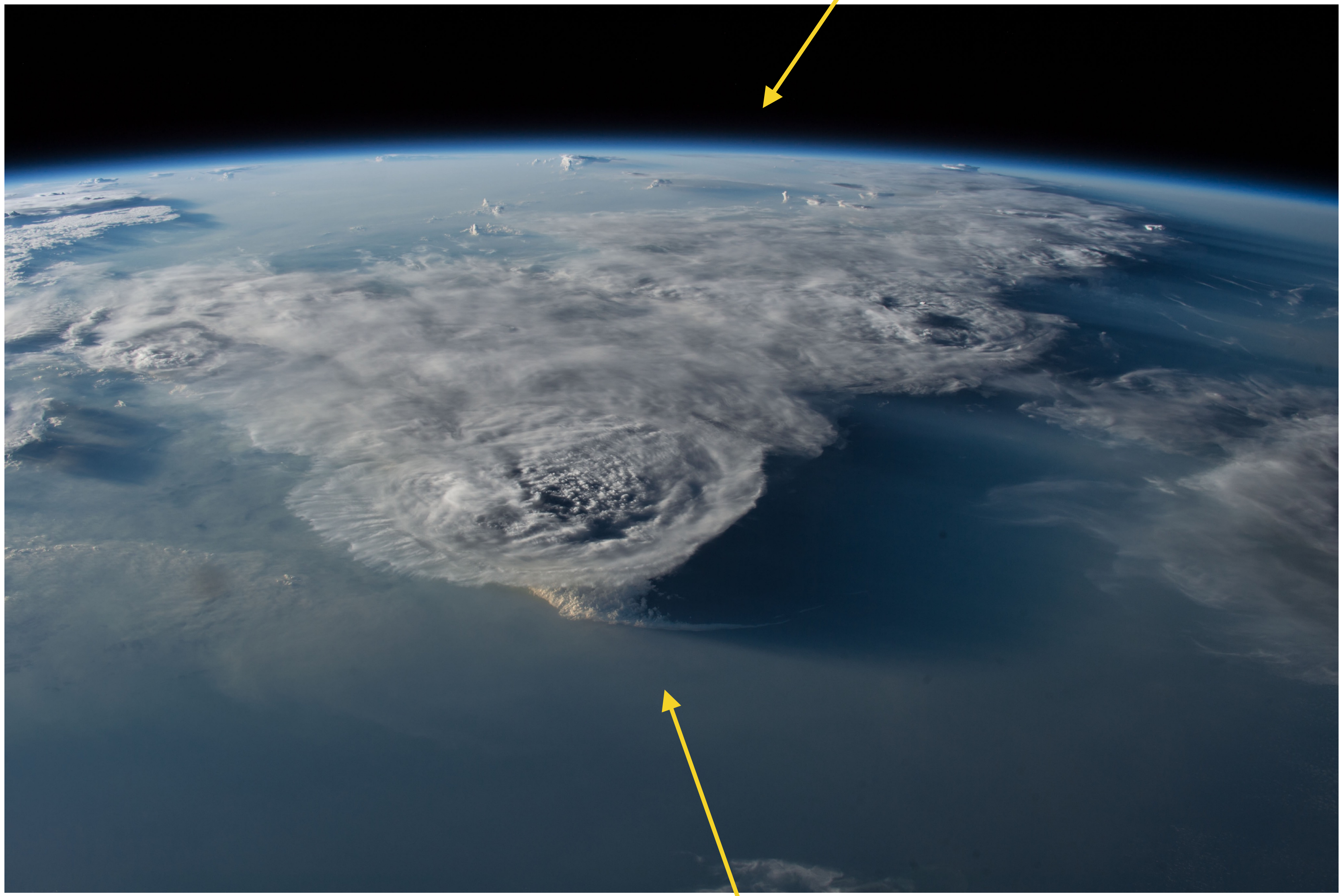
What determines the depth of the extratropical troposphere?

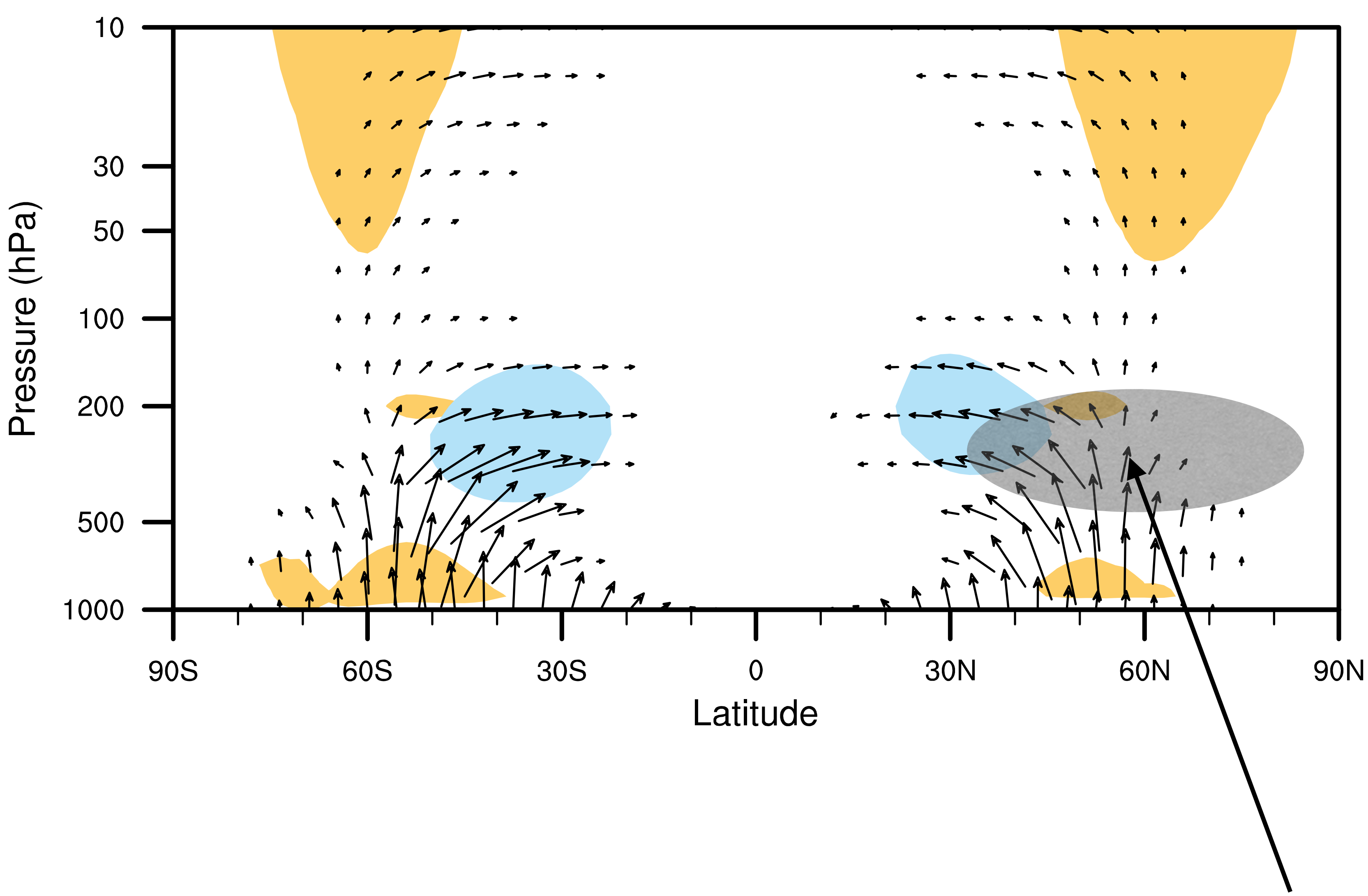
David WJ Thompson (CSU)
Sandrine Bony (LMD)
Ying Li (CSU)

The stratosphere (“the layered sphere”) is characterized by weak diabatic mixing.



The troposphere (“the turning sphere”) is marked by vigorous diabatic motions.

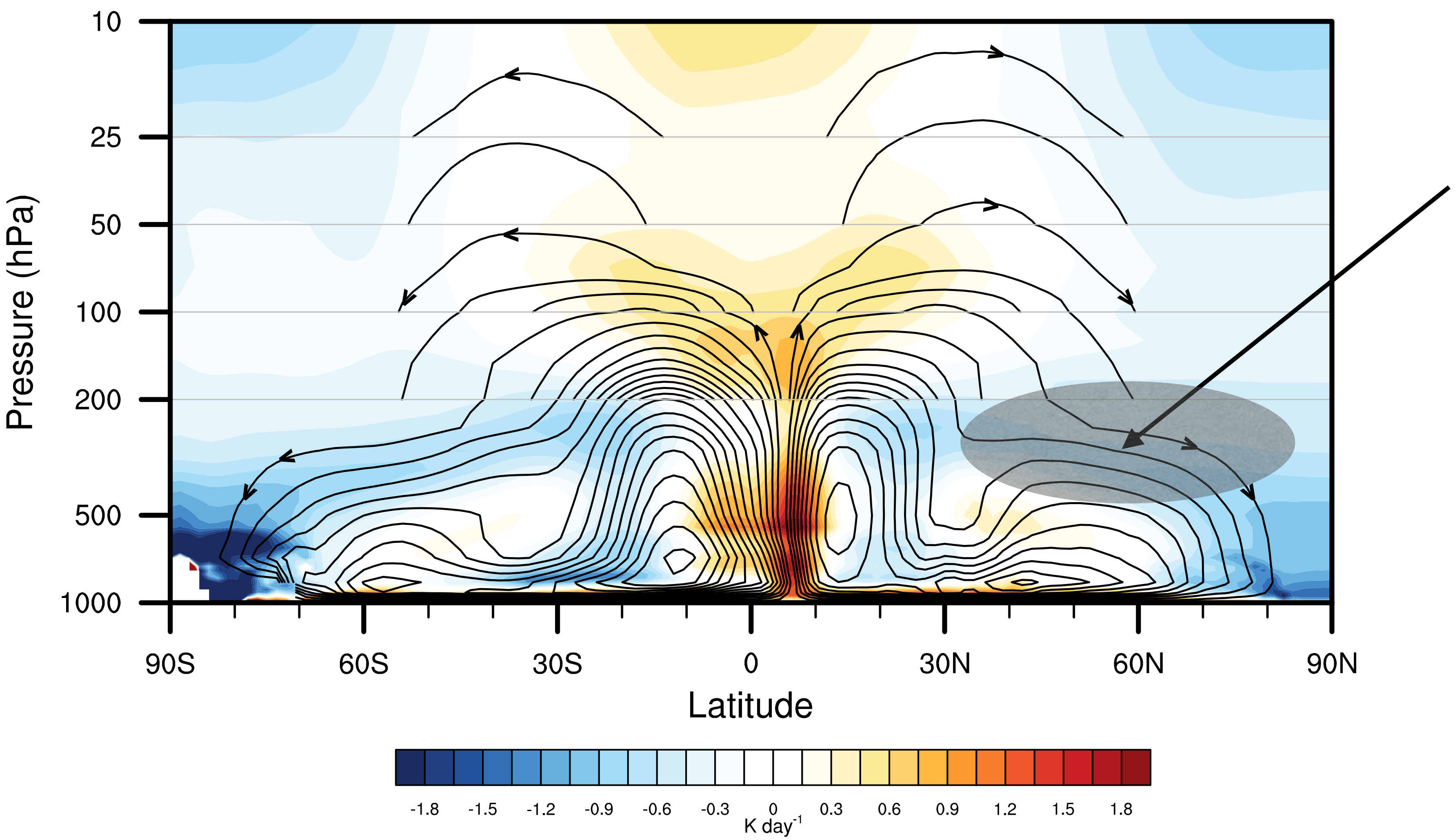
Climatological mean circulation



Vectors are EP fluxes. Shading highlights regions of heat and momentum fluxes.

The largest convergence of wave activity in the extratropics (wave driving; grey) is located at the tropopause level.

Climatological mean circulation

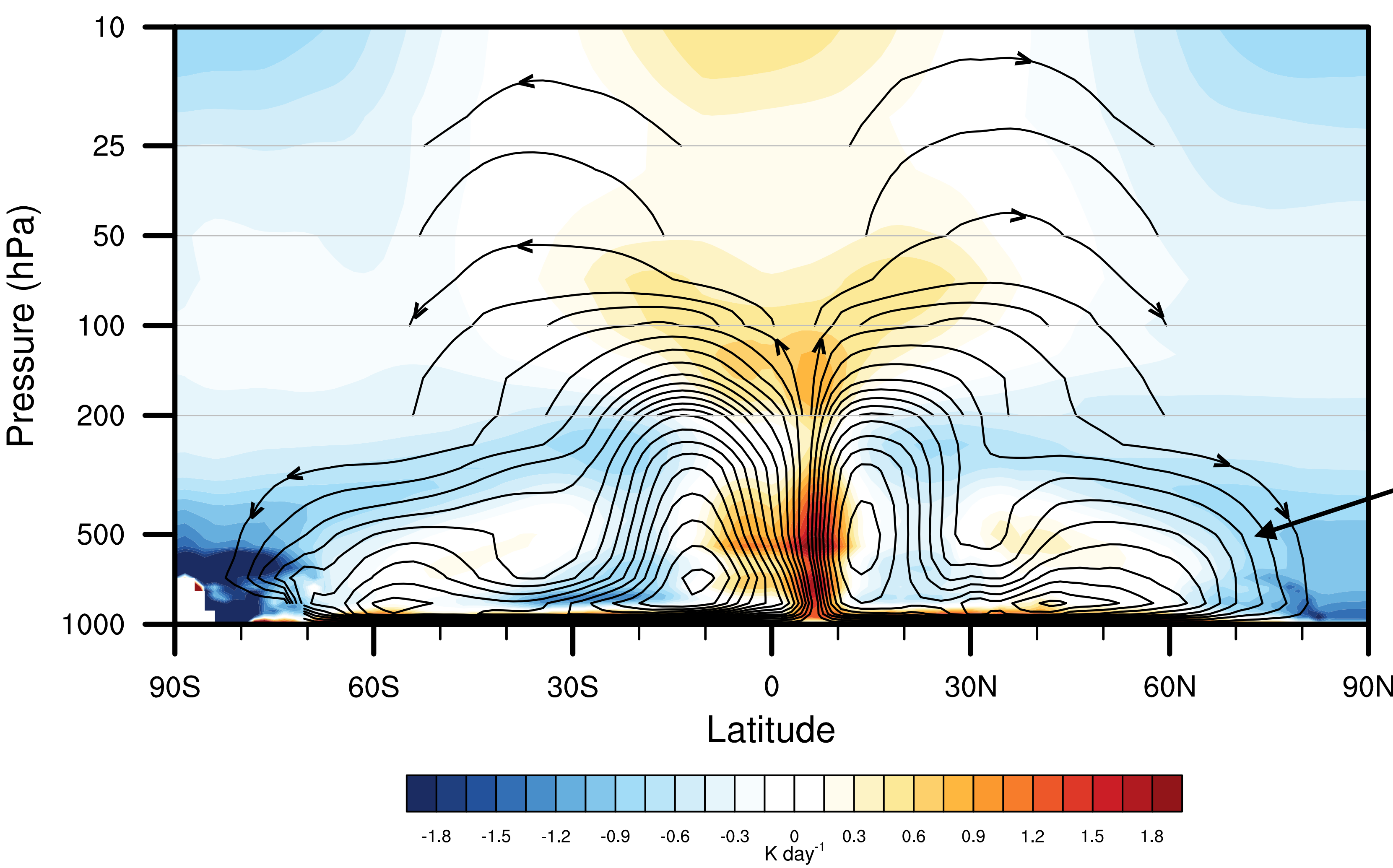


$$f\bar{v}^* = -\nabla \cdot F$$

TEM circulation (contours) and diabatic heating (shading)

Wave driving is balanced by Coriolis torque acting on poleward flow.

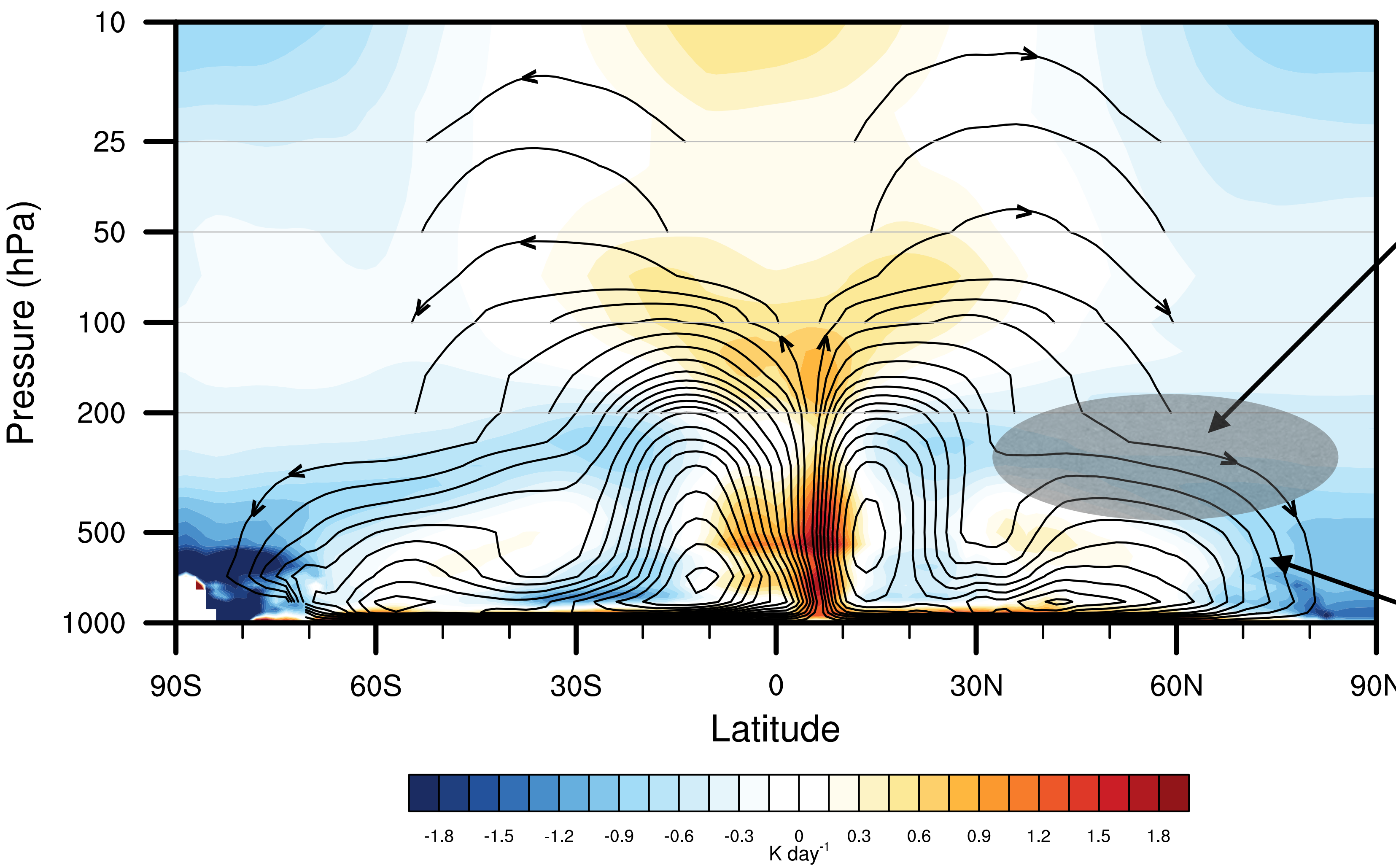
Climatological mean circulation



$$-\bar{\omega}^{*}S = \overline{Q}$$

Associated sinking motion is balanced by diabatic cooling.

What causes what?

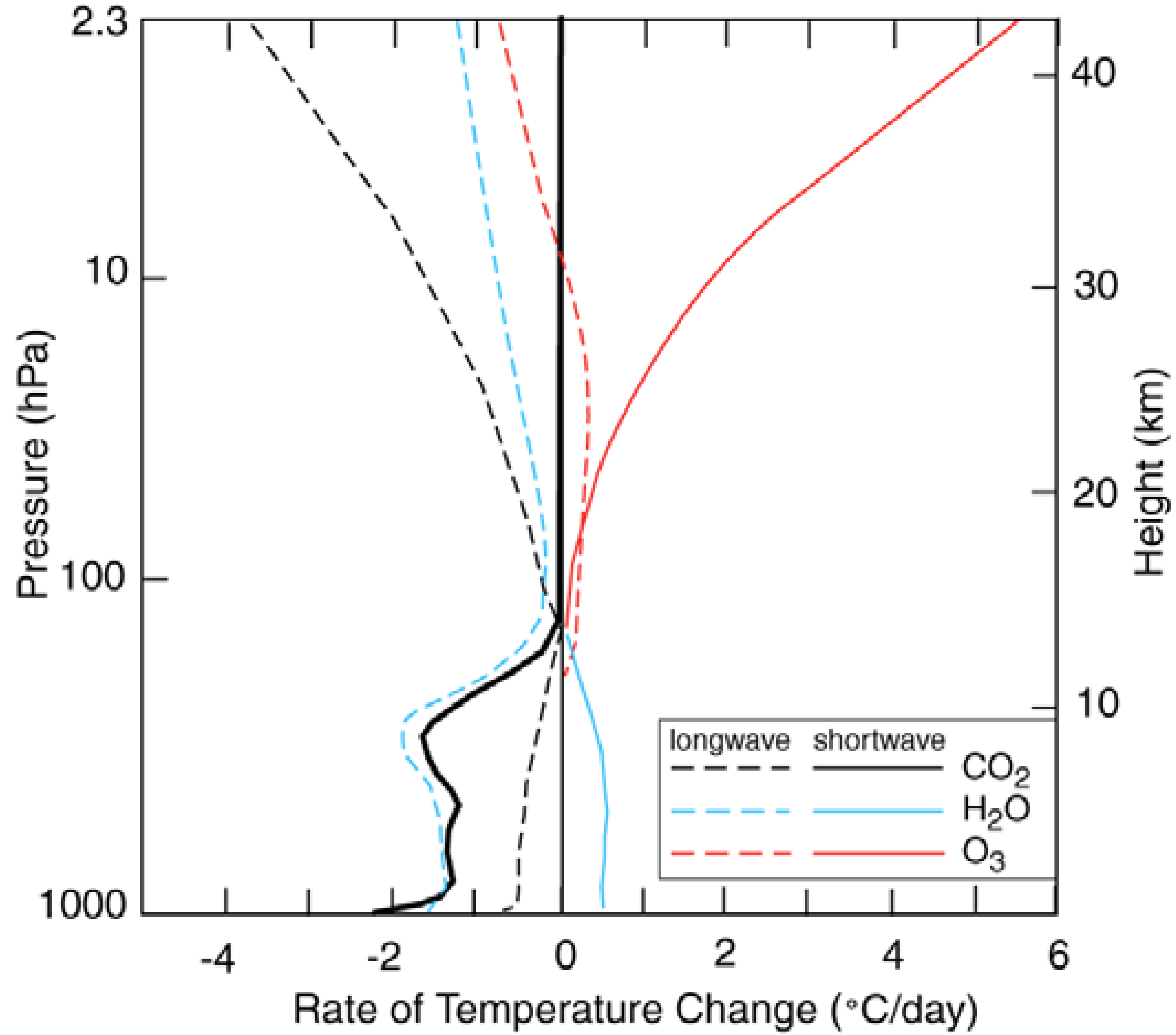


$$f\bar{v}^* = -\nabla \cdot F$$

$$-\bar{\omega}^* S = \overline{Q}$$

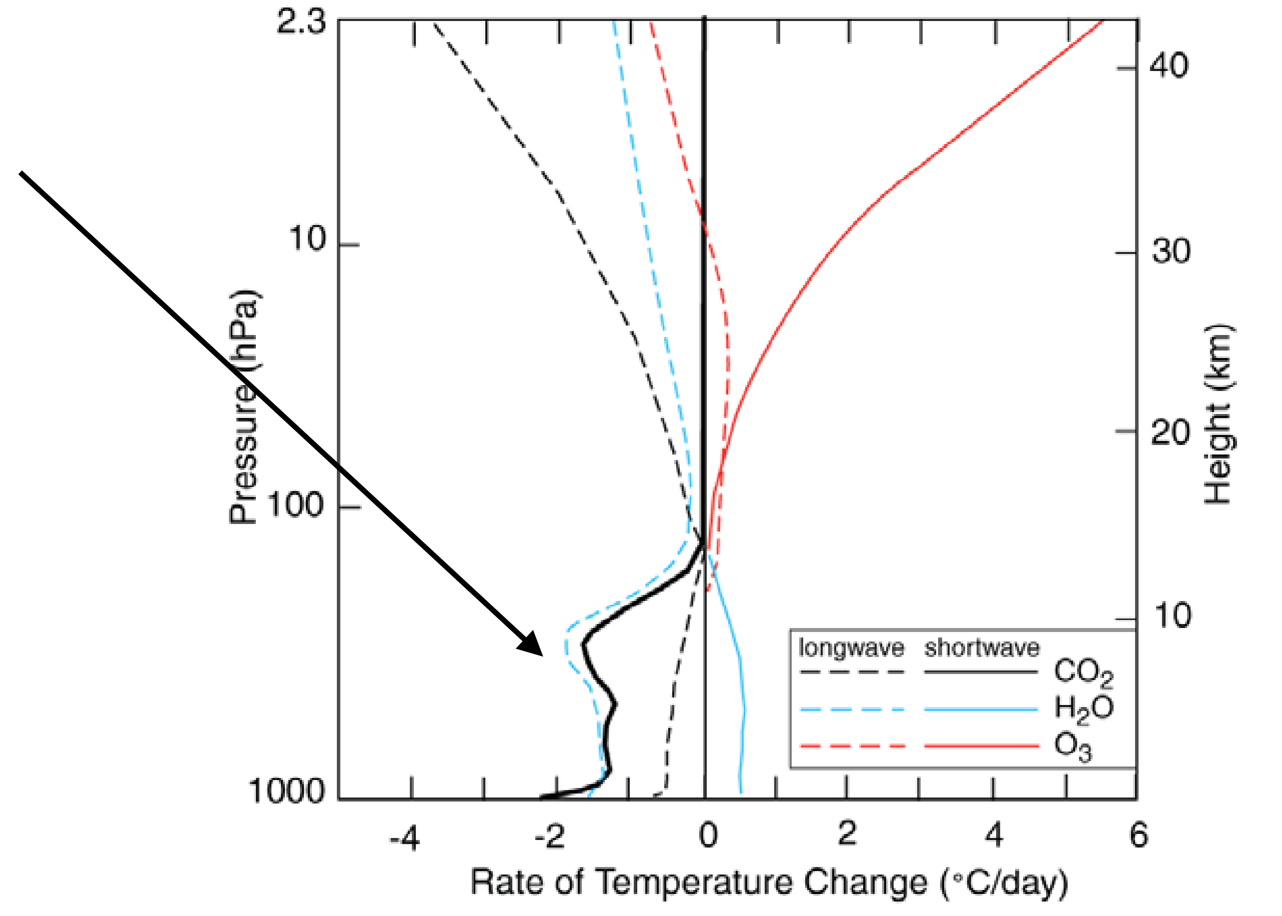
TEM circulation (contours) and diabatic heating (shading)

… the clear-sky radiative cooling is dominated by water vapor



Wallace and Hobbs. Adapted from Manabe and Stickler 1964.

The Clausius-Clapeyron relationship leads to a nearly discontinuous decrease in radiative cooling in the upper troposphere at temperatures ~210-220K



Hypothesis

The depth of mixing by large-scale extratropical variability is controlled by the thermodynamic constraints on water vapor radiative cooling in clear sky regions.

(Analogous to the physics that control the temperature of tropical cirrus clouds - Hartmann and Larson 2002)

tests

Observations:

* *CloudSAT/CALIPSO/ECMWF-AUX clouds and clear sky radiative fluxes*

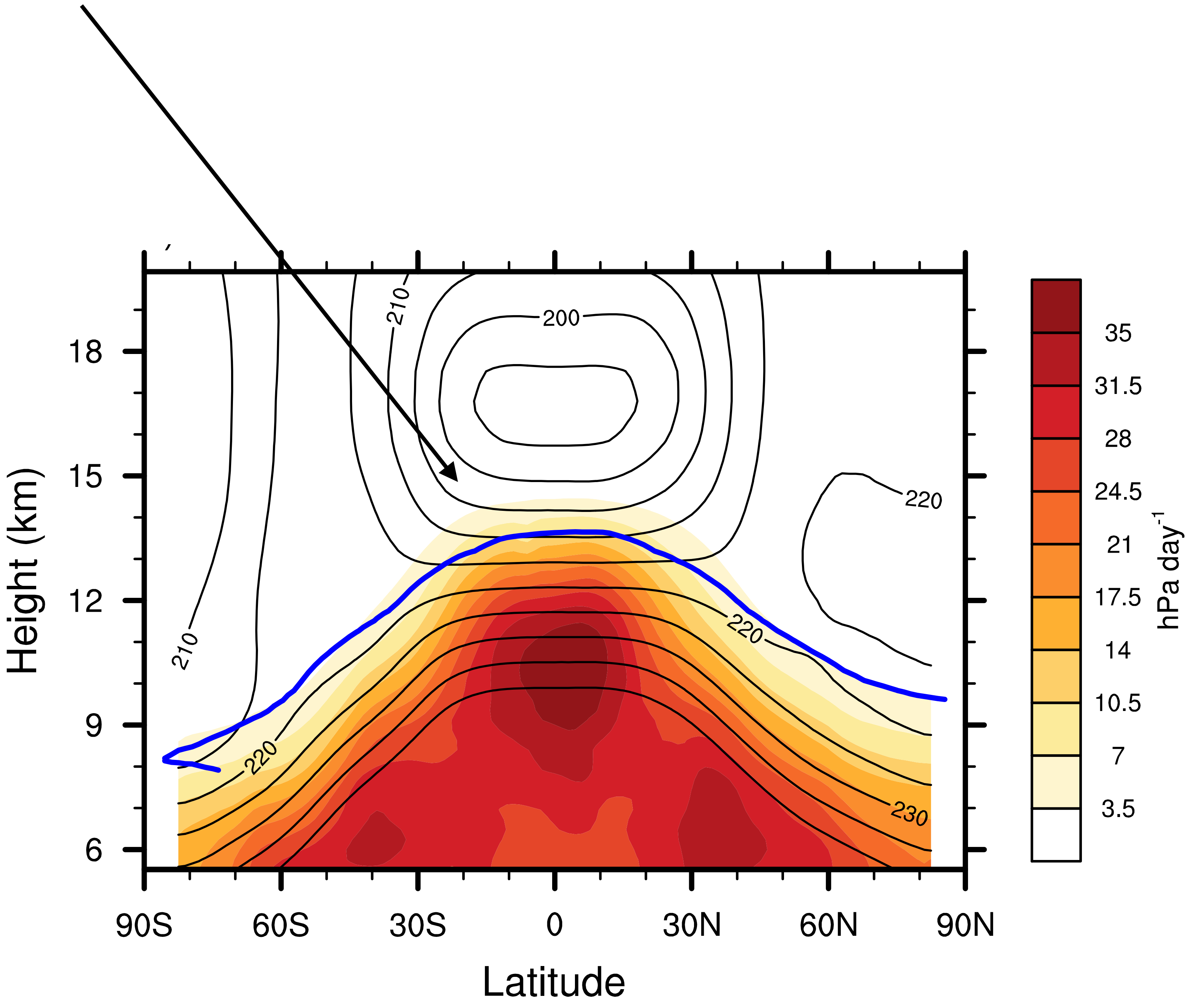
* *MSL water vapor*

The mass flux required to balance clear sky cooling is given as:

$$\omega_D = -\frac{Q}{S}$$

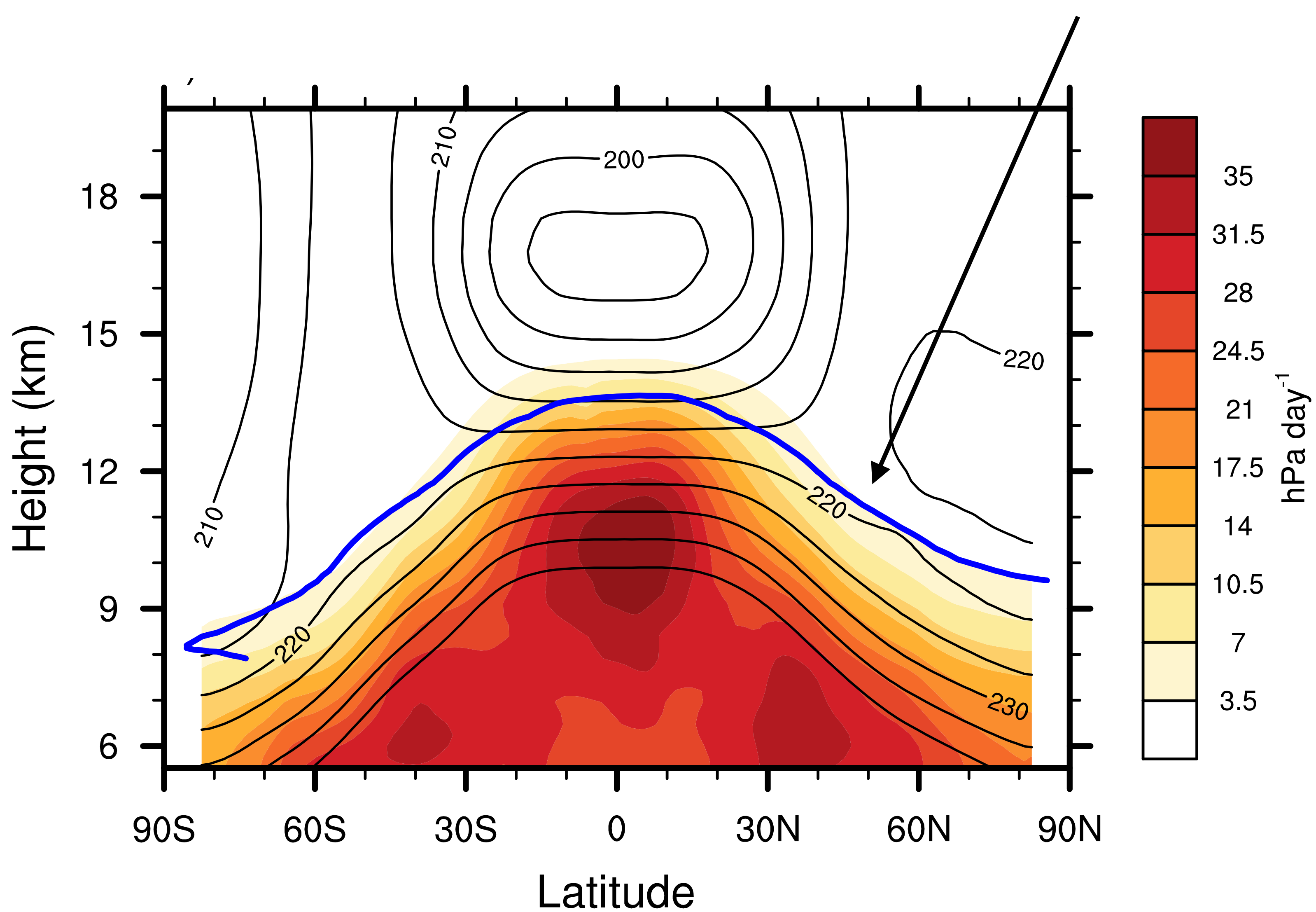
observed mass flux (shading) and T

diabatic mass fluxes decrease rapidly ~210K in tropics



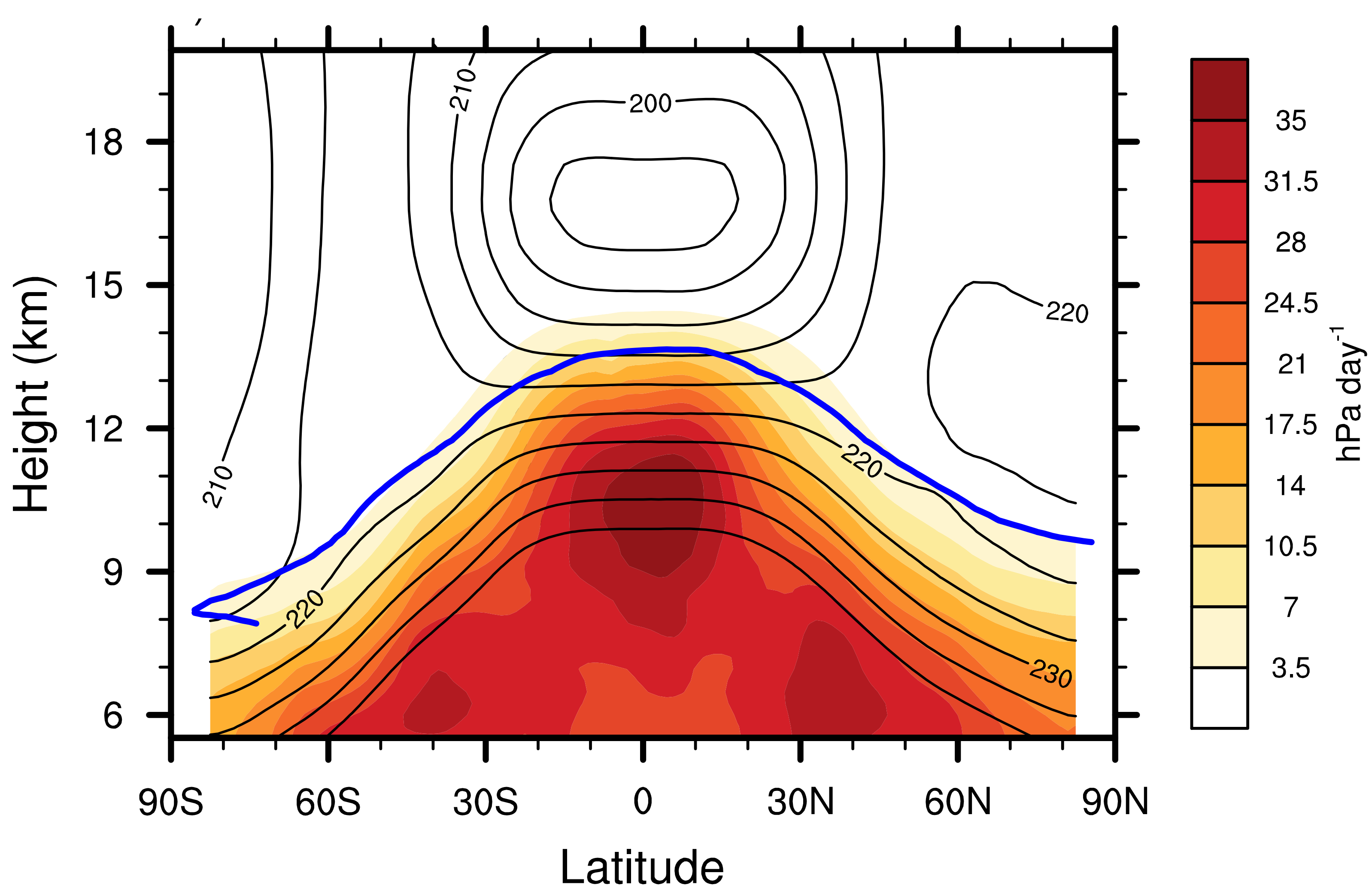
observed mass flux (shading) and T

and ~220K in extratropics

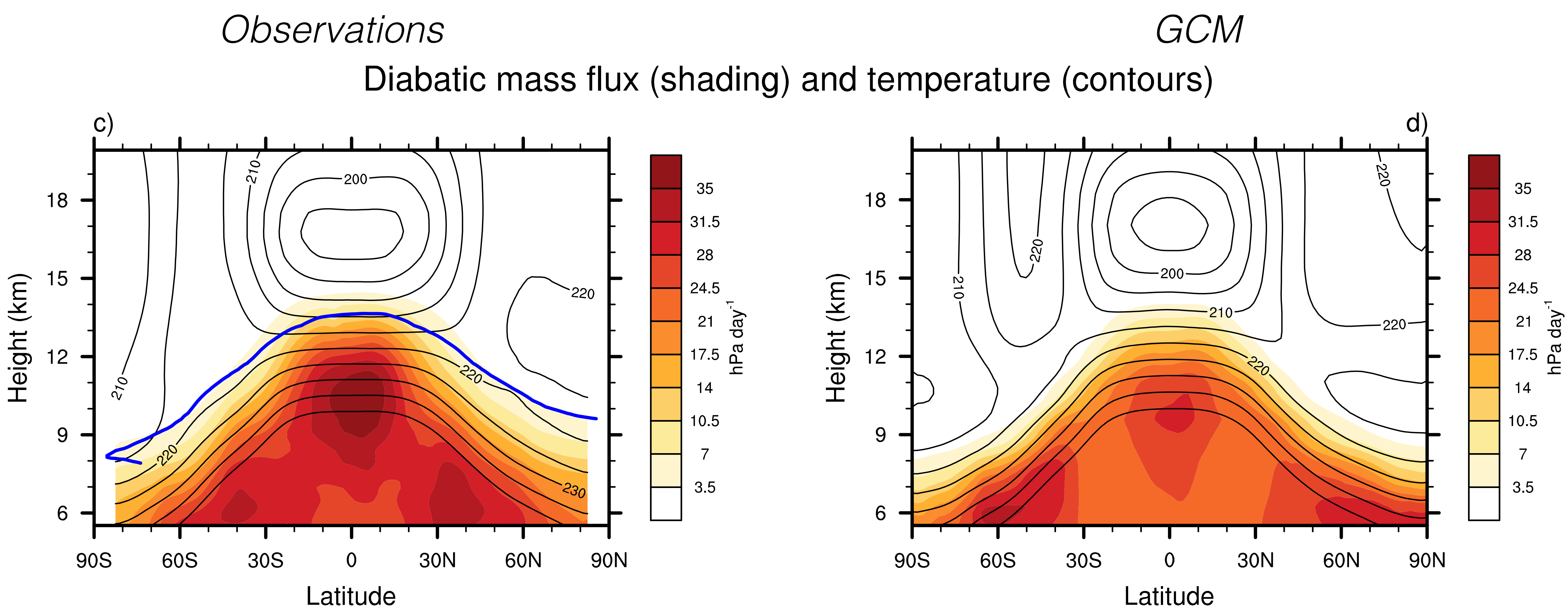


observed mass flux (shading) and T

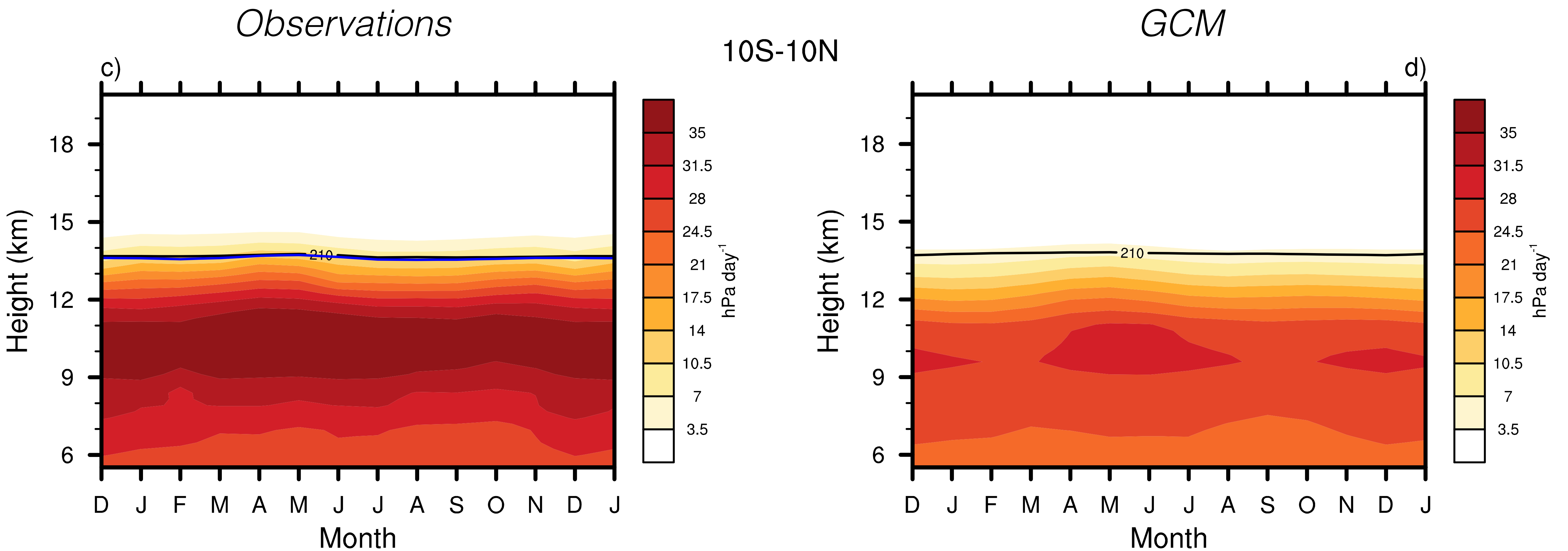
which is ~20 ppmv H20 in both locations (blue)



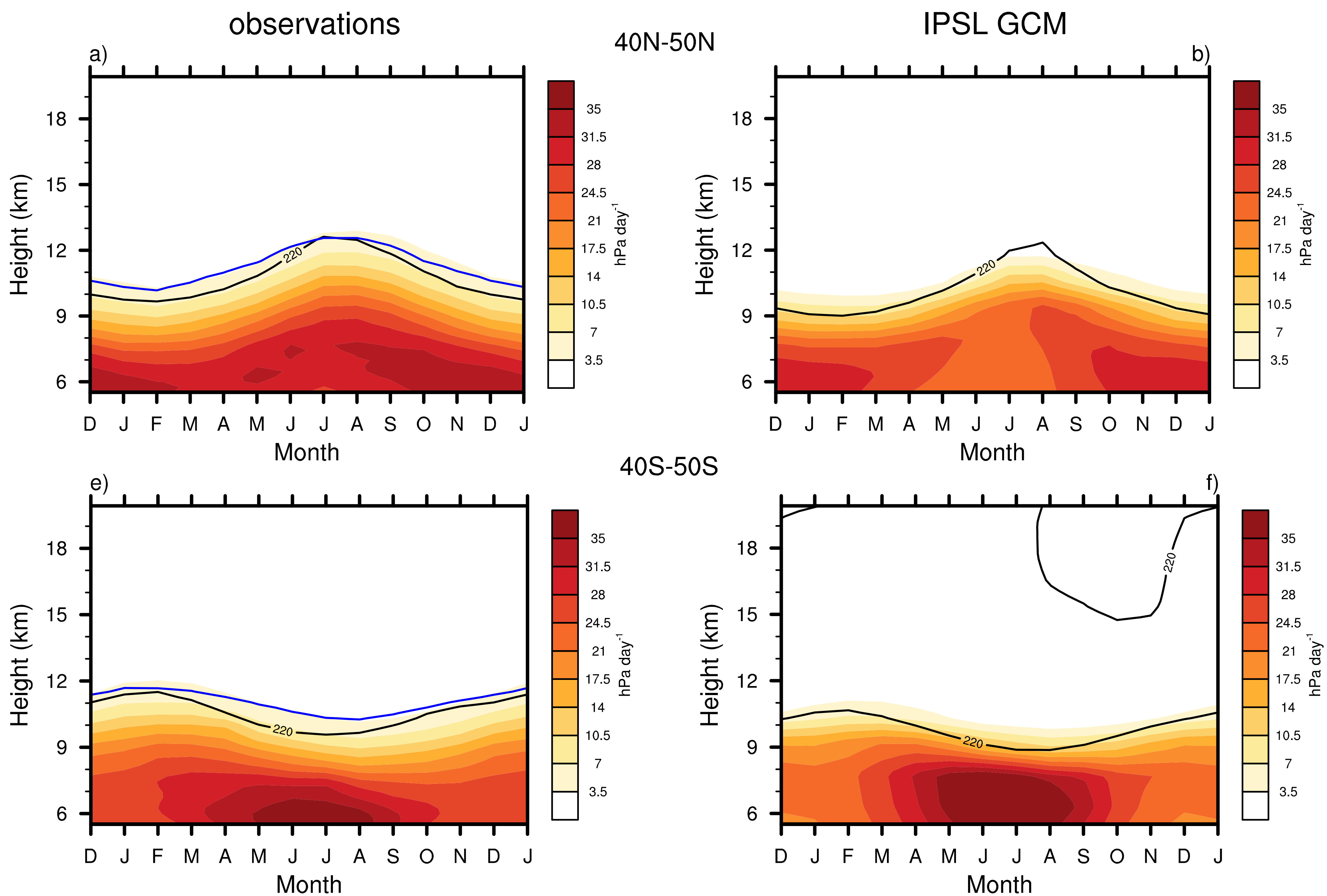
model closely matches observations



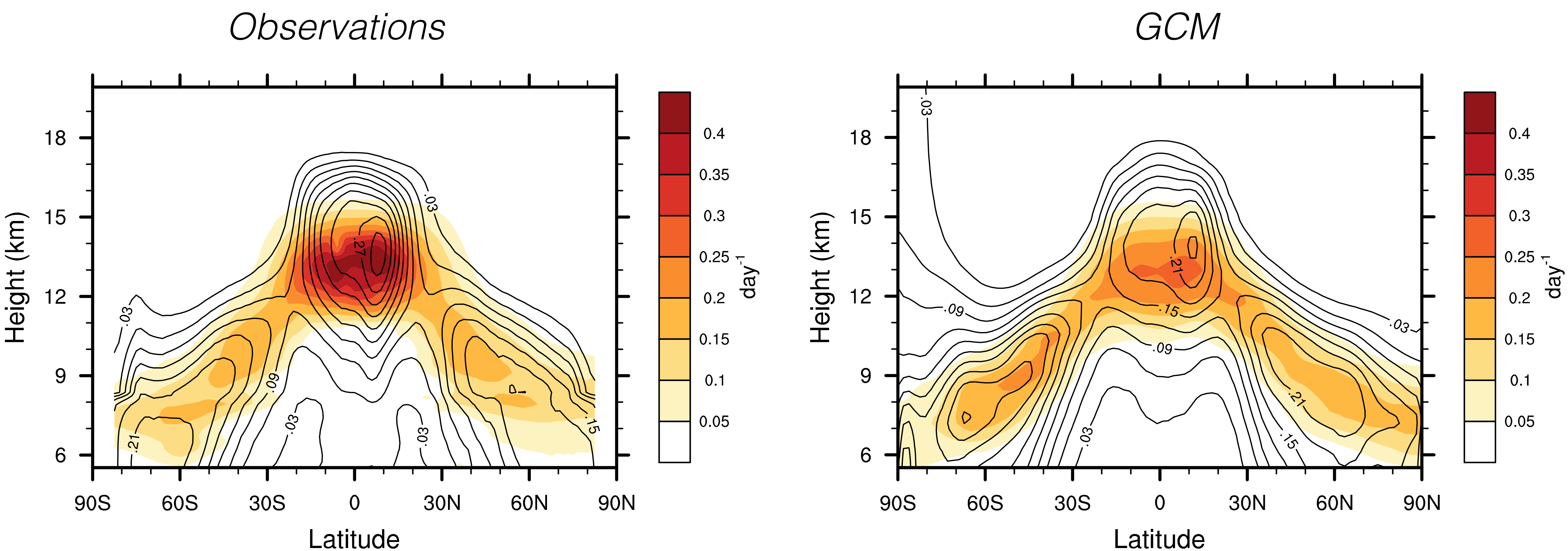
holds during all seasons in the tropics



and in the extratropics

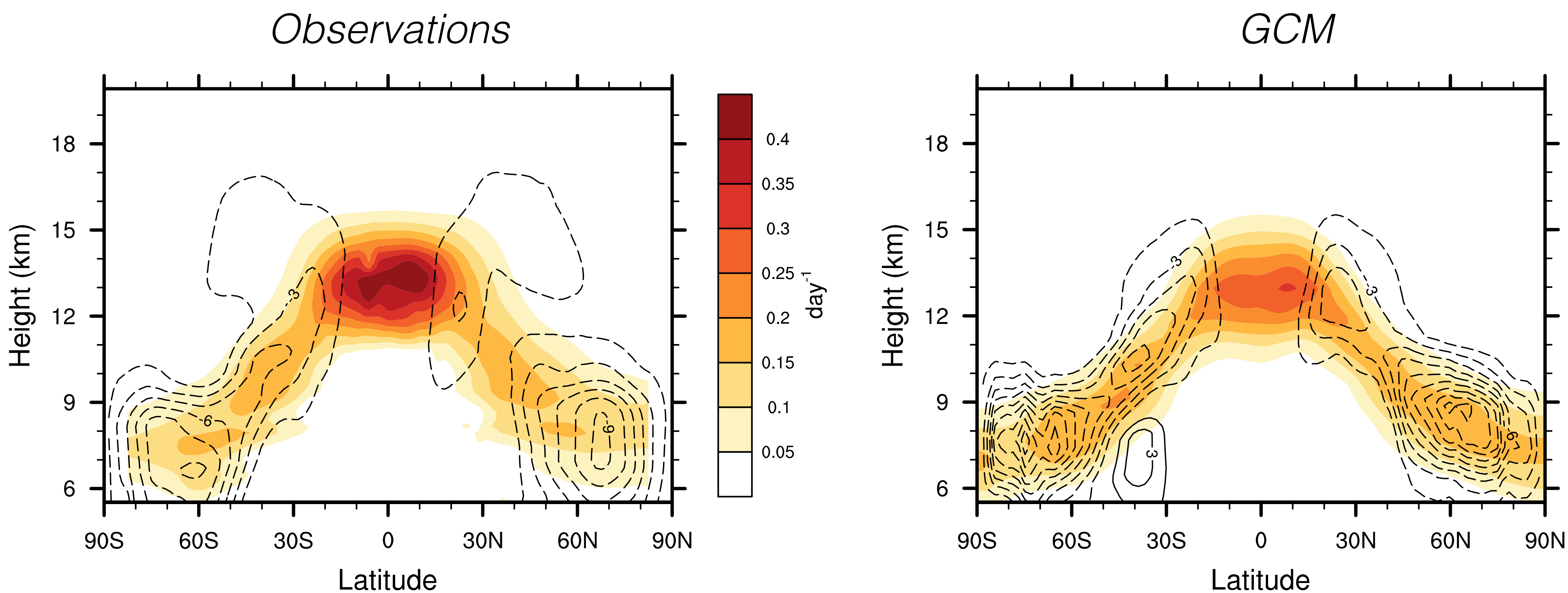


mass flux governs cloud fraction globally



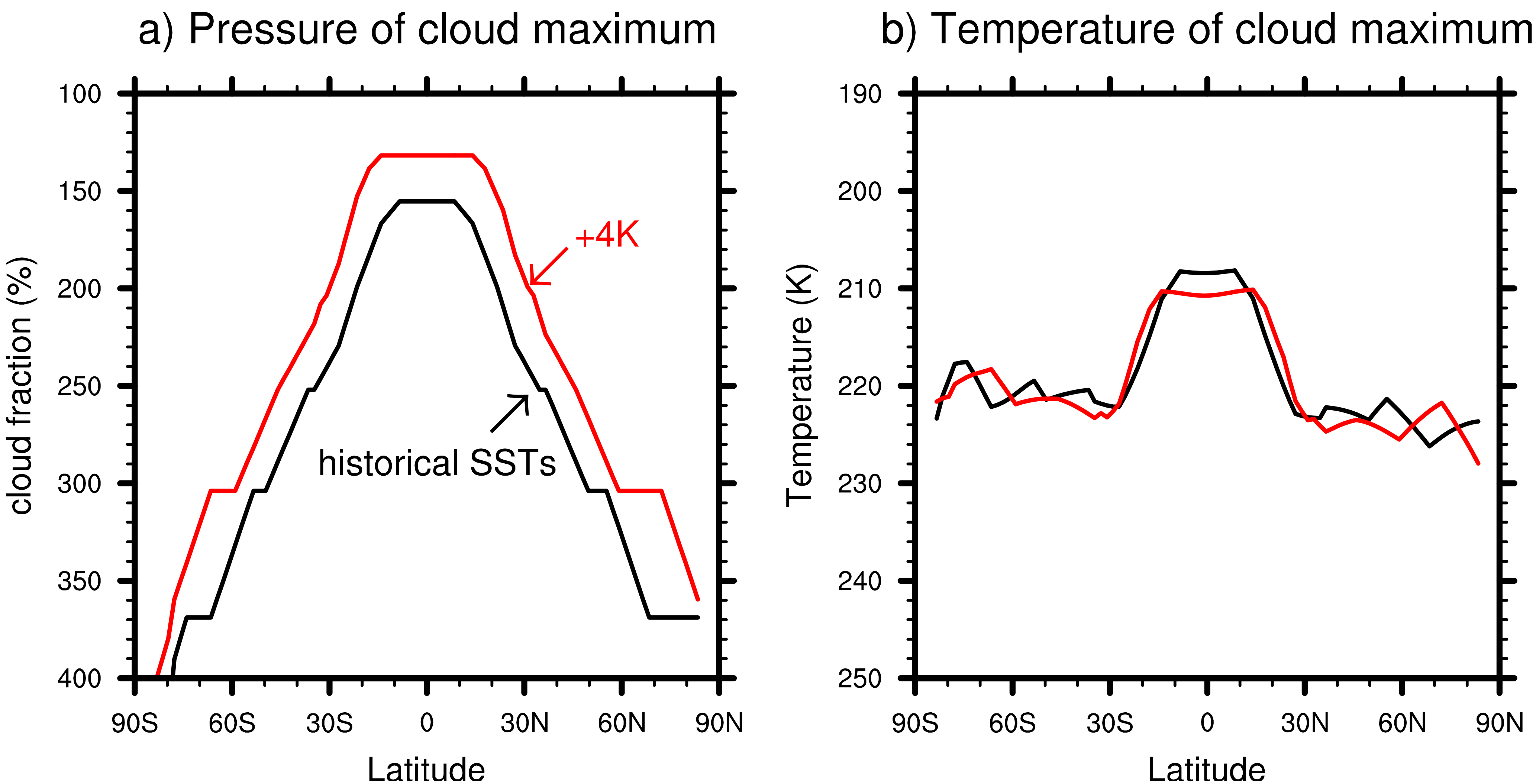
shading (mass flux divergence)
contours (cloud incidence)

mass flux aligns closely with wave driving



shading (mass flux divergence)
contours (EP flux divergence or PV fluxes)

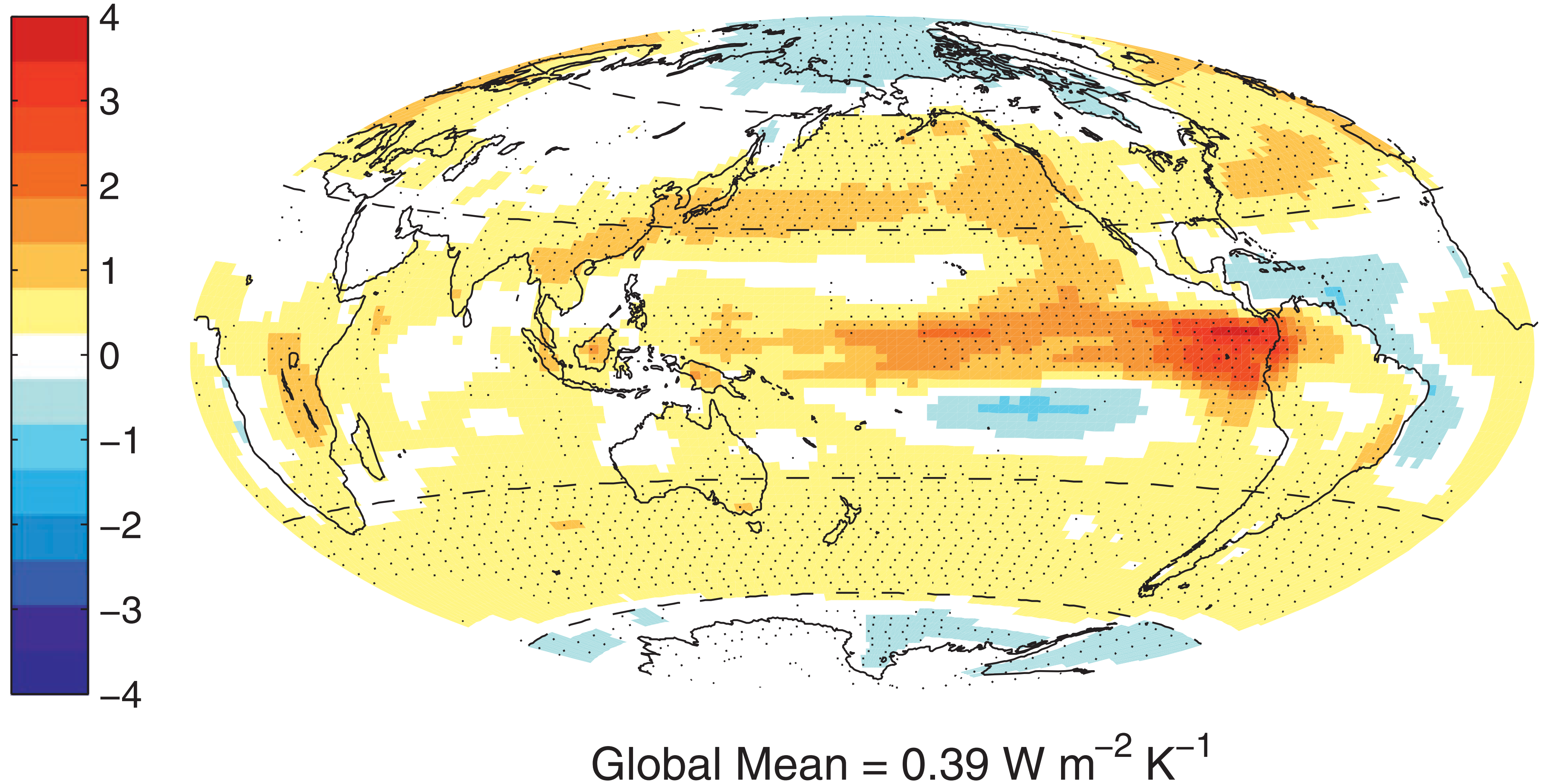
AMIP-style simulations



temperature of cloud top remains largely fixed globally as SSTs warm

historical SSTs are time varying observations 1979-2008

High cloud feedbacks extend beyond tropics



(from Zelinka et al 2012

longwave feedback due to cloud top altitude per deg. K global-mean temperature change

key points…

radiative cooling by water vapor plays a central role in governing the depth of vigorous diabatic mixing and thus eddy activity in both the tropics *and* extratropics

(from a TEM perspective: The PV fluxes and thus residual circulation can only be as strong as radiative cooling allows)

key points

the extratropical tropopause should remain at roughly the same temperature as surface temperature increases.

(i.e., the tropospheric circulation should lift under climate change, e.g., Singh and O'Gorman).

key points

positive climate feedbacks due to rising high clouds should hold not only in the tropics, but in the extratropics as well.

(this is the case in the CMIP5 runs; e.g. Zelinka et al. 2012)

FAT is a specific example of a more general, global constraint on diabatic mixing.

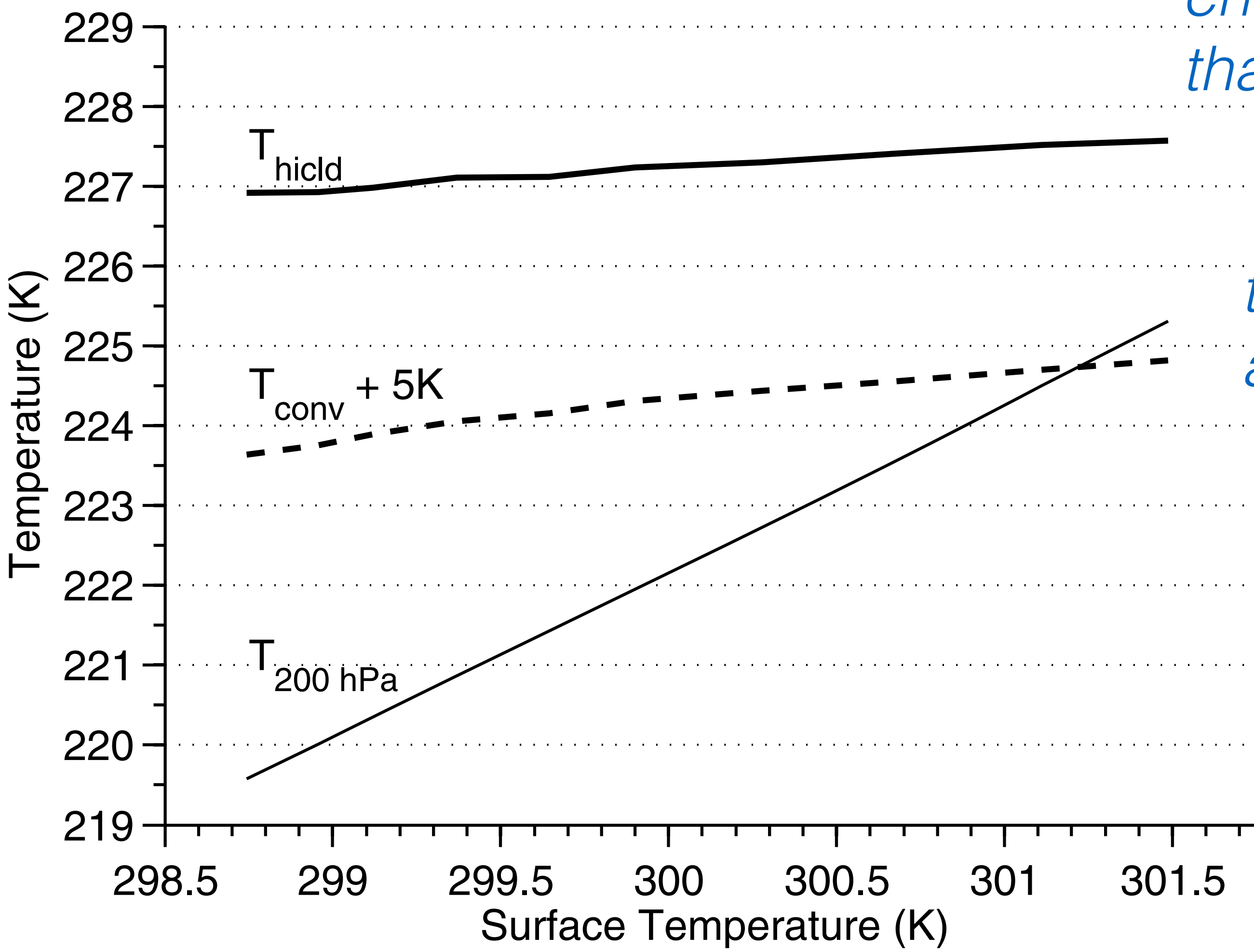
extras…

ozone and the BDC both change upper tropospheric static stability and thus the temperature of the largest clear sky mass flux divergence (e.g., Harrop and Hartmann 2012).

more *ozone heating -> warmer level of maximum clear sky mass flux divergence*

stratospheric sinking motion *-> warmer level of maximum clear sky mass flux divergence*

fixed anvil temperature hypothesis (FAT)



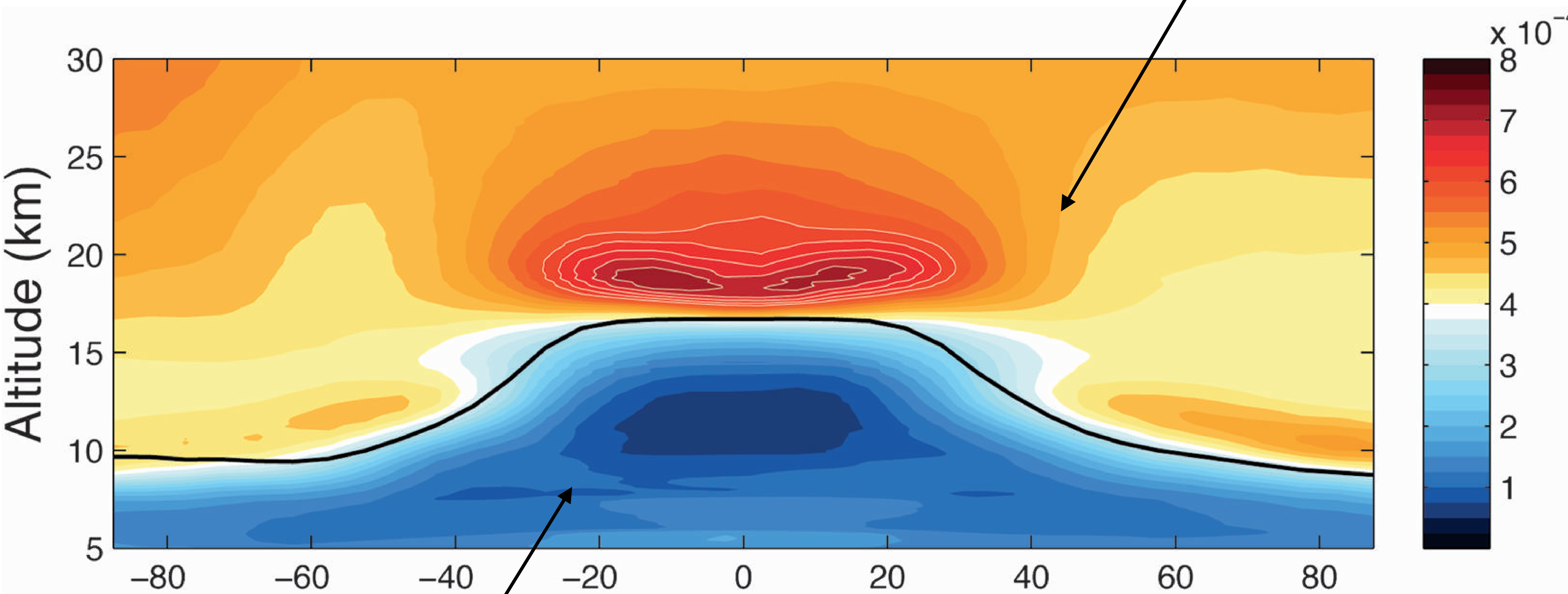
temperature of hi clouds changes only slightly (much less than the surface)

temperature at 200 hPa goes up as per the moist adiabat

(Zelinka and Hartmann 2010)

Static stability from GPS

high stratification (stratosphere)



well-mixed region (troposphere)

Grise et al. 2010