Slowdown of Tropical Circulation in a Warming Climate

G. A. Vecchi, B. J. Soden, A. Clement,
I.M. Held. A.T. Wittenberg, A. Leetmaa

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

PLEASE INTERRUPT ME WITH QUESTIONS OR COMMENTS.

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From IPCC-AR4

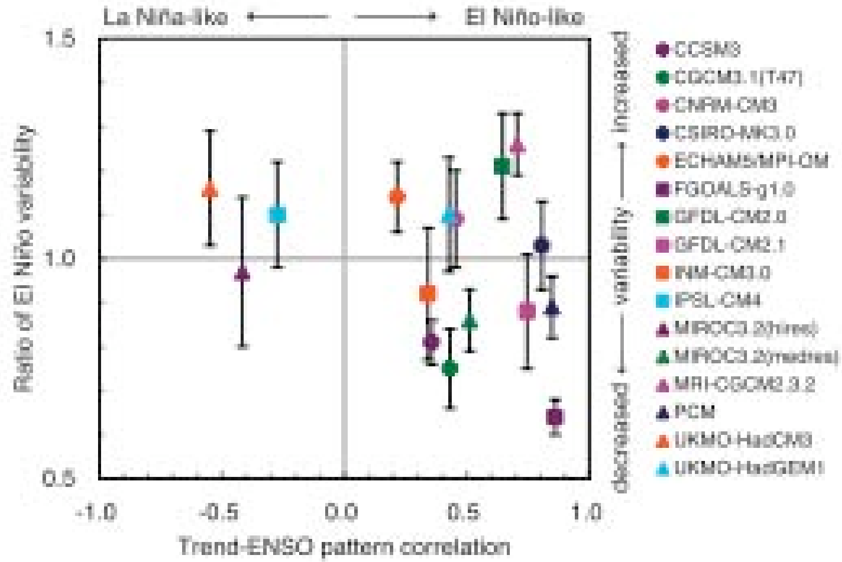


Figure 10.16. *Base state change in average tropical Pacific SSTs and change in El Niño variability simulated by AOGCMs (see Table 8.1 for model details). The base*

"*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

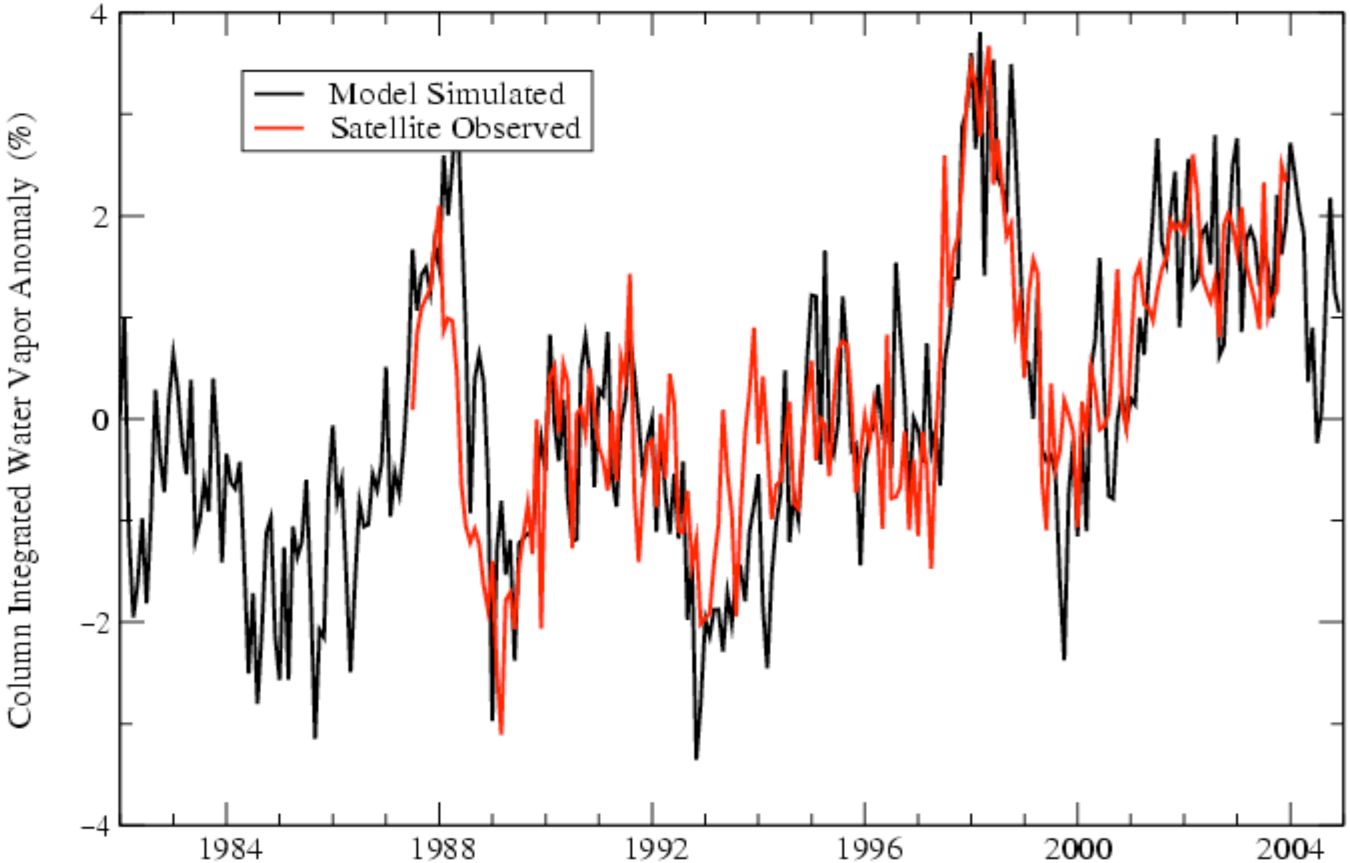
Broader Objective

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)

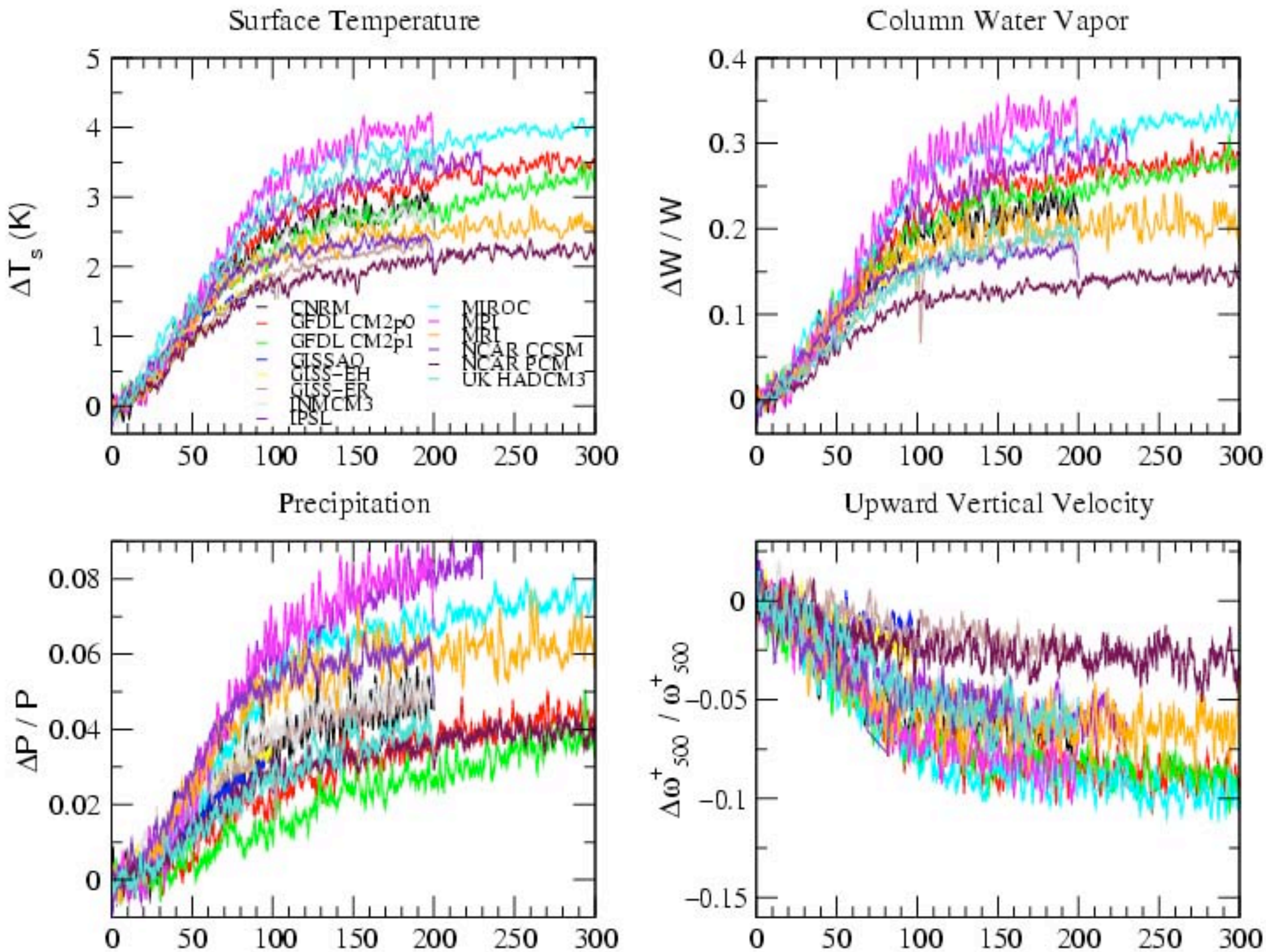
- A increase in horizontal moisture transport

- 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

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

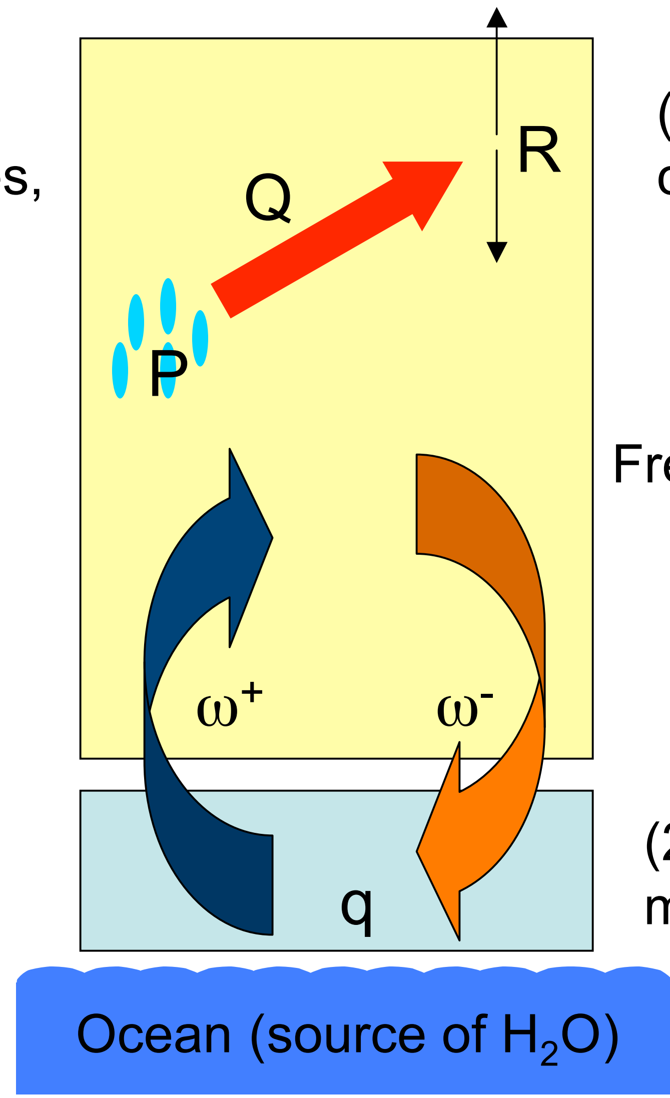
Simplified view of atmospheric water/energy balance

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

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

$$Q = L_v * P$$

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



(5) Energy released from condensation radiates.

$$R = Q$$

Free troposphere

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

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

(2) Boundary Layer: moist from evaporation

$$q = rh \cdot q_s$$

(1) Heated: evaporates/stores

Tropical Atmospheric circulation

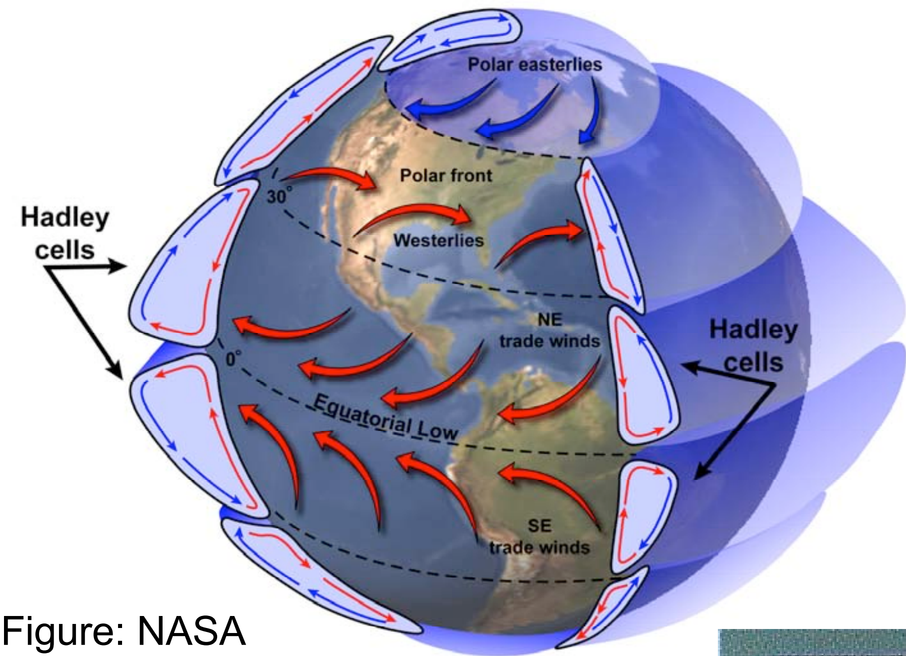


Figure: NASA

Large-Scale circulation:

- Zonally symmetric “Hadley Cells”
- Zonally asymmetric “Walker Cells”
- Monsoons

Transient features (storms, etc).

How are the various aspects of Trop. Atm. Circ. are likely to change/vary?

Today focus largely on Walker Cell

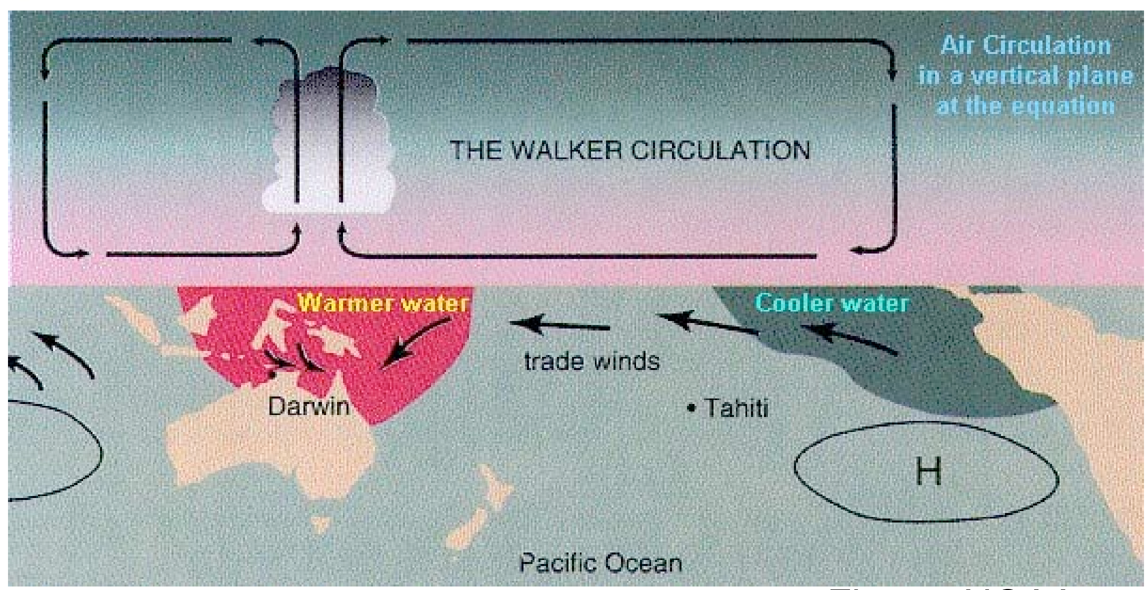


Figure: NOAA

Normal Conditions

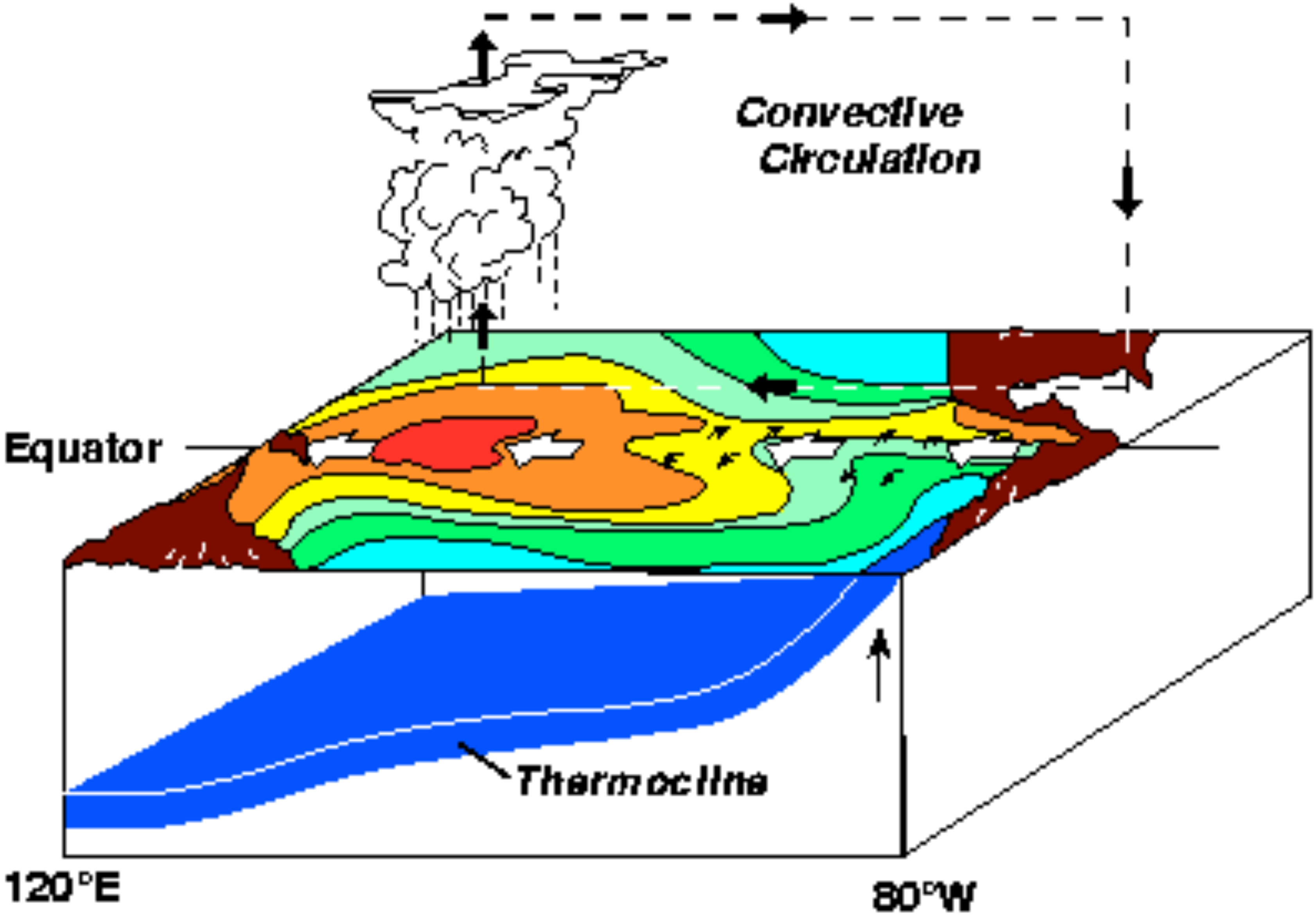


Image courtesy of NOAA/PMEL

El Niño Conditions

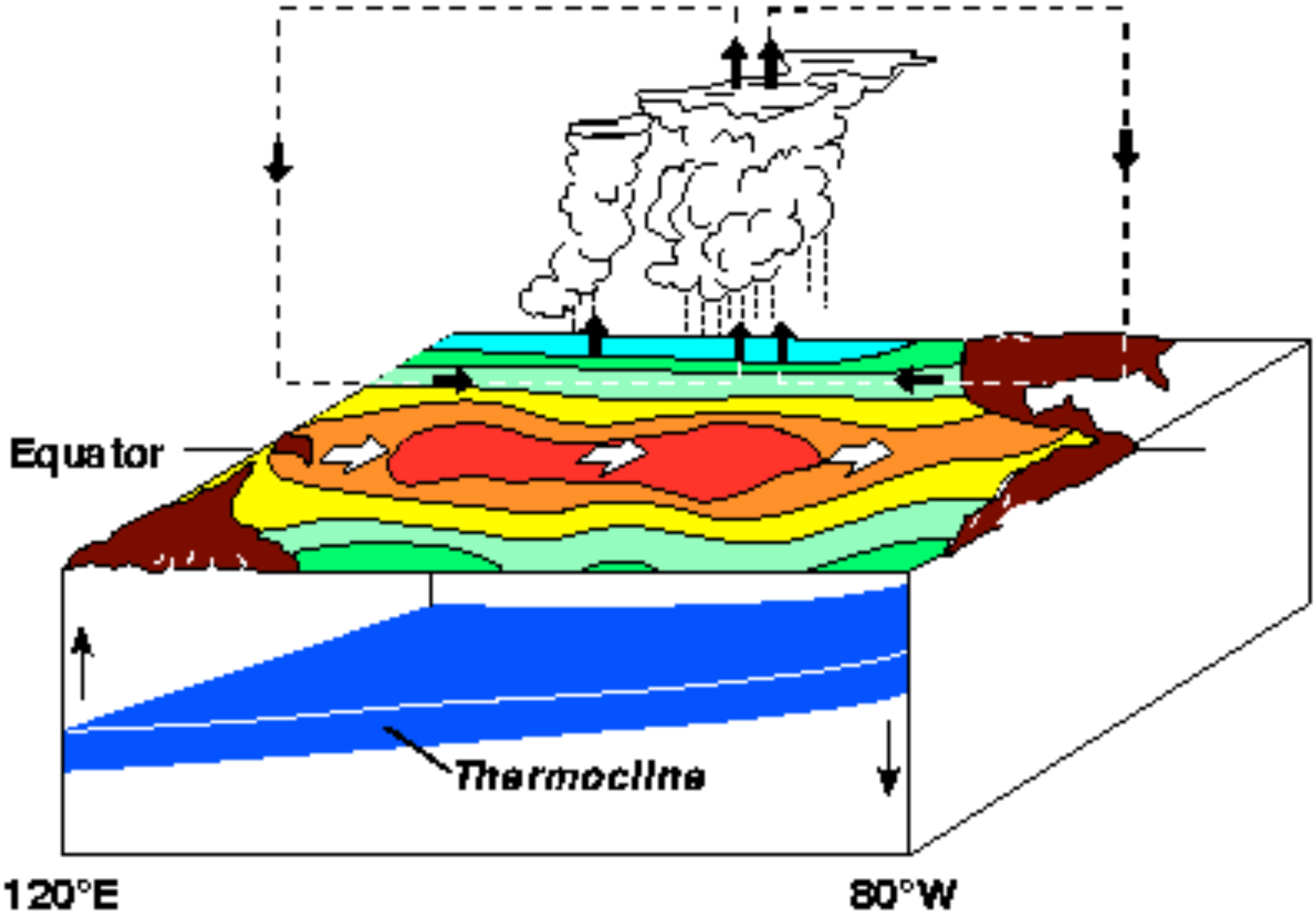


Image courtesy of NOAA/PMEL

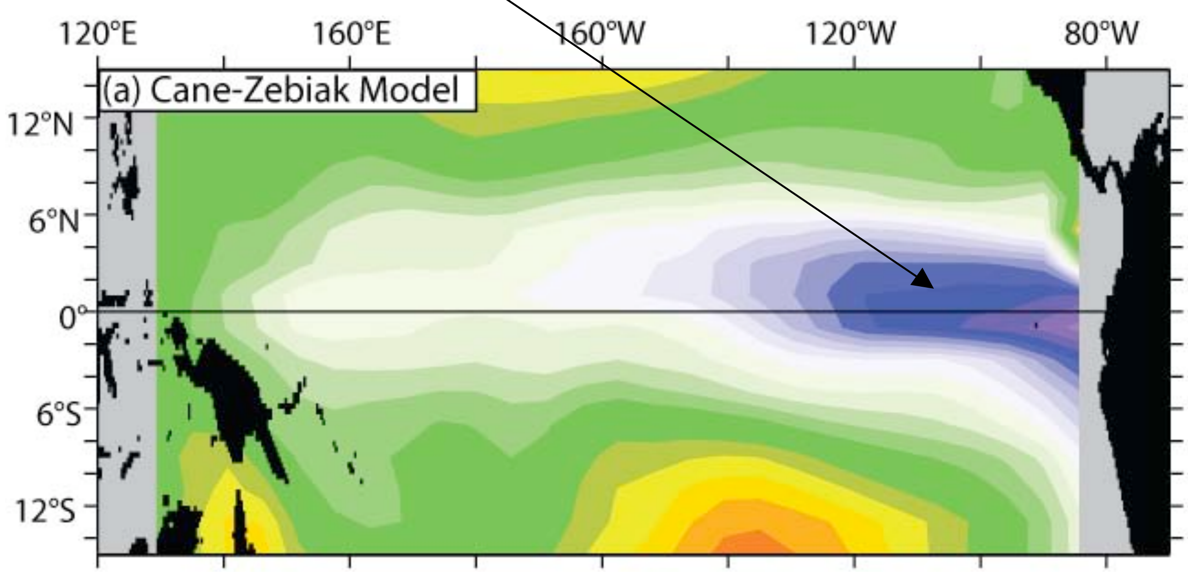
Outline

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

Ocean Dynamical Thermostat

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

- 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

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

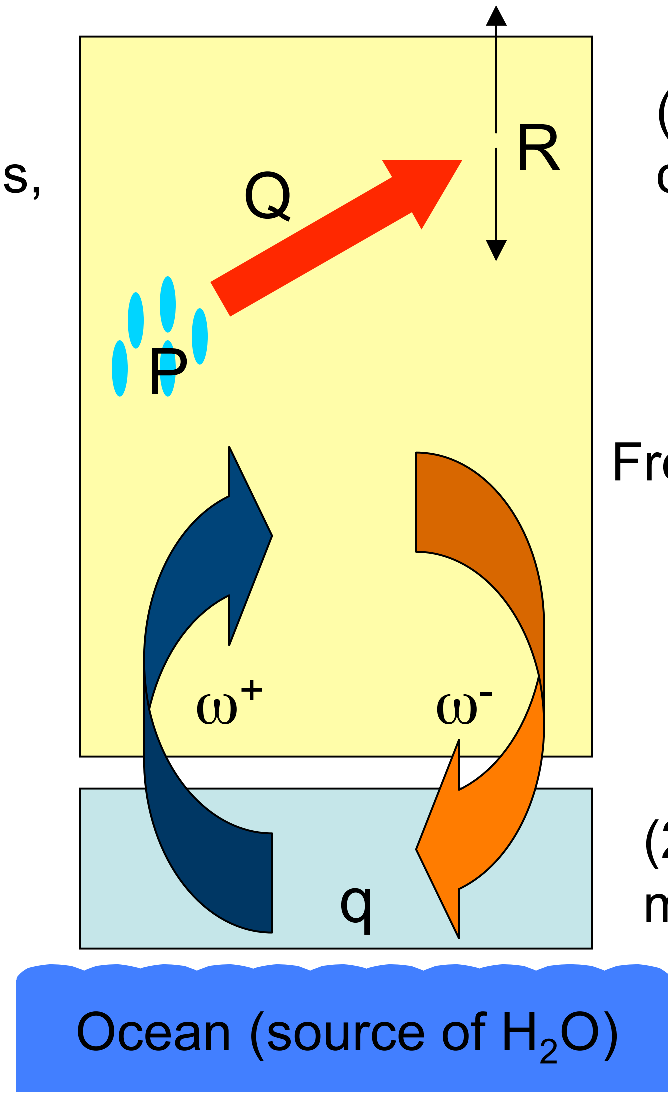
(4) Moist air condenses, heats troposphere, and precipitates.

$$Q = L^*P$$

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

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

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



(5) Energy released from condensation radiates.

$$R = Q$$

Free troposphere

(2) Boundary Layer: moist from evaporation

$$q = rh \cdot q_s$$

(1) Heated: evaporates/stores

Thermodynamic constraint on circulation: response in warming climate

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

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

- 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.**

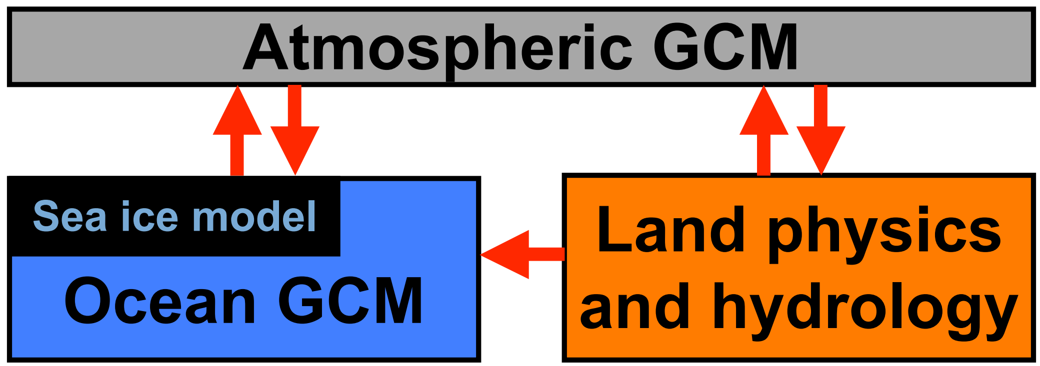
- Walker Circulation weakens? “El Niño-like”?

Outline

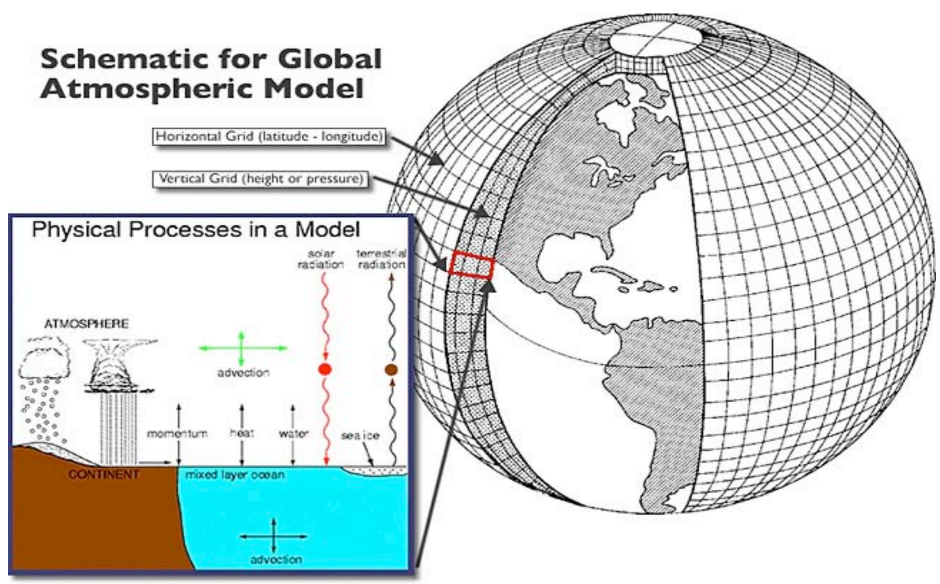
- Introduction/background
- Theory
- **Numerical Modeling**
  (theory that is too comprehensive to solve by hand)
- Implications
- Observations

GCMs allow us to make fewer simplifications than in previous theoretical development:

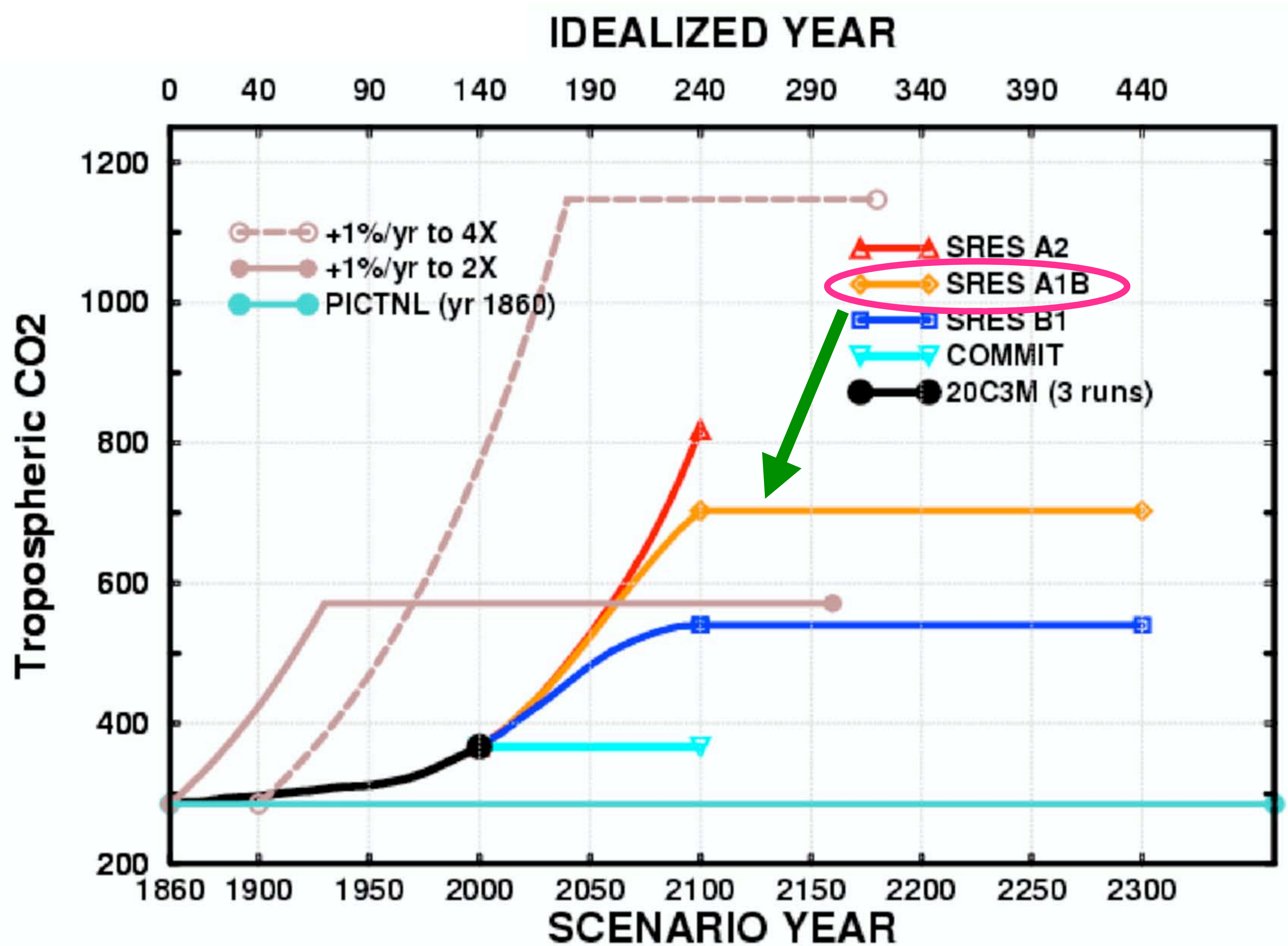
Allow ocean coupling, 3-D circulation, interactive radiation, explicit Walker Circulation, etc.…



Numerical representations of thermodynamic, dynamic and radiative-transfer controls on climate - constrained by available computer power.

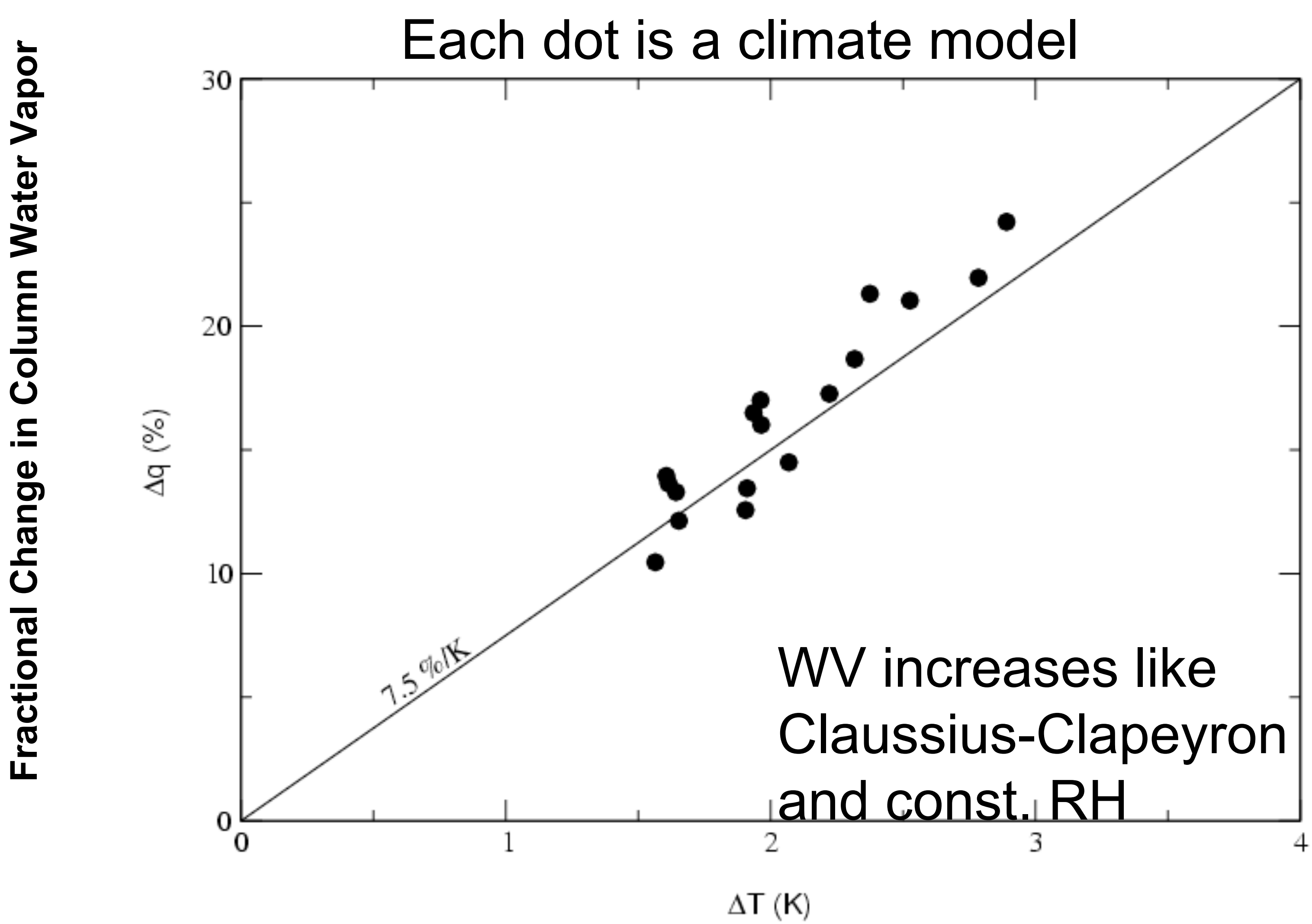


Idealized greenhouse warming experiments



Atmospheric Constraint on Tropical Circulation

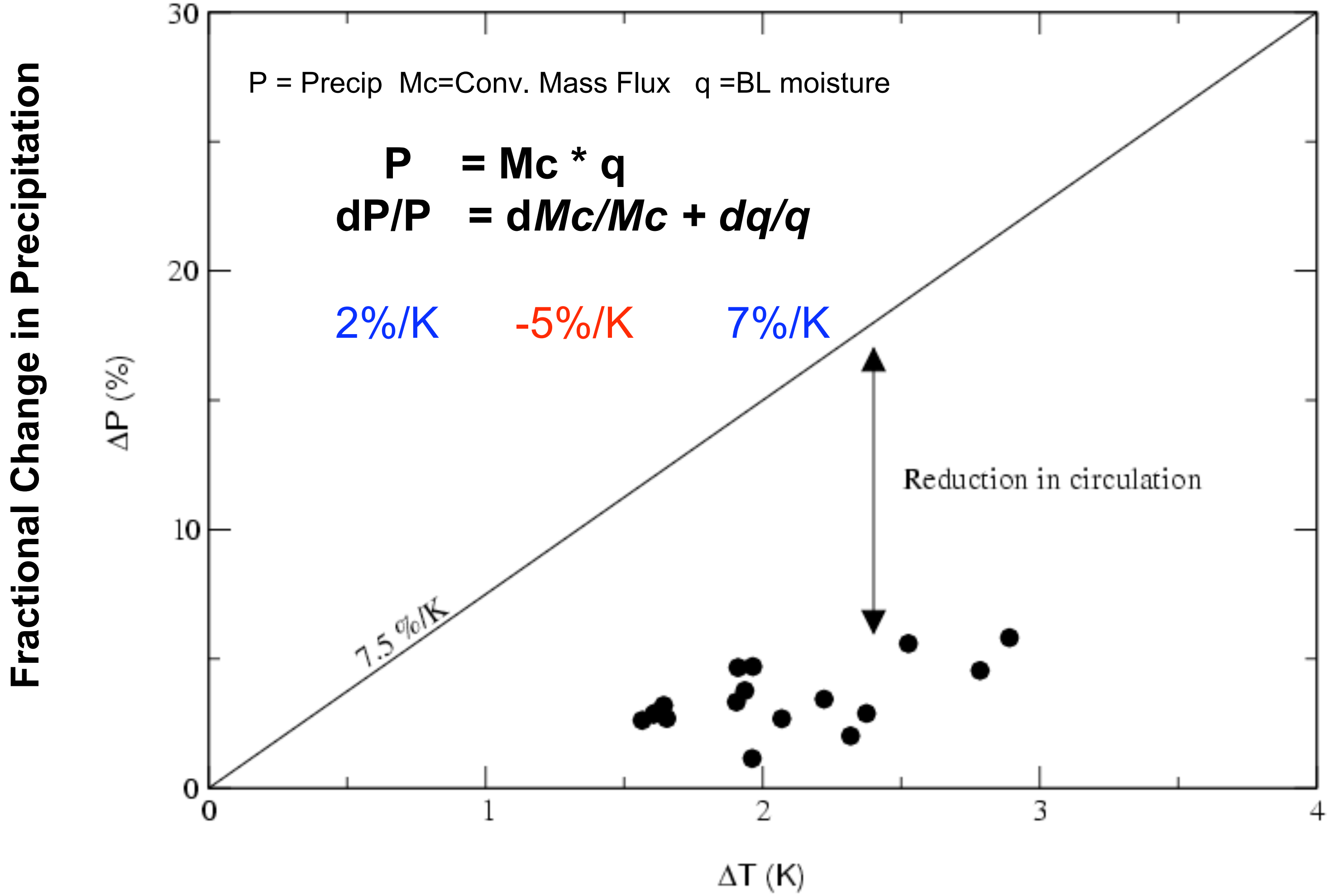
Change in Global Water Vapor at 2100



Held and Soden (2006, J. Clim)

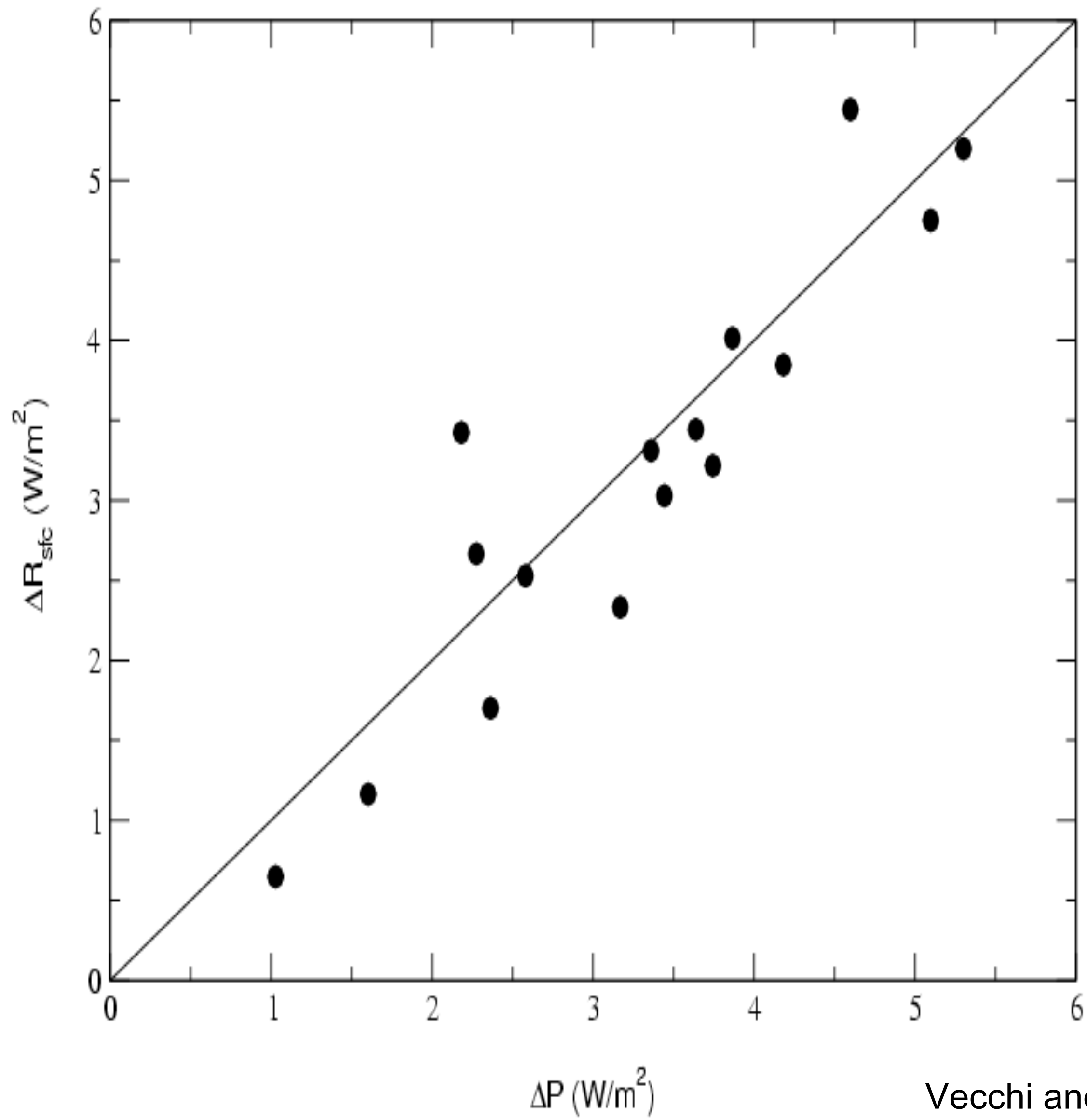
Atmospheric Constraint on Tropical Circulation

Change in Global Precipitation at 2100



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

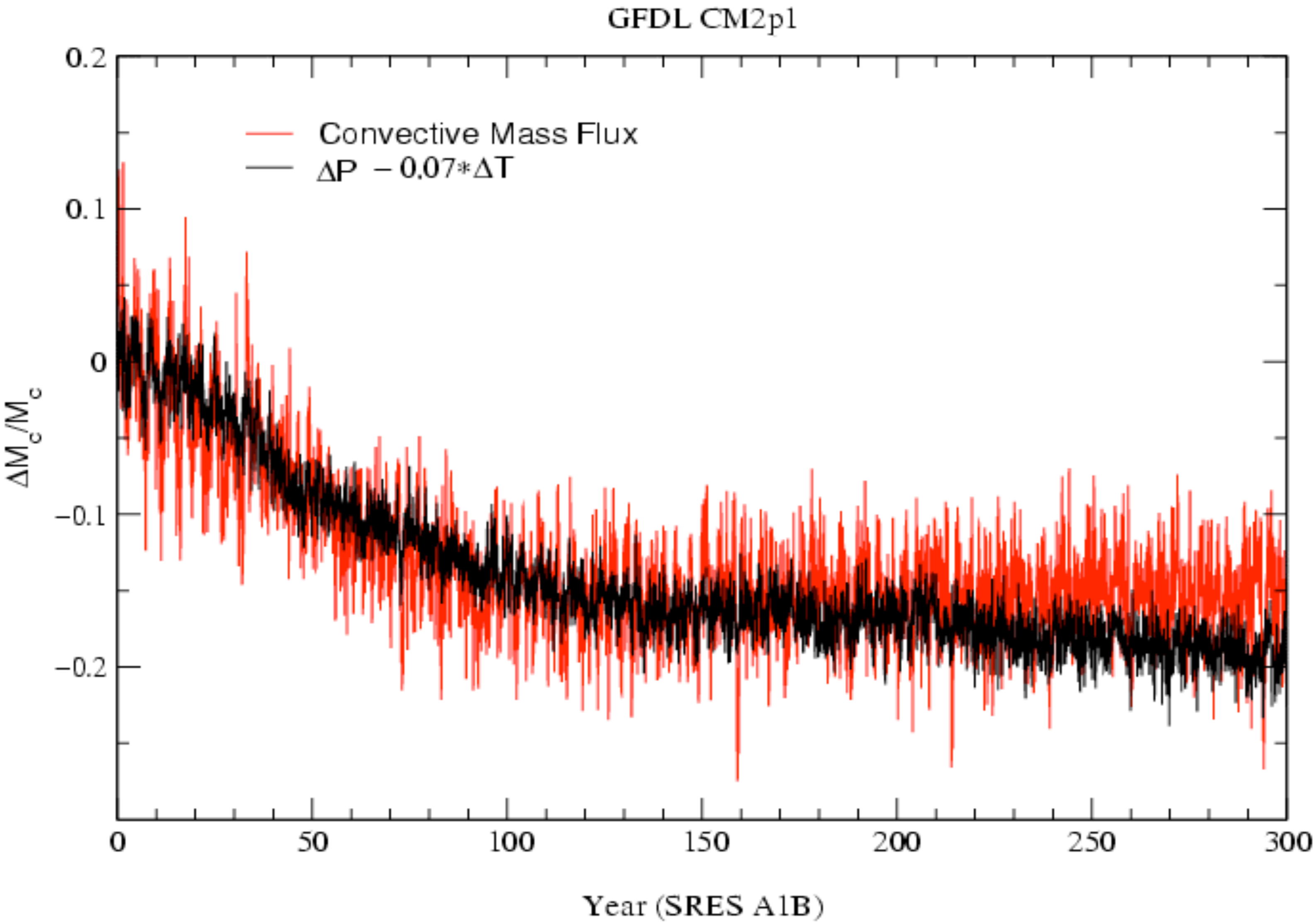
Global precipitation scales with surface radiative imbalance



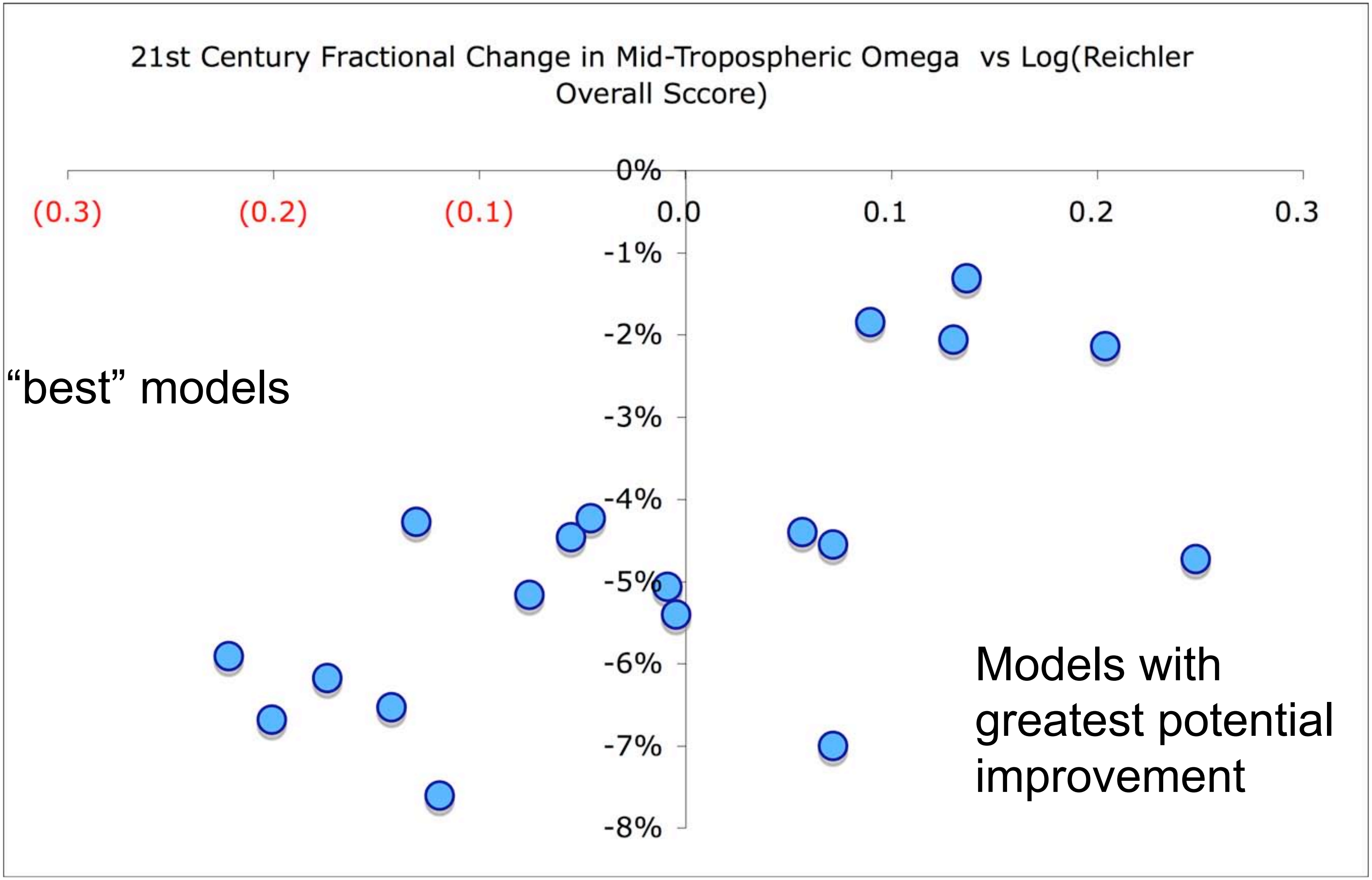
Vecchi and Soden (2007), J.Clim.

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

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

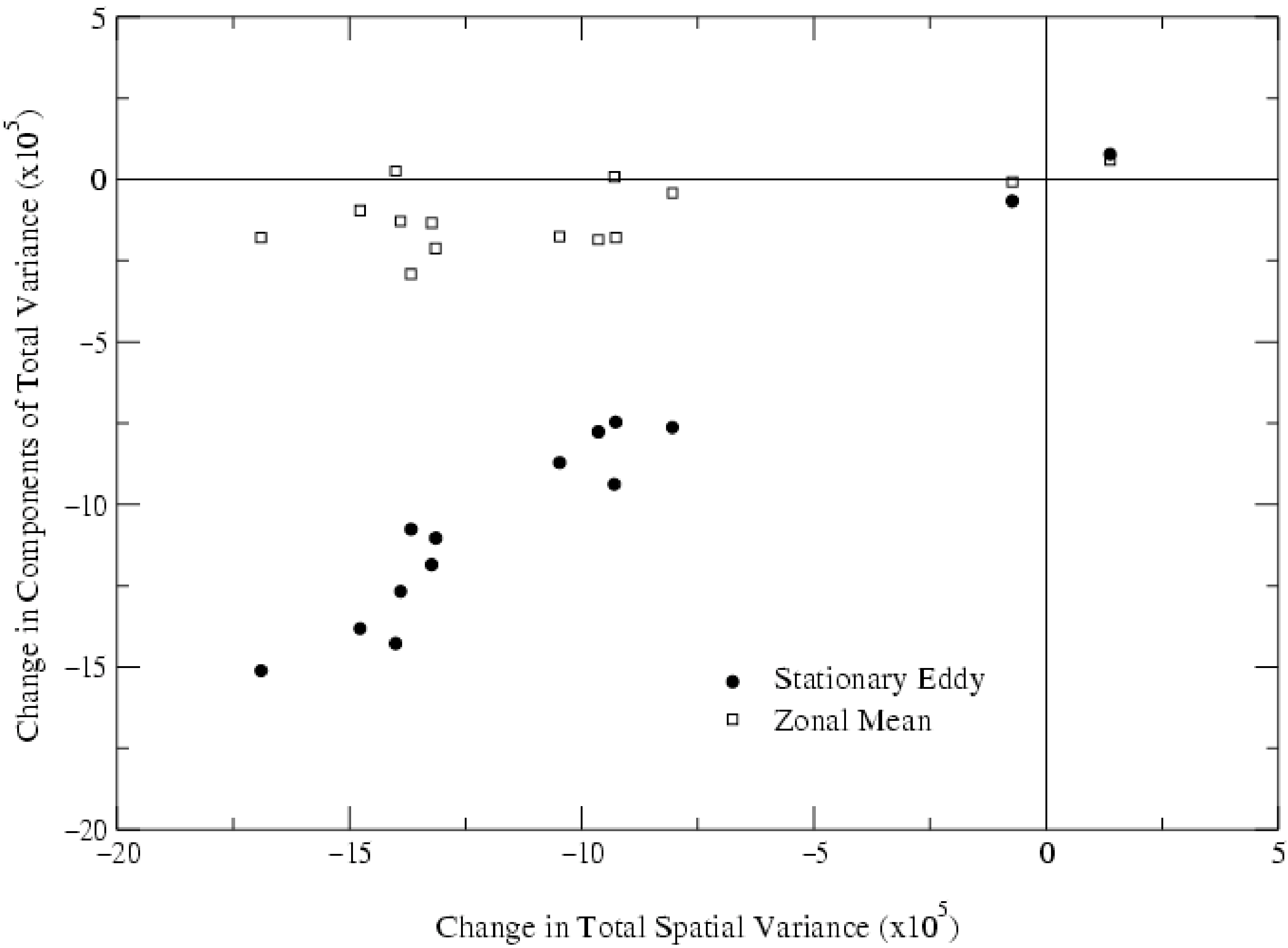


“Best” IPCC-AR4 Models show a large weakening of circulation



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

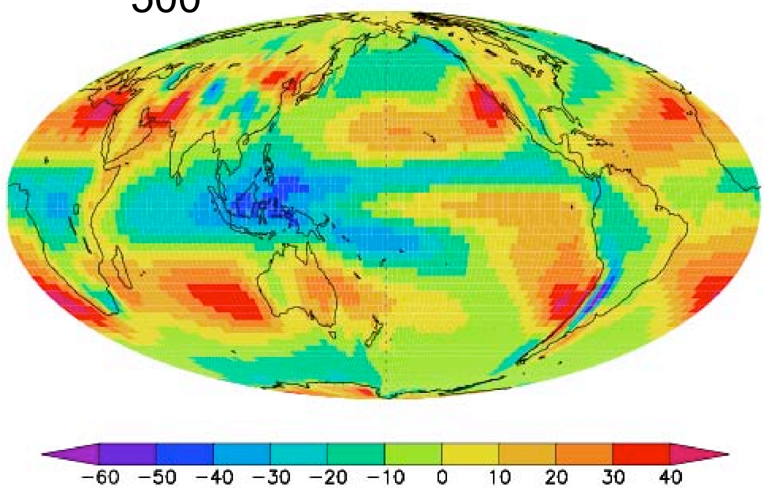
Reduction of Circulation largely in Walker Circulation



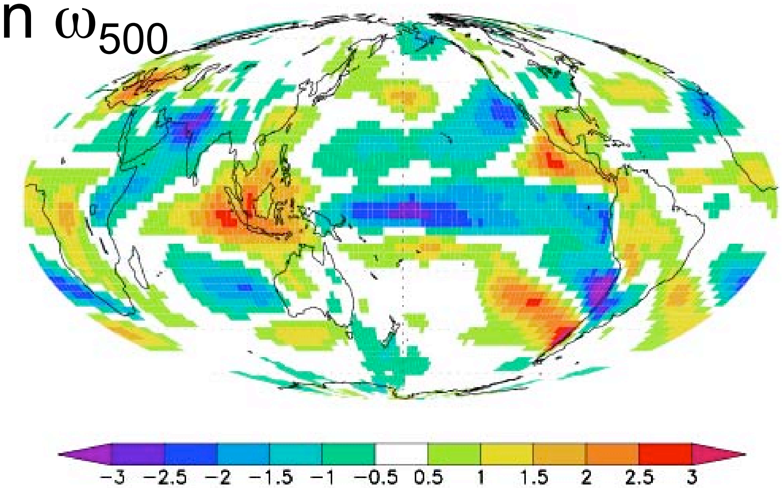
Vecchi and Soden (2007, J. Clim.)

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**

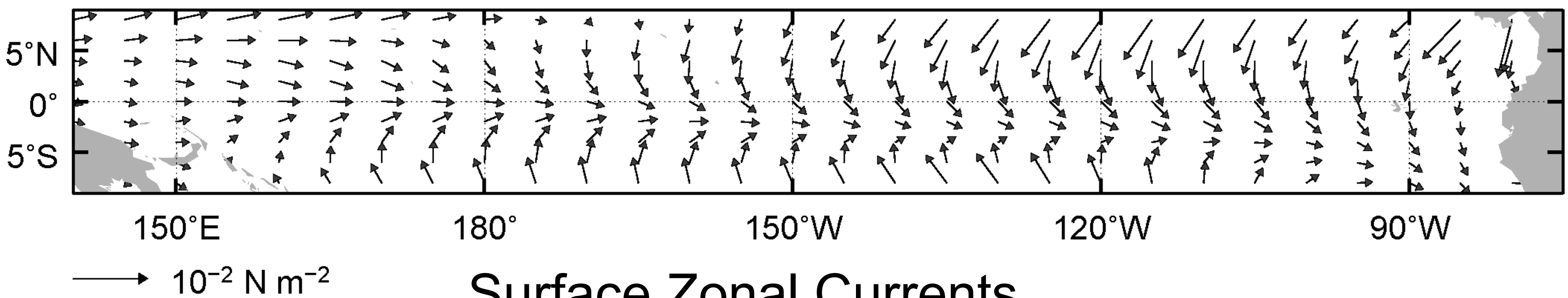
Not “El Niño-like”:
- **Ocean changes oppose it**
- **Pacific thermocline shoals**
- **Teleconnections not “El Niño-like” (Lu et al. 2007, 2008; Seager et al. 2007…)**

Vecchi and Soden (2007, J. Clim.)

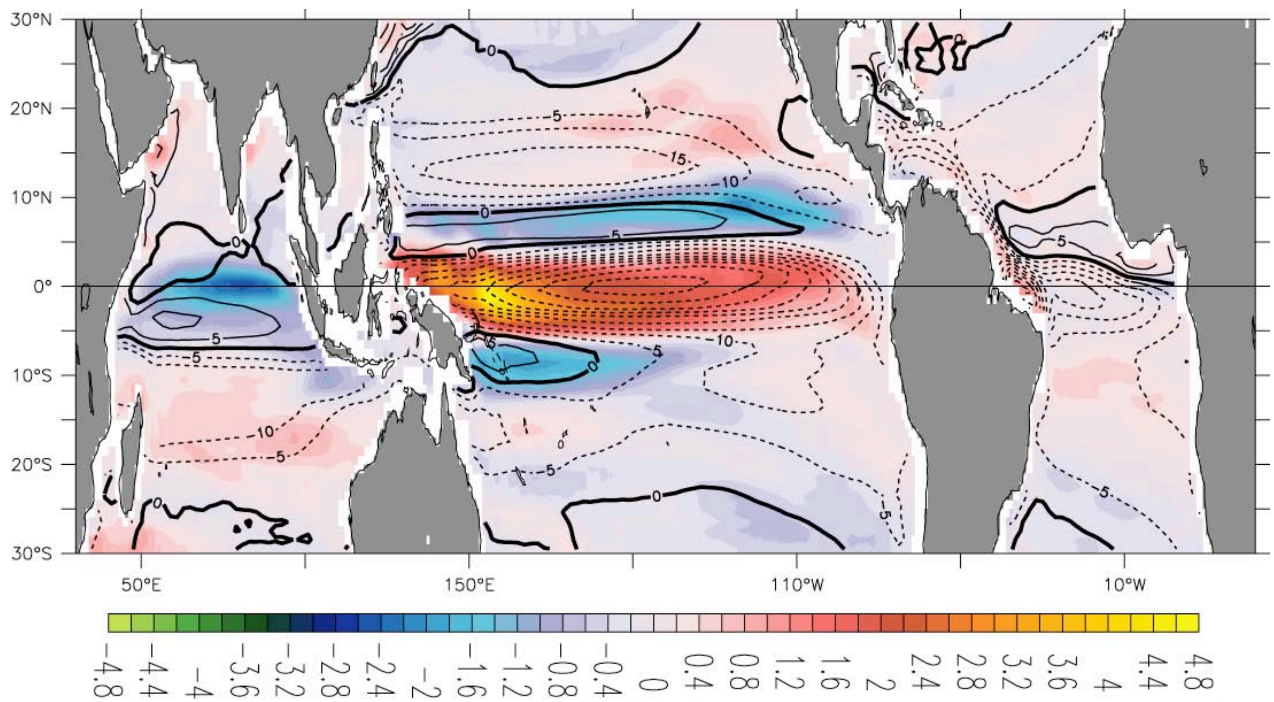
Wind Stress and Currents

Stress

DiNezio et al (2009, J. Clim.)



Surface Zonal Currents



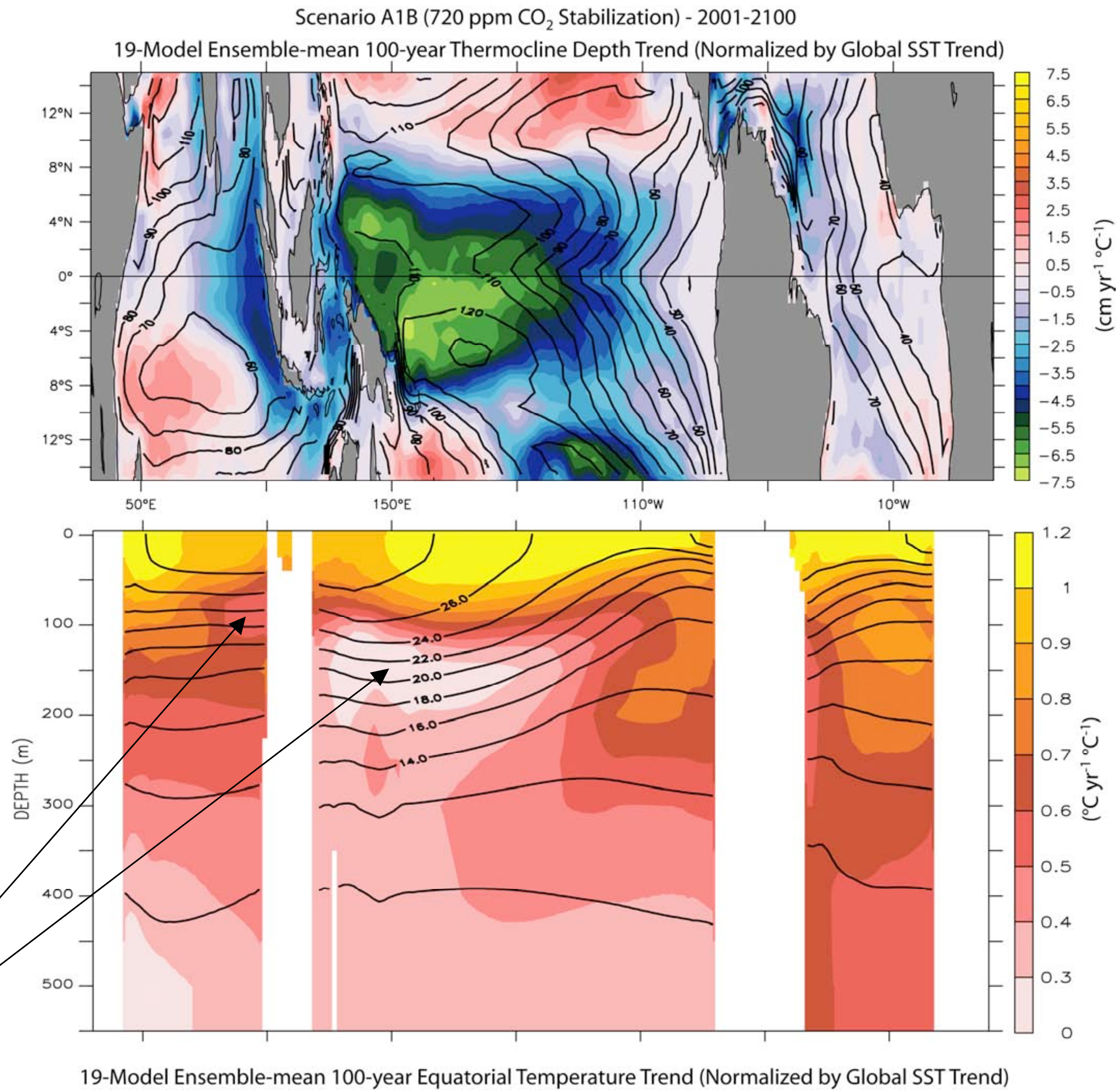
Shade: 2001-2100 trend (10^{-4} m s^{-1} yr^{-1} °C^{-1}) - Contour, 2001-2020 Average (cm s^{-1})

Vecchi and Soden (2007, J. Clim.)

Equatorial Pacific thermocline flattens and shoals.

Increased thermal stratification.

Minimum in warming

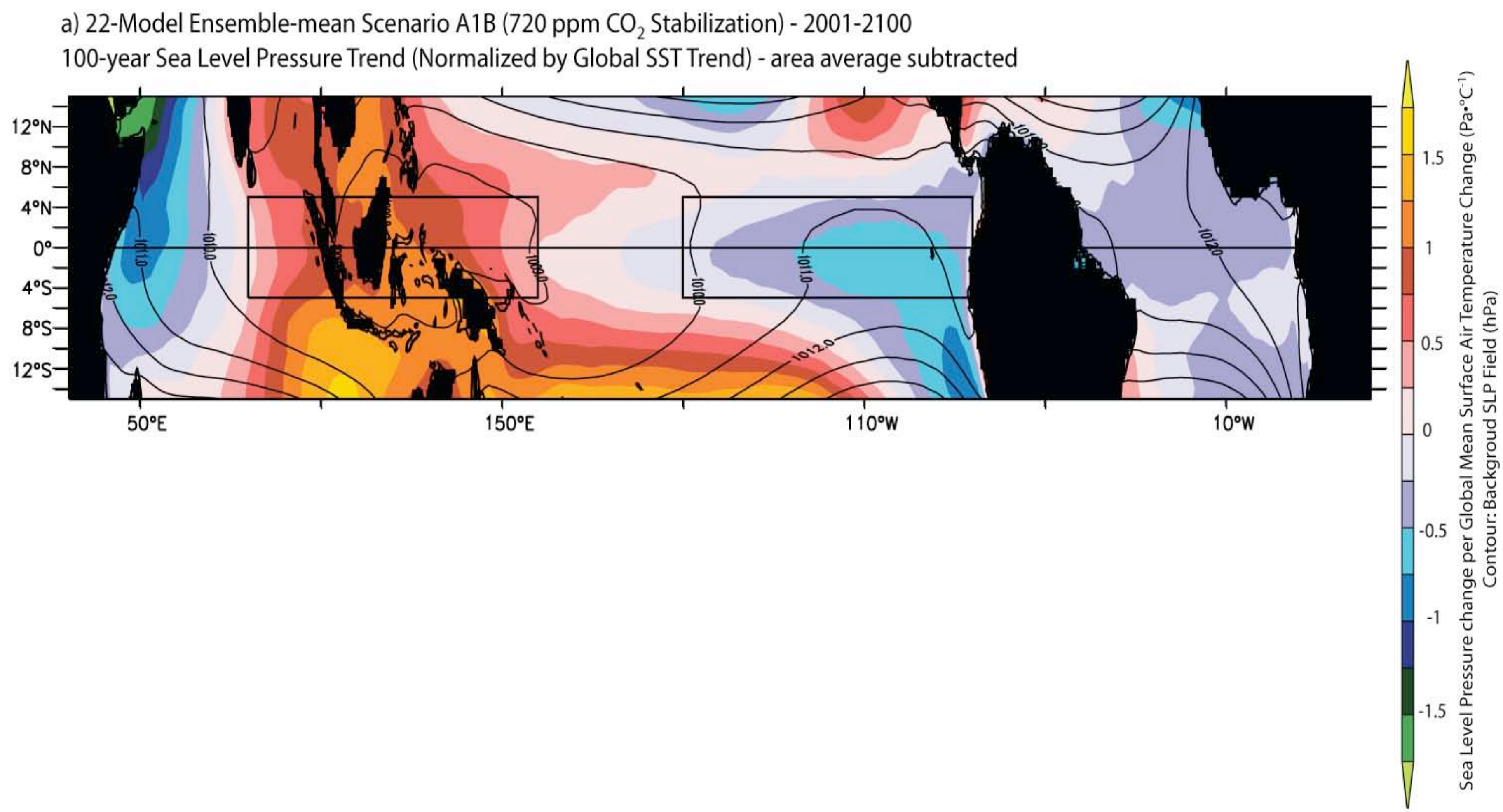


Vecchi and Soden (2007, J. Clim.)

El Niño is not an appropriate analogue for climate change response.

Near-equatorial Indo-Pacific Zonal SLP gradients decrease

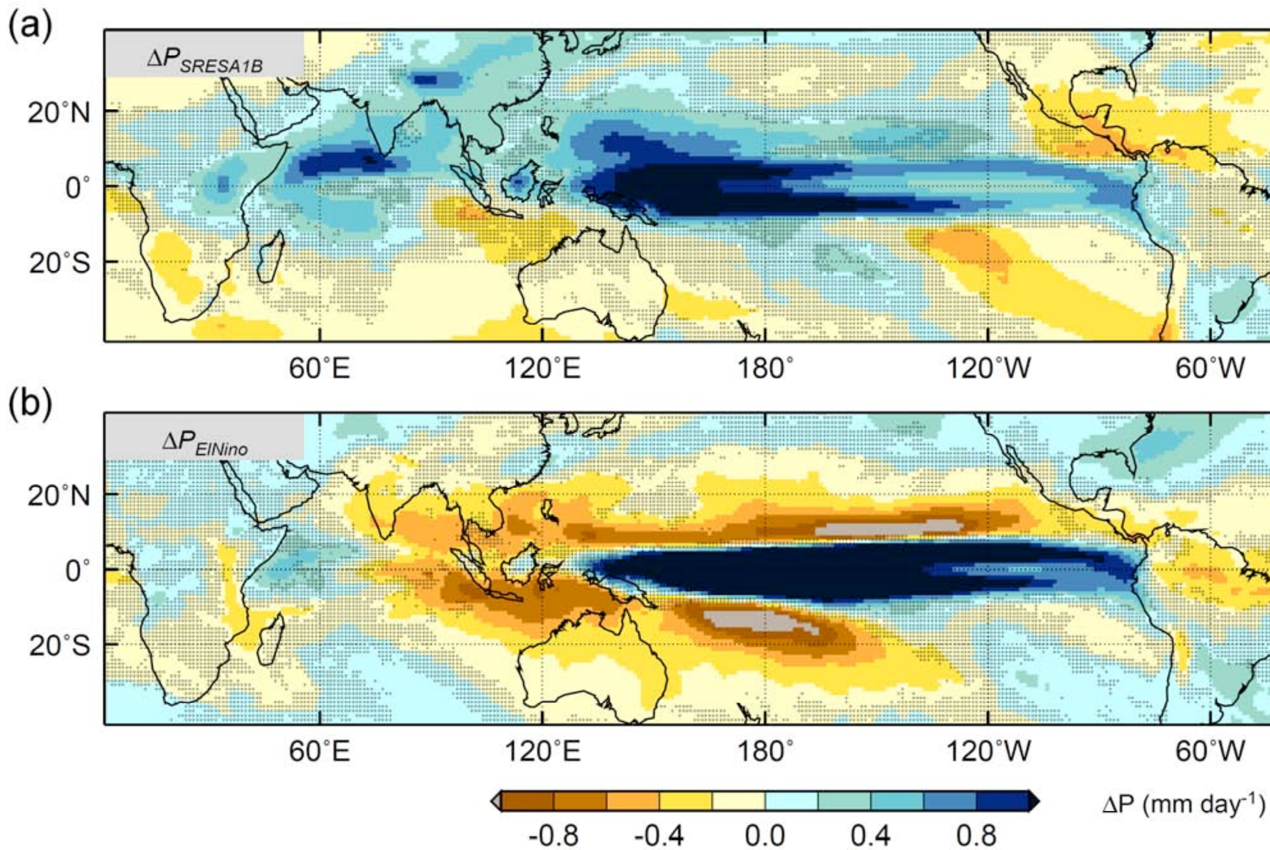
Full ocean GCMs



Vecchi and Soden (2007, J. Clim.)

Precipitation response: CO_2 and El Niño

multi-GCM Precipitation response to CO_2



multi-GCM Precipitation response to El Niño

DiNezio, Clement and Vecchi (2009, Submitted)

Outline

- Introduction/background
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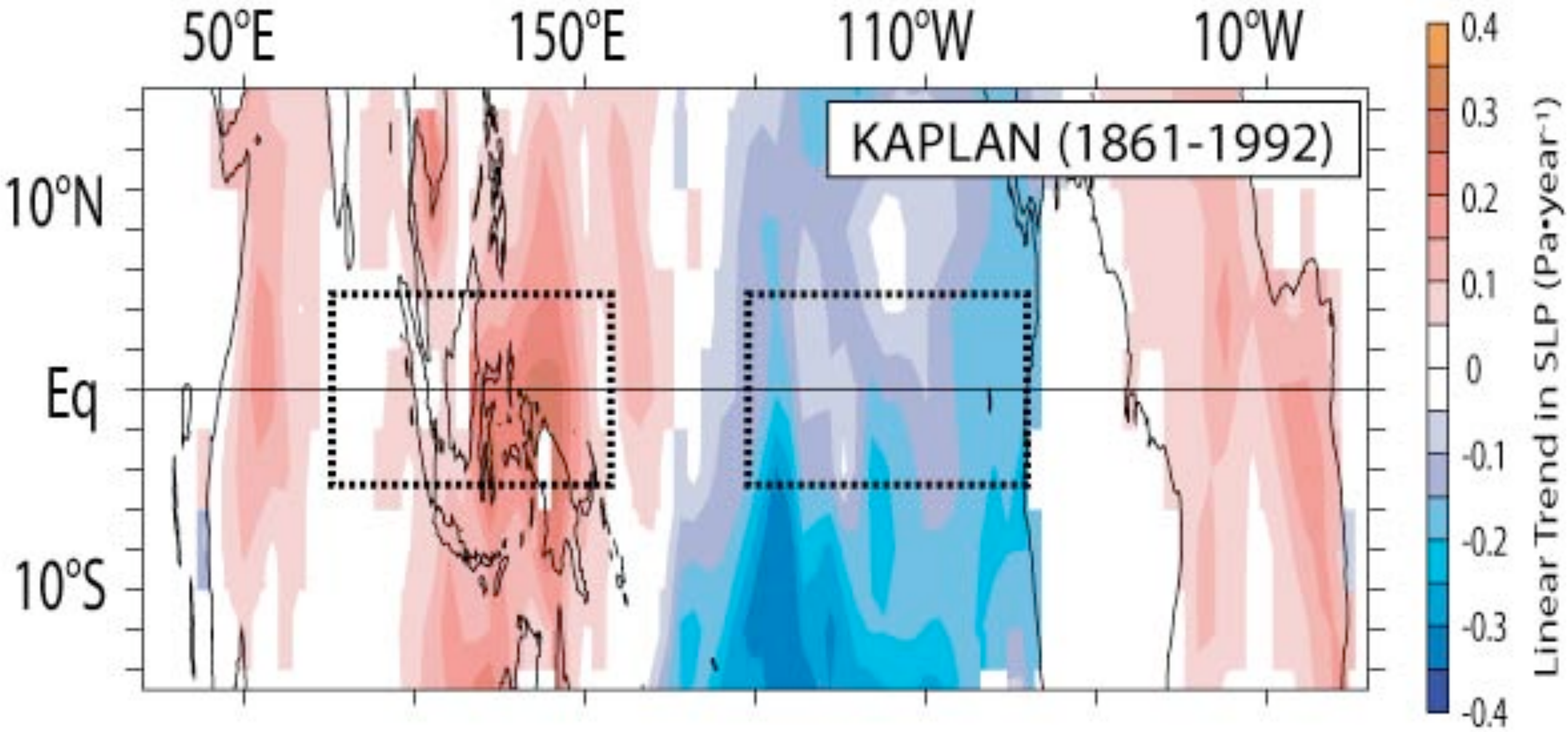
- Implications

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



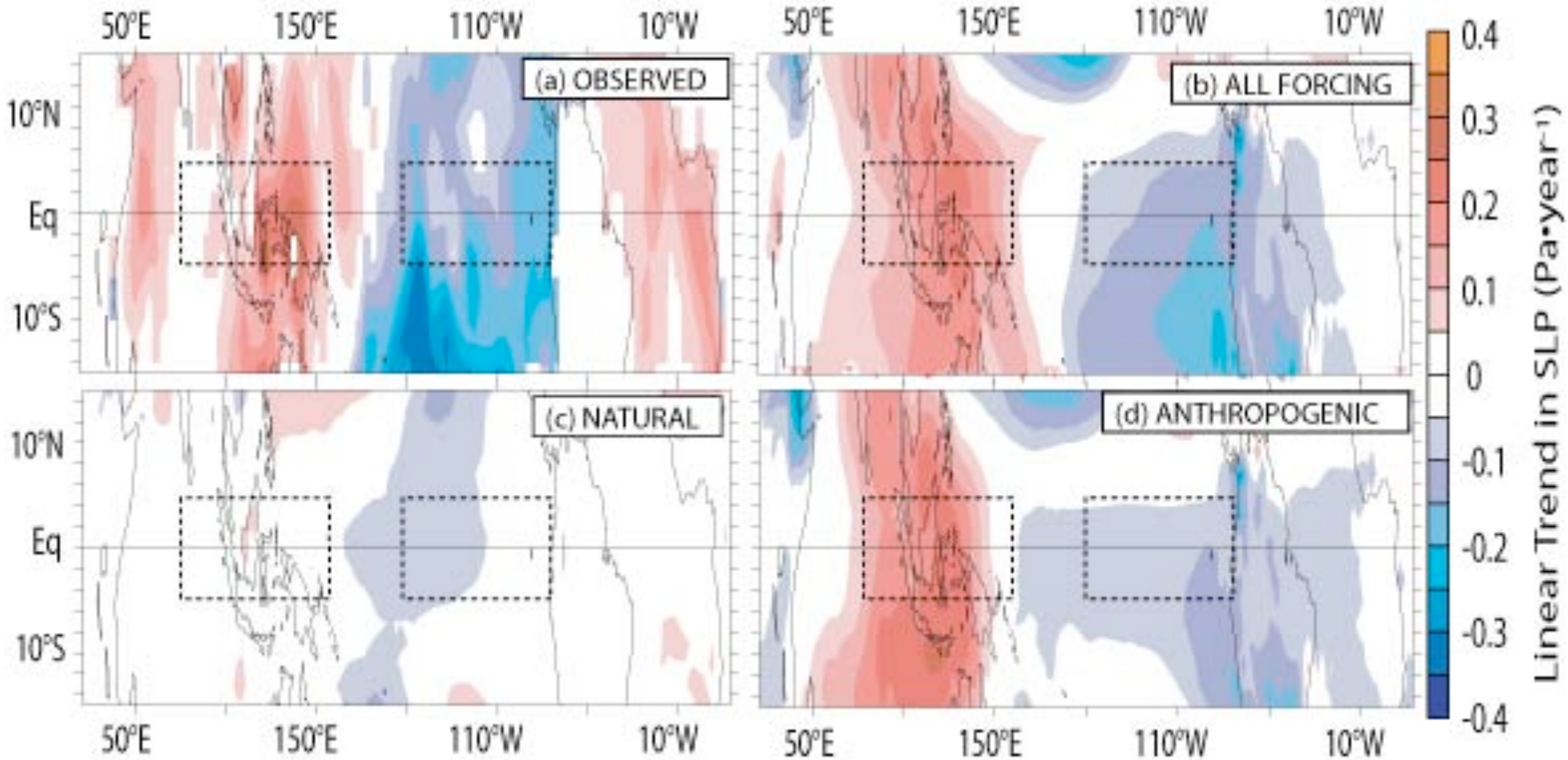
Reduction of E-W SLP gradient across Pacific.

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.

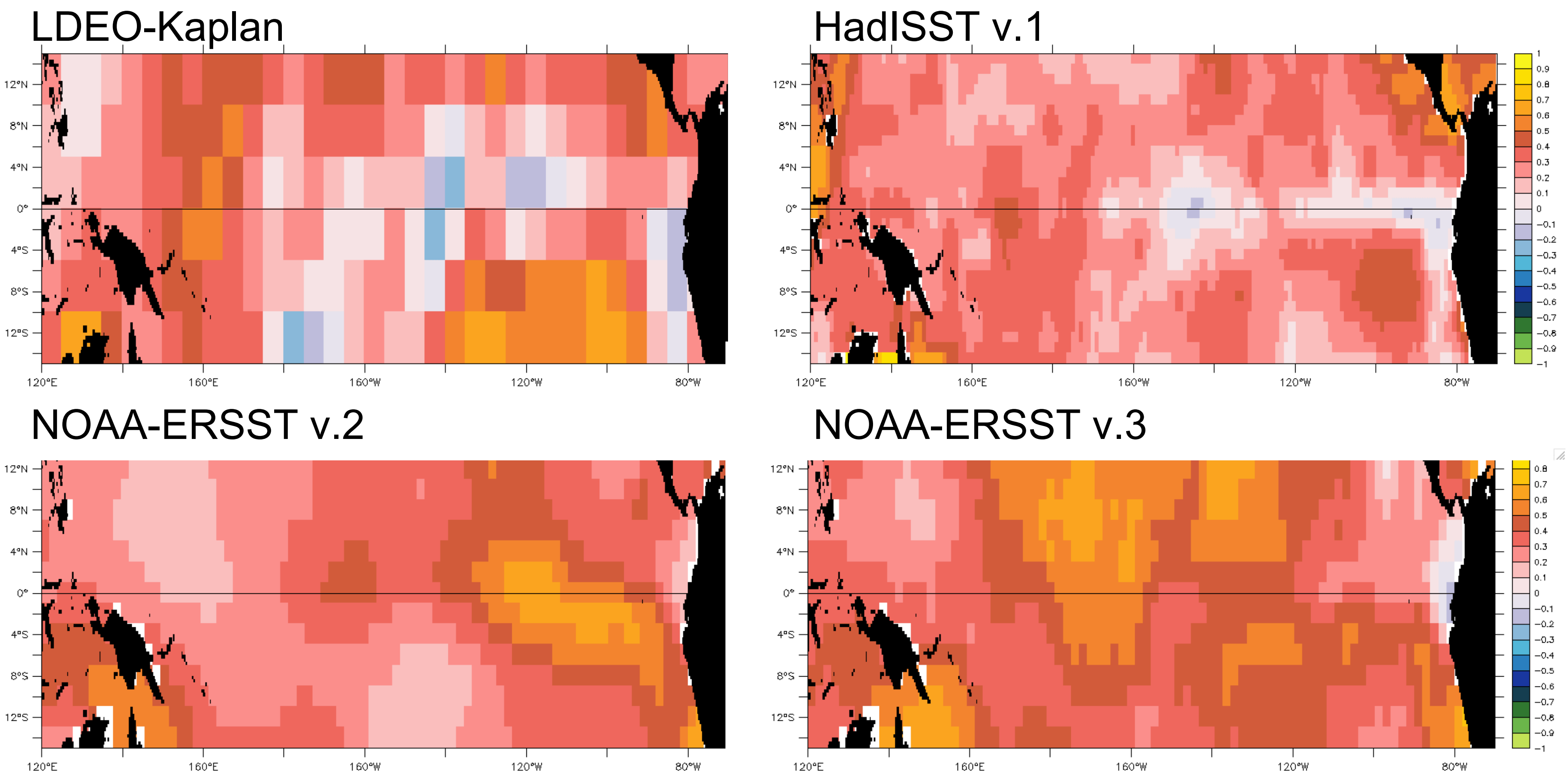


TRENDS COMPUTED 1861-1992

Vecchi et al (2006)

Look at SST?

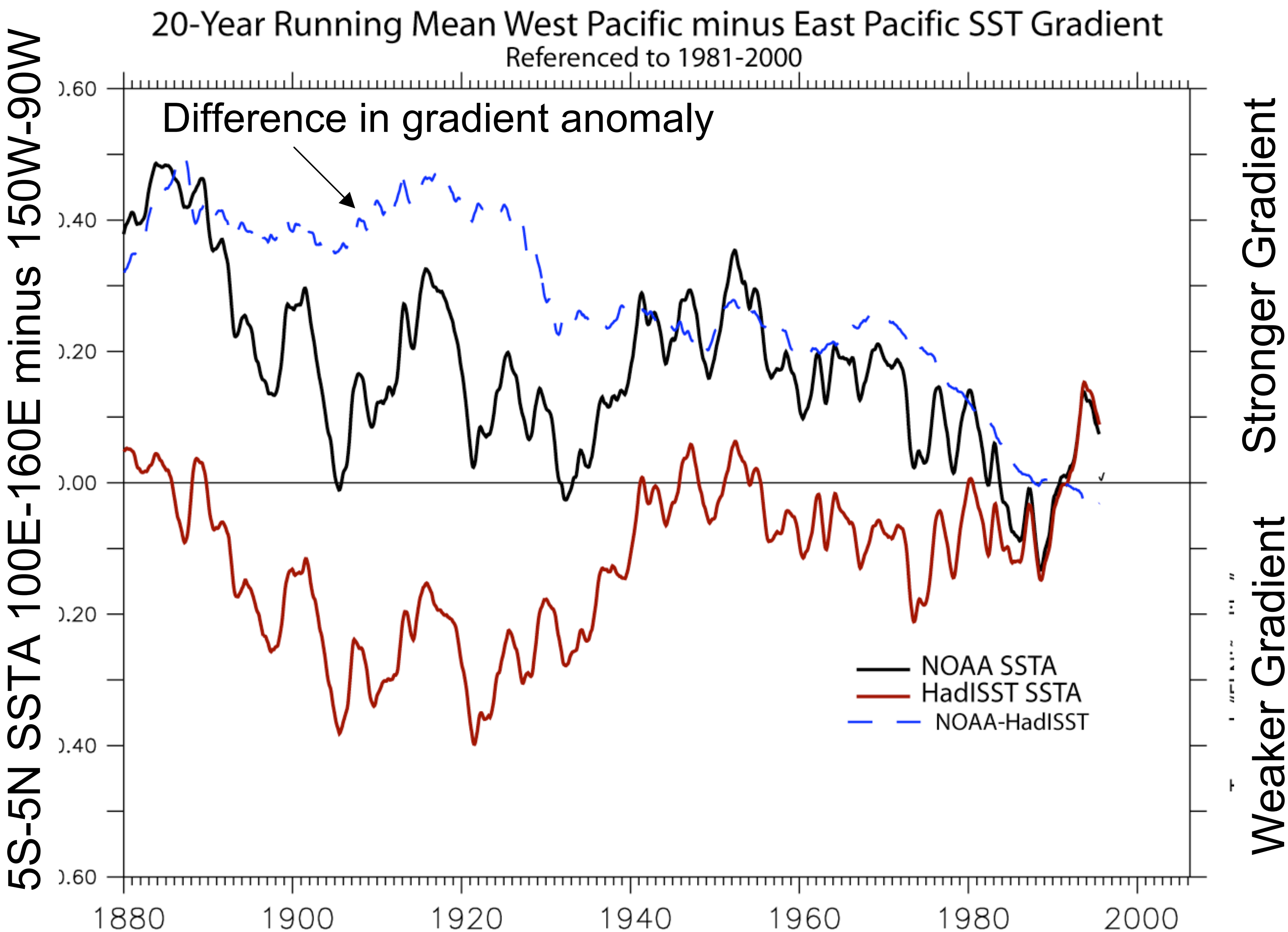
Linear trends (1880-2005) in four SST estimates.



Overall warming seen in all.
Structure dependent on reconsruction.

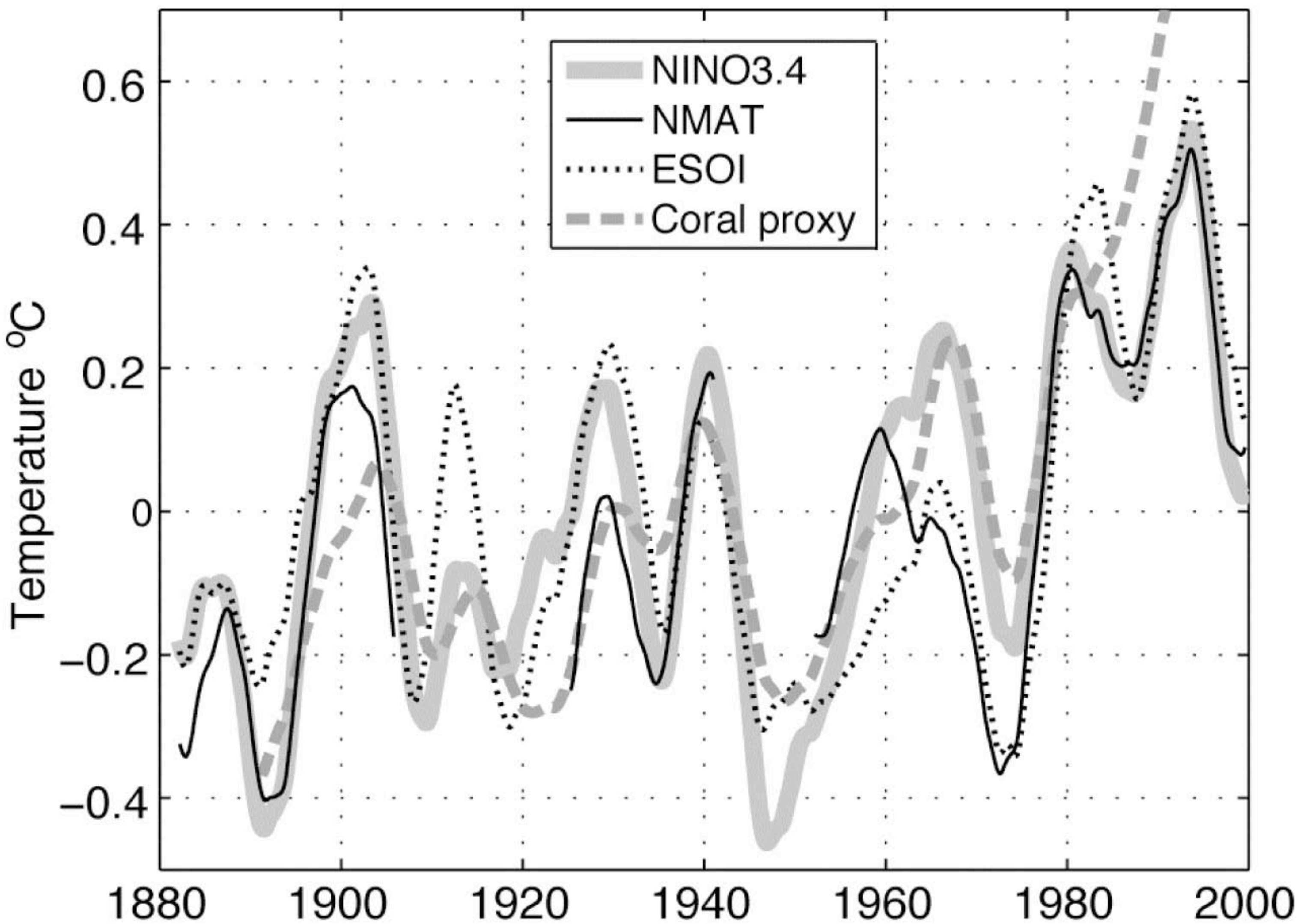
Adapted from Vecchi, Clement and Soden (2008, EOS)

When do differences between SST products emerge?



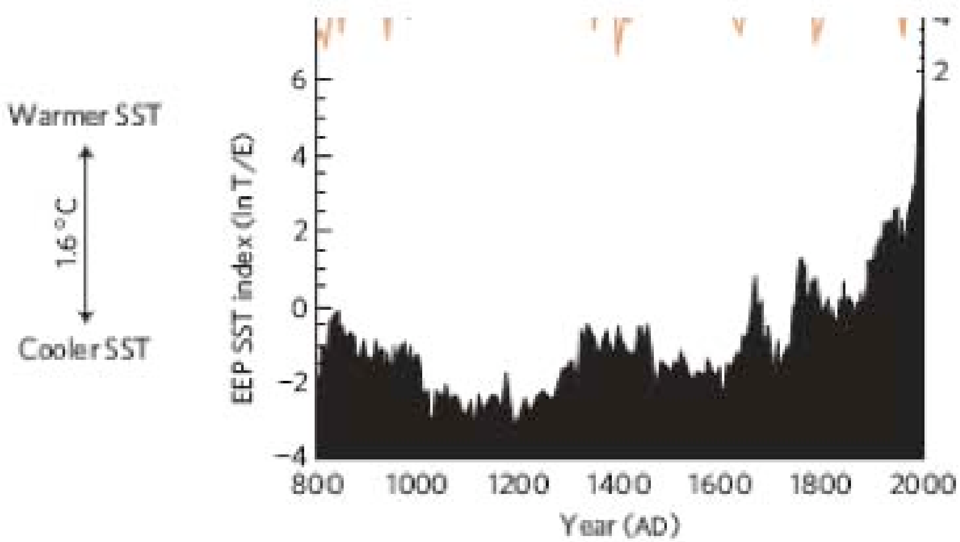
From Vecchi, Clement and Soden (2008, EOS)

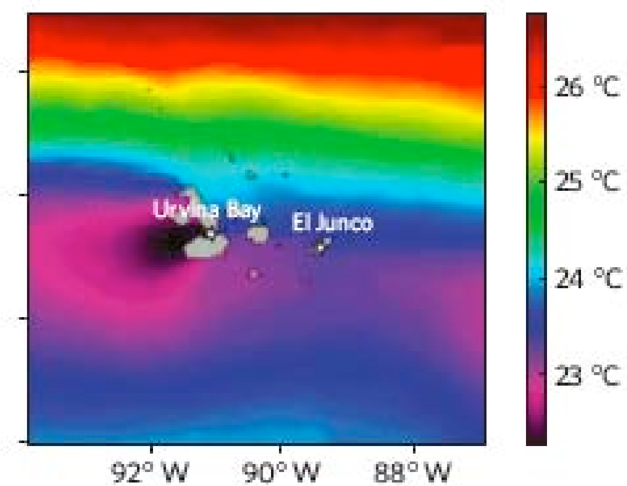
New "Pacific-centric" analysis



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

Lake Sediment Record
El Junco Lake, Galapagos

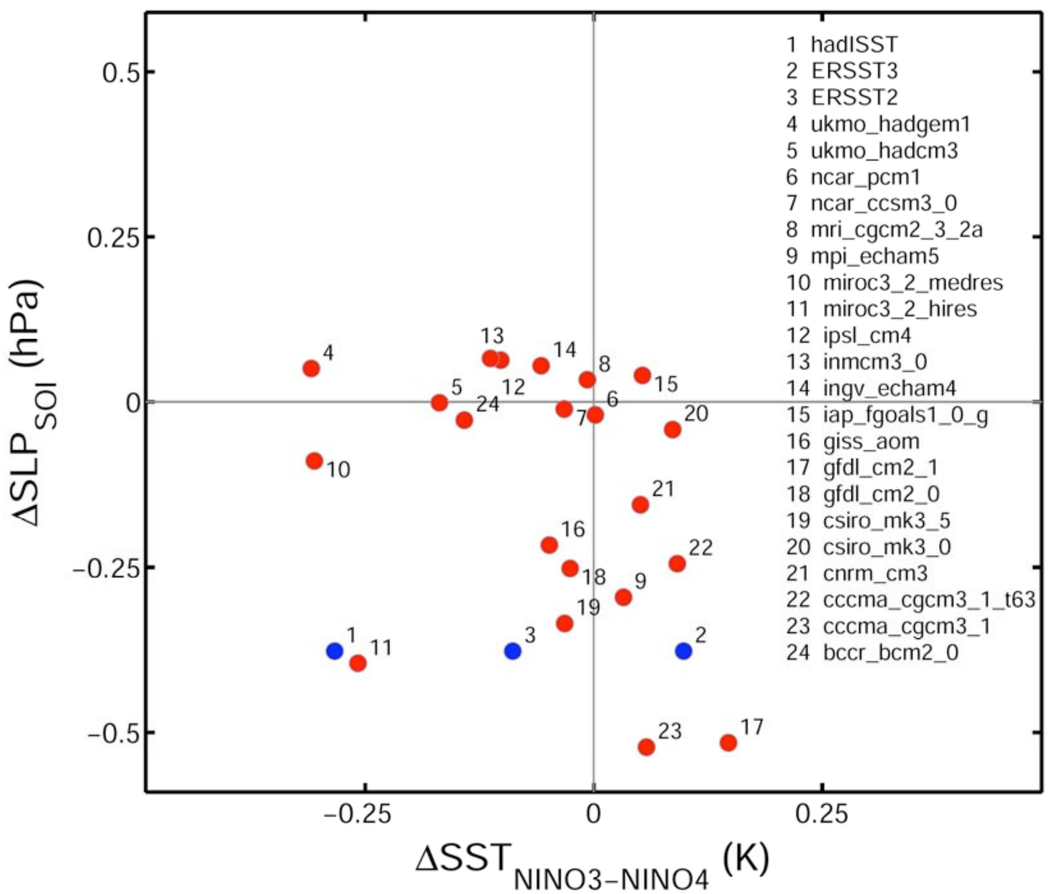




Conroy et al (2009, Nature. Geosci.)

- Indicate warmer(wetter) East Pacific in 20th Century.
- Interpretation of similar records still ongoing (Sachs et al 2009, …)

Climate Change: Gradient of SST vs. Gradient of SLP

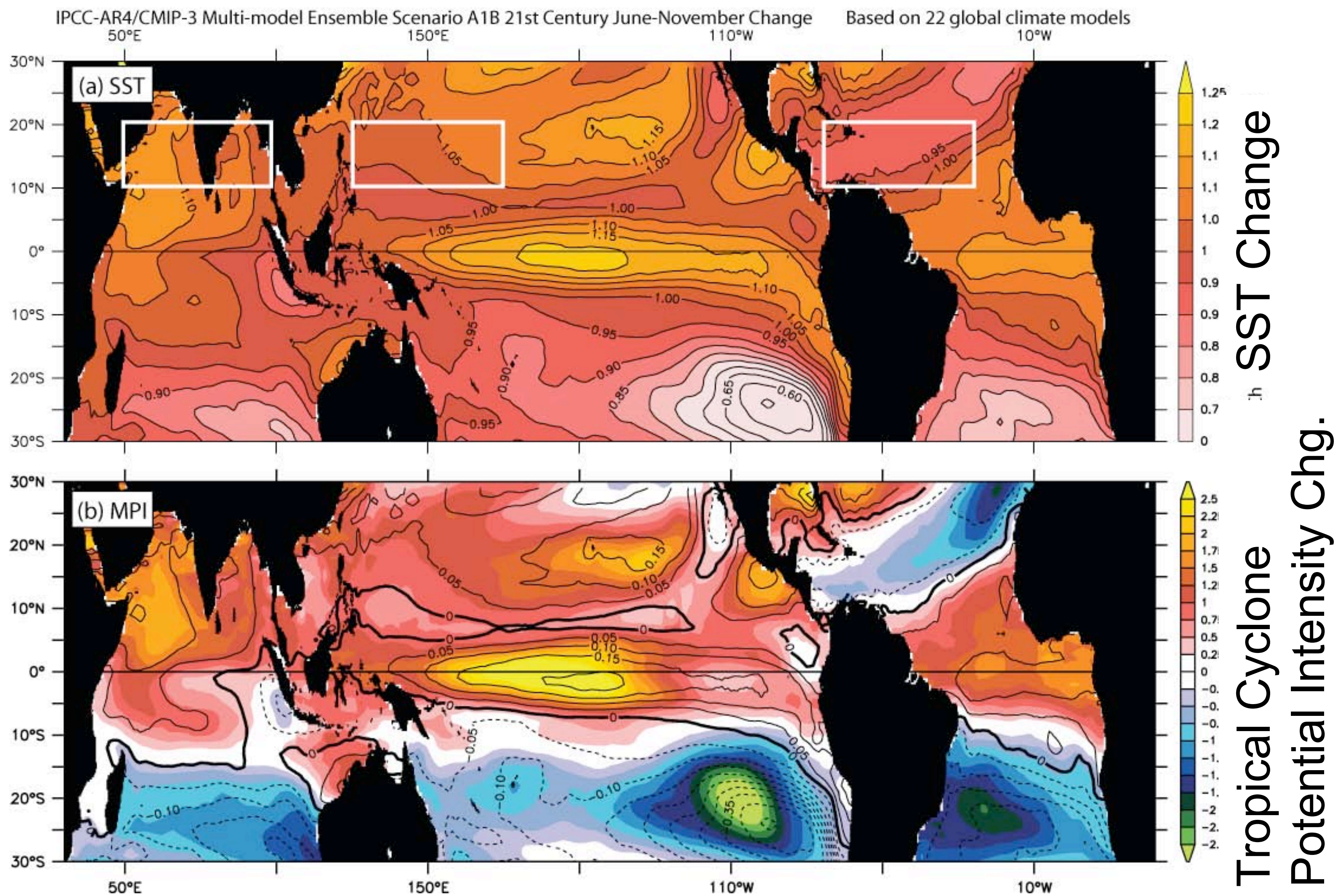


- 20th Century GCM response.
- Observed.

SST Gradient not a strong constraint on models.

DiNezio, Clement and Vecchi (2009, Submitted)

Structure of SST Change Matters, Example:
SST structure controls cyclone potential intensity change



From Vecchi and Soden (2007 Nature)

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-like" a very imperfect analogue
    - Although some aspects of the mean ocean/atmosphere climate more "El Niño-like".
  - Weaker Walker is not physically related to El Niño:
    - Driven by global energy/mass constraints
    - Dynamical ocean changes act against atmospheric changes.
  - And some changes not "El Niño-like":
    - 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?

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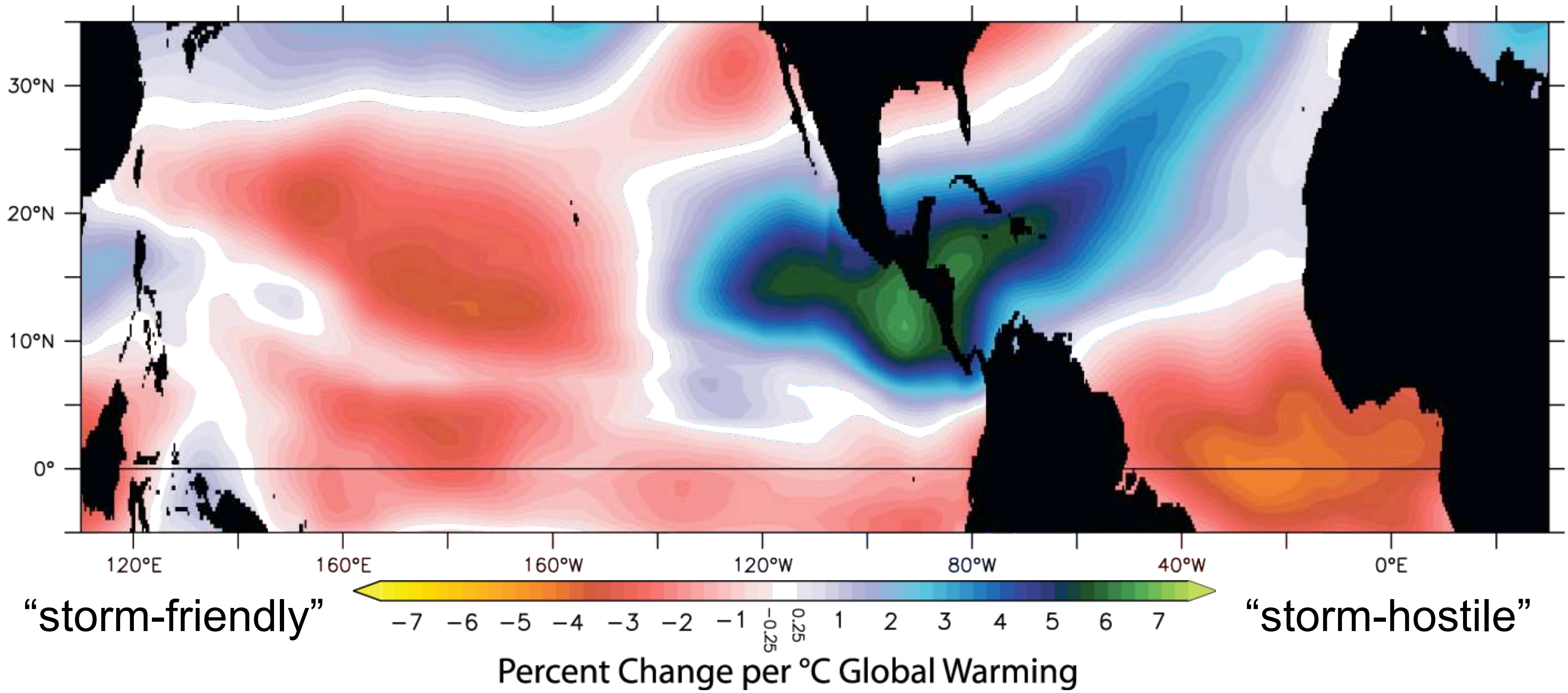
Projected 21st Century Changes in Vertical Wind Shear

from Vecchi and Soden (2007, GRL)

Average of 18 models, Jun-Nov

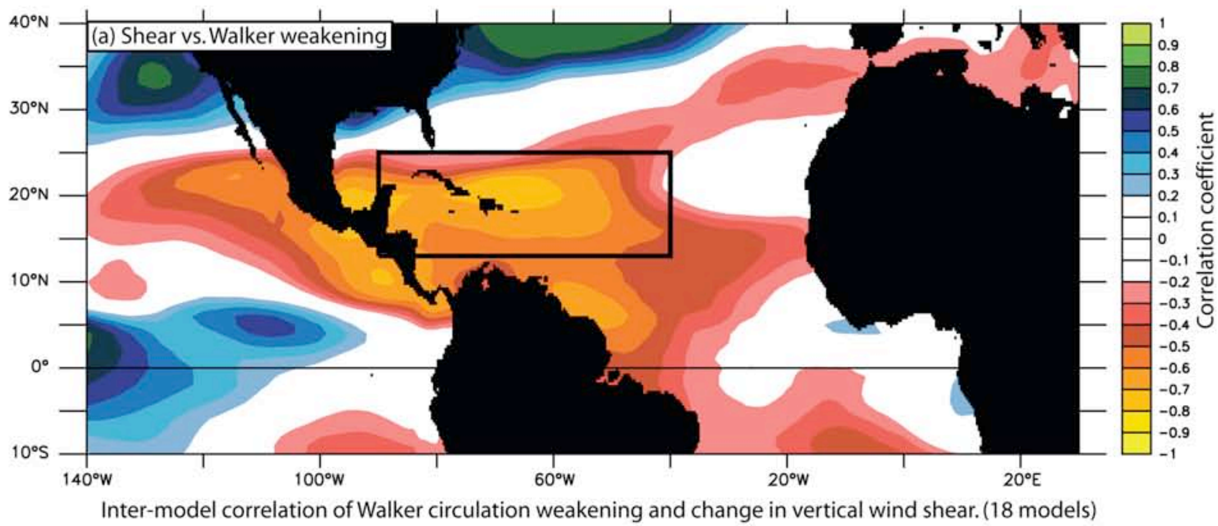


Over swath of tropical Atlantic and East Pacific, increased wind-shear.

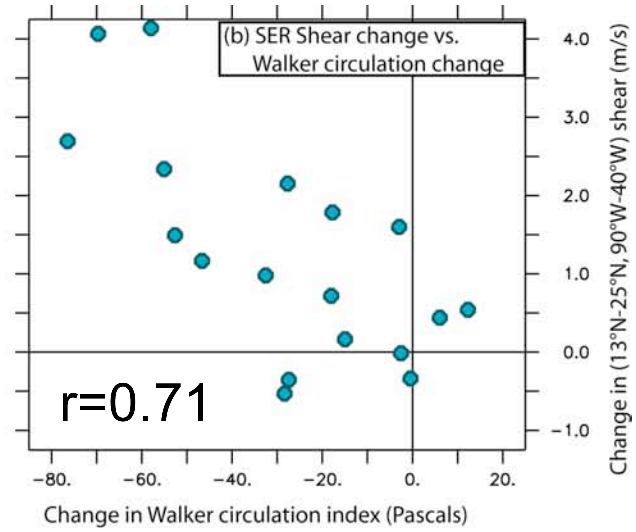
What is net effect of increased potential intensity and wind shear?

V_s and Pacific Walker Circulation

Correlation of local shear change with Pacific Walker weakening across models



Walker circulation vs. shear change



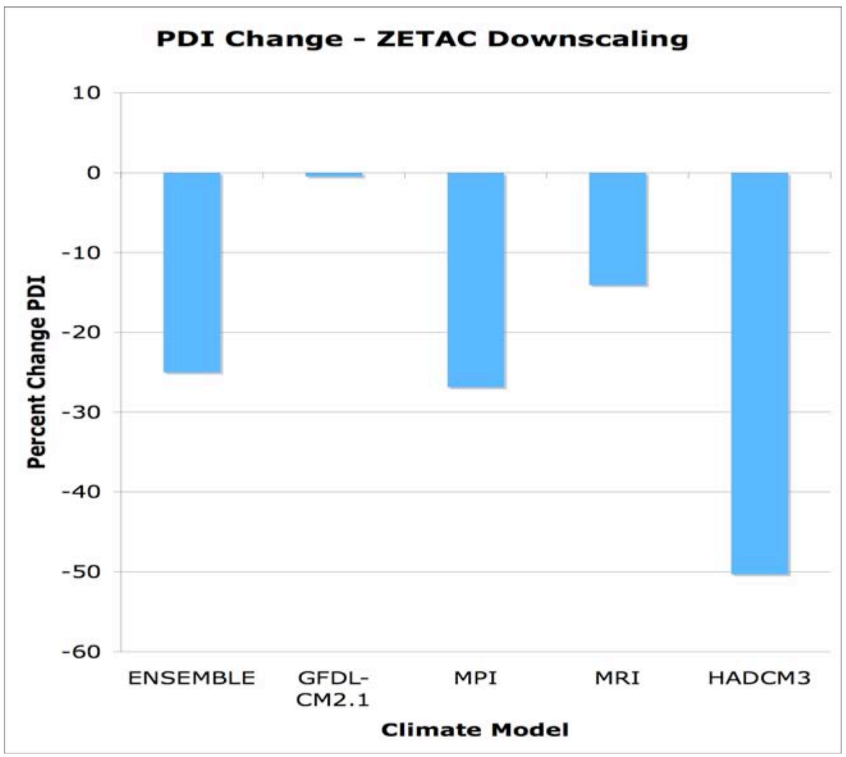
Models with largest Walker weakening have largest shear enhancement.

From Vecchi and Soden (2007, GRL)

High-resolution hurricane model projections

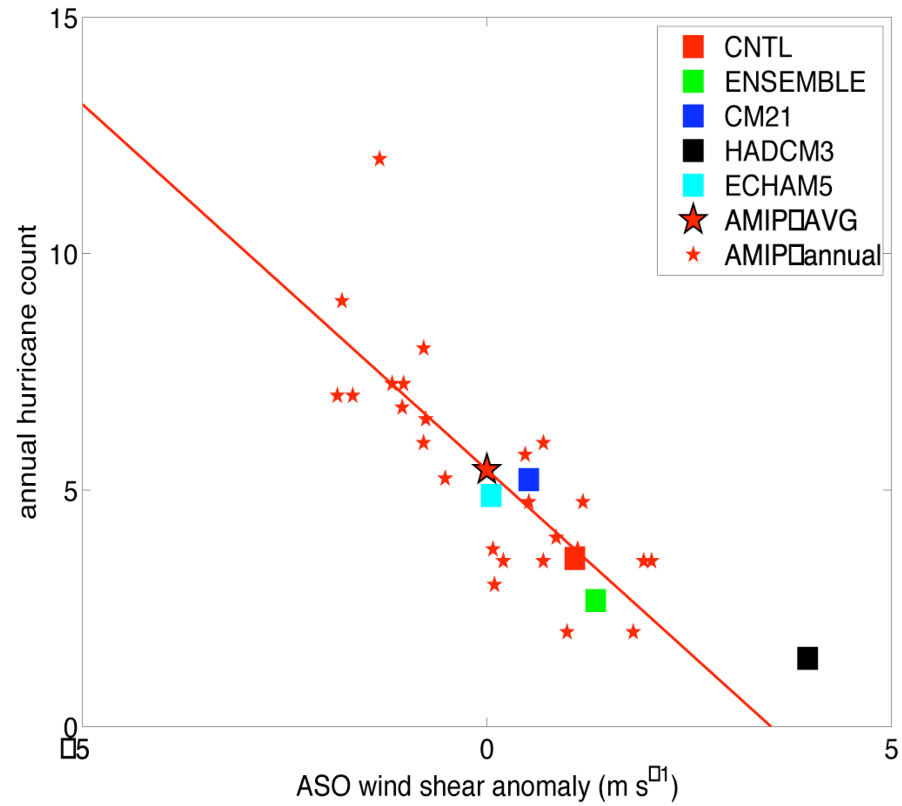
Increased shear Associated with Reduced Atlantic Hurricane Activity

Regional downscaling

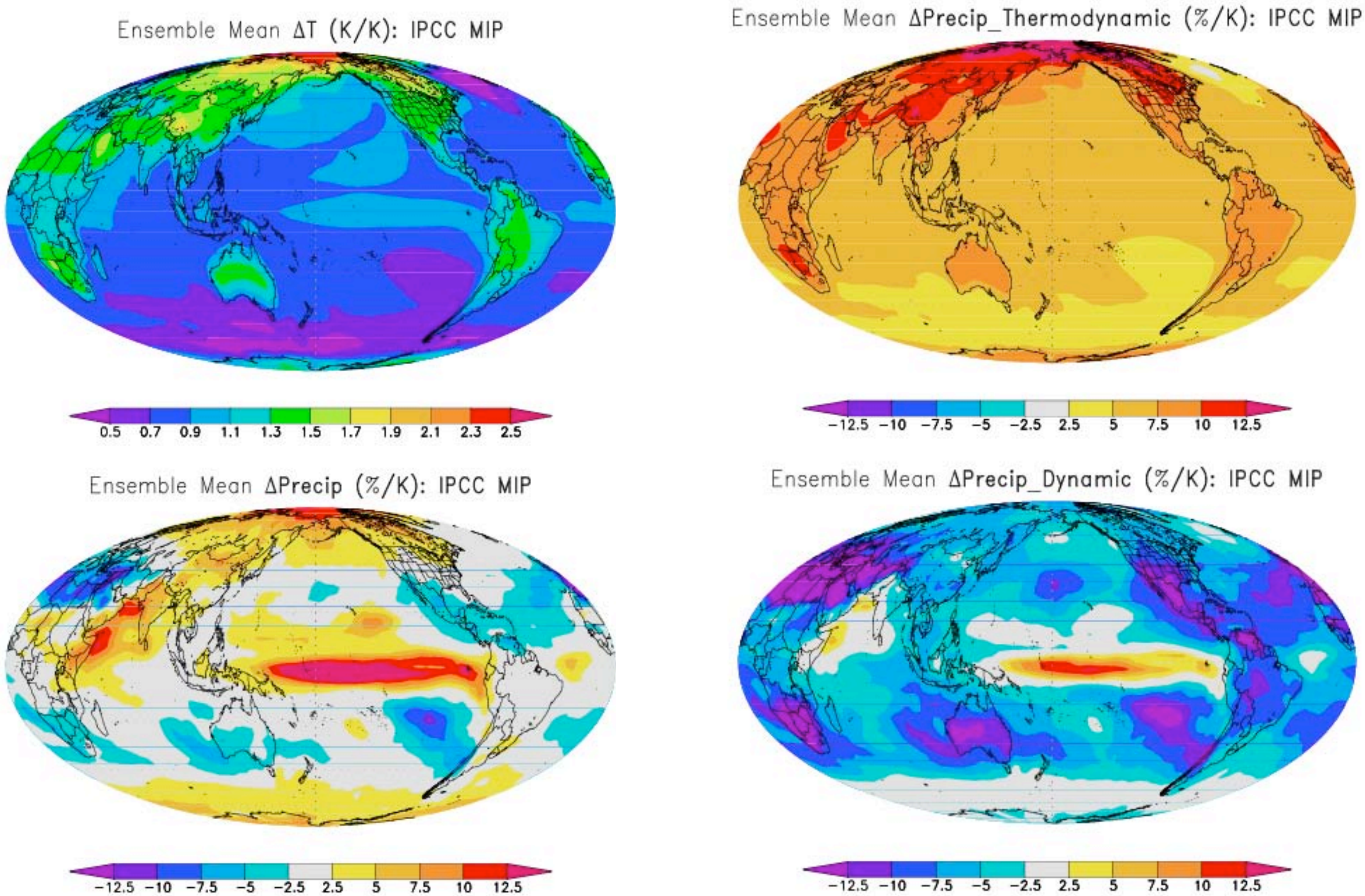


Adapted from
Knutson et al (2008, Nature Geosci.)

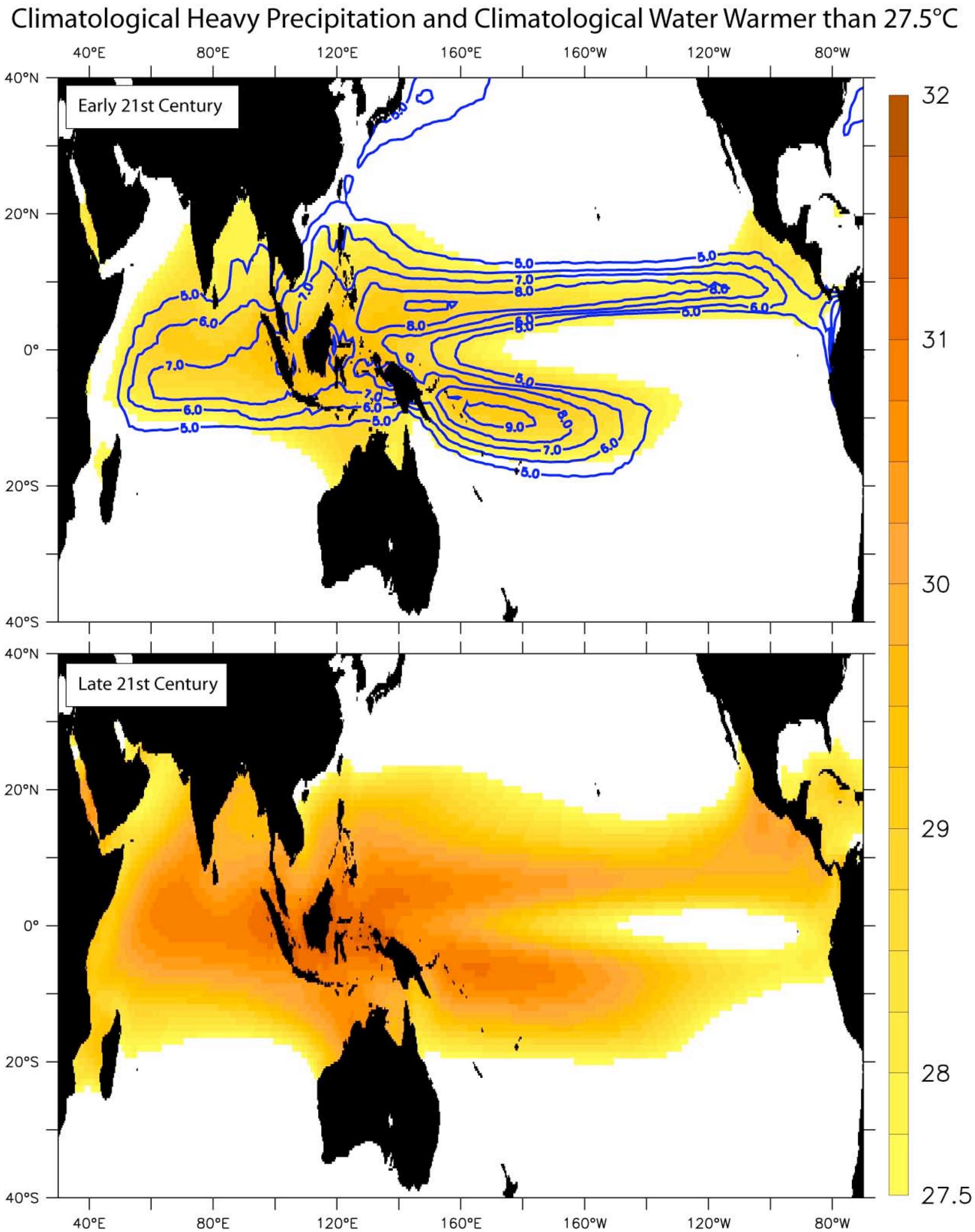
Global downscaling



Zhao et al (2009, J. Clim.)



Ensemble Mean ΔT (K/K): IPCC MIP
0.5 0.7 0.9 1.1 1.3 1.5 1.7 1.9 2.1 2.3 2.5
Ensemble Mean ΔPrecip_Thermodynamic (%/K): IPCC MIP
−12.5 −10 −7.5 −5 −2.5 2.5 5 7.5 10 12.5
Ensemble Mean ΔPrecip (%/K): IPCC MIP
−12.5 −10 −7.5 −5 −2.5 2.5 5 7.5 10 12.5
Ensemble Mean ΔPrecip_Dynamic (%/K): IPCC MIP
−12.5 −10 −7.5 −5 −2.5 2.5 5 7.5 10 12.5



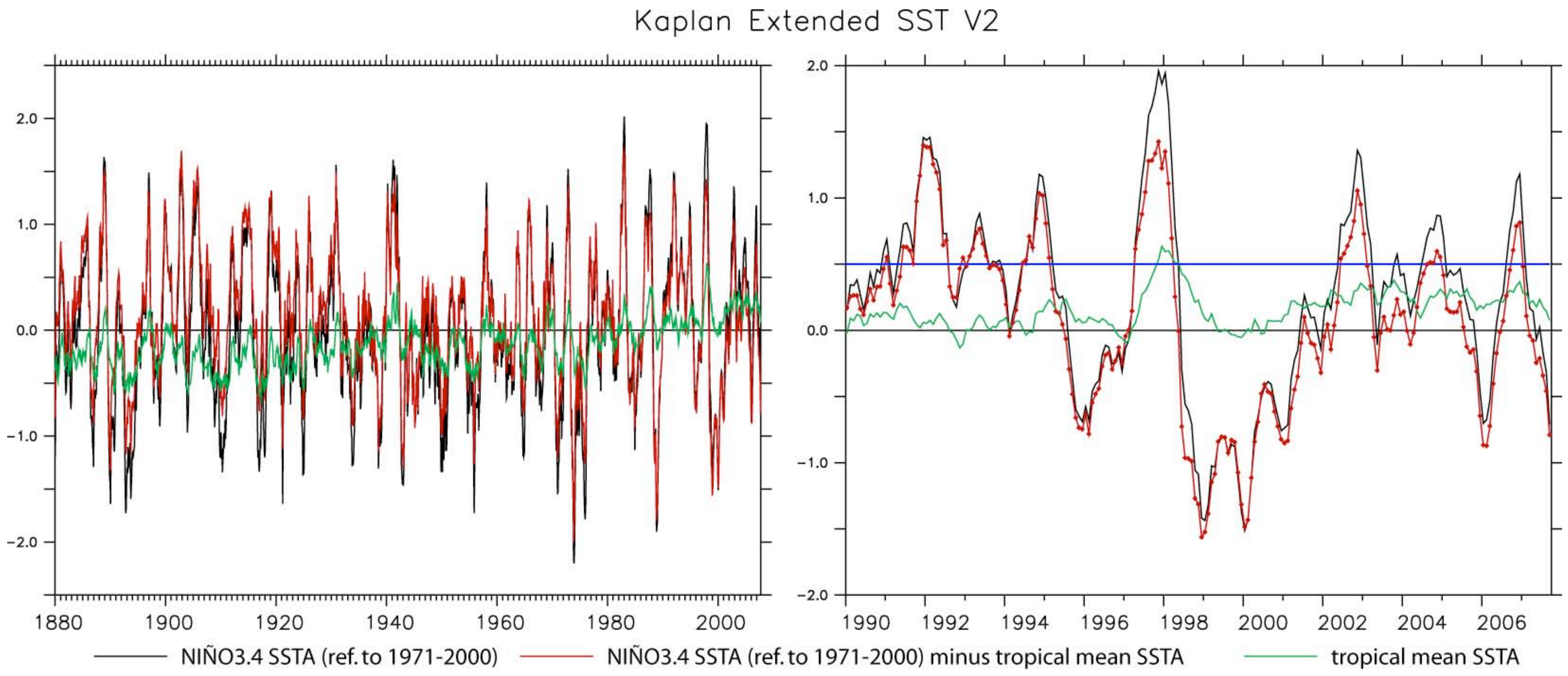
Precipitation and Warm SST

Strong precipitation tends to overlie waters warmer than 27.5°C

Waters warmer than 27.5°C projected to expand considerably under global warming:

Expansion of strong rainfall?

Indices in a Changing Climate: ENSO



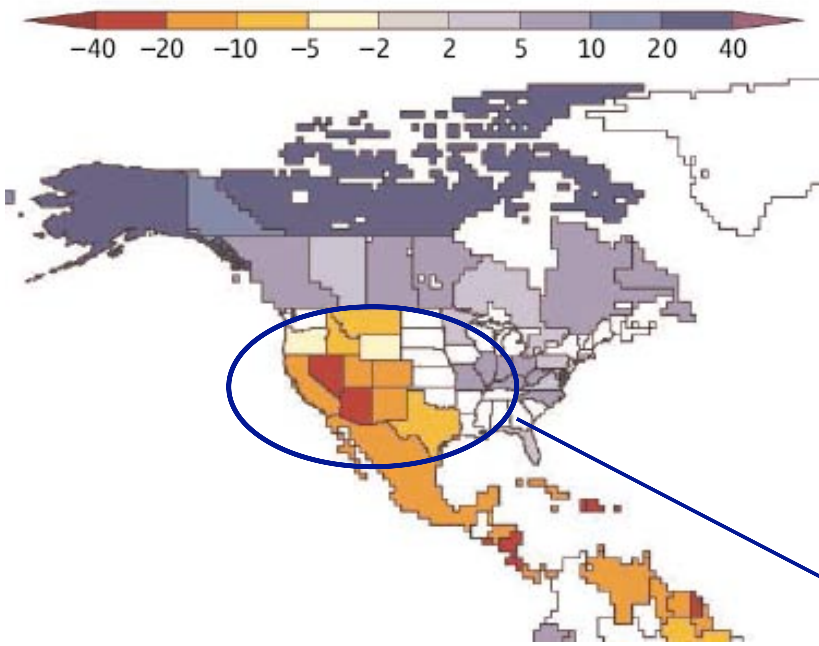
- Tropics have been warming, expected to continue to warm.
  - Part of NIÑO3.4 warm anomalies due to tropical-mean

- But, ENSO impacts tropical-mean SST…so not unidirectional.

- Should tropical-mean warming be included or not for interannual?
- What if radiatively-forced warming not homogeneous?
  - Could we define ourselves into a “permanent El Niño”?

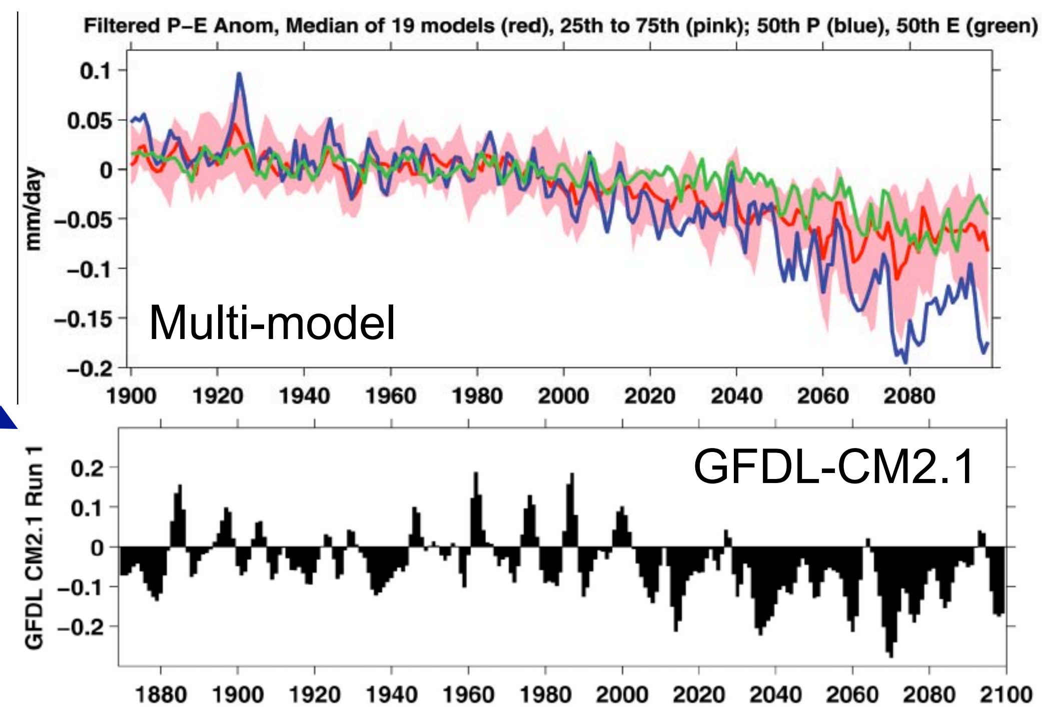
Southwest Drying Projections

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.

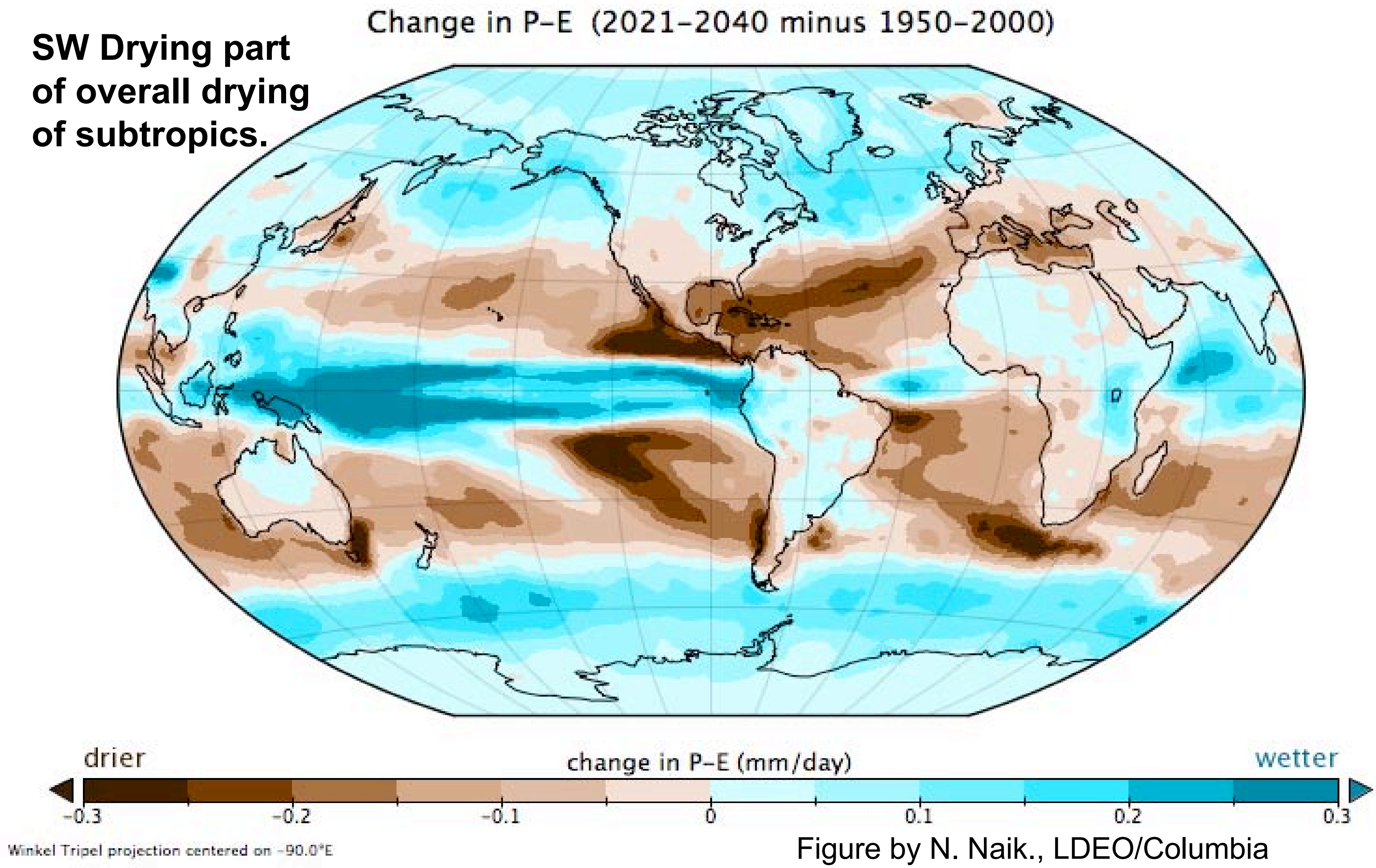


Figure by N. Naik., LDEO/Columbia

Mechanisms for CO_2-Forced Drying

Thermodynamic Control:

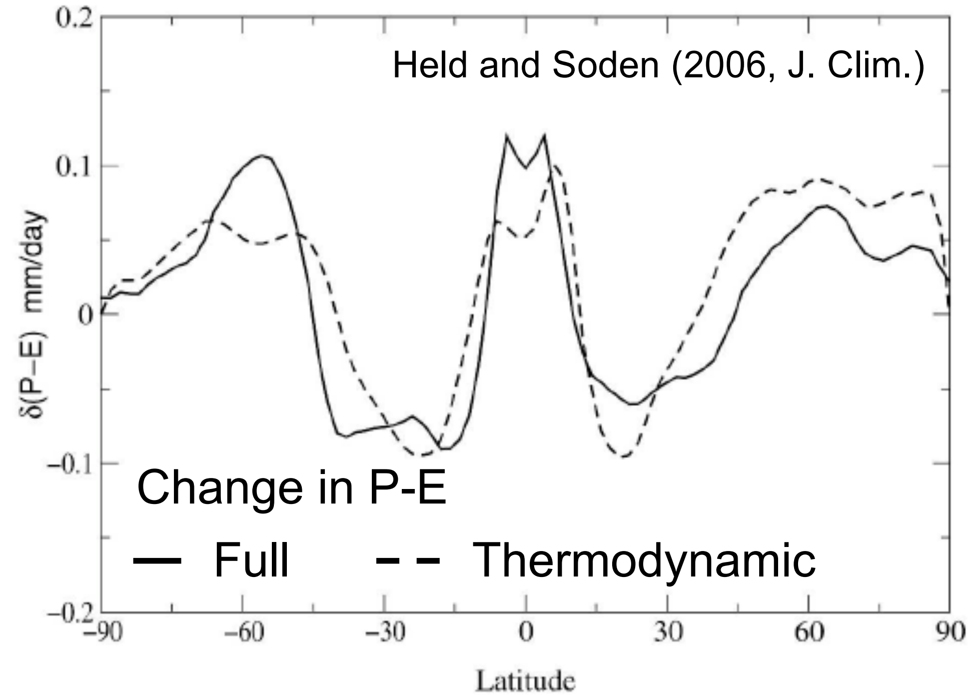
Warming (increase q_{sat})

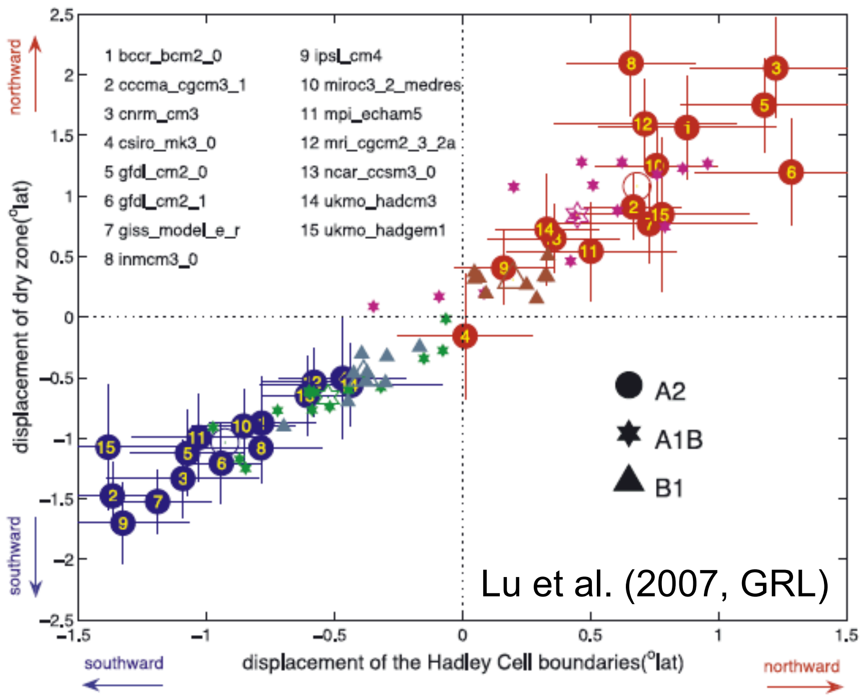
↓

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.

Conclusions

- **"Wet get wetter, dry get drier" and "Poleward expansion of dry zones"**

- **Weaker tropical circulation.**
  - Connected to sub-Claussius-Clapeyron rate of:
    - Increase in radiative cooling
    - Increase in surface radiative imbalance

- **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? Source of discrepancies needs to be understood

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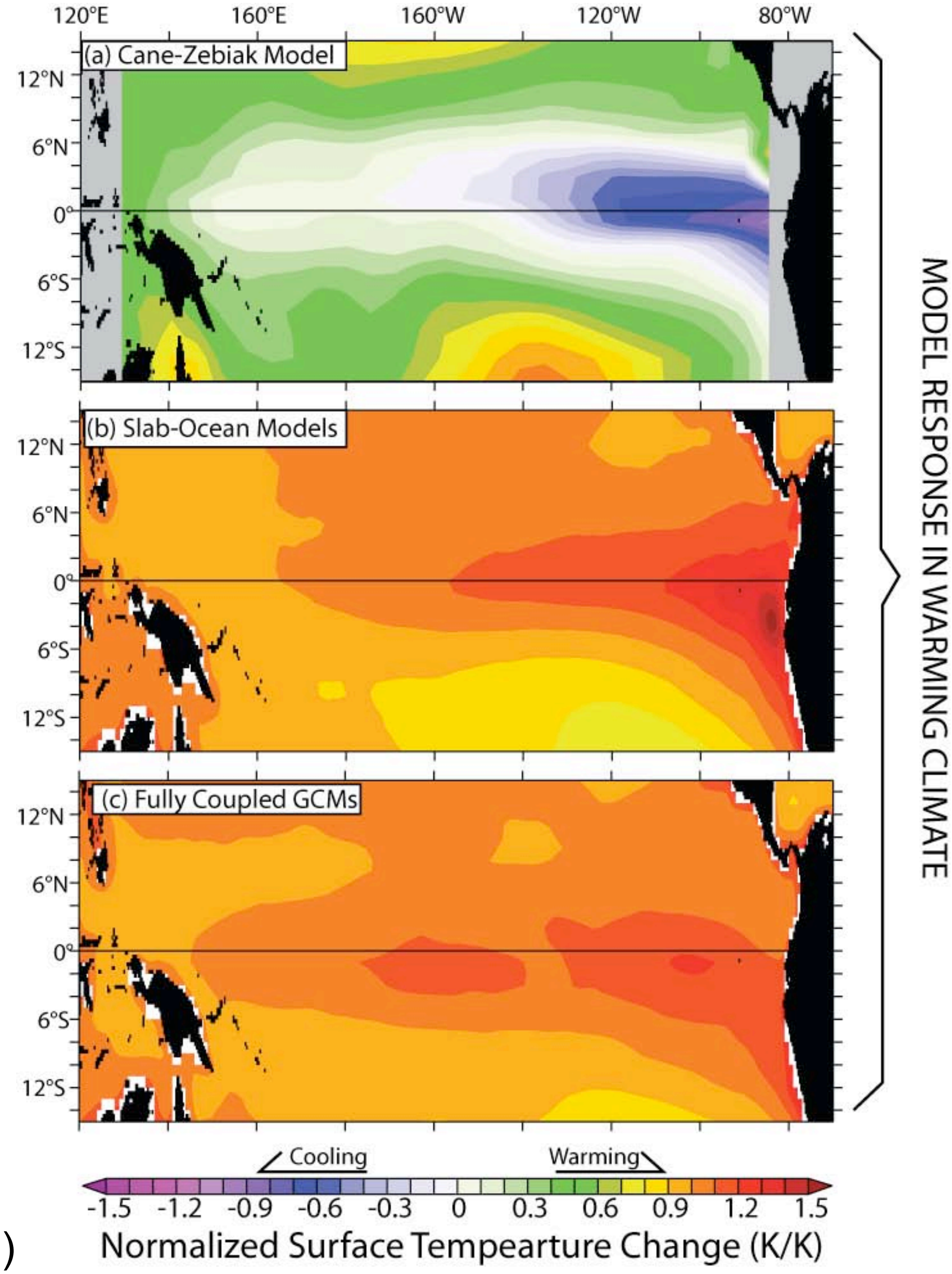
Modeled SST Response to Heating

Simplified atmosphere
(forced by uniform heating)

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

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

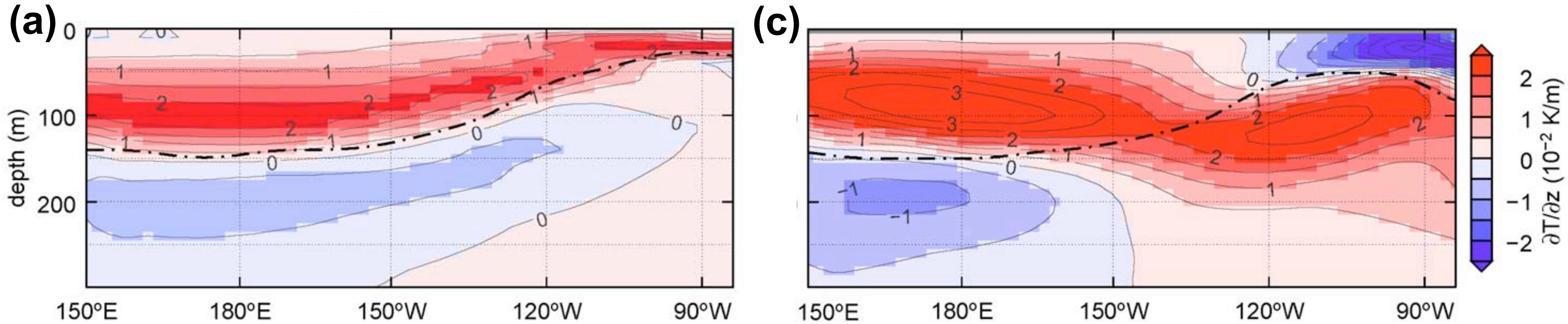


From Vecchi, Clement and Soden (2008, EOS)

T(z): ENSO vs. GW

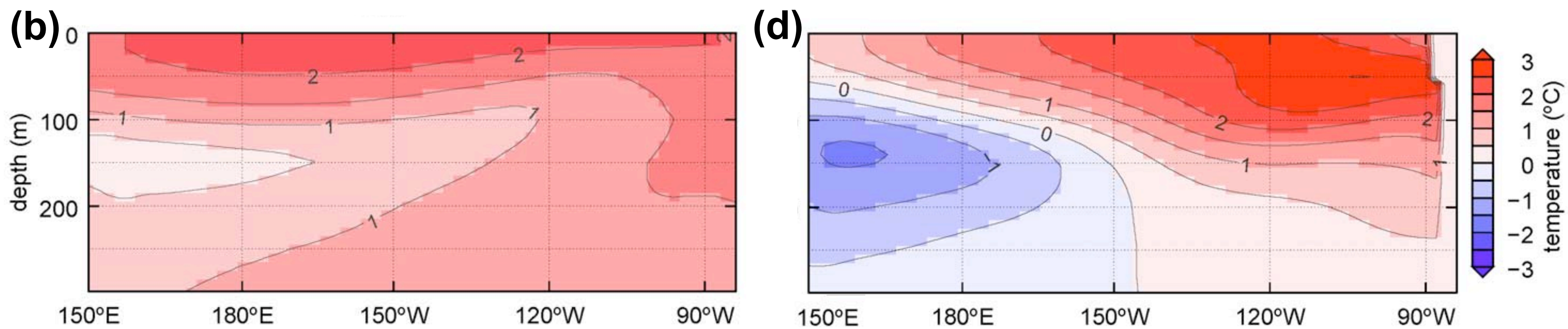
Change in Vertical T Gradient

GW El Niño

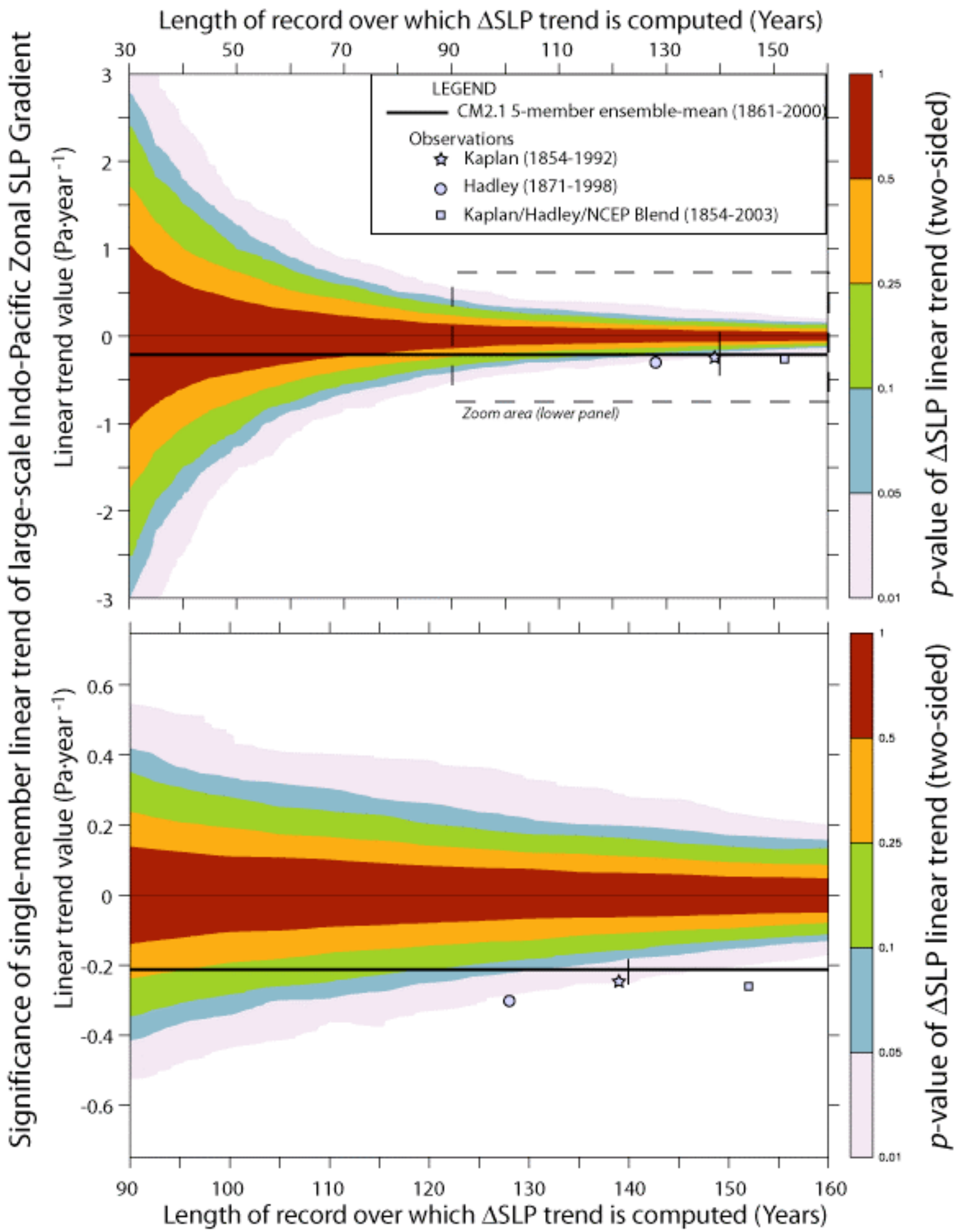


Change in Temperature

GW El Niño

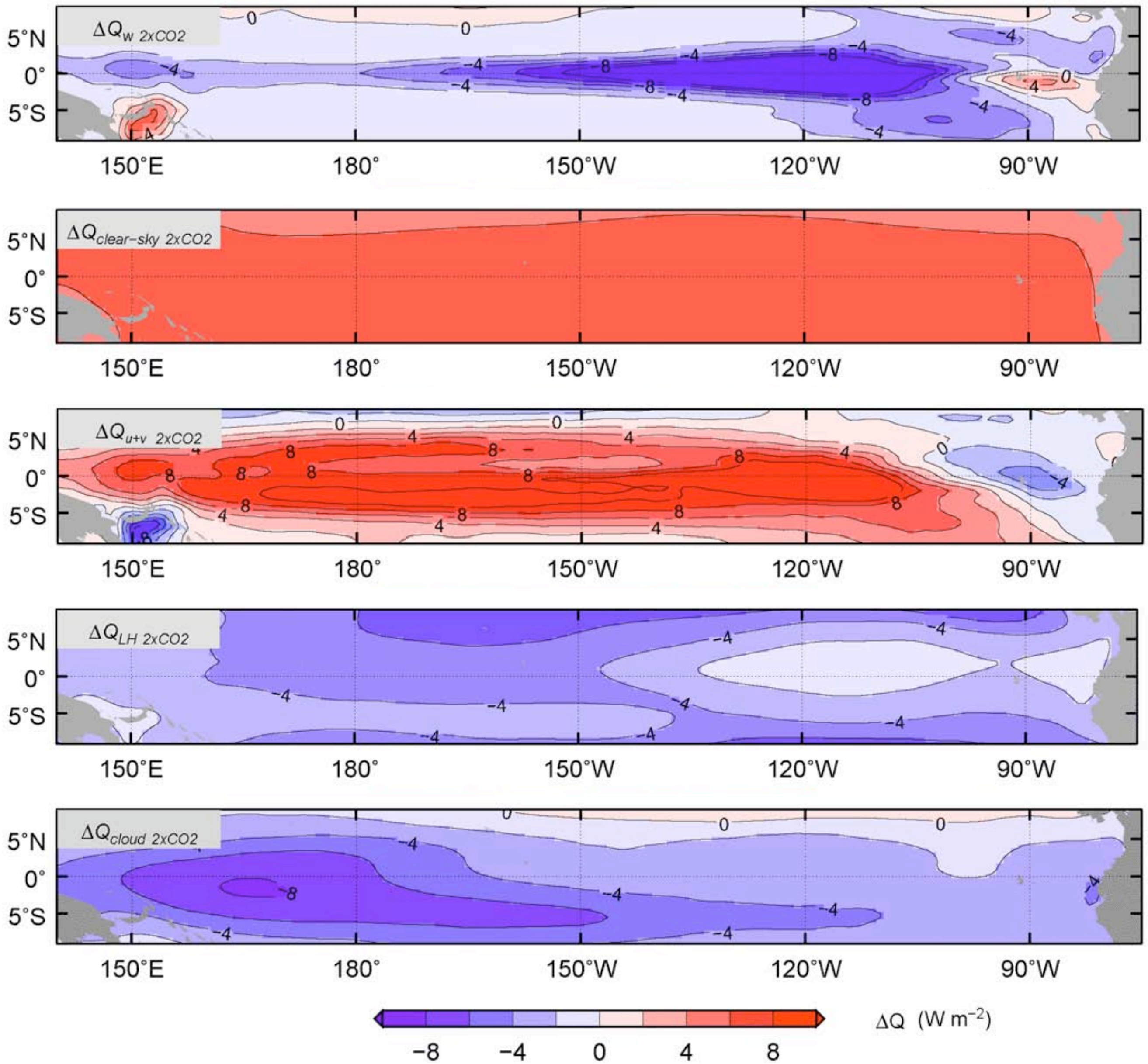


DiNezio et al (2009, J. Clim.)



For trends in ΔSLP of the amplitude projected by CM2.1 for the period 1860-2000, record lengths less than 100-120 years are insufficient for detection.

Mixed-layer heat balance in response to GW



Ocean vert.

Clear-sky

Ocean horiz.

Latent

Clouds

DiNezio et al (2009, J. Clim.) (positive is into the ocean, i.e. heating)