{\partial t} + \vec{v} \cdot \nabla_\theta q = \frac{q}{\sigma}\frac{\partial}{\partial \theta}\left(\sigma \dot{\theta}\right) + \sigma^{-1}\vec{k} \cdot \nabla_\theta \times \left(\vec{F}_r - \dot{\theta}\frac{\partial \vec{v}}{\partial \theta}\right)$$

**Zonal mean equation based on the mass-weighted isentropic zonal means**

$$\frac{\partial \overline{q^*}}{\partial t} = -\frac{\overline{v^*}}{a}\frac{\partial \overline{q^*}}{\partial \phi} - \overline{\dot{\theta}^*}\frac{\partial \overline{q^*}}{\partial \theta} - \frac{1}{a\cos\phi}\frac{\partial \overline{(v'q')^*\cos\phi}}{\partial \phi} - \frac{1}{\rho_0}\frac{\partial \rho_0 \overline{(\dot{\theta}'q')^*}}{\partial z_\dagger} + \overline{\left(q\frac{\partial \dot{\theta}}{\partial \theta}\right)^*}$$

If the source/sink effect is negligible, this analysis provides insights into transport processes related to formation of long-lived tracer concentration gradients

**Analysis of maintain mechanisms of vertical PV gradients**

$$\frac{\partial}{\partial t}\left(\frac{\partial \overline{q^*}}{\partial \theta}\right) = \underbrace{-\frac{\partial \overline{q^*}}{a\partial\phi}\frac{\partial \overline{v^*}}{\partial \theta}}_{MEY1} \underbrace{-\overline{v^*}\frac{\partial^2 \overline{q^*}}{a\partial\phi\partial\theta}}_{MEY2} \underbrace{-\frac{\partial \overline{\dot{\theta}^*}}{\partial \theta}\frac{\partial \overline{q^*}}{\partial \theta}}_{MEZ1} \underbrace{-\overline{\dot{\theta}^*}\frac{\partial^2 \overline{q^*}}{\partial \theta^2}}_{MEZ2}$$

$$\underbrace{-\frac{\partial}{\partial \theta}\left(-\frac{1}{a\cos\phi}\frac{\partial \overline{(v'q')^*\cos\phi}}{\partial \phi}\right)}_{EDY} \underbrace{-\frac{\partial}{\partial \theta}\left(\frac{1}{\rho_0}\frac{\partial \rho_0 \overline{(\dot{\theta}'q')^*}}{\partial \theta}\right)}_{EDZ} + \underbrace{\frac{\partial}{\partial \theta}\left(\overline{\left(q\frac{\partial \dot{\theta}}{\partial \theta}\right)^*}\right)}_{source/sink}$$

# Maintain mechanisms of PV gradients

$$\frac{\partial}{\partial t}\left(\frac{\partial \overline{q^*}}{\partial \theta}\right) = \underbrace{-\frac{\partial \overline{q^*}}{a\partial\phi}\frac{\partial \overline{v^*}}{\partial \theta}}_{MEY1} \underbrace{-\overline{v^*}\frac{\partial^2 \overline{q^*}}{a\partial\phi\partial\theta}}_{MEY2} \underbrace{-\frac{\partial \overline{\dot{\theta}^*}}{\partial\theta}\frac{\partial \overline{q^*}}{\partial\theta}}_{MEZ1} \underbrace{-\overline{\dot{\theta}^*}\frac{\partial^2 \overline{q^*}}{\partial\theta^2}}_{MEZ2} + EDY + EDZ + source$$

**January** **July**

(a) Mean meridional (MEY1): JAN (b) Mean meridional (MEY2): JAN (a) Mean meridional (MEY1): JUL (b) Mean meridional (MEY2): JUL

Winter: mean downward transport and isentropic mixing

Summer: mean downward transport and vertical mixing

(c) Mean vertical (MEZ1): JAN (d) Mean vertical (MEZ2): JAN (c) Mean vertical (MEZ1): JUL (d) Mean vertical (MEZ2): JUL

MEZ1 MEZ2 MEZ1 MEZ2

(e) Eddy meridional (EDY): JAN (f) Eddy vertical (EDZ): JAN (e) Eddy meridional (EDY): JUL (f) Eddy vertical (EDZ): JUL

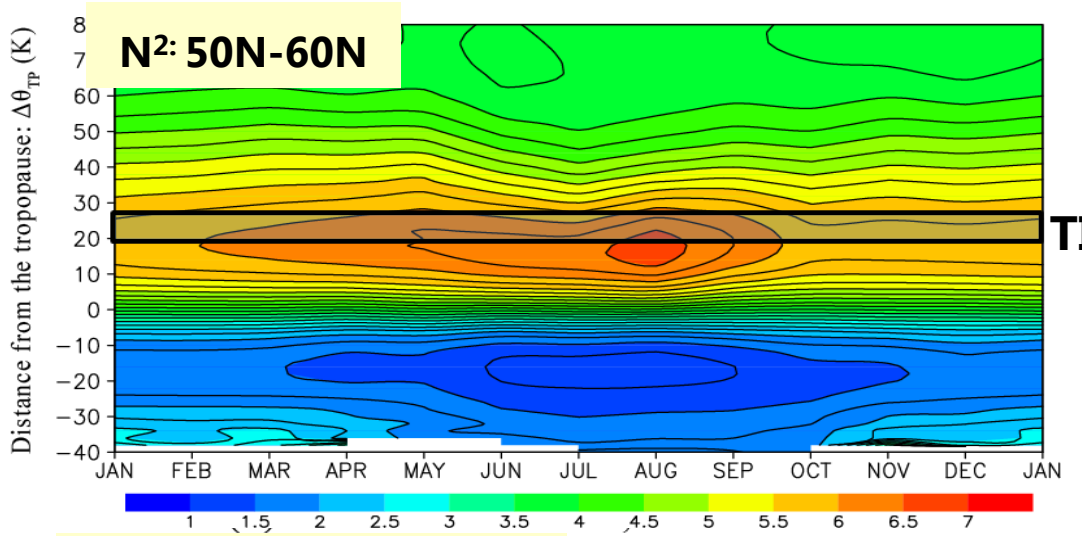
EDY EDZ EDY EDZ

Distance from the tropopause: $\Delta\theta_{TP}$ (K)

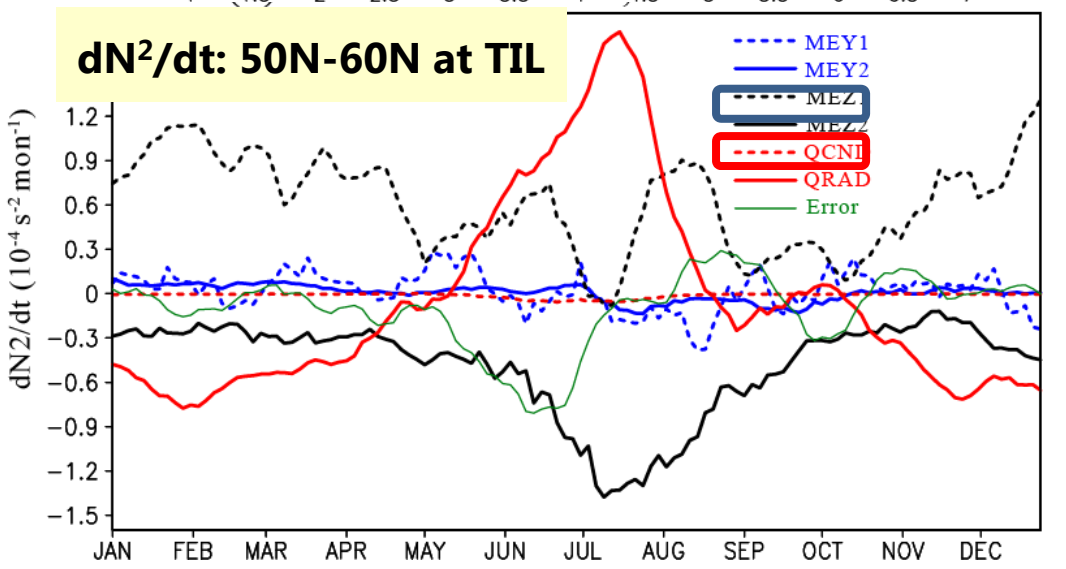
60S 30S EQ 30N 60N

−2 −1.5 −1 −0.5 −0.2 −0.1 0.1 0.2 0.5 1 1.5 2

# TIL formation mechanisms




TIL




-**Stratification by radiation** and **downward advection of the static stability profile** determine seasonal variation of the TIL.

- **Radiation -> summertime maximum**

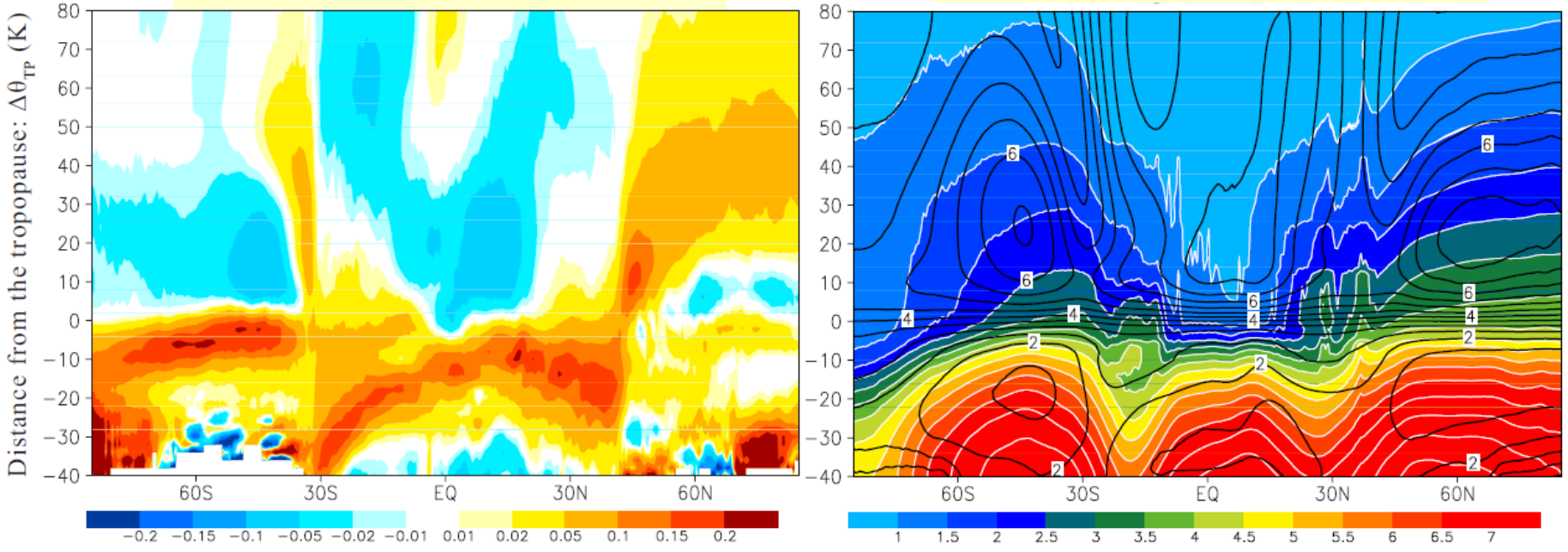
**Thermodynamic analysis**

$$\frac{\partial \overline{N^{2*}}}{\partial t} = \left( \underbrace{-\frac{\overline{v^*}}{\partial z_\dagger}\frac{\partial \theta}{a\partial\phi}}_{MEY1} \underbrace{-\overline{v^*}\frac{\partial^2\theta}{a\partial\phi\partial z_\dagger}}_{MEY2} \underbrace{-\frac{\partial \overline{w_\dagger^*}}{\partial z_\dagger}\frac{\partial \theta}{\partial z}}_{MEZ1} \underbrace{-\overline{w_\dagger^*}\frac{\partial^2\theta}{\partial^2 z_\dagger}}_{MEZ2} \underbrace{-\frac{\partial \frac{\overline{Q^*_{rad}}}{\Pi}}{\partial z_\dagger}}_{QRAD} \underbrace{+\frac{\partial \frac{\overline{Q^*_{cnd}}}{\Pi}}{\partial z_\dagger}}_{QCND} \right) / \left(\frac{\theta}{g}\right)$$

July

dN²/dt by radiation

Log(H2O)




**- ExTL and TIL can have similar locations, as a result of common dynamic processes and interactions between constituent distributions and thermal structure**

-downward advection of constituents and heat at the lower part

-eddy mixing (suppression) of constituents (e.g., H2O) and radiative stratification at the upper part

# Downward control

PW: n=1-3

MW: n=4-20

GW: n=21-

Div. EP-F

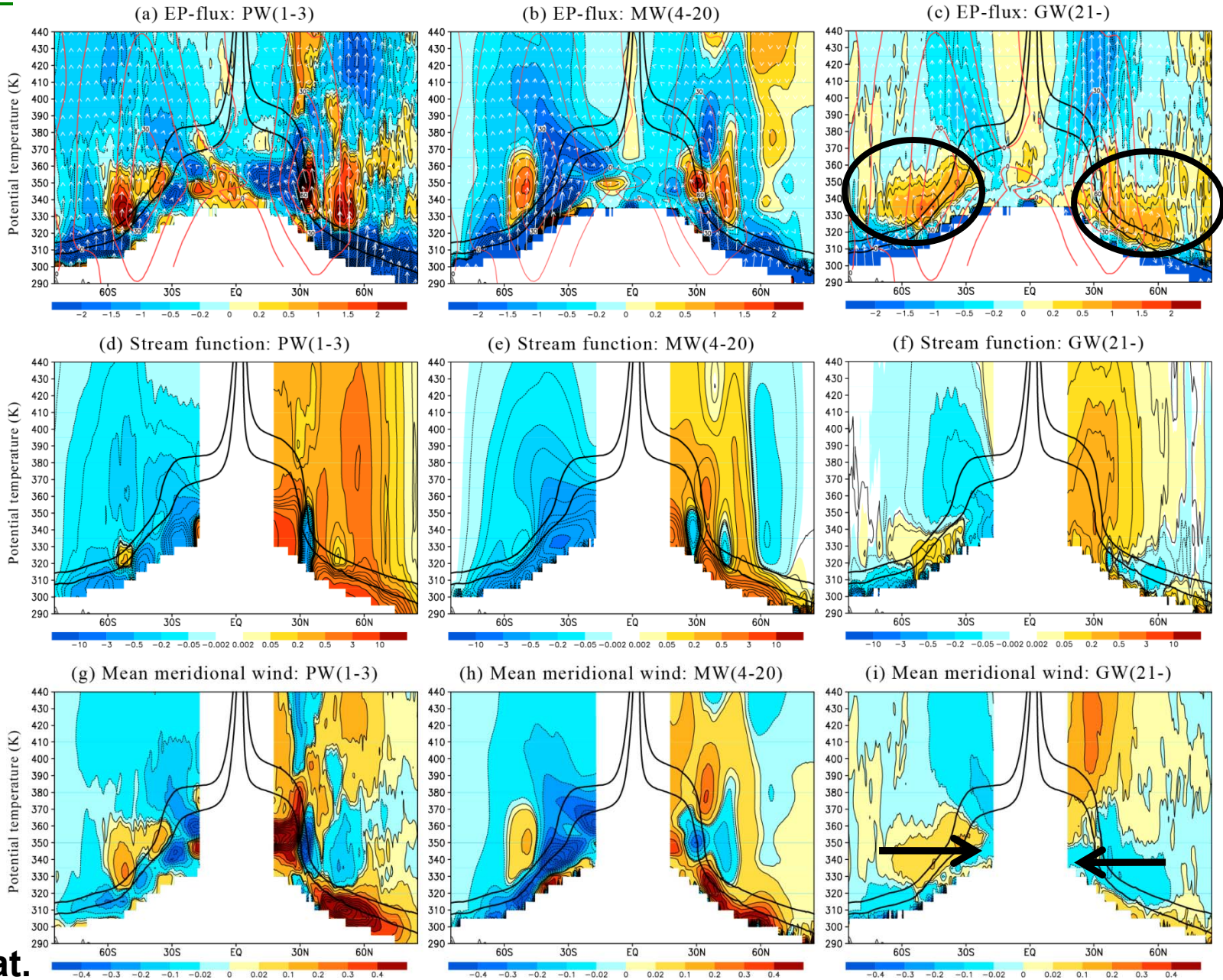
Stream func.

**January**

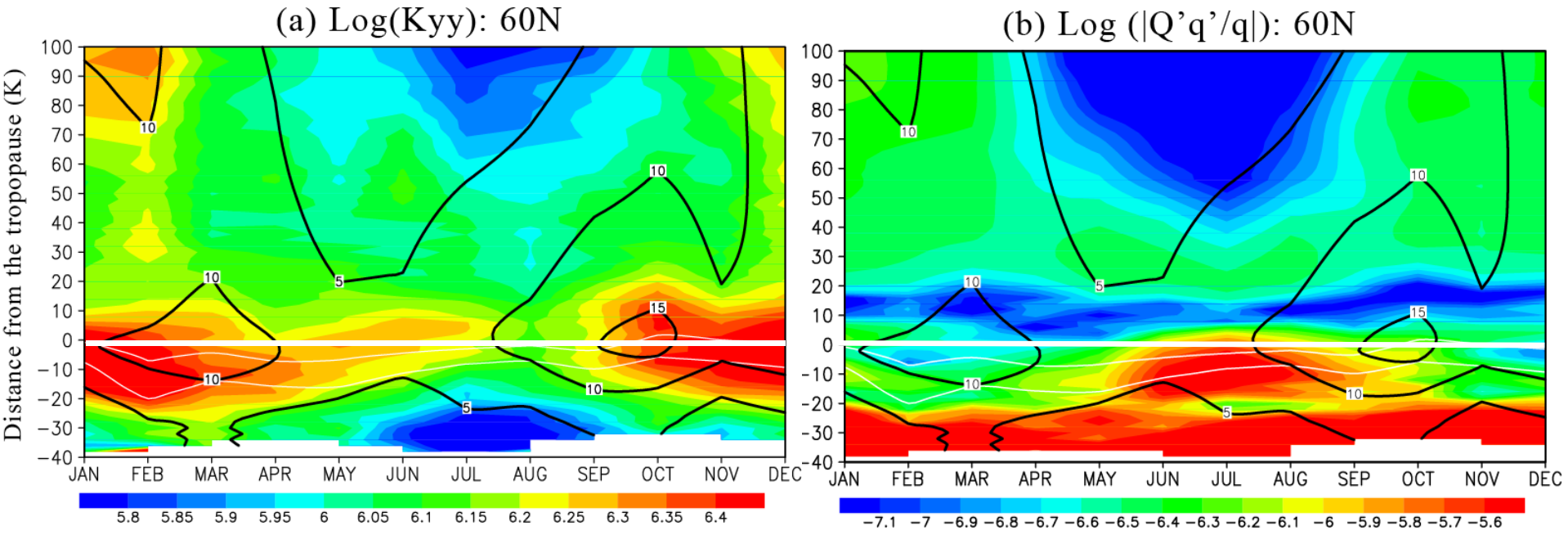
θ

V*

Lat.



# Seasonal variation of horizontal and vertical mixing




**Horizontal diffusion coefficient**

$$\left[\overline{(v'q')^*}\right]_t \simeq -K_{yy}(t)\left[\left(\frac{\partial \overline{q^*}}{a\partial\phi}\right)_\theta\right]_t$$

**Vertical diffusion**

$$\left|\frac{\overline{Q'q'}}{\overline{q}}\right|$$

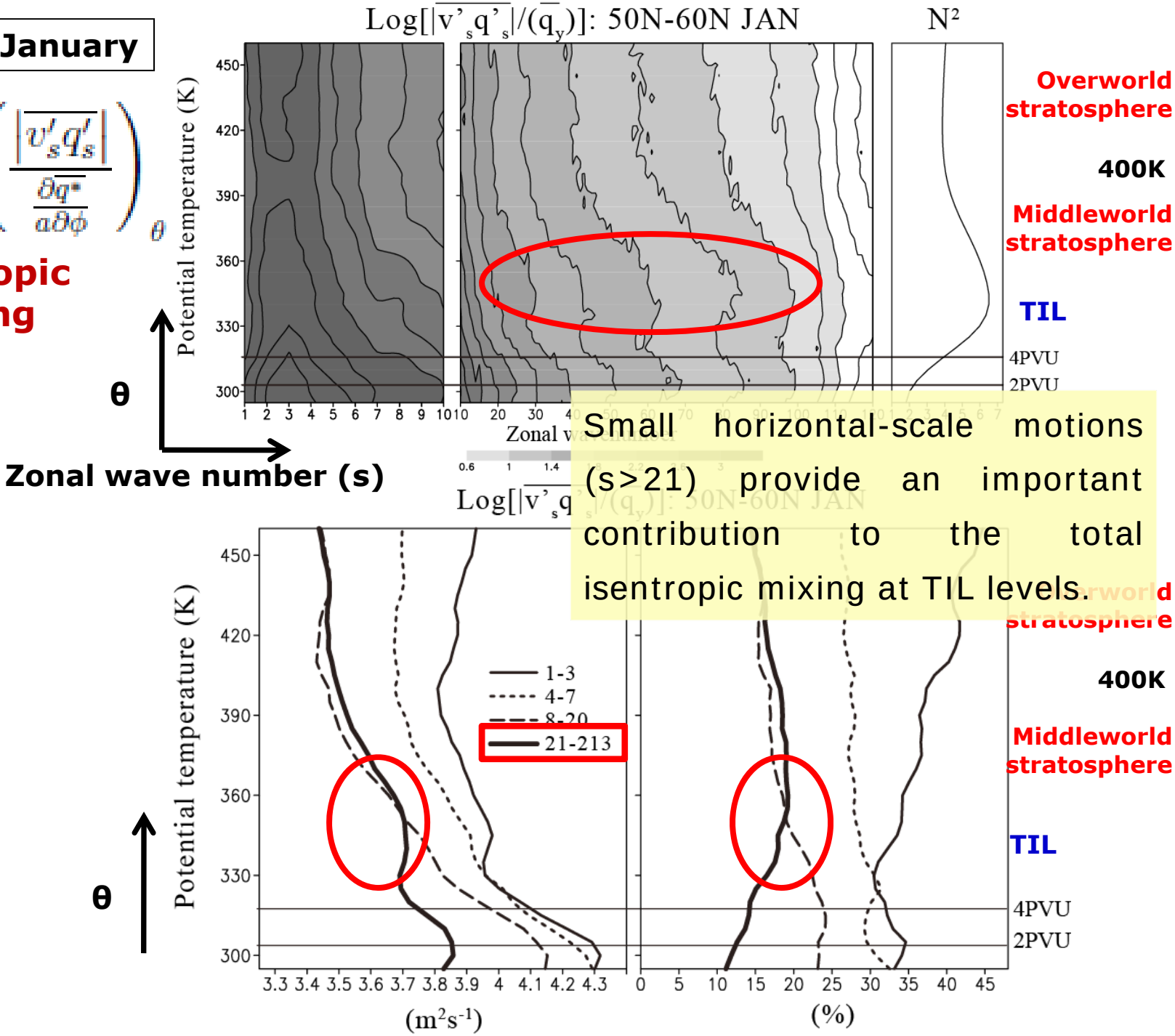
**- Strong isentropic mixing between 20 K below-10 K above the tropopause**

**-Vertical eddy mixing is substantial in the tropopause region during summer, but is strongly suppressed just above the well-mixed region**

**50N-60N January**

$$K_{yy(s)} = \left( \frac{\left|\overline{v_s' q_s'}\right|}{\frac{\partial \overline{q^*}}{a \partial \phi}} \right)_\theta$$

**Isentropic mixing**



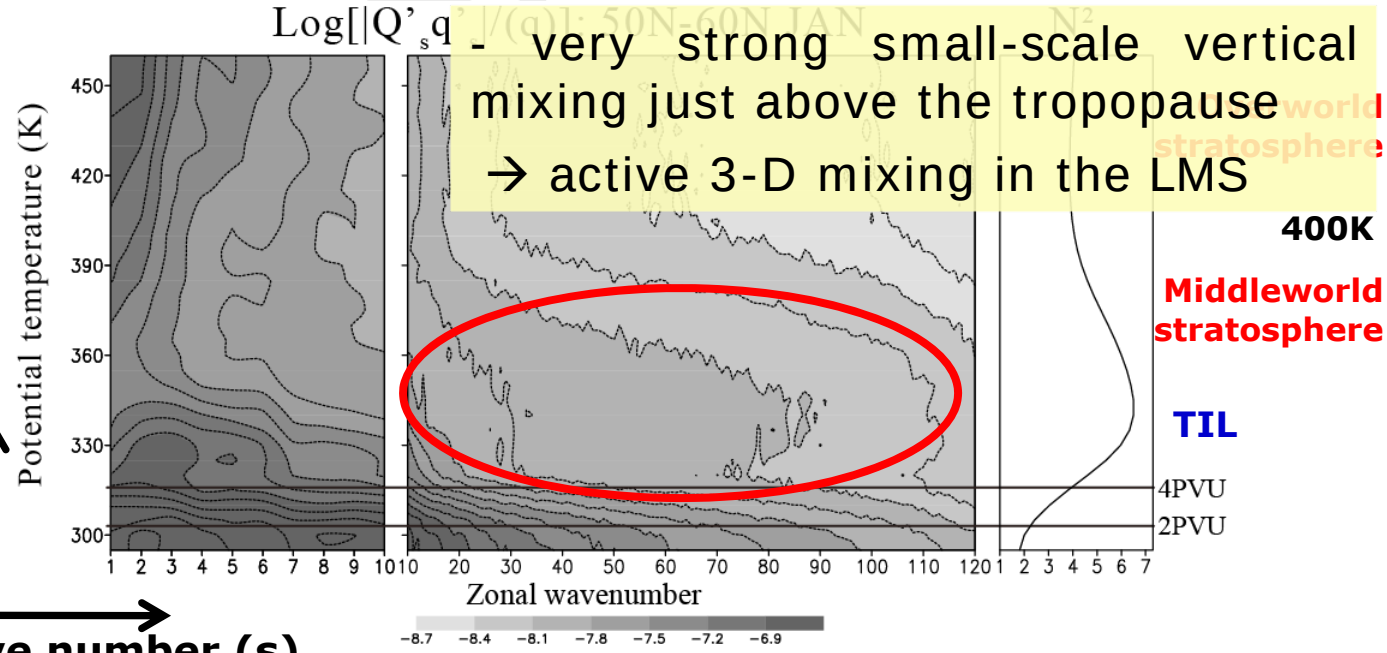

Small horizontal-scale motions (s>21) provide an important contribution to the total isentropic mixing at TIL levels.

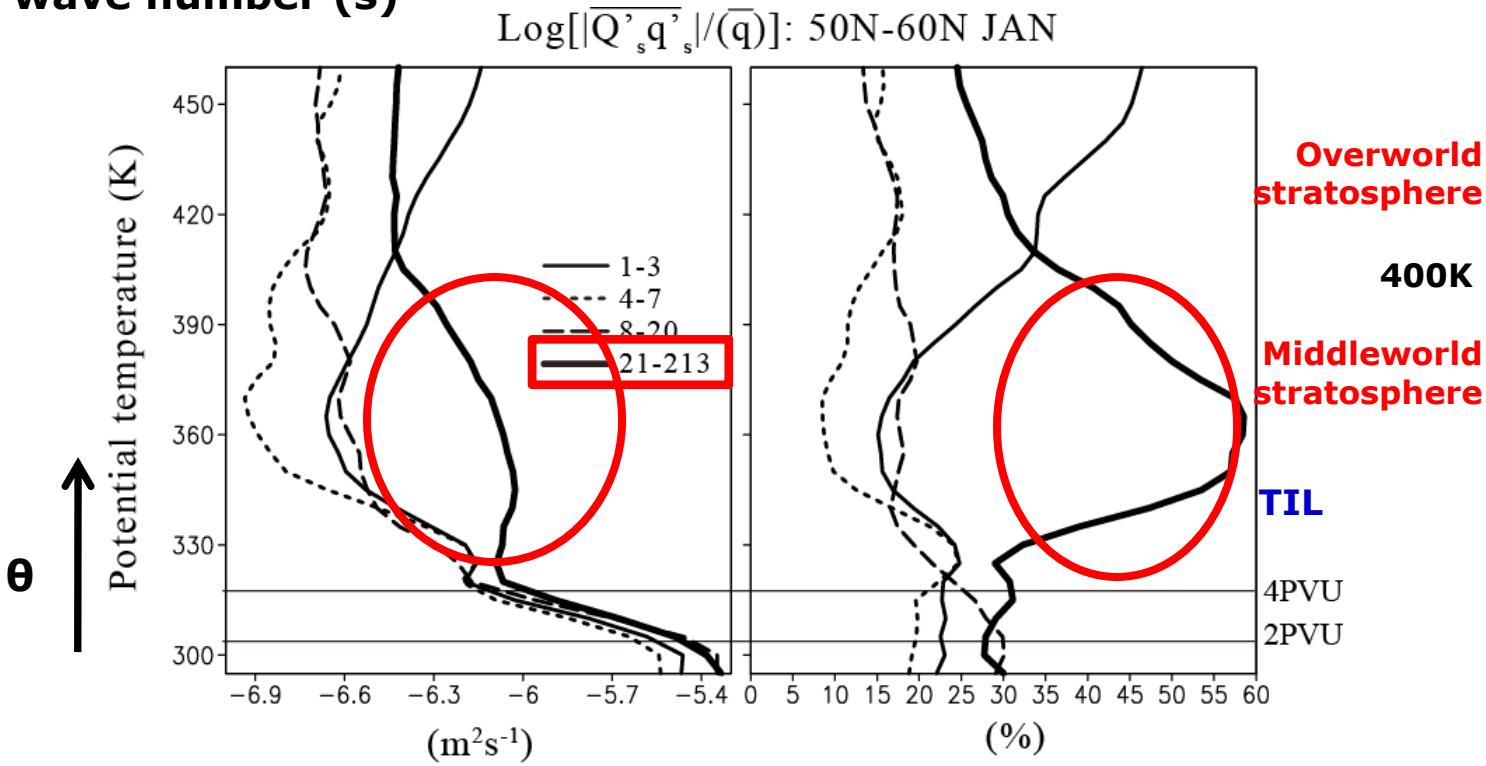
**50N-60N January**

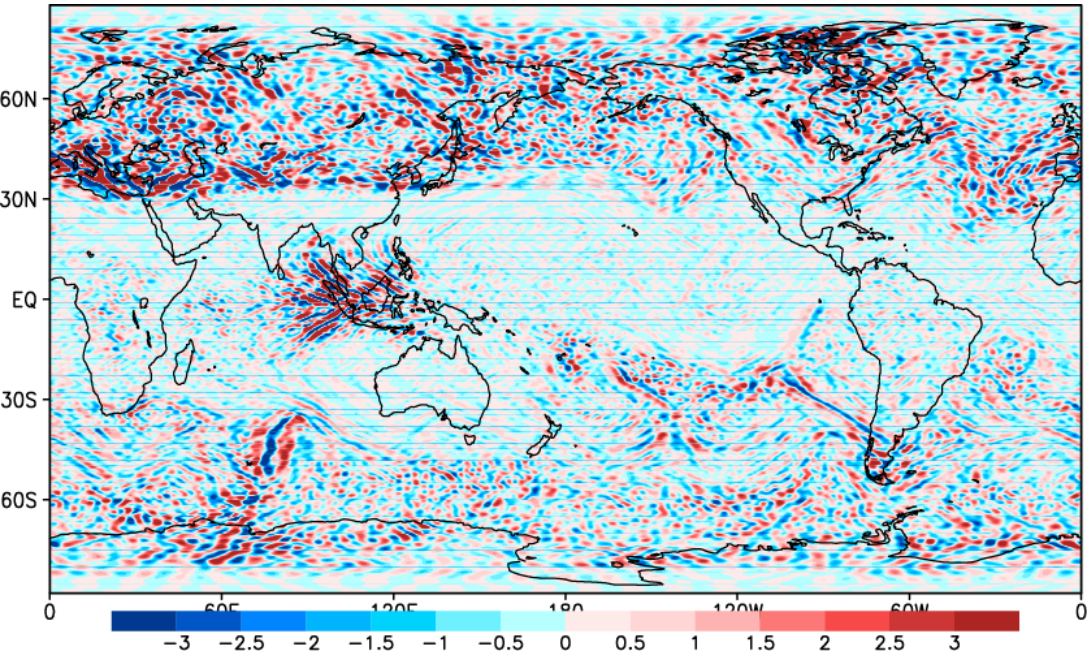
$$\left| \frac{\overline{Q'_s q'_s}}{\overline{q}} \right|$$

**Vertical mixing**

- very strong small-scale vertical mixing just above the tropopause
→ active 3-D mixing in the LMS



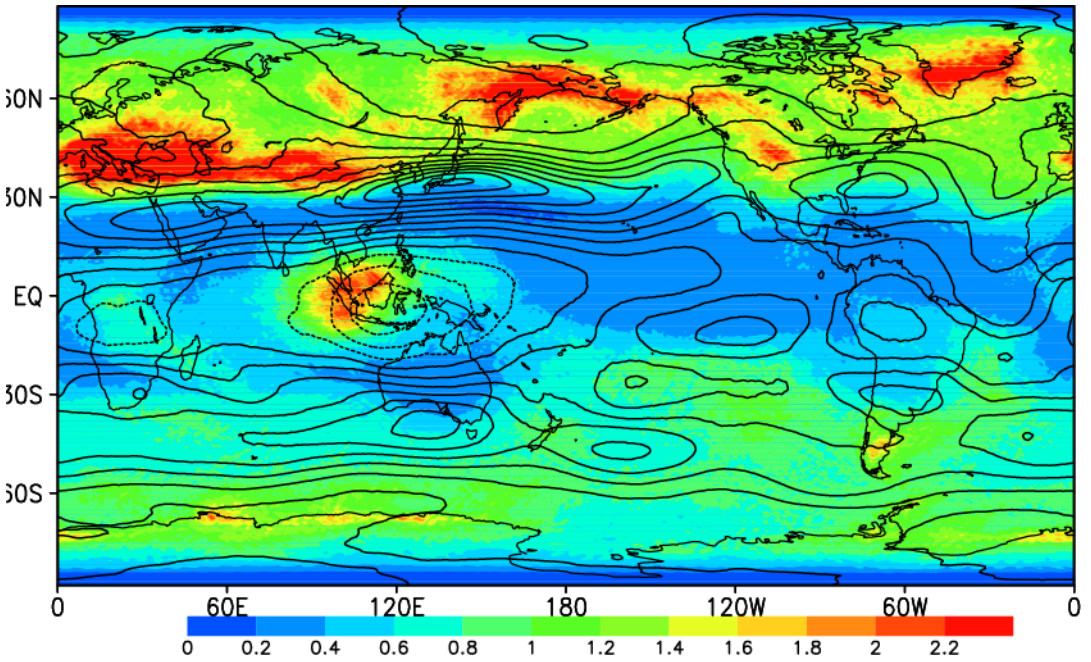






## PV' for n>21 at 360K

← **Snap-shot picture**

**The small-scale disturbances occur over possible sources of gravity waves (mountains, cyclones, fronts, convection)**




***-> The propagation and breaking of gravity waves activate 3-D mixing in the TIL.***

**January**

←**Monthly mean amplitude**

# Discussions: GWs and small-scale mixing around the TIL

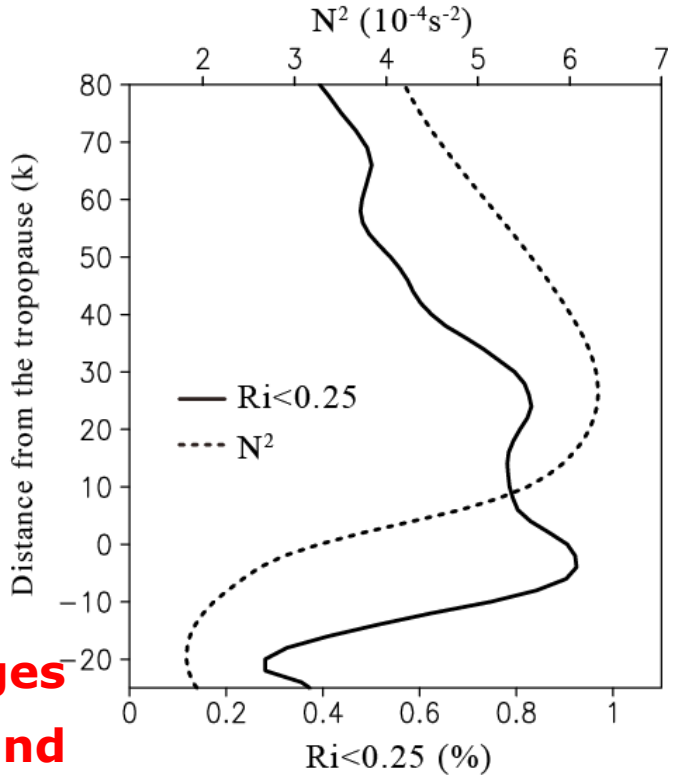
- **The linear wave theory: a large static stability allows the occurrence of large-amplitude GWs due to increase of the saturation amplitude.**

- **Even when GWs do not break, large-amplitude GWs can be dissipated due to radiative relaxation and can cause eddy vertical dispersions (under non-uniform diabatic heating fields).**

- **Just above the TIL, GWs can easily reach their saturation limit and breaking level because of a rapid decrease in static stability (and ρ) with height.**

- **Dynamic instability occurs more frequently in the tropopause region than at other levels, which also may lead to the saturation.**

- **These situations associated with rapid changes in static stability and the dissipation and saturation of GWs can cause small-scale 3-D mixing around the TIL.**




**N² & Probability of the occurrence of Ri<0.25**

•**The ExTL arises from downward transports in the lower levels and isentropic (winter) and vertical (summer) mixing in the upper levels.**

•**The TIL and the ExTL can be collocated because of common transport processes for constituents and heat and interactions between them.**

•**The small-scale dynamics associated with GWs play important roles in driving tracer transports. It is important to include these effects in GCMs or CTMs to obtain better simulations of the TIL and ExTL.**