Global hydrological cycle response to rapid and slow global warming

Larissa Back, Kuniaki Inoue, Karen Russ, Zhengyu Liu

*Simulations implemented by Feng He and Jiaxu Zhang

Outline:

- Anthropogenic global warming causes “robust” changes in the global hydrological cycle
- “Robust” changes (in this context) means changes are directly related to global mean temperature change*

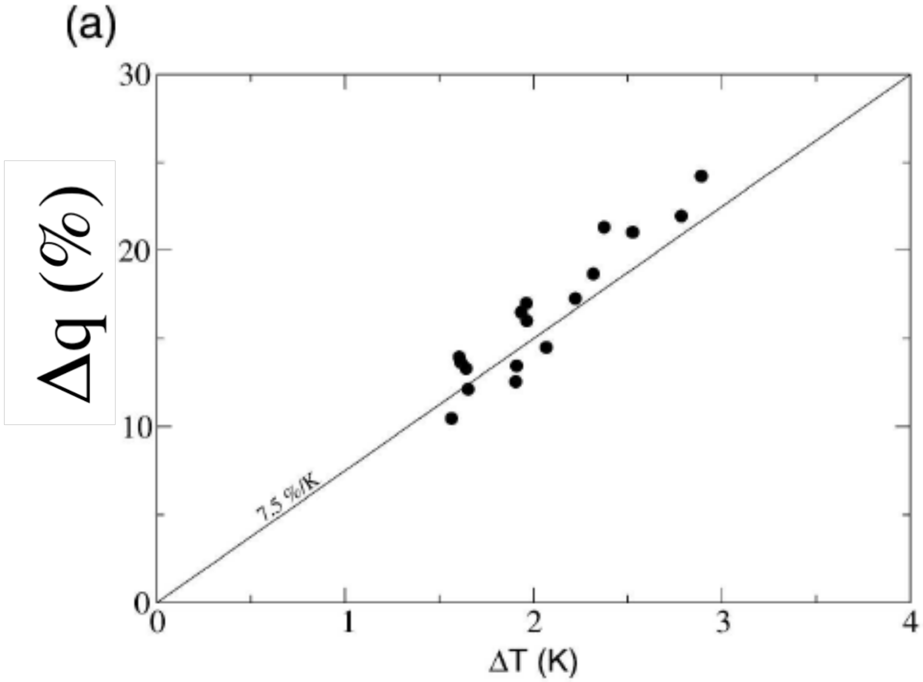
$$\frac{d \ln e_s}{dT} = \frac{L}{RT^2} \equiv \alpha(T)$$

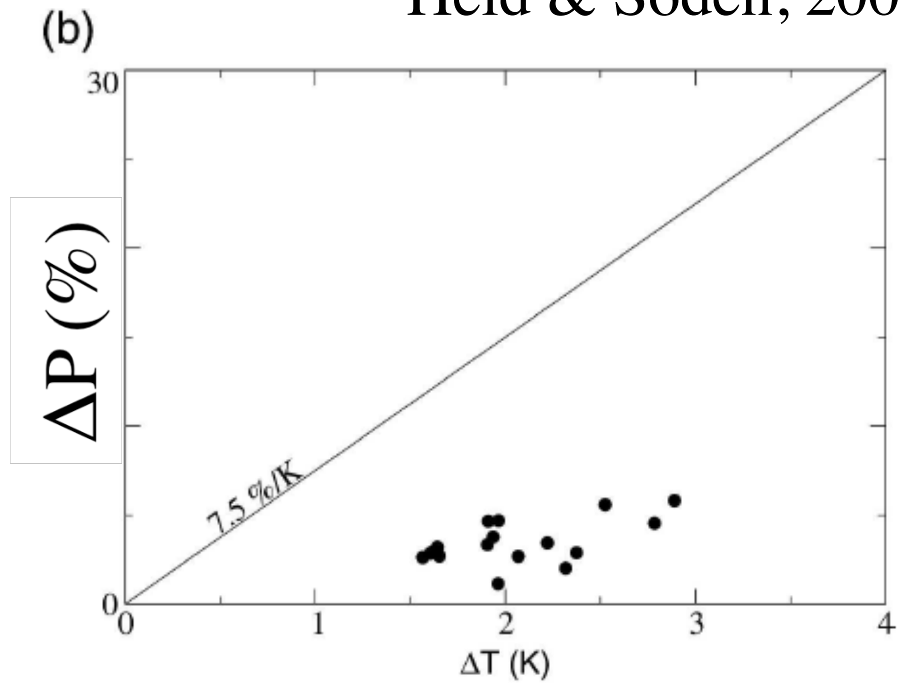
*e.g. Held & Soden 2006

- Question: Are hydrological cycle changes in the paleoclimate (last 22ky) similarly “robust?”
  - Answer: Only sort of. We’ll examine why this is.

“Robust” changes in the global hydrological cycle due to anthropogenic global warming

Held & Soden, 2006





$$\frac{d\ \ln e_s}{dT} = \frac{L}{RT^2} \equiv \alpha(T)$$

Atmospheric radiative cooling constraints (surface energy balance)

“Robust” rainfall changes: wet get wetter and the dry get drier

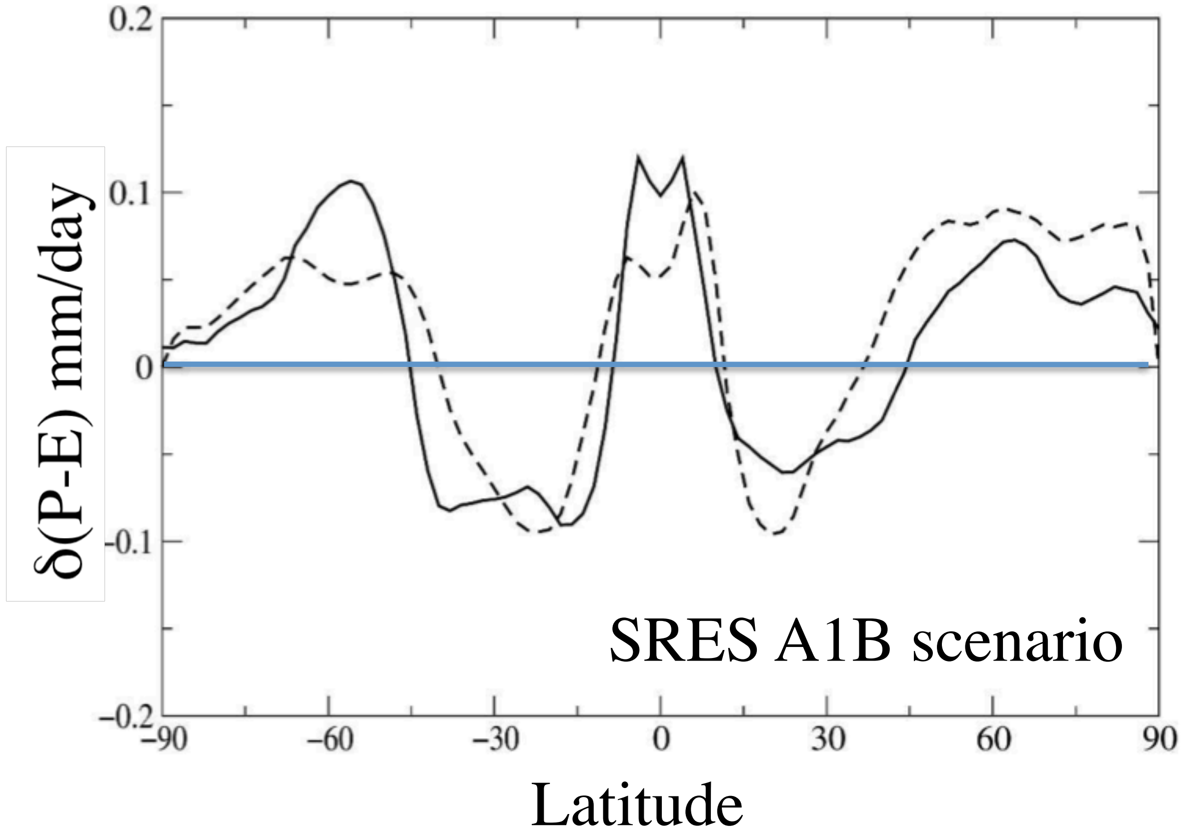


Fig. 6b From Held & Soden (2006)

FIG. 6. The zonal-mean $\delta(P-E)$ from the ensemble mean of PCMDI AR4 models (solid) and the thermodynamic component (dashed) predicted from (6). $\delta(P-E) = \alpha\delta T(P-E)$.

We examine hydrological cycle in TRACE—21

Transient Climate Evolution of the Last 21000 years

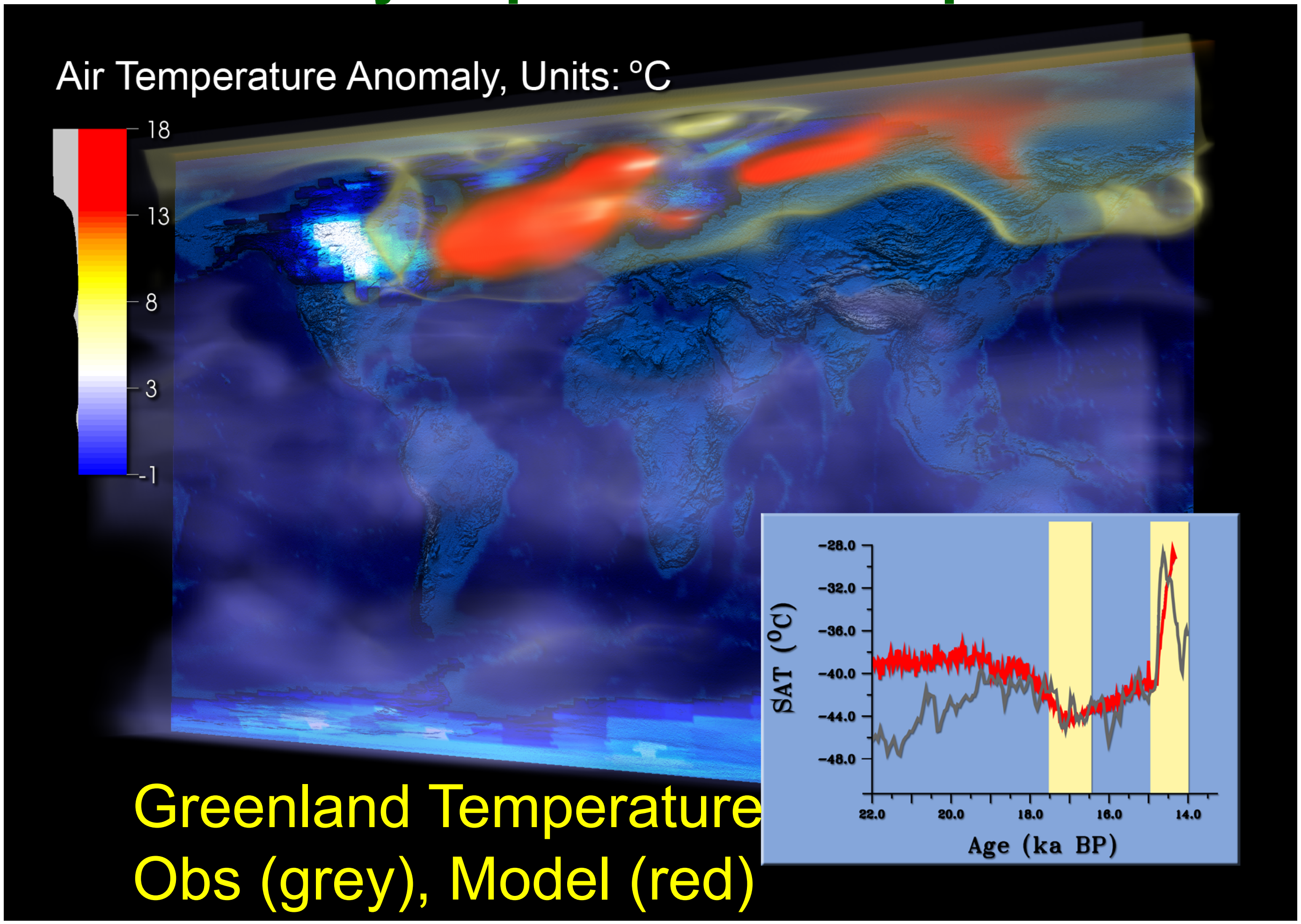
Zhengyu Liu (UW-Madison), B. Otto-Bliesner (NCAR)

Model: NCAR-CCSM3 – fully coupled ocean-atmosphere GCM

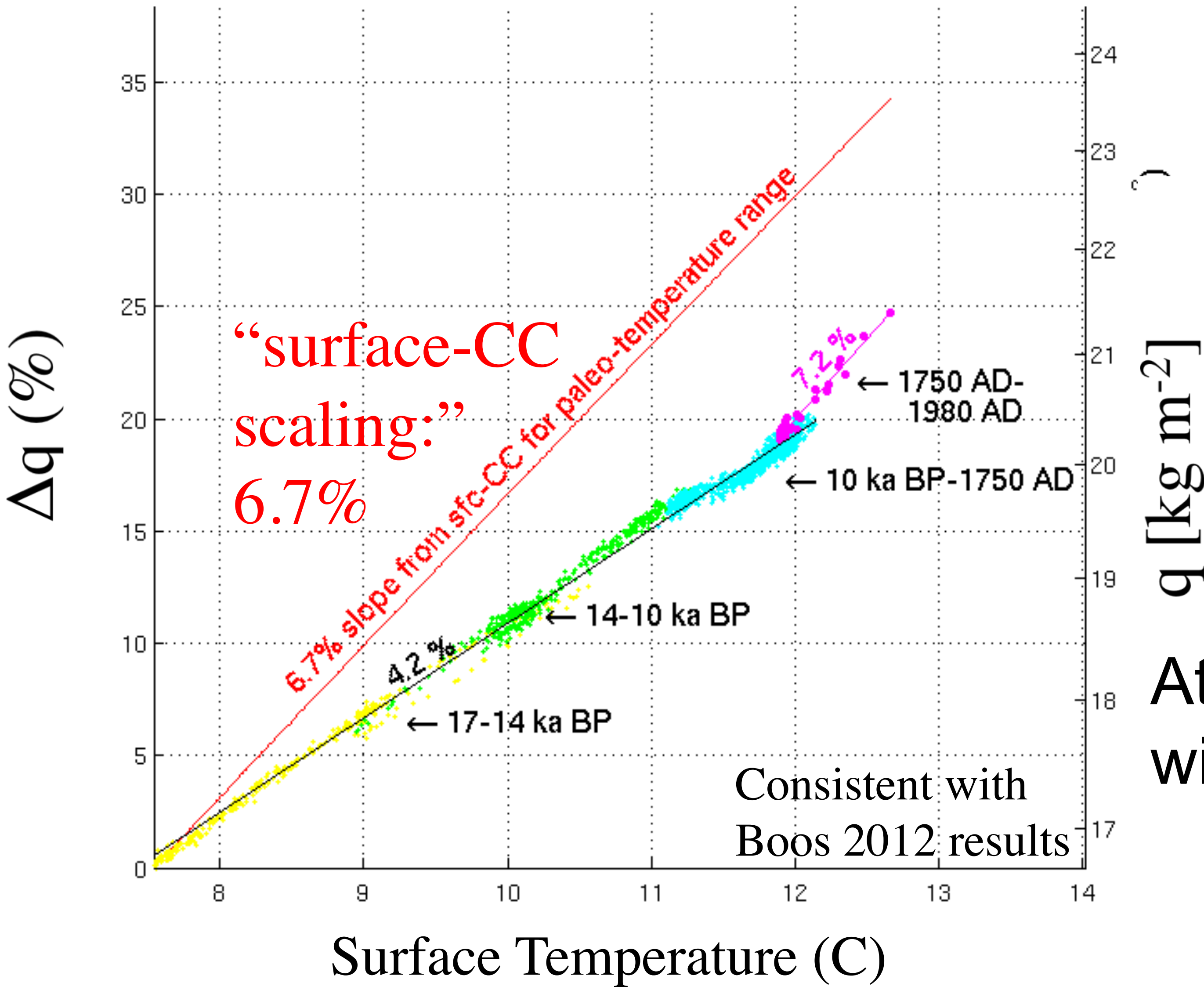
Realistic Forcing

Insolation
GHGs
Meltwater
Icesheet

Liu et al., 2009, Science



Unexpected TRACE paleoclimate results: q (global water vapor) versus surface T

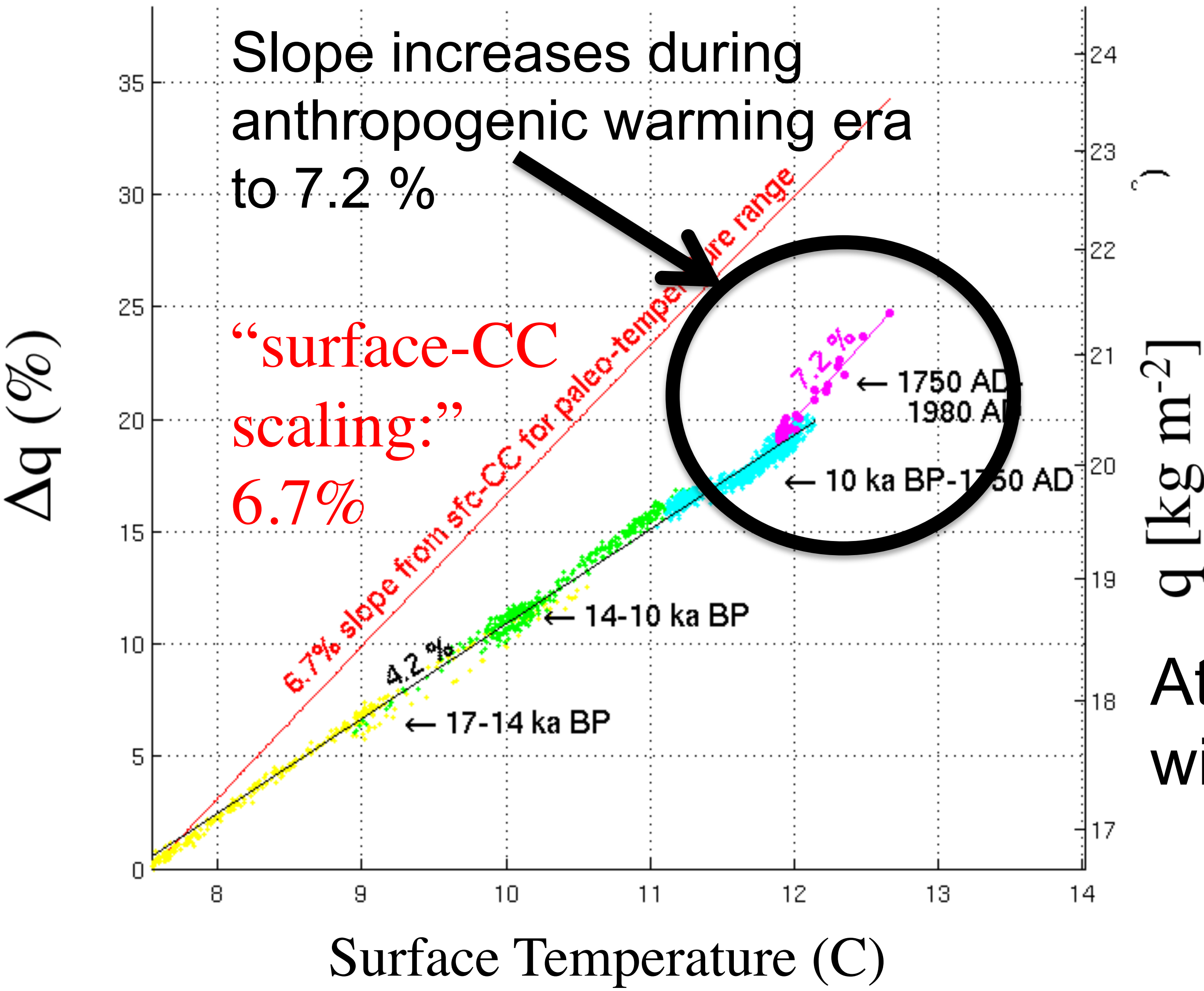


shows 4.2 % q increase per unit T change.

At apparent odds with:

$$\frac{d\ln e_s}{dT} = \frac{L}{RT^2}$$

Unexpected TRACE paleoclimate results: q (global water vapor) versus surface T



shows 4.2 % q increase per unit T change.

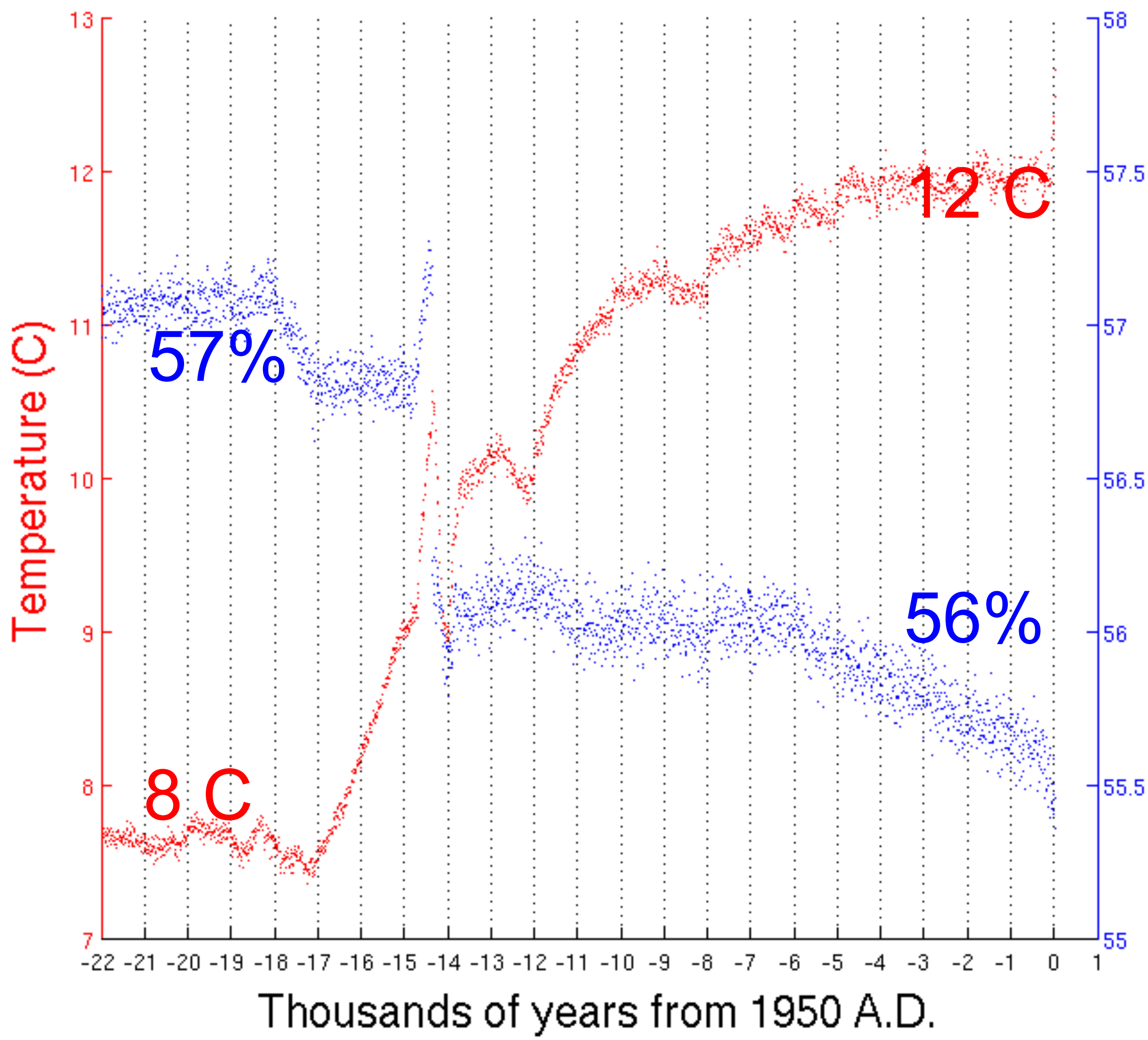
At apparent odds with:

$$\frac{d\ln e_s}{dT} = \frac{L}{RT^2}$$

Possible explanations for 4.2% water vapor increase per unit K warming

- *Relative humidity is not constant over climate-change time scales?*
- *Clausius-Clapeyron relationship non-linearities?*
- *Tropical upper troposphere warms more than surface at warmer temperatures?*
- *Rapid CO2-induced warming affects global water vapor differently than slow CO2-induced warming?*

Relative humidity is not constant over climate-change time scales?



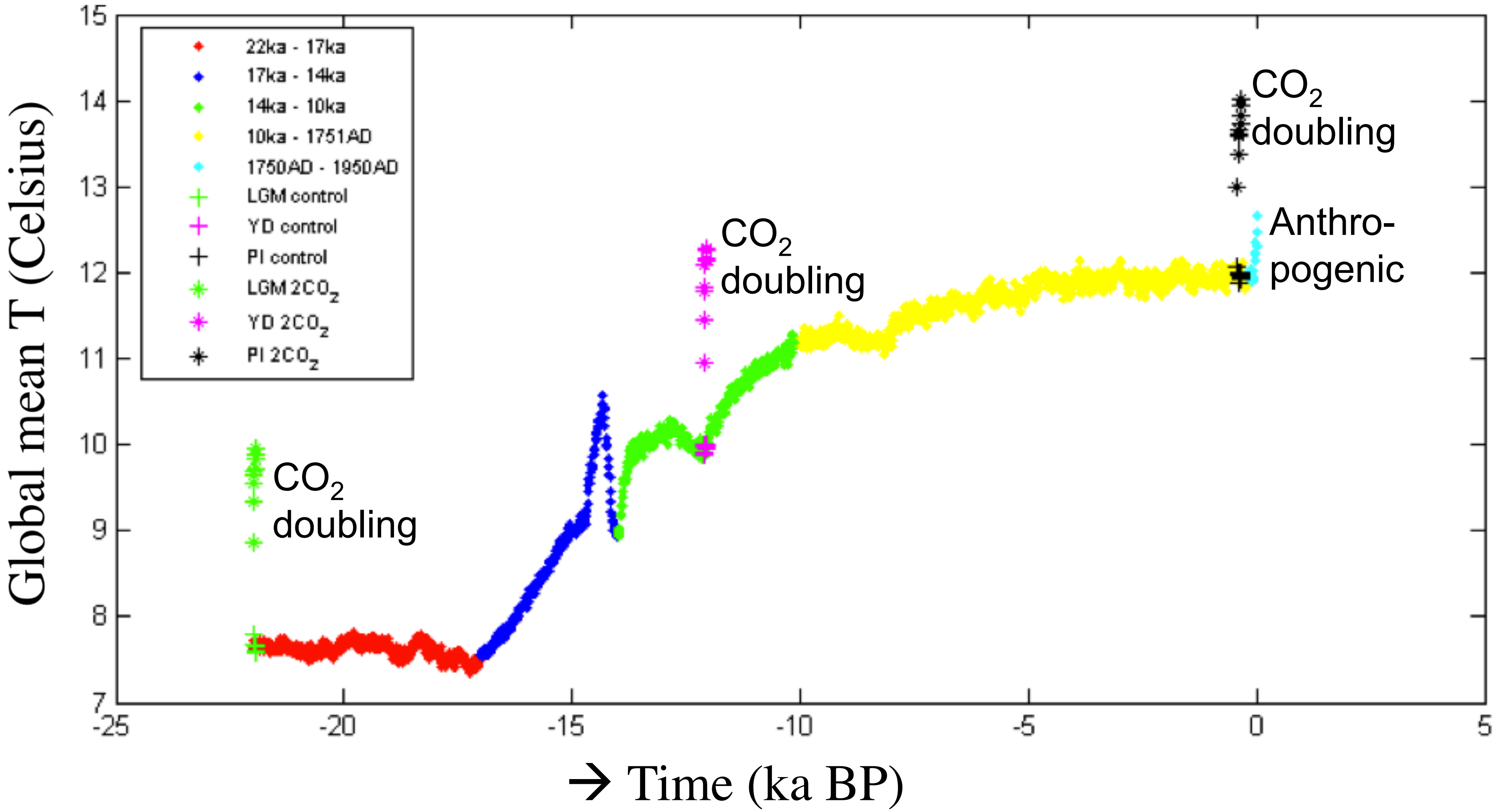
Blue shows:

Total water vapor in atmosphere

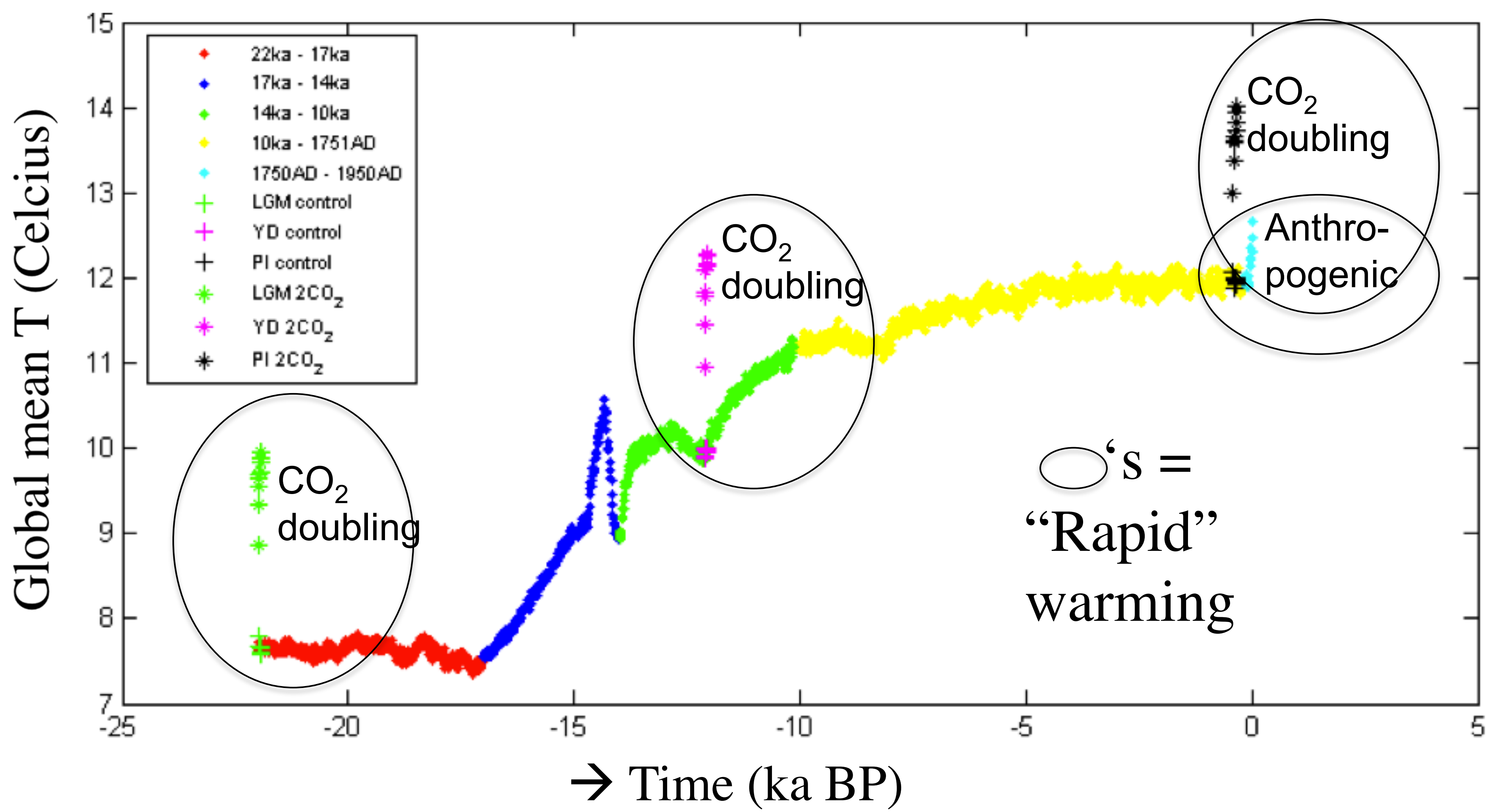
Total water vapor atmosphere would have if saturated

Column relative humidity changes small

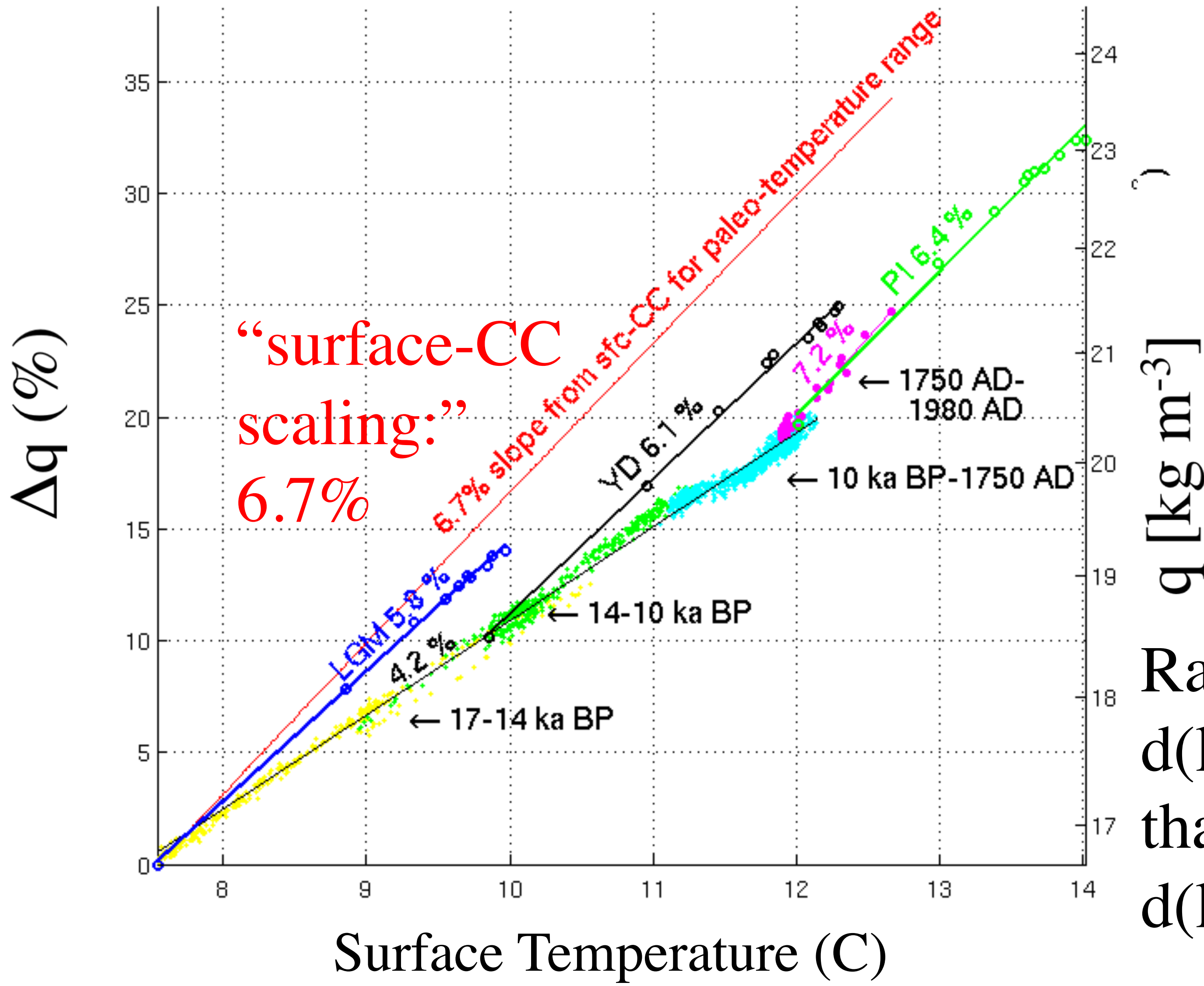
Try changing CO_2 rapidly by running branch simulations where CO_2 doubles instantaneously



Try changing CO_2 rapidly by running branch simulations where CO_2 doubles instantaneously



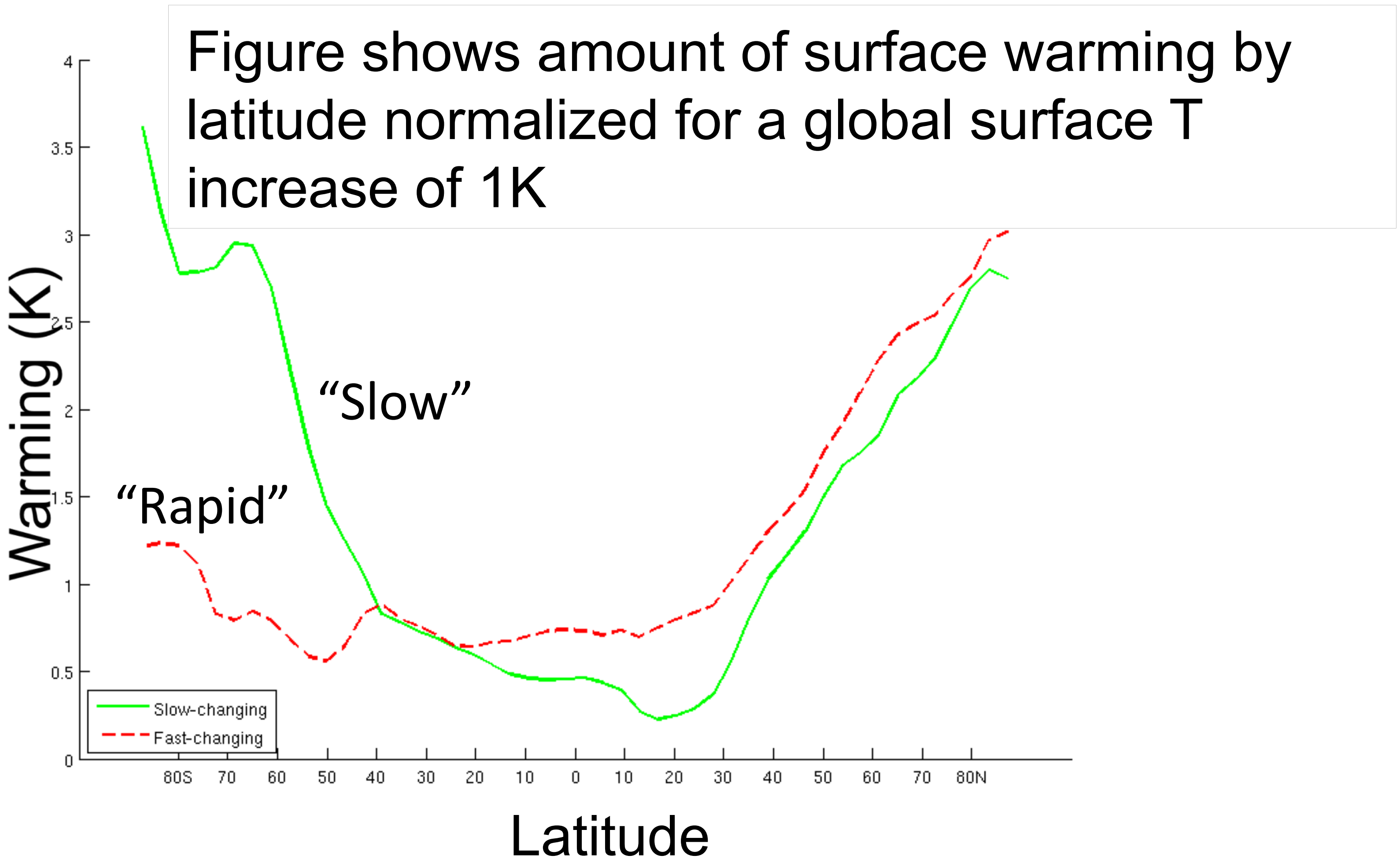
Rapid CO_2-induced warming affects global water vapor differently than slower warming



Rapid warming d(lnq)/dT greater than slow warming d(lnq)/dT

Slow CO2 increases → symmetric warming

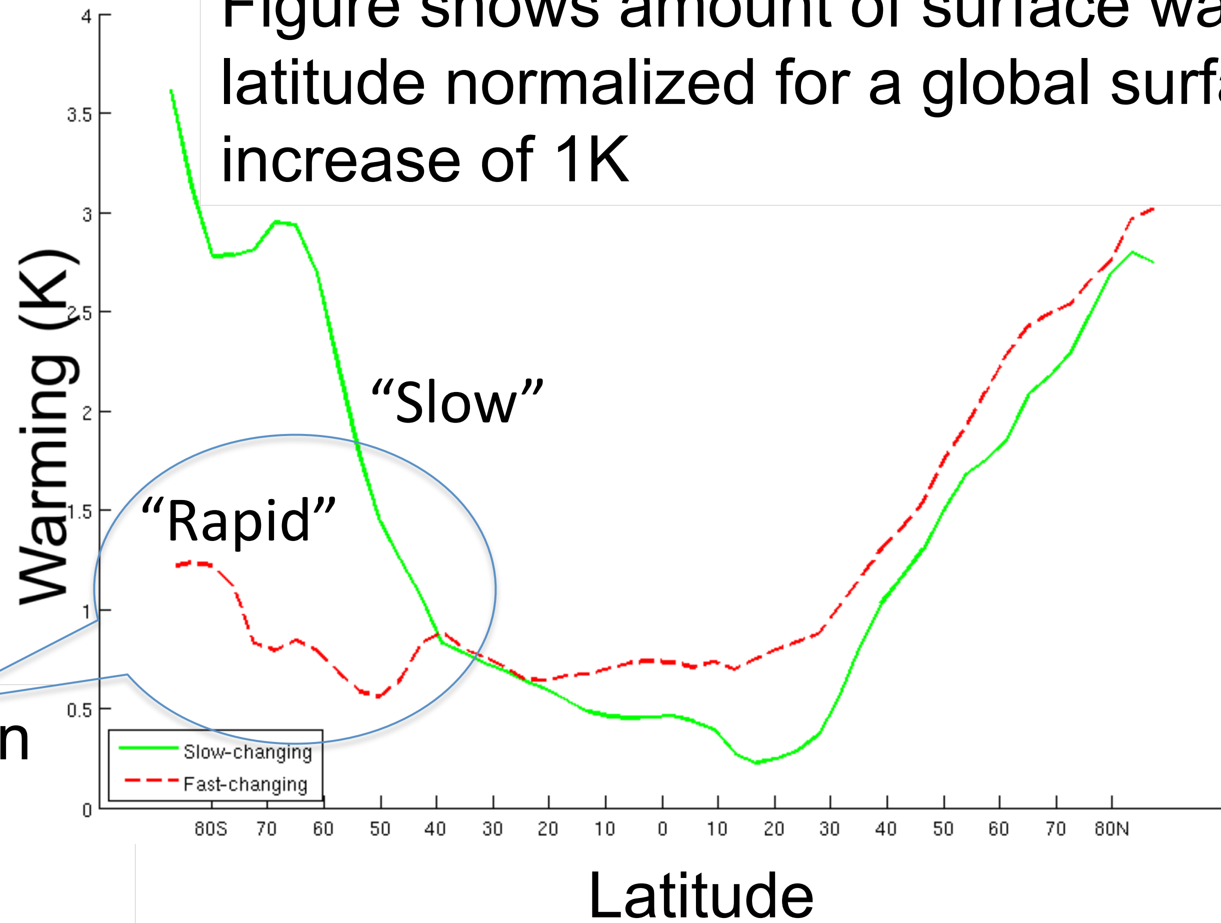
Rapid CO2 increases → N.H. warms more



Slow CO2 increases → symmetric warming

Rapid CO2 increases → N.H. warms more

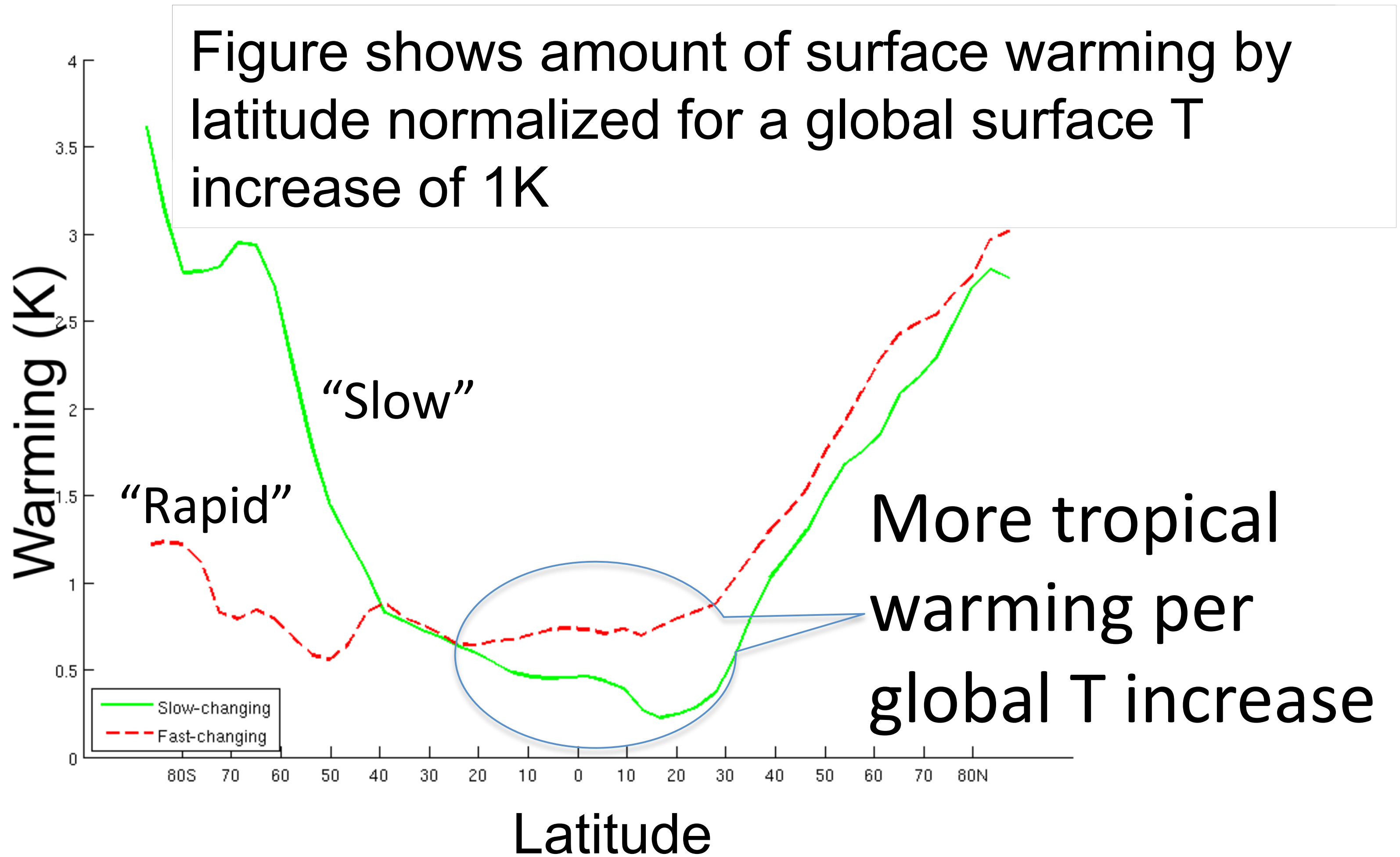
Figure shows amount of surface warming by latitude normalized for a global surface T increase of 1K



S. Ocean thermal inertia

Slow CO2 increases → symmetric warming

Rapid CO2 increases → N.H. warms more



Consider a hypothetical 3-box model of warming patterns

- Assume most water vapor is in tropics due to warmest temperatures there
  - Water vapor increases exponentially with T
- Assume warming pattern in 3 equal-area boxes:

	S. H.	Tropics	N. H.
Rapid	0	1	1
Slow	1	0	1

- “Slow” has less global d(lnq)/dT than “rapid” case

Real 3-box model numbers, where each box has equal area, support interpretation

- For 1 degree global temperature change:

	S. H.	Tropics	N. H.
Rapid	0.75	0.71	1.5
Slow	1.4	0.42	1.2

Why does global water vapor increase more (% per K global T change) in response to rapid (anthropogenic-like) CO_2 change?

- Most water vapor is in the tropics

  --> amount of tropical warming strongly influences global water vapor change
- Tropics warm more (per unit global T change) if warming is concentrated in one hemisphere
- Therefore, one-hemisphere warming --> larger global water vapor increase (%) per K global warming

Alternative prediction of global water vapor increases:

$$q = q_0 e^{\alpha \delta T} \longrightarrow \iint q \frac{dp}{g} dS = \iint q_0 exp\{\alpha \delta T\} \frac{dp}{g} dS$$

Local mixing ratio increases at Clausius-Clapeyron

Global water vapor

Function of initial water vapor & delta T

$$\delta T = \overline{\delta T} + \delta T'$$

= Mean surface T change + perturbation T change

$$\frac{d ln\left(\iint q \frac{dp}{g} dS\right)}{\overline{\delta T}} = \alpha + \frac{1}{\overline{\delta T}} ln\left(\frac{\iint q_0 exp\{\alpha (\delta T)'\} \frac{dp}{g} dS}{\iint q_0 \frac{dp}{g} dS}\right)$$

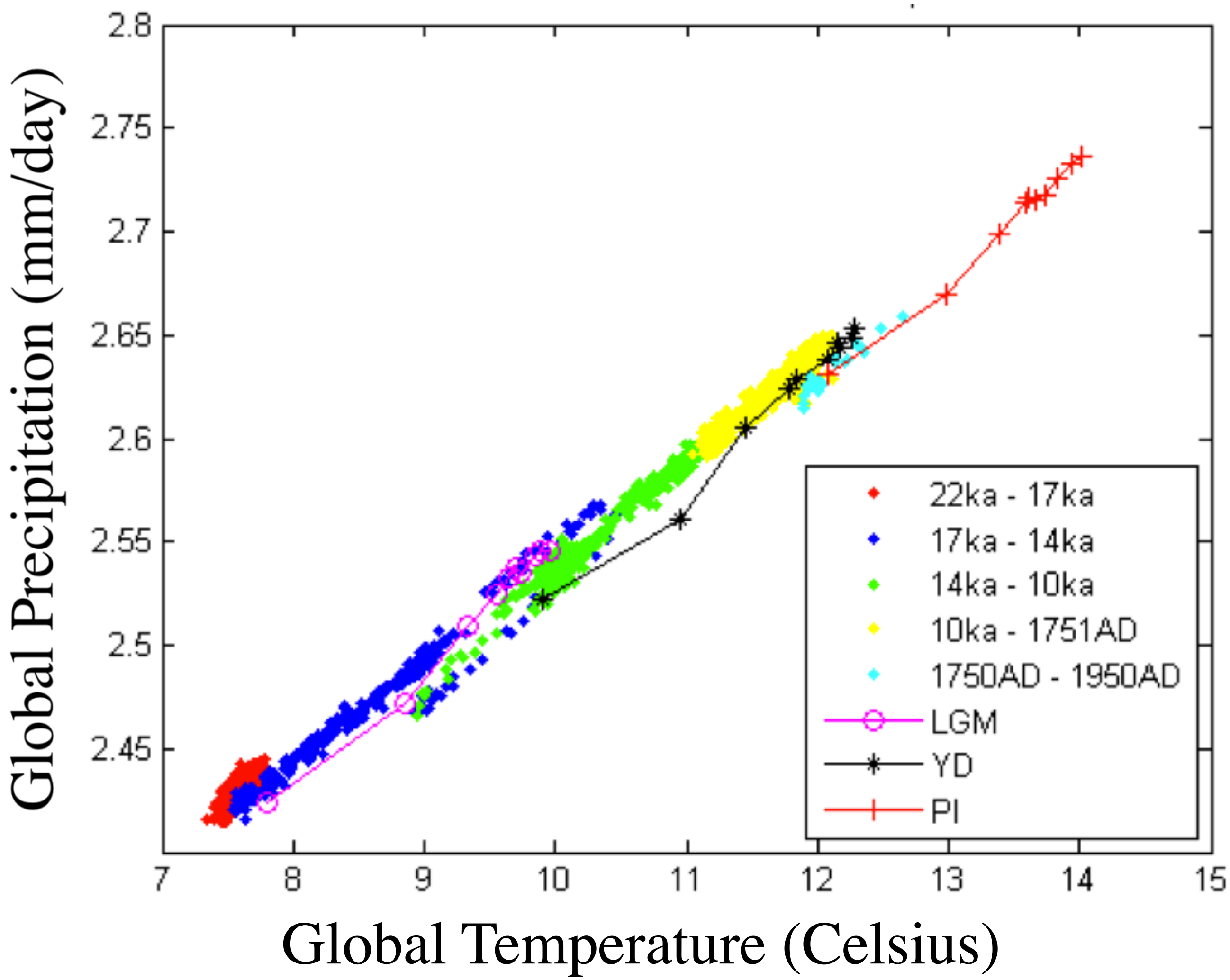
Correction due to inhomogeneous temperature increases

Alternative theoretical prediction of water vapor increases matches simulated increases

$$\frac{d ln\left(\iint q \frac{dp}{g} dS\right)}{\overline{\delta T}} = \alpha + \frac{1}{\overline{\delta T}} ln\left(\frac{\iint q_0 exp\{\alpha(\delta T)'\} \frac{dp}{g} dS}{\iint q_0 \frac{dp}{g} dS}\right)$$

Slow	4.3 %	6.7%	-2.6 %
Rapid	6.2 %	6.6 %	-0.3 %

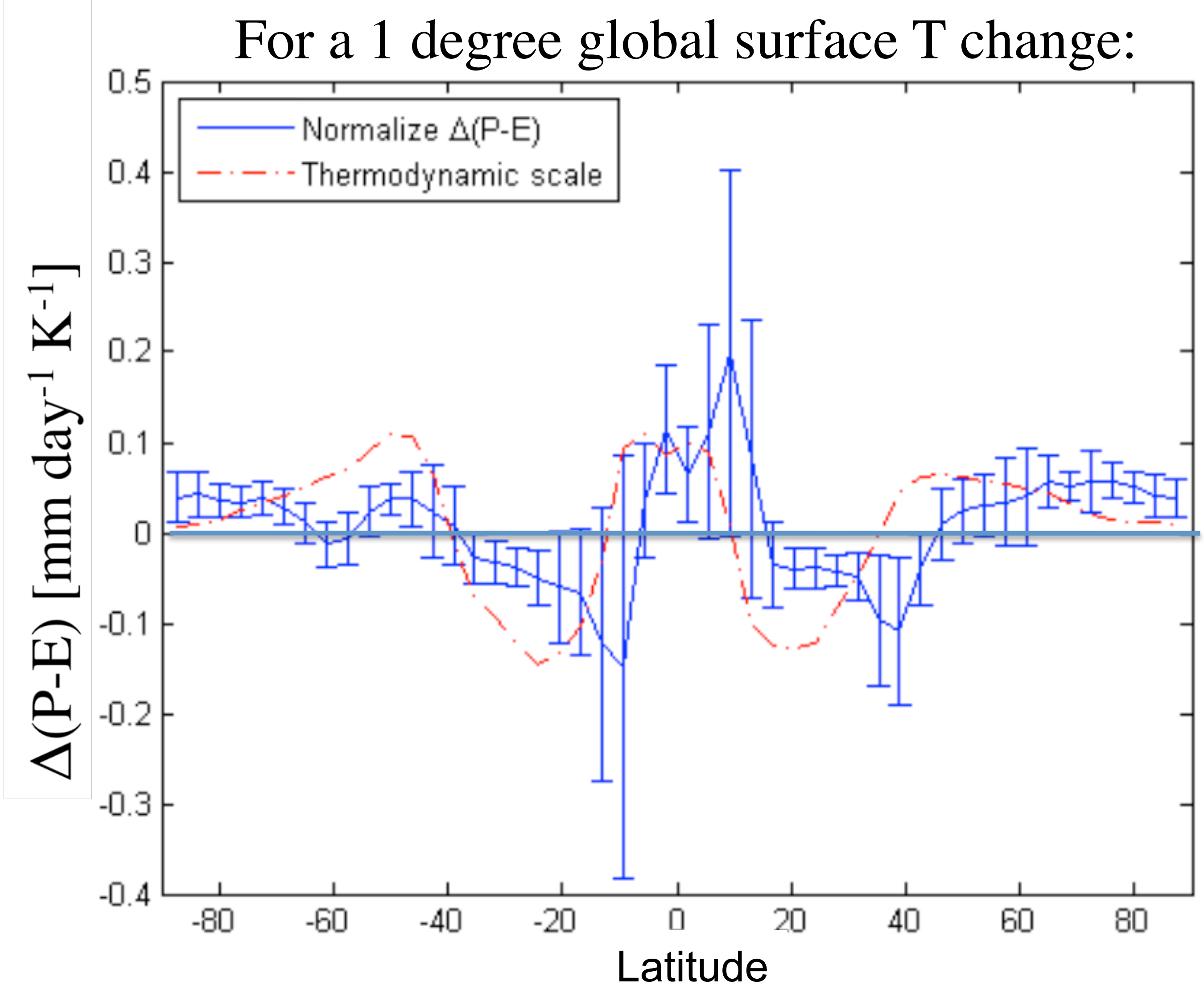
TRACE Paleoclimate results: Global precipitation vs. surface T



"Slow" and "Rapid" cases behave similarly

P increases at 1.9% per unit surface T warming

TRACE paleoclimate warming: Wet [mostly] get wetter & dry [mostly] get drier

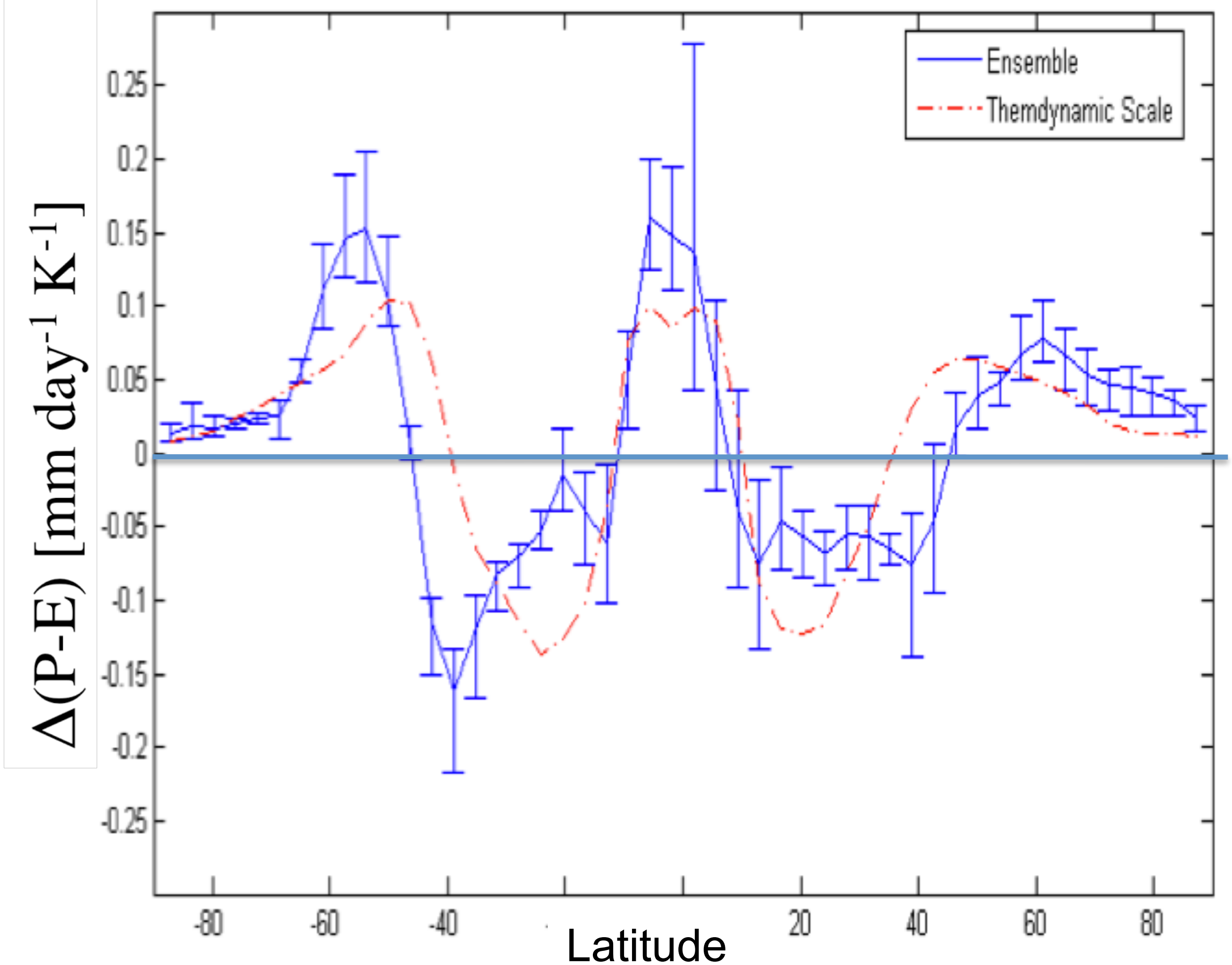


Mean Δ(P-E) and +/- a standard deviation

"thermodynamic" scaling

Rapid CO_2 doubling: Wet [mostly] get wetter & dry [mostly] get drier

For a 1 degree global surface T change:

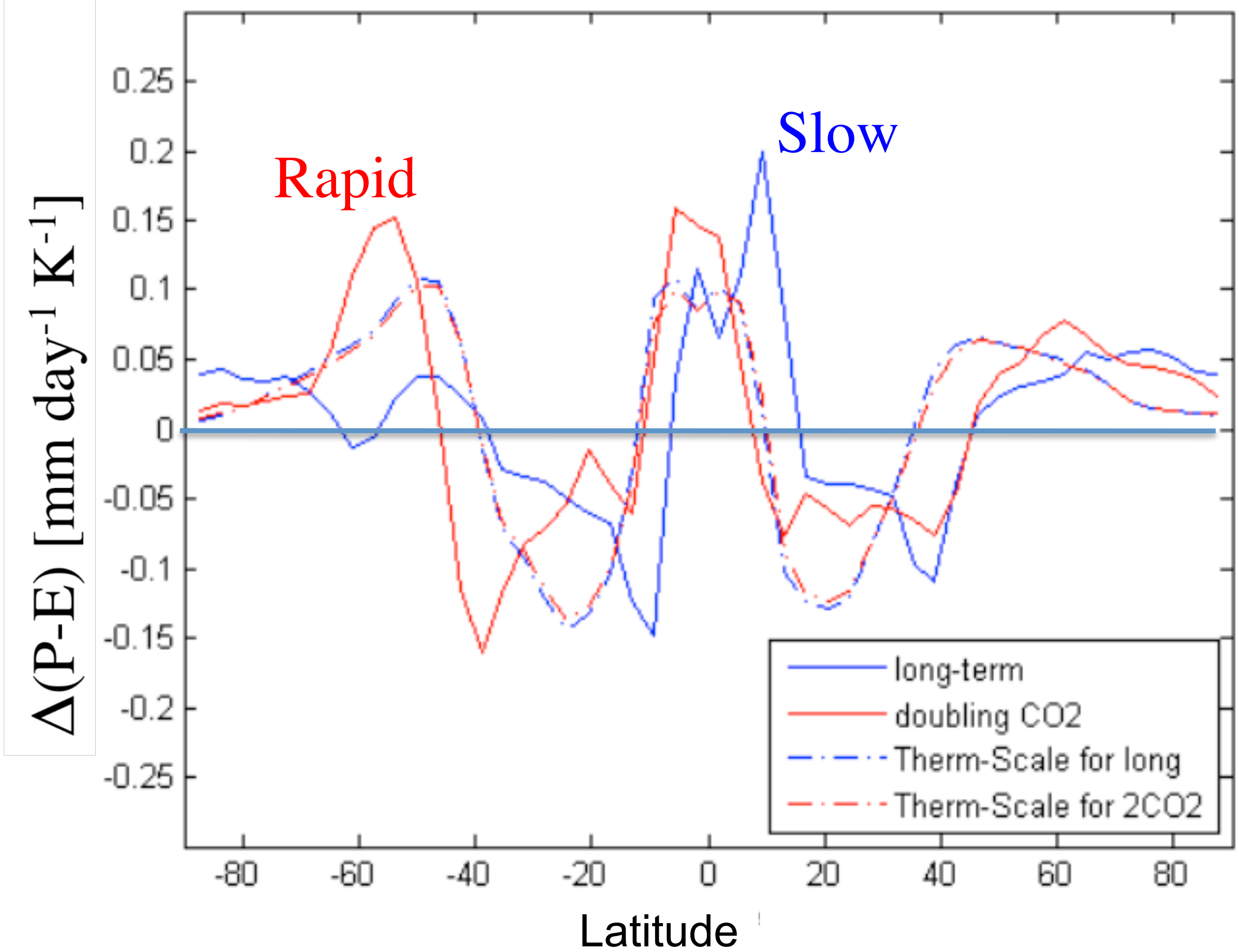


Mean Δ(P-E) and +/- range (for CO2 doubling cases, anthropogenic)

"thermodynamic" scaling

“Rapid” & “Slow” T changes lead to somewhat different precipitation changes

For a 1 degree global surface T change:



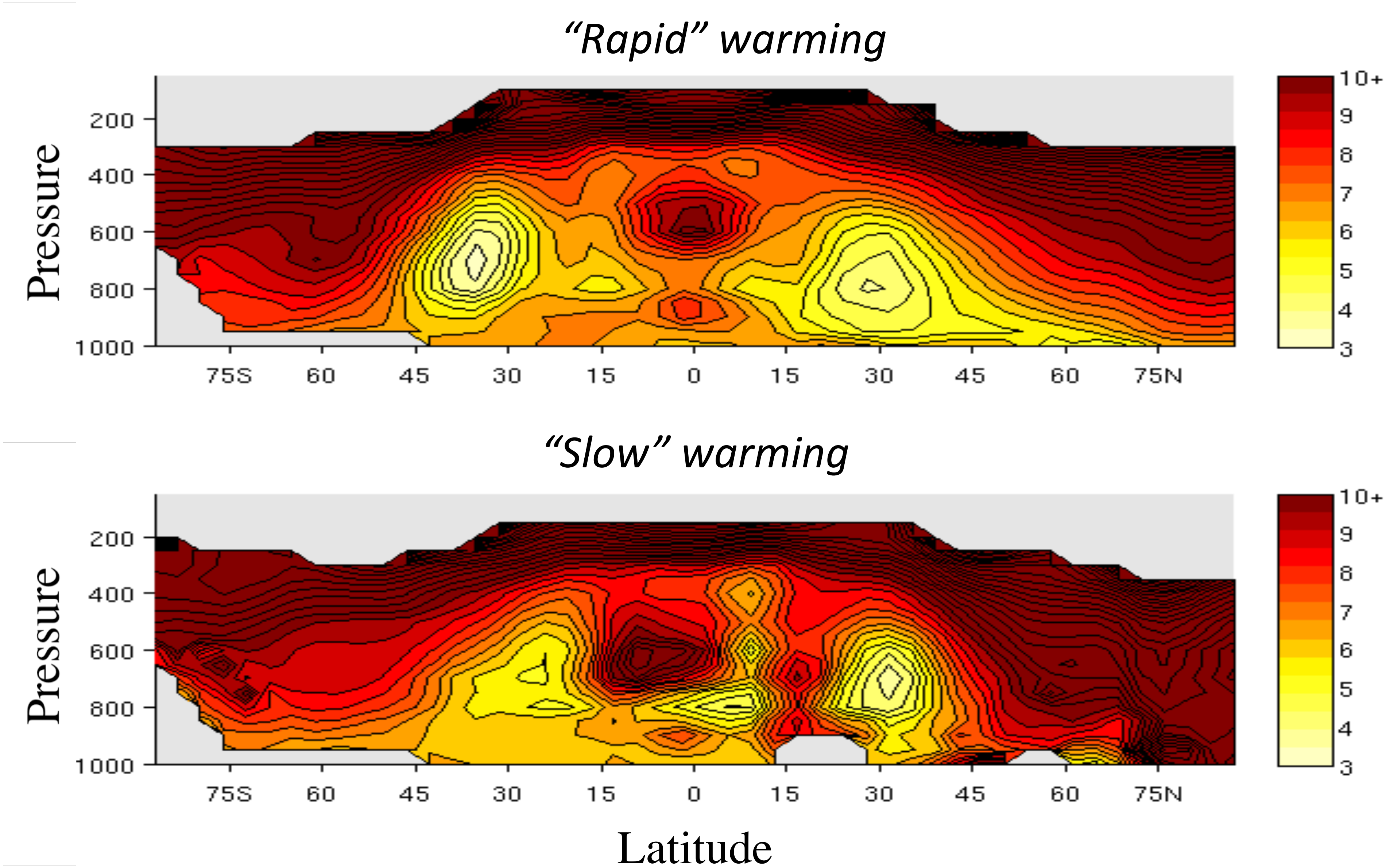
Thermodynamic scaling (dashed lines) is similar for rapid and slow changes.

Modeled changes significantly different

Hydrological cycle changes in TRACE paleoclimate (last 22ky) compared to rapid (anthropogenic-like) CO_2-induced changes:

- Global water vapor increases less (per unit warming) in TRACE paleoclimate
  - Longer timescale of S. Ocean adjustment → different spatial pattern of warming for rapid vs. slow warming
  - most q in tropics (Clausius-Clapeyron non-linearity) → global dlnq/dT dependent on tropical warming amount
- Global mean precipitation changes comparable
- Zonal precipitation pattern changes somewhat different due to circulation pattern changes

“Local” d(ln q)/dT by latitude and height



"Local" temperature change patterns: