AOS 801: Advanced Tropical Meteorology

Lecture 5   Spring 2023

Radiative-Convective Equilibrium, Convective Quasi-Equilibrium

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Photo from International Space Station

Announcements

HW1 and PA1 are uploaded. They are due on Feb 20.

Feel free to send me pictures of cool tropical clouds if you have any.

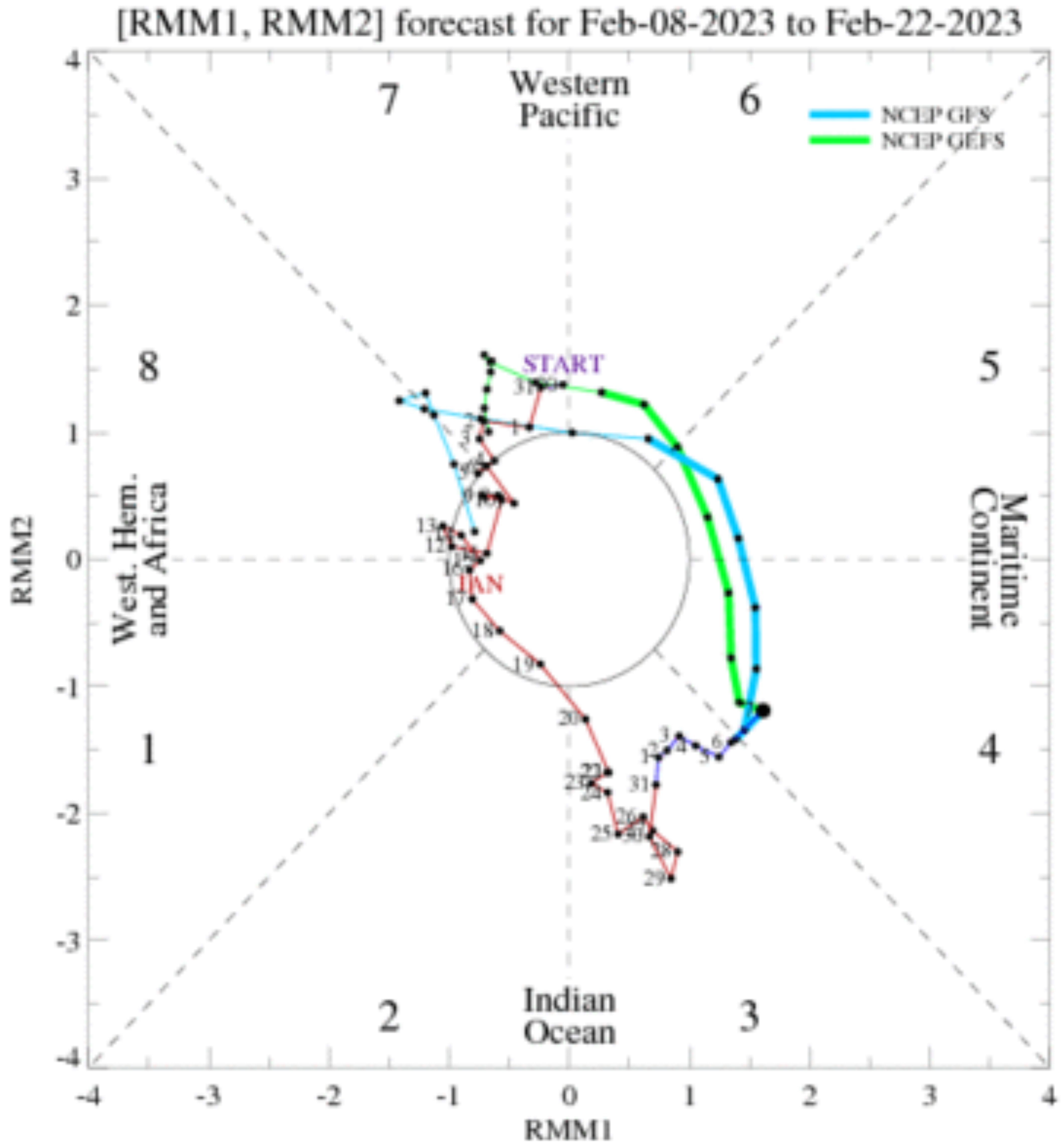
Today in the tropics

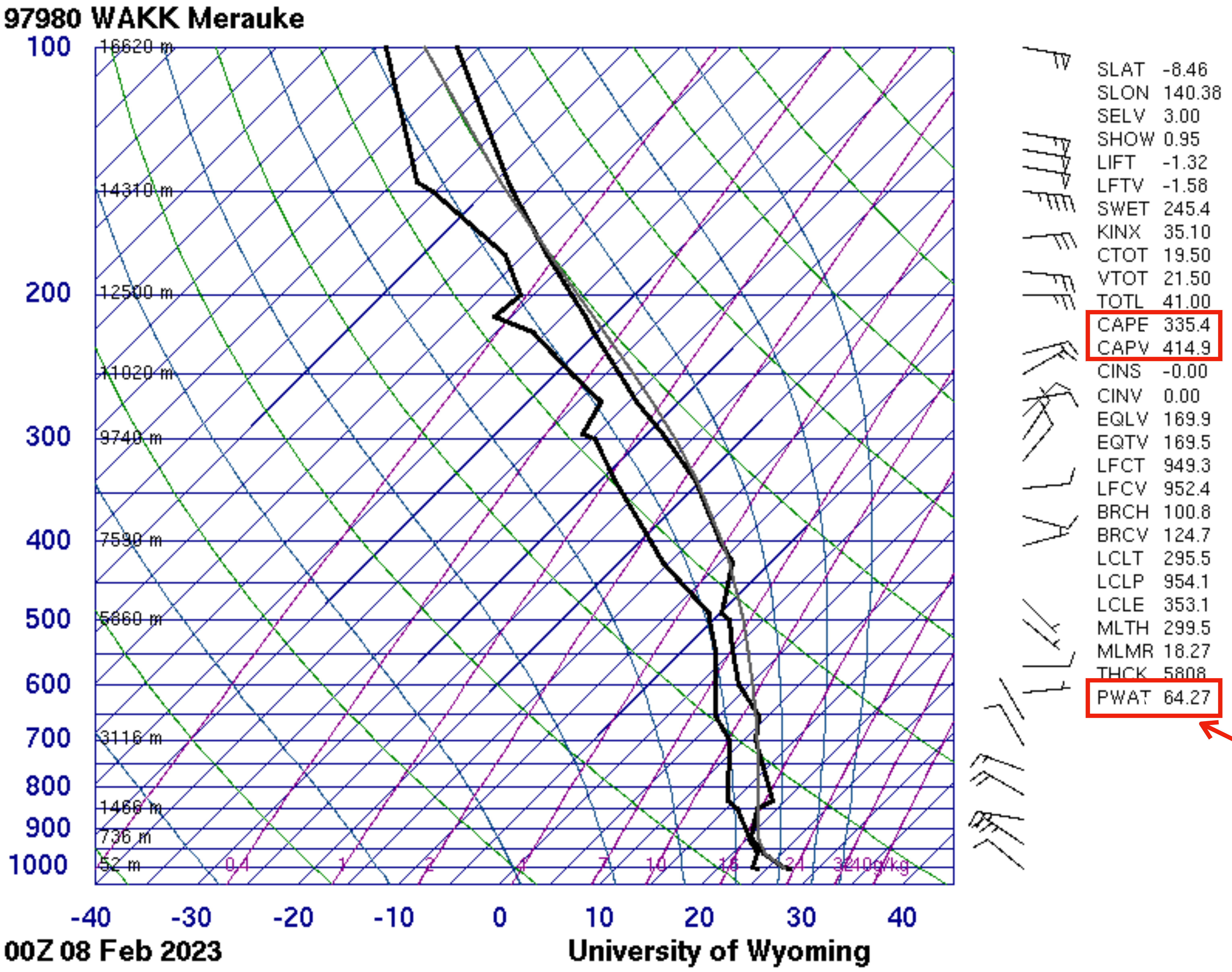
https://a.atmos.washington.edu/~ovens/wxloop.cgi?ir_moll+/14d/

http://tropic.ssec.wisc.edu/real-time/mtpw2/product.php?color_type=tpw_nrl_colors&prod=global2&timespan=120hrs&anim=html5

http://tropic.ssec.wisc.edu/real-time/mtpw2/product.php?color_type=tpw_nrl_colors&prod=indo&timespan=120hrs&anim=html5

https://col.st/1J33i

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00Z 08 Feb 2023
University of Wyoming
SLAT -8.46
SLON 140.38
SELV 3.00
SHOW 0.95
LIFT -1.32
LFTV -1.58
SWET 245.4
KINX 35.10
CTOT 19.50
VTOT 21.50
TOTL 41.00
CAPE 335.4
CAPV 414.9
CINS -0.00
CINV 0.00
EQLV 169.9
EQTV 169.5
LFCT 949.3
LFCV 952.4
BRCH 100.8
BRCV 124.7
LCLT 295.5
LCLP 954.1
LCLE 353.1
MLTH 299.5
MLMR 18.27
THCK 5808
PWAT 64.27

Diabatic heating table

Continuous atmosphere

$Q = Q_c + Q_r$ Diabatic Heating

$Q_c = L_v(\mathscr{C} - \mathscr{E}) + L_f(\mathscr{F} - \mathscr{M}) + L_f(\mathscr{D} - \mathscr{S})$ Convective Heating

$Q_r = -\partial_p F_{SW} - \partial_p F_{LW}$ Radiative Heating

$Q_e = Q_r + L_f(\mathscr{F} - \mathscr{M} + \mathscr{D} - \mathscr{S}) - \nabla \cdot L_v \boldsymbol{F}_q$ Equivalent Heating

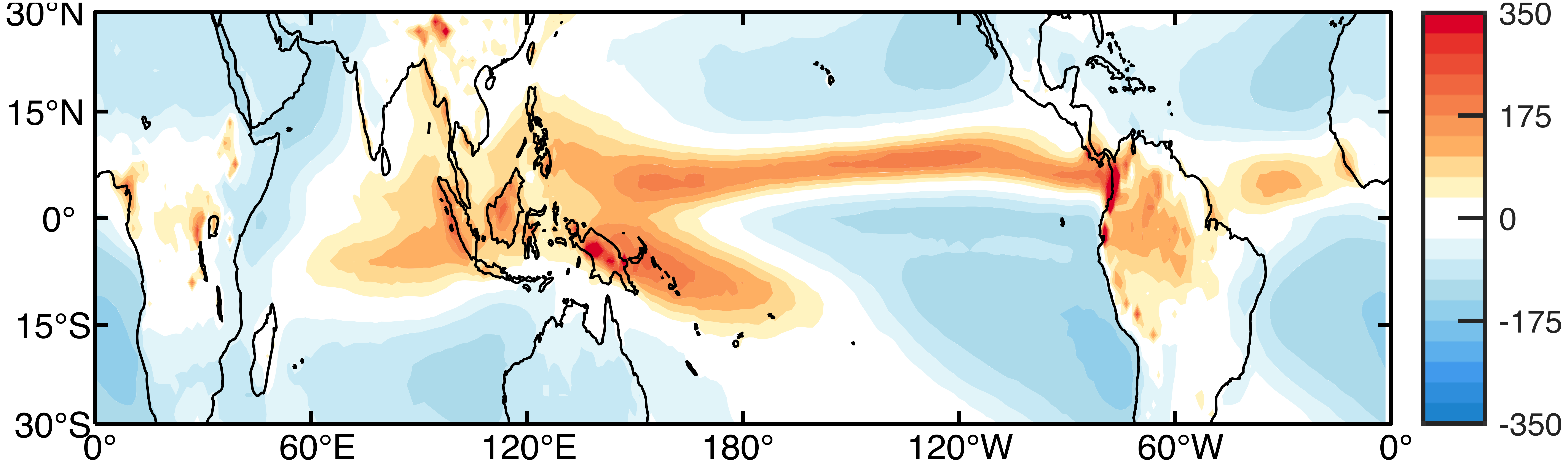
Area-averaged heating

$Q_1 = \overline{Q} - \partial_p \overline{\omega' \mathrm{DSE}}$ Apparent Heating (overlines are area averages)

$Q_2 = -\overline{S_q} + L_v \partial_p \overline{\omega' q'}$ Apparent Moisture Sink

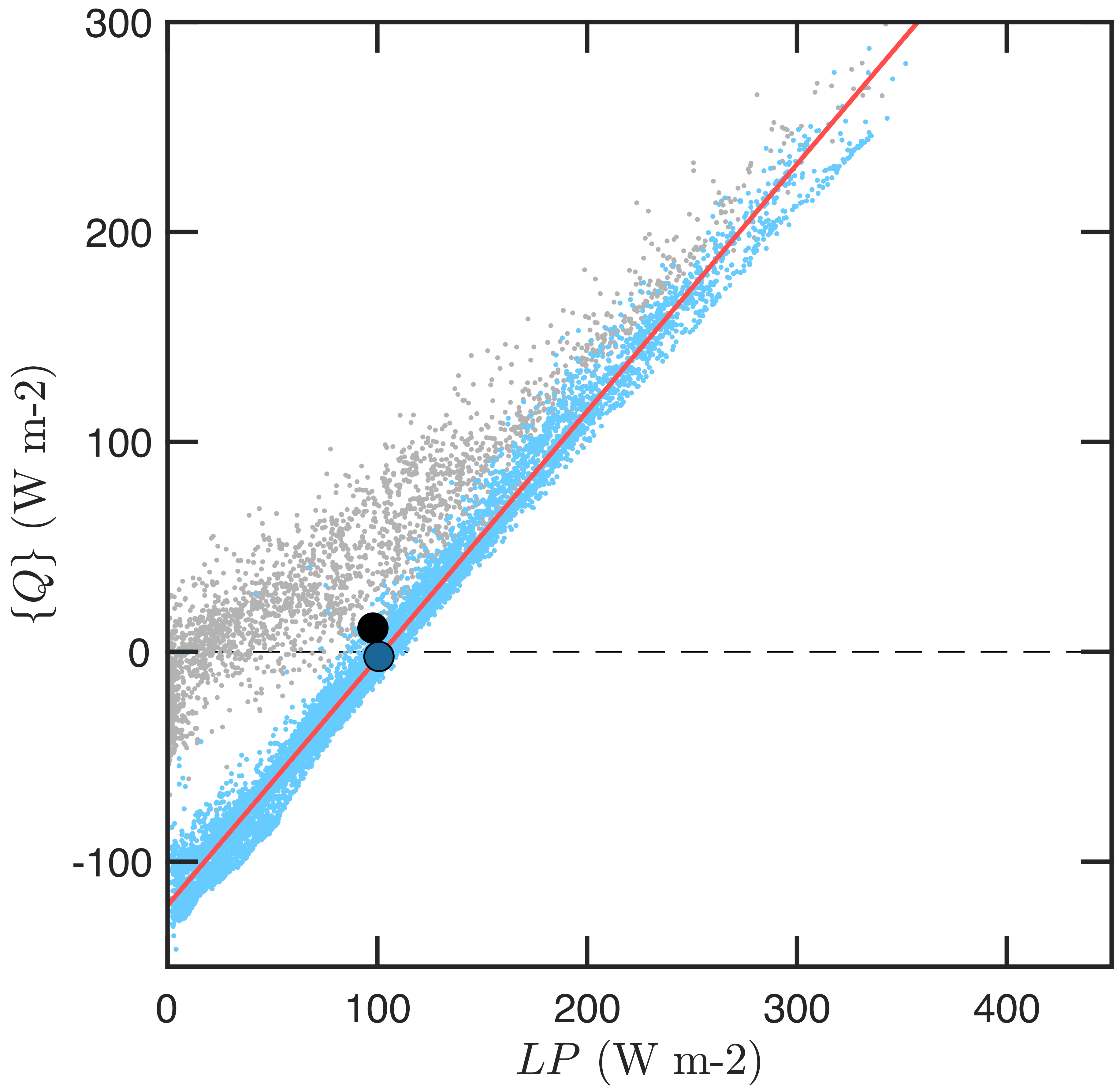
Radiative-Convective Equilibrium

Last Class: Radiative Convective Equilibrium



Diabatic heating in the tropics can be decomposed into a cloud component and a residual.

Radiative Convective Equilibrium

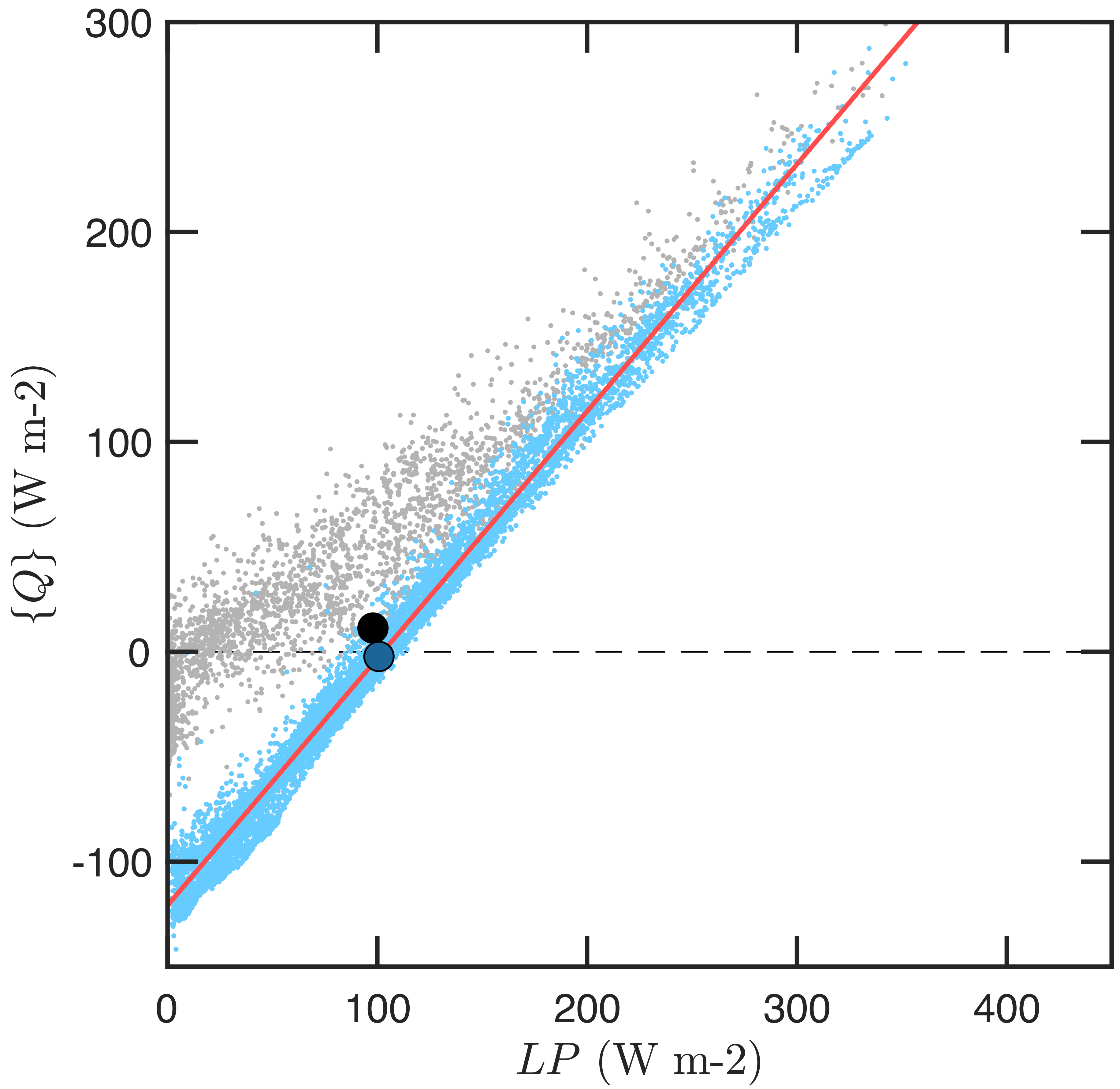


When we look at all points in the tropics, we see a large scatter with regions of heating and cooling.

However, the mean (centroid) of the cloud of points lies at a value of Q_1 that is close to zero.

This is especially true for oceanic points.

Radiative Convective Equilibrium

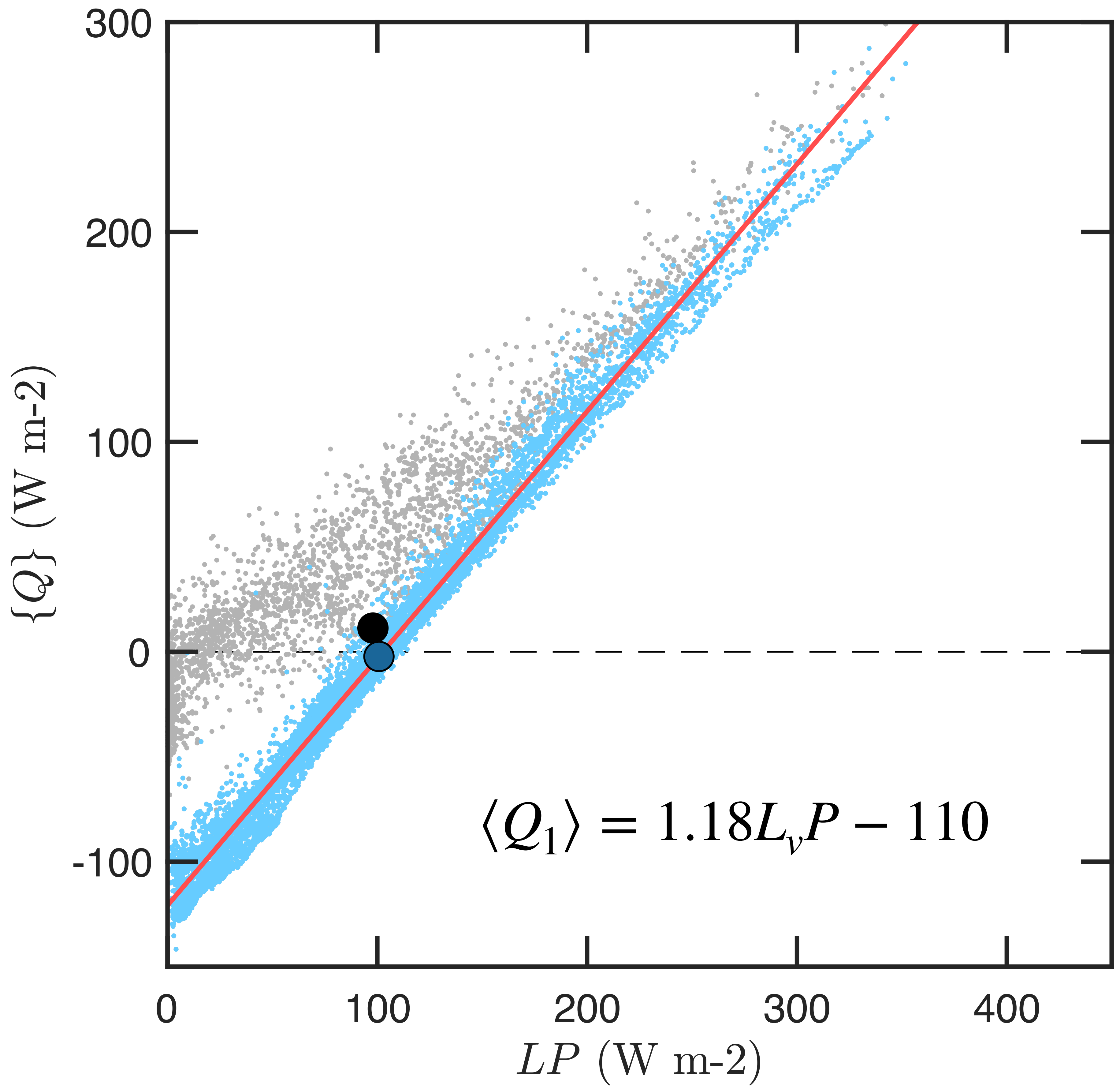


These results imply that the apparent heating averaged over the tropics is nearly zero, i.e:

$$Q_1 \simeq 0$$

What does this mean?

Radiative Convective Equilibrium



Linear regression:

$$y = mx + b$$

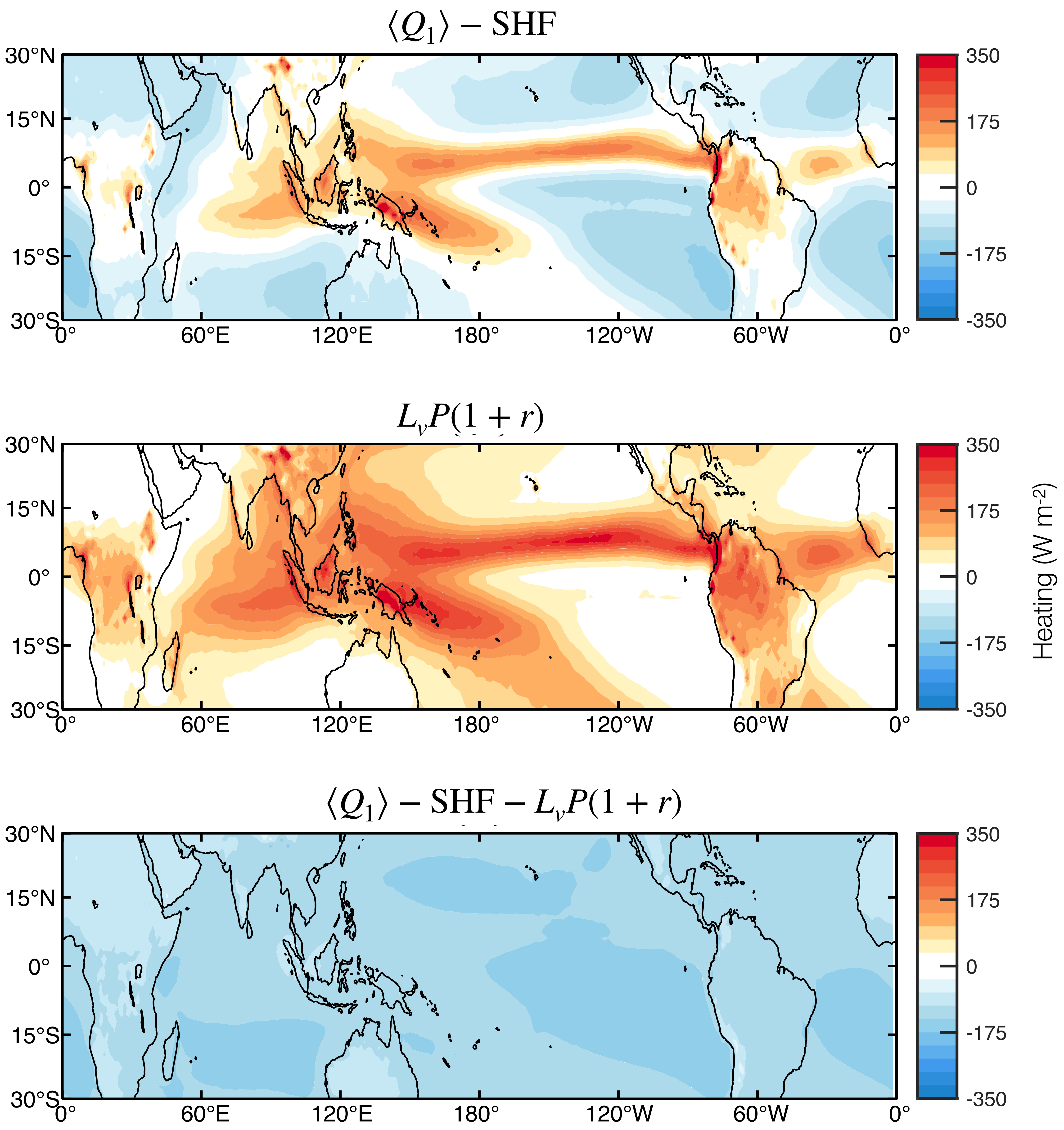
$$\langle Q_1 \rangle = L_v(1 + r)P + \langle Q_{r_0} \rangle$$

$\langle Q_{r_0} \rangle$ = clear sky radiative cooling

r = cloud-radiative feedback parameter

Diabatic heating in the tropics is a linear function of the mean rainfall with a constant clear sky cooling term.

Radiative Convective Equilibrium



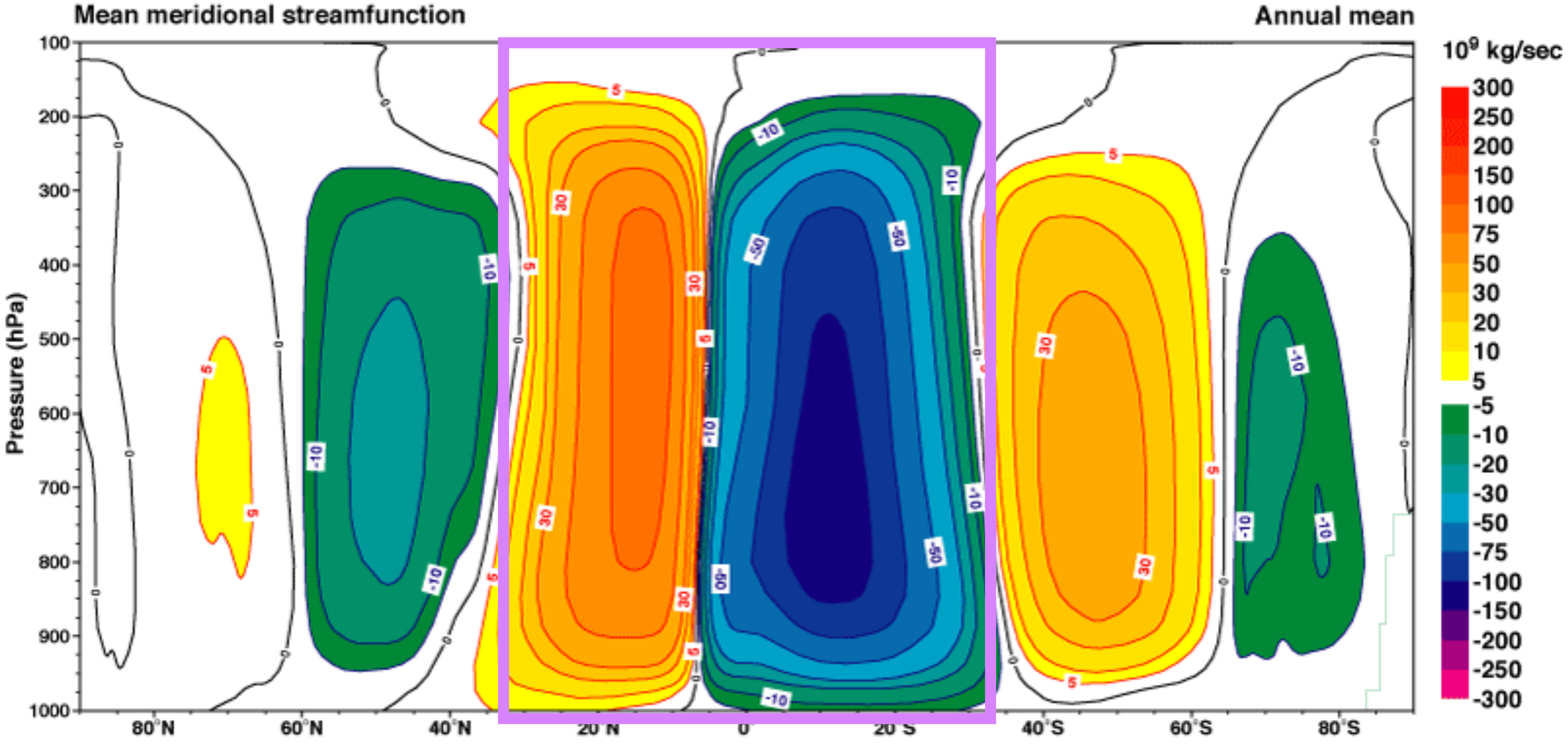
These results imply that the apparent heating averaged over the tropics is nearly zero, i.e:

$$L_v P(1+r) \simeq \langle Q_{r_0} \rangle$$

Cloud heating Clear sky cooling

Radiative Convective Equilibrium

Ψ



The Mean Meridional Circulations are often described by a **Mass Streamfunction**

$$\frac{\partial \Psi}{\partial y} = -\omega$$

Show at home that the vertical velocity averaged within the boundaries of the Hadley cell ($\Psi = 0$) is zero.

Radiative Convective Equilibrium

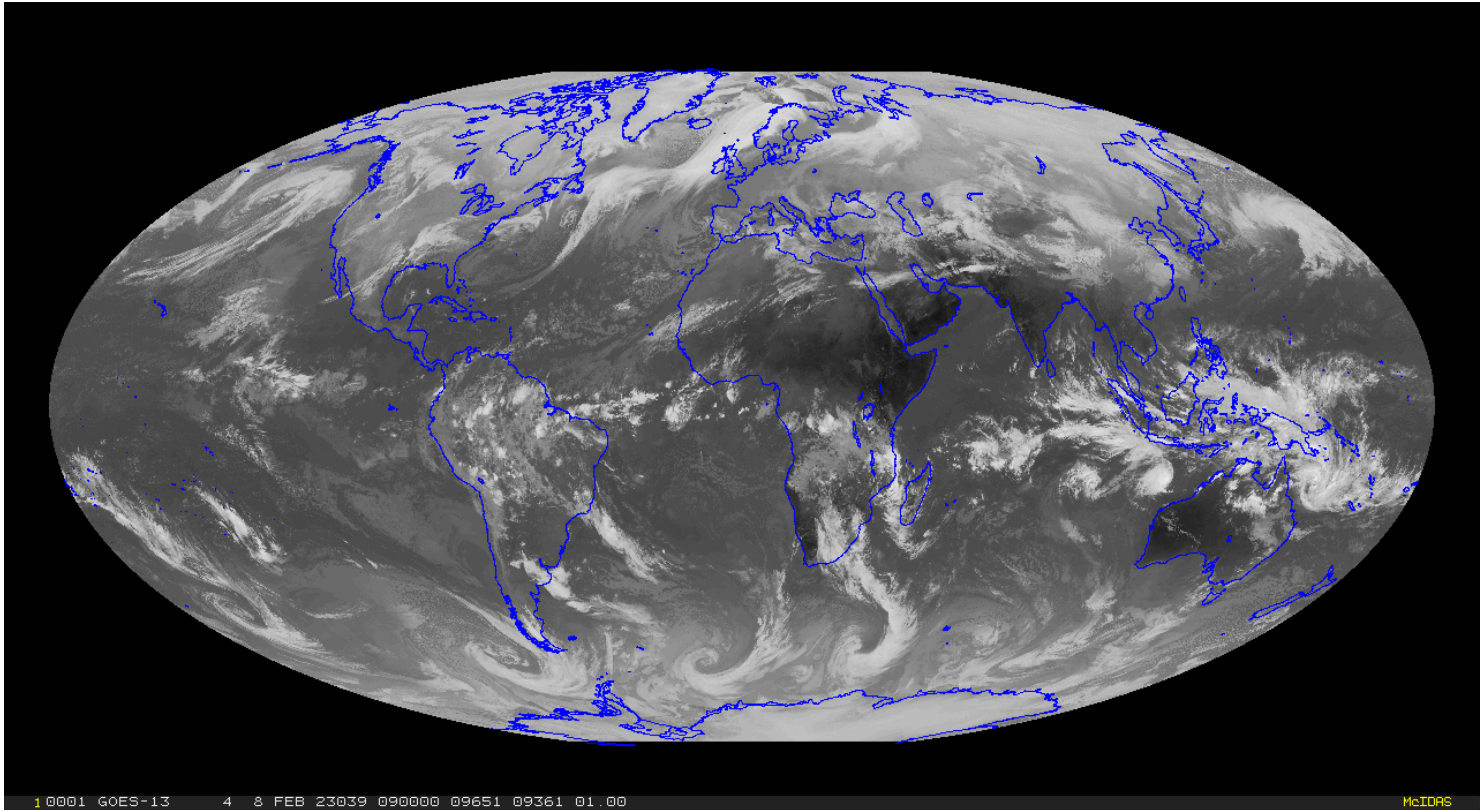
If the tropics are in WTG balance, the vertical DSE gradient should be roughly the same everywhere.

Following mass continuity, the amount of mass that rises must equal the amount of mass that's sinking within the tropics.

$$\omega \frac{\partial \mathrm{DSE}}{\partial p} \simeq Q_1$$

Wait a minute …

How do we get to this balance in the first place??



Wait a minute …

How do we get to this balance in the first place?

Let us consider the adjustment towards RCE

$$C_p \frac{\partial \langle T \rangle}{\partial t} = L_v P(1 + r) + \langle Q_{r_0} \rangle$$

Let's assume that $\langle Q_{r_0} \rangle$ can be qualitatively understood using Newton's Law of Cooling.

The convective heating, in turn, heats the atmosphere until it reaches the temperature of the convection itself, i.e., the temperature you get from moist adiabatic ascent T_c

$$\frac{\partial \langle T \rangle}{\partial t} = \frac{\langle T_c \rangle - \langle T \rangle}{\tau_c} - \frac{\langle T \rangle}{\tau_r}$$

Radiative Convective Equilibrium

The first-order ODE has a solution of the form

$$\langle T \rangle = \langle T_c \rangle \frac{(\tau_c + \tau_r)}{\tau_c \tau_r} - \exp\left(-\frac{t(\tau_c + \tau_r)}{\tau_r} \right)$$

Is there a way to simplify this? Which timescale is shorter?

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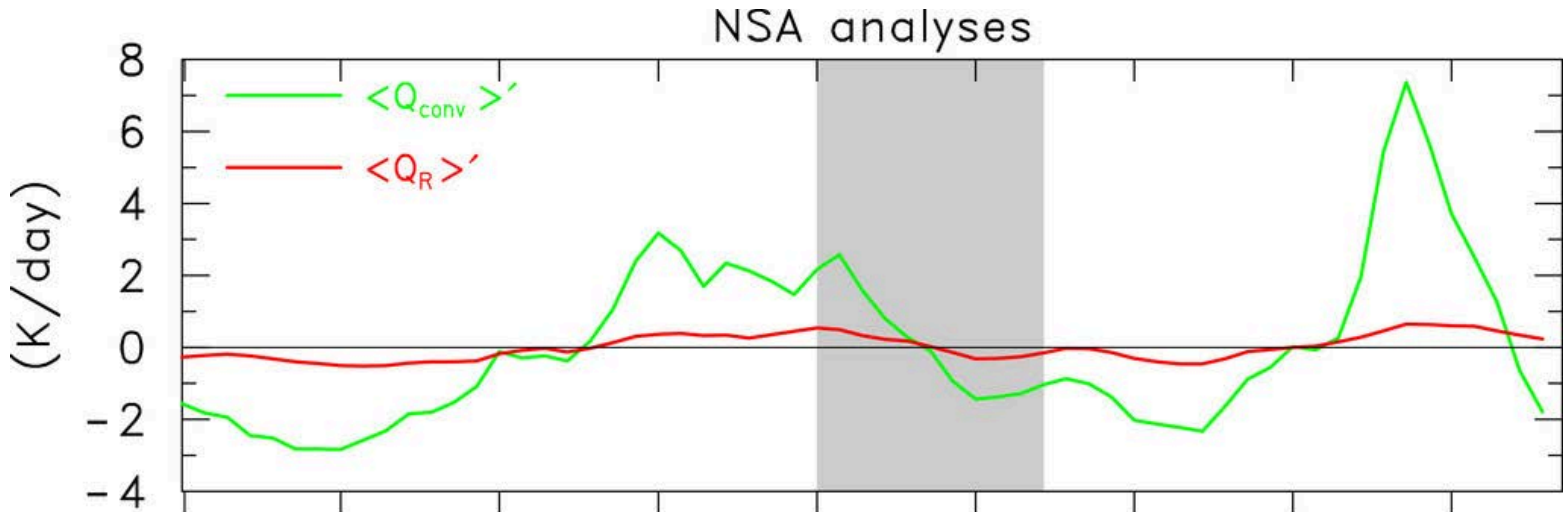
Radiative Convective Equilibrium



Johnson et al. (2014)

$$\langle T \rangle = \langle T_c \rangle \frac{(\tau_c + \tau_r)}{\tau_c \tau_r} - \exp\left(-\frac{t(\tau_c + \tau_r)}{\tau_r}\right)$$

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Radiative Convective Equilibrium

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$$\langle T \rangle = \langle T_c \rangle \frac{(\tau_c + \tau_r)}{\tau_c \tau_r} - \exp\left(-\frac{t(\tau_c + \tau_r)}{\tau_r}\right)$$

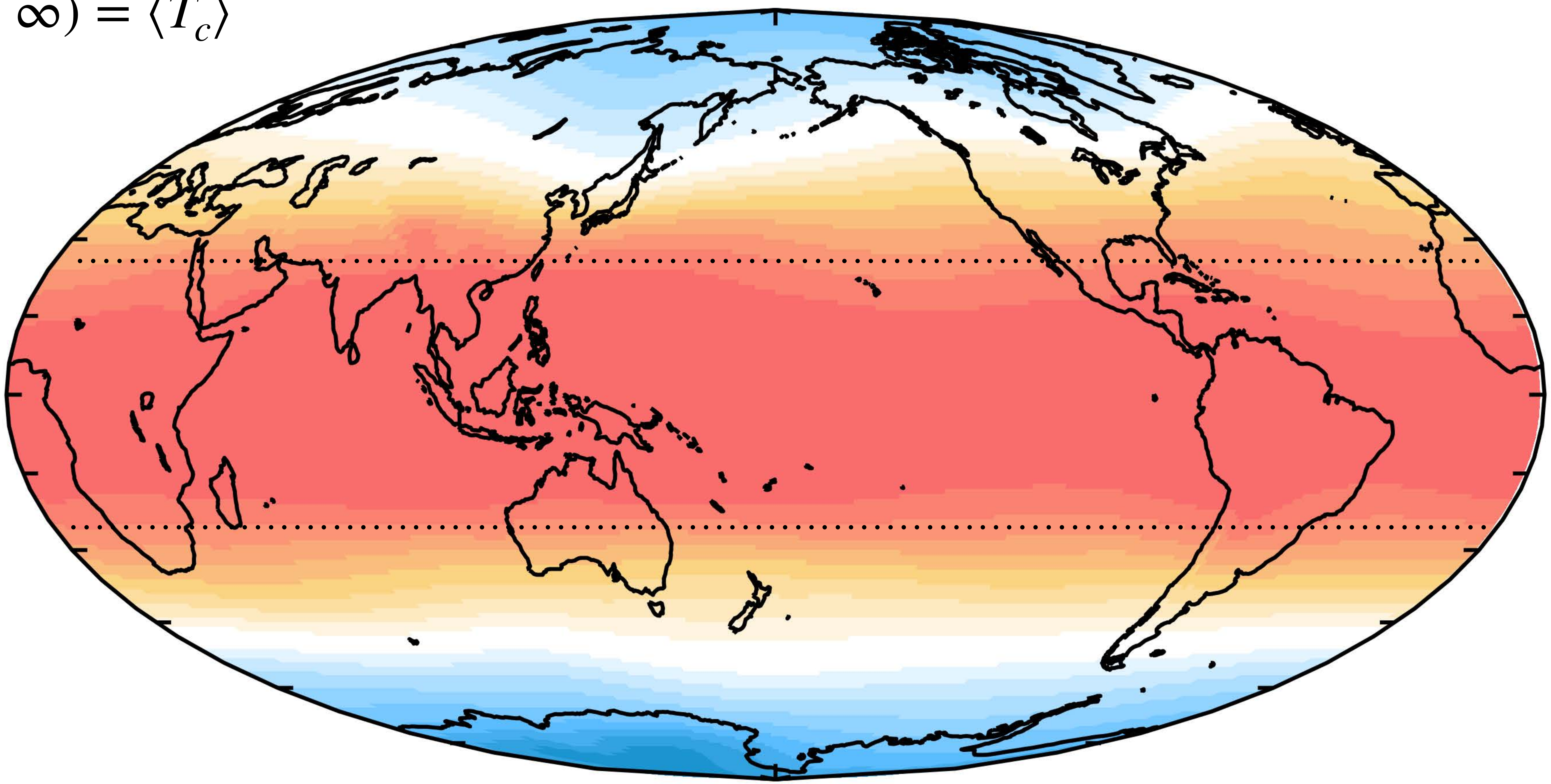
If $\tau_c \ll \tau_r$ and wait a really long time, we get the following answer

$$\langle T \rangle (t \to \infty) = \langle T_c \rangle$$

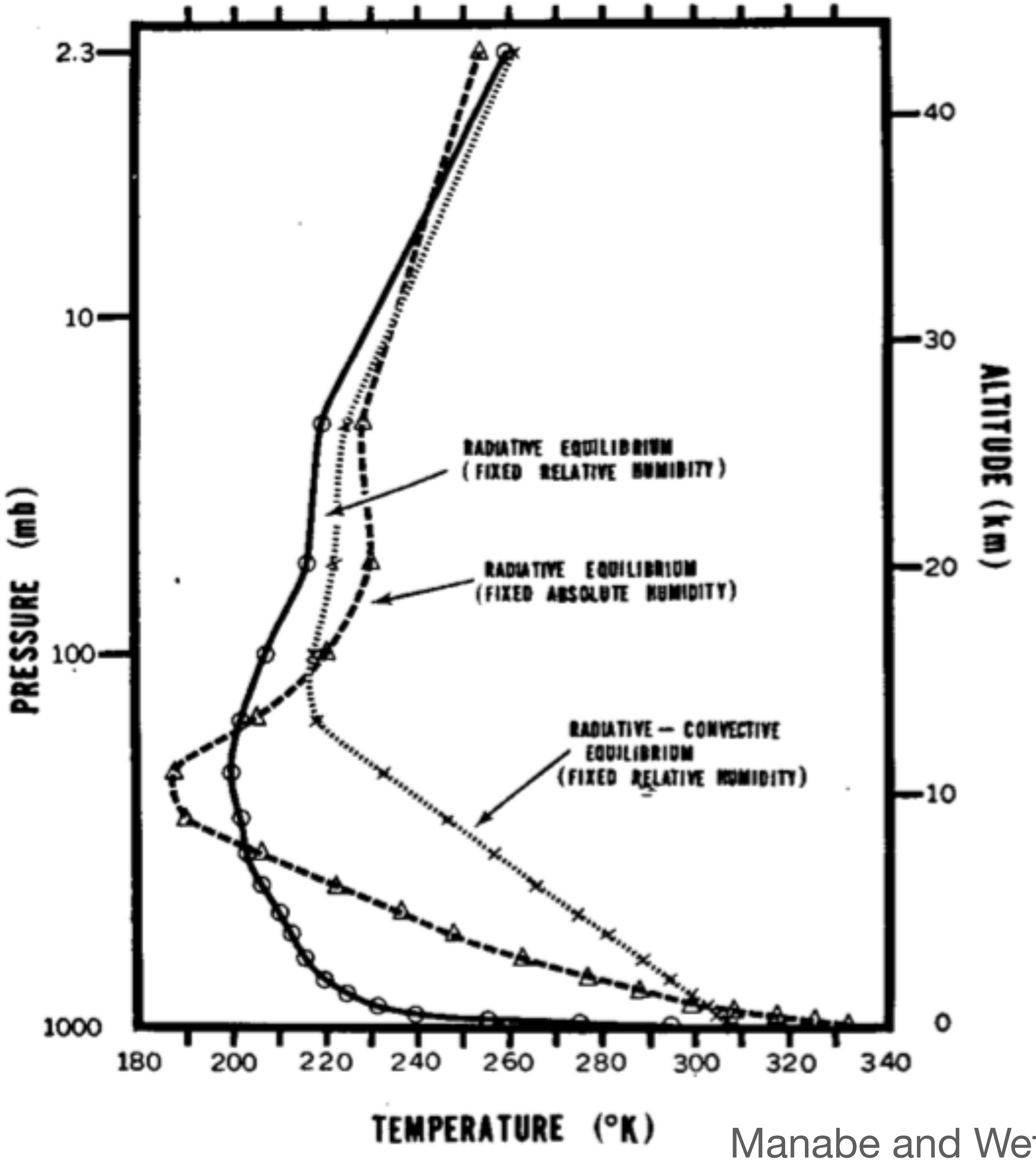
Radiative Convective Equilibrium

The mean temperature of the tropics is the mean temperature of deep convection

$$\langle T \rangle (t \to \infty) = \langle T_c \rangle$$



Radiative Convective Equilibrium



Manabe and Wetherald (1967)

Radiative-convective equilibrium has been applied to understand the global lapse rate.

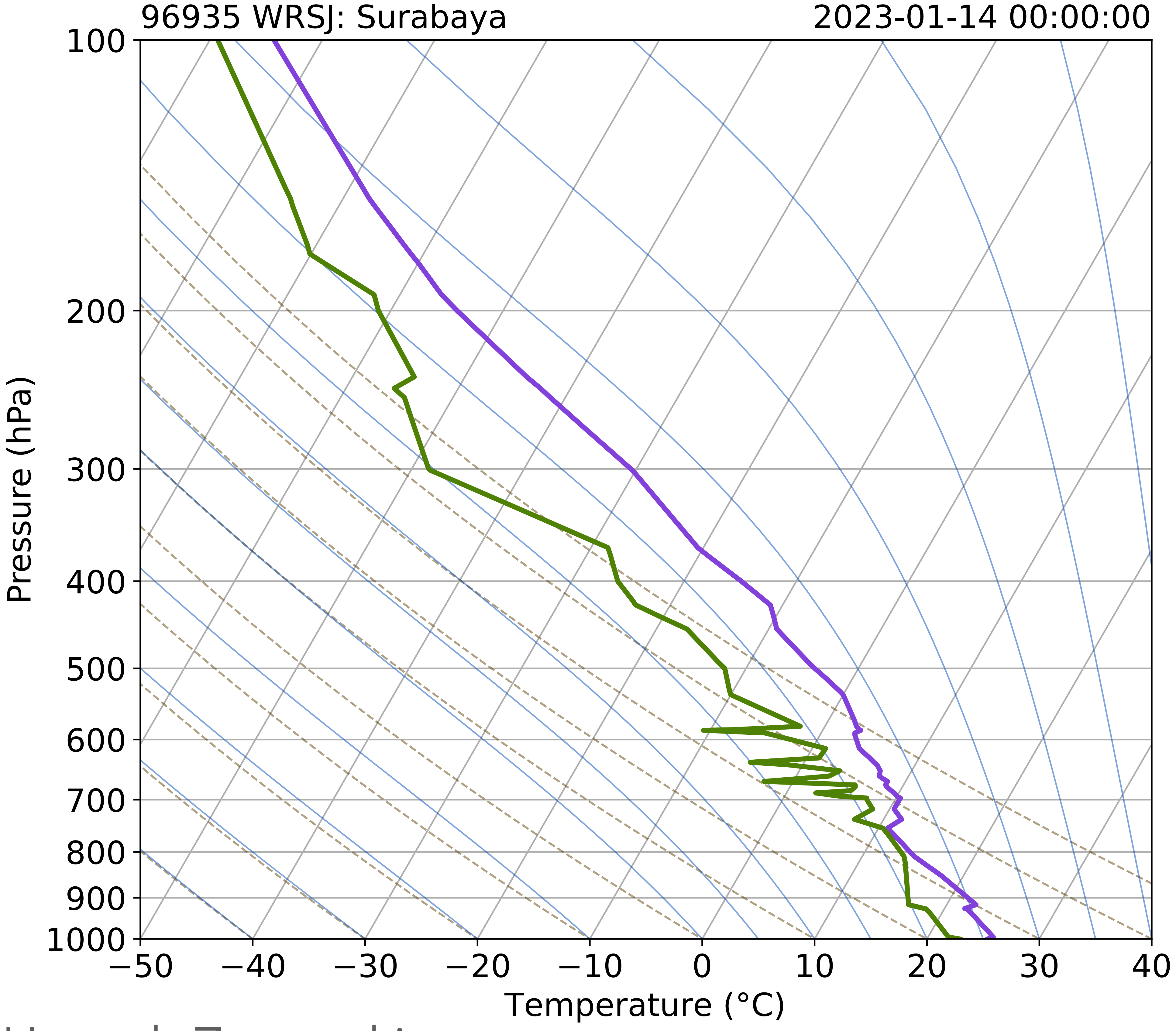
But it can also be used to understand the tropics specifically since it behaves like a closed system.

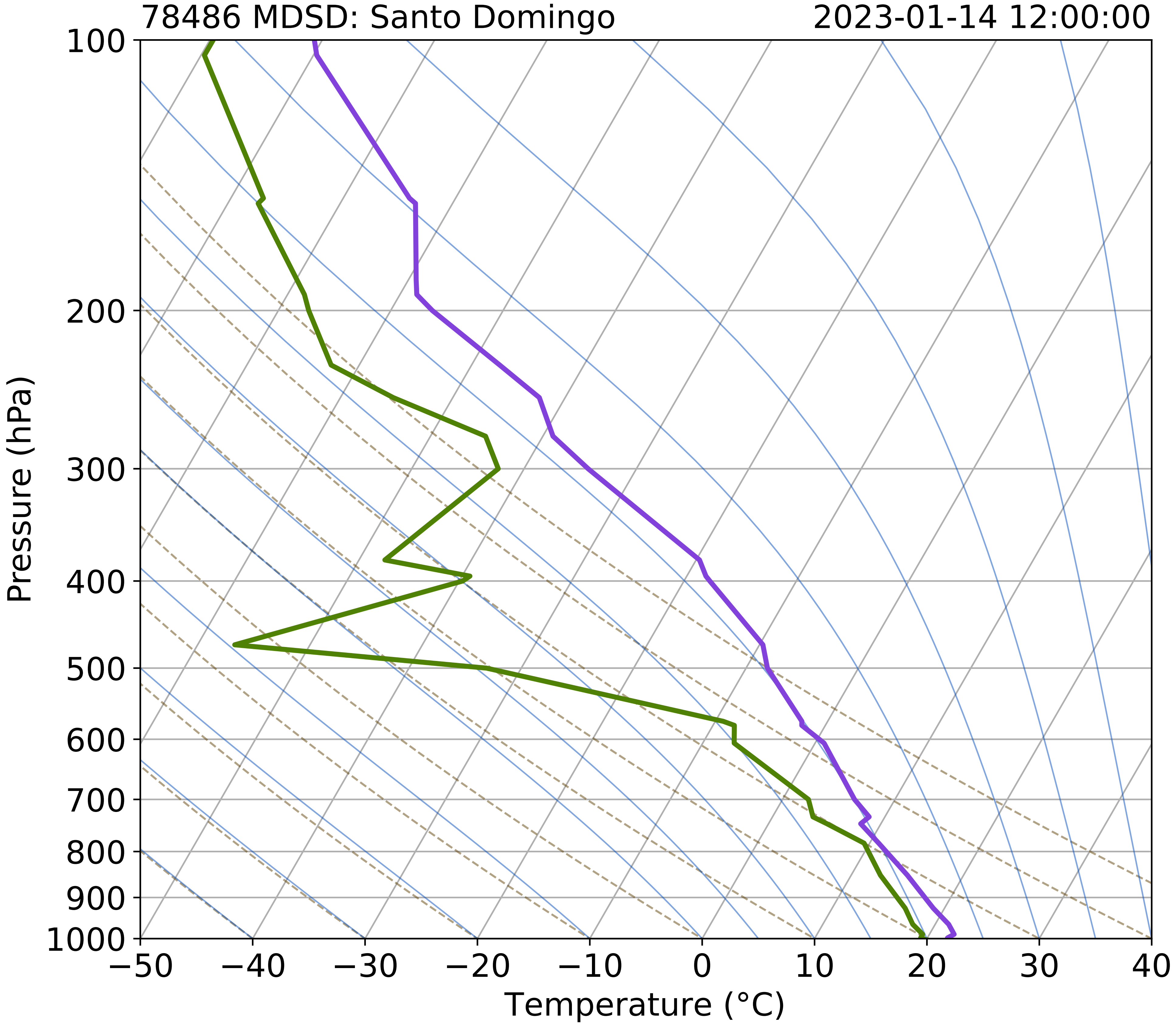
$$\frac{\partial \overline{\Gamma}}{\partial t} = -\frac{\overline{\Gamma} - \Gamma_m}{\tau_c} - \frac{\overline{\Gamma}}{\tau_r}$$

Radiative Convective Equilibrium

$$\overline{\Gamma}(t \rightarrow \infty) = \Gamma_m$$

The mean tropical lapse rate is a moist adiabatic





Courtesy of Hannah Zanowski

So you're telling me that the temperature and lapse rate are determined by convection everywhere, even over the dry areas?

Convective Quasi-Equilibrium

Quasi-Equilibrium

If the tropical lapse rate is a close to a moist adiabat, what does this mean for CAPE?

Do you think this is true always and everywhere?

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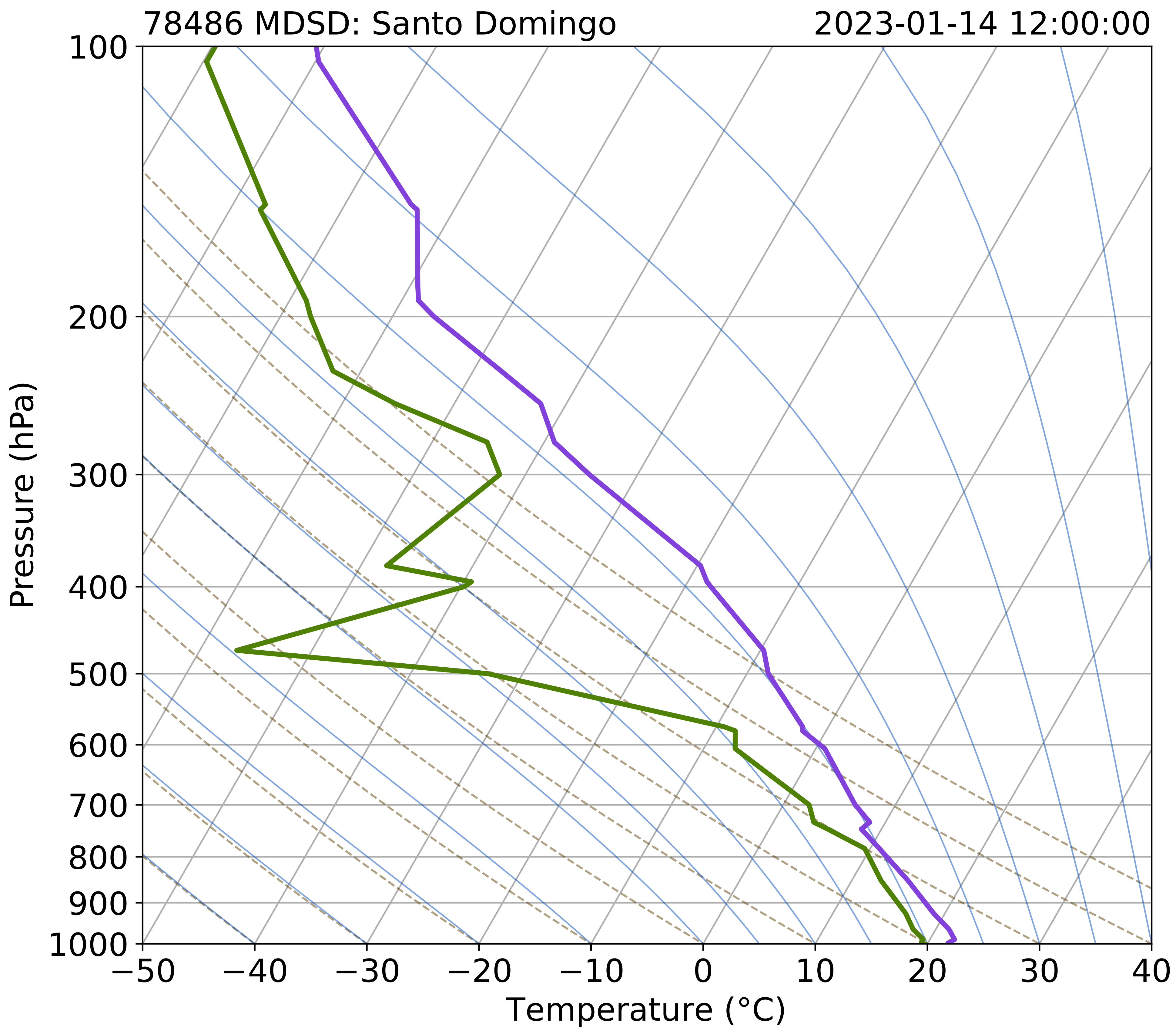
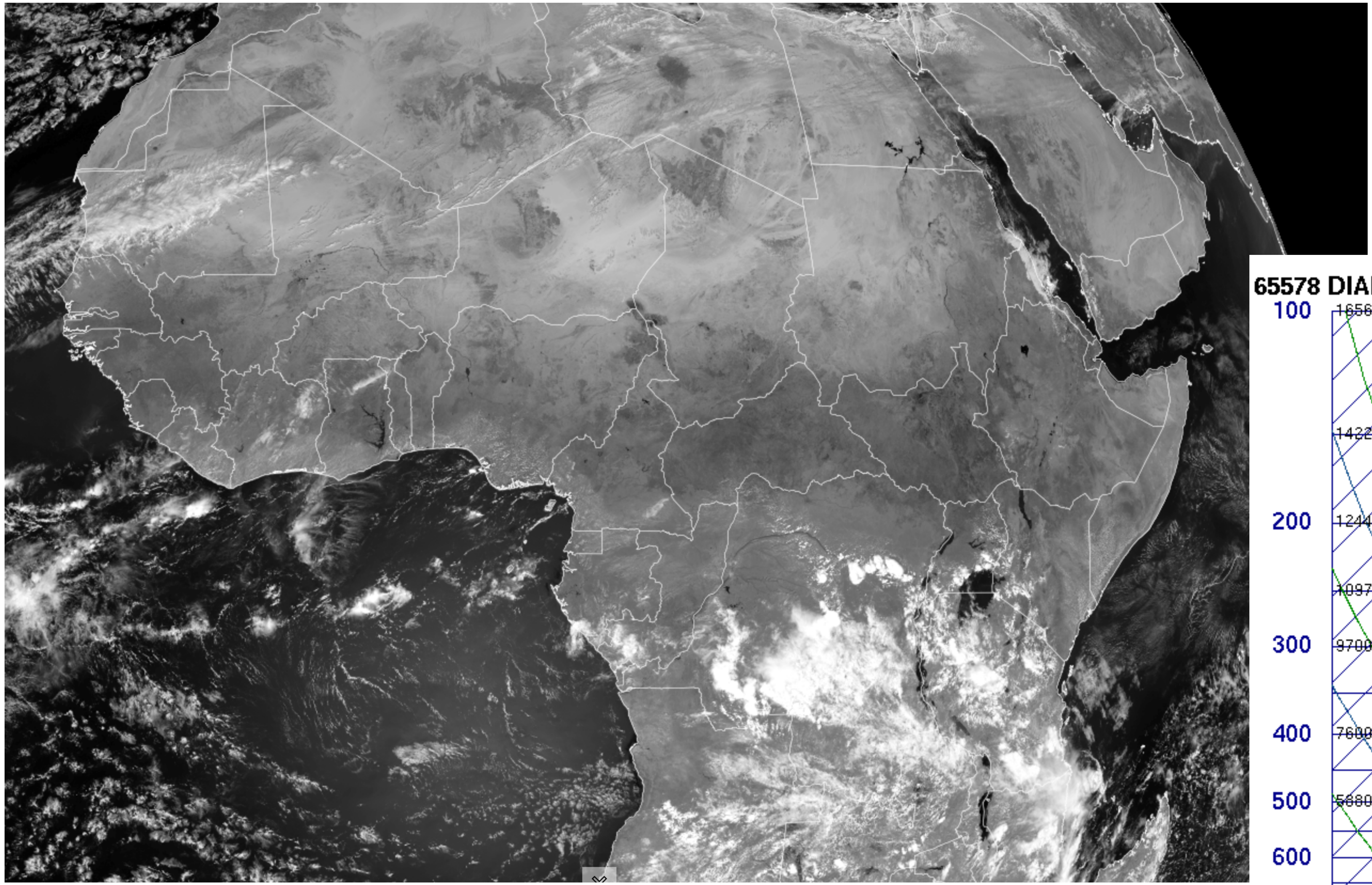
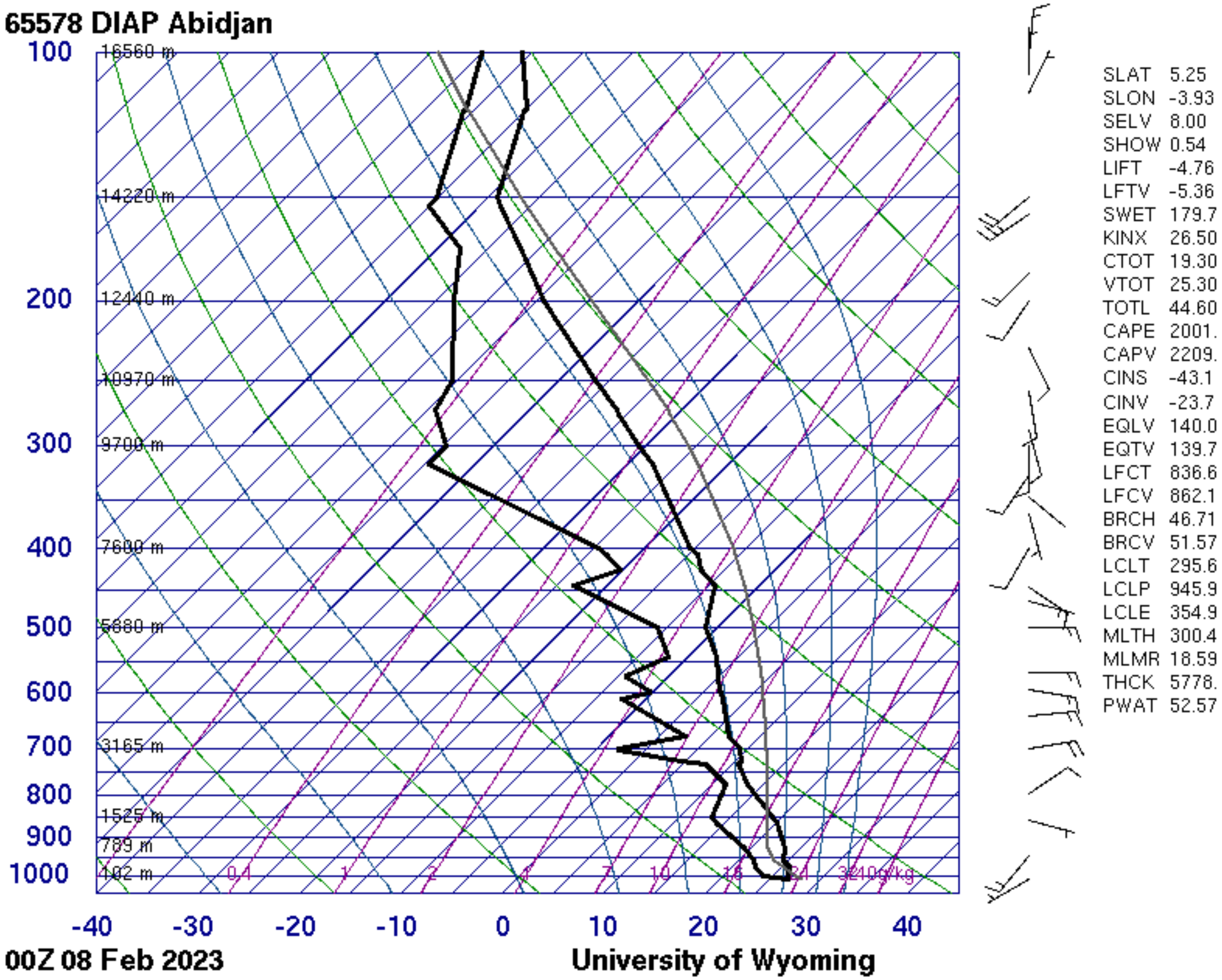


Courtesy of Hannah Zanowski

Exception

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100
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3165 m
1525 m
789 m
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-40 -30 -20 -10 0 10 20 30 40
00Z 08 Feb 2023
University of Wyoming
SLAT 5.25
SLON -3.93
SELV 8.00
SHOW 0.54
LIFT -4.76
LFTV -5.36
SWET 179.7
KINX 26.50
CTOT 19.30
VTOT 25.30
TOTL 44.60
CAPE 2001.
CAPV 2209.
CINS -43.1
CINV -23.7
EQLV 140.0
EQTV 139.7
LFCT 836.6
LFCV 862.1
BRCH 46.71
BRCV 51.57
LCLT 295.6
LCLP 945.9
LCLE 354.9
MLTH 300.4
MLMR 18.59
THCK 5778.
PWAT 52.57

Convective Quasi-Equilibrium

Deep convection is more widespread in the deep tropics than anywhere else on Earth

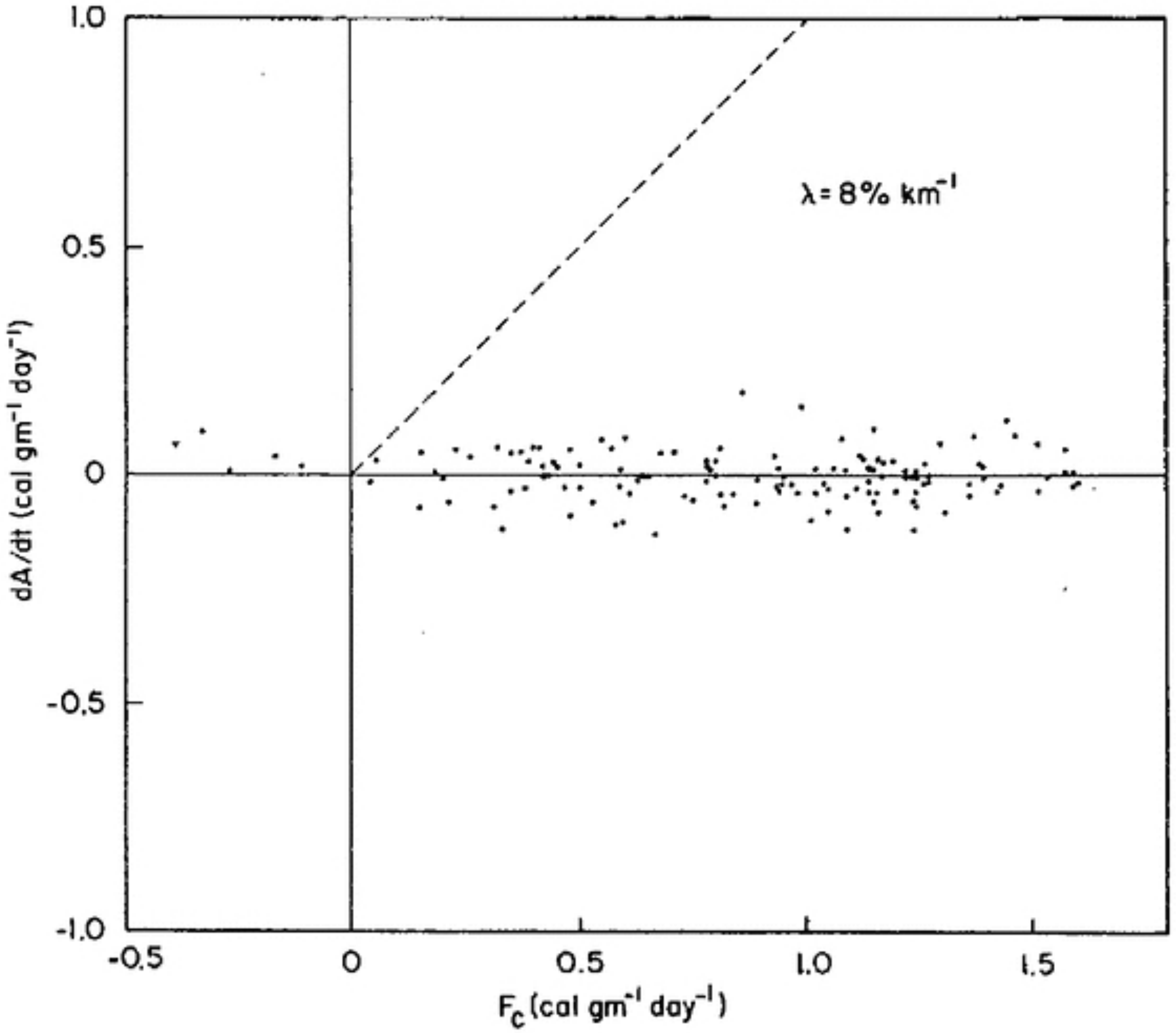
How is so much convection sustained in the absence of widespread instability?

Convective Quasi-Equilibrium

Convection quickly eliminates convective instability from the column, resulting in small CAPE values that vary little in time.

$$\frac{\partial \mathrm{CAPE}}{\partial t} \simeq 0. \qquad \mathrm{CAPE} = \int_{LFC}^{LNB} B dz$$

This hypothesis is known as **Convective Quasi-Equilibrium**



Arakawa and Schubert (1974)