Tropical Response to Warming: Oceanic and Atmospheric Feedbacks

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- What is the expected response of the tropical climate system to a warming climate?
  - Weakening of tropical circulation.
  - Ocean Feedbacks.
- "El Niño-like" and "La Niña-like" climate change.
- For which response is there observational evidence?

PLEASE INTERRUPT ME WITH QUESTIONS OR COMMENTS.

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Outline

- **Introduction/background**
- Theory
- Modeling
- Observations
- Implications (time permitting)

From IPCC-AR4

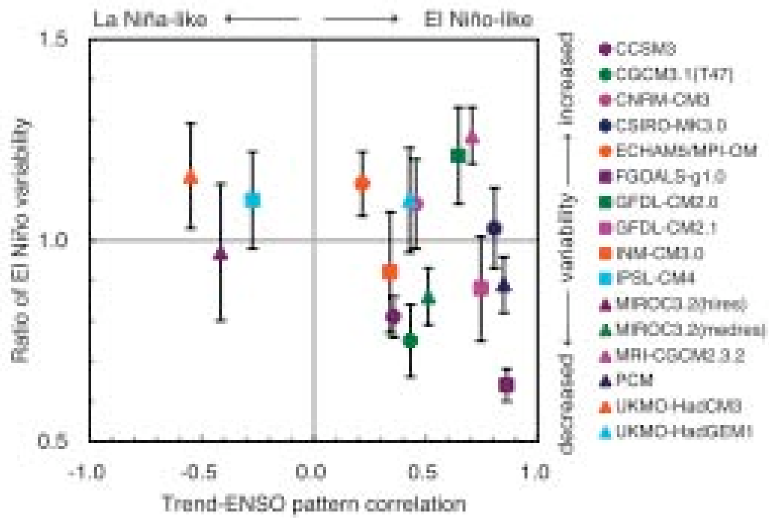


Figure 10.16. *Base state change in average tropical Pacific SSTs and change in El Niño variability simulated by AOGCMs (see Table 8.1 for model details). The base*

"In summary, **the multi-model mean projects a weak shift towards conditions which may be described as 'El Niño-like'**, with SSTs in the central and eastern equatorial Pacific warming more than those in the west, and with an eastward shift in mean precipitation, associated with weaker tropical circulations."

IPCC-AR4 (2007), WG-I, Section 9.3.5.3

Broader Objective

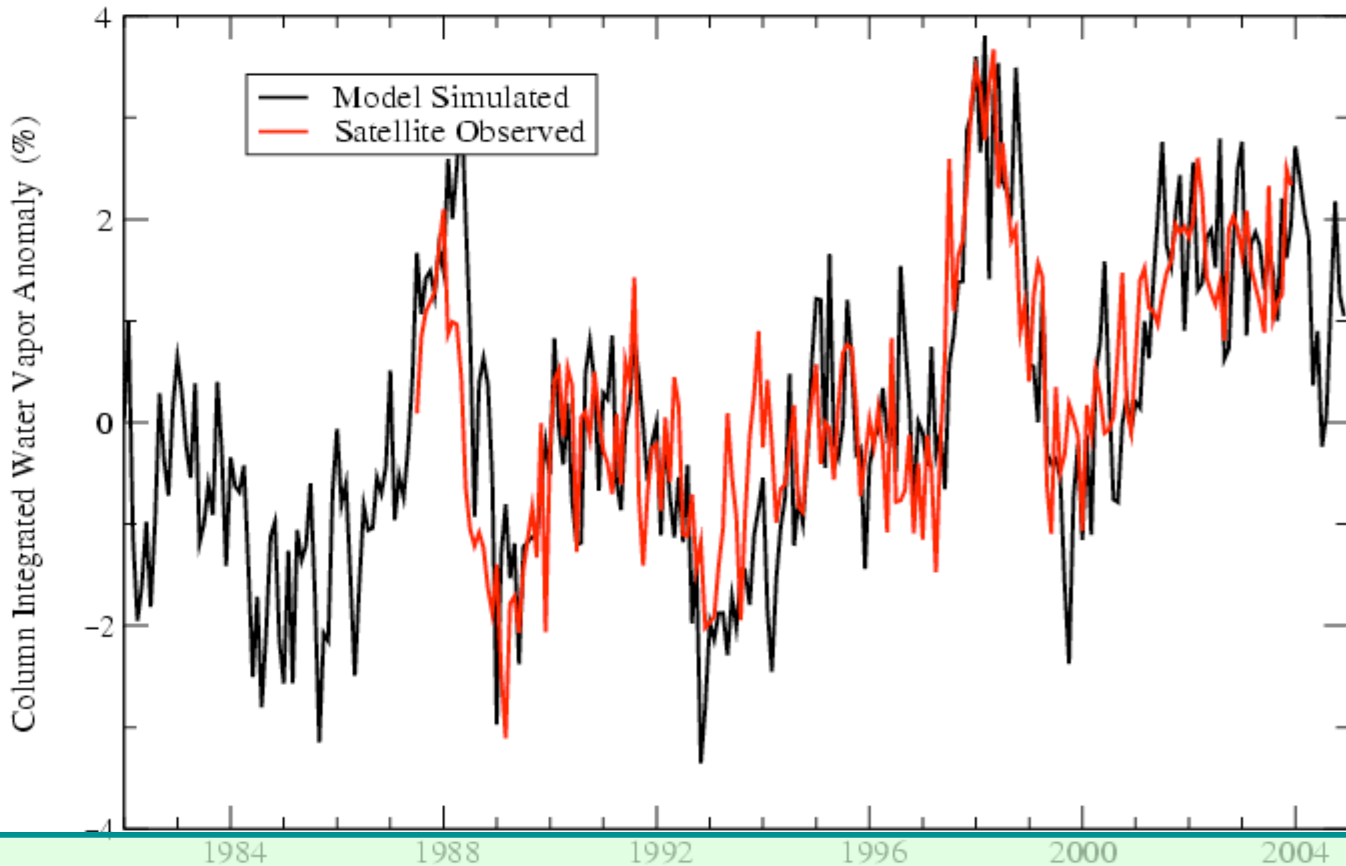
1) Identify those aspects of tropical climate change that are:

- Consistent across a large number of models

- Are supported by simple physical arguments

2) Motivate observational studies to determine whether these responses are currently detectable.

Many of these robust features are related directly or indirectly to changes in lower tropospheric water.



Total Column Water Vapor Anomalies (1987-2004)

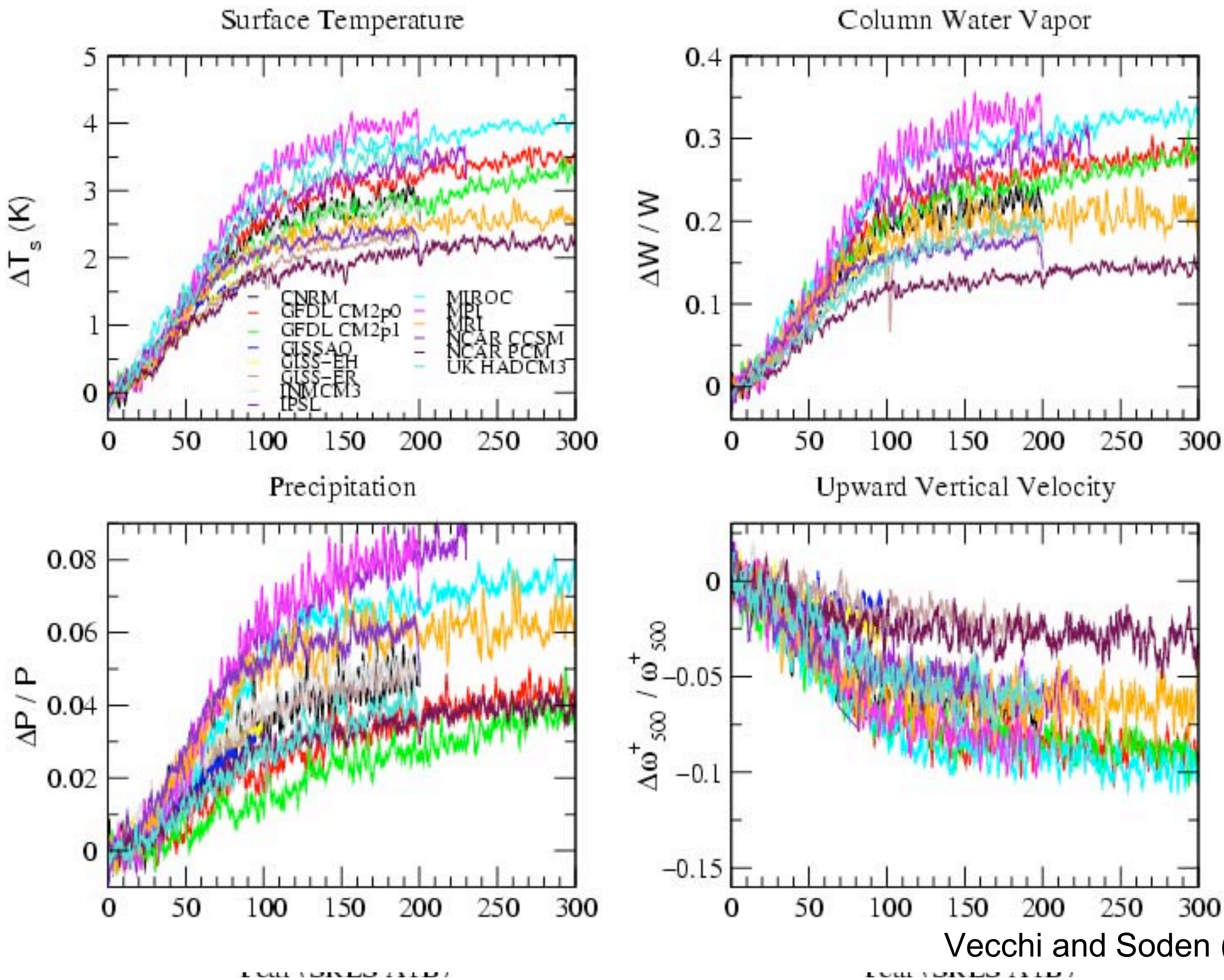
Held and Soden (2006, J. Clim)

Robust Responses to Global Warming

These robust responses include (e.g. Held and Soden 2006, JClim):

- A decrease in convective mass flux
  (atmospheric circulation weakens)
- A increase in horizontal moisture transport
- An enhancement of the pattern of P-E
  (wet regions become wetter, dry regions become drier)
- An enhancement of the variance of P-E
  (more droughts and floods)
- A decrease in the horizontal sensible heat transport in the extratropics.

Tropical Response of IPCC-AR4 Models - SRESA1B (720ppm CO_2 Stabilization)



Vecchi and Soden (2007, J. Clim.)

Outline

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    - Oceanic constraint
    - Atmospheric constraint
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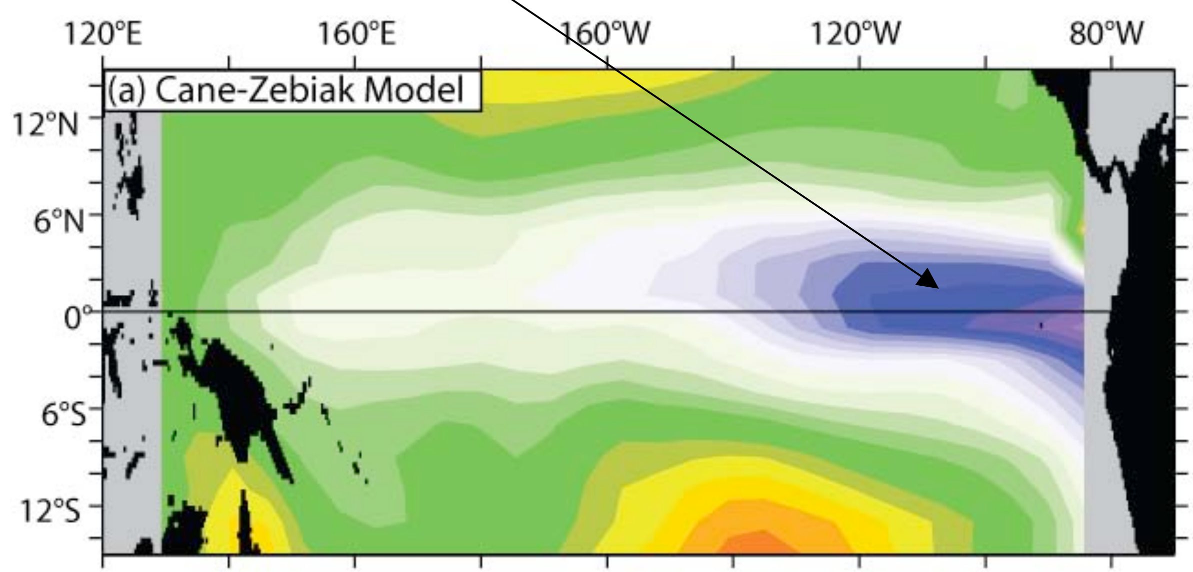
Ocean Dynamical Thermostat

Clement et al (1996, J. Clim.), Cane et al (1997, Science), Seager and Murtugudde (1999)

- In warming world, tropical ocean thermal stratification increases.
- Thus, upwelling zones warm more slowly than rest - upwell (c)older water.
- Coupled (Bjerkes) feedbacks.
- “La Niña-like” response.



Response of “Cane-Zebiak” model to global warming (Adapted from Clement et al 1996).

Simplified view of atmospheric water/energy balance

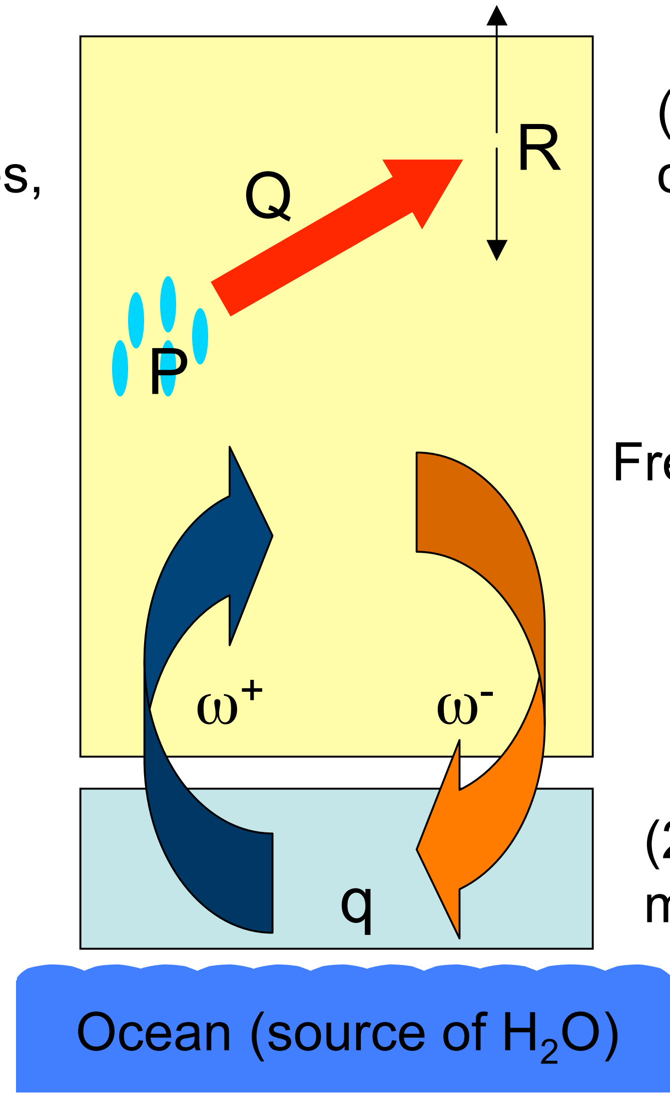
$$R \propto P = q \cdot \omega^+ \longrightarrow dR/R = dP/P = dq/q + d\omega^+/\omega^+$$

(4) Moist air condenses, heats troposphere, and precipitates.

$$Q = L_v * P$$
$$P = q * \omega^+$$

(3) Circulation: moist air rises, dry air descends

$$H_2O\text{-Flux-up} = q \cdot \omega^+$$



(1) Heated: evaporates/stores

(5) Energy released from condensation radiates.

$$R = Q$$

Free troposphere

(2) Boundary Layer: moist from evaporation

$$q = rh \cdot q_s$$

Thermodynamic constraint on circulation: response in warming climate

See: Betts and Ridgway (1989, JAS), Knutson and Manabe (1995, JCli)
Held and Soden (2006, JCli)

$$\mathbf{R \propto P = q \cdot \omega^+ \longrightarrow dR/R = dP/P = dq/q + d\omega^+/\omega^+}$$

- Assume small change in *rh*
  - Thus, *q* increases like Claussius-Clapeyron (~7% per K)

- Water flux constrained by precipitation
- Precipitation constrained by radiation
  - Radiation changes more slowly than C.-C.
- **Since dP/P < dq/q, circulation (ω^+) must weaken.**

- Walker Circulation weakens? “El Niño-like”?

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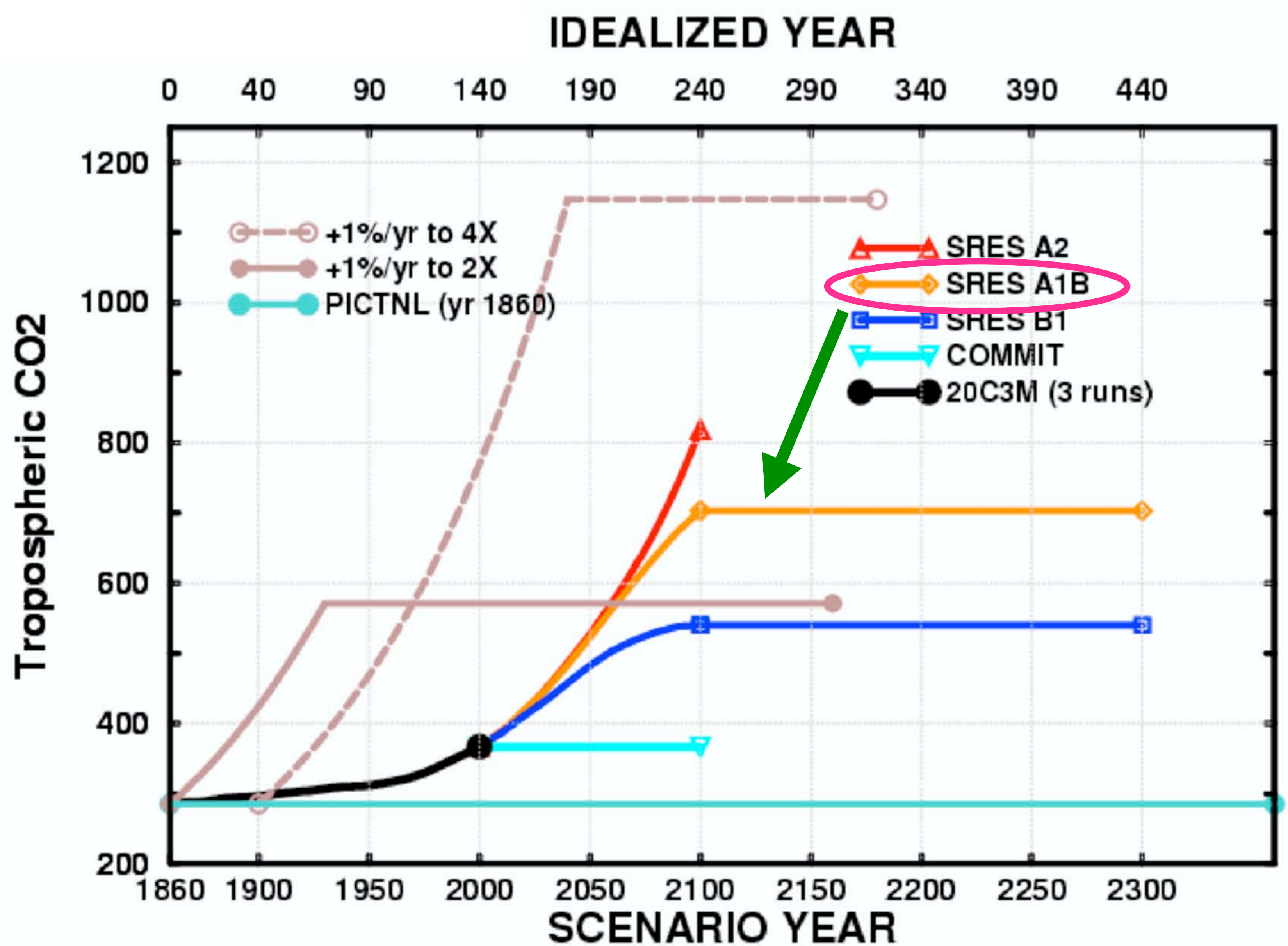
- **Numerical Modeling**
  explore IPCC-AR4/CMIP3 model database.
- Observations
- Implications

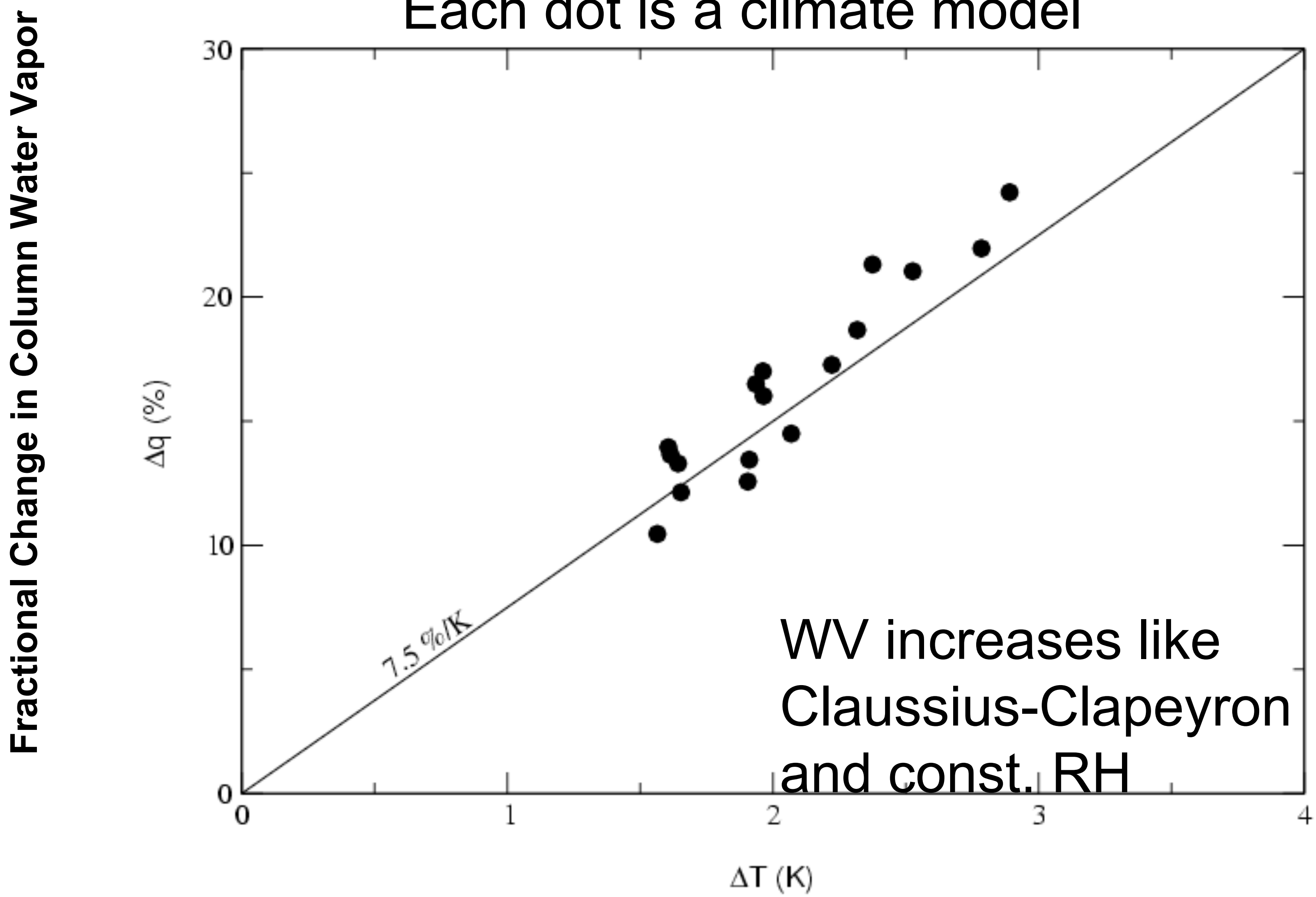
Idealized greenhouse warming experiments



Atmospheric Constraint on Tropical Circulation

Change in Global Water Vapor at 2100

Each dot is a climate model

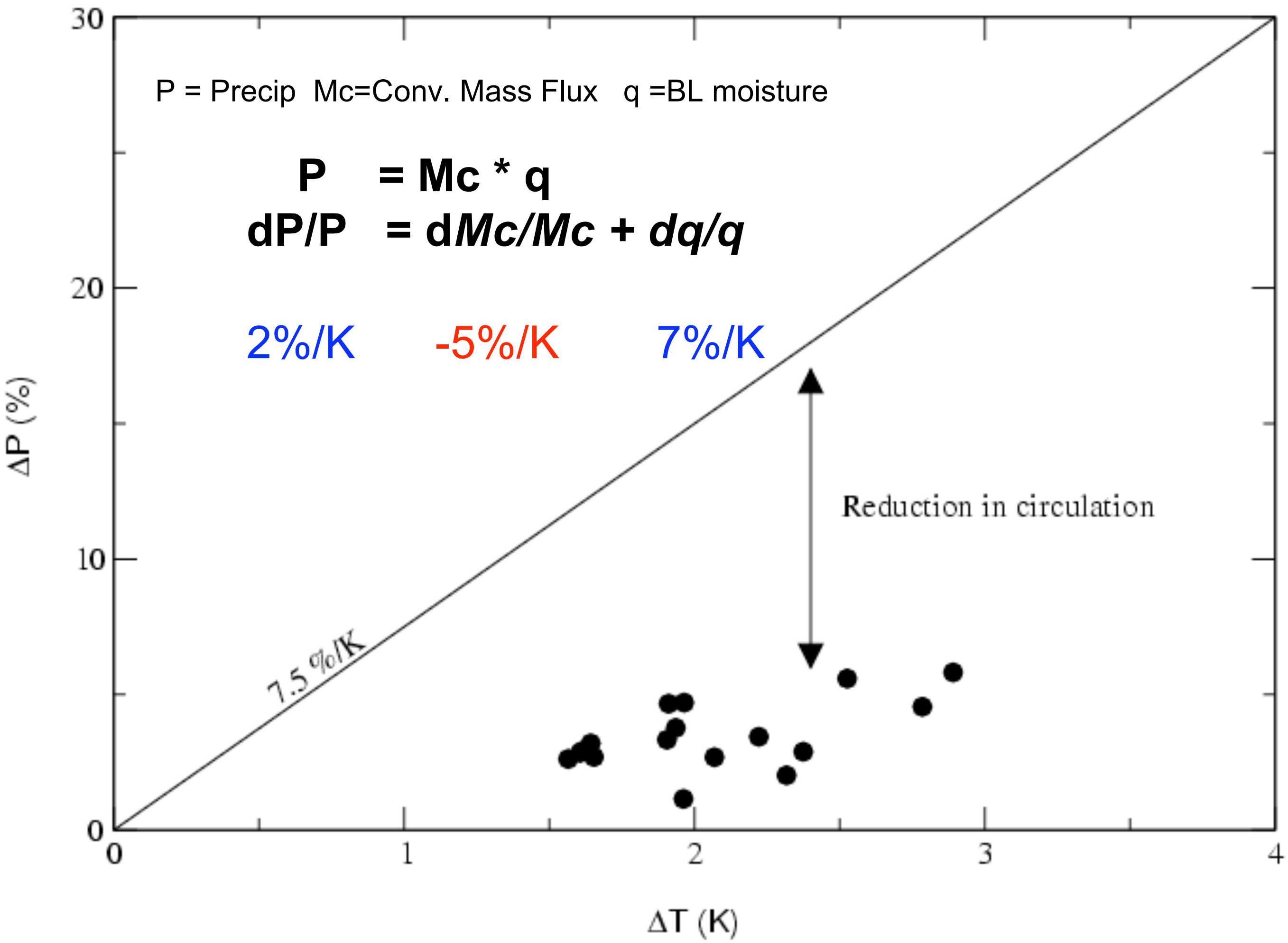


Held and Soden (2006, J. Clim)

Atmospheric Constraint on Tropical Circulation

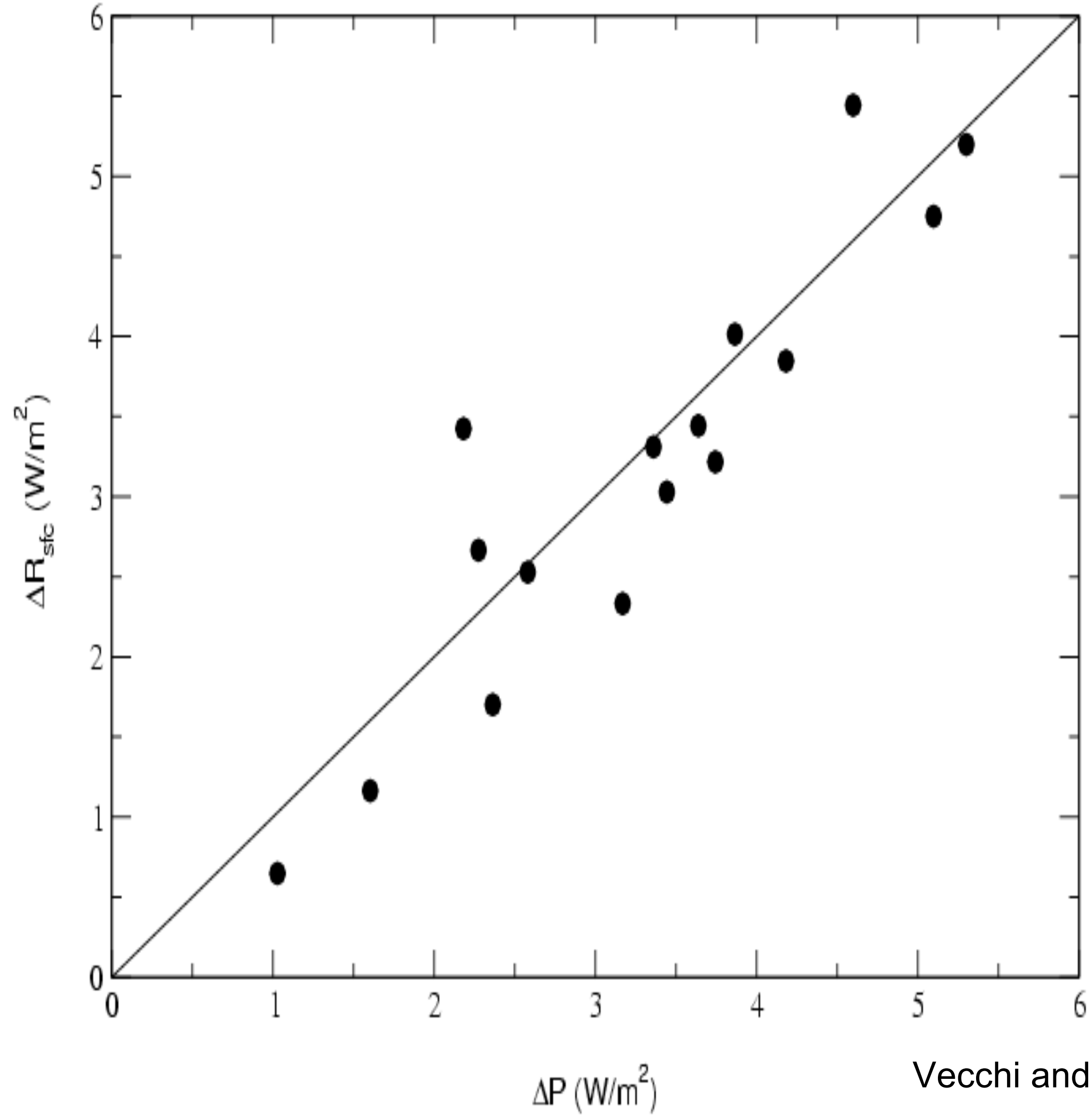
Change in Global Precipitation at 2100

Fractional Change in Precipitation



Held and Soden 2006, J. Clim.,
similar arguments: Betts and Ridgway 1989, Knutson and Manabe 1995

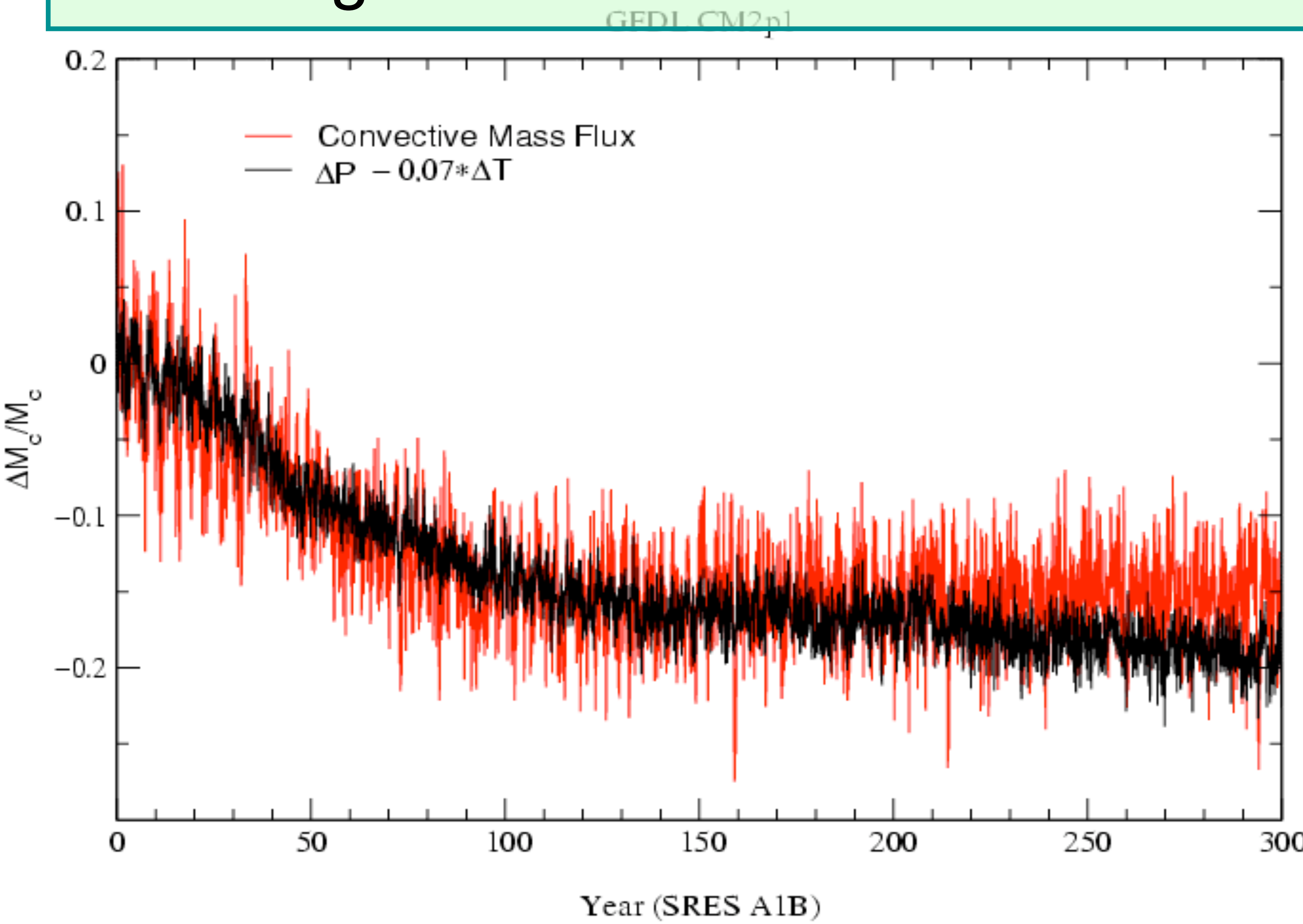
Global precipitation scales with surface radiative imbalance



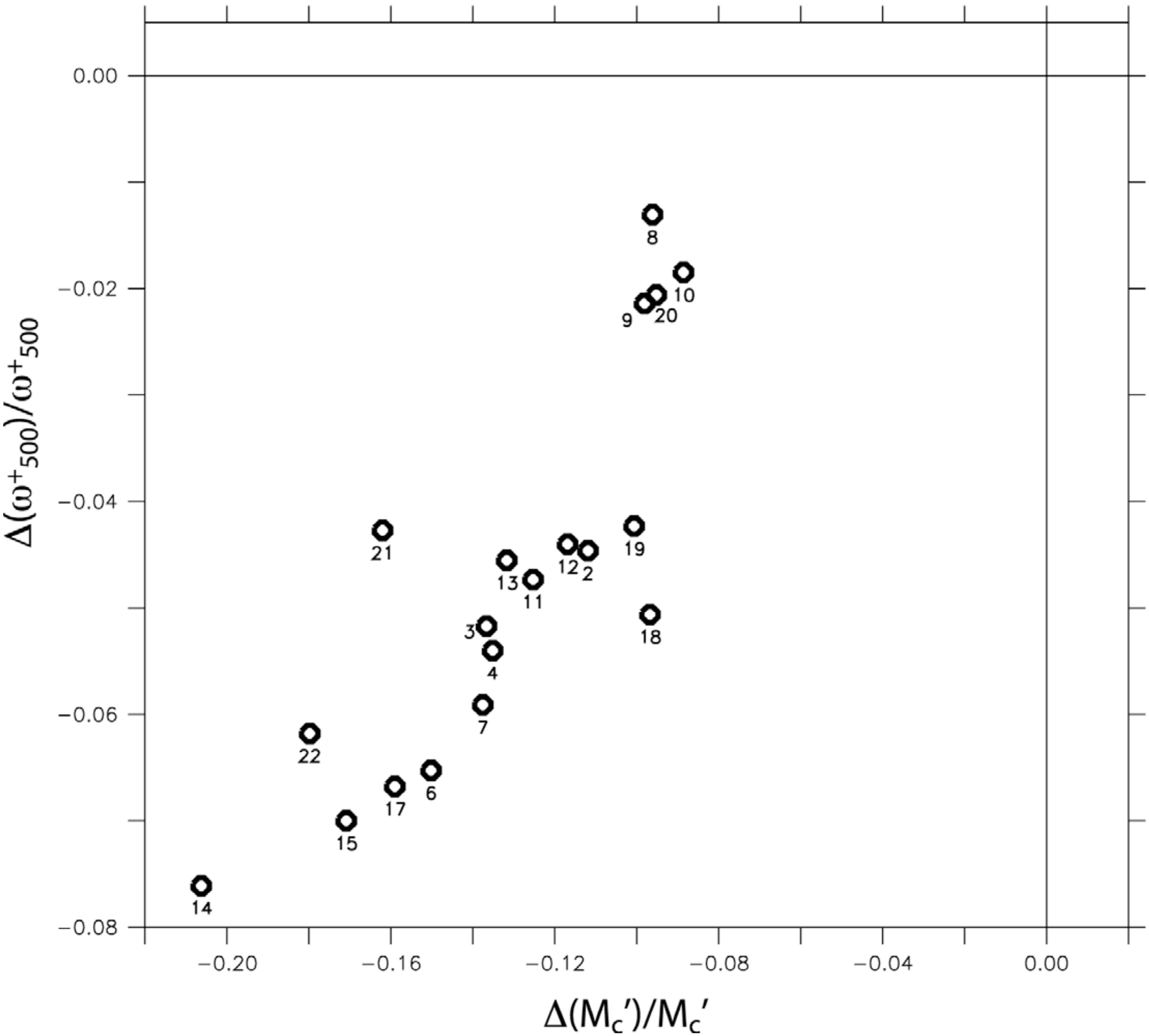
Vecchi and Soden (2007), J.Clim.

IPCC AR4 Model Global Response to SRESA1B (720 ppm CO_2)

In GFDL CM2.1, convective mass flux changes track theoretical estimate.

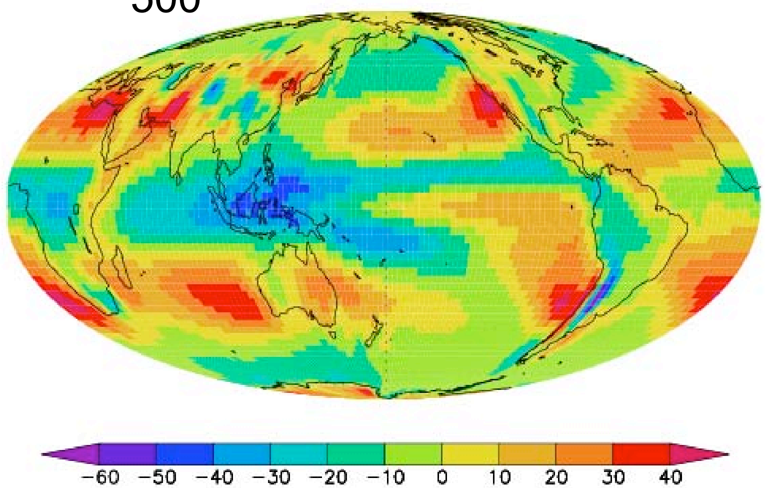


Upward 500 hPa ω vs. estimated convective mass flux

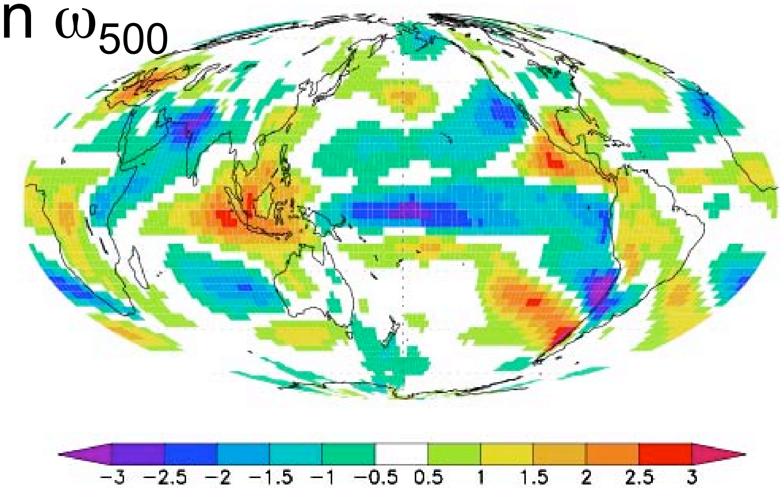


Spatial Structure of Weakened Circulation (multi-model ensemble mean)

Background ω_{500}



Change in ω_{500}



Changes in vertical velocity oppose mean state (except Central Pacific)

Weakening occurs primarily as a reduction in the Walker Cell, not Hadley Cell.

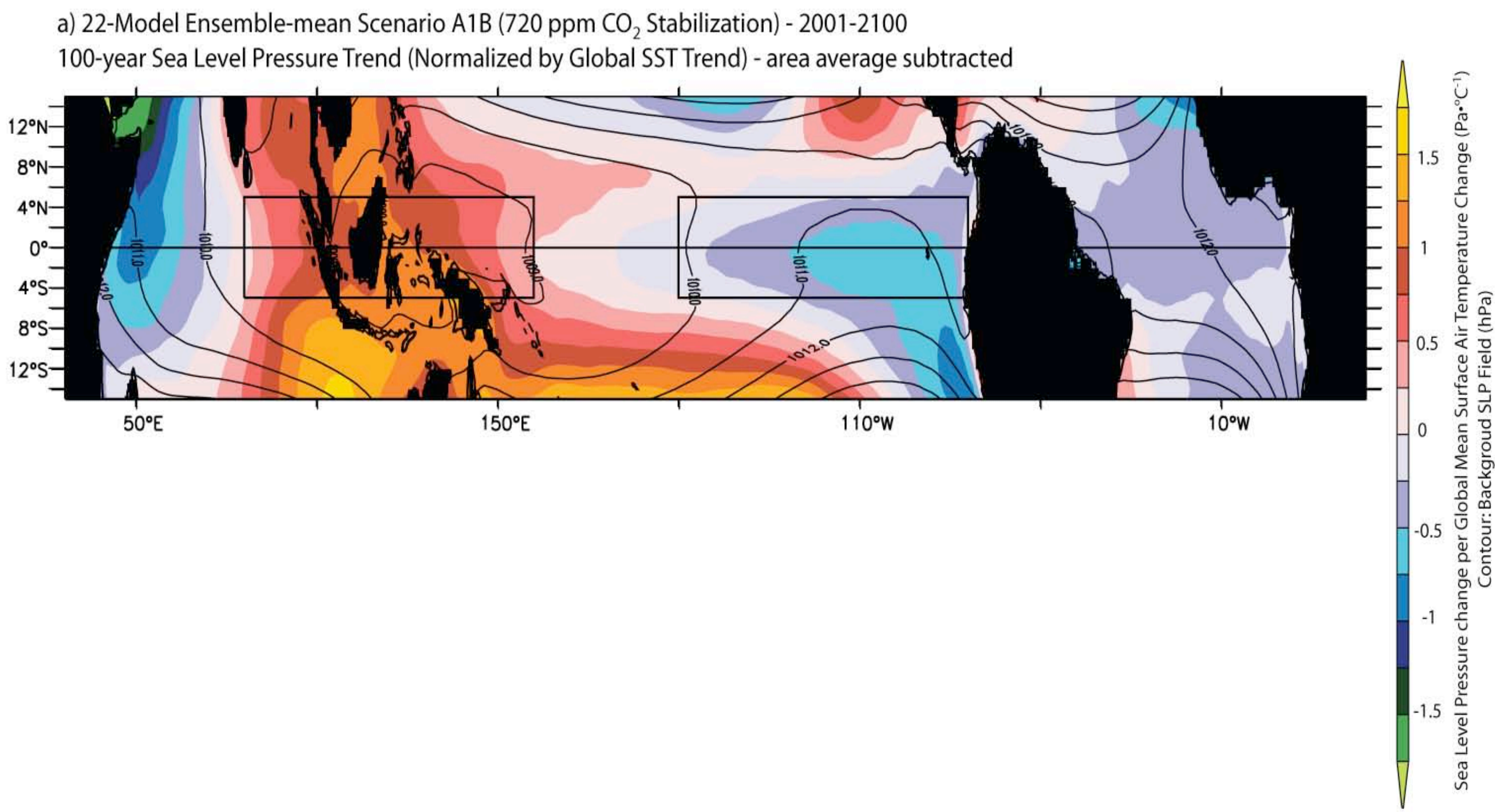
Some "El Niño-like" patterns:
- **Eastward shift of precipitation**
- **Reduction in SST gradient**
- **Reduction in thermocline tilt**

Not "El Niño-like":
- **Ocean changes oppose it**
- **Pacific thermocline shoals**
- **Teleconnections not "El Niño-like" (Lu et al. 2007, 2008; Seager et al. 2007…)**

Vecchi and Soden (2007, J. Clim.)

Near-equatorial Indo-Pacific Zonal SLP gradients decrease

Full ocean GCMs

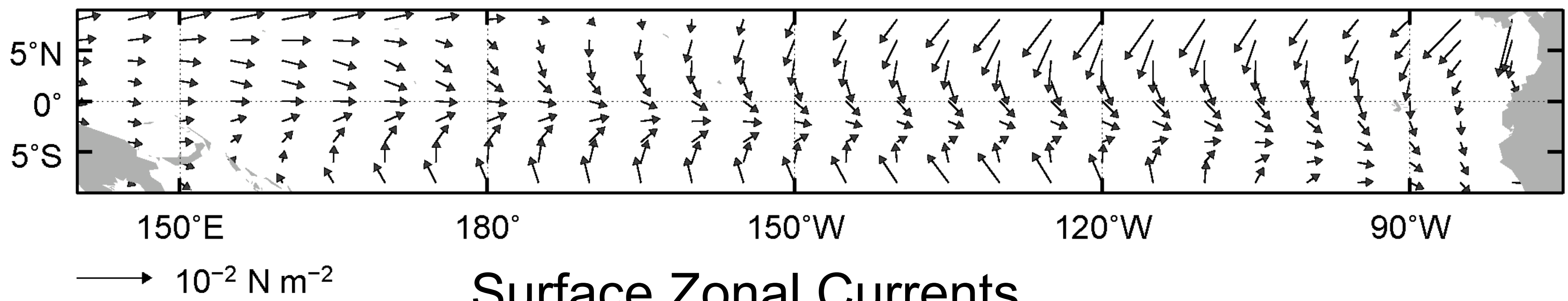


Vecchi and Soden (2007, J. Clim.)

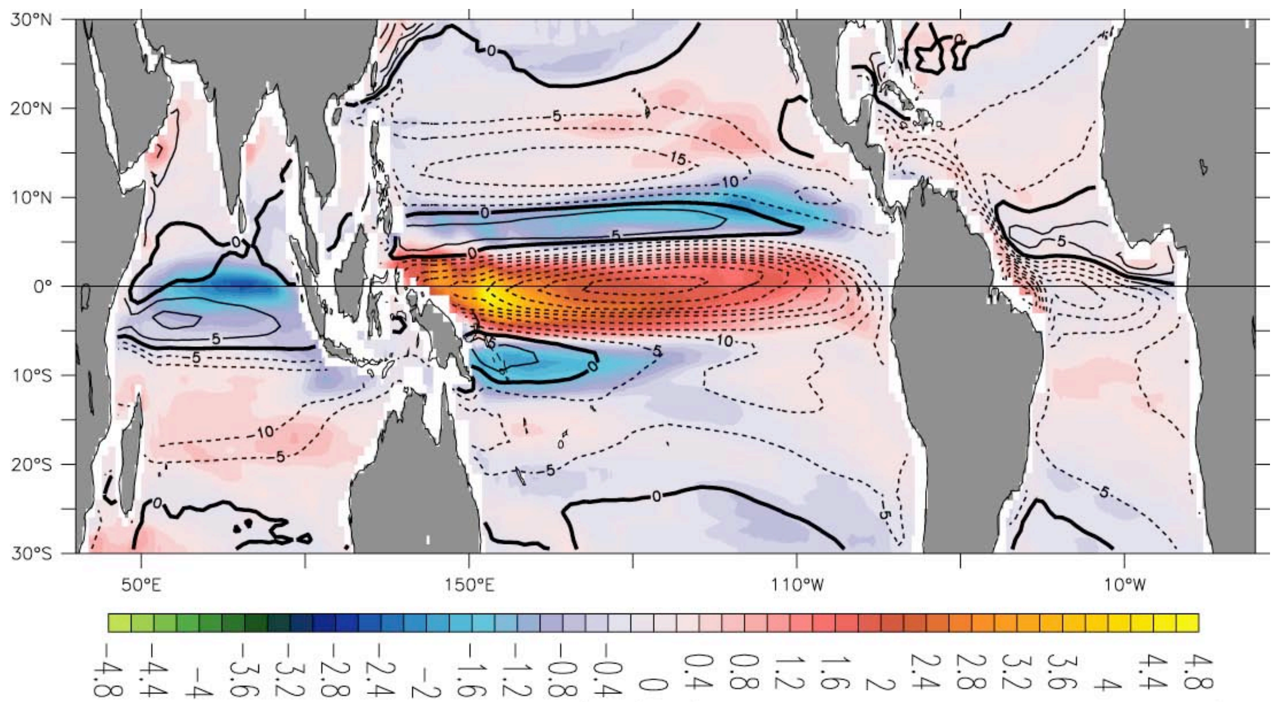
Wind Stress and Currents

Stress

DiNezio et al (2009, J. Clim.)



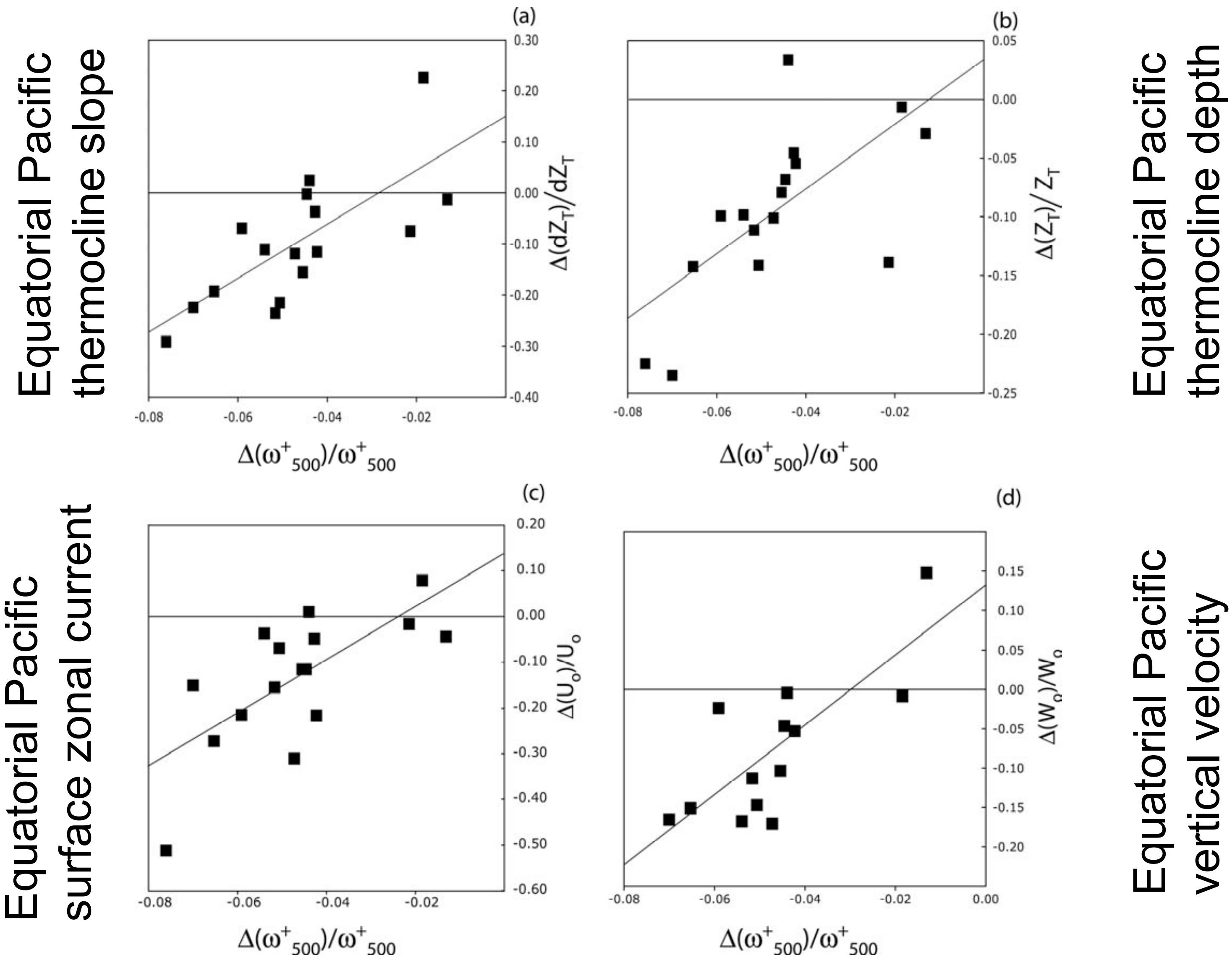
Surface Zonal Currents



Shade: 2001-2100 trend (10^{-4} m s^{-1} yr^{-1} °C^{-1}) - Contour, 2001-2020 Average (cm s^{-1})

Vecchi and Soden (2007, J. Clim.)

Many projected tropical ocean changes scale with slowing atmospheric circulation.



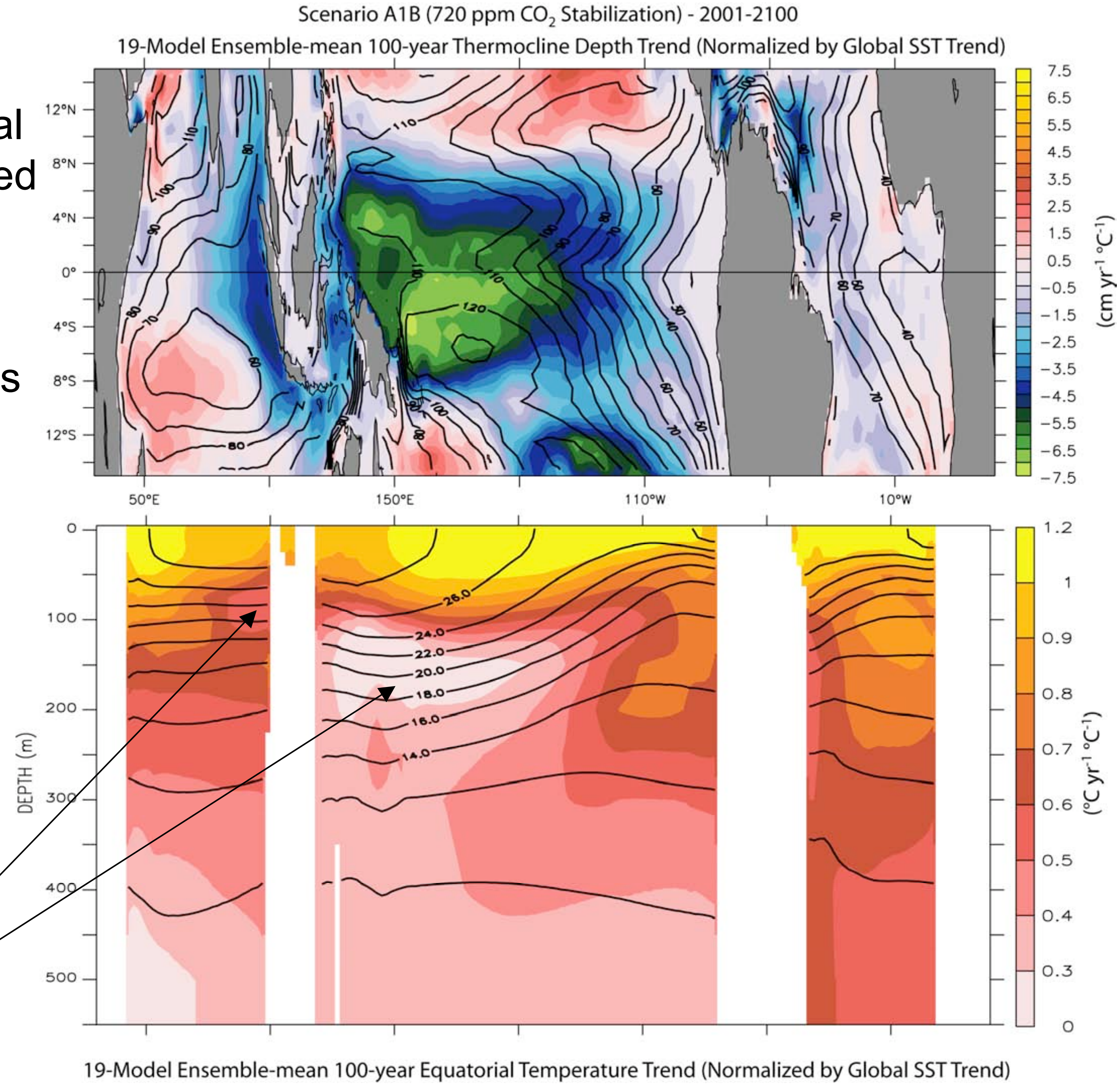
Ensemble-mean response of tropical thermocline (defined as maximum of dT/dz).

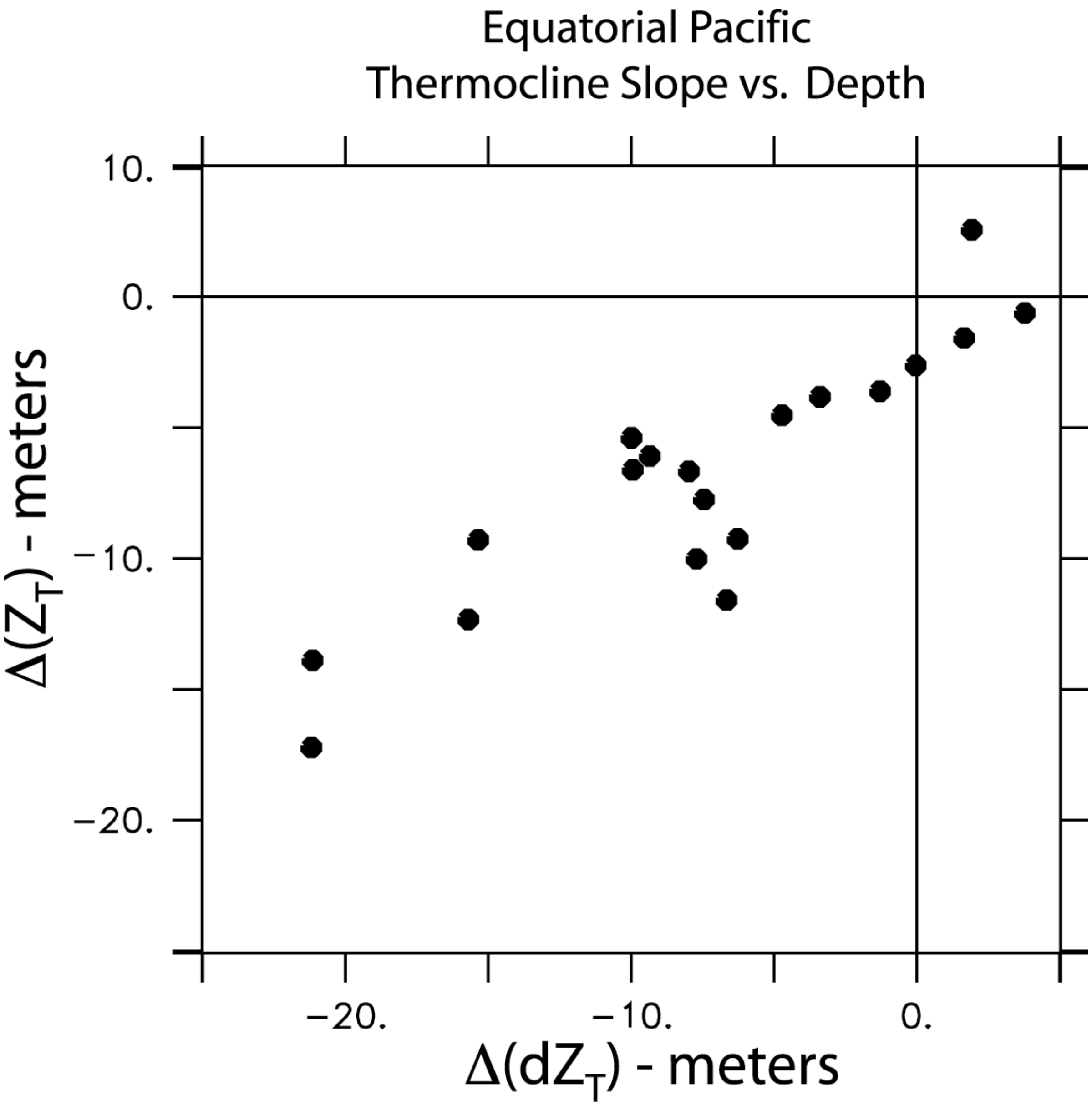
Equatorial Pacific thermocline flattens and shoals.

Ensemble-mean response of equatorial subsurface temperatures.

Increased thermal stratification.

Minimum in warming





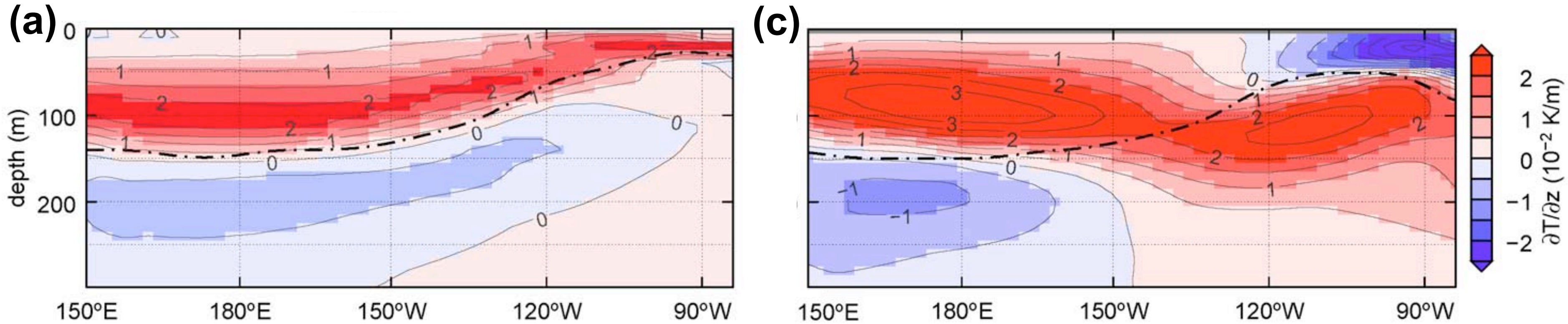
Changes in thermocline depth scale with changes in thermocline slope.

Bjerknes feedbacks not effective on long timescales. (reason El Niño events don't last forever)

T(z): ENSO vs. GW

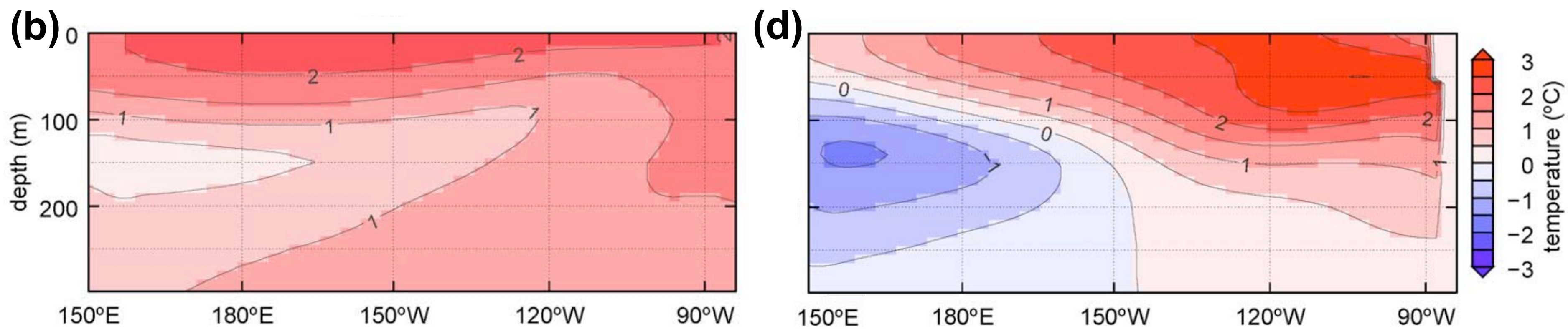
Change in Vertical T Gradient

GW | El Niño



Change in Temperature

GW | El Niño



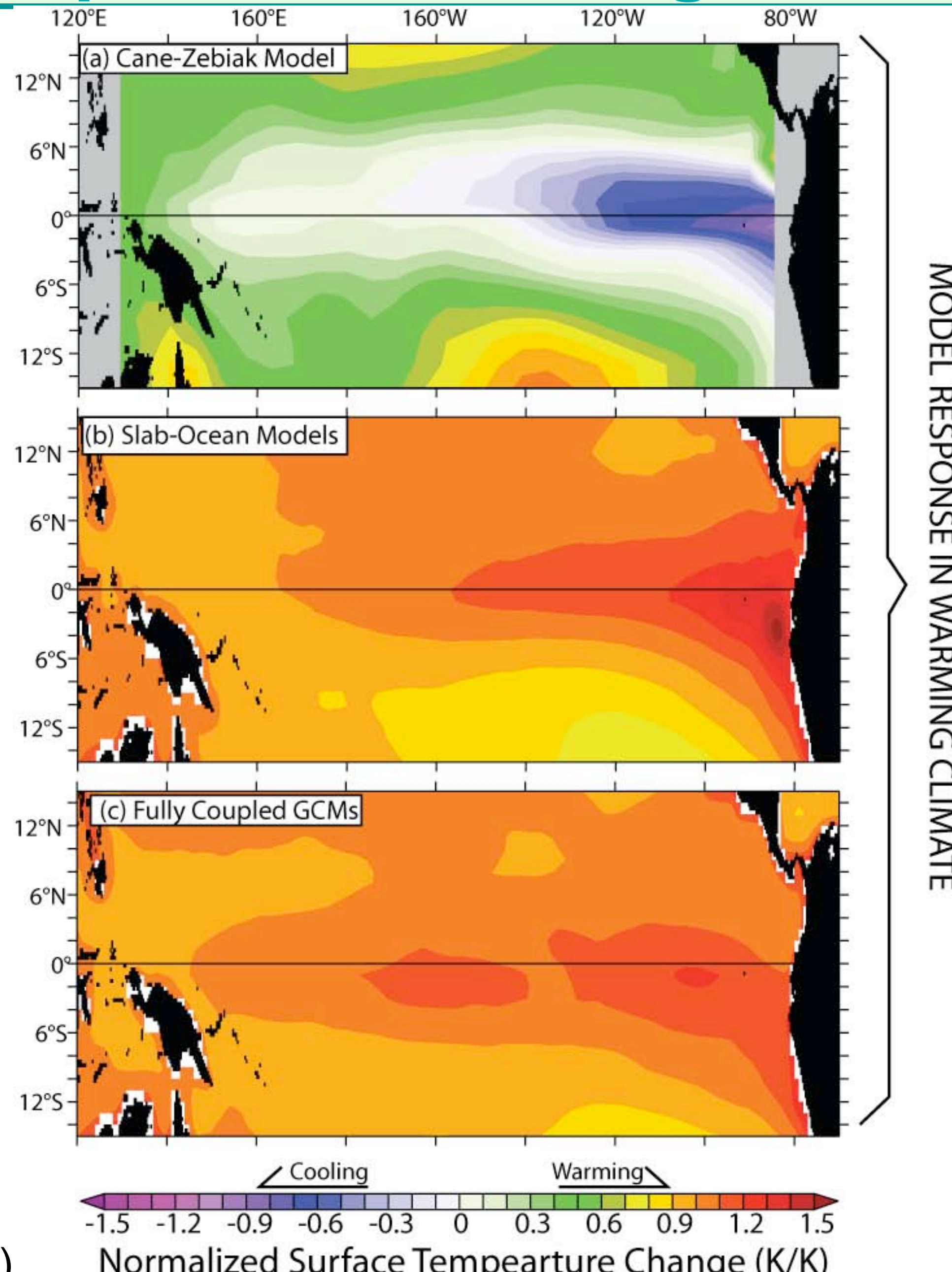
DiNezio et al (2009, J. Clim.)

Modeled SST Response to Heating

Simplified atmosphere
(forced by uniform heating)

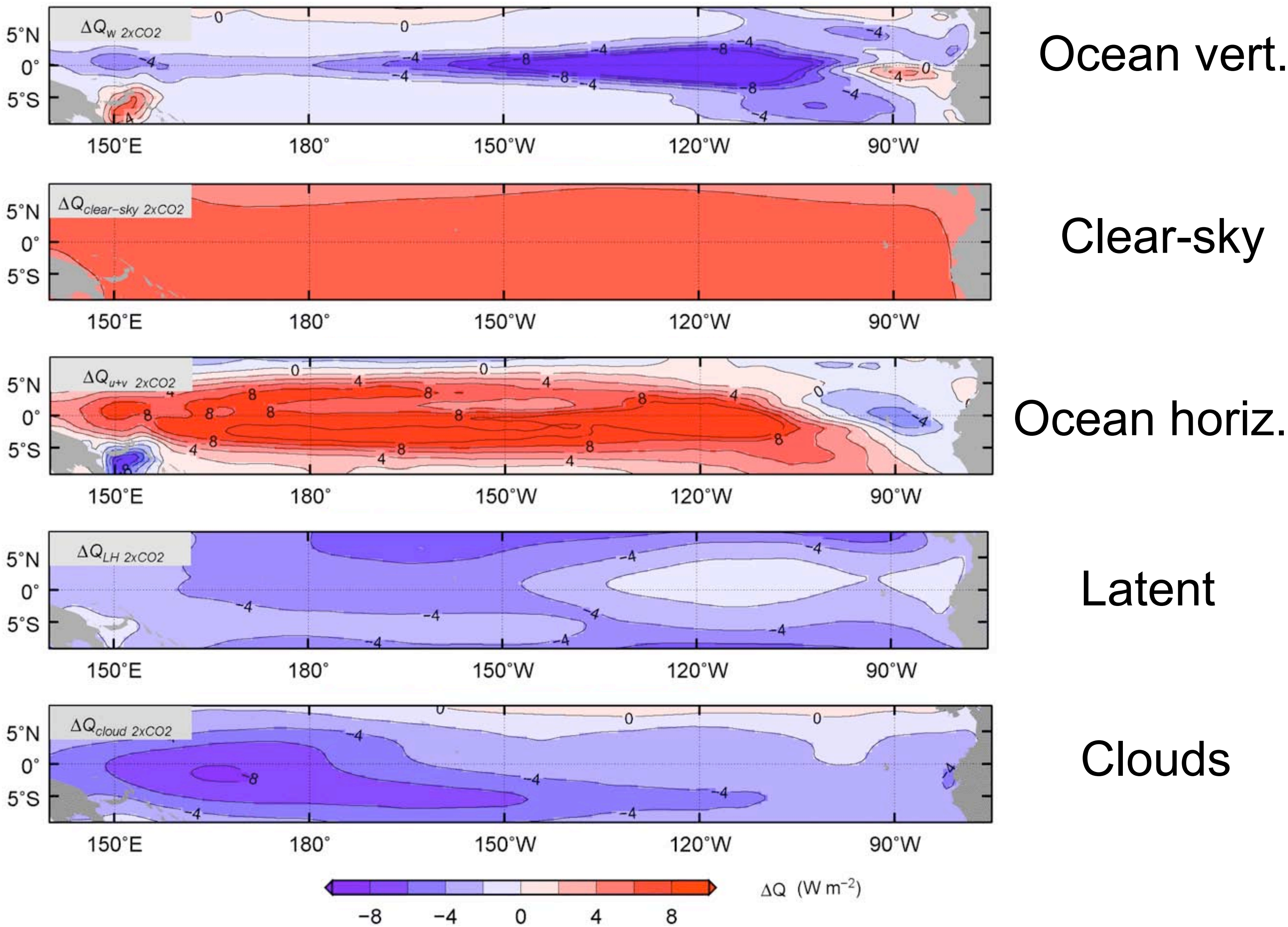
Simplified ('slab') ocean
(13 models, doubled-CO_2)

Full-dynamics GCMs
(13 models, doubled-CO_2)



From Vecchi, Clement and Soden (2008, EOS)

Mixed-layer heat balance in response to GW



DiNezio et al (2009, J. Clim.)

(positive is into the ocean, i.e. heating)

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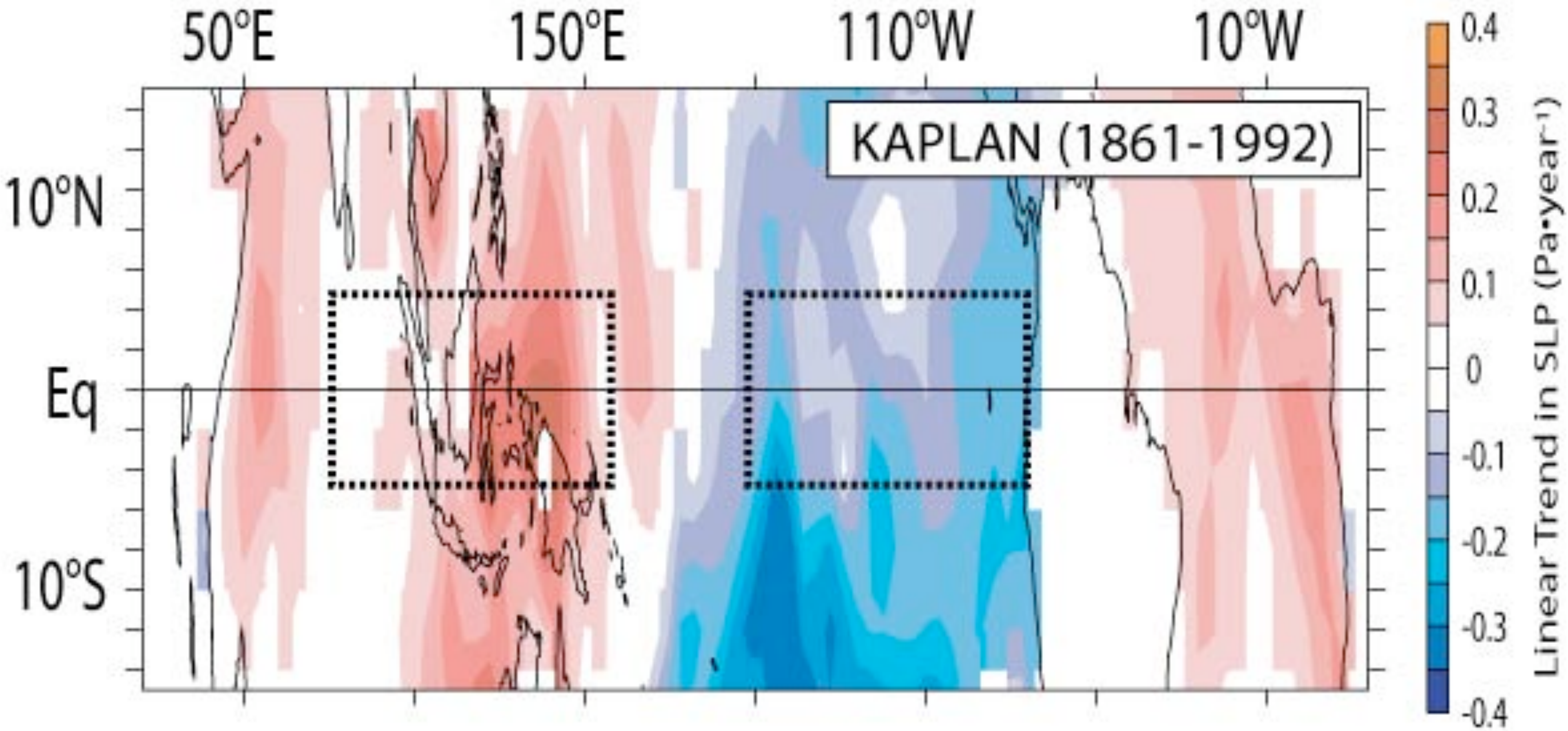
Can the observational evidence distinguish between the two?

- Sea level pressure: suggests Walker circulation weakened.

- Sea surface temperature: Depends on dataset you use.

Linear trend in Kaplan SLP reconstruction



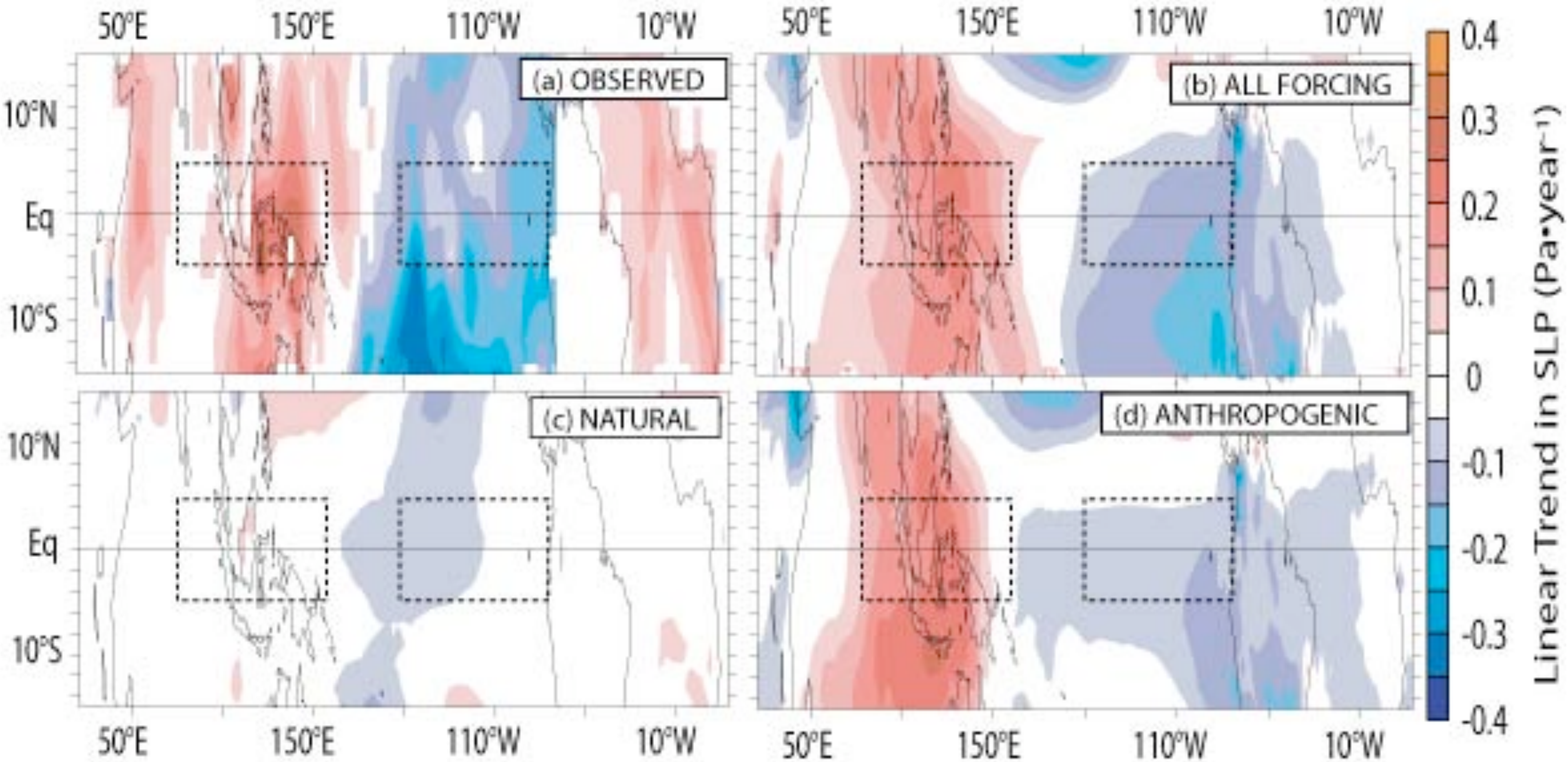
Reduction of E-W SLP gradient across Pacific.

Consistent with weakening of Walker circulation.

Vecchi et al (2006, Nature)

Structure of observed linear trends in SLP recovered with historical forcing and anthropogenic forcing.

Linear trends in SLP weak with natural forcing.

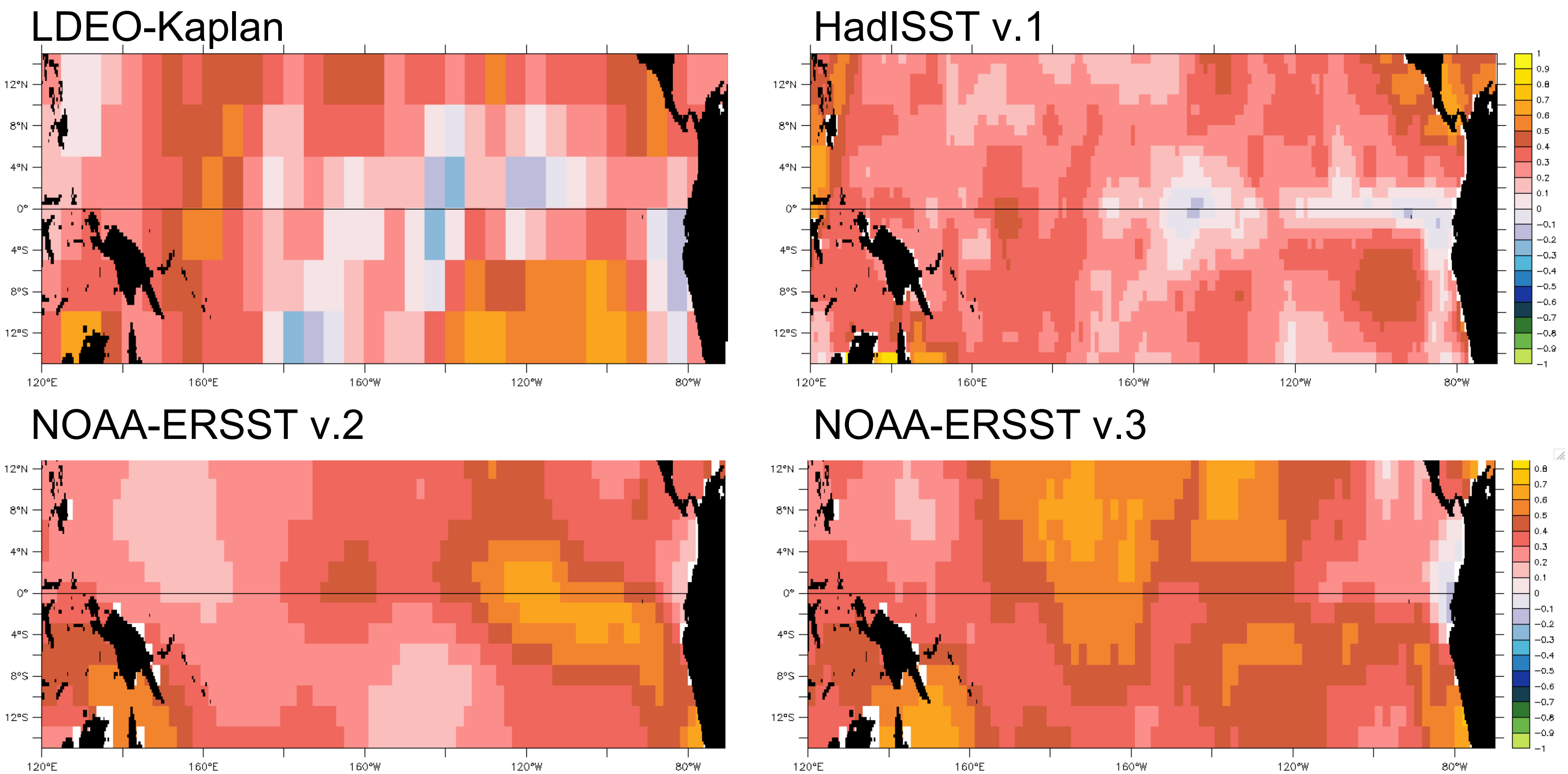


TRENDS COMPUTED 1861-1992

Vecchi et al (2006)

Look at SST?

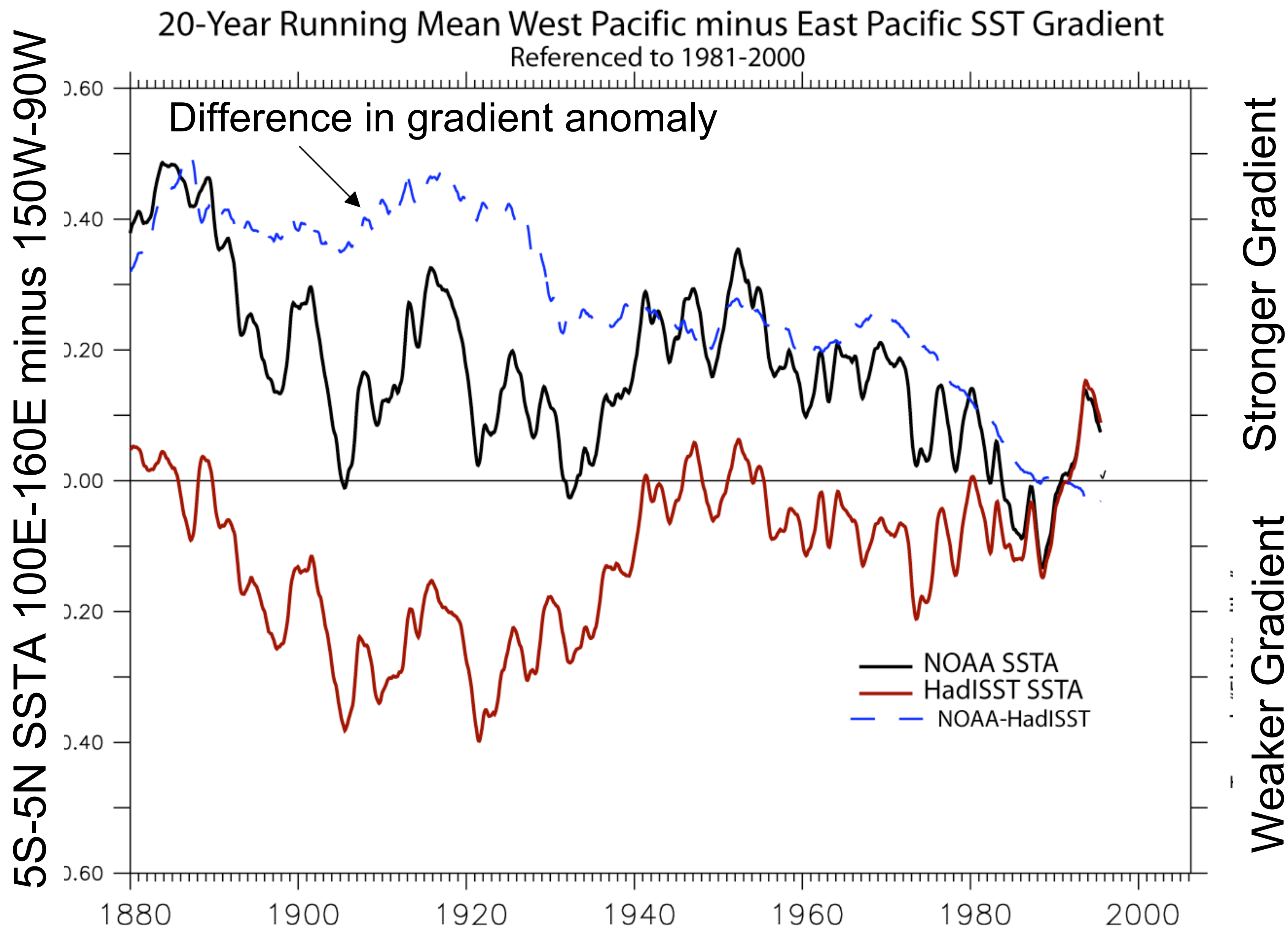
Linear trends (1880-2005) in four SST estimates.



Overall warming seen in all.
Structure dependent on reconsruction.

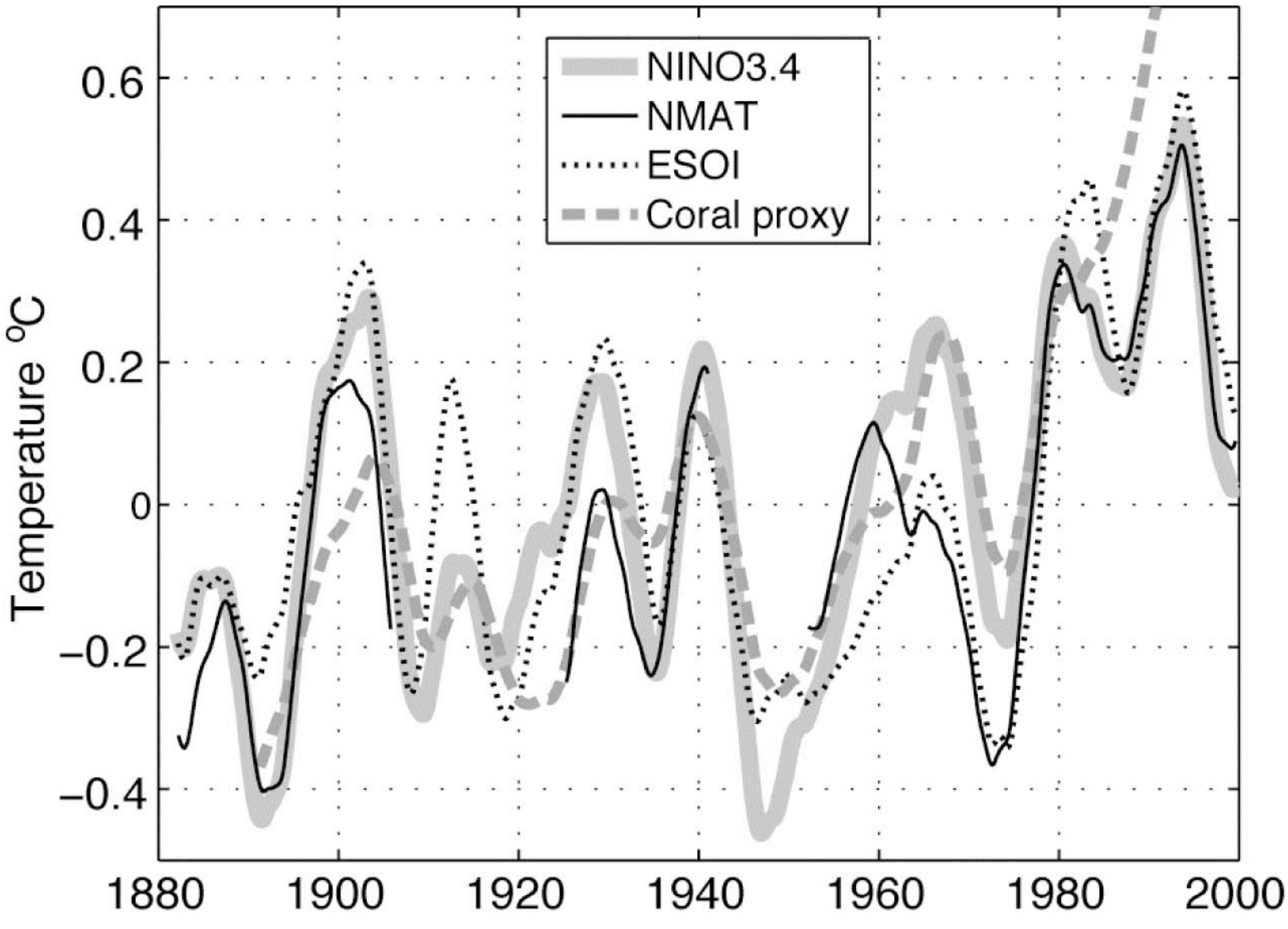
Adapted from Vecchi, Clement and Soden (2008, EOS)

When do differences between SST products emerge?



From Vecchi, Clement and Soden (2008, EOS)

New "Pacific-centric" analysis



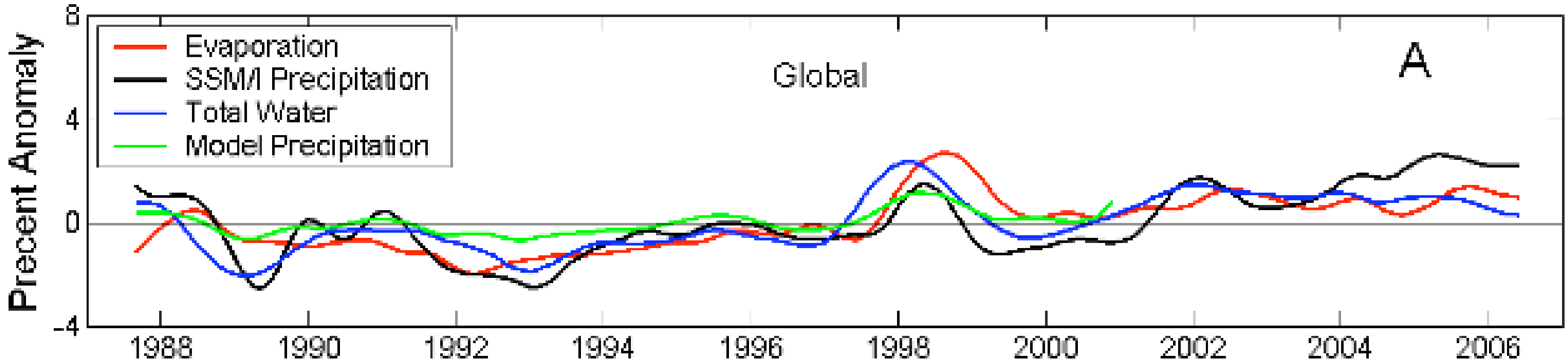
Bunge & Clarke (2009, J. Climate) "A verified estimation…since 1877"

Coral Proxy data

Proxies over historical era: a way forward in reconciling SST inconsistencies?

Satellite-estimated Precipitation

- Wentz et al (2007, Science) find a **~6.5%/°C (±2.5%/°C)** increase in global SSM/I precipitation 1987-2006.
- GCMs give **~2%/°C.**
- Soden (2000, J. Clim.) finds large interannual precip. Variability in SSM/I than in models.
- Can estimates be reconciled?



Wentz et al (2007, Science)

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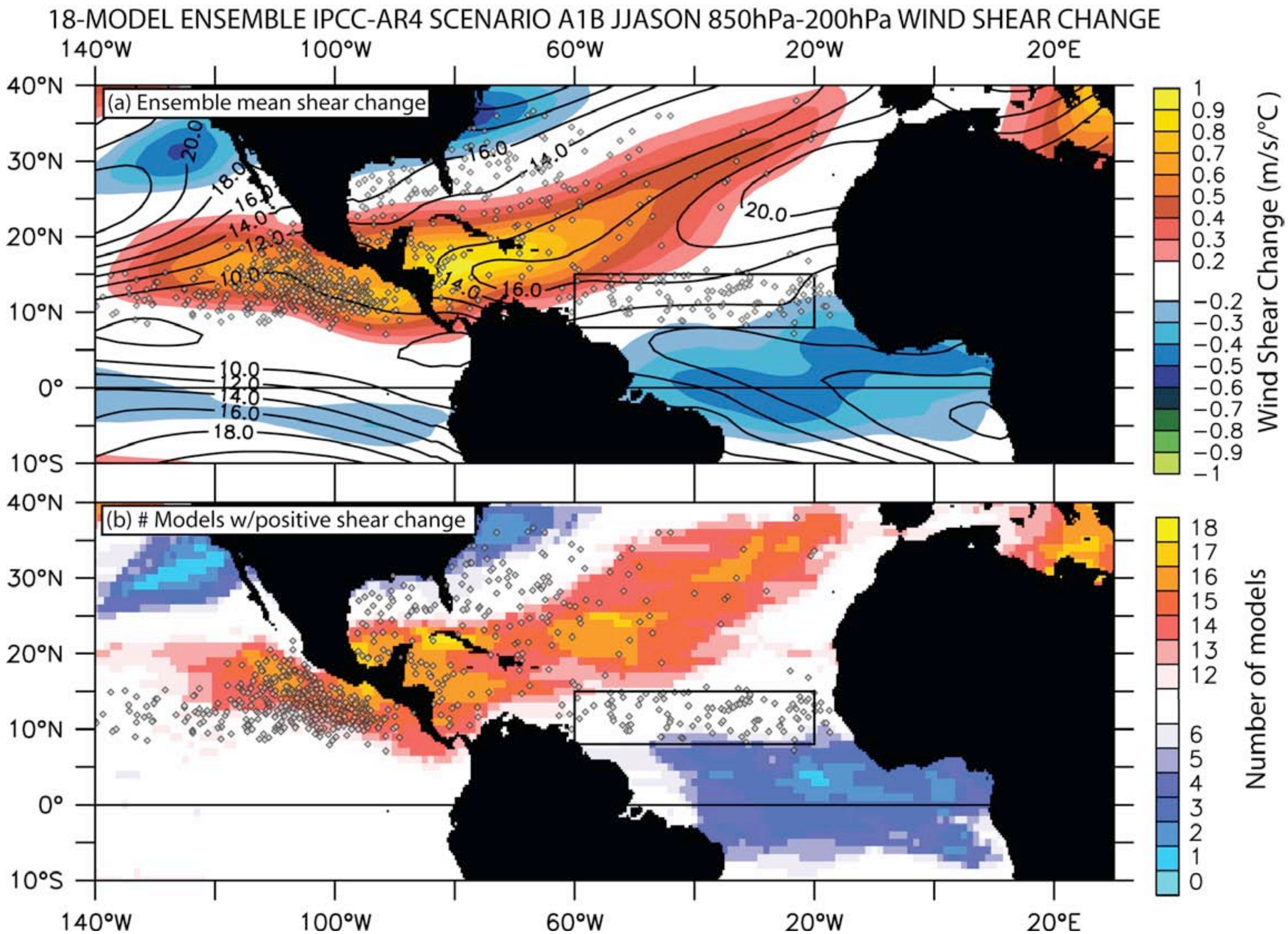
- **Implications:**
  - Atlantic wind shears
  - ENSO bad analogue for some teleconnections.

Model projected 21st Cy vertical wind shear changes



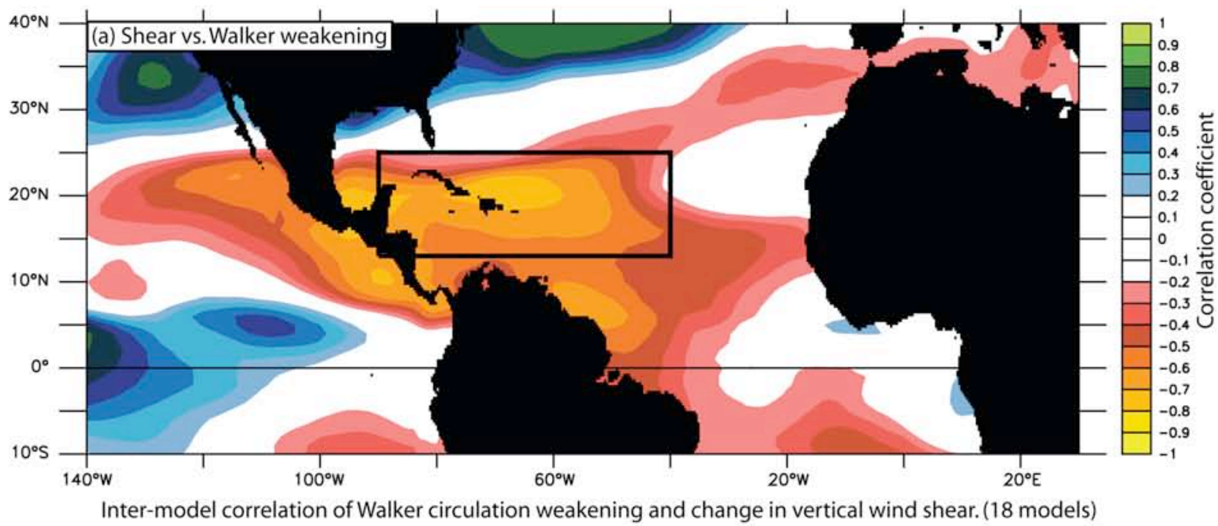
Vecchi and Soden (2007, GRL)

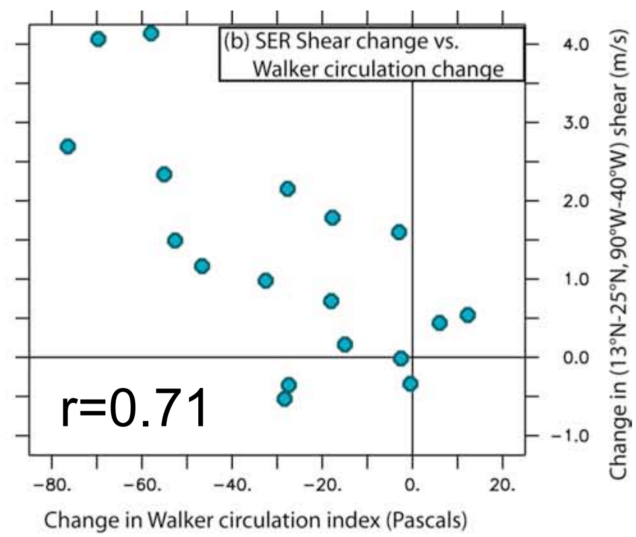
Increased wind shear over much of Tropical Atlantic and eastern Pacific.

V_s and Pacific Walker Circulation

Correlation of local shear change with Pacific Walker weakening across models

Walker circulation vs. shear change



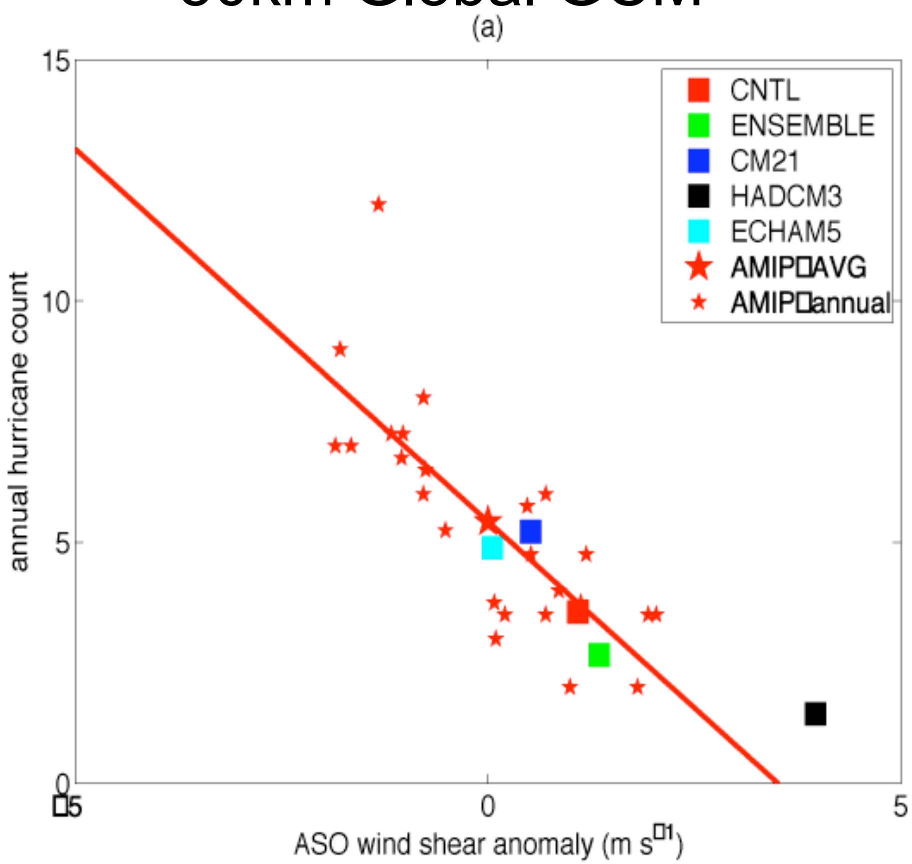


Models with largest Walker weakening have largest shear enhancement.

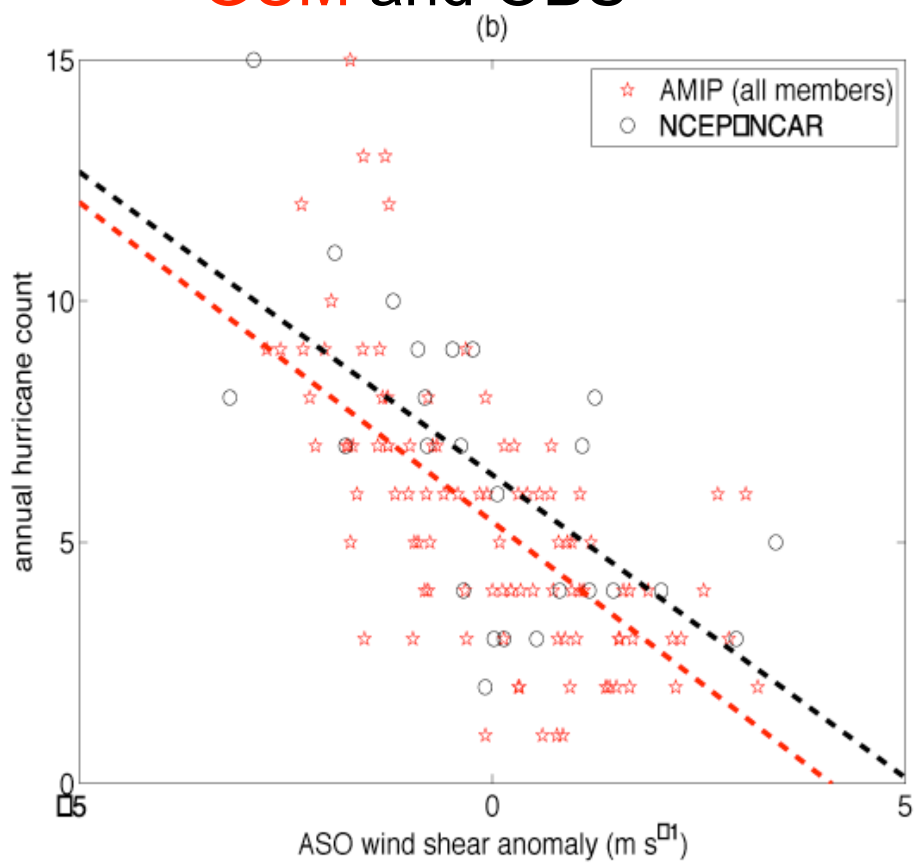
From Vecchi and Soden (2007, GRL)

Shear changes and Atlantic hurricane activity

50km Global GCM



GCM and OBS



Zhao, Held, Lin and Vecchi (2009, J. Clim.)

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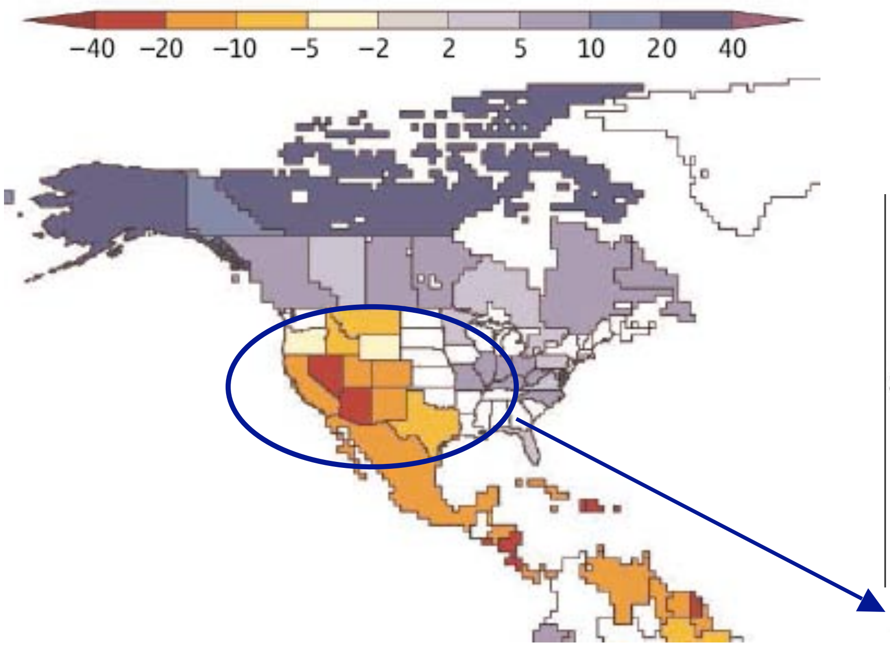
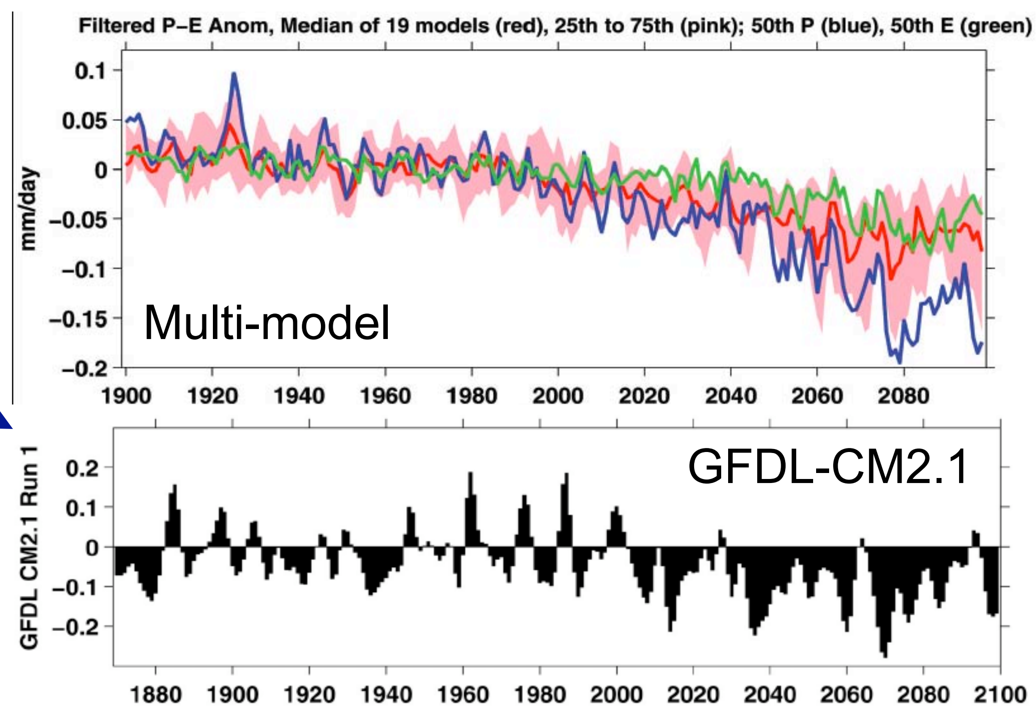
Southwest Drying Projections

21st Century Projected
% Change in Runoff



Milly et al (2008, Science)

Change in SW US Precip. minus Evap.



Seager et al (2007, Science)

SW Drying part of global pattern

SW Drying part of overall drying of subtropics.

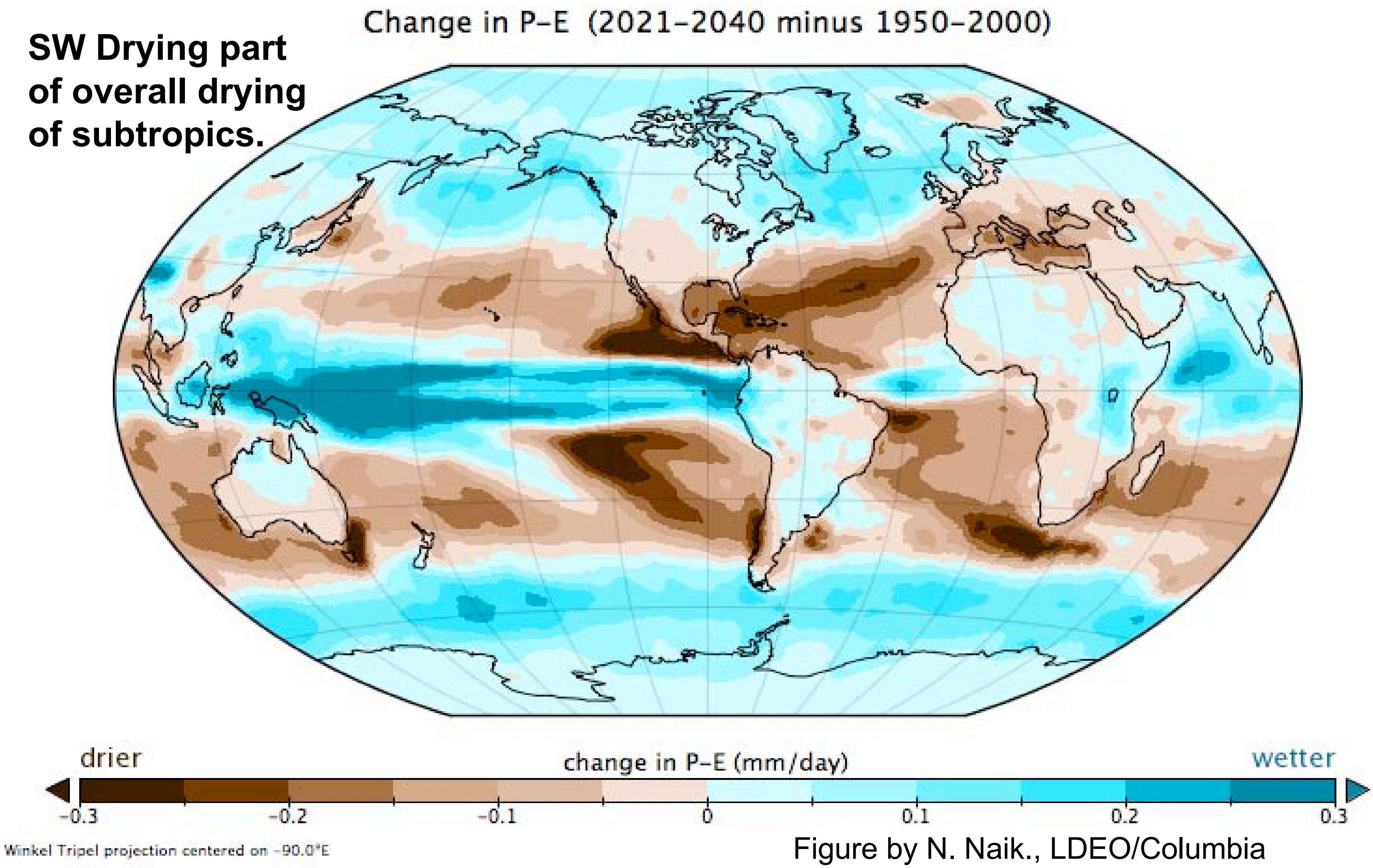


Figure by N. Naik., LDEO/Columbia

Mechanisms for CO_2-Forced Drying

Thermodynamic Control:

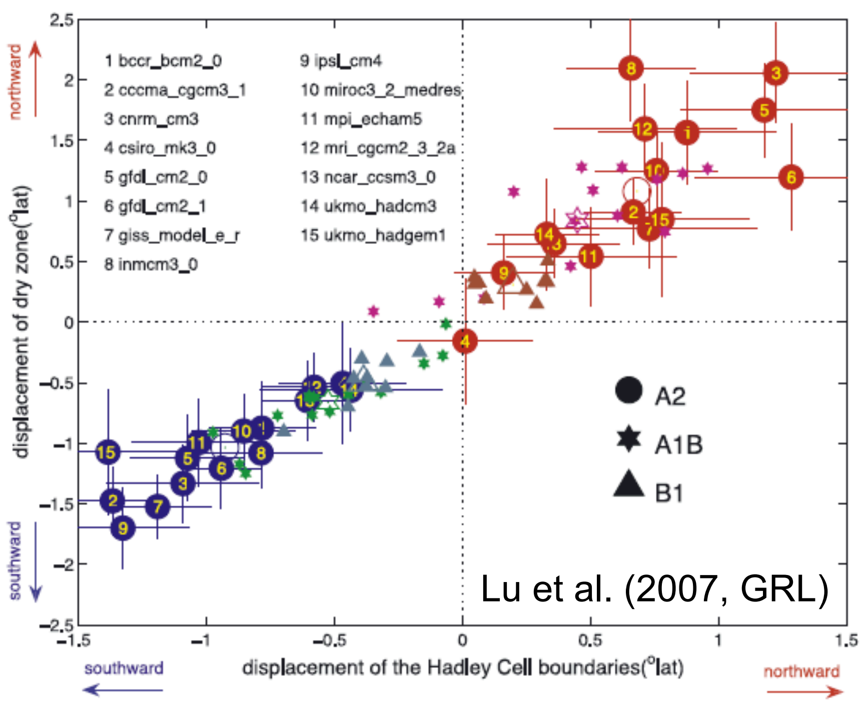
Warming (increase q_{sat})

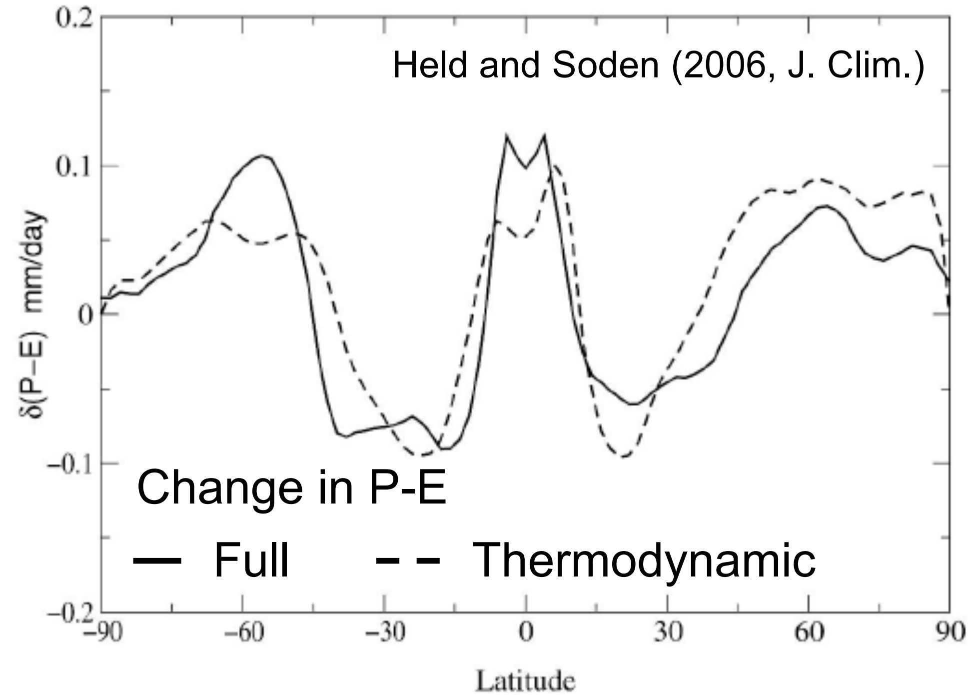
↓

increase atmospheric moisture.

↓

increase moisture flux divergence/ convergence.



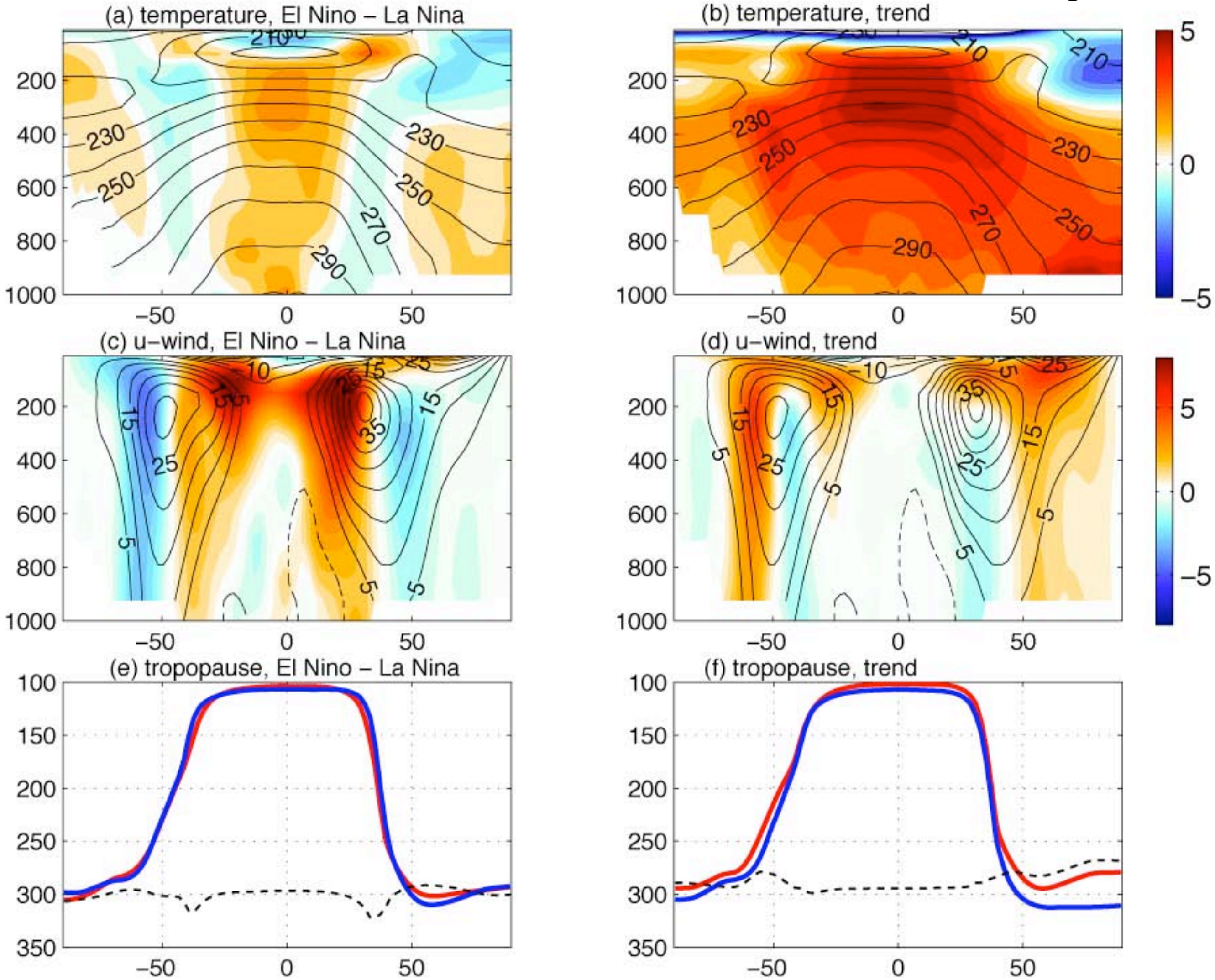


Circulation Changes:

Poleward shift of descending branch of Hadley Circulation is associated with a poleward shift of dry zones.

Zonal-mean response not “El Niño-like”

ENSO | Global warming



Lu, Chen and Frierson (2009, J. Clim.)

Conclusions

- The weakening of the tropical circulation is a robust projection of all climate models.
  - Connected to sub-Claussius-Clapeyron rate of:
    - Increase in radiative cooling
    - Increase in surface radiative imbalance

- The slower circulation is manifest primarily as a weakened Walker Cell.
  - El Niño bad analogue for mean ocean/atmosphere climate change.
  - Not physically related to El Niño:
    - Dynamical ocean changes act against atmospheric changes.
  - And some changes not “El Niño-like” at all:
    - Eq.Pac. Thermocline shoals
    - Teleconnections can differ from El Niño:
      Dry U.S. Southwest, Wet Maritime Continent

- Both Ocean Thermostat and Weaker Walker present in GCMs

- Observations:
  - SLP indicates Weaker Walker Circulation
  - SST? Discrepancies need to be resolved - proxy data spanning 20th Cy?

- Weaker Walker Cell associated with increased Atlantic wind shear.

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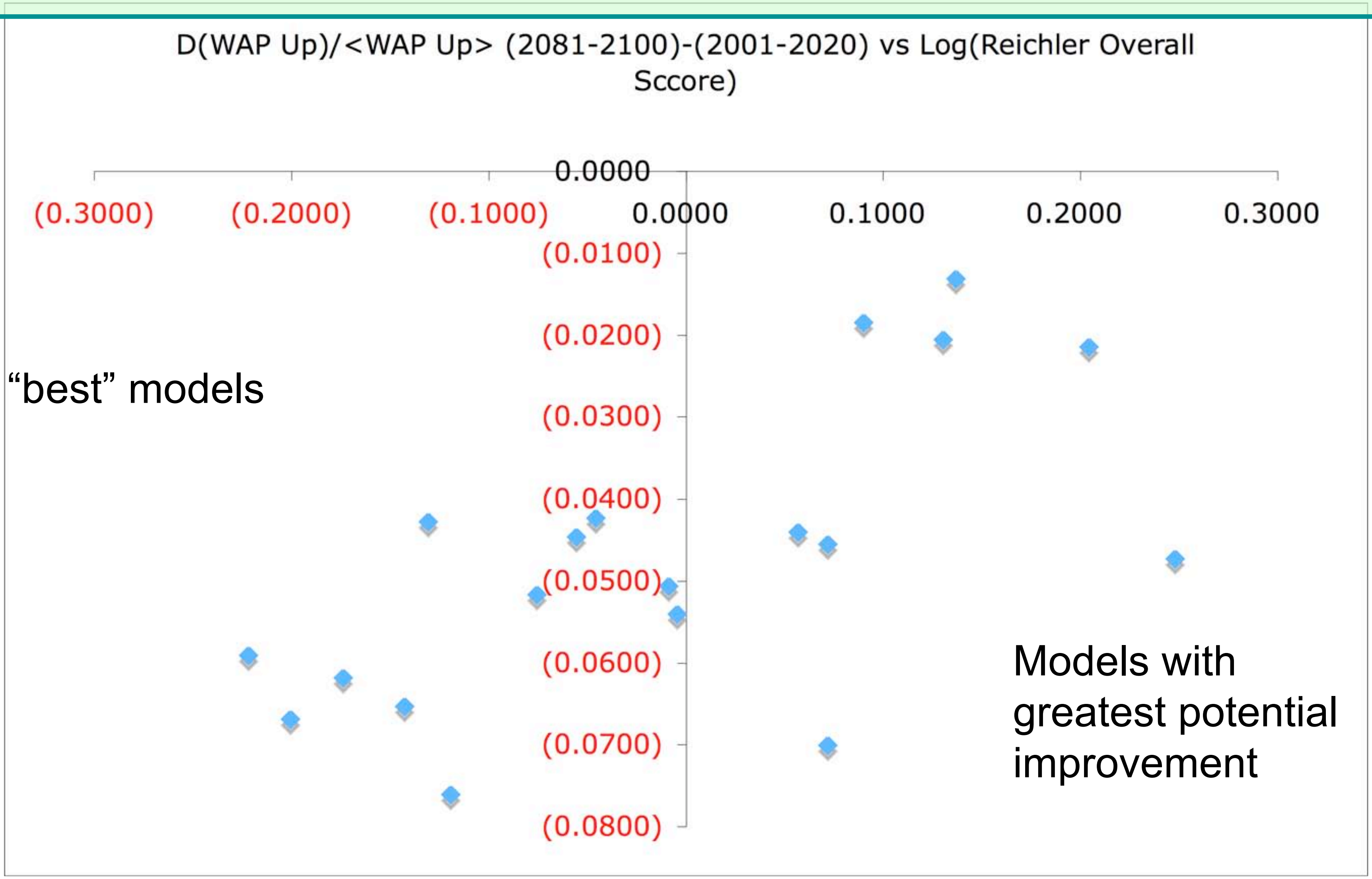
“Best” IPCC-AR4 Models show a large weakening of circulation



Score from Reichler and Kim (2008, BAMS) comparing each model to a wide range of 20th Century observations.