The weakening of tropical circulation in response to global warming: a perspective from the radiative-convective equilibrium

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Outline

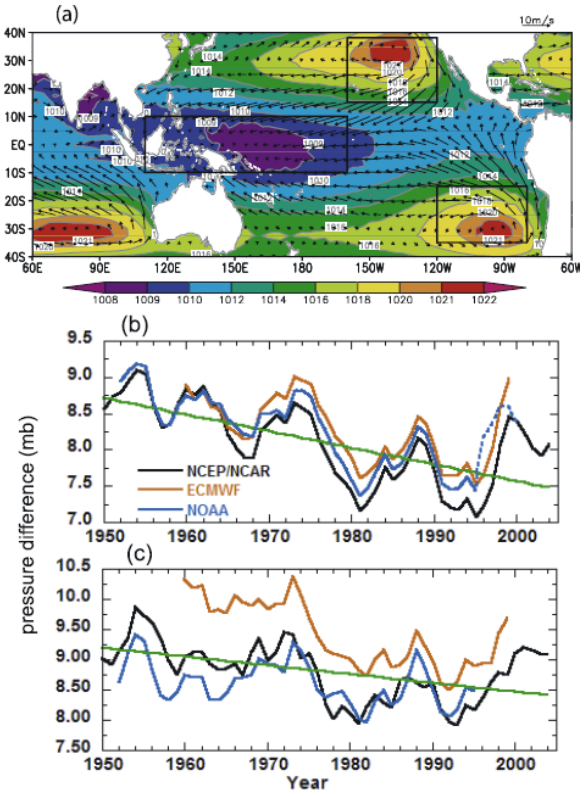
- Motivation and introduction
- Two-box RCE model
- An RCE-based heuristic argument
- Comparison with GFDL simulations
- Conclusions

Motivations: Weakening circulation

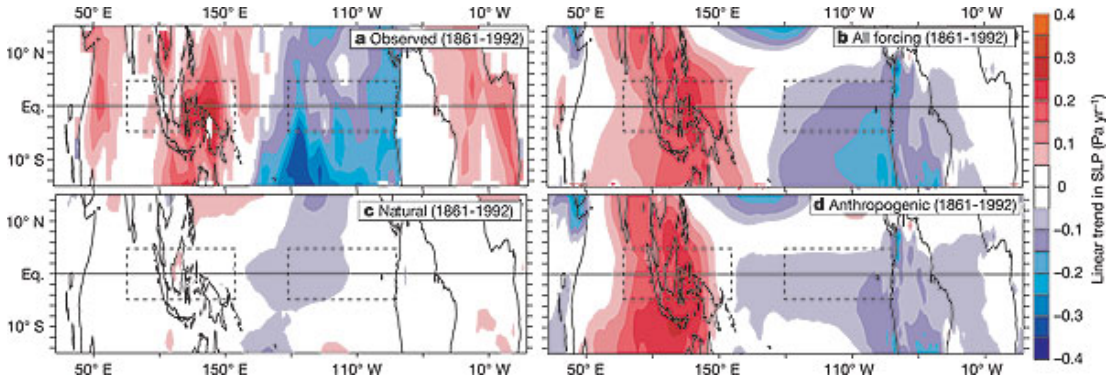
- Weakening of the Walker circulation (∇SLP, ω_{500})

Knutson & Manabe, 1995; *Zhang & Song*, 2006; *Vecchi et al.*, 2006; *Vecchi & Soden*, 2007

- Vs. the change of Hadley circulation



(Zhang & Song 2006)



(Vecchi et al., 2006)

Motivations: Weakening circulation

- No comprehensive explanation so far
  - Knutson & Manabe (1995)
    - examined factors such as lapse rate and q_{rad} in UT
  - *Held & Soden* (2006):

$$P = Mc \cdot q \qquad \frac{\delta P}{\overline{P}} = \frac{\delta Mc}{\overline{Mc}} + \frac{\delta q}{\overline{q}}$$

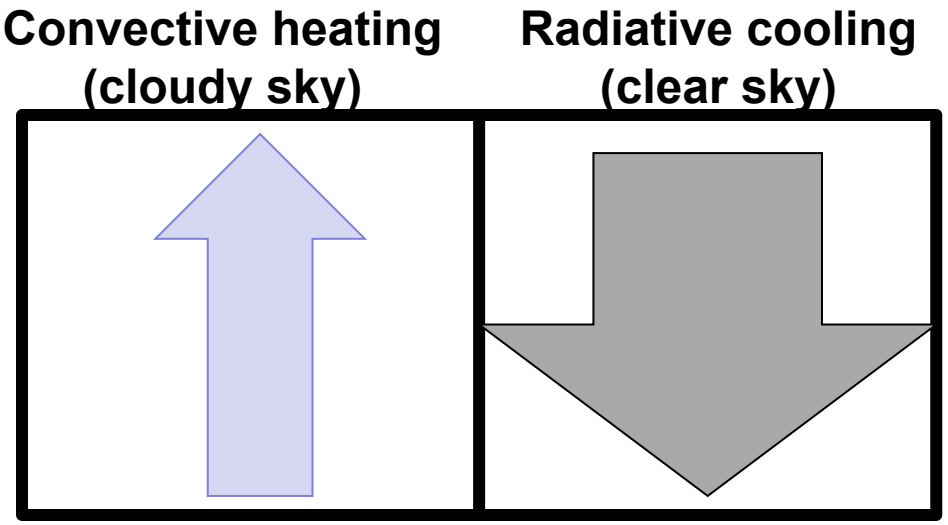
IPCC AR4 GCMs project ~2%/K and ~7%/K

(Global average) $\rightarrow \frac{\delta Mc}{\overline{Mc}}$ **~ -5%/K**

Hold true for the global average, not for the Walker circulation

Two-box RCE model

- In the tropics



Descending motion: Adiabatic warming

Balanced by the clear-sky radiative cooling

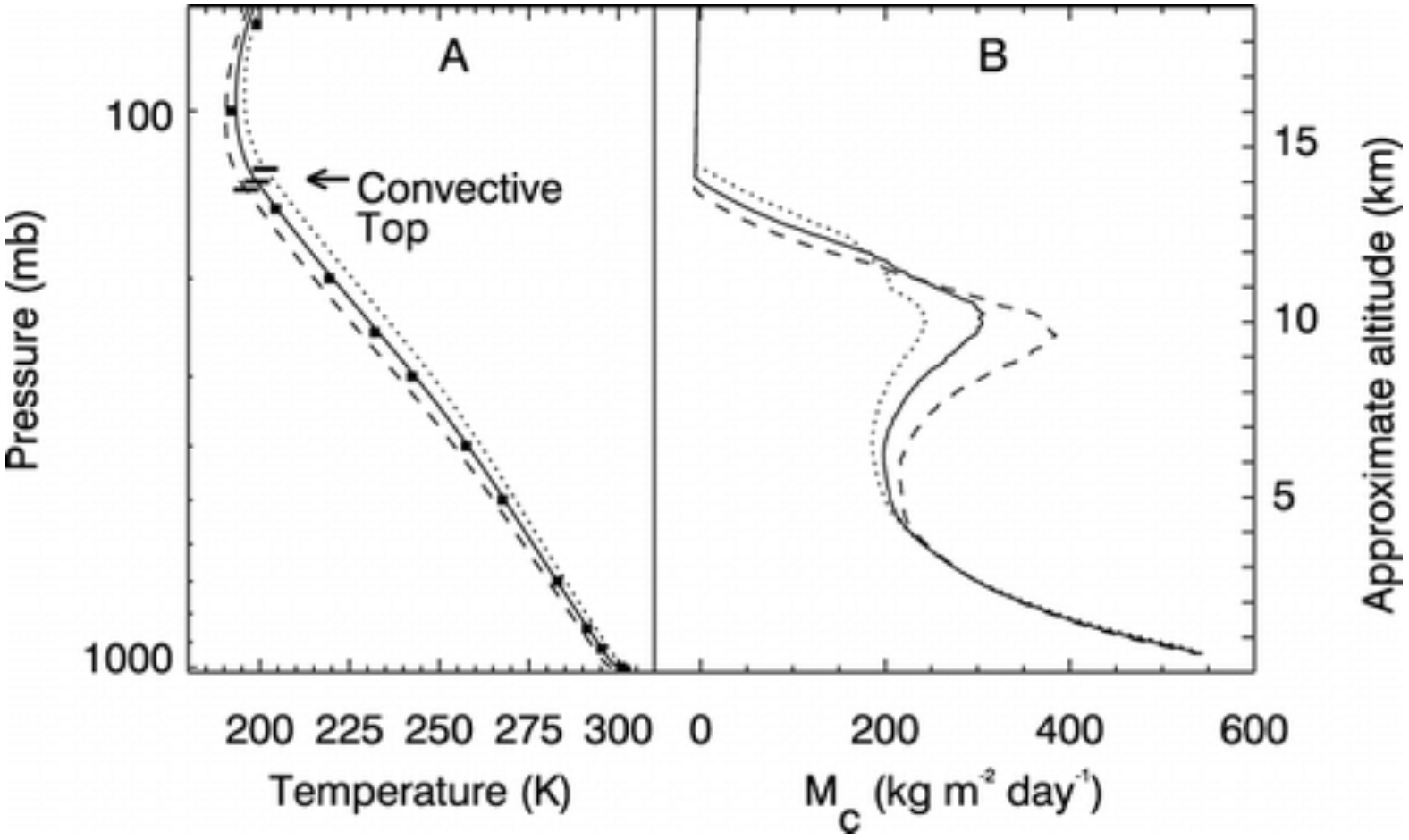
Mass flux balance between two boxes

❖ Downward velocity in the clear-sky box

$$\omega = \frac{g \cdot Q_R}{C_p\left(\frac{dT}{dz} + \Gamma_d\right)}$$

Q_R: clear-sky radiative cooling rate
$-dT/dz$: lapse rate
Γ_d: dry-adiabatic lapse rate
g: gravity acceleration
C_p: specific heat capacity of dry air

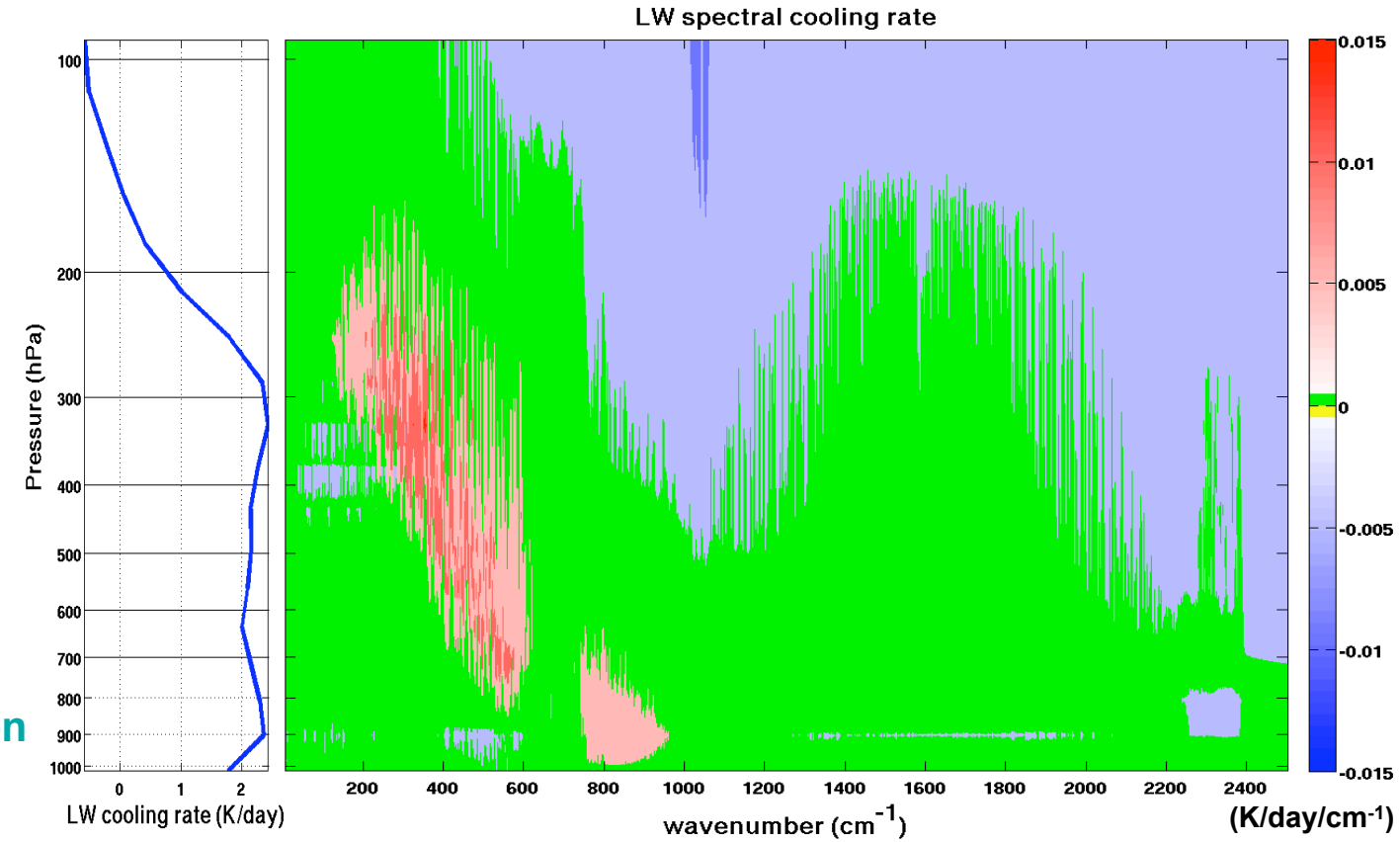
Minschwaner and Dessler (2004)



A heuristic argument (1)

$$\omega = \frac{g \cdot Q_R}{C_p(\frac{dT}{dz} + \Gamma_d)}$$

1. Clear-sky Q_R in the troposphere is mainly due to water vapor absorption and emission.



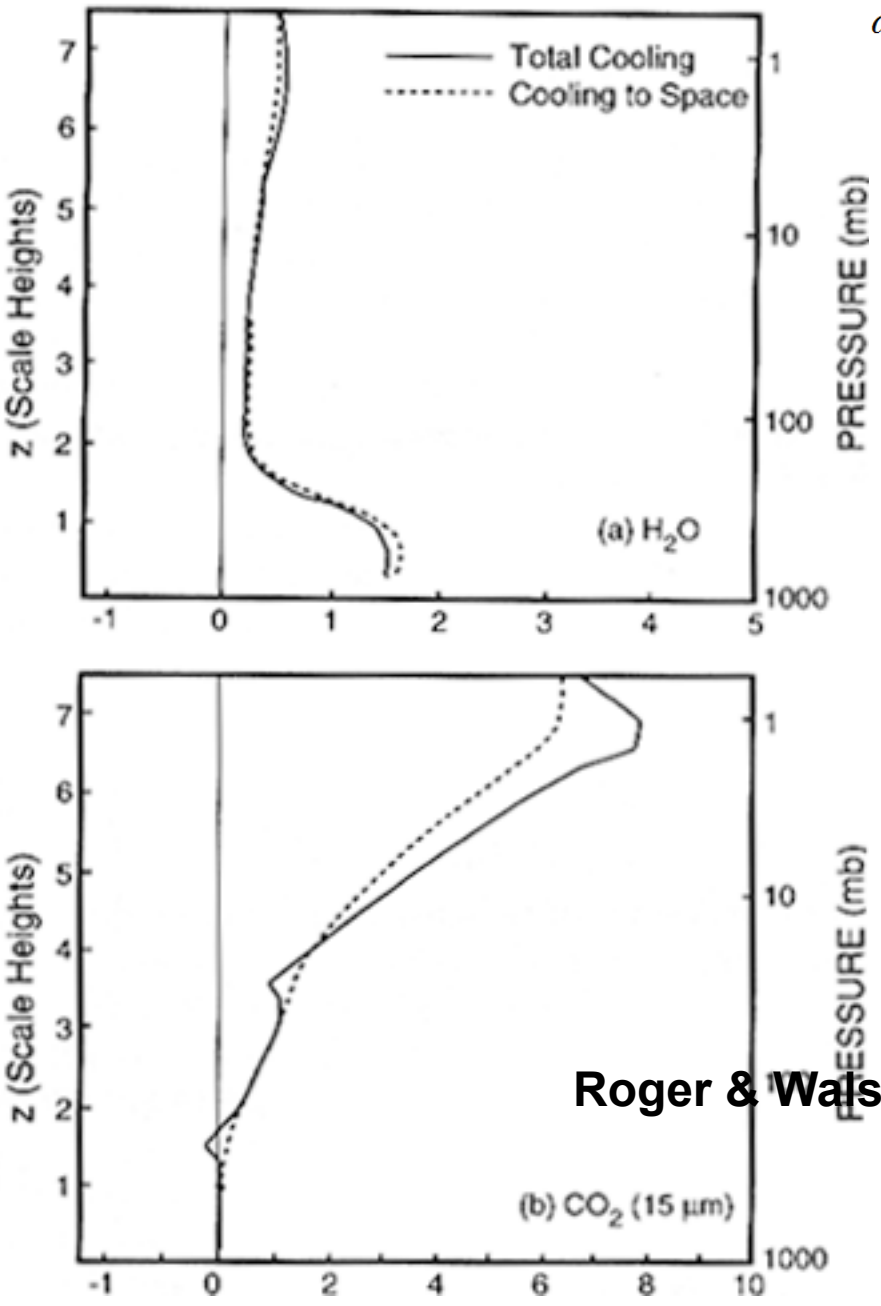
- **water vapor pure rotational band**
- **Continuum absorption**

A heuri

$$\omega = \frac{g \cdot Q_R}{C_p(\frac{dT}{dz} + \Gamma_d)}$$

2. Cooling-to-space (CTS) appr

$$Q_{Rv} \sim B_v(T)\frac{\partial \mathcal{T}}{}$$



- **At the top of the atmosphe**

  ρ → 0, so W(TOA) → 0

- **At the surface**

  $e^{-\tau}$ → 0, so W(surface) →

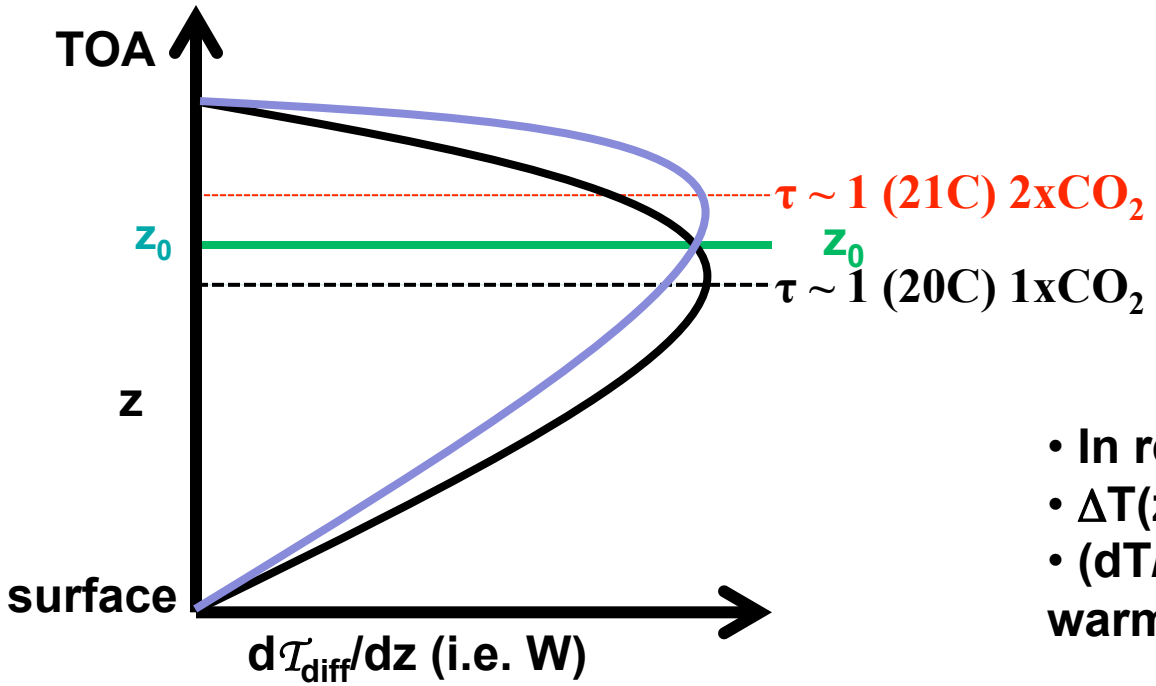
→ W(z) has a convex curvat

→ W(z) peaks at τ~1 and ver

Roger & Walshaw, 1966

3. T(surface) ↑ → water vapor ↑ → altitude of the $W_v(z)$ peak ↑

$$\omega = \frac{g \cdot Q_R}{C_p(\frac{dT}{dz} + \Gamma_d)}$$



If all other UNCHANGED

Above z_0: $W_{21C} > W_{20C}$
$Q_{R21C} > Q_{R20C}$
$\omega_{21c} > \omega_{20C}$
Below z_0: $\omega_{21c} < \omega_{20C}$
(weakened circulation)

- **In reality, as T_s warms**
- **$\Delta T(z) > 0 \rightarrow \Delta B(T) > 0$**
- **$(dT/dz)_{21c} > (dT/dz)_{20c}$ as UT warms faster than LT**

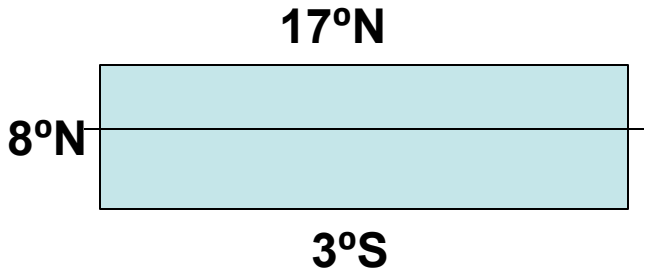
A sketch of the change of diffusive weighting function

Questions

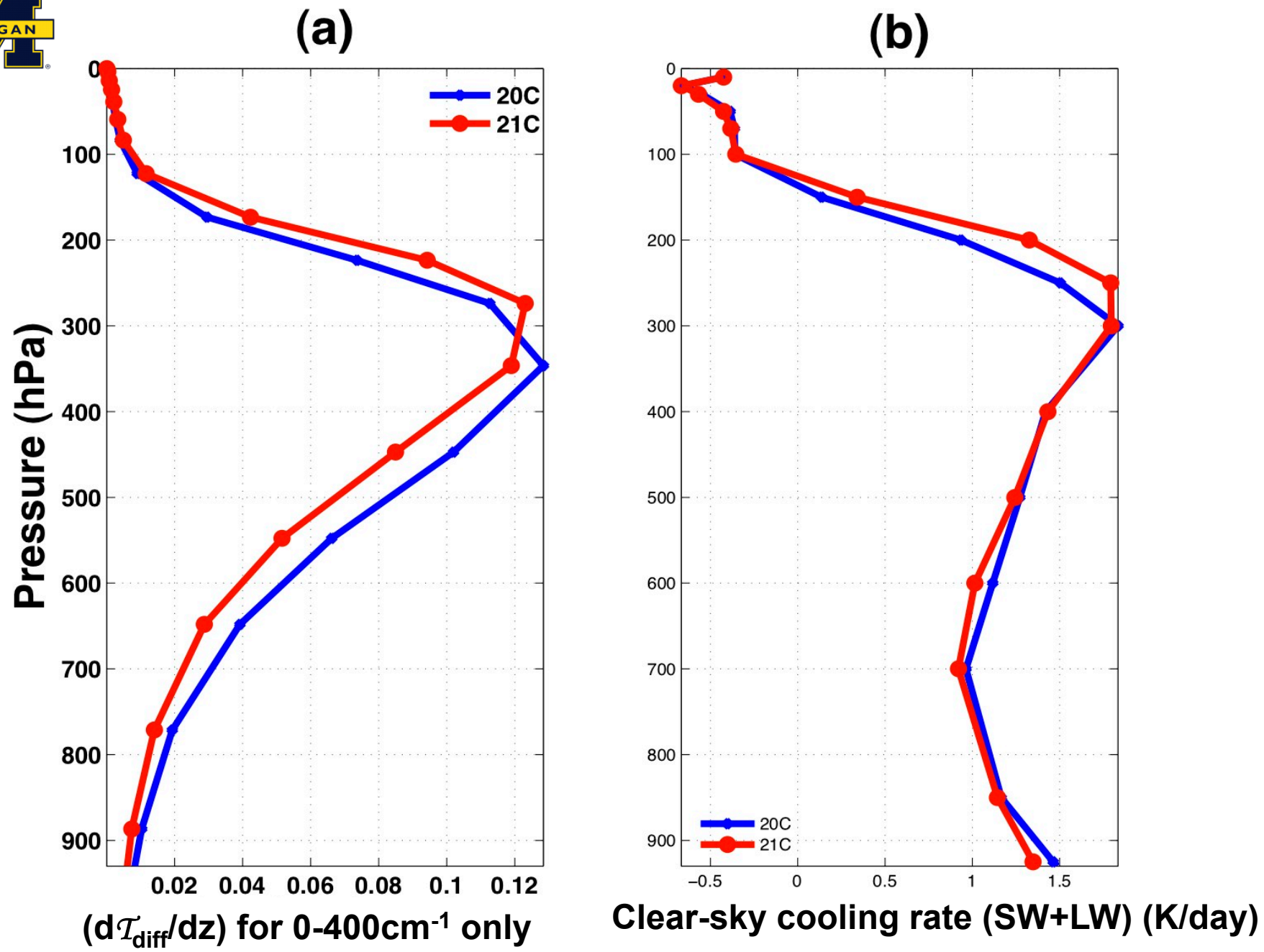
- Can such simple RCE framework give a reasonable estimation of the change of vertical velocity simulated by the coupled-GCM?
- If so, can it be used to assess the relative importance of each contributing factor?

Model and data analysis

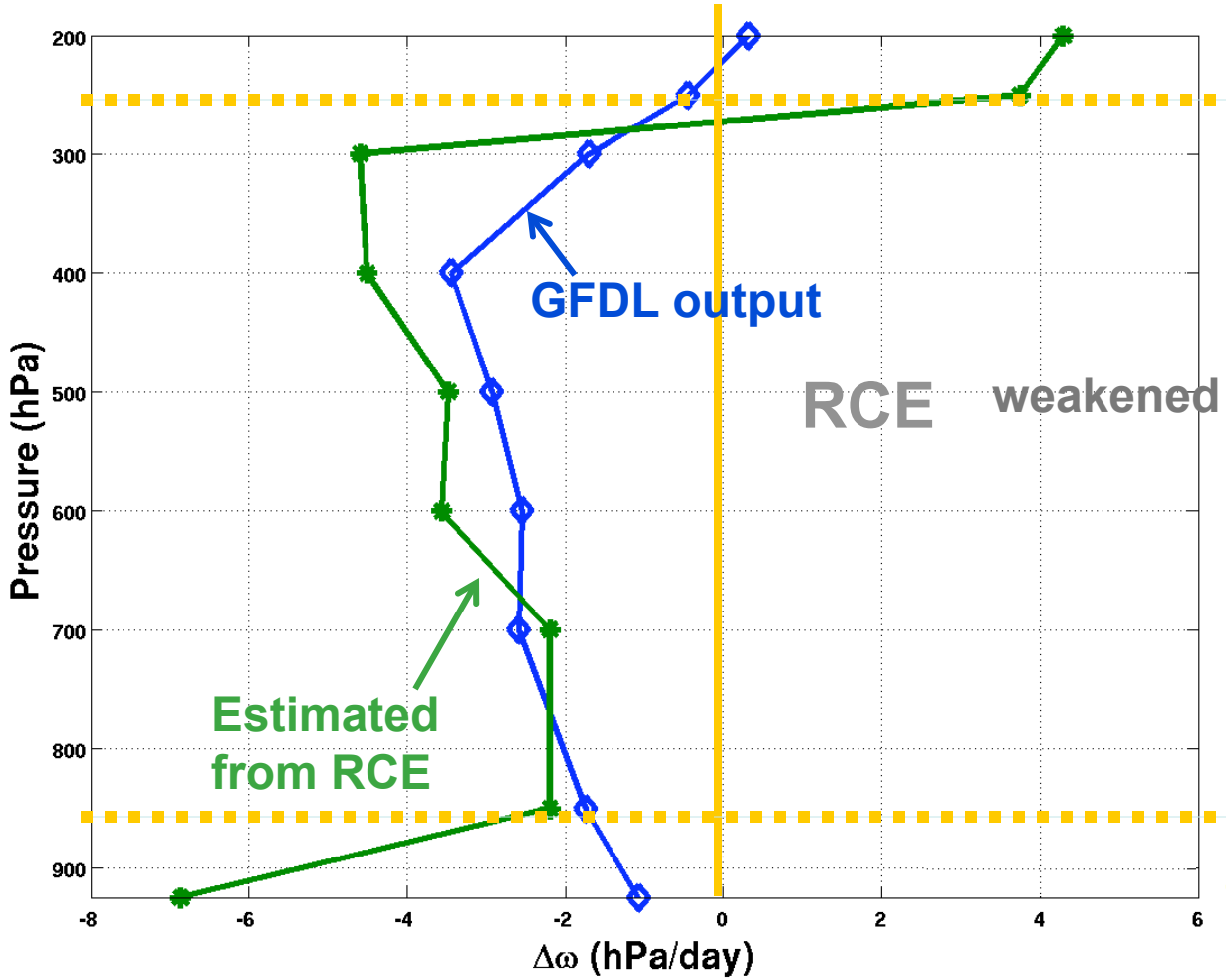
- The GFDL CM2.1 coupled-GCM runs
- Historical run for the 20th century
- SA1B run for the 21th century
- Monthly mean output of T, ω, $(dT/dt)_{SW_clr}$, $(dT/dt)_{LW_clr}$, $(dT/dt)_{SW}$, $(dT/dt)_{LW}$
- Inner tropics only (3°S – 17°N)
- Two 30-year segements
  - 1971-2000 (**20C**) vs. 2071-2100 (**21C**)



$$\omega = \frac{g \cdot Q_R}{C_p\left(\frac{dT}{dz} + \Gamma_d\right)}$$


(a)
(b)
20C
21C
Pressure (hPa)
0
100
200
300
400
500
600
700
800
900
0.02
0.04
0.06
0.08
0.1
0.12
−0.5
0
0.5
1
1.5
(d$\mathcal{T}_{diff}$/dz) for 0-400cm^{-1} only
Clear-sky cooling rate (SW+LW) (K/day)

- similar patterns below 250 and above PBL



$$\omega = \frac{g \cdot Q_R}{C_p(\frac{dT}{dz} + \Gamma_d)}$$

Sensitivity test

$$\omega = \frac{g \cdot Q_R}{C_p\left(\frac{dT}{dz} + \Gamma_d\right)}$$

$$\omega_f = \omega_c \frac{\left(1 + \frac{Q_{R_f} - Q_{R_c}}{Q_{R_c}}\right)}{\left(1 + \frac{\left(\frac{dT}{dz}\right)_f - \left(\frac{dT}{dz}\right)_c}{\left(\frac{dT}{dz} + \Gamma_d\right)_c}\right)}$$

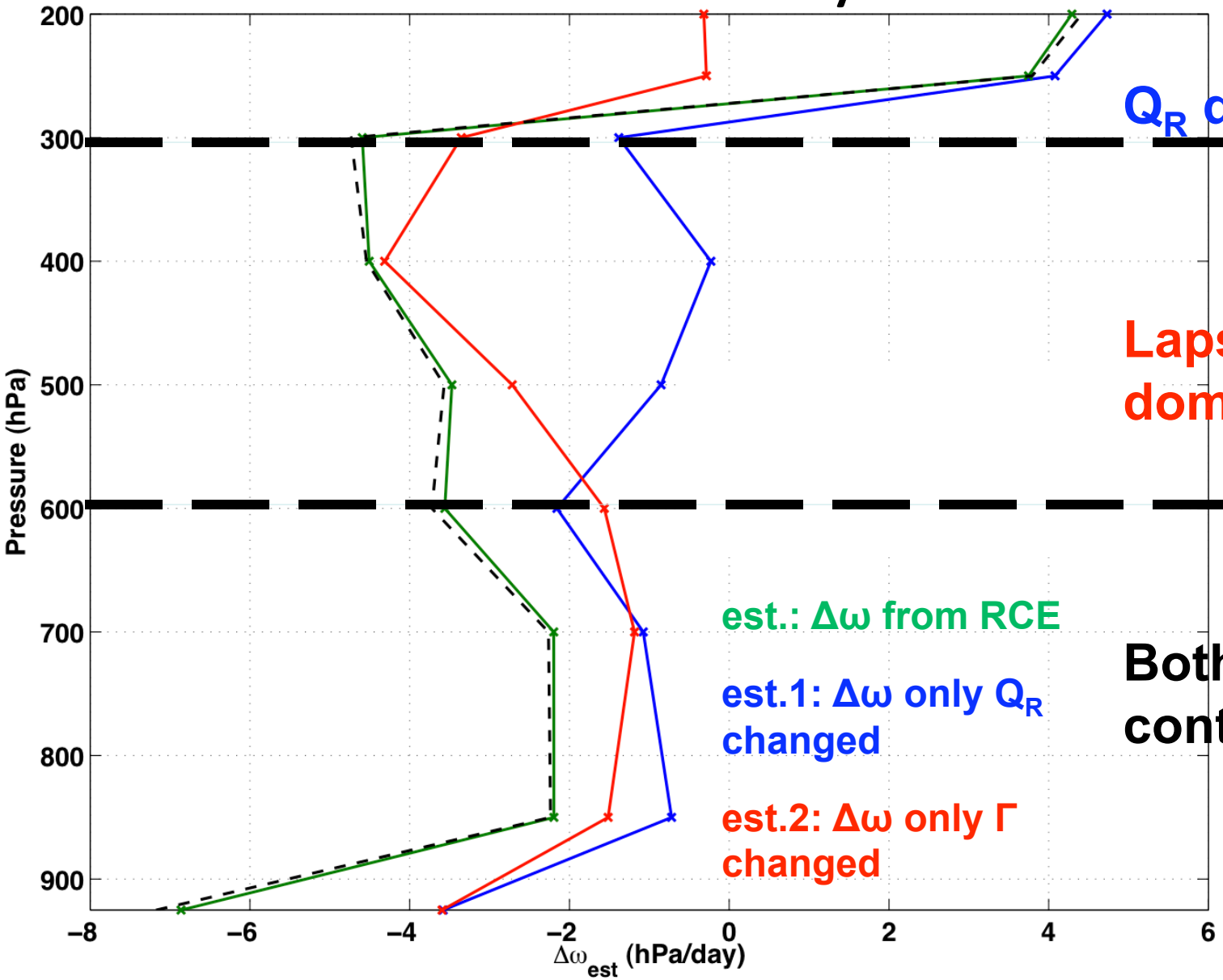
f: future (21C)
c: current (20C)

$\Delta\omega = \omega(Q_R|_f, dT/dz|_f) - \omega(Q_R|_c, dT/dz|_c)$

$\Delta\omega = \omega(Q_R|_f, dT/dz|_c) - \omega(Q_R|_c, dT/dz|_c)$

$\Delta\omega = \omega(Q_R|_c, dT/dz|_f) - \omega(Q_R|_c, dT/dz|_c)$

Sensitivity test

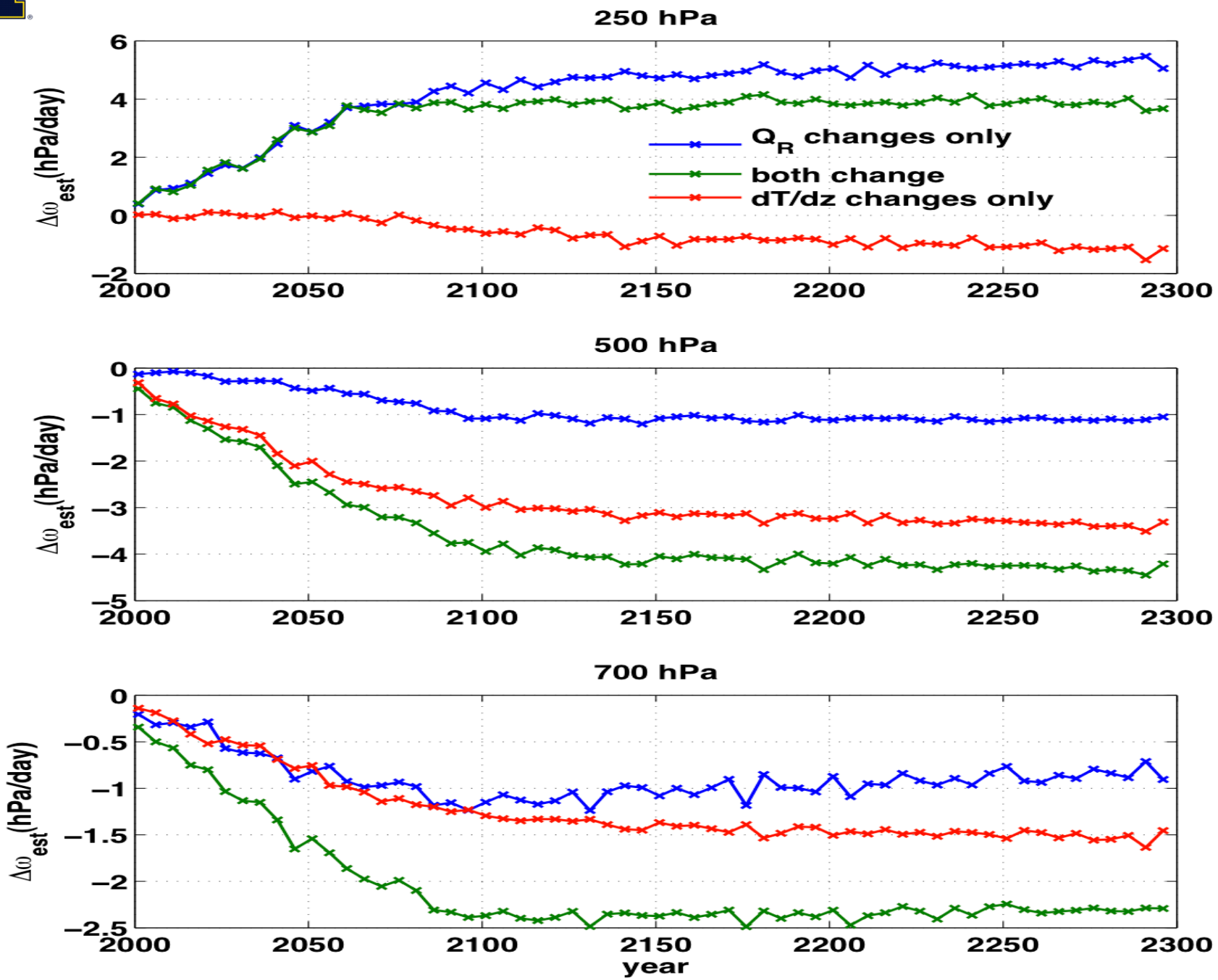


Q_R dominates

Lapse rate Γ dominates

Both Q_R and Γ contribute

Time-dependent behaviors



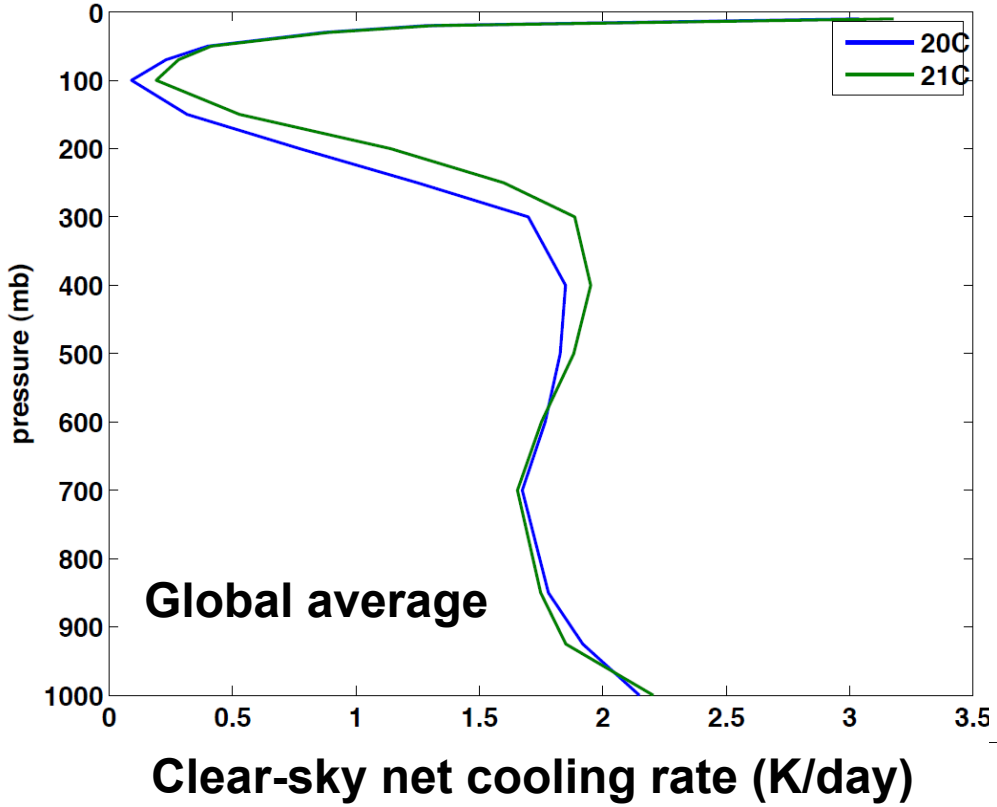
Summary and Discussion

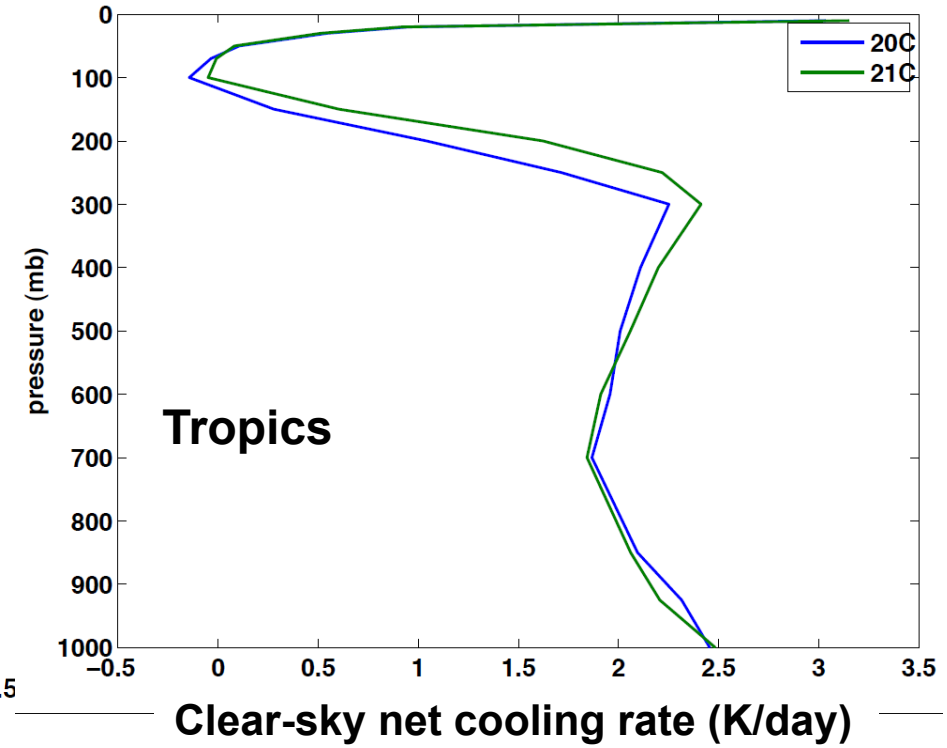
- 2-box RCE framework explains the weakening of Walker circulation as a result of lapse rate and cooling rate changes in response to the warming of surface.
- Separate the effects on the change of Walker circulation
  - the effect of lapse rate change
  - the effect of radiative cooling change

	Cooling rate Q_R	Lapse rate Γ
Upper	+	–
Middle	–	–
Lower	–	–

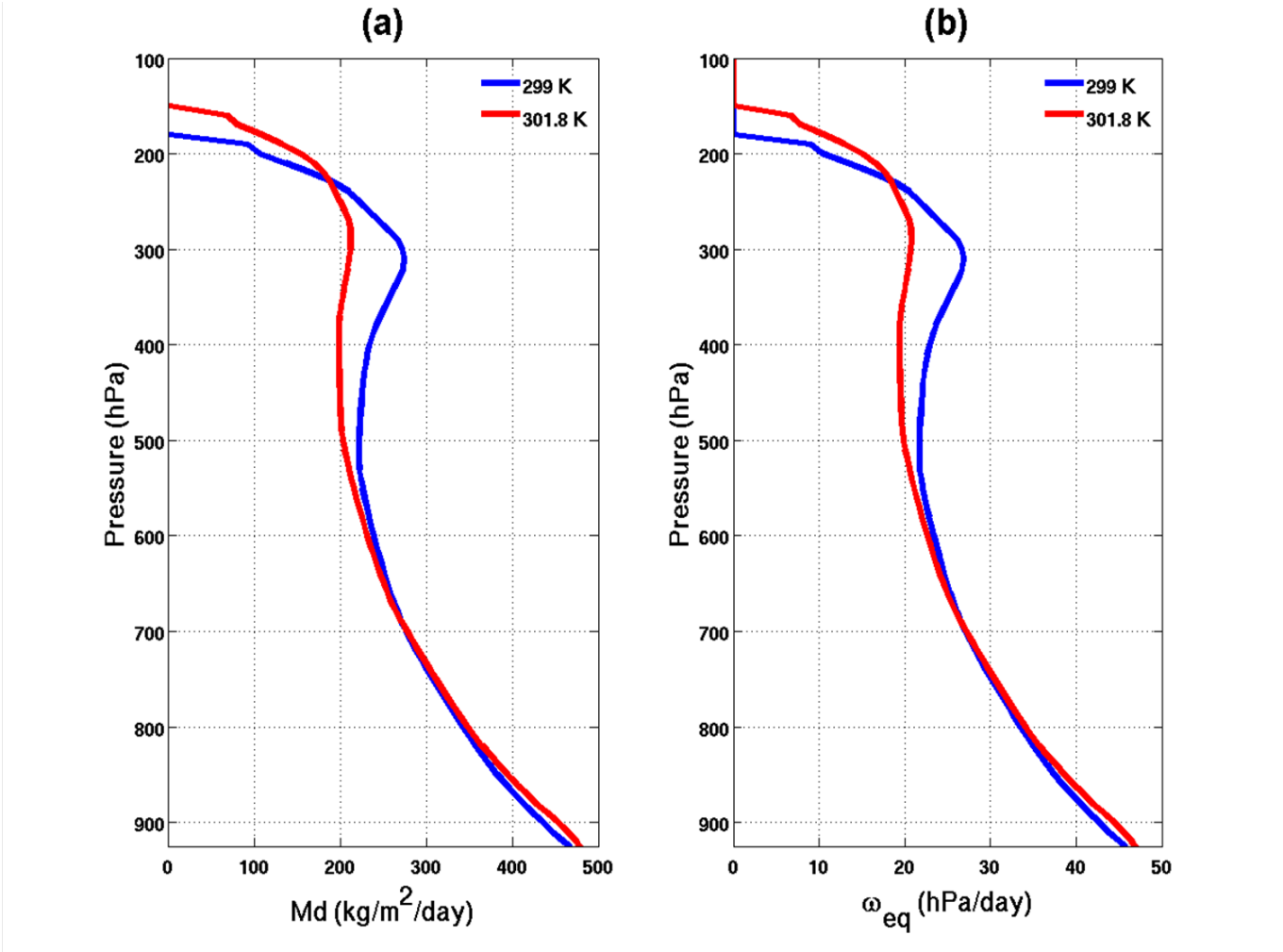
Summary and Discussion (II)

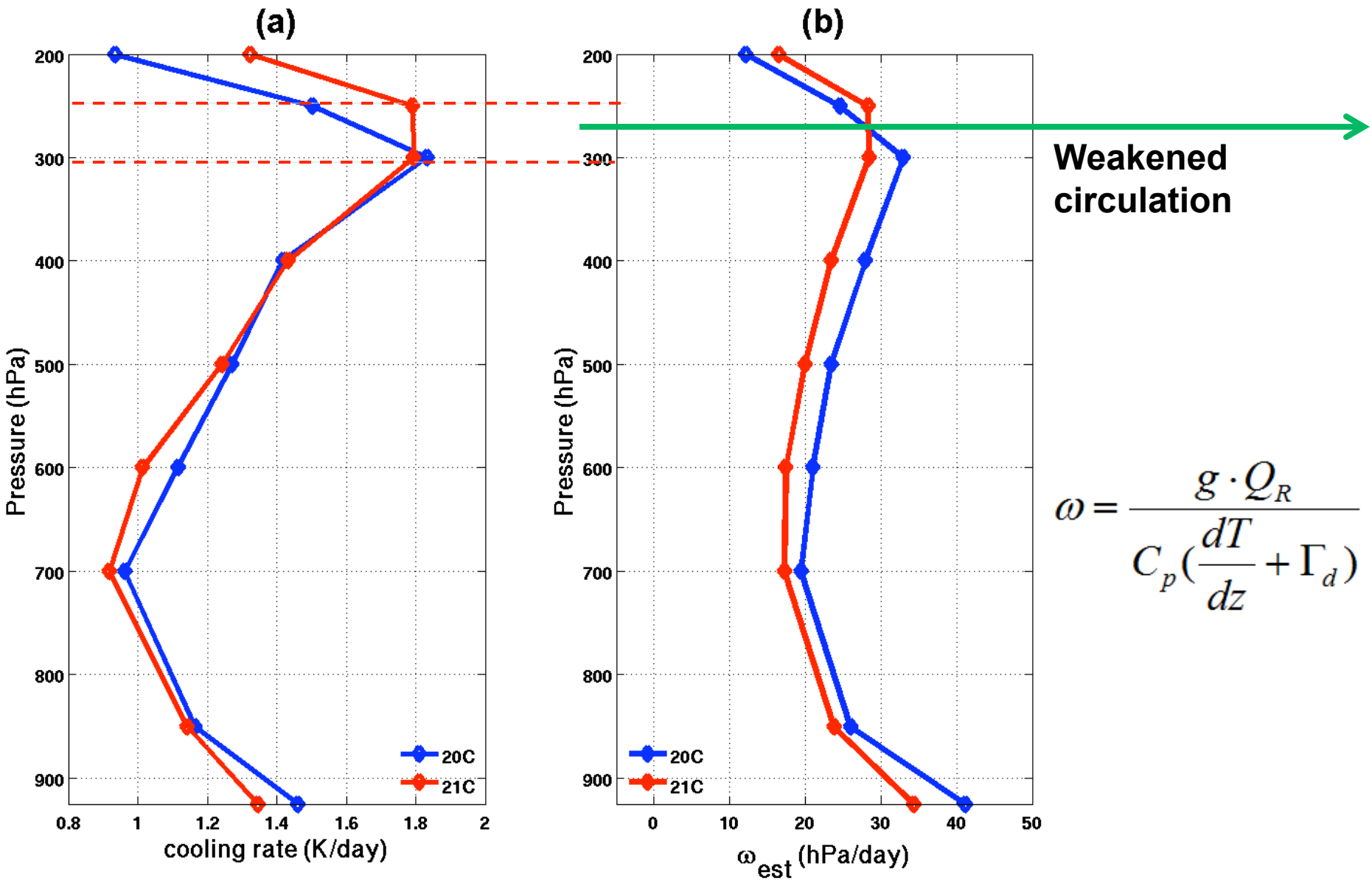
- It's well known that for column-integrated cooling $\Delta Q_R > 0$ (so $L\Delta precip \sim \Delta Q_R$)
- But the UT and LT changes are different. This is also true for the entire tropical average or global average



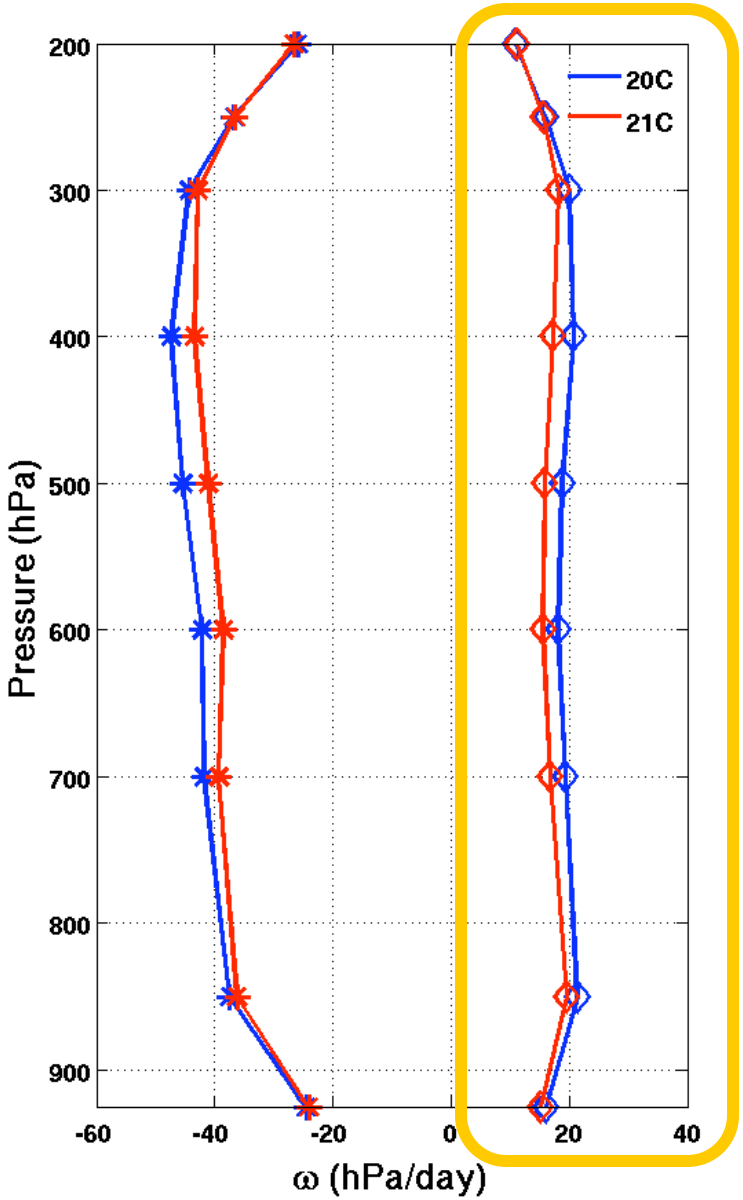


Thank You!


(a)
(b)
299 K
301.8 K
Pressure (hPa)
Md (kg/m^2/day)
ω_{eq} (hPa/day)
100
200
300
400
500
600
700
800
900
0
100
200
300
400
500
10
20
30
40
50


(a)
(b)
Pressure (hPa)
cooling rate (K/day)
ω est (hPa/day)
20C
21C
Weakened circulation
$\omega = \frac{g \cdot Q_R}{C_p(\frac{dT}{dz} + \Gamma_d)}$

Comparing with GFDL CM3 output



Compute the downward ω:

only average over the grid box with a monthly-mean downward ω for each month and each pressure level.

Same to upward ω

In RCE: $\omega_{dn} A_{dn} = \omega_{up} A_{up}$ ($A_{up} << A_{dn}$)

Here: $\omega_{dn} A_{dn} = \omega_{up} A_{up}$ ($A_{dn} \sim A_{up}$)

$(\omega_{up})_{RCE} >> (\omega_{up})_{here}$

But ω_{dn} might be comparable

The fraction of inner tropics with downward monthly-mean ω remains essentially same from 20C to 21C.

Contribution from each factor

$$\omega = \frac{g \cdot Q_R}{C_p\left(\frac{dT}{dz} + \Gamma_d\right)}$$

$$\omega_f = \omega_c \frac{\left(1 + \frac{Q_{R_f} - Q_{R_c}}{Q_{Rc}}\right)}{\left(1 + \frac{\left(\frac{dT}{dz}\right)_f - \left(\frac{dT}{dz}\right)_c}{\left(\frac{dT}{dz} + \Gamma_d\right)_c}\right)}$$

f: future (21C)
c: current (20C)

- So far direct output is used (every change included)
- $\Delta\omega$ from the RCE is comparable to $\Delta\omega$ from the GFDL model output
- Now we can compute $\Delta\omega$ by changing Q_R and lapse rate separately