PV-θ – View* of Diabatic-Dynamical Interaction in the General Circulation

Aarnout van Delden
Institute for Marine and Atmospheric Research Utrecht (IMAU)
Utrecht University, The Netherlands
a.j.vandelden@uu.nl

* *Inspired by Hoskins, Tellus, 1991*

This talk:

Is about the zonal mean ***potential vorticity*** *(PV-) distribution, the associated jets and how* **diabatic** *processes (radiation and latent heat release) interact with* **adiabatic** *dynamical processes (heat and momentum transport) to produce this PV-distribution.*

$$PV \equiv Z \equiv \frac{\zeta_\theta + f}{\sigma} \quad [\mathrm{m^2 K\ s^{-1} kg^{-1}}]$$

$$10^{-6}\ \mathrm{m^2 K\ s^{-1} kg^{-1}} \equiv 1\ \mathrm{PVU}$$

isentropic density

relative vorticity on an isentropic surface

Other variables playing a central role

Potential temperature (θ) *is the vertical coordinate*

$$\theta \equiv T\left(\frac{p_{ref}}{p}\right)^{R/c_p} \quad [\mathrm{K}]$$

Isentropic density:

$$\sigma = -\frac{1}{g}\frac{\partial p}{\partial \theta} = \frac{\rho \partial z}{\partial \theta} \quad [\mathrm{kg\ m^{-2} K^{-1}}]$$

This talk

Observed hemispheric mean isentropic density profile

Isentropic density and cross-isentropic flow **determined by radiation**

Observed zonal mean isentropic density and cross-isentropic flow

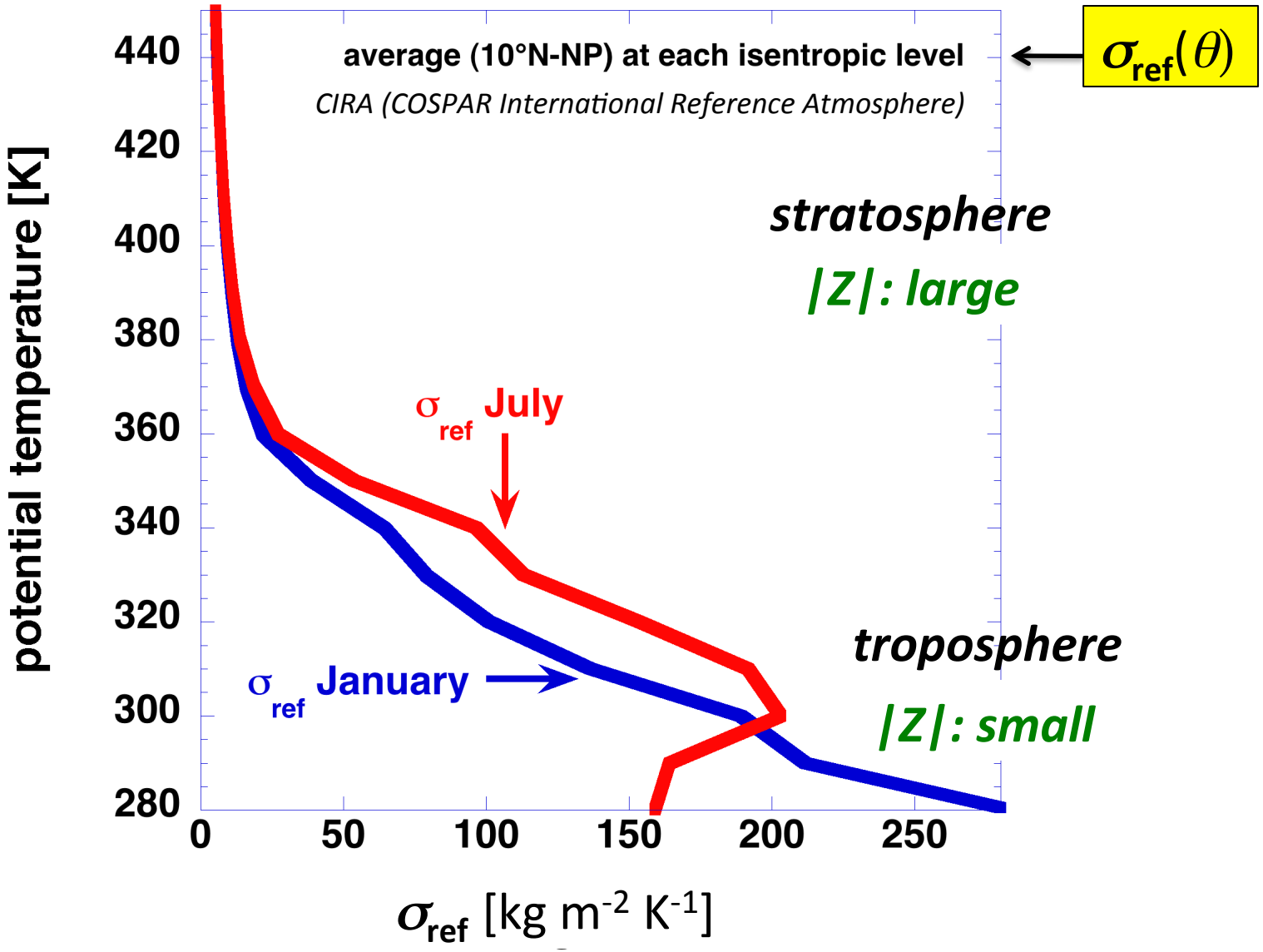
Zonal mean *PV*-anomalies in the upper troposphere and lower stratosphere

Link between zonal mean zonal wind and zonal mean *PV*-anomalies (***PV*-inversion**)

Simulations revealing the mechanisms that establish the zonal mean *PV*-distribution and associated jets

Observed mean isentropic density profile

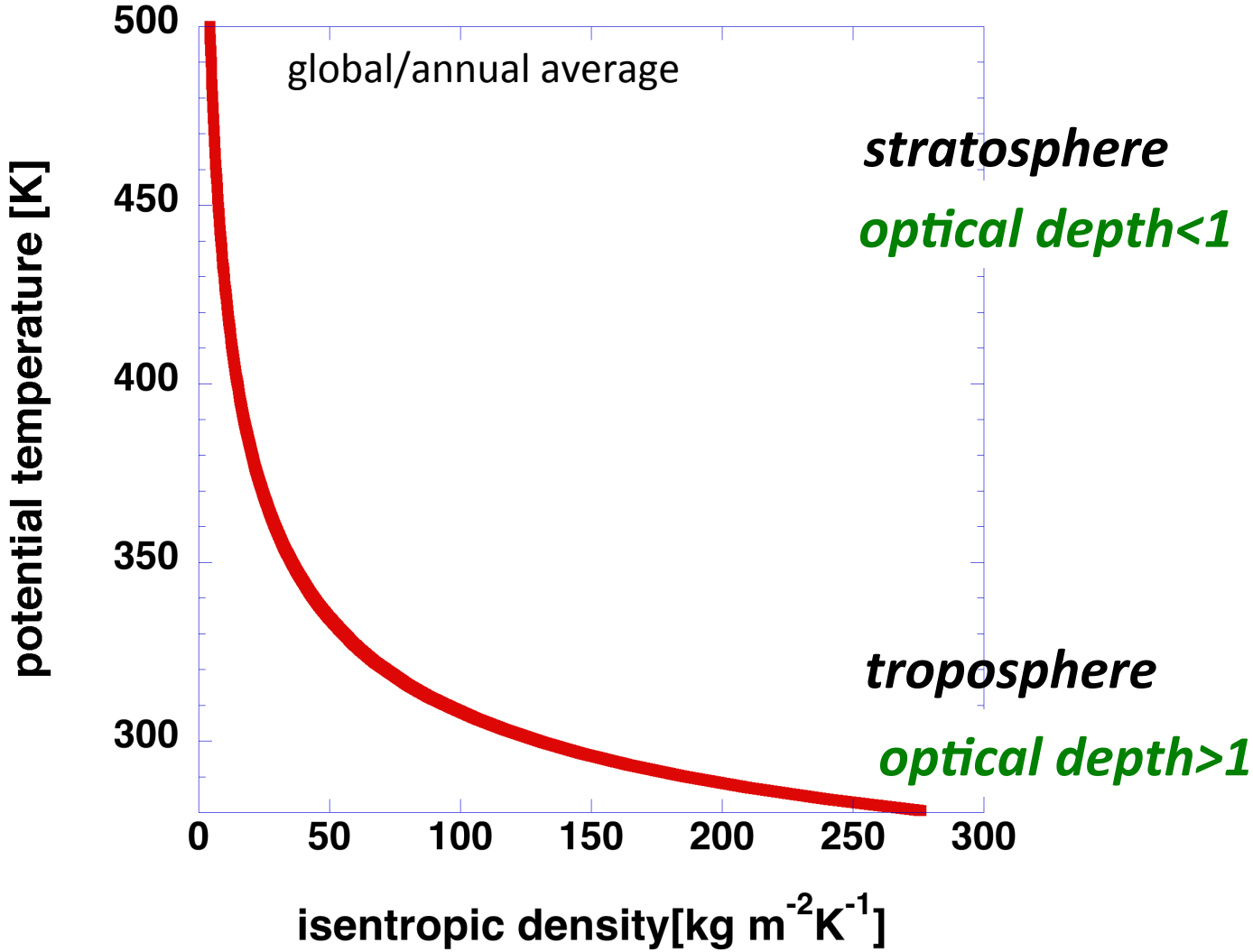
Average isentropic density in N. hemisphere poleward of 10° latitude



Theoretical radiative equilibrium isentropic density

homogeneous "grey" atmosphere

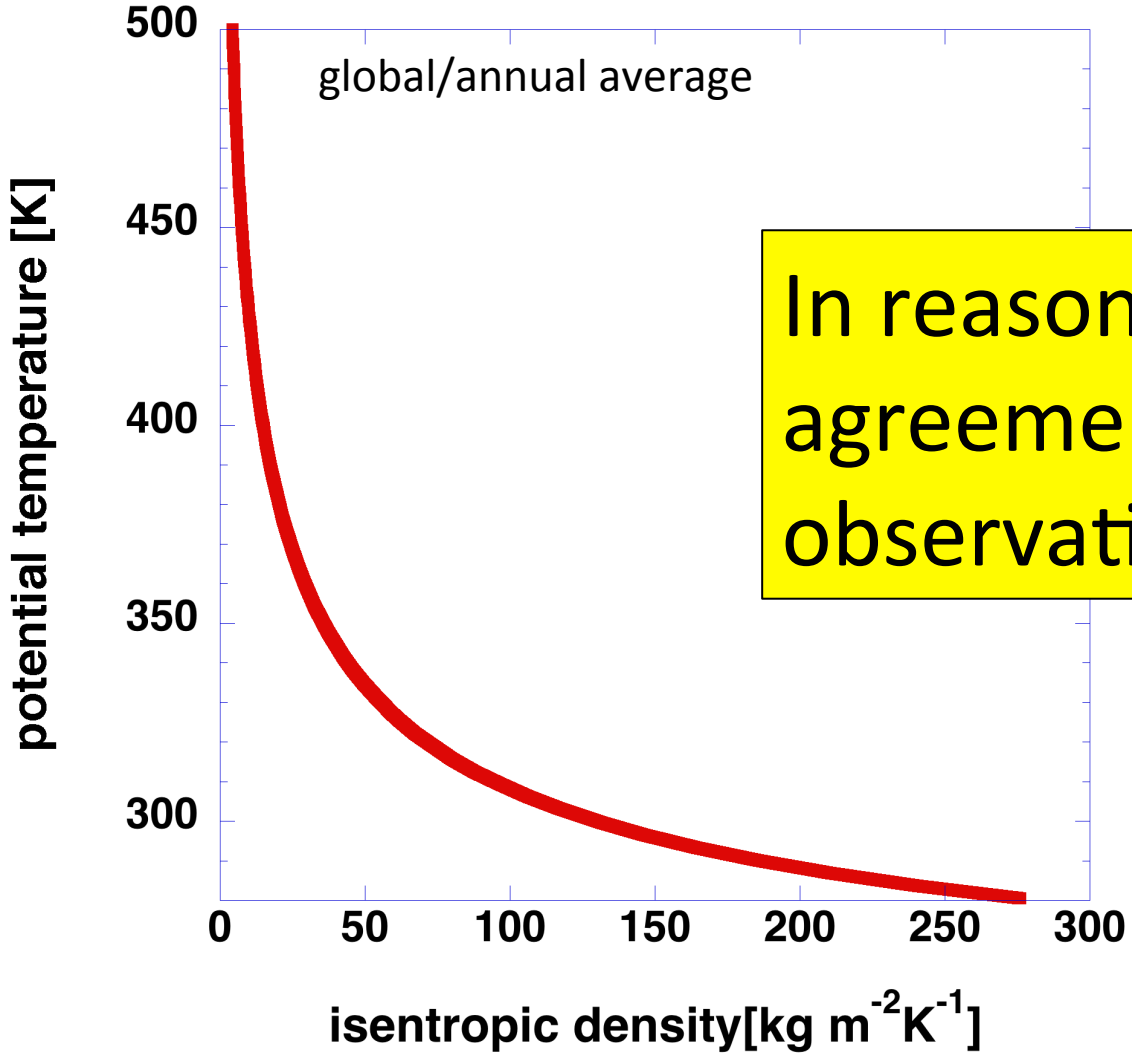
One well-mixed greenhouse gas and no atmospheric absorption of Solar radiation



Theoretical radiative equilibrium isentropic density

homogeneous "grey" atmosphere

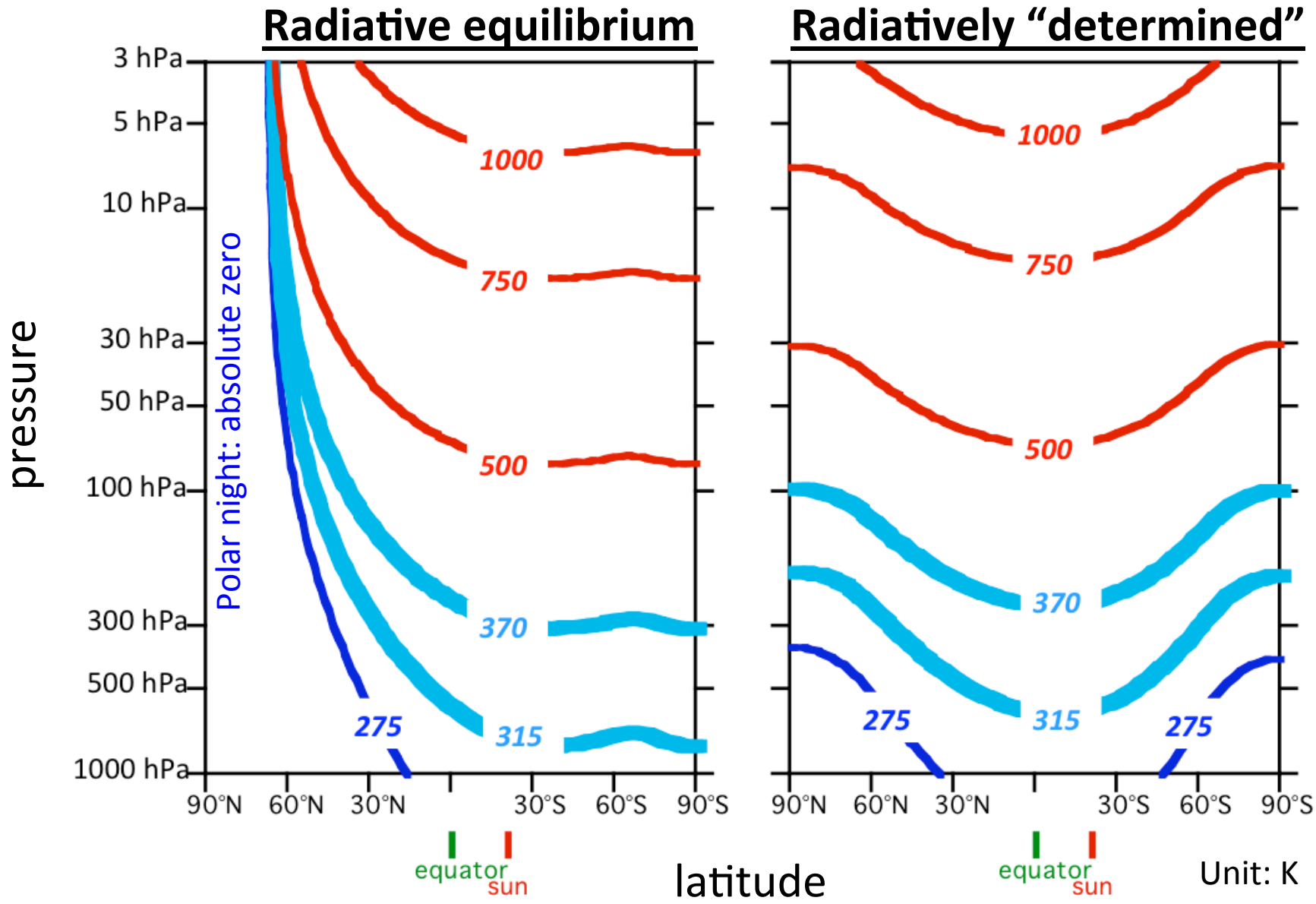
One well-mixed greenhouse gas and no atmospheric absorption of Solar radiation



In reasonable agreement with observations!

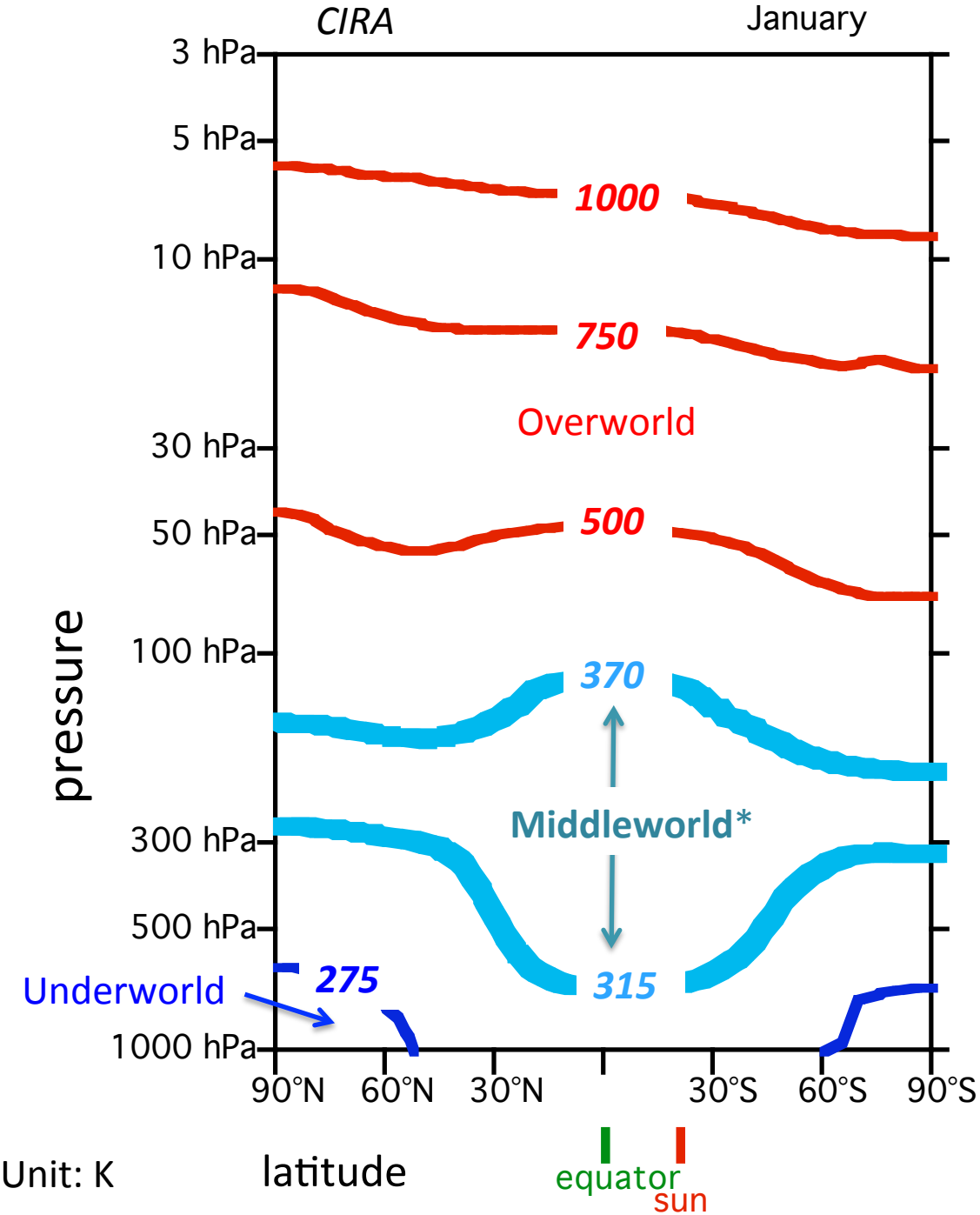
Potential temperature: January 15

(in a "grey", homogeneous atmosphere)



Observed potential temperature: January

Tropical Middleworld is inflated with mass !!



Unit: K

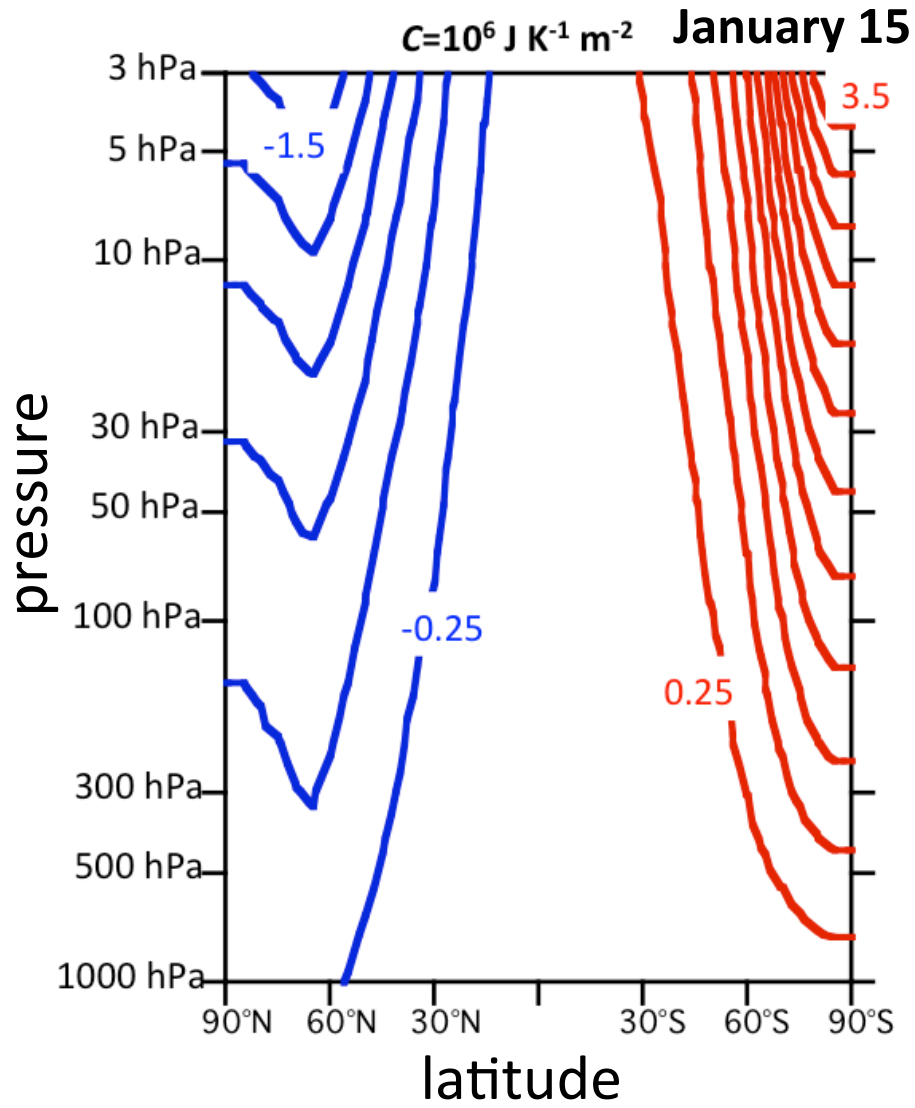
* *Hoskins, Tellus 1991*

Cross-isentropic flow, determined by radiation

(in a "grey", homogeneous atmosphere)

$d\theta / dt$ Unit: K day^{-1}

Cooling in winter hemisphere
Heating in summer hemisphere
Tropics in radiative equilibrium

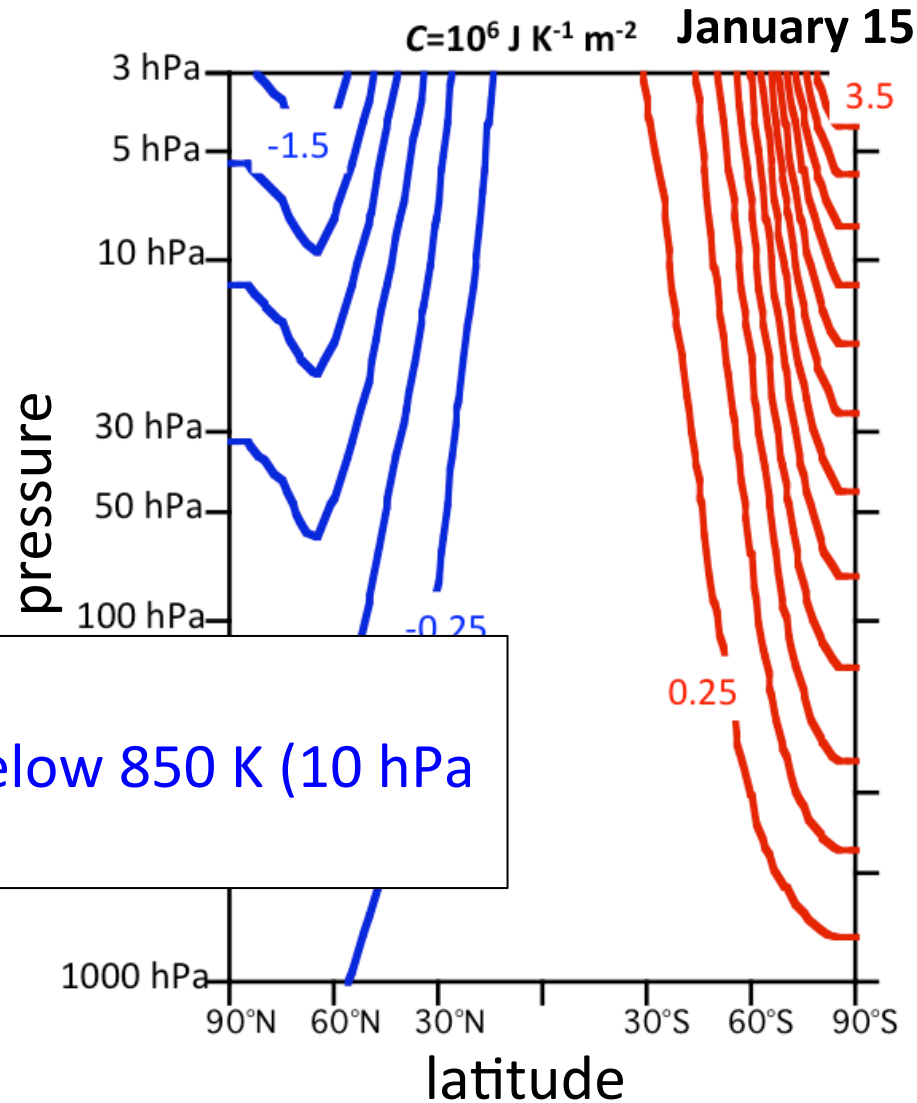


Cross-isentropic flow, determined by radiation

(in a "grey", homogeneous atmosphere)

$d\theta / dt$ Unit: K day^{-1}

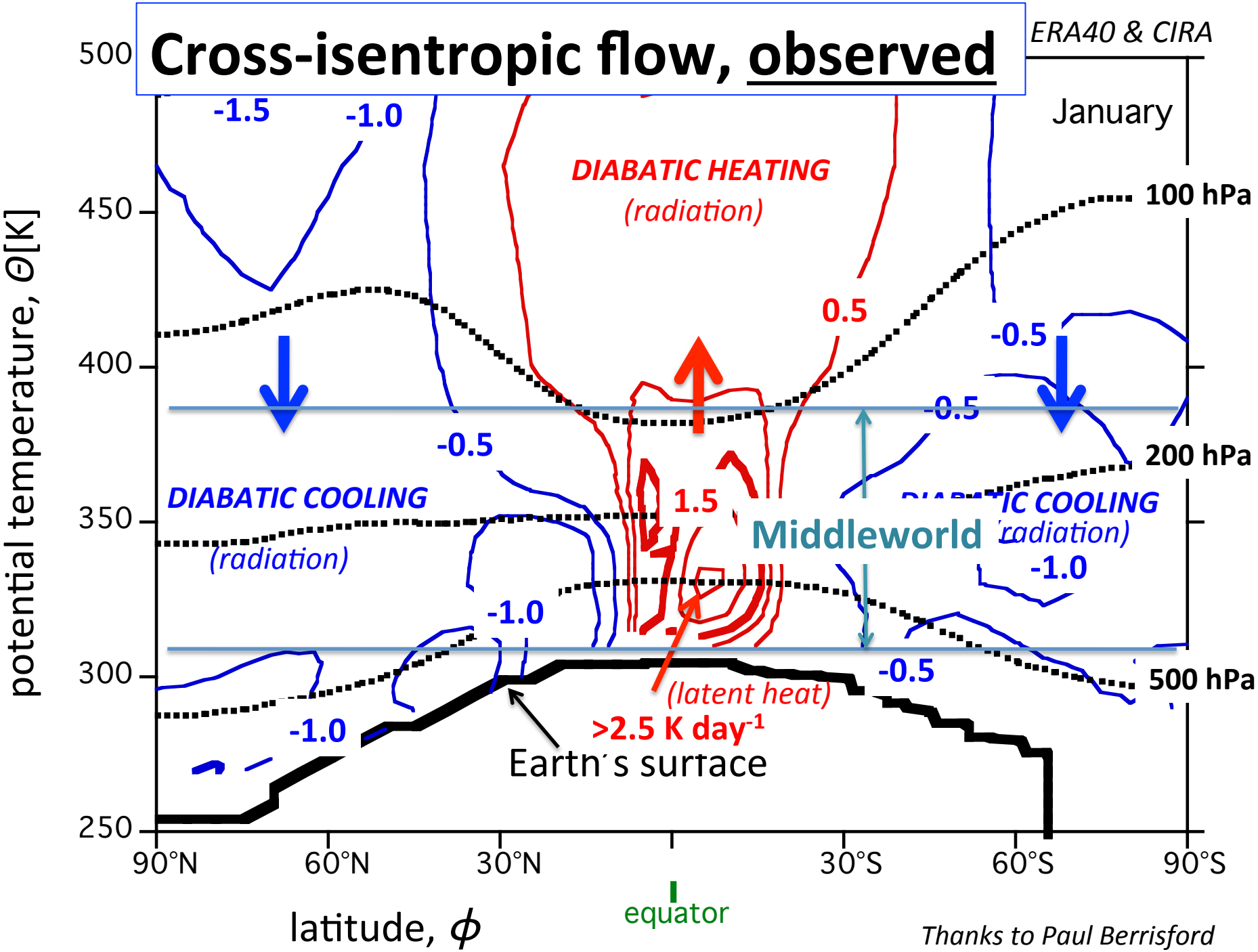
Cooling in winter hemisphere
Heating in summer hemisphere
Tropics in radiative equilibrium



In reality (see next slide):

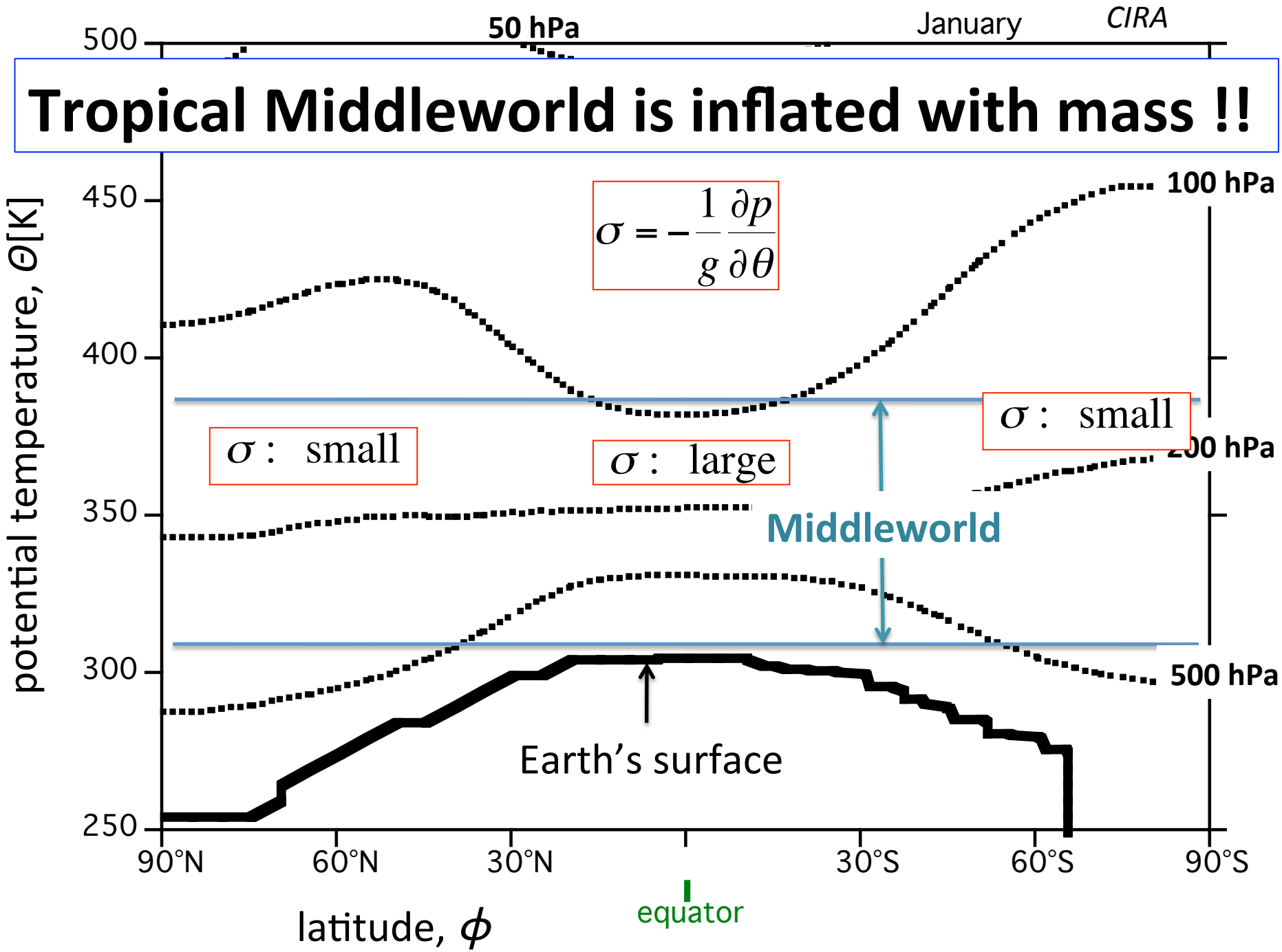
Cooling in winter hemisphere
Cooling in summer hemisphere below 850 K (10 hPa
Heating in tropics

Cross-isentropic flow, observed

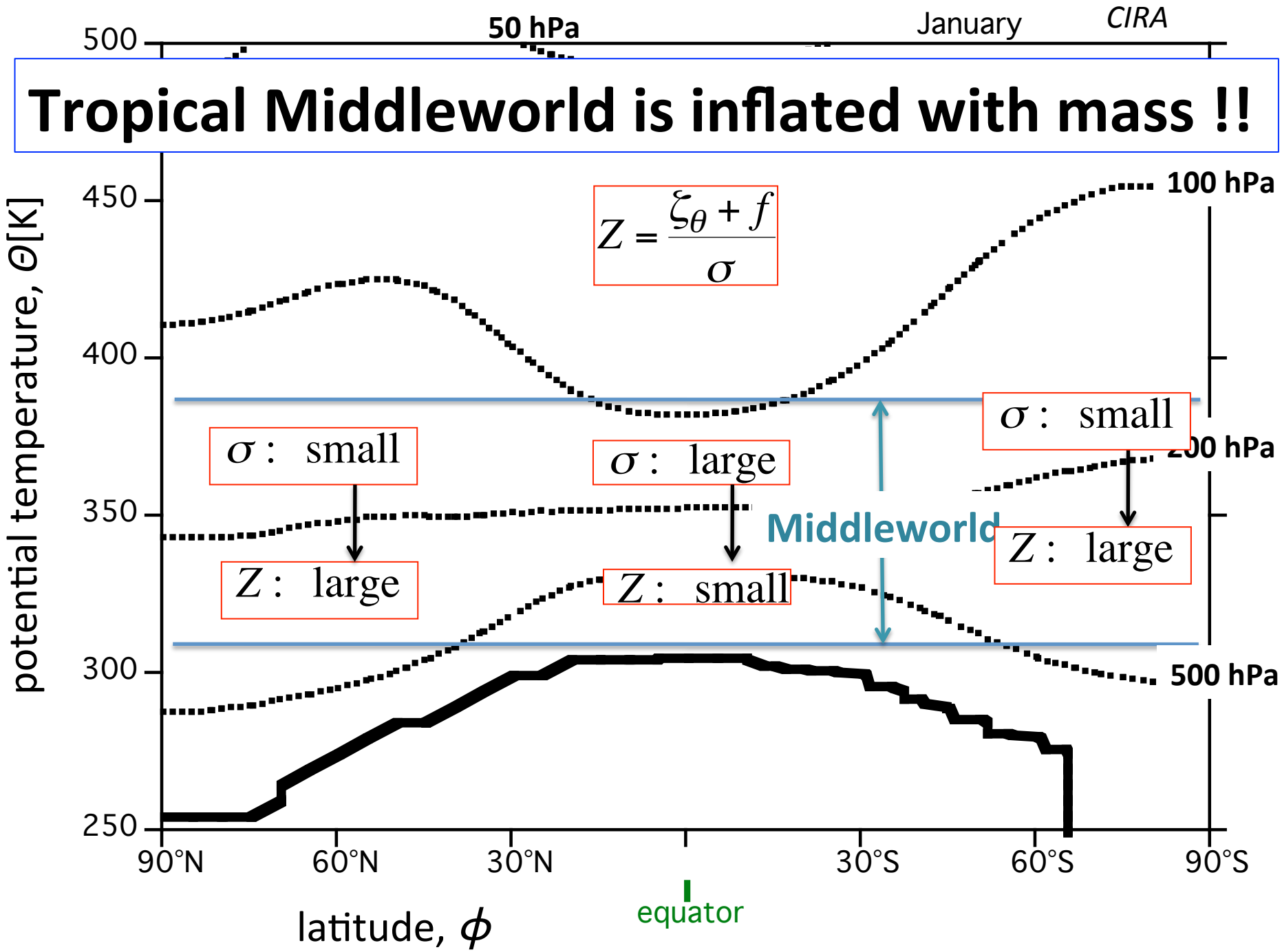


Thanks to Paul Berrisford

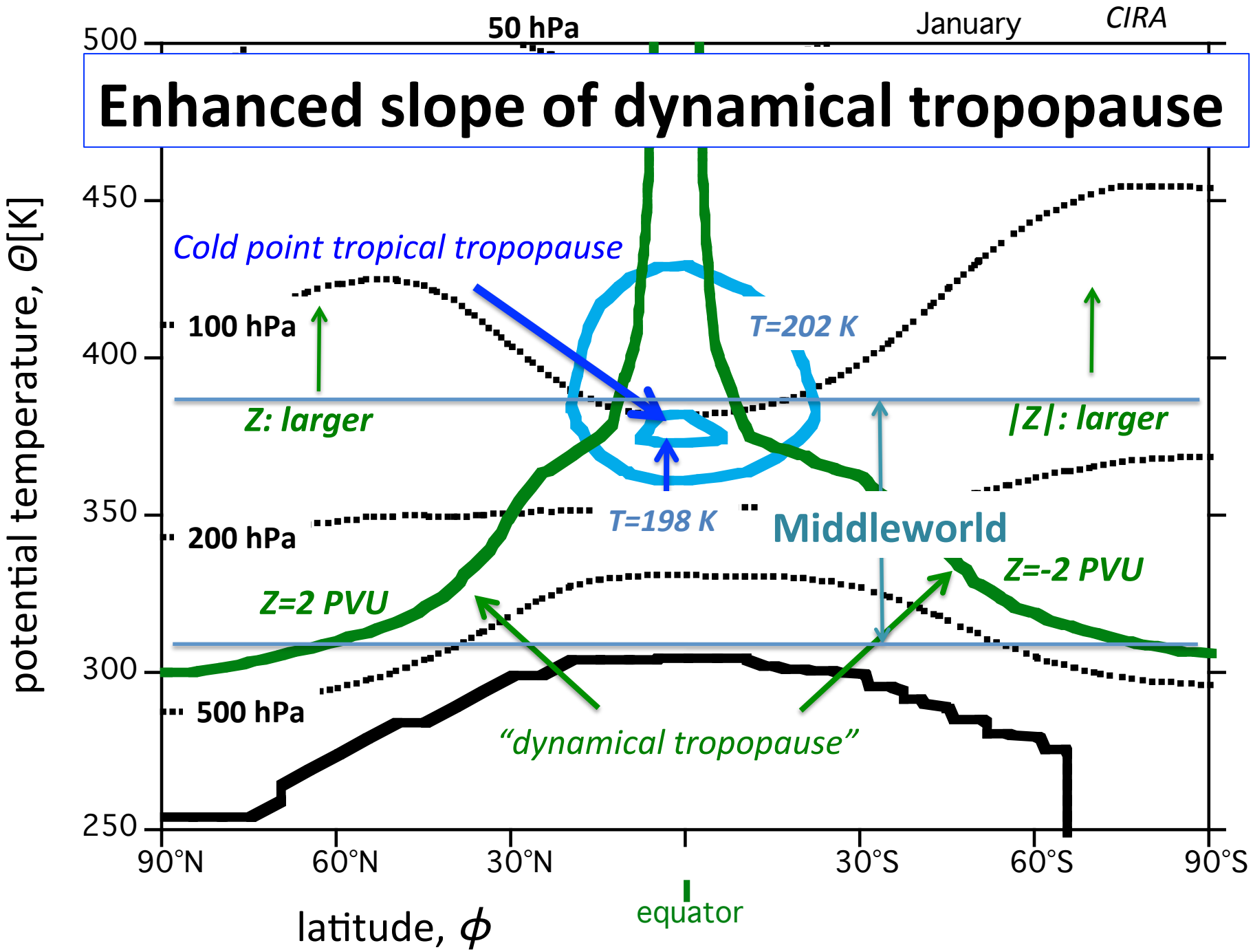
Tropical Middleworld is inflated with mass !!



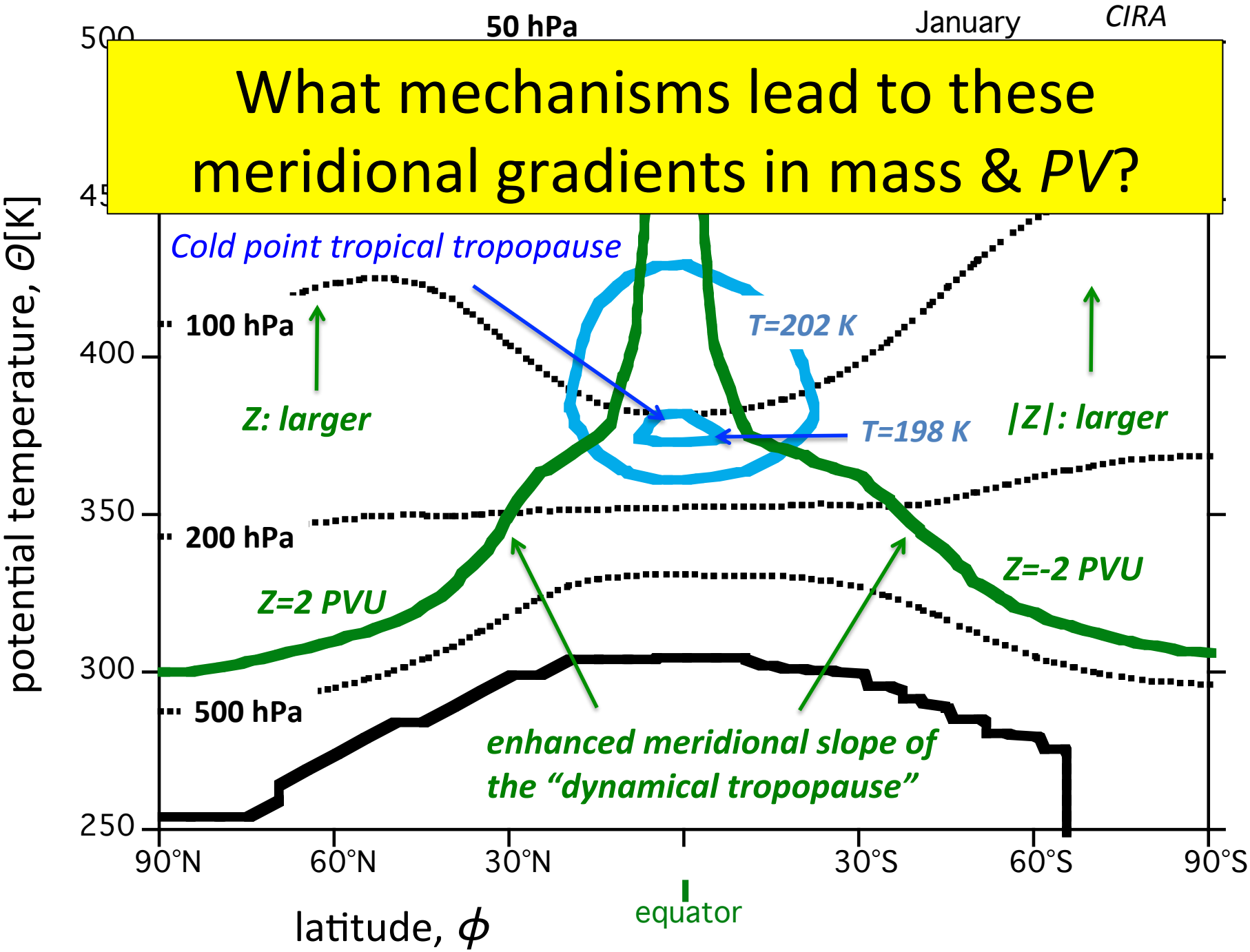
Tropical Middleworld is inflated with mass !!



Enhanced slope of dynamical tropopause



What mechanisms lead to these meridional gradients in mass & *PV*?



"potential vorticity substance" (*PVS*)

$PV \equiv Z \equiv \dfrac{PVS}{\sigma}$ is the "mixing ratio" of *PVS*

<u>Impermeability theorem for *PVS* *</u>:

cross-isentropic flux of *PVS*=0

i.e. no flux of *PVS* across isentropic surfaces !

**Haynes and McIntyre, J.Atmos,Sci., 1987, 1990.*

Cross-isentropic mass flux:

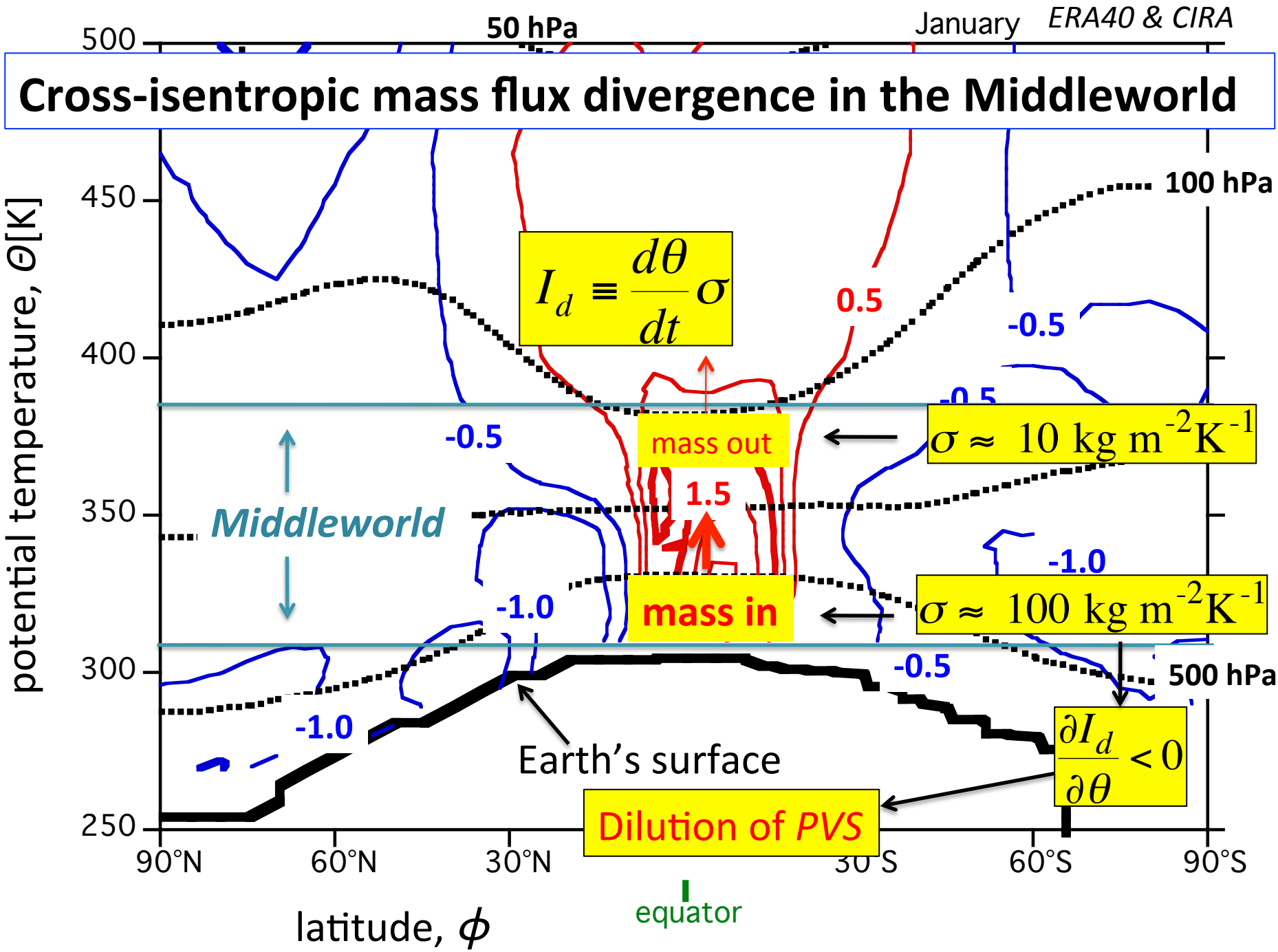
$$I_d \equiv \frac{d\theta}{dt}\sigma$$

$\partial I_d/\partial\theta > 0$ leads to **concentration of *PVS*** (decrease of σ), therefore **increase of *PV***

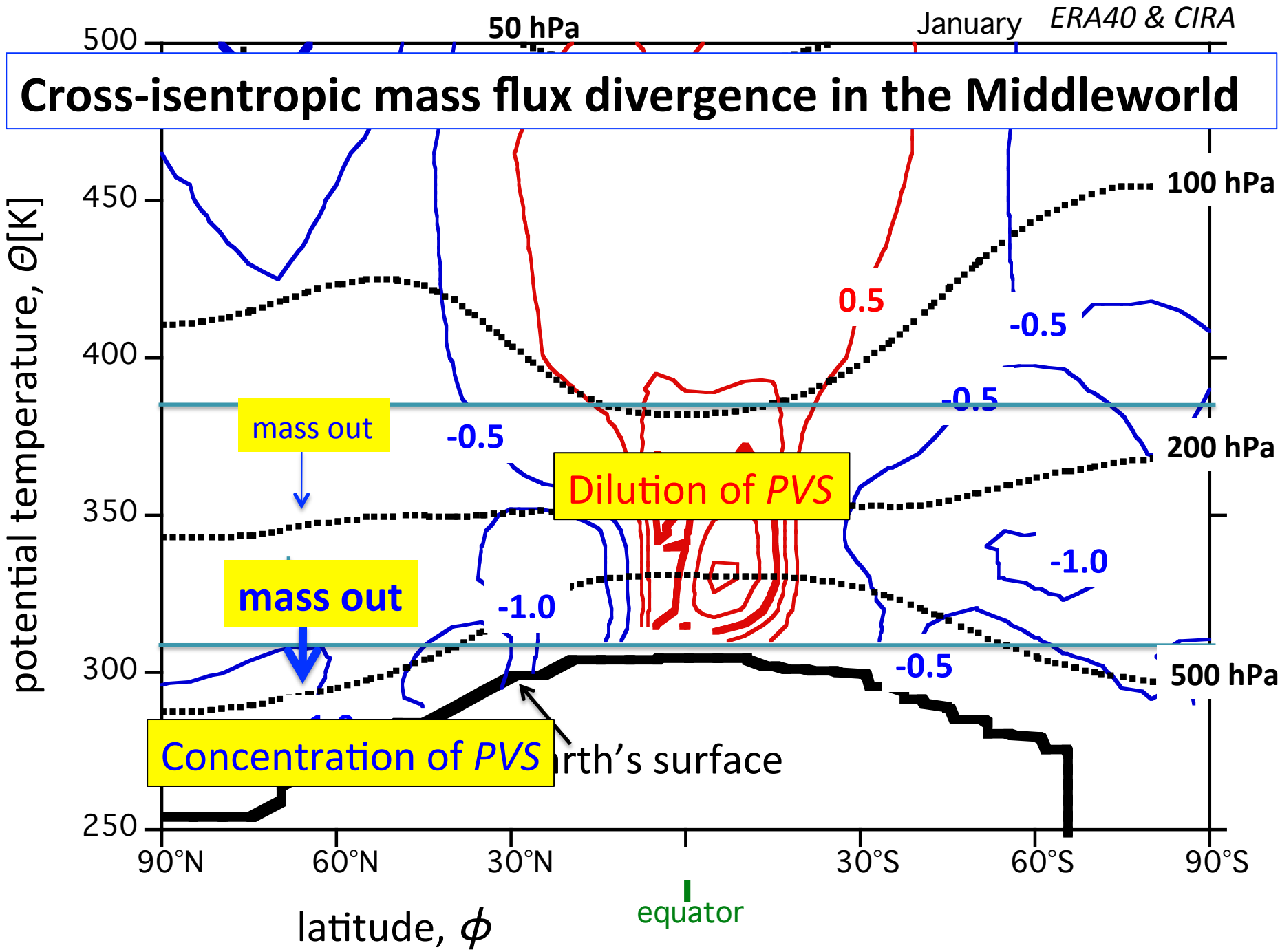
(extratropics)

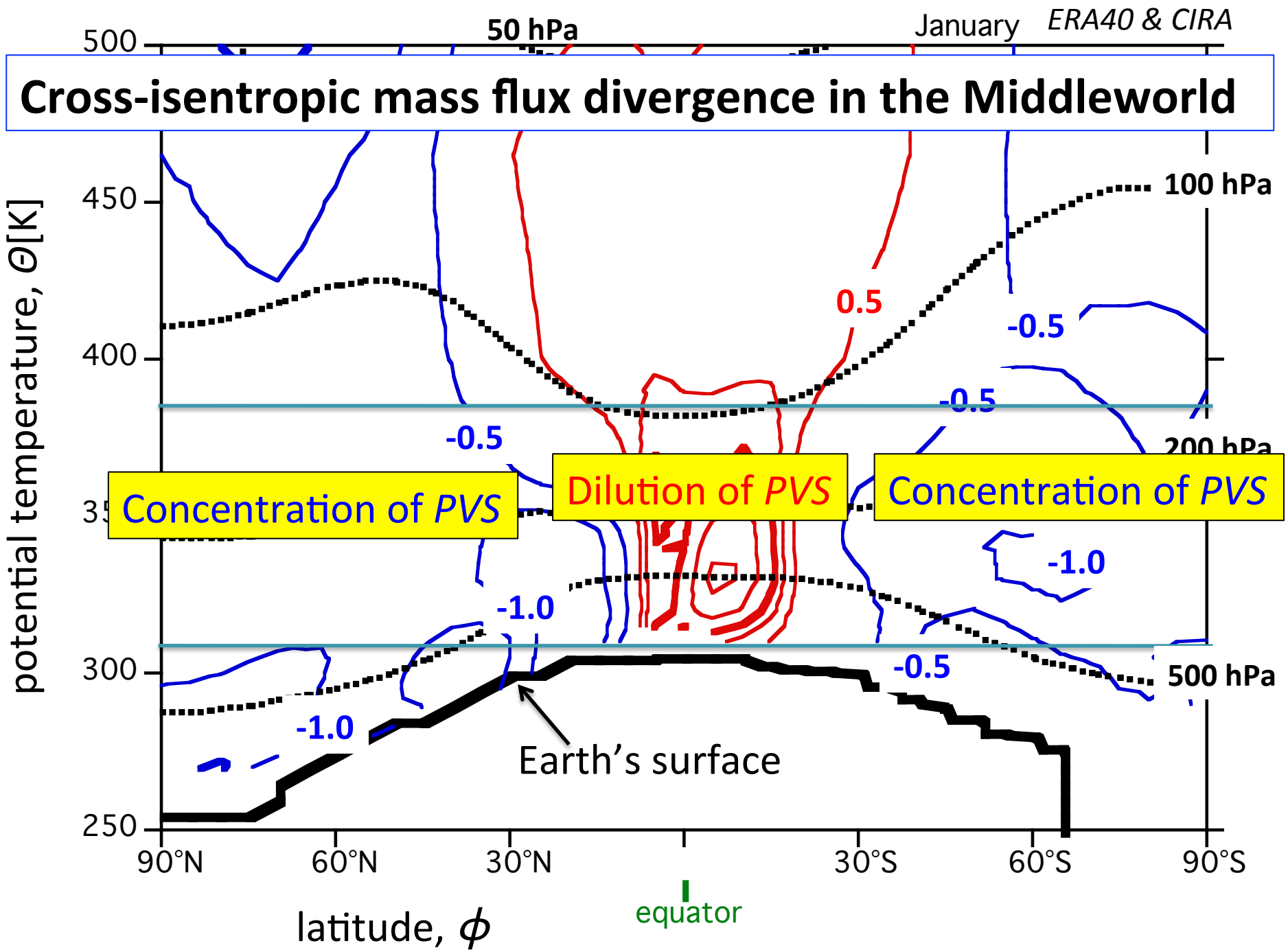
$\partial I_d/\partial\theta < 0$ leads to **dilution of *PVS*** (increase of σ), therefore **decrease of *PV***

(tropics)

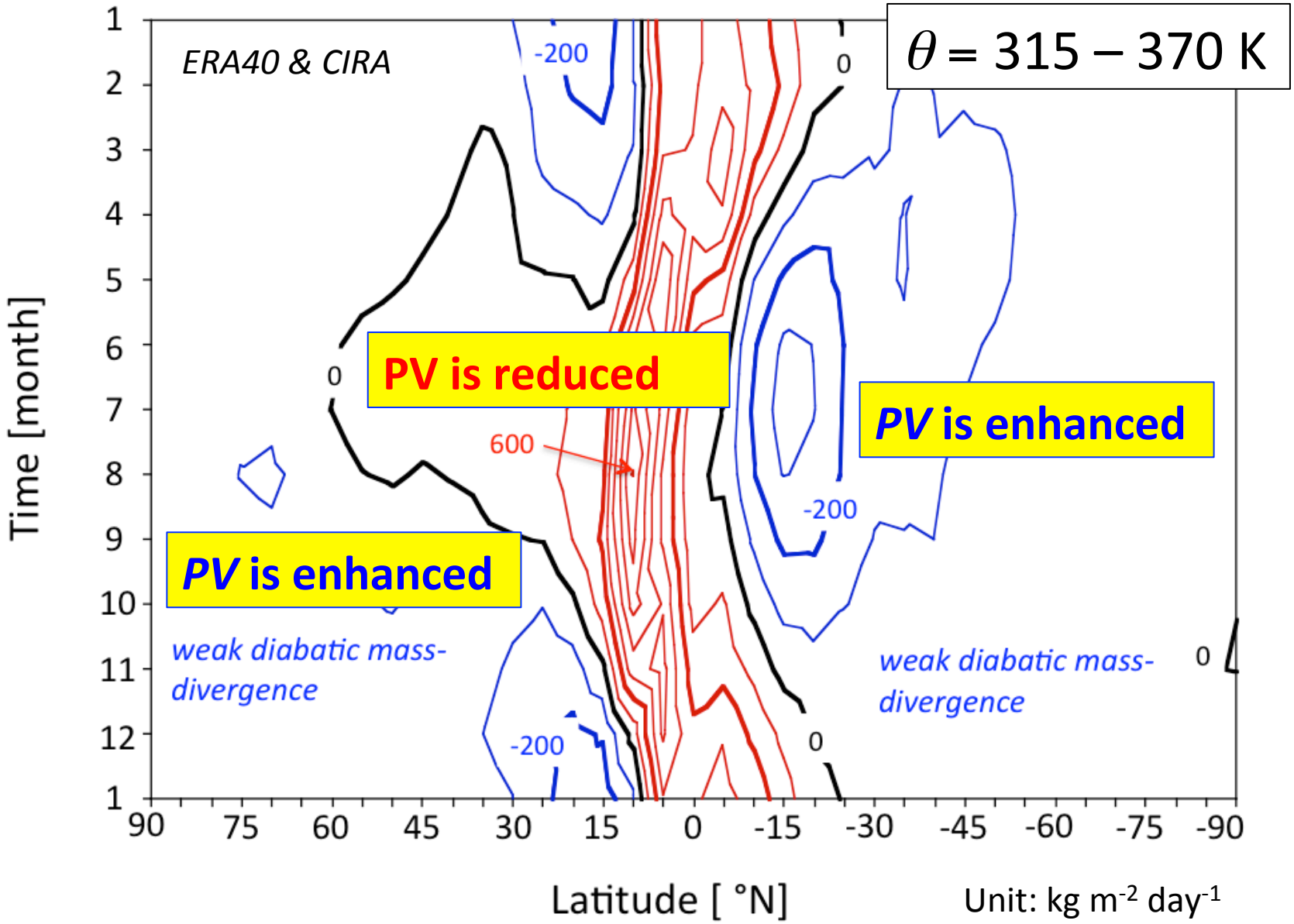

Cross-isentropic mass flux divergence in the Middleworld
January
ERA40 & CIRA
50 hPa
100 hPa
500 hPa
$I_d \equiv \frac{d\theta}{dt}\sigma$
0.5
1.5
-0.5
-1.0
mass out
mass in
$\sigma \approx 10\ \mathrm{kg\ m^{-2}K^{-1}}$
$\sigma \approx 100\ \mathrm{kg\ m^{-2}K^{-1}}$
Middleworld
$\frac{\partial I_d}{\partial \theta} < 0$
Dilution of PVS
Earth's surface
potential temperature, θ[K]
500
450
400
350
300
250
90°N
60°N
30°N
30°S
60°S
90°S
equator
latitude, ϕ

Cross-isentropic mass flux divergence in the Middleworld




Cross-isentropic mass flux divergence in the Middleworld
January
ERA40 & CIRA
50 hPa
100 hPa
200 hPa
500 hPa
0.5
-0.5
-1.0
Concentration of PVS
Dilution of PVS
Concentration of PVS
Earth's surface
potential temperature, Θ[K]
500
450
400
300
250
90°N
60°N
30°N
30°S
60°S
90°S
equator
latitude, ϕ

Cross-isentropic mass flux divergence in the Middleworld



Observed zonal mean *PV*-distribution

Define: **Reference state**

$$Z = Z_{\mathrm{ref}} \equiv \frac{f}{\sigma_{\mathrm{ref}}}$$

Reference state + anomaly

$$Z = Z_{\mathrm{ref}} + Z'$$

Non-dimensional *PV*-anomaly

$$Z^* = \frac{Z'}{Z_{\mathrm{ref}}}$$

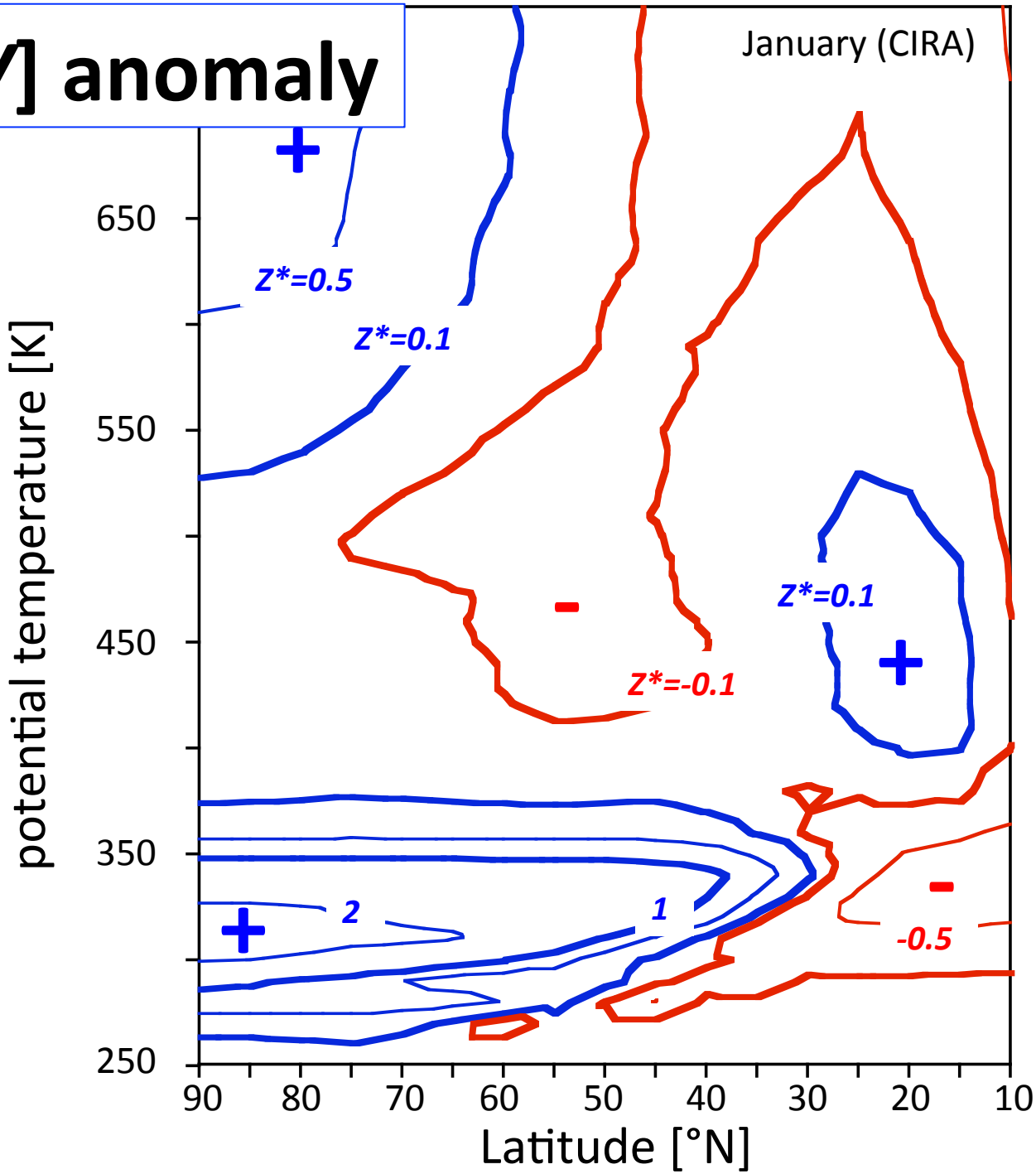
Analysed [*PV*] anomaly

January n.h.

Analysed *positive* and *negative* PV-anomalies

$$Z^* = \frac{Z'}{Z_{\mathrm{ref}}}$$

Unit: [*PV*]: non-dimensional
[*u*]: m s^{-1}



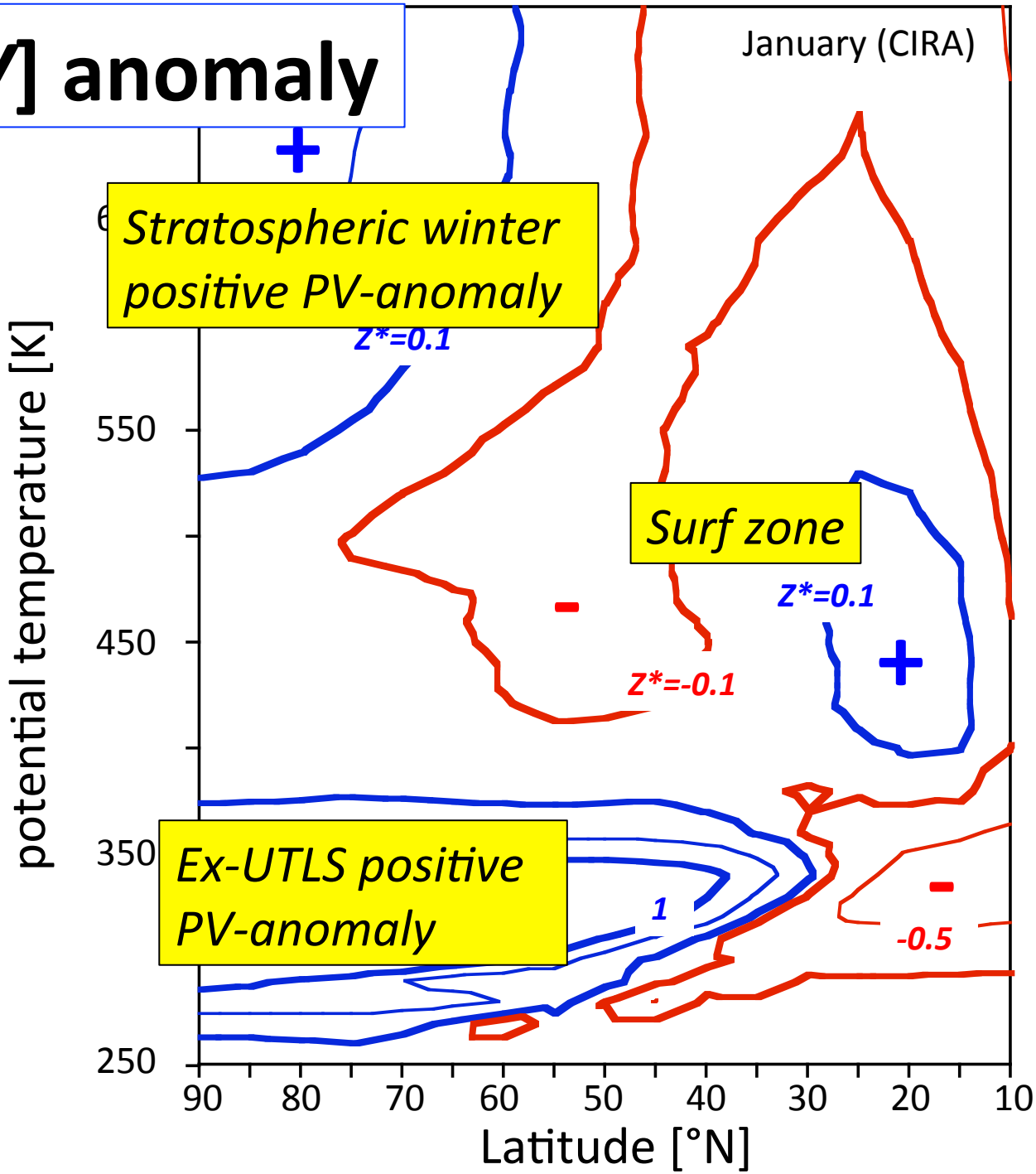
Analysed [*PV*] anomaly

January n.h.

Analysed *positive* and *negative* PV-anomalies

$$Z^* = \frac{Z'}{Z_{\mathrm{ref}}}$$

Unit: [*PV*]: non-dimensional
[*u*]: m s^{-1}



PV-inversion

Now I will show, by piecewise PV-inversion, that the Ex-UTLS PV-anomaly induces the subtropical jet and westerly flow in the troposphere and lower stratosphere

Relation *PV* ([*Z*]) and zonal wind, [*u*]

<u>Zonal mean potential vorticity (*PV*) inversion equation</u>
looks like this:

$$\frac{\partial^2[u]}{\partial y^2} + A\frac{\partial^2[u]}{\partial \theta^2} = \frac{df}{dy} - \sigma\frac{\partial[Z]}{\partial y}$$

r.h.s. represents the "forcing". If "forcing"=0 and *homogeneous boundary conditions**, then solution of this elliptic equation is $[u]$=0 (<u>rest state</u>).

This is the case if $[Z] = Z_{\mathrm{ref}} \equiv \frac{\sigma_{\mathrm{ref}}}{f}$ ← Is associated with the state of rest !

***<u>PV</u>*-anomalies induce the full zonal wind!!**

*(***no thermal wind at lower boundary!***)

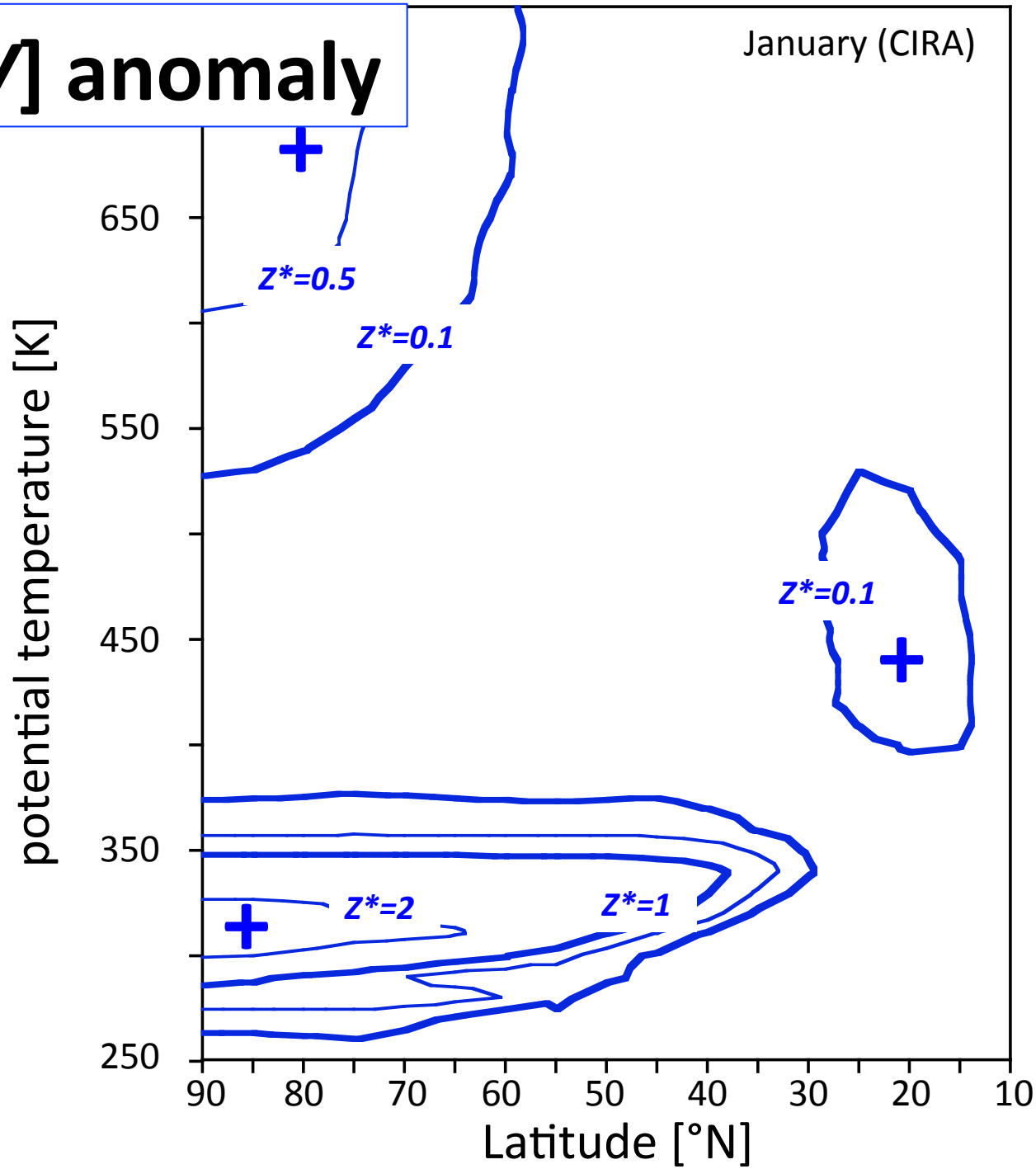
Analysed [*PV*] anomaly

January n.h.

Analysed *positive* PV-anomalies

$$Z^* = \frac{Z'}{Z_{\mathrm{ref}}}$$

Unit: [*PV*]: non-dimensional



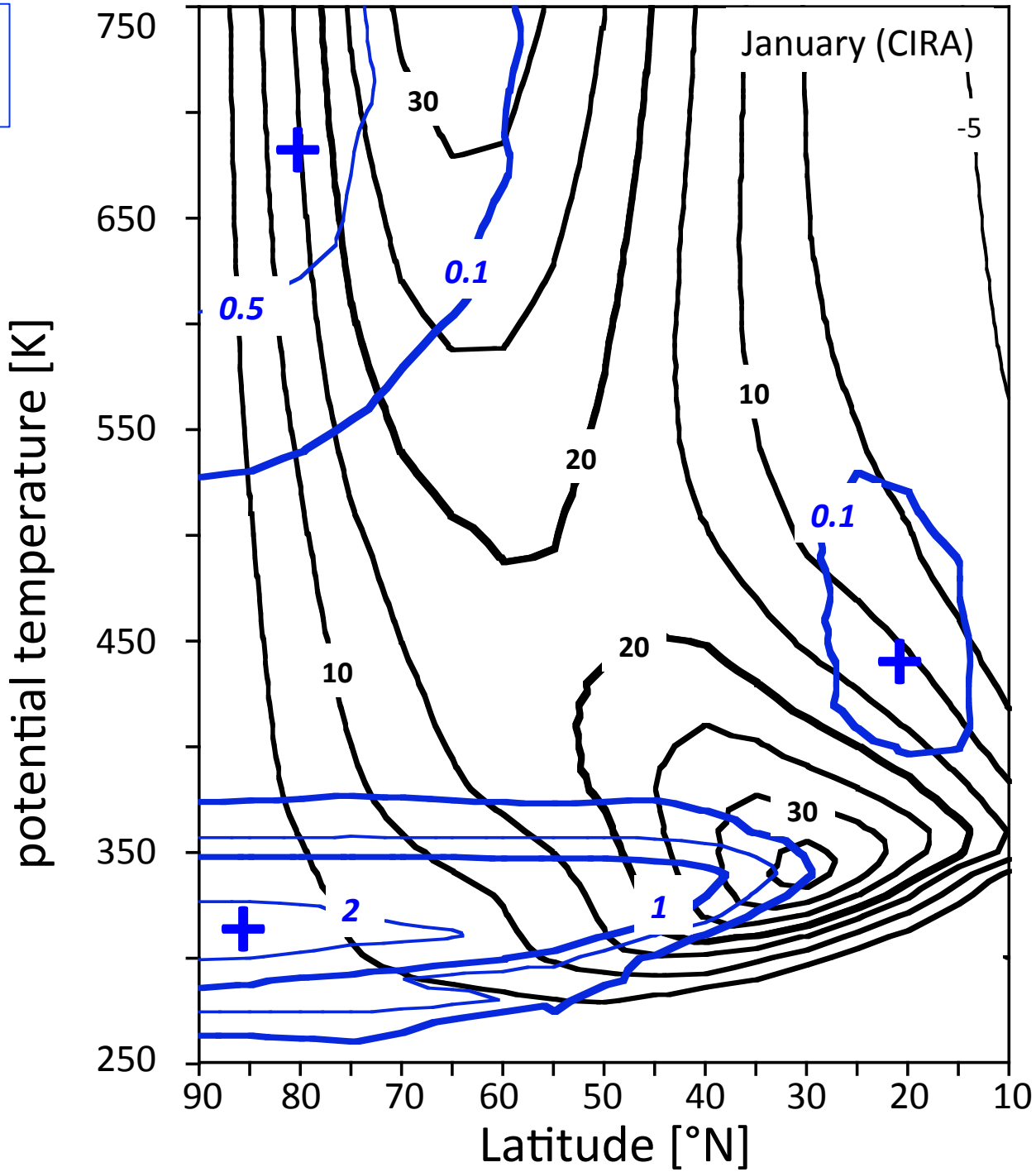
Analysed [*u*]

January n.h.

Analysed *positive* PV-anomalies and [*u*] *(*zonal mean zonal wind)

Unit: [*PV*]: non-dimensional
[*u*]: m s^{-1}

$$Z^* = \frac{Z'}{Z_{\mathrm{ref}}}$$



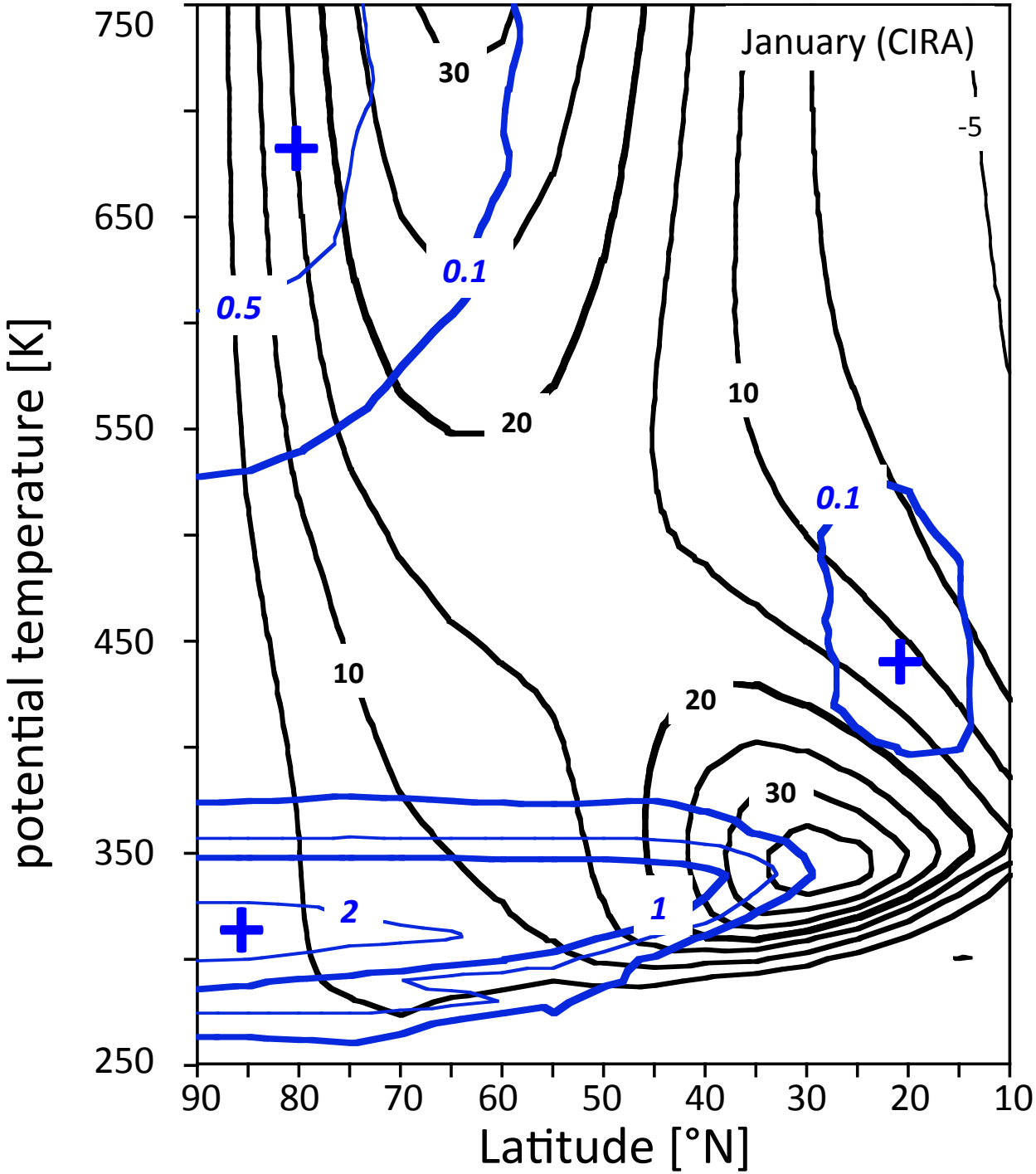
Inverted [*u*]

January n.h.

Inverted zonal mean zonal wind velocity [m/s] and analysed *positive* PV-anomalies

Unit: [*PV*]: non-dimensional
[*u*]: m s^{-1}

$$Z^* = \frac{Z'}{Z_{\mathrm{ref}}}$$

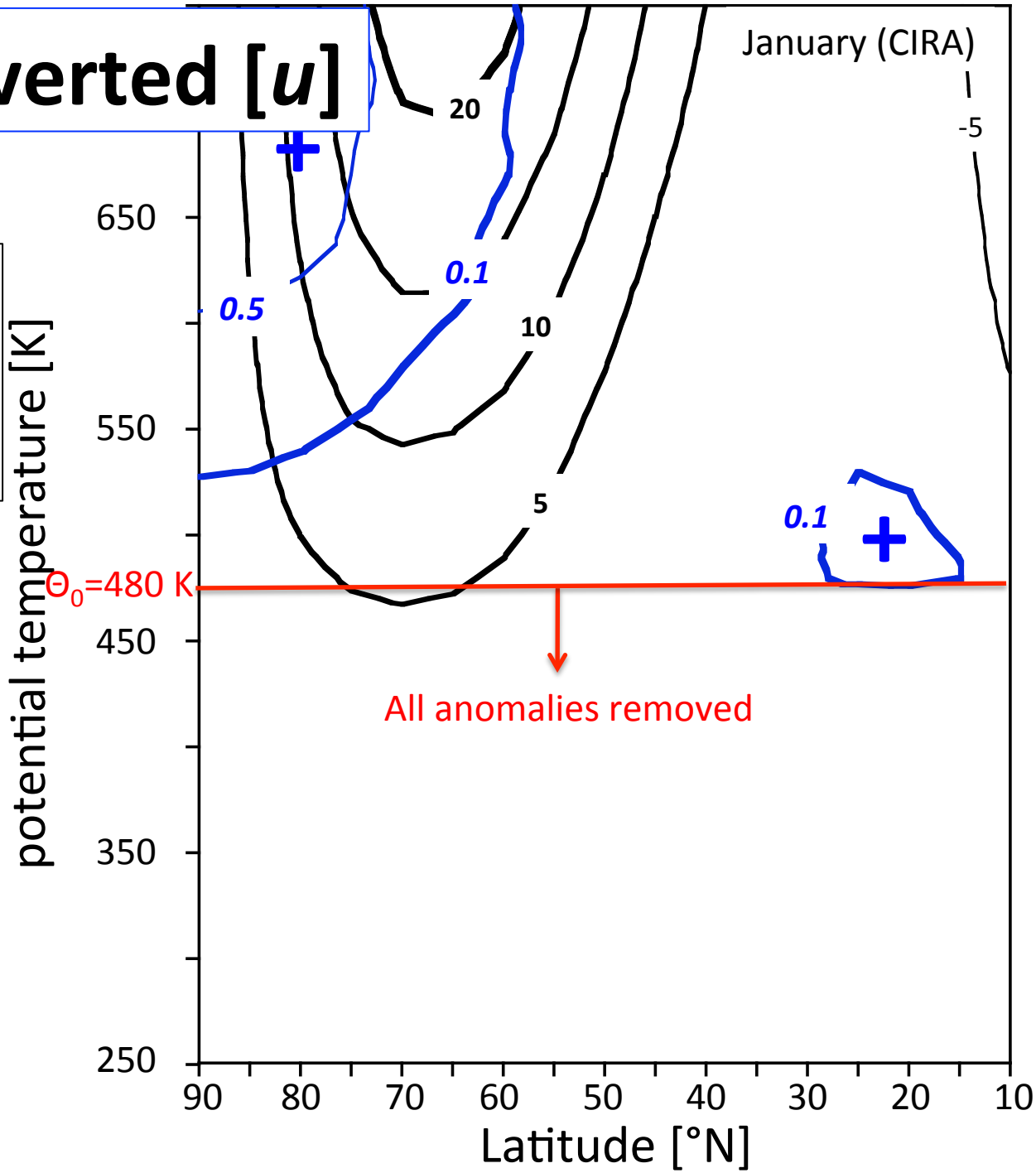


Piecewise inverted [*u*]

January n.h.

Inverted zonal mean zonal wind velocity if *PV*-anomaly **below** θ=Θ_0 and lower boundary temperature anomaly are removed.

Unit: [*PV*]: non-dimensional
[*u*]: m s^{-1}

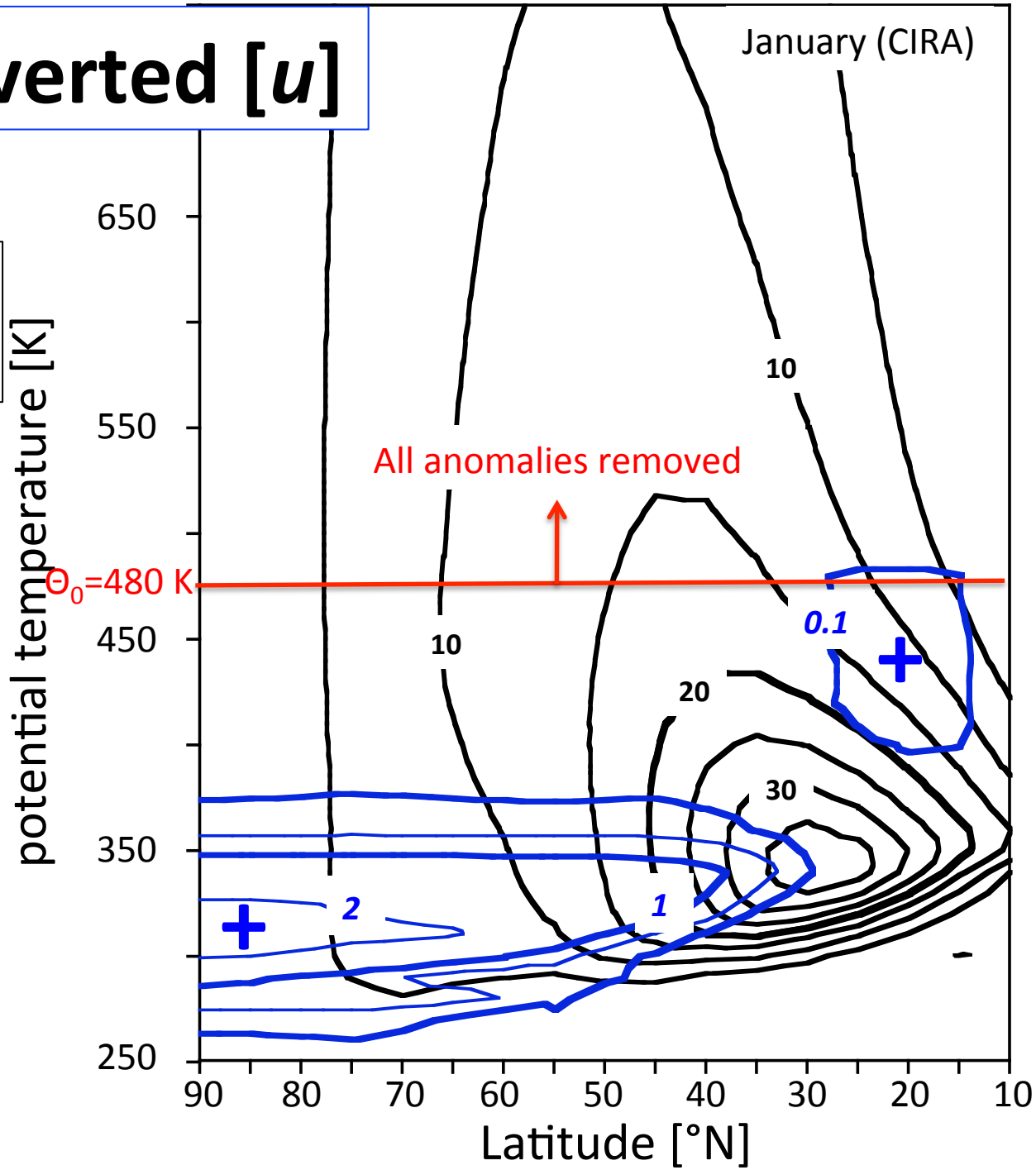


Piecewise inverted [*u*]

January n.h.

Inverted zonal mean zonal wind velocity if *PV*-anomaly **above** $\theta=\Theta_0$ is removed.

Unit: [*PV*]: non-dimensional
[*u*]: m s^{-1}



Conclusion

Ex-UTLS PV-anomaly induces the subtropical jet and the surface westerlies

What processes establish the Ex-UTLS PV-anomaly?

There is more to it than diabatic convergence or divergence of mass in the Middleworld,

Basic question is:

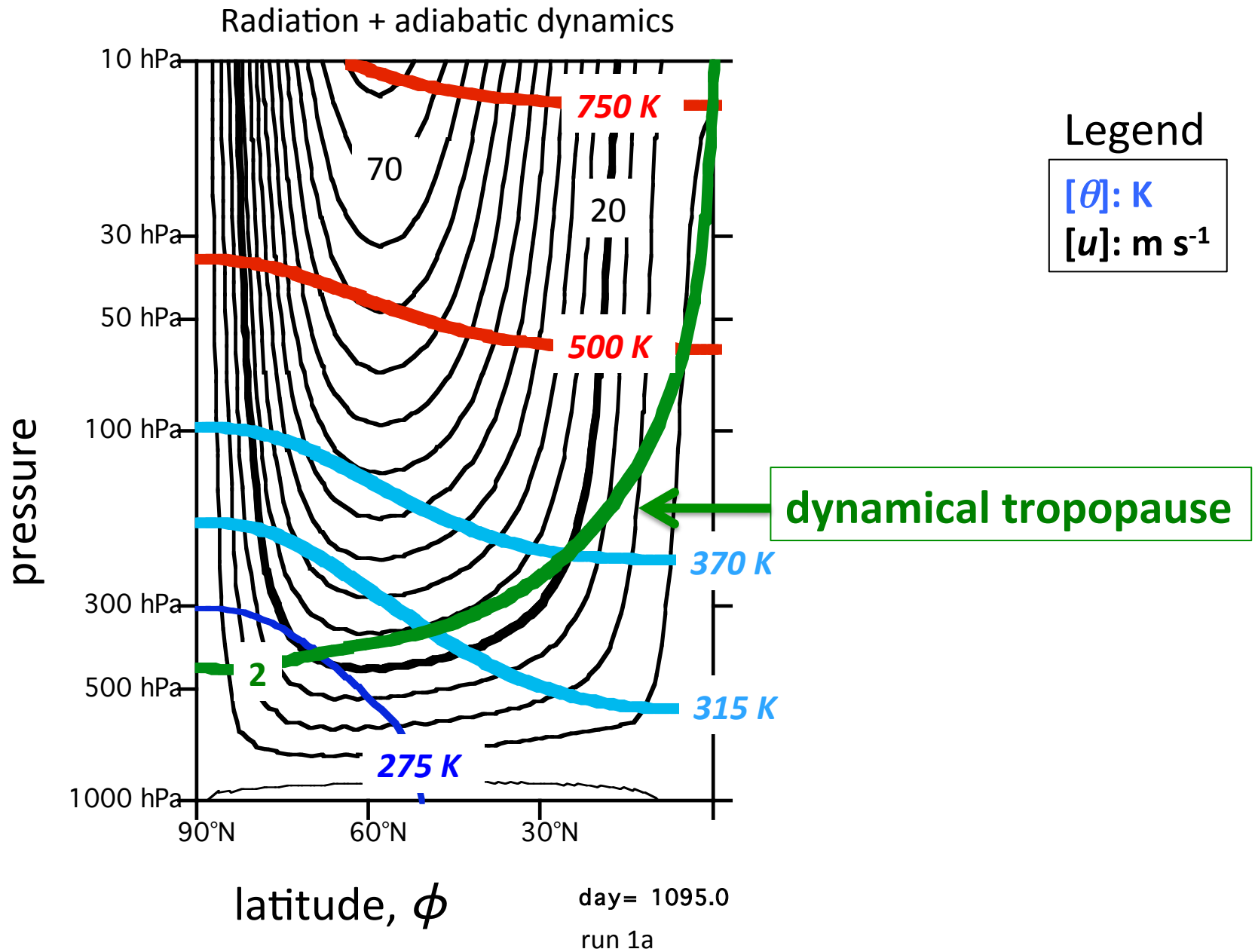
Why is the cross-isentropic flow upward in the tropics and downward in the extratropics?

2D (lat, height) primitive equation model

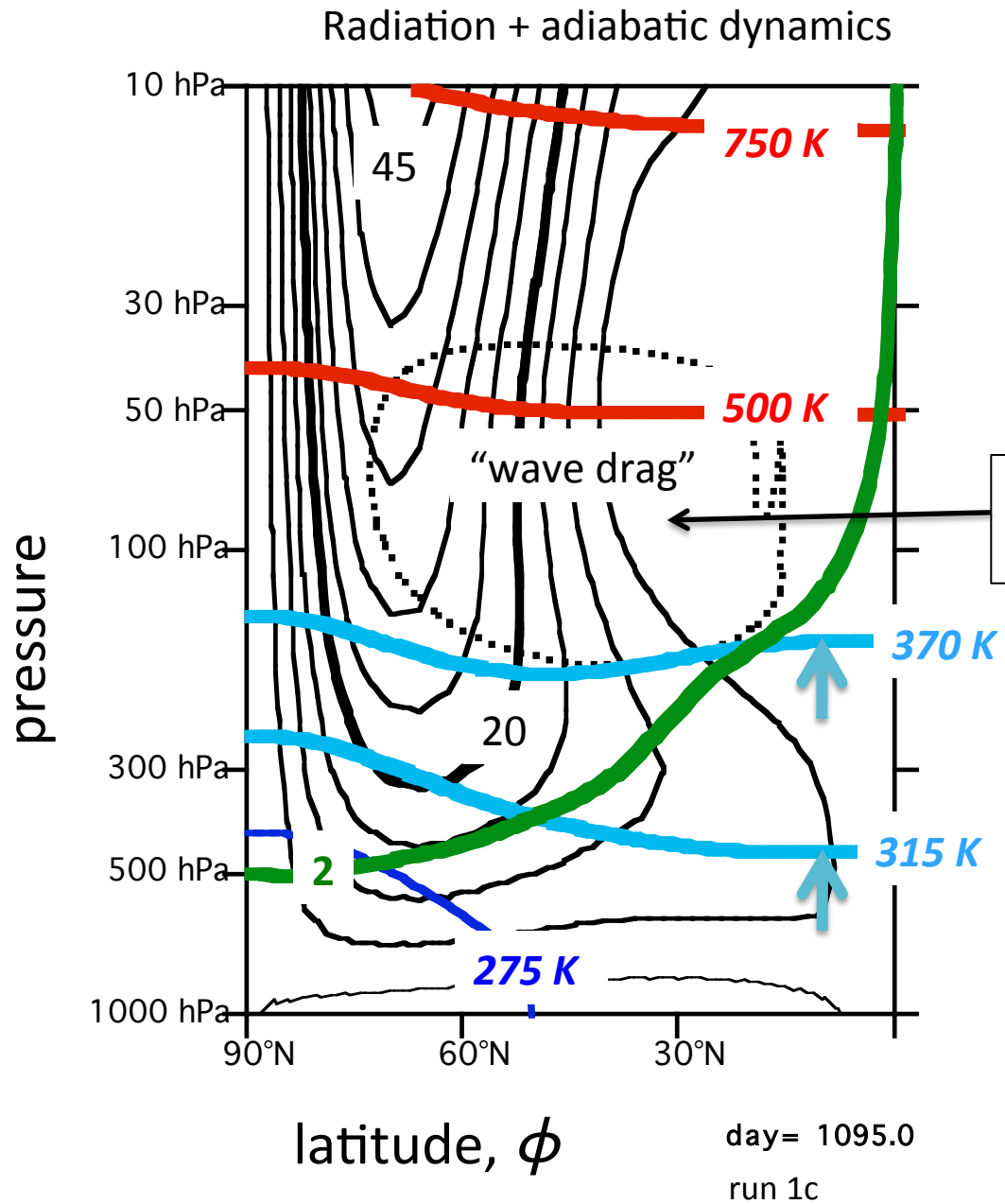
Contains parametrizations of

1 Radiation
2 Dry convective adjustment
3 "Wave drag"
4 Water cycle (latent heat release)

Permanent equinox steady state: *no drag; no water*



Permanent equinox steady state: *drag; no water*



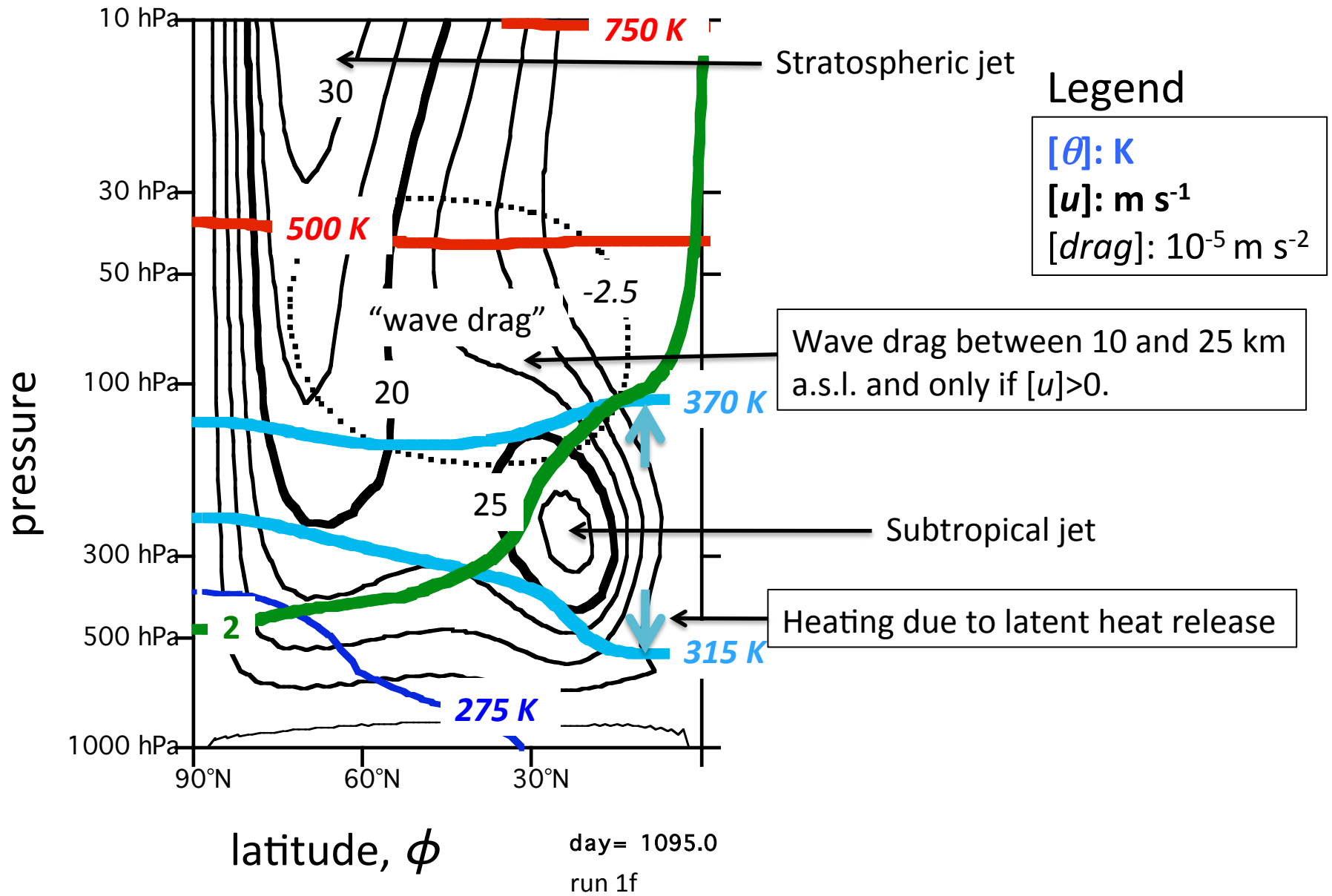
Legend

[θ]: K
[u]: m s^{-1}
[$drag$]: 10^{-5} m s^{-2}

Wave drag between 10 and 25 km a.s.l. and only if [u]>0.

Permanent equinox steady state: *drag + water*

Add: water cycle (latent heat release)



Conclusion

All features of the zonal mean general circulation are interconnected!

The zonal mean general circulation, including the subtropical jets, the cold-point tropical tropopause and the strong meridional gradient of the dynamical tropopause, is a product a complex interaction between radiation, latent heat release and heat transport by the circulation.

“Wave drag” (in fact *PV*-mixing !) plays a crucial role

Thank you

Thanks also to *Yvonne Hinssen*, *Theo Opsteegh*, *Wouter de Geus*, *Roos de Wit*, *Niels Zweers*, *Koen Manders*, *Bruce Denby* and *Marcel Portanger*.

Results of this research are published in Tellus-A (2012, 2014)
http://www.staff.science.uu.nl/~delde102/publications.htm

References

A.J. van Delden and Y.B.L. Hinssen, 2012: PV-theta view of the zonal mean state of the atmosphere. **Tellus A 2012, 64, 18710, http://dx.doi.org/10.3402/tellusa.v64i0.18710**

A.J. van Delden, 2014: PV-theta view of Diabatic-Dynamical Interaction in the General Circulation. Accepted for publication in **Tellus A (18 October 2014)**

http://www.staff.science.uu.nl/~delde102/publications.htm