To what extent are fine-scale processes and structures near the tropopause important for climate?

Thomas Birner

University of Munich & German Aerospace Center, Germany

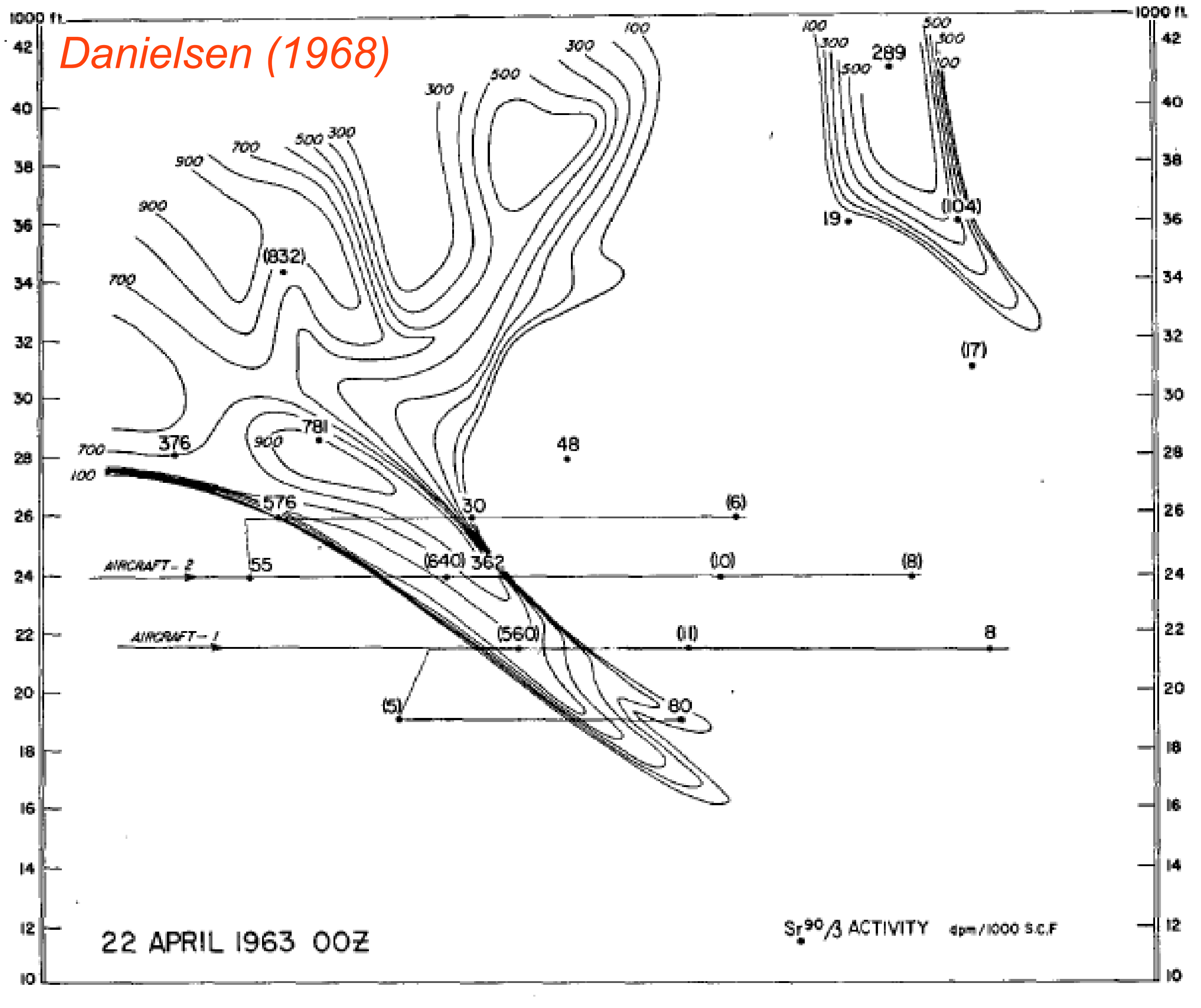


FIG. 4. Potential vorticity (contoured at intervals of 100×10^{-10} cm sec (°K) gm^{-1}) computed from Fig. 2 and β activity of strontium-90 (dpm/KSCF).

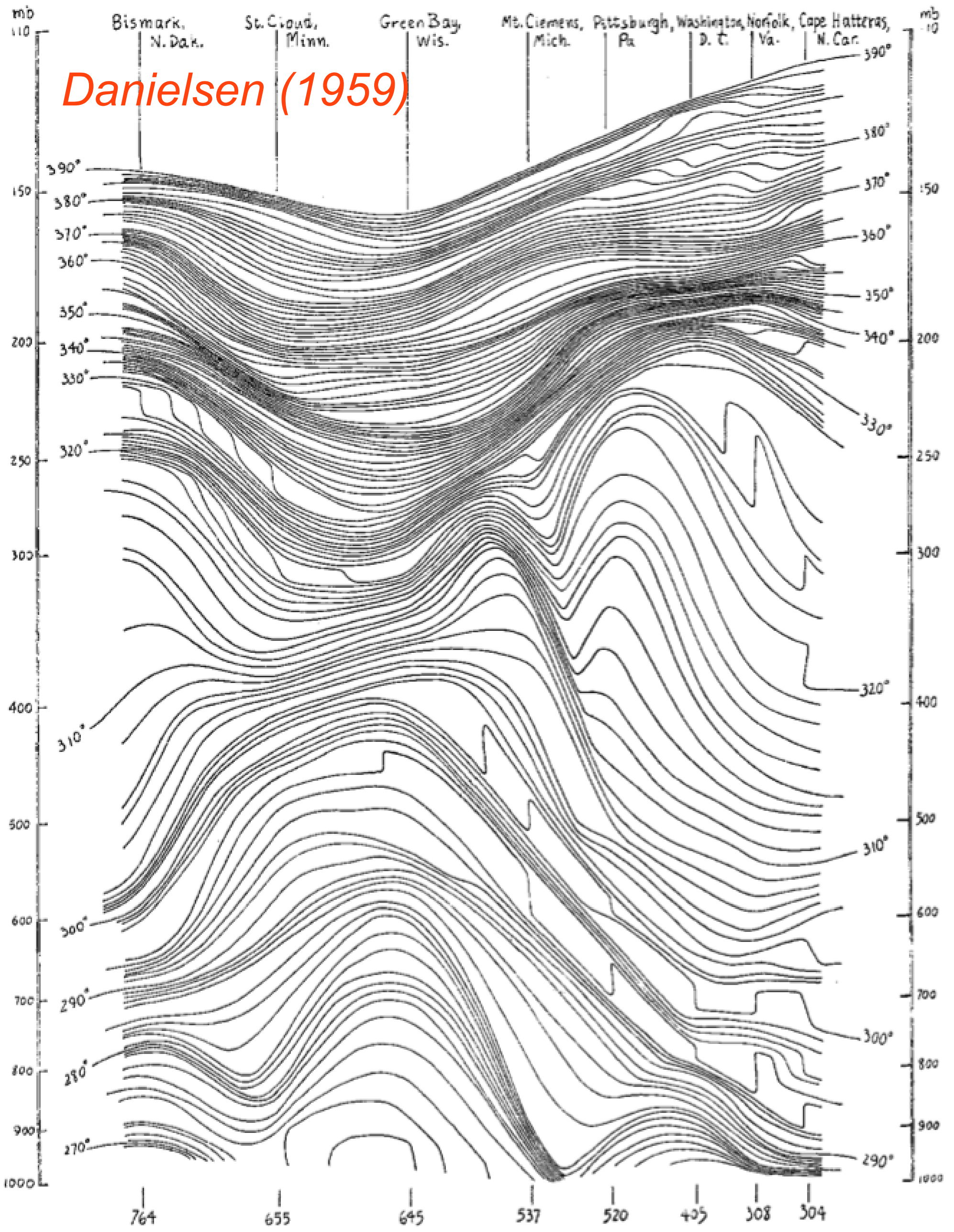
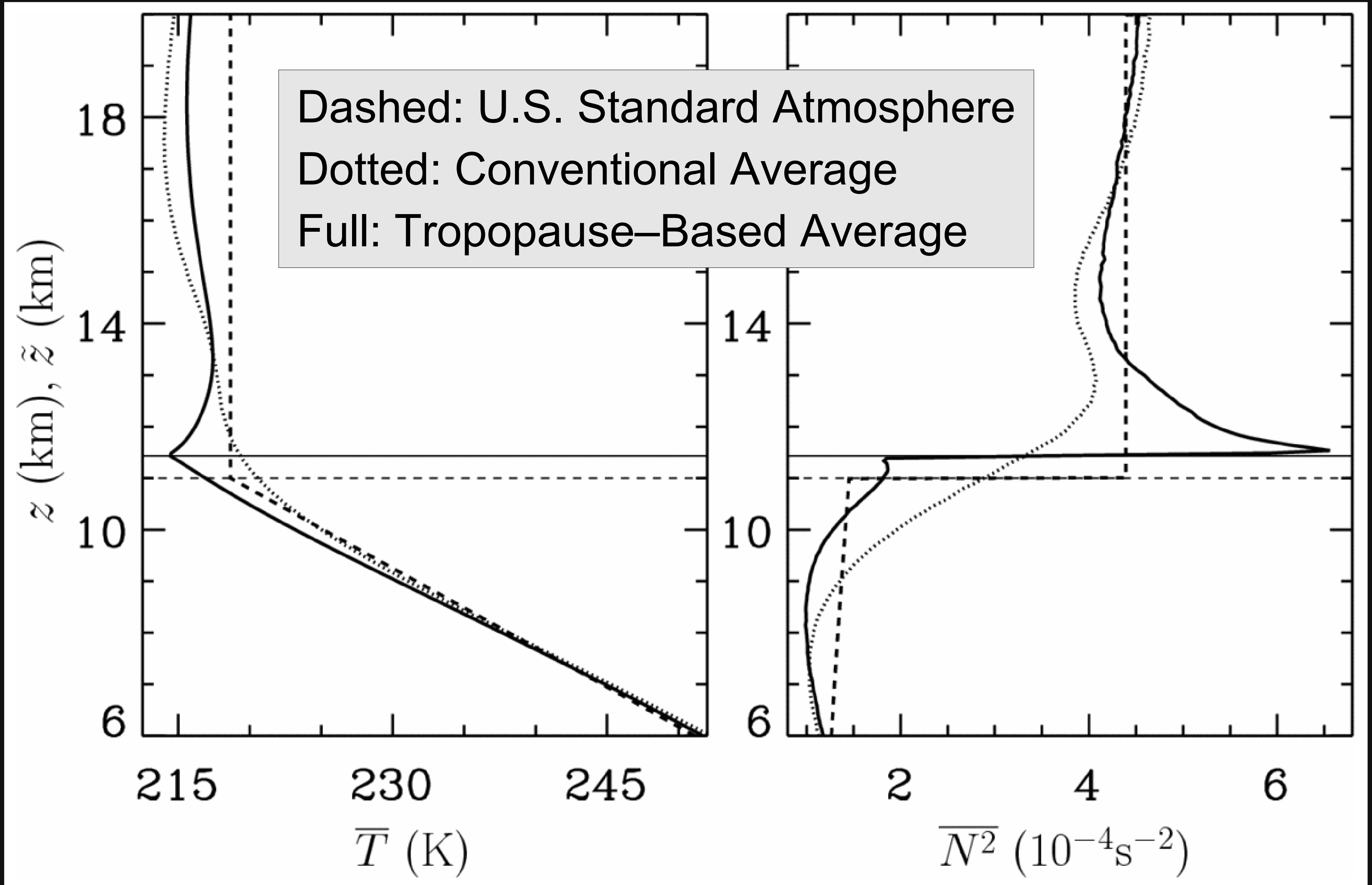


Fig. 25. Detailed vertical cross section from Bismarck, North Dakota to Cape Hatteras, North Carolina, 15.00 GMT, 29 March, 1956

Take-home points

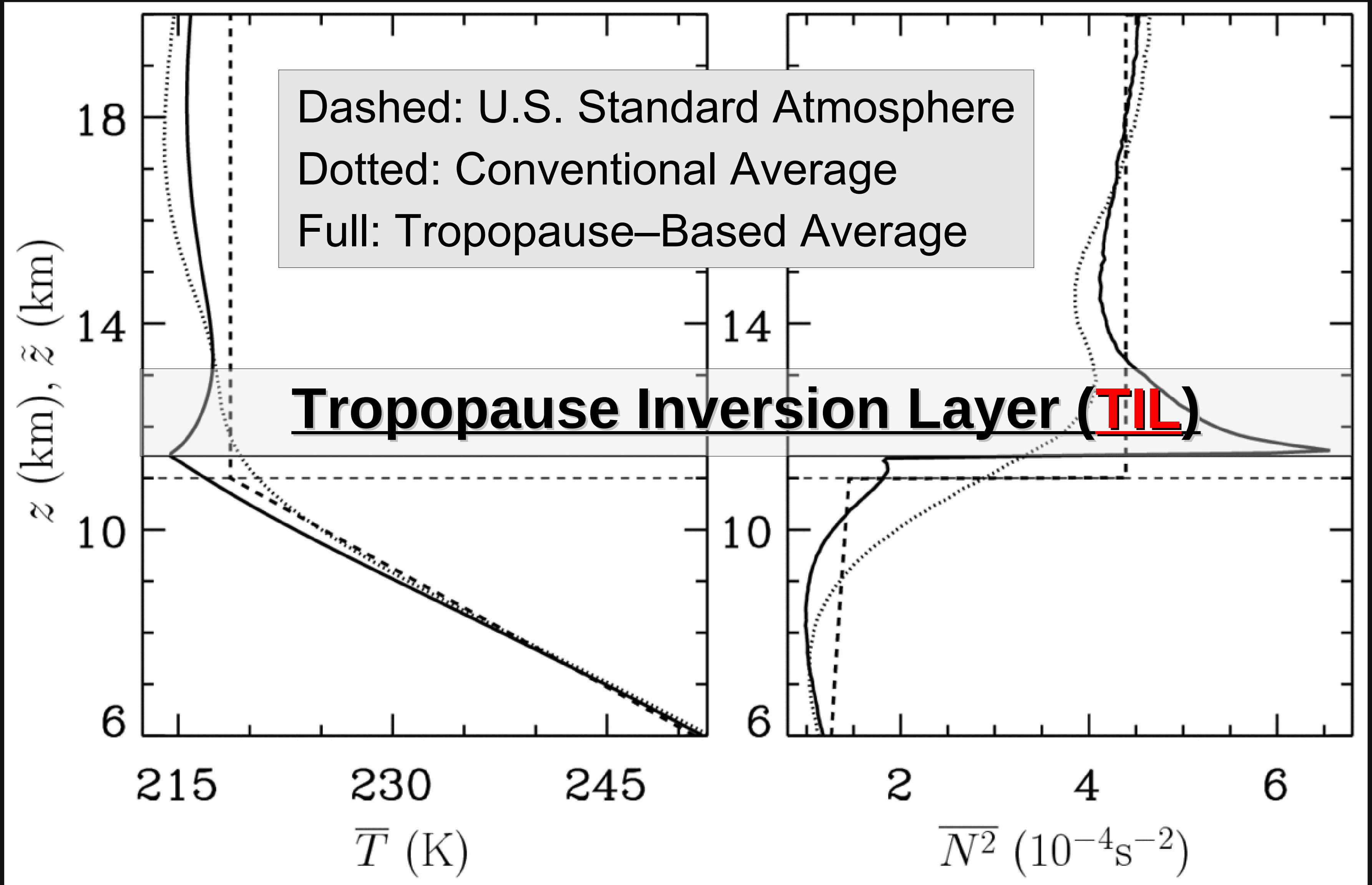
- potential modulation of general circulation features by tropopause sharpness: stronger TIL → equatorward jet shift
- Tropopause-level moist bias in current climate models due to overly dispersive transport → poleward jet bias, too strong Brewer-Dobson circulation
- Potential role of vertical mixing in regulating transport just above tropical tropopause

Climatology (annual mean) ~ 45° N
High Vertical Resolution Radiosonde Data



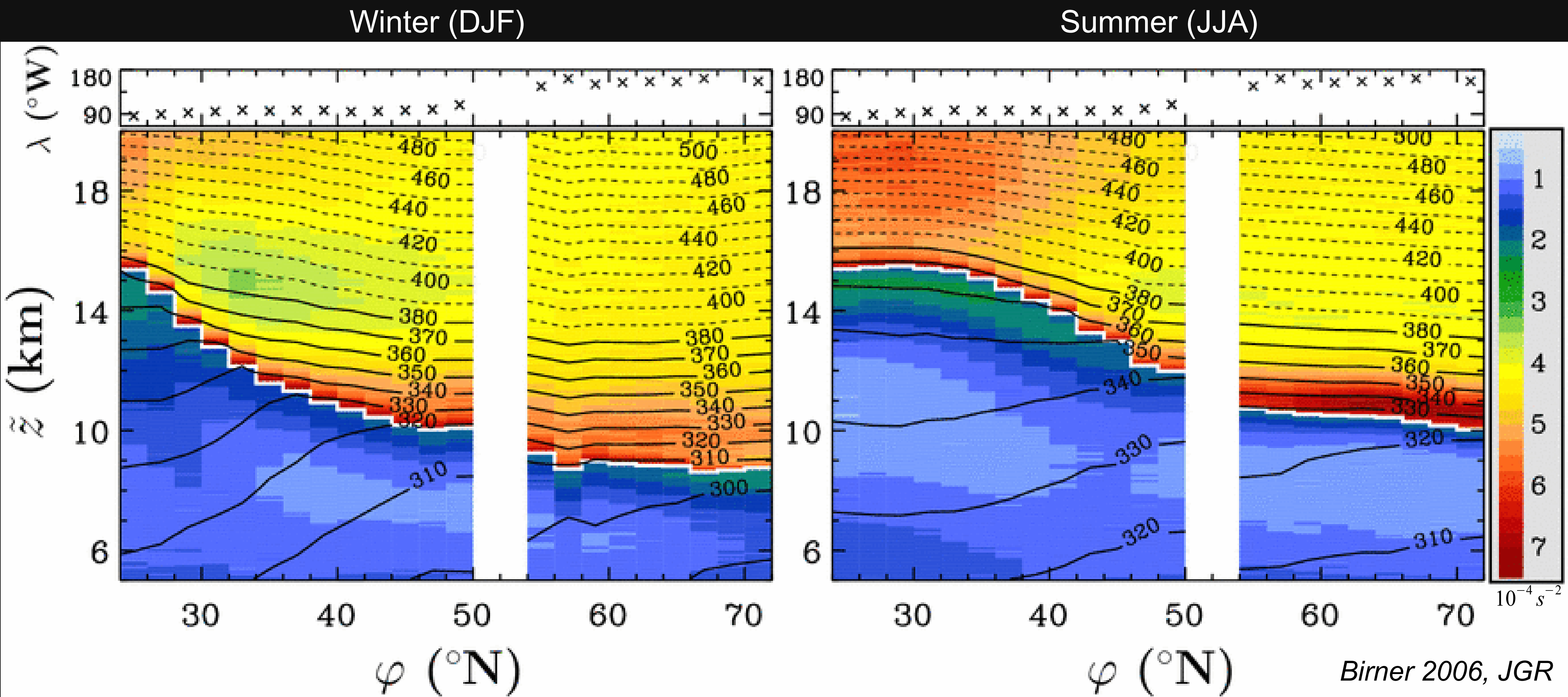
Birner (2006)

Climatology (annual mean) ~ 45° N
High Vertical Resolution Radiosonde Data



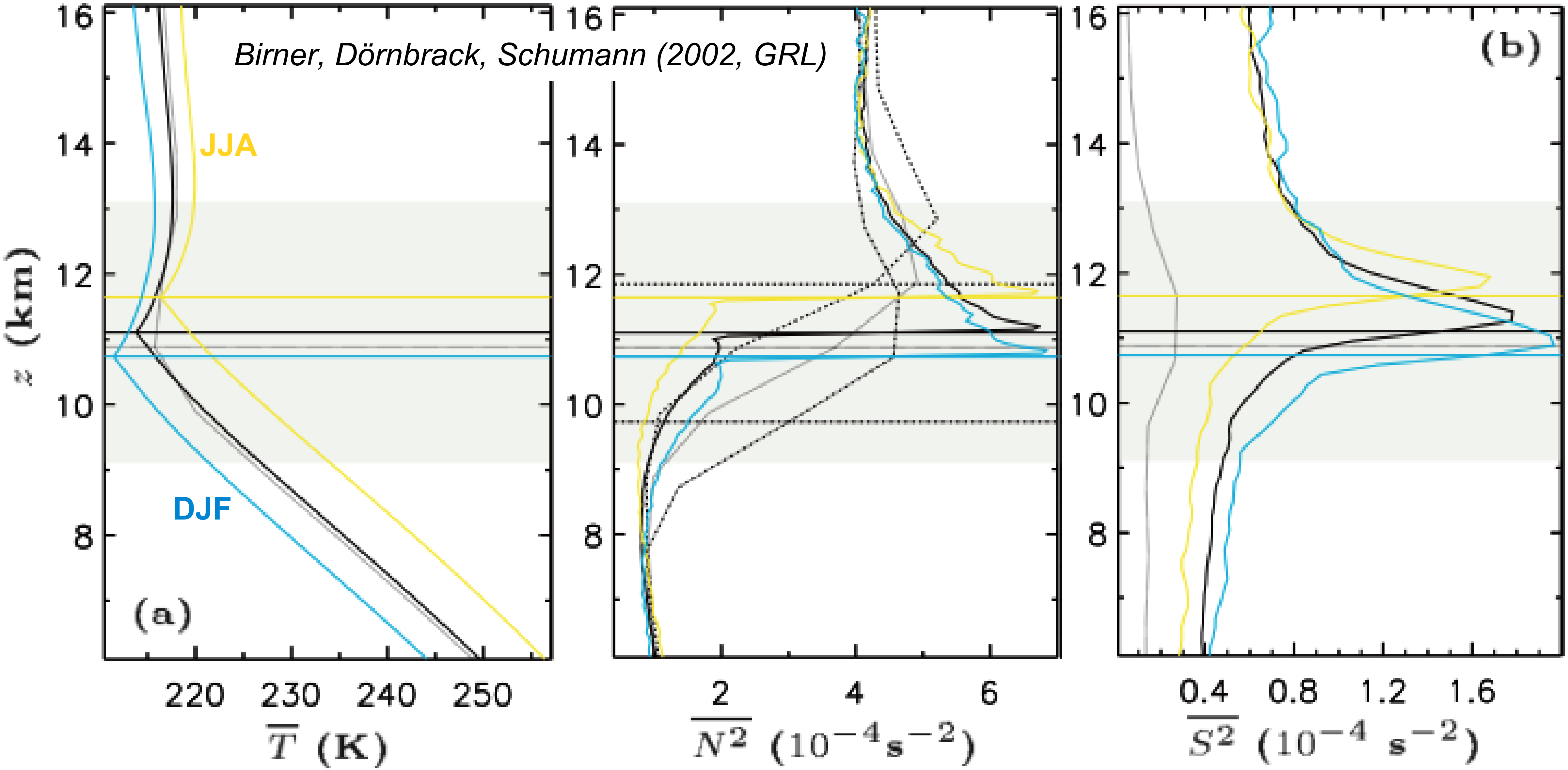
Birner (2006)

Zonal Averages, N^2 & Isentropes
US Radiosondes (1998–2002), Tropopause–Based



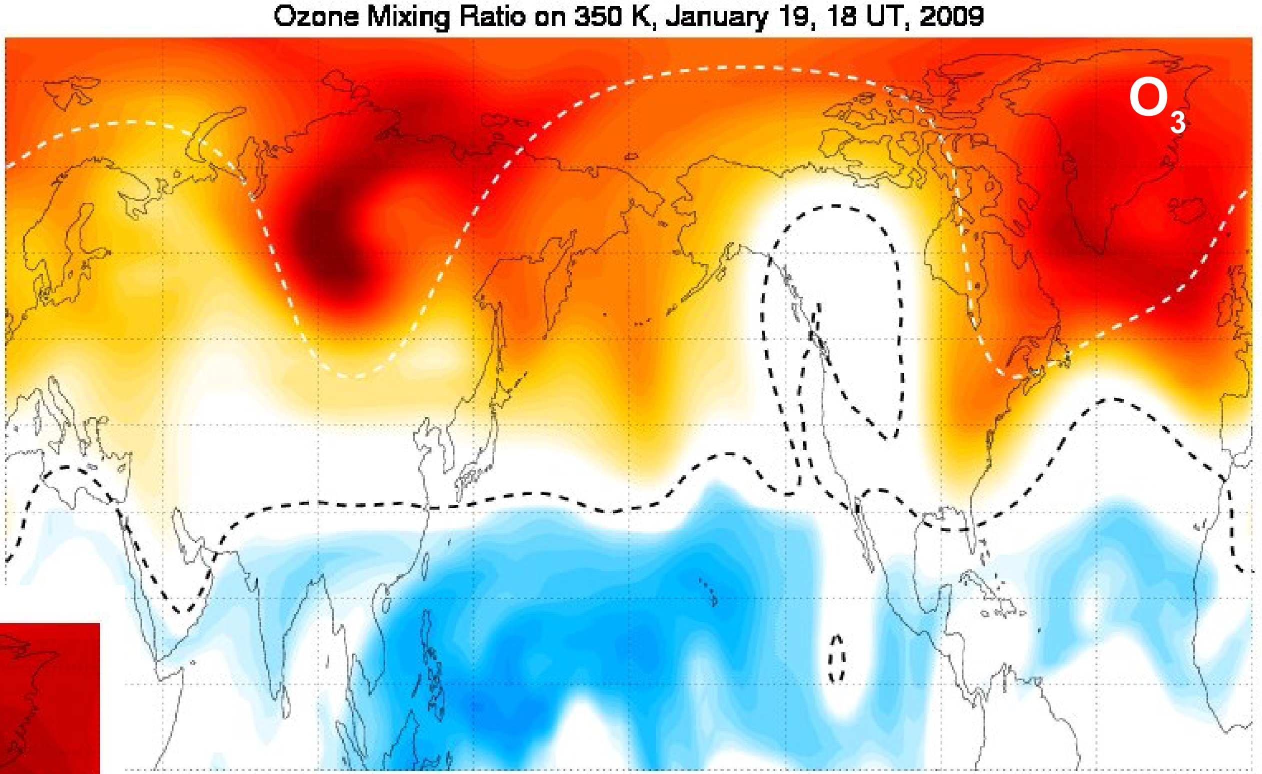
Birner 2006, JGR

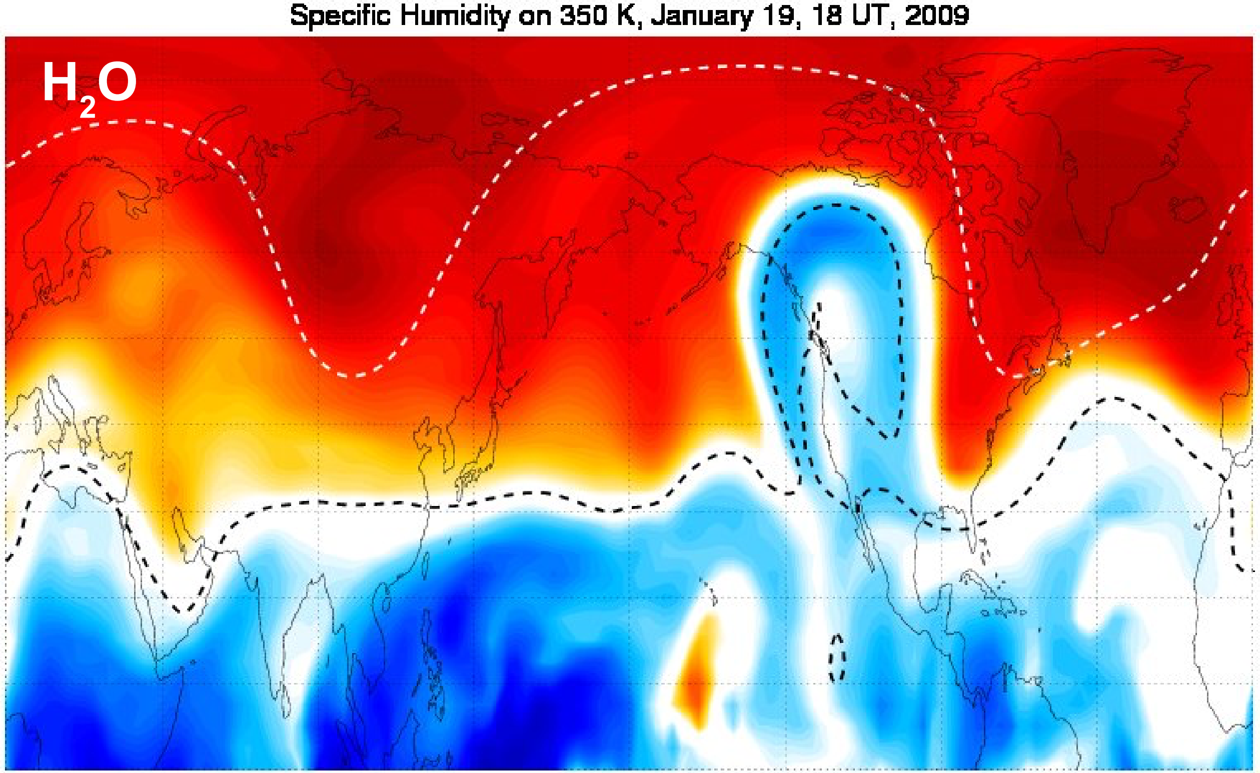
Tropopause-based climatologies for Munich, Germany

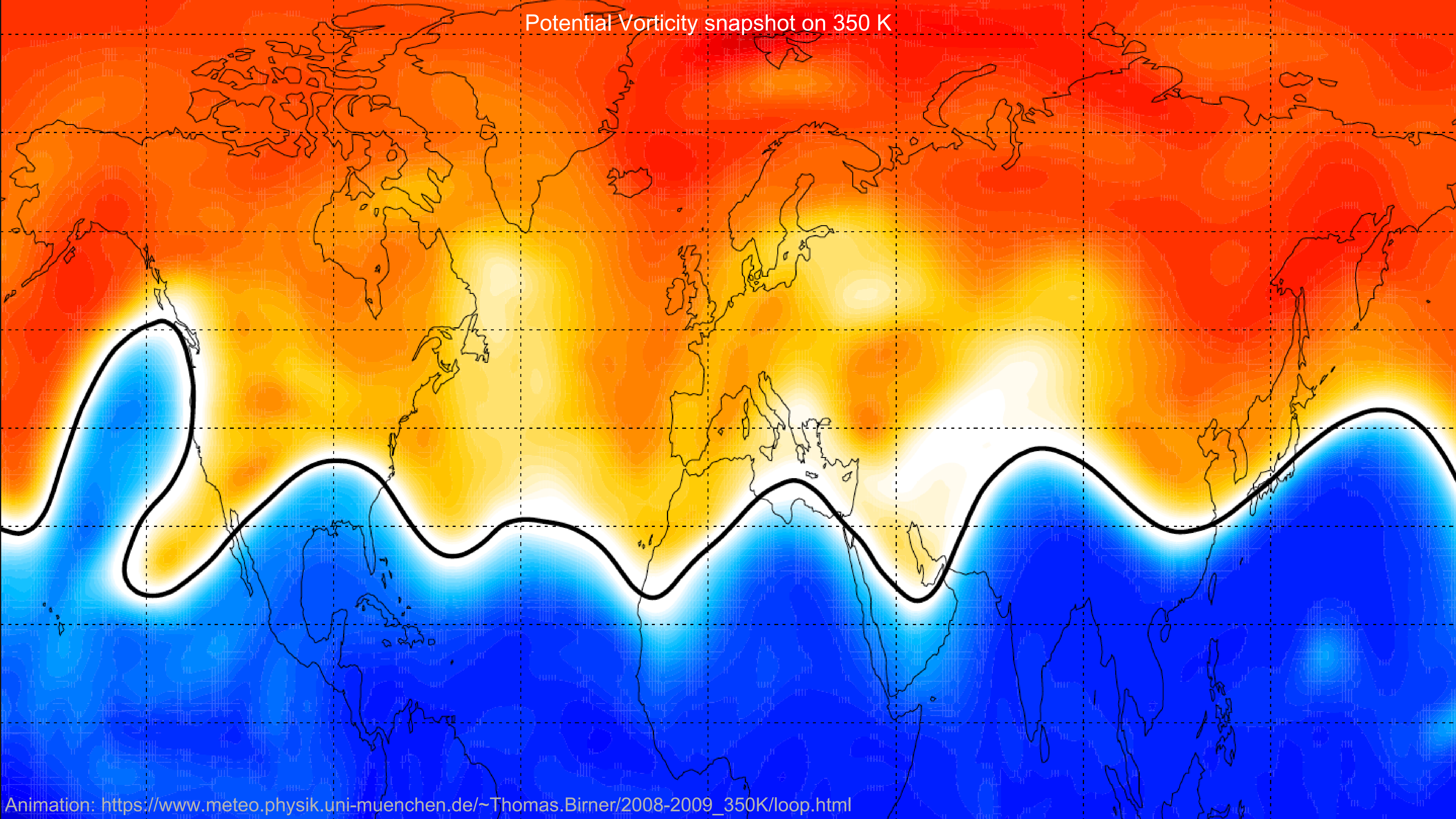


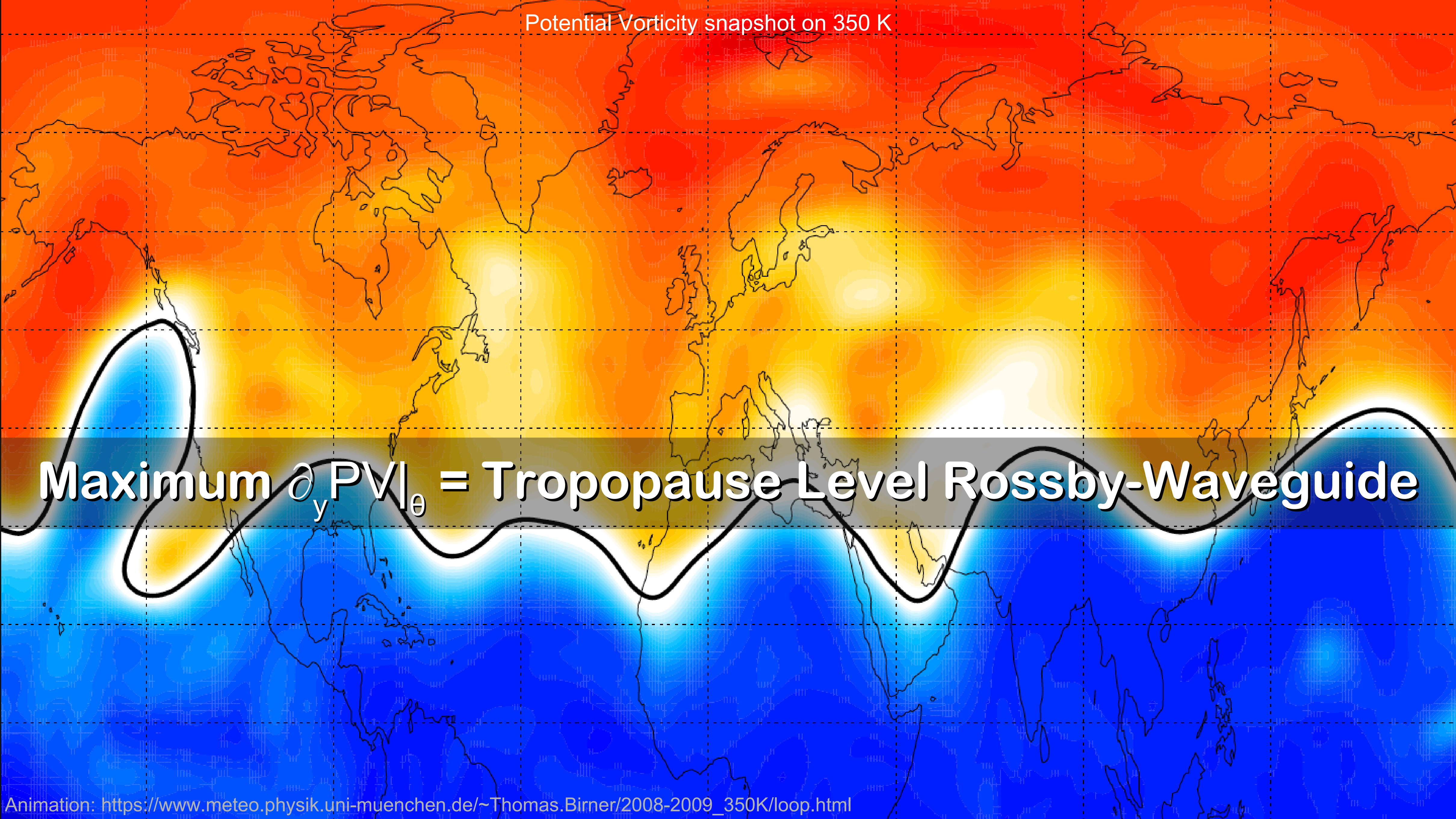
Strong horizontal tracer gradients at tropopause

Fields from ERA-Interim






Potential Vorticity snapshot on 350 K
Animation: https://www.meteo.physik.uni-muenchen.de/~Thomas.Birner/2008-2009_350K/loop.html


Potential Vorticity snapshot on 350 K
Maximum $\partial_y PV|_\theta$ = Tropopause Level Rossby-Waveguide
Animation: https://www.meteo.physik.uni-muenchen.de/~Thomas.Birner/2008-2009_350K/loop.html

Potential Vorticity: $P = \frac{\zeta_\theta + f}{\sigma} \sim (\zeta_\theta + f)\partial_z \theta$

→ PV gradient at tropopause determined by:

- vorticity gradient ~ jet sharpness/curvature $(-\partial_{yy} u)$
- thickness gradient ~ troposphere-stratosphere static stability contrast ~ thermal tropopause sharpness

→ related to tropopause inversion layer (TIL: maximum $\partial_z T$ just above mid-lat tropopause)

$\sigma = -g^{-1}\partial_\theta p \sim (\partial_z \theta)^{-1}$

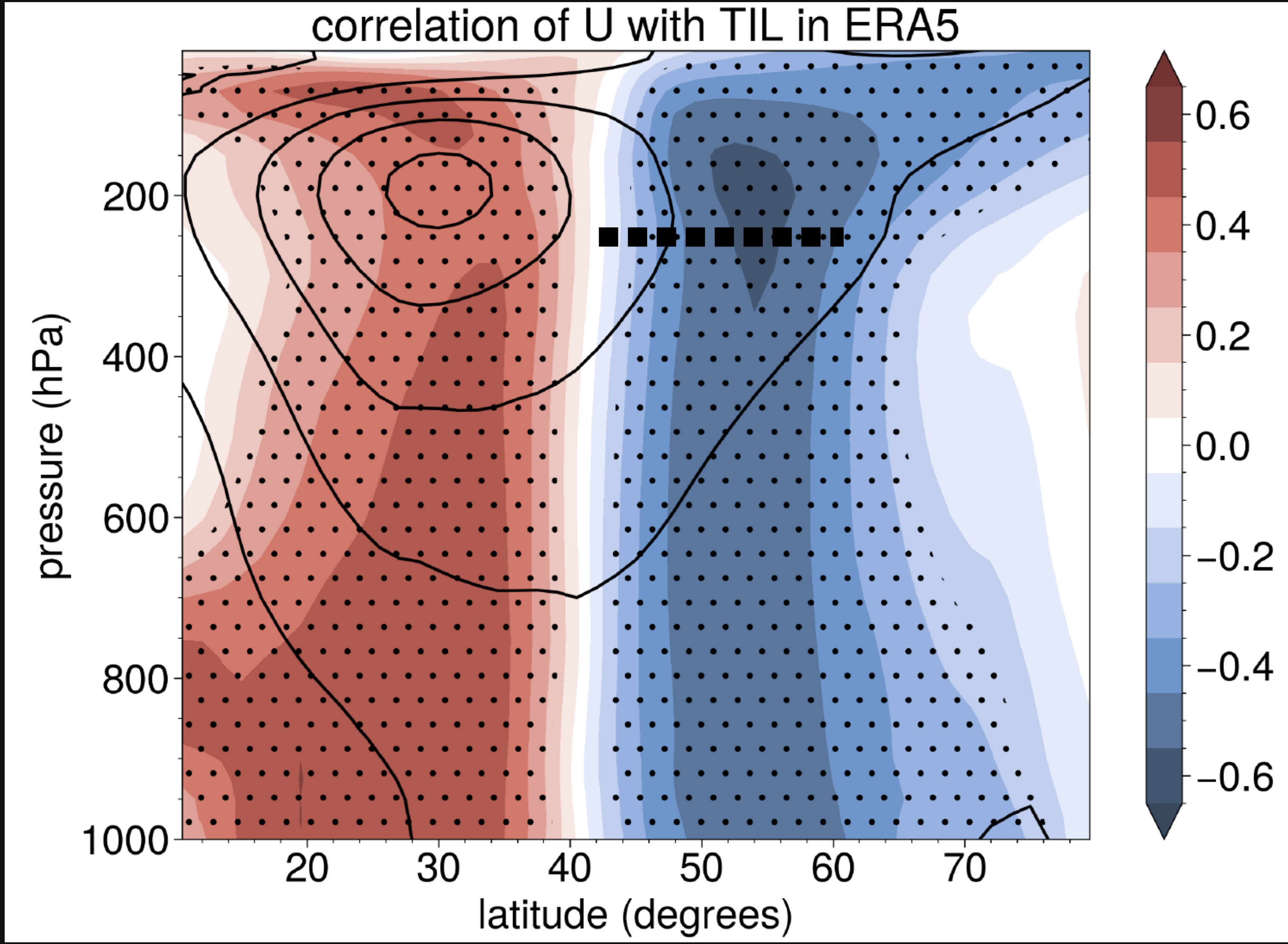
Potential impact of tropopause sharpness on the structure and strength of the general circulation

(Boljka & Birner, 2022)

https://www.nature.com/articles/s41612-022-00319-6

Co-Variability between mid-lat tropopause sharpness (~TIL strength) and jet on inter-annual time scales?

Tropopause Sharpness–Jet Inter-Annual Co-Variability

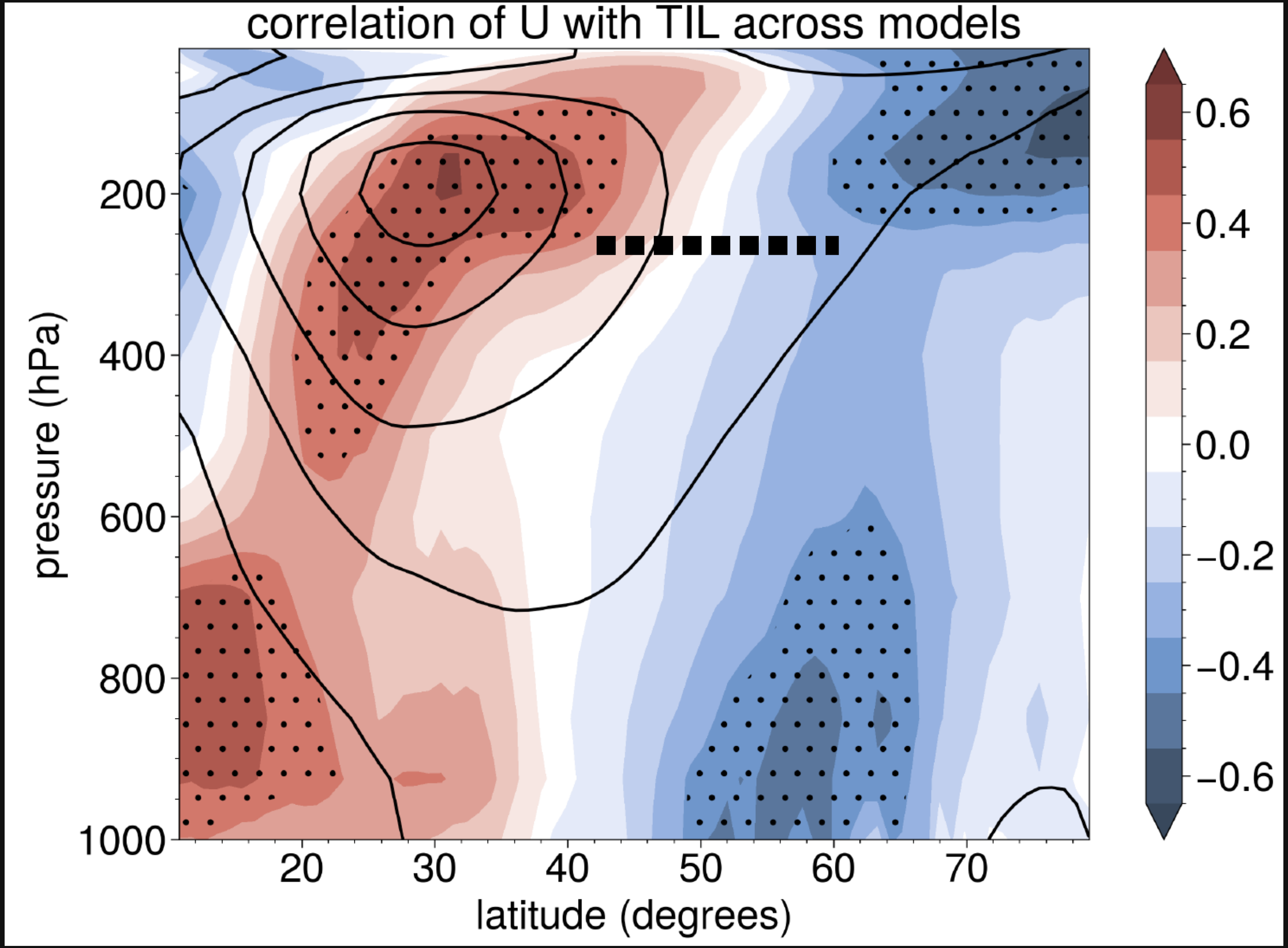


Correlation of zonal mean zonal wind with mid-lat TIL strength (NH winter, ERA5):

- sharper tropopause in mid-lat → equatorward EDJ shift, stronger STJ, Hadley cell contraction
- annular mode-like co-variability (~negative phase, e.g., Lorenz & Hartmann, 2003)

Boljka & Birner (2022)

Tropopause Sharpness–Jet Inter-Model Co-Variability



Correlation of zonal mean zonal wind with mid-lat TIL strength (NH winter, across CMIP6 models):

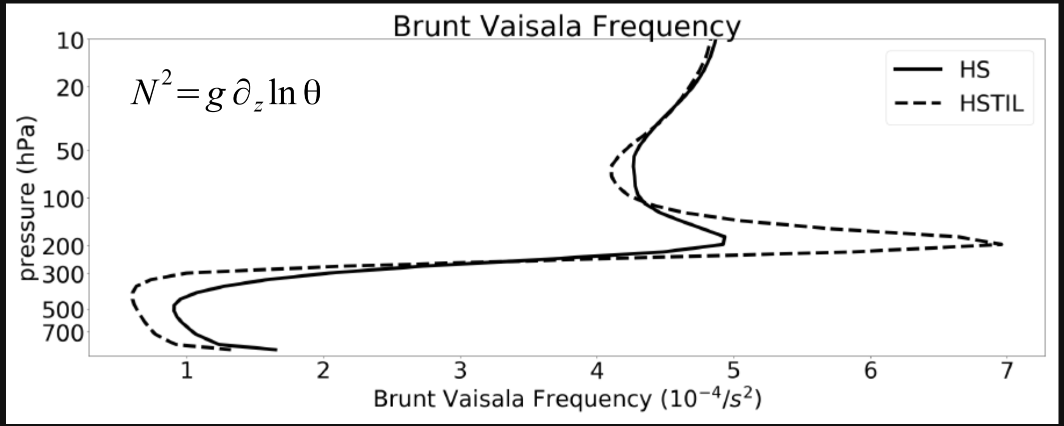
- Overall similar to inter-annual variability in ERA5
- Models with sharper tropopause tend to have more equatorward EDJ & stronger STJ

Boljka & Birner (2022)

Mechanistic link between mid-lat tropopause sharpness (~TIL strength) and jet?

Mechanistic numerical experiments with dry-dynamical core GCM

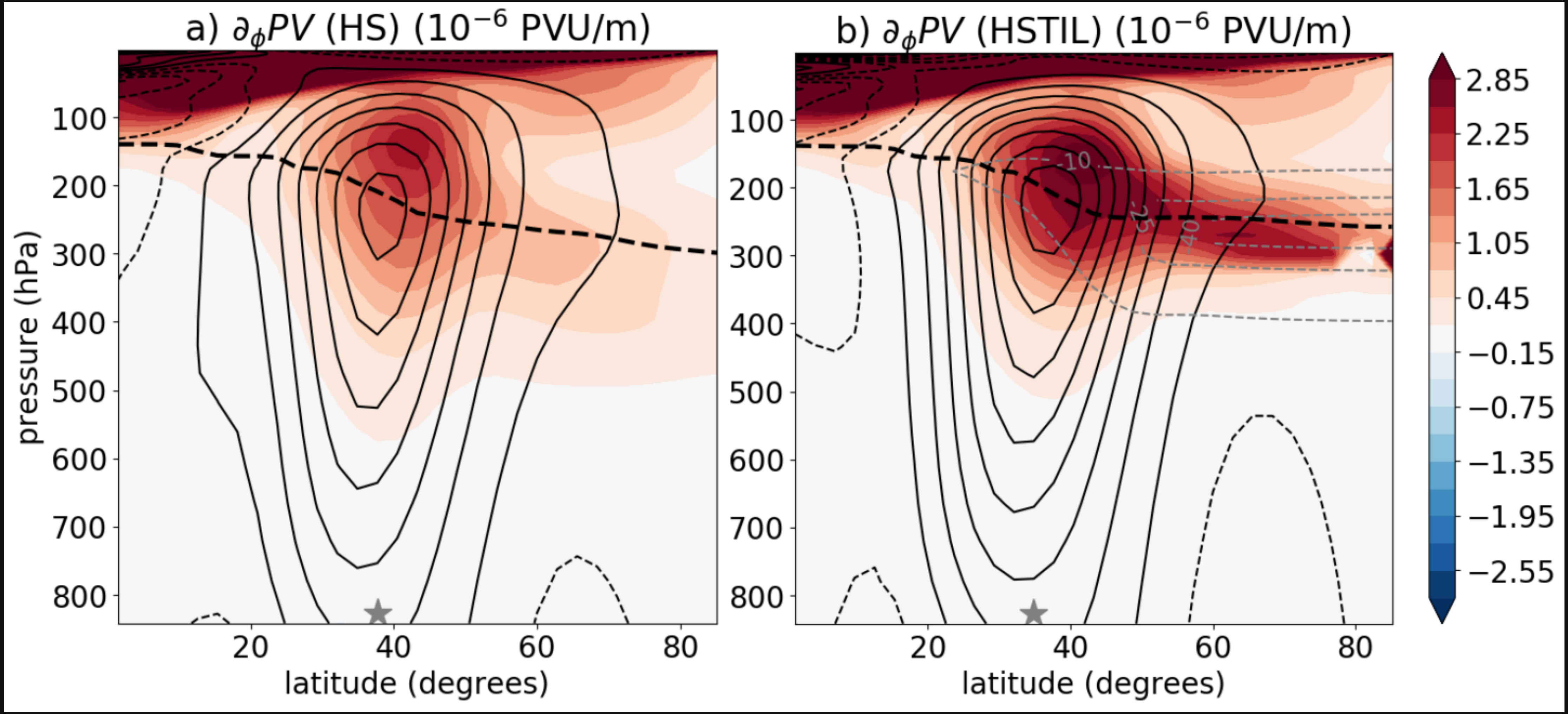
- Held-Suarez (HS) type simulations
- Standard/control run: weak TIL/tropopause sharpness
- Modified run: imposed tropopause cooling, i.e., imposed TIL



Stronger TIL → Stronger PV Gradient

Control run (weak TIL)

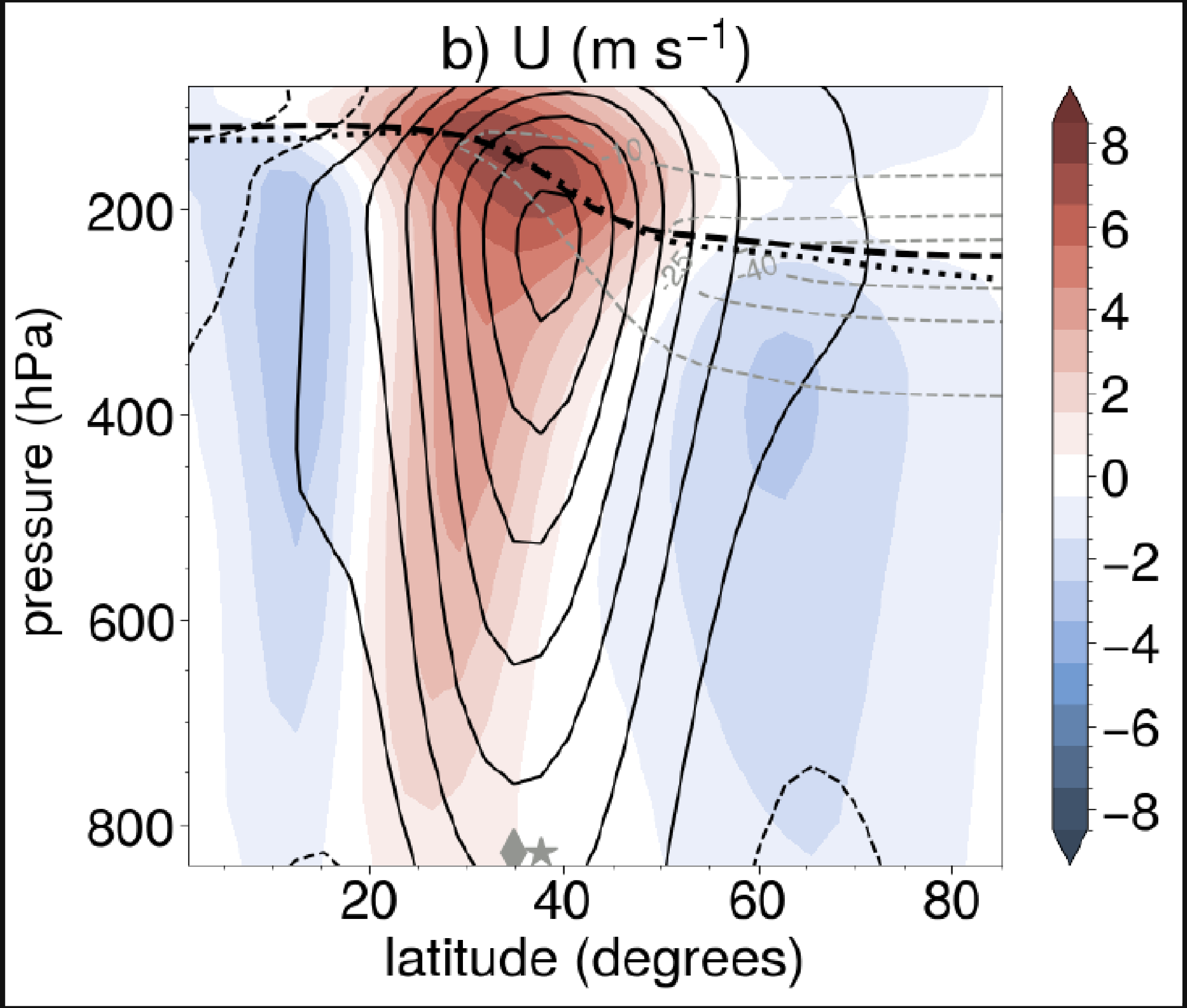
Imposed-TIL run



Boljka & Birner (2022)

Gray contours: imposed cooling

Stronger TIL → Equatorward Jet Shift



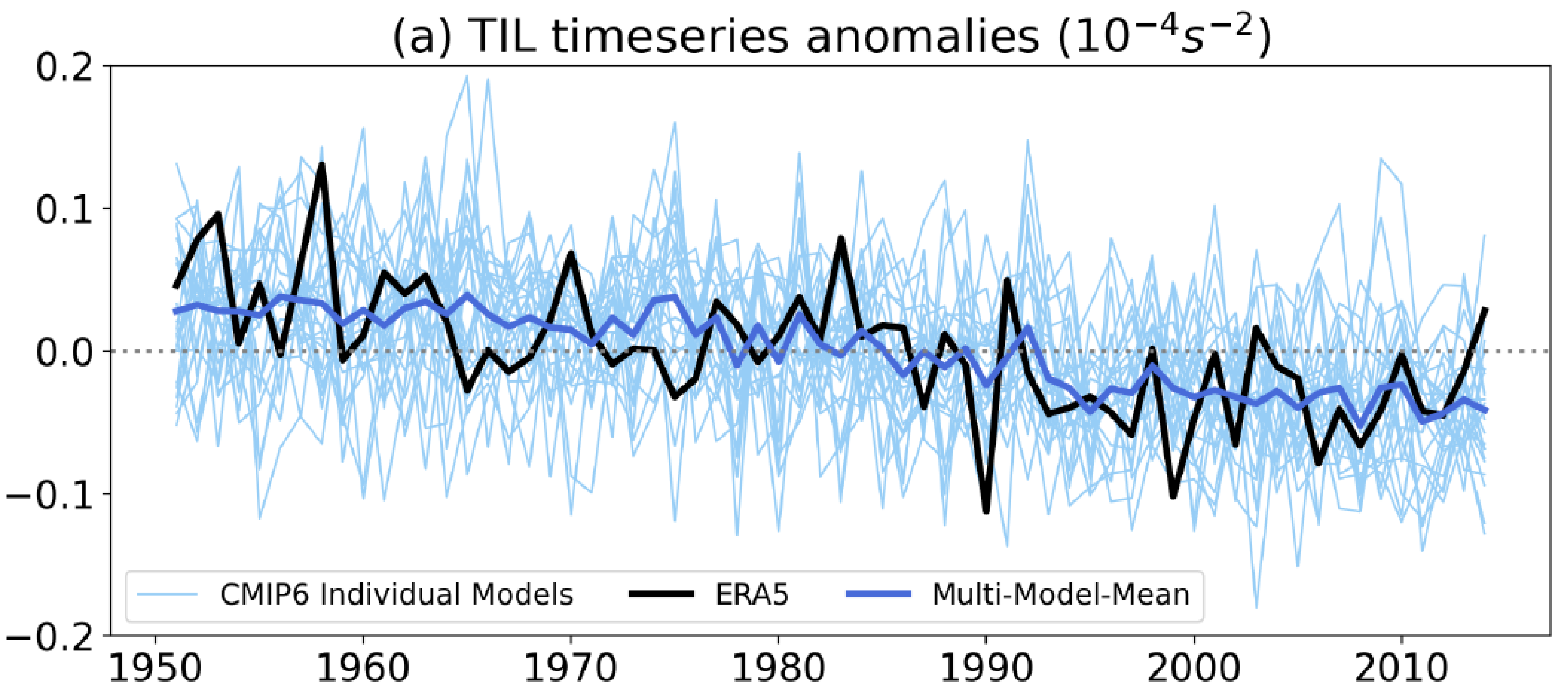
Boljka & Birner (2022)

Color shading: difference imposed-TIL minus control run

Black contours: Control run zonal wind

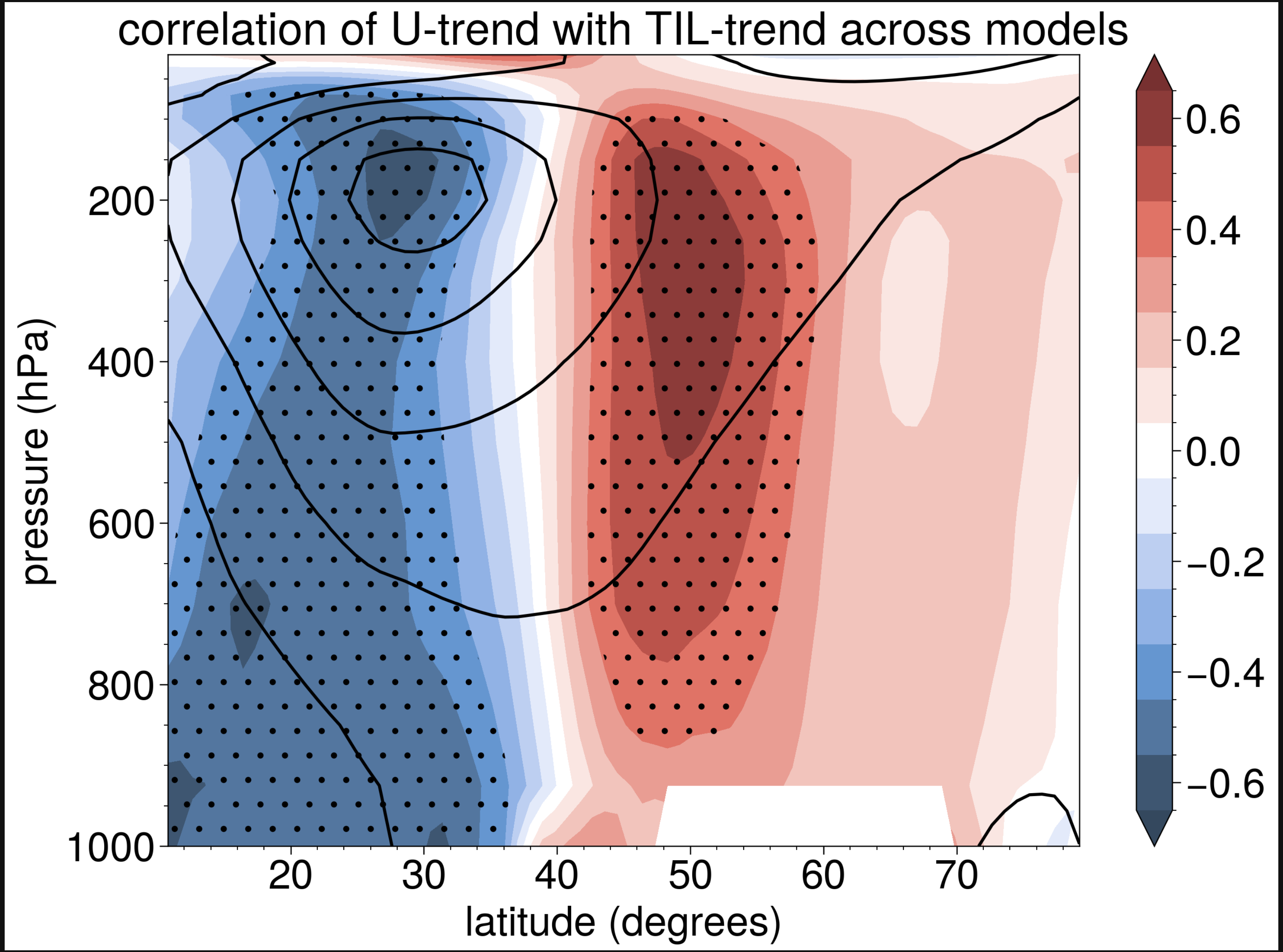
Gray contours: Imposed cooling

Weakening long-term trend in NH winter mid-lat TIL strength



Boljka & Birner (2022)

Stronger TIL weakening → more poleward jet shift



Correlation of long-term trends (historical) in zonal mean zonal wind with mid-lat TIL strength across models:

- Models with larger trend toward less sharp tropopause show stronger poleward EDJ shift, stronger weakening of STJ, stronger Hadley cell widening

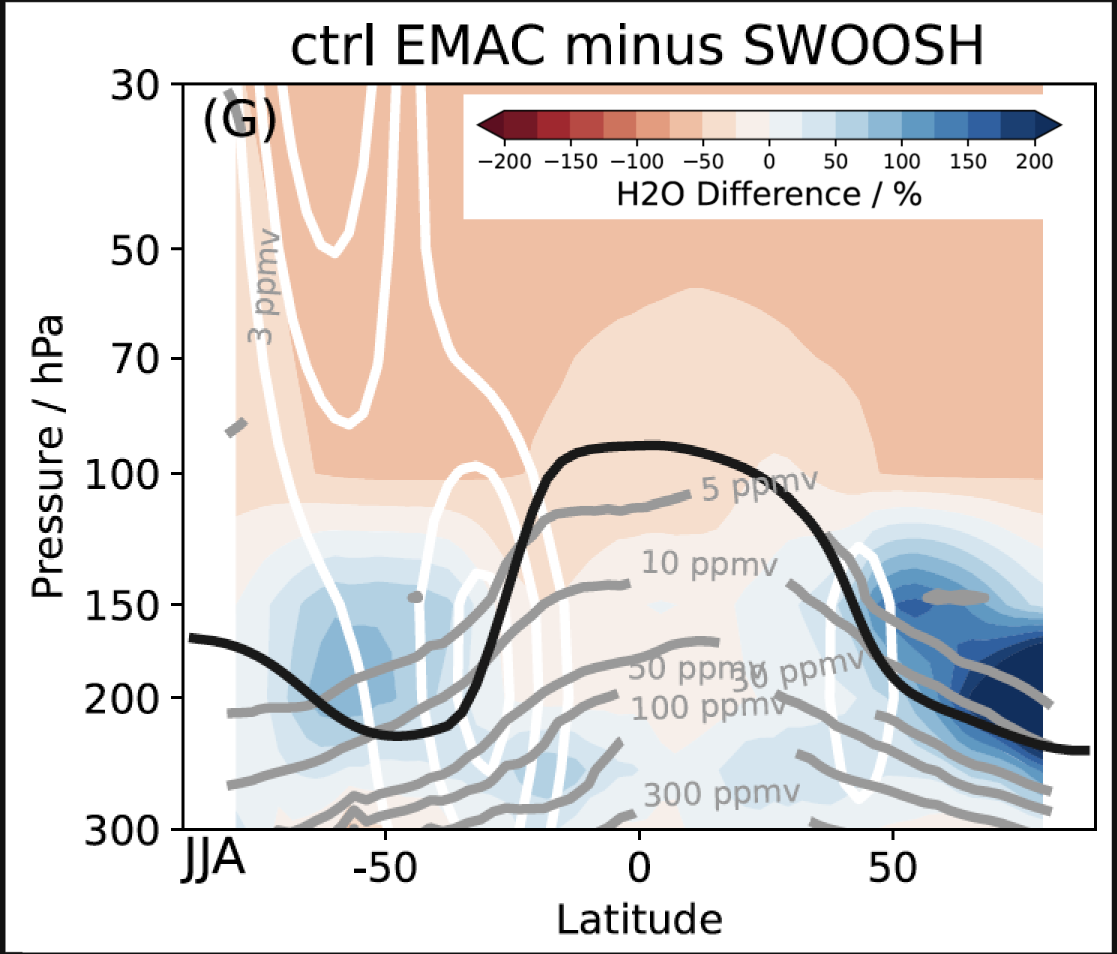
Boljka & Birner (2022)

Tropopause-level moist bias in current climate models due to overly dispersive transport □ Circulation?

(Charlesworth et al., 2023)

https://www.nature.com/articles/s41467-023-39559-2

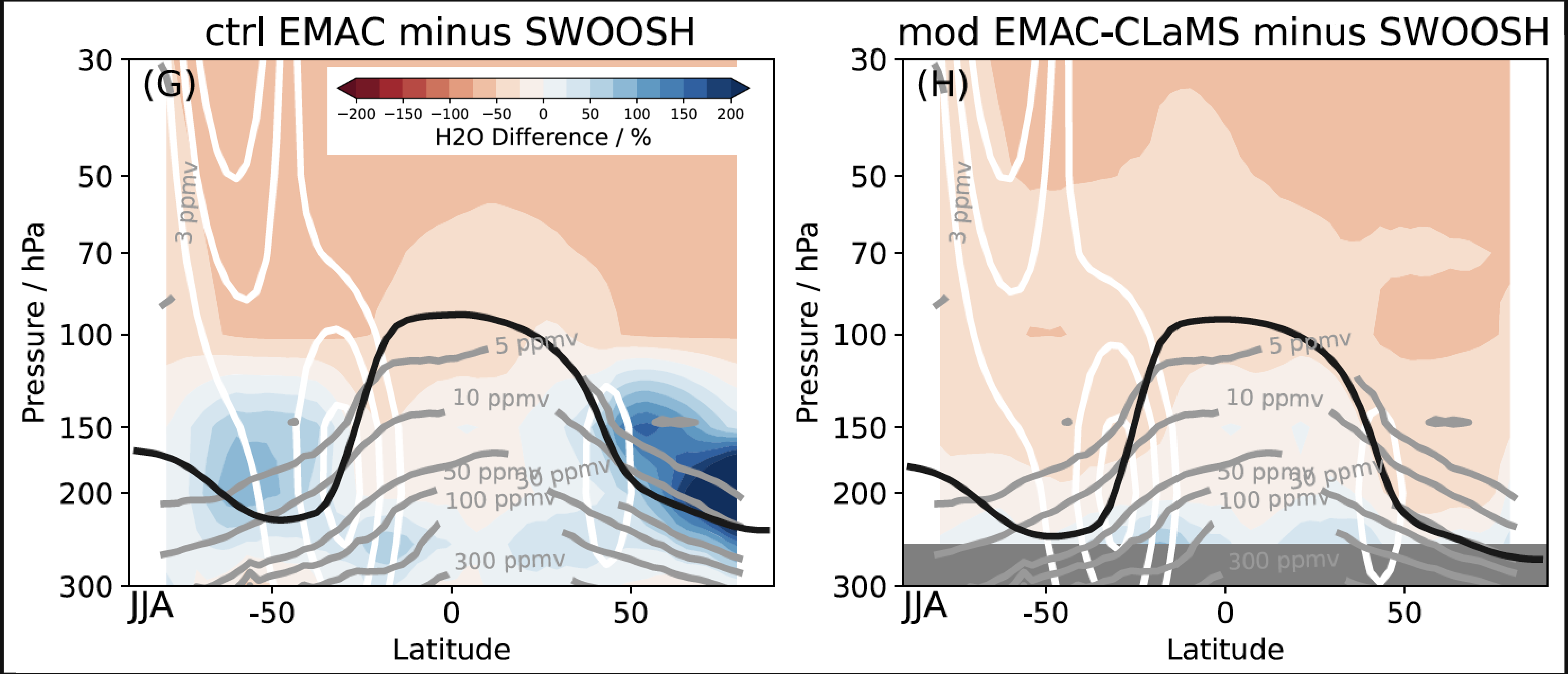
Lowermost stratospheric moist bias in climate model simulations



JJA

Charlesworth et al., 2023

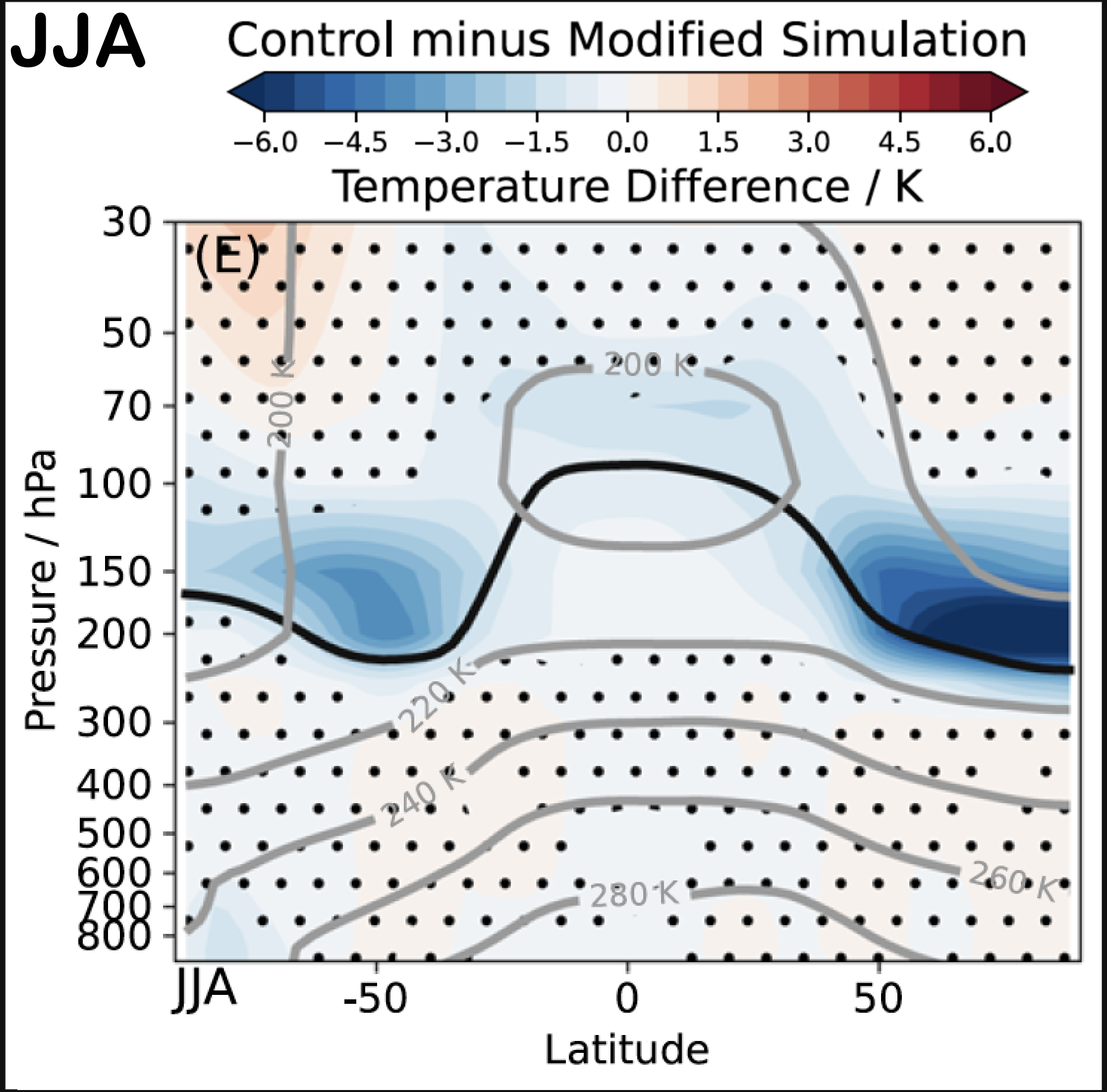
Lowermost stratospheric moist bias in climate model simulations



JJA

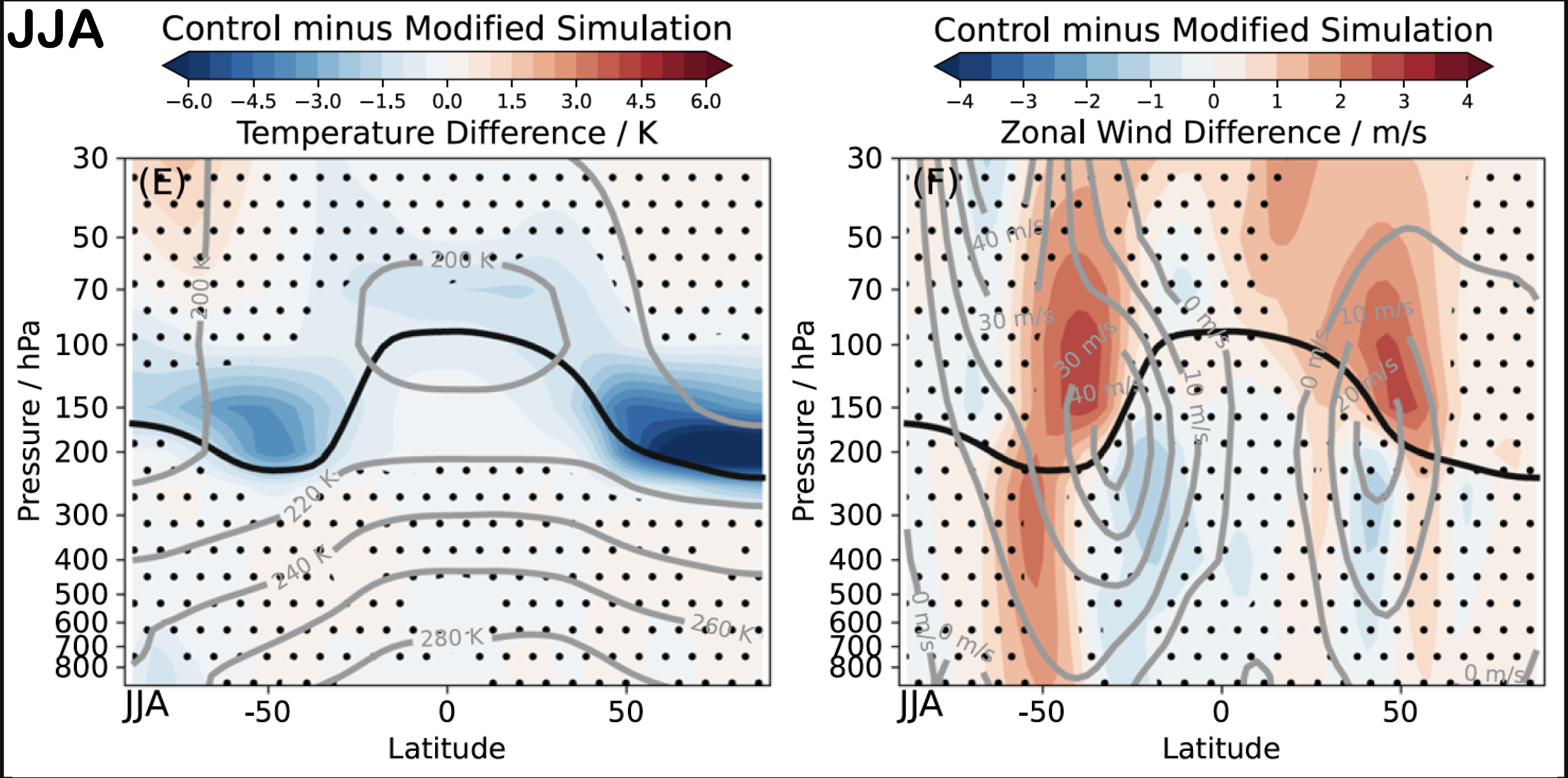
Charlesworth et al., 2023

Circulation response to lowermost stratospheric moist bias



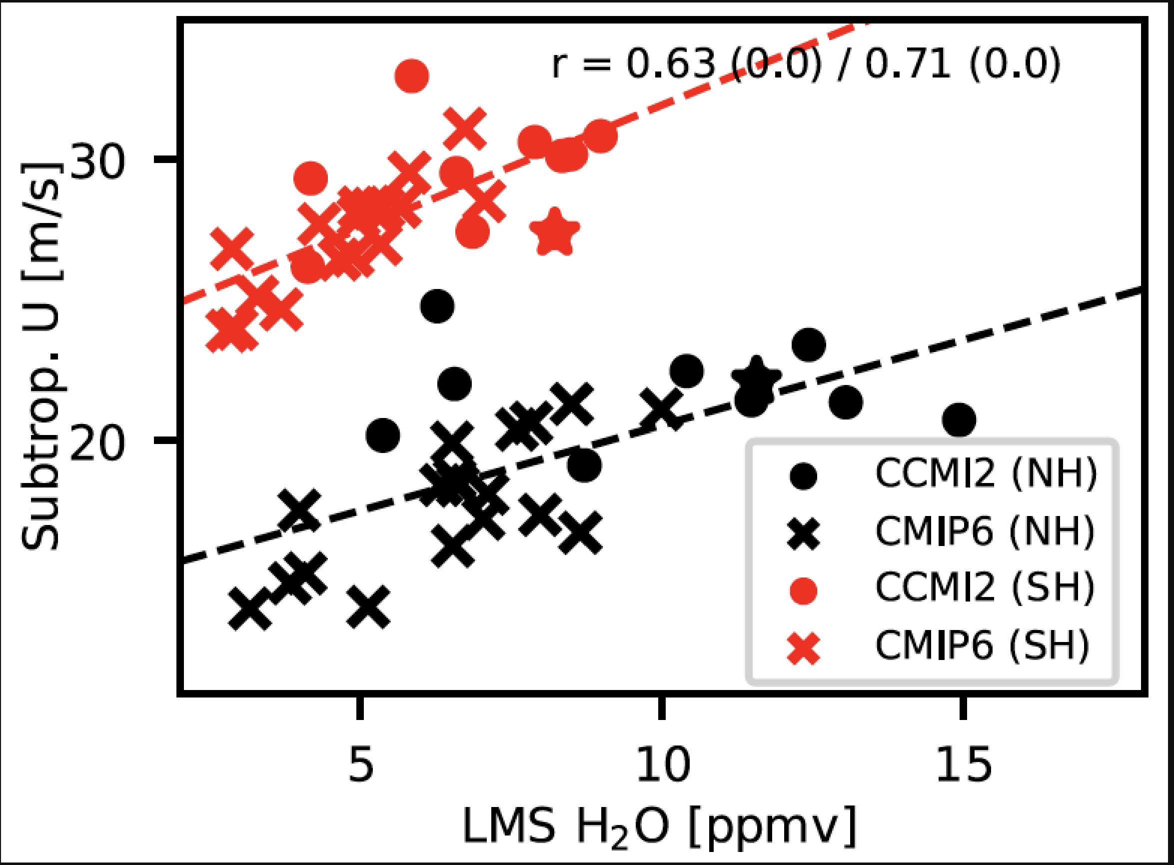
Charlesworth et al., 2023

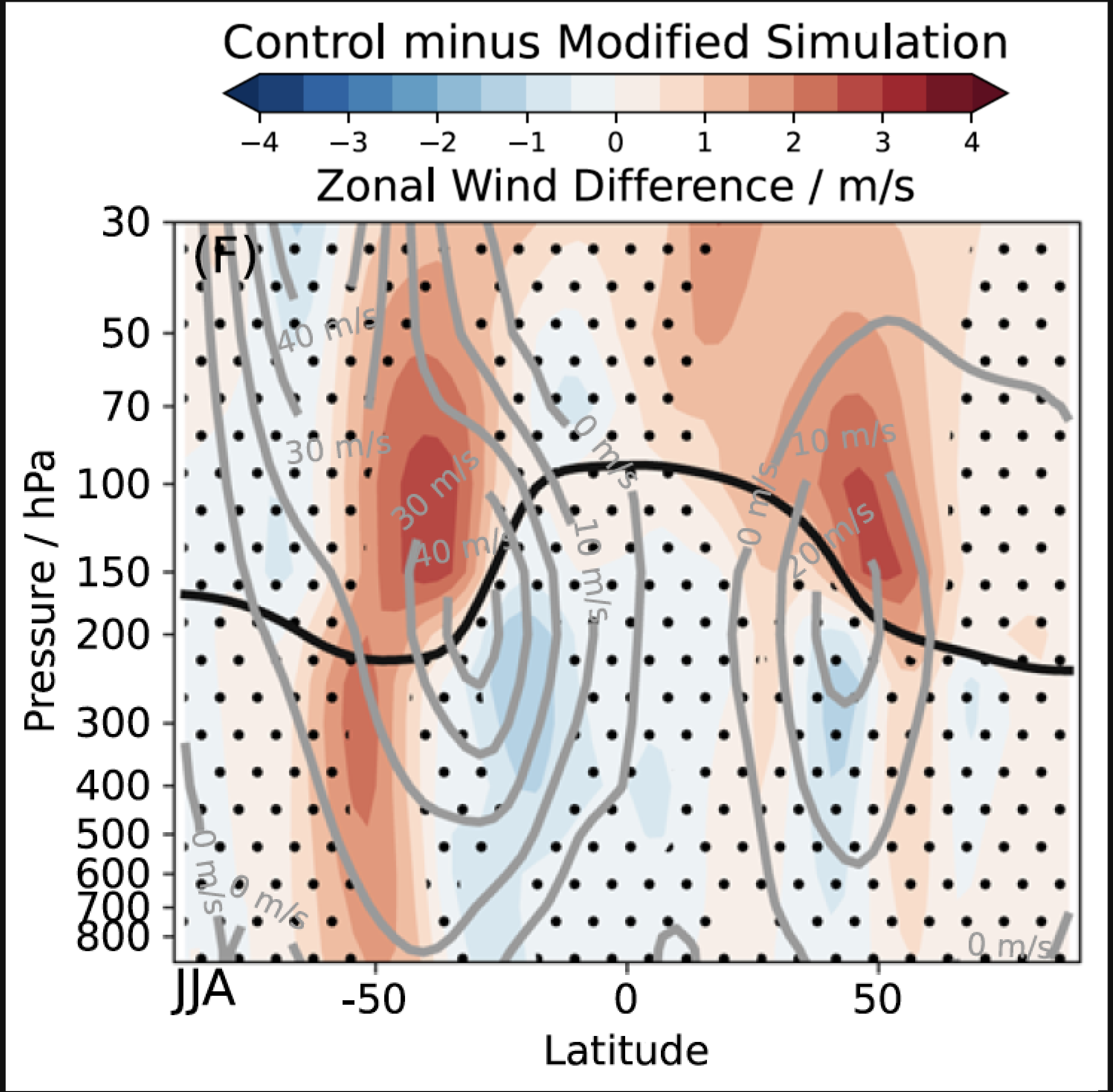
Circulation response to lowermost stratospheric moist bias



Charlesworth et al., 2023

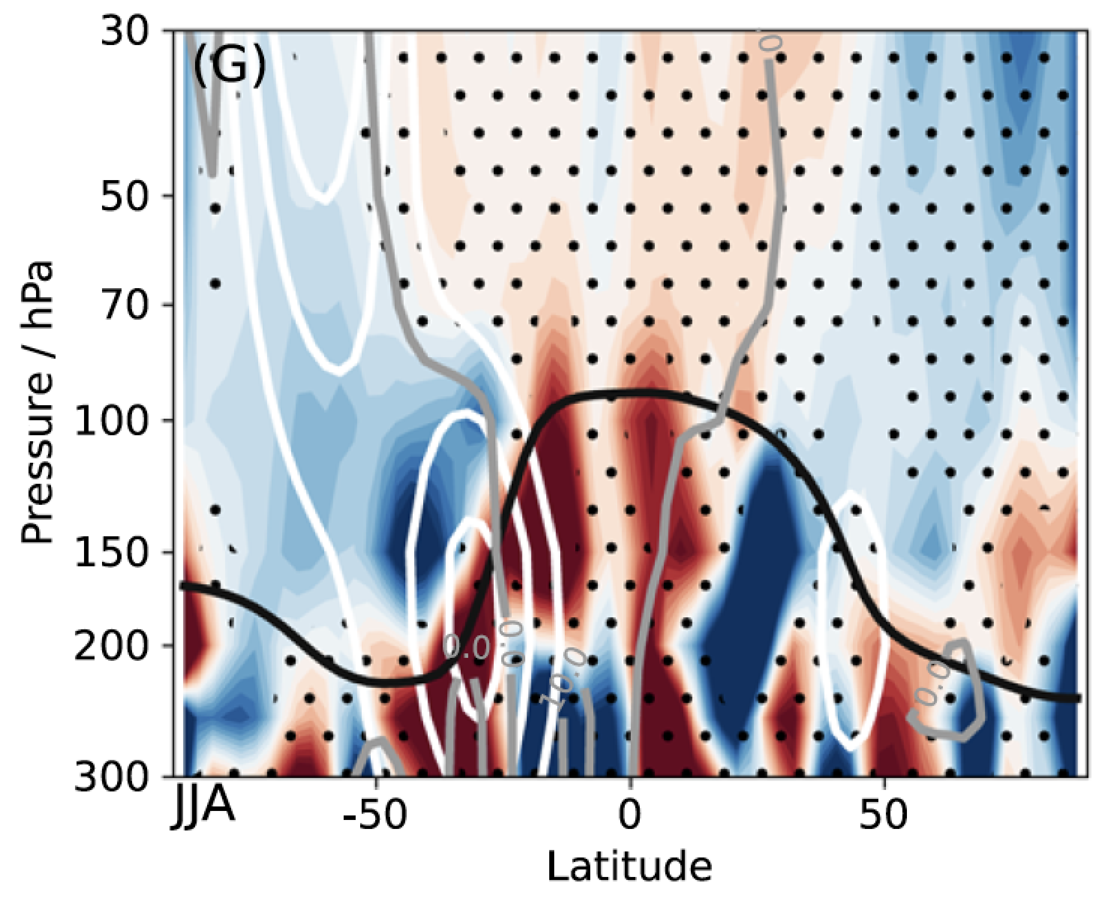
Circulation response to lowermost stratospheric moist bias

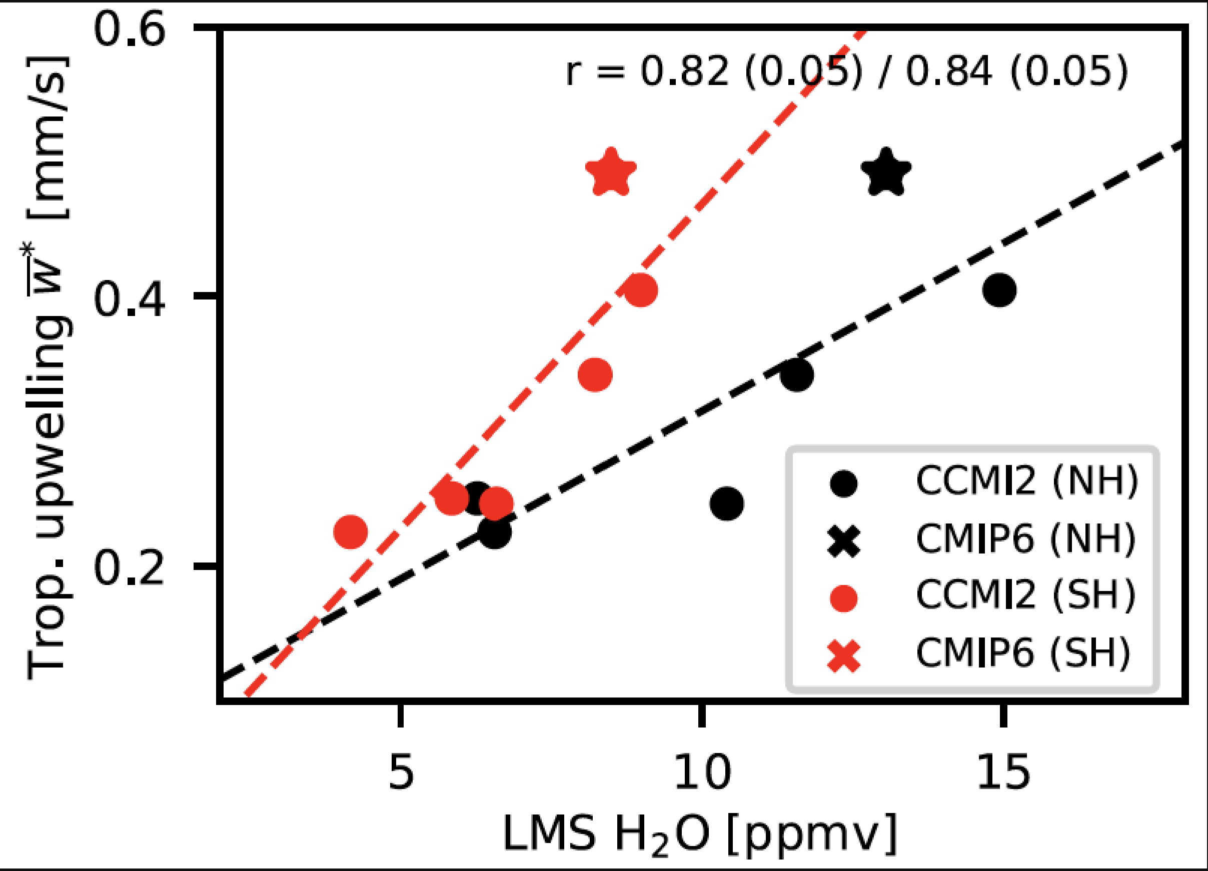




Charlesworth et al., 2023

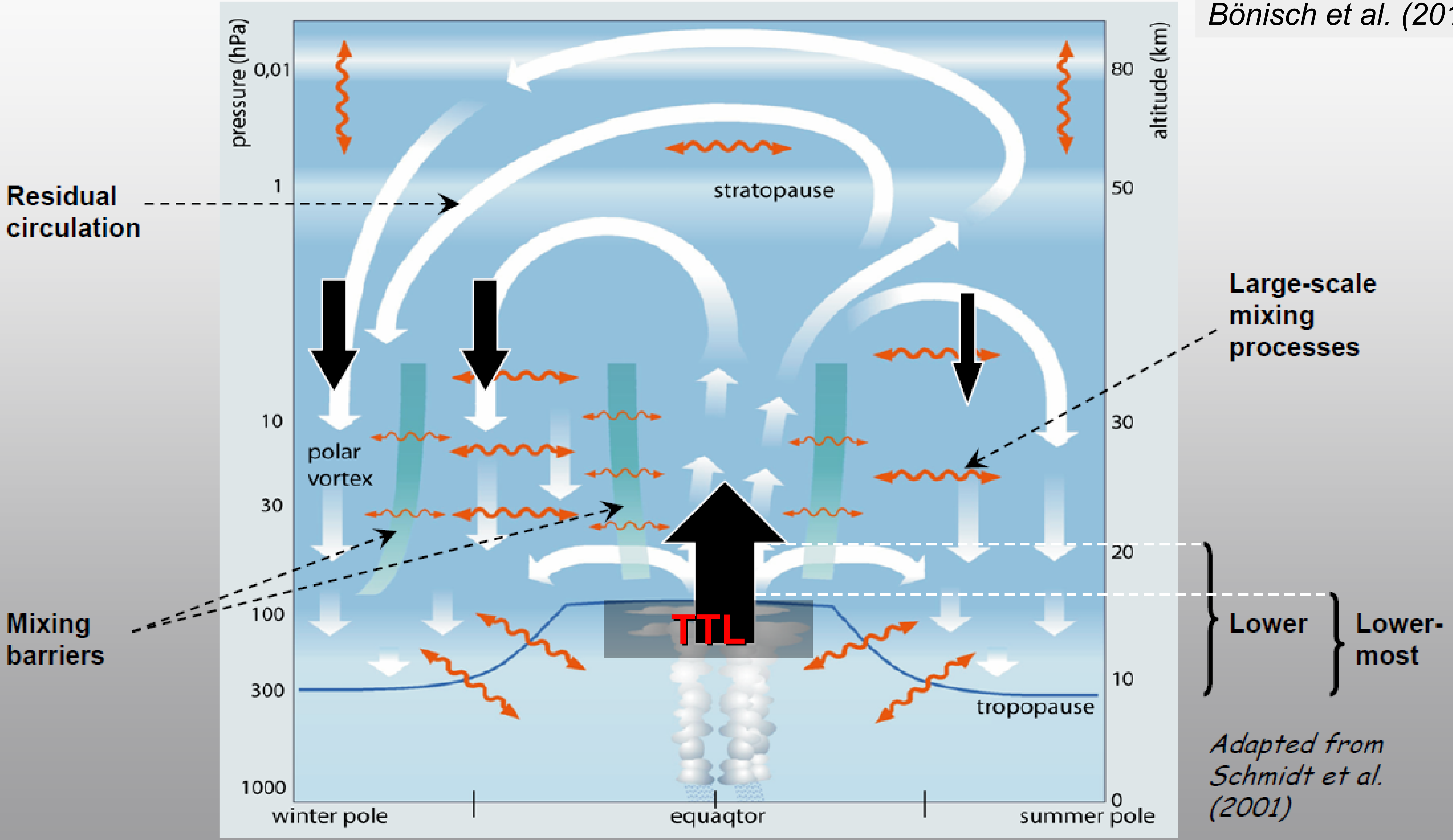
Brewer-Dobson circulation vs. LMS moist bias





Charlesworth et al., 2023

Bönisch et al. (2011)

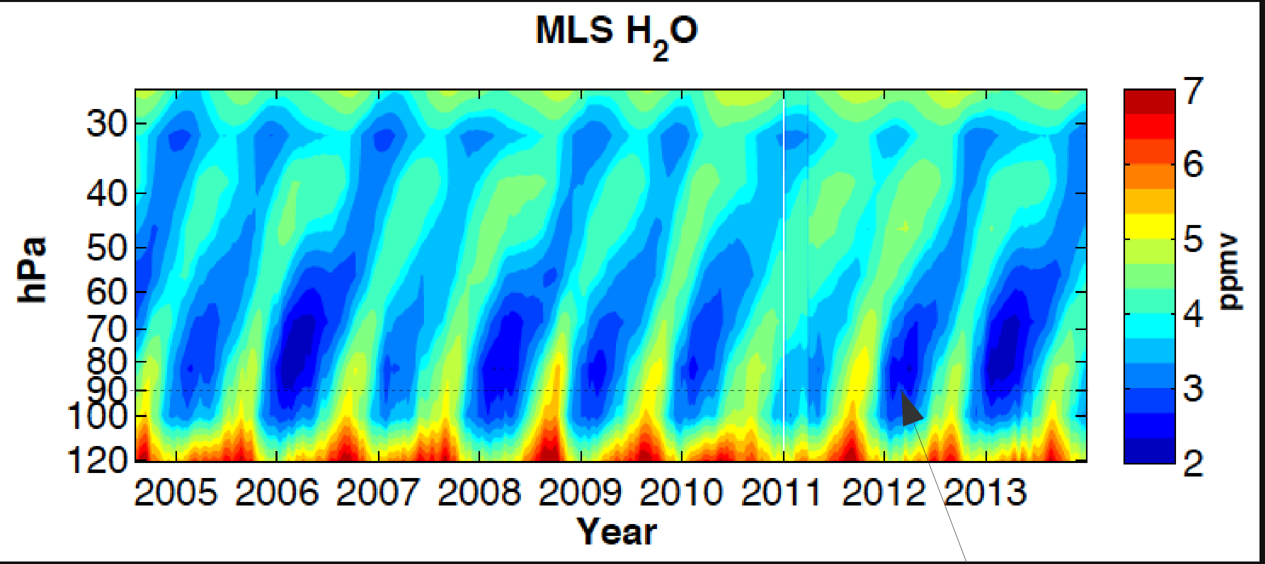


Adapted from Schmidt et al. (2001)

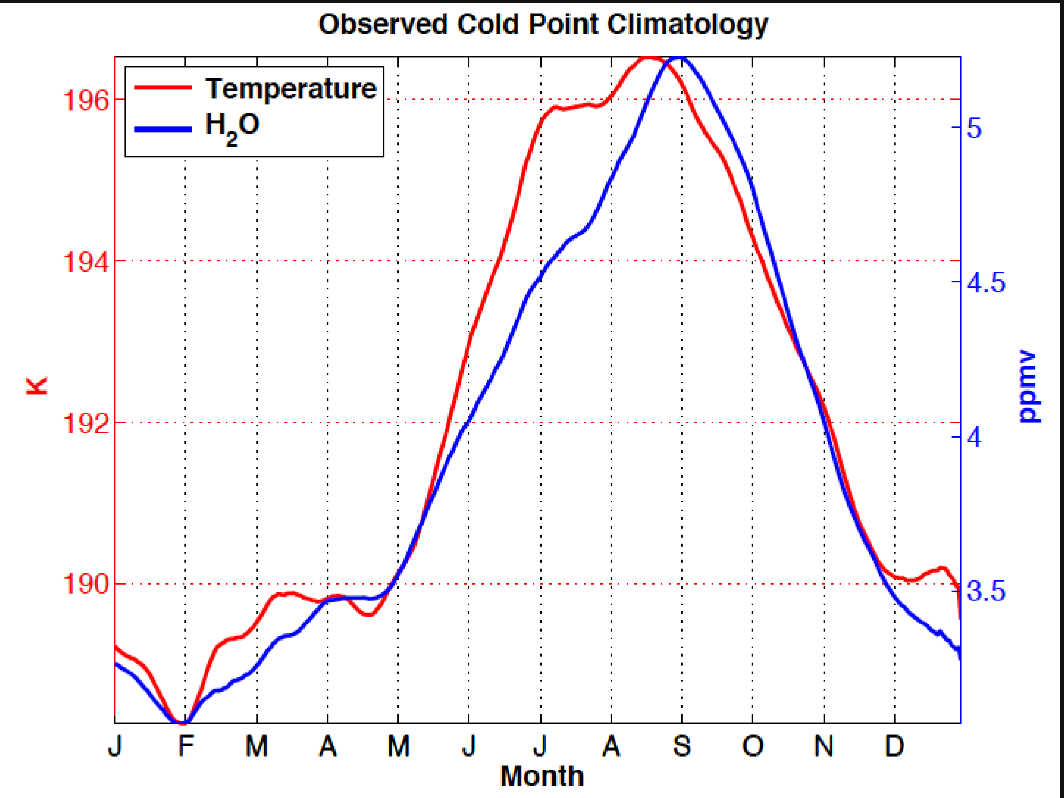
Mote et al., 1996: **An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor**

In other words, air is "marked," on emergence above the highest cloud tops, like a signal recorded on an upward moving magnetic tape.

Tape Recorder Signal in H_2O



cold point tropopause



Is the tape recorder signal caused by vertical advection within the stratospheric residual circulation?

(Glanville & Birner 2017, ACP)

Synthetic tape recorder by solving simple 1-d transport Eq., similar to Mote et al. (1998), but with seasonally varying transport coefficients

$$\partial_t \overline{\chi} = -\overline{\omega}^* \partial_p \overline{\chi} + \partial_p (K_p \partial_p \overline{\chi}) - \alpha_p (\overline{\chi} - \overline{\chi}_{ML}) + S$$

vertical advection

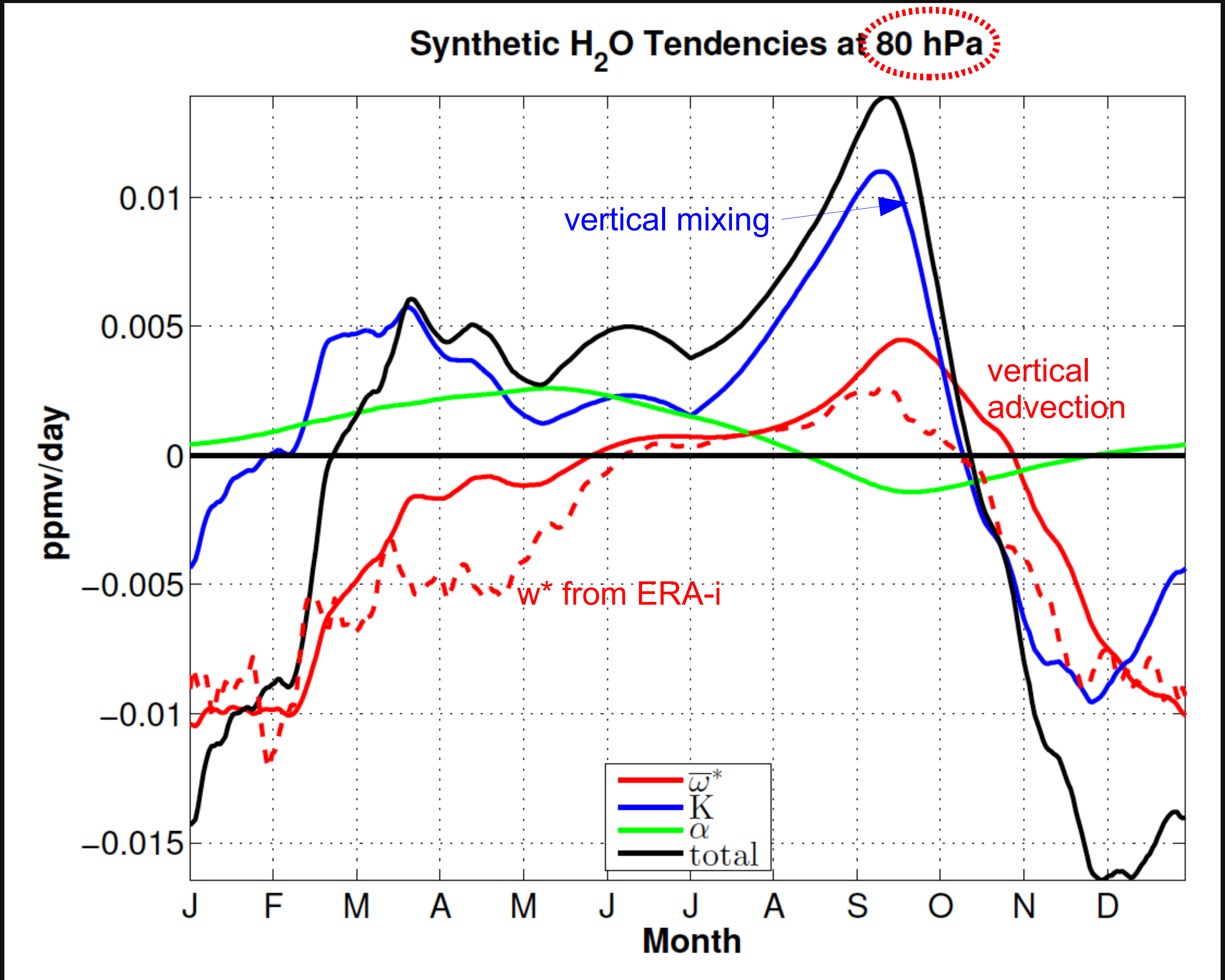
vertical mixing/diffusion

horizontal mixing/dilution

→ parameter sweep to find optimal combination

Vertical mixing as important as vertical advection!

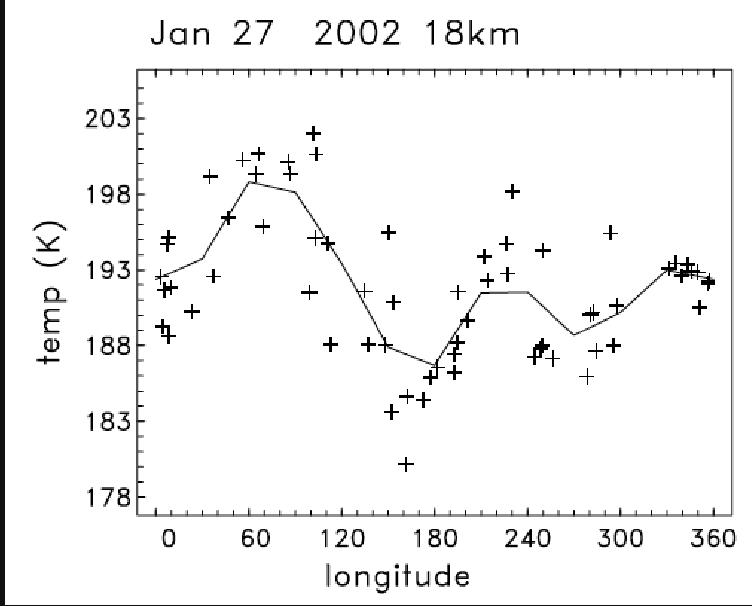
quadrupled(!) vertical mixing compared to Mote et al
(but same vertical advection & horizontal mixing)



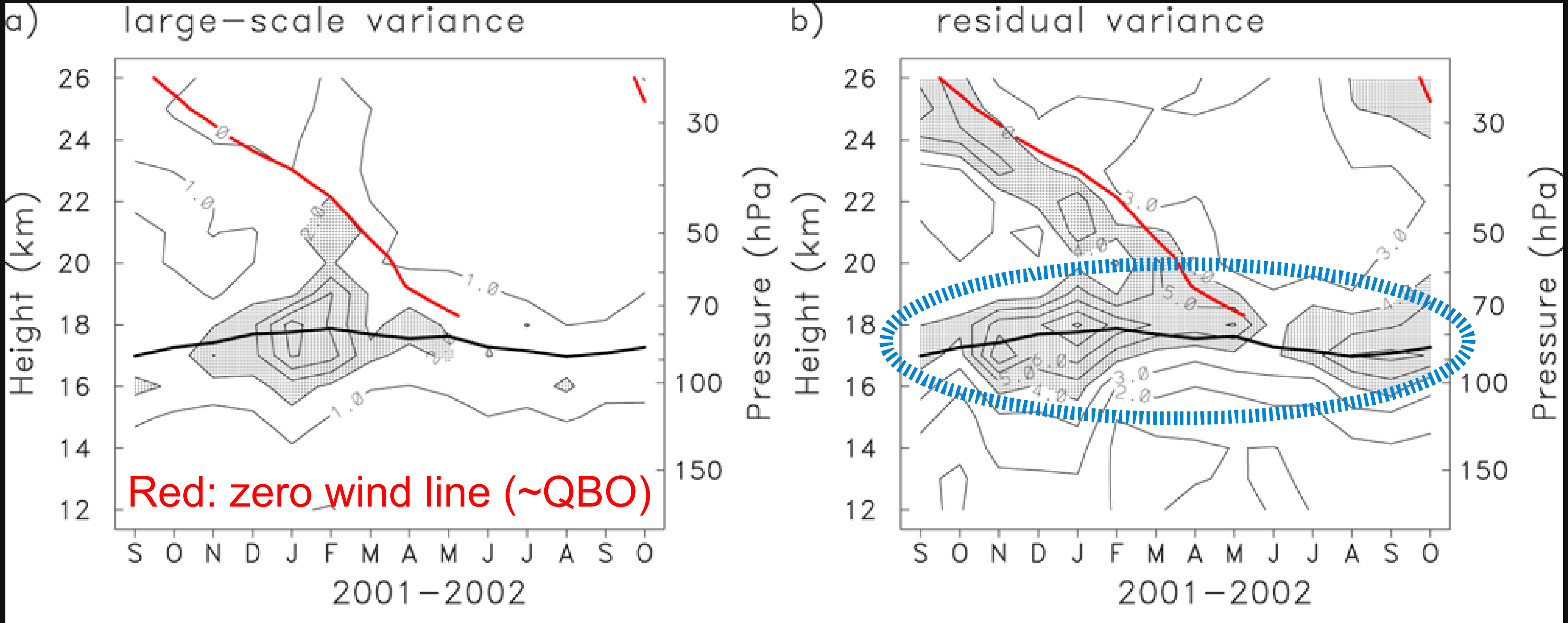
Glanville & Birner (2017)

(for ERAi, optimal solution requires 10 times vertical mixing and 5 times horizontal mixing)

Zonal variance from gridded GPS-RO temperature profiles versus residual variance:



Randel & Wu (2005)

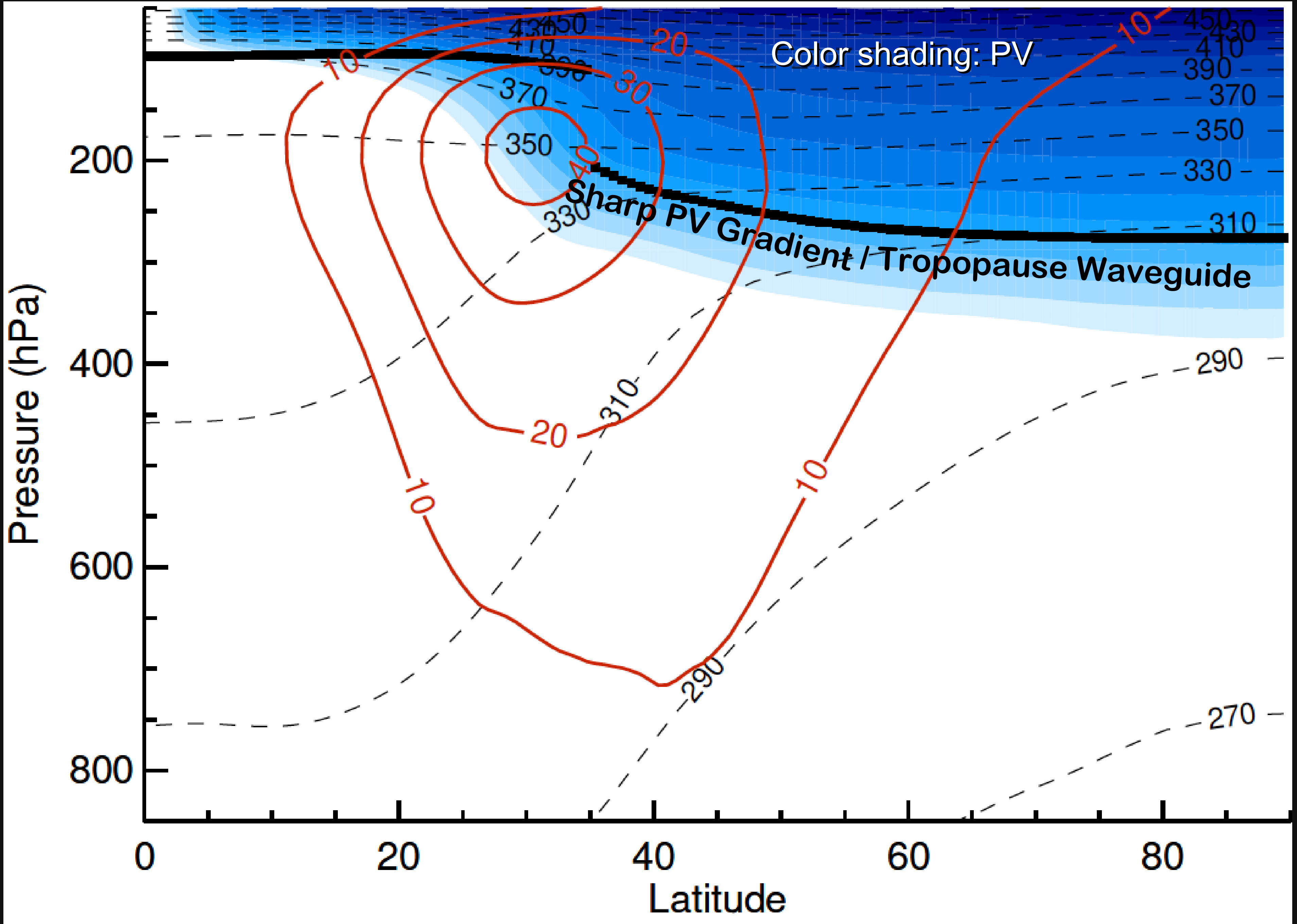


Take-home points

- potential modulation of general circulation features by tropopause sharpness: stronger TIL → equatorward jet shift

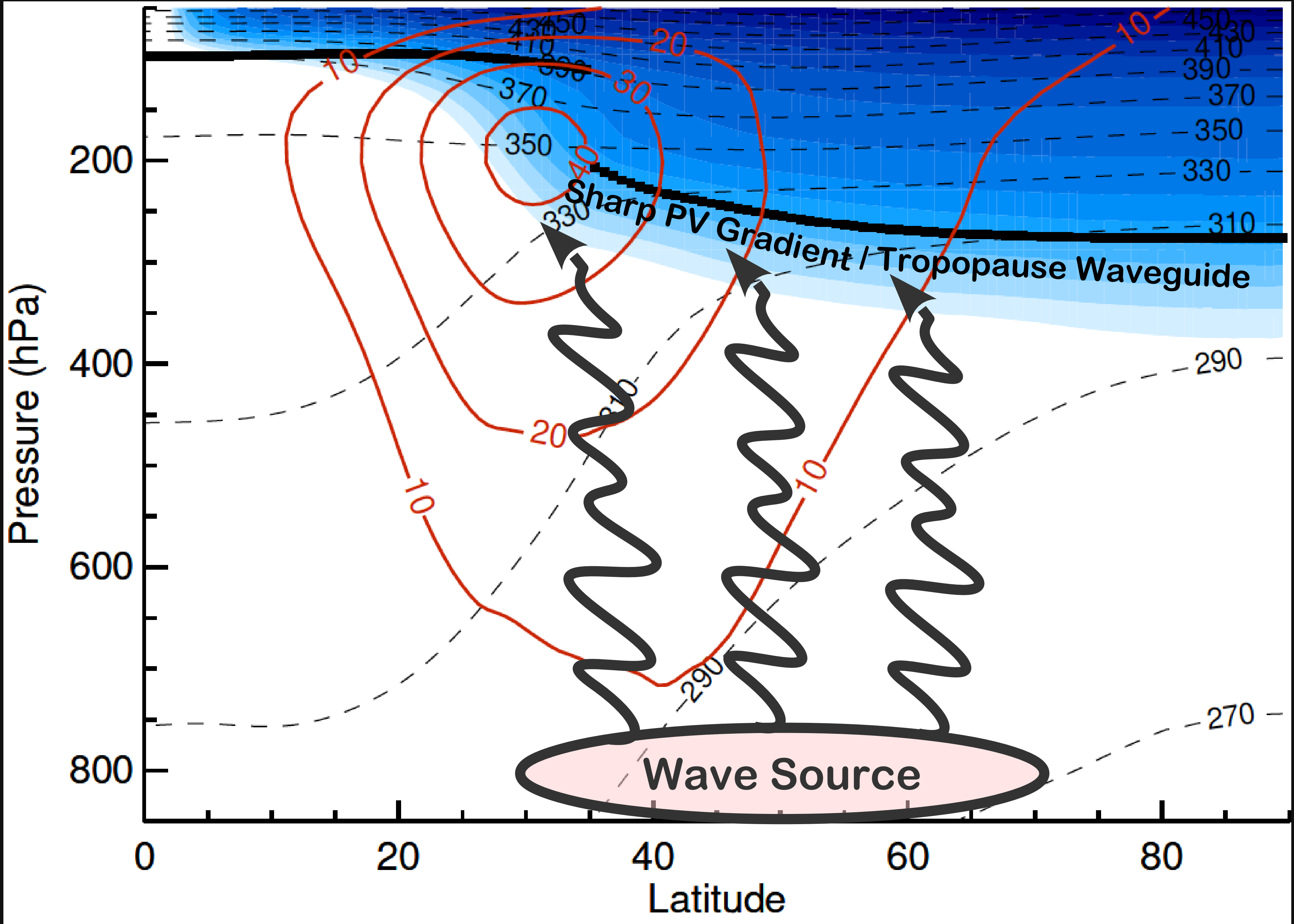
- Tropopause-level moist bias in current climate models due to overly dispersive transport → poleward jet bias, too strong Brewer-Dobson circulation

- Potential role of vertical mixing (due to ??) in regulating transport just above tropical tropopause



e.g.:
Wirth (2020)

NH winter
climatology



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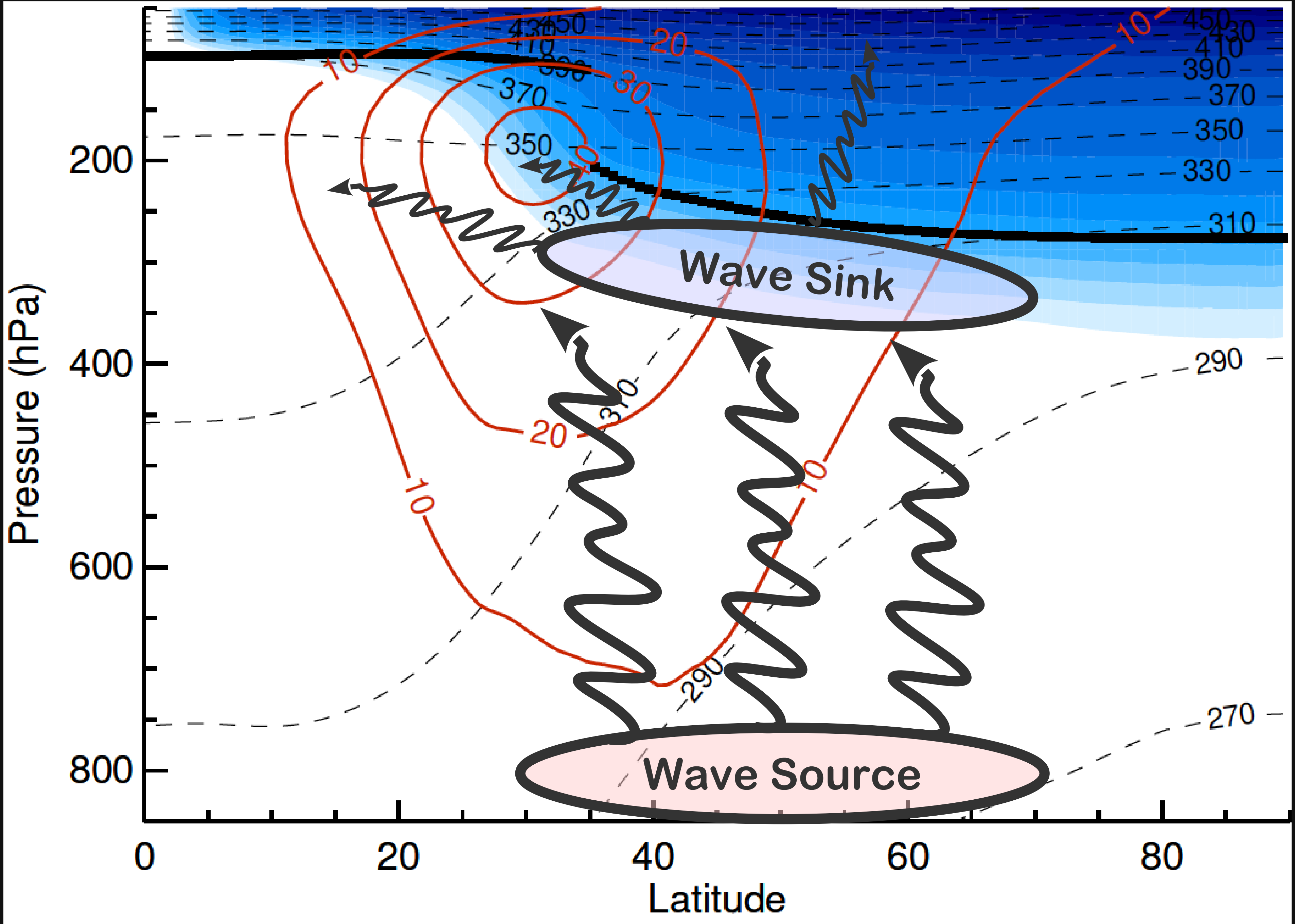
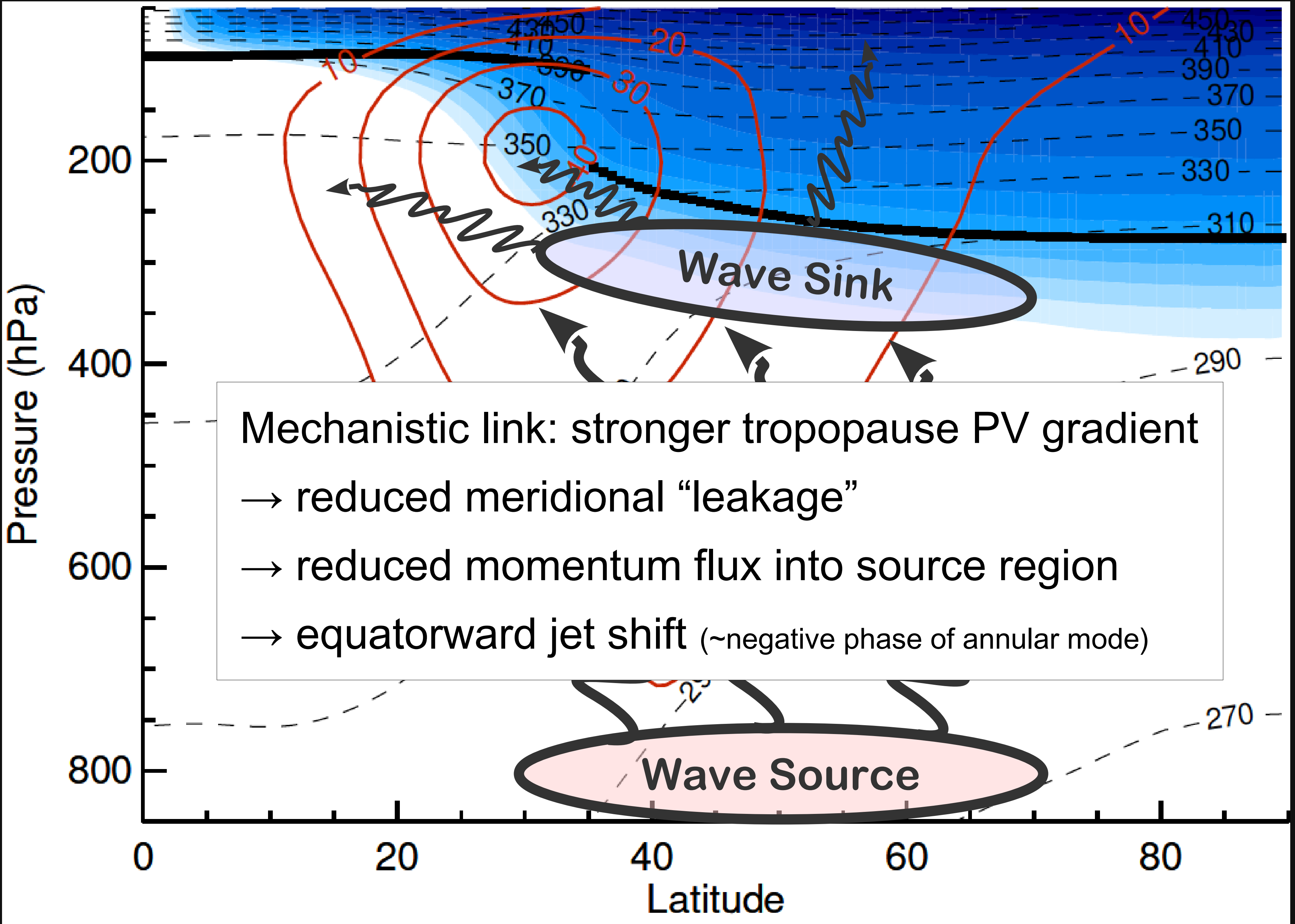


NH winter
climatology



Mechanistic link: stronger tropopause PV gradient

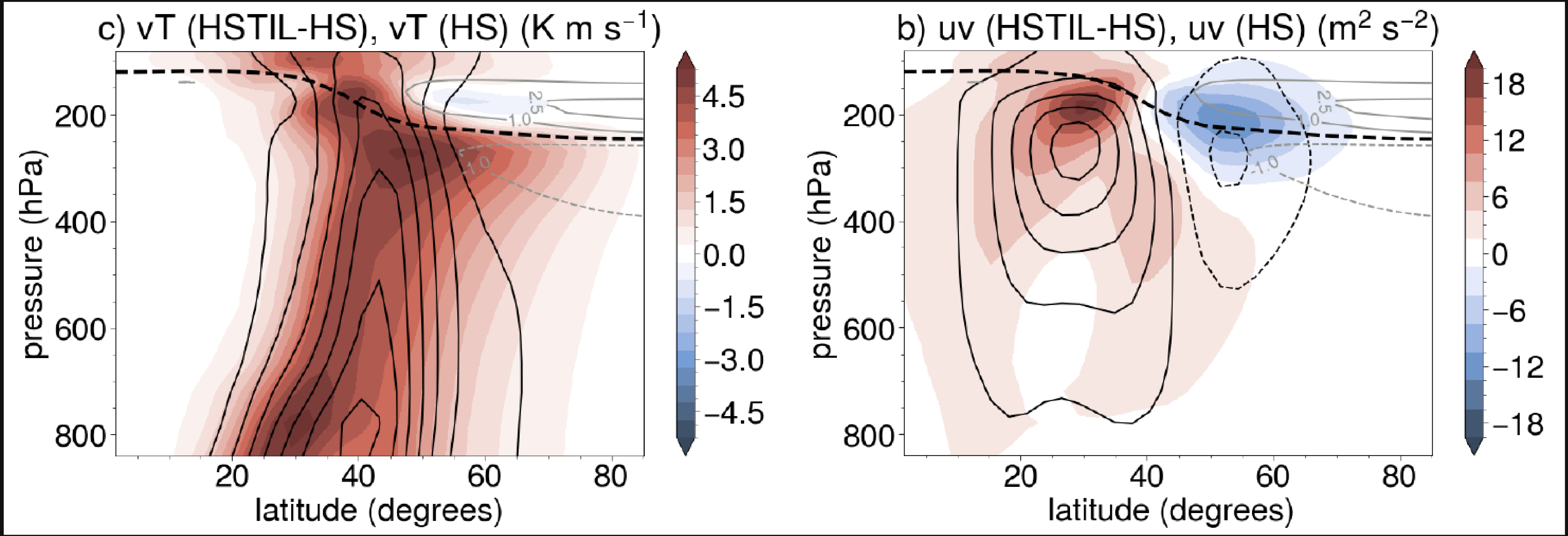
→ reduced meridional “leakage”

→ reduced momentum flux into source region

→ equatorward jet shift (~negative phase of annular mode)

NH winter climatology

Stronger TIL → Stronger Eddy Heat & Momentum Fluxes

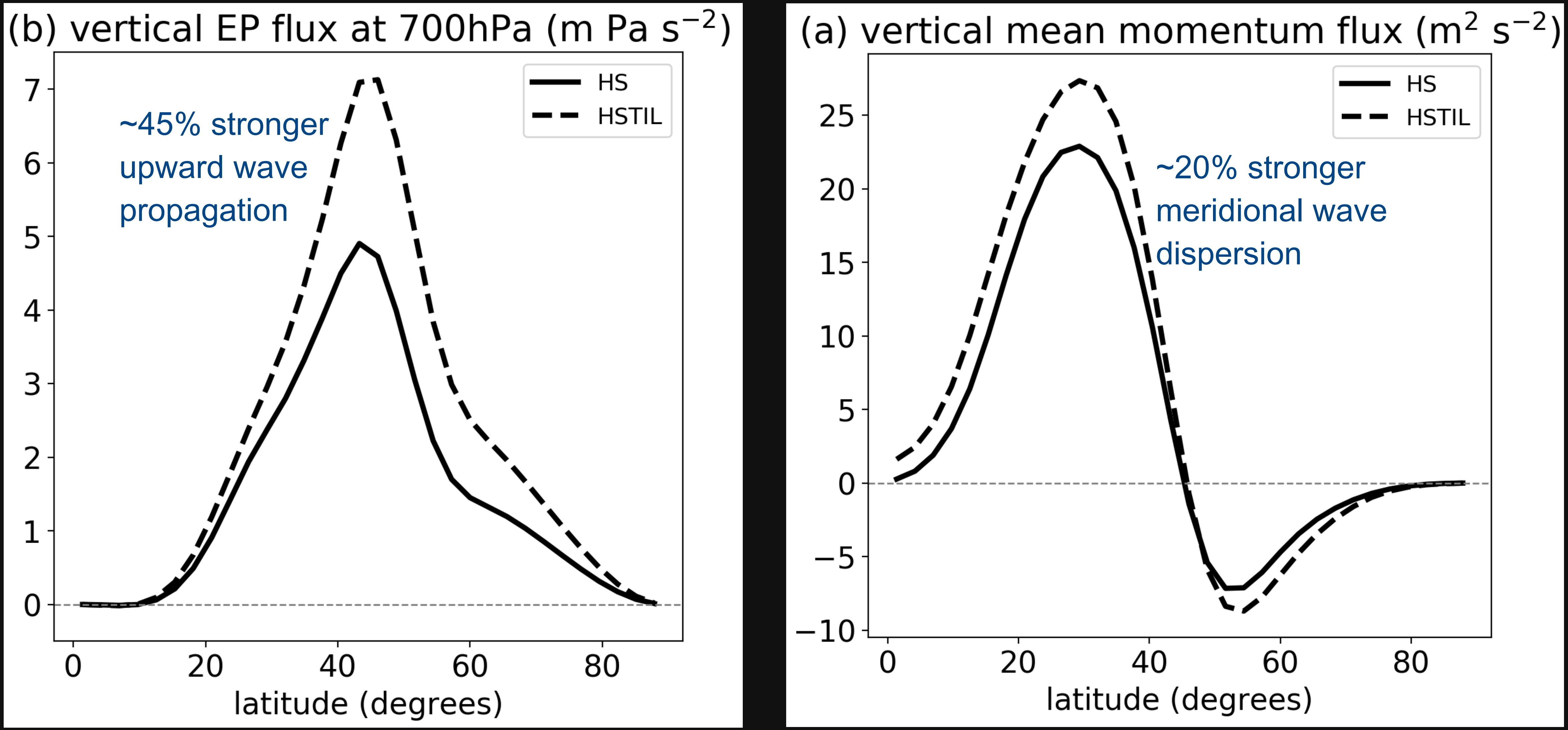


Boljka & Birner (2022)

→ stronger, more equatorward baroclinic eddy activity that extends further upward

Gray contours: static stability response (HSTIL-HS)

Stronger TIL → relatively less equatorward wave dispersion



Boljka & Birner (2022)