Weaker Tropical Circulation in Response to Warming: Oceanic and Atmospheric Feedbacks

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I.M. Held., A.T. Wittenberg, P. DiNezio

- 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)

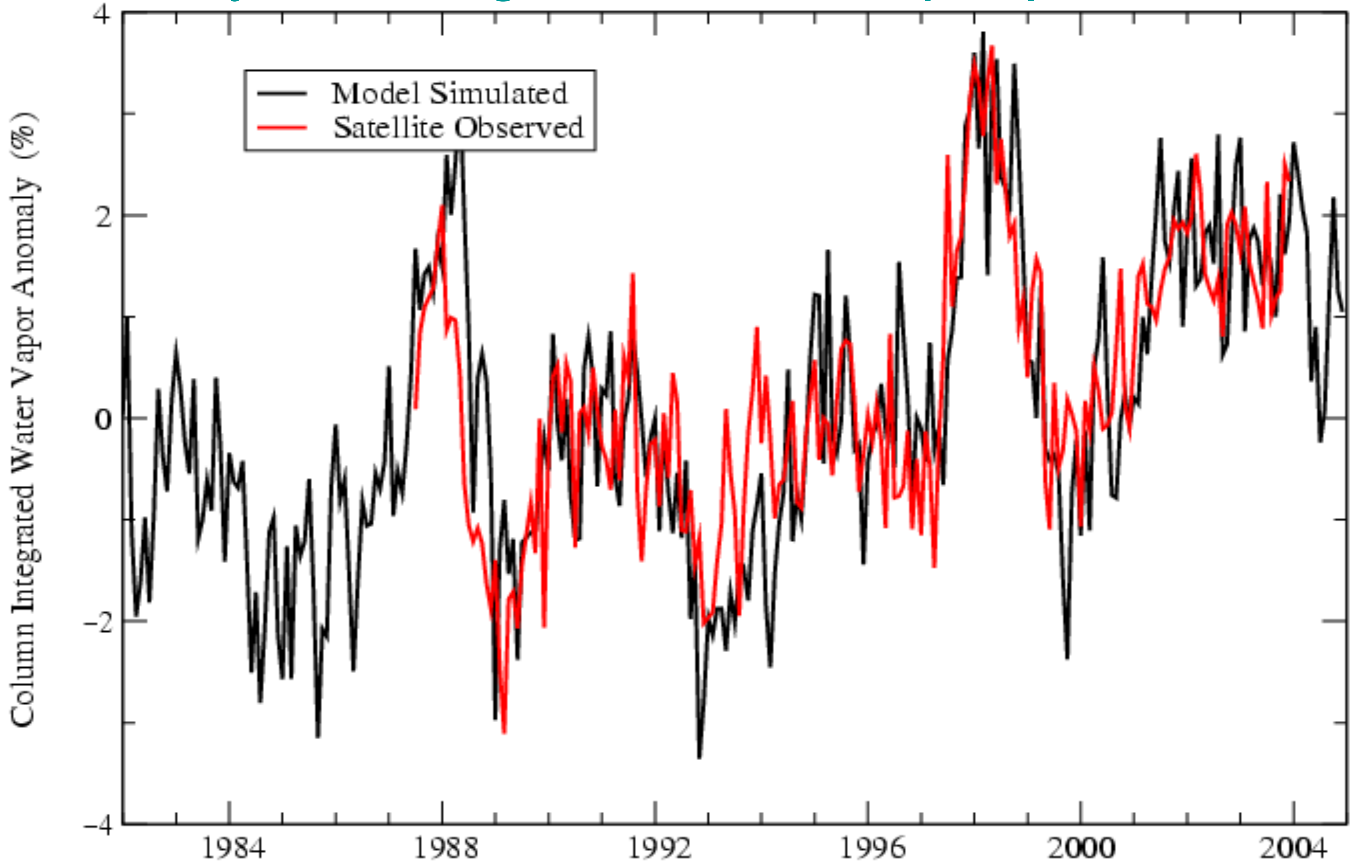
Broader Objective

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)

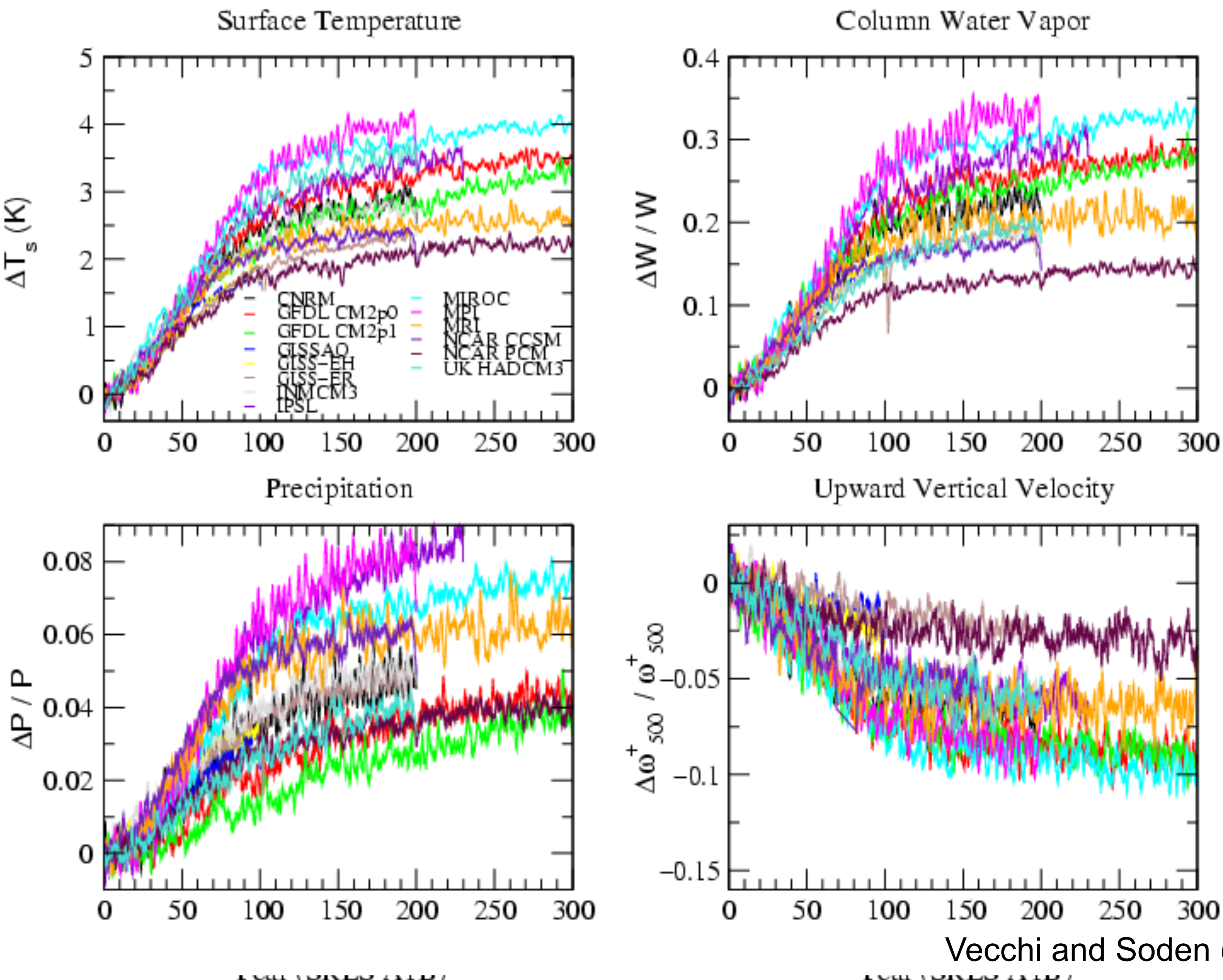
Held and Soden (2006, J. Clim)

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**
    - Oceanic constraint
    - Atmospheric constraint
- Modeling
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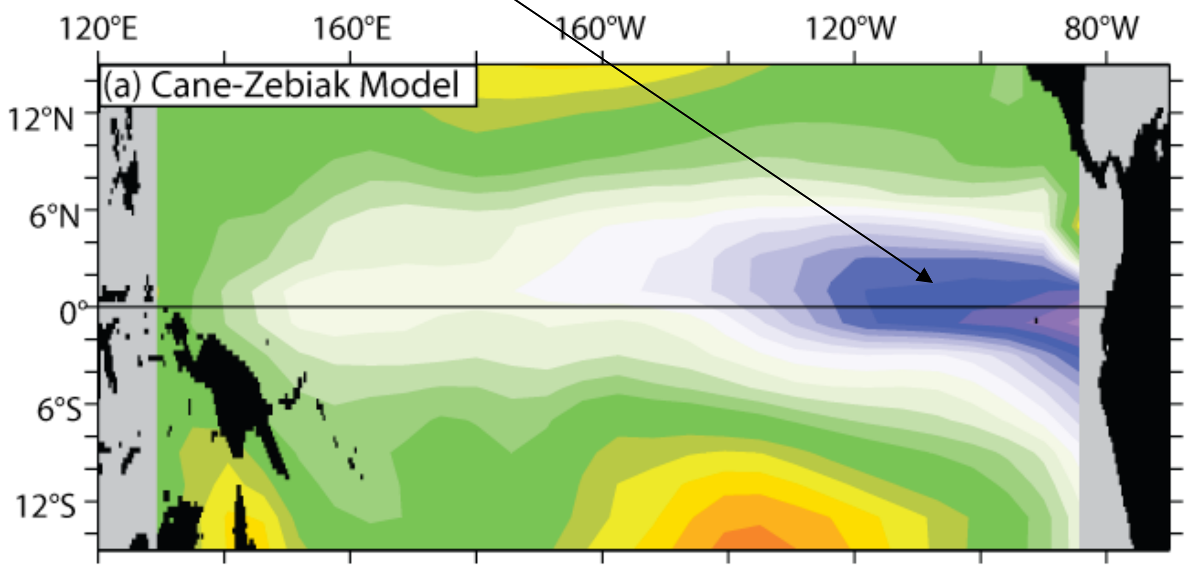
Ocean Dynamical Thermostat

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

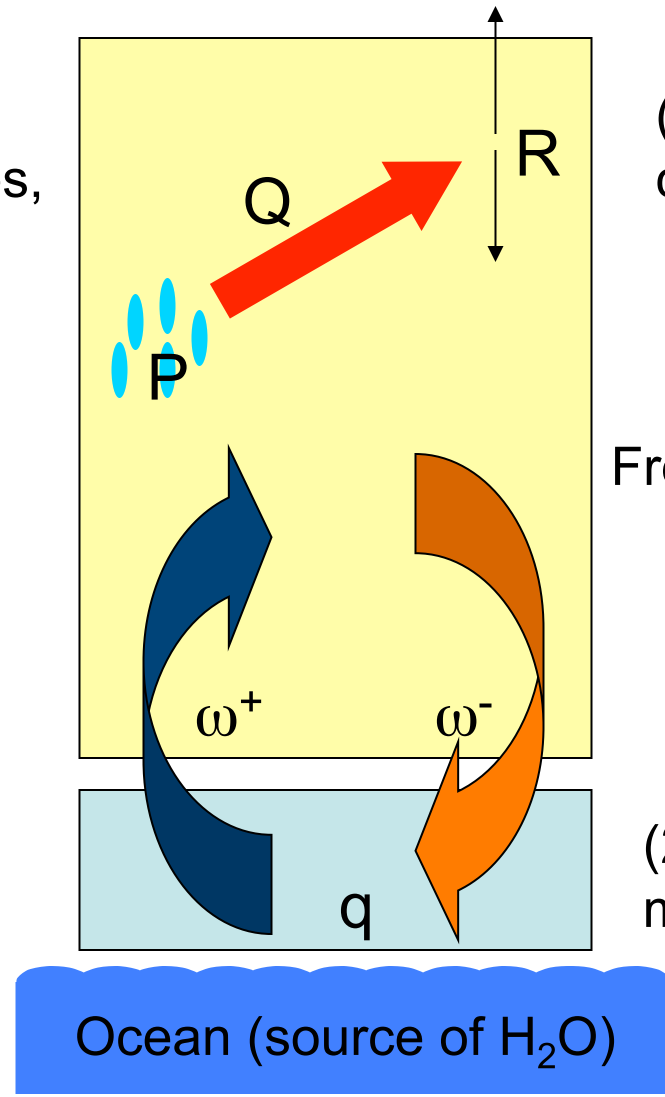
$$R \propto P = q \cdot \omega^{+} \longrightarrow dR/R = dP/P = dq/q + d\omega^{+}/\omega^{+}$$

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

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

(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

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"?

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- Introduction/background
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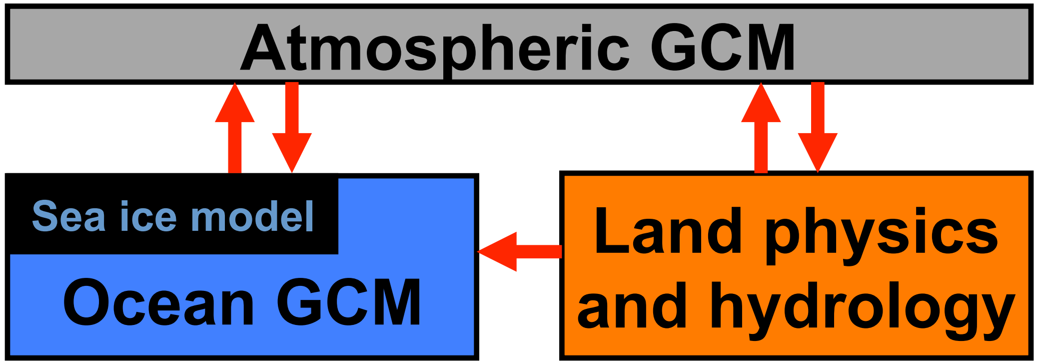
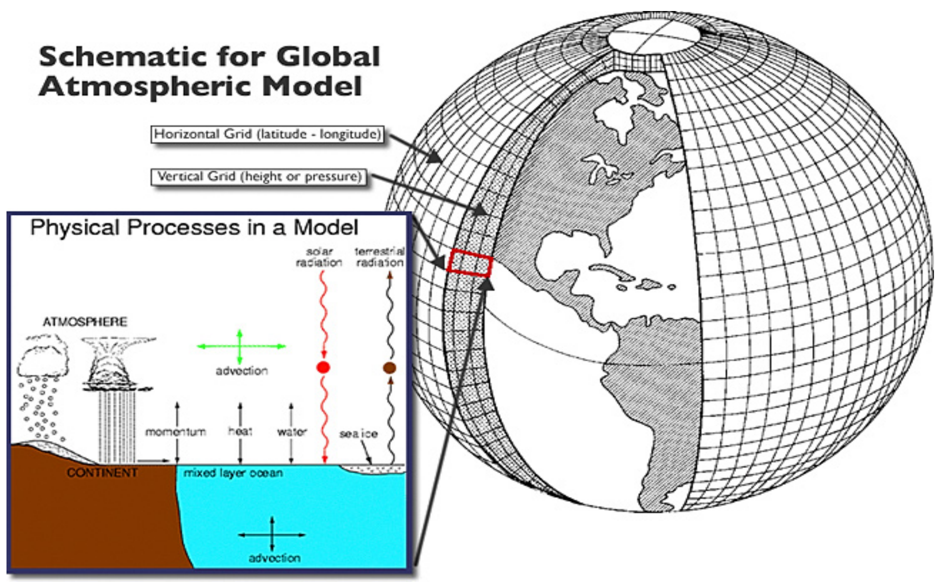
- **Numerical Modeling**
  explore CMIP3/IPCC-AR4 & CMIP5/IPCC-AR5 databases.
- Observations
- Implications

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

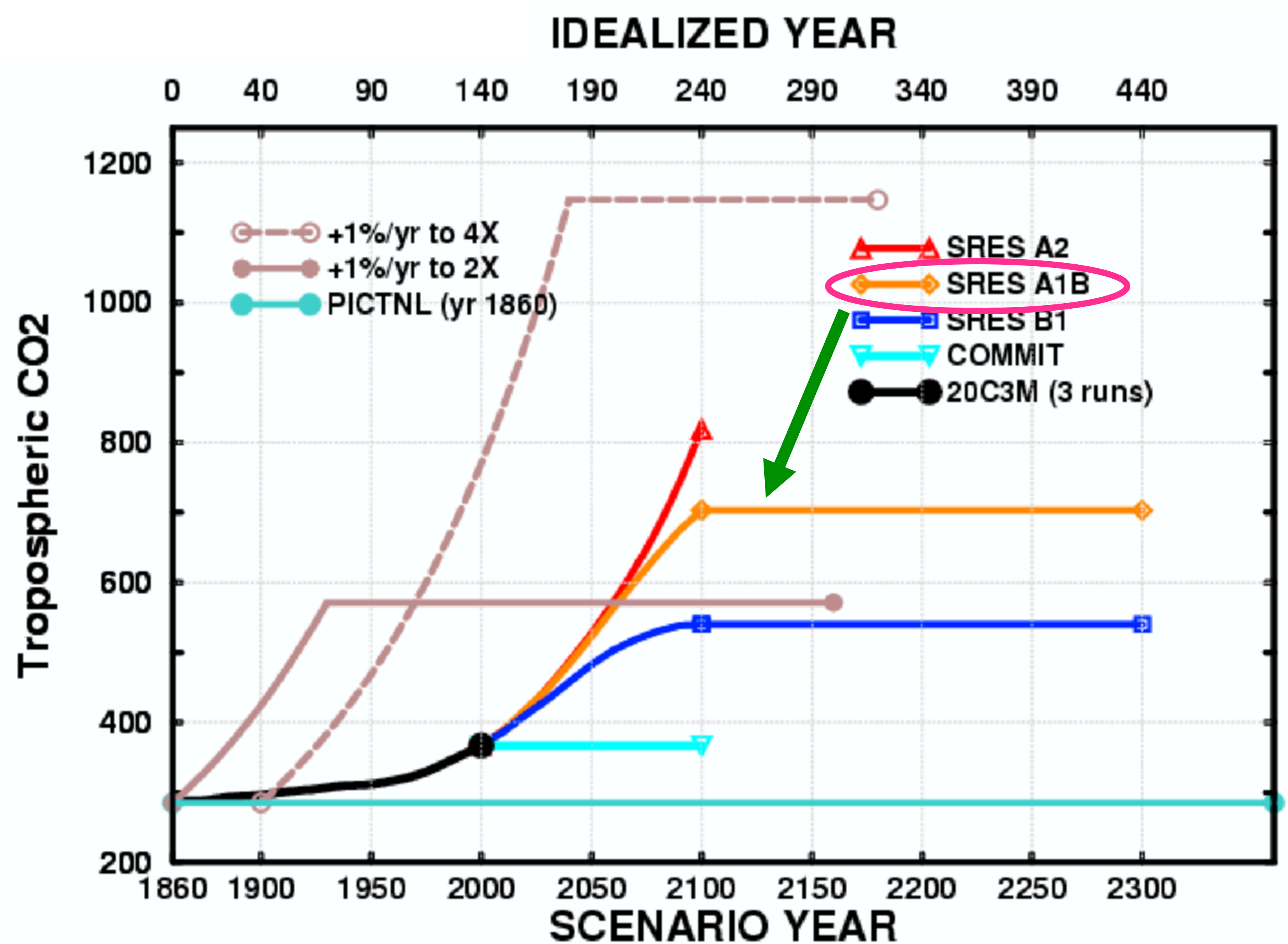
Allow ocean coupling, 3-D circulation, interactive radiation, emergent Walker Circulation, etc.…



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

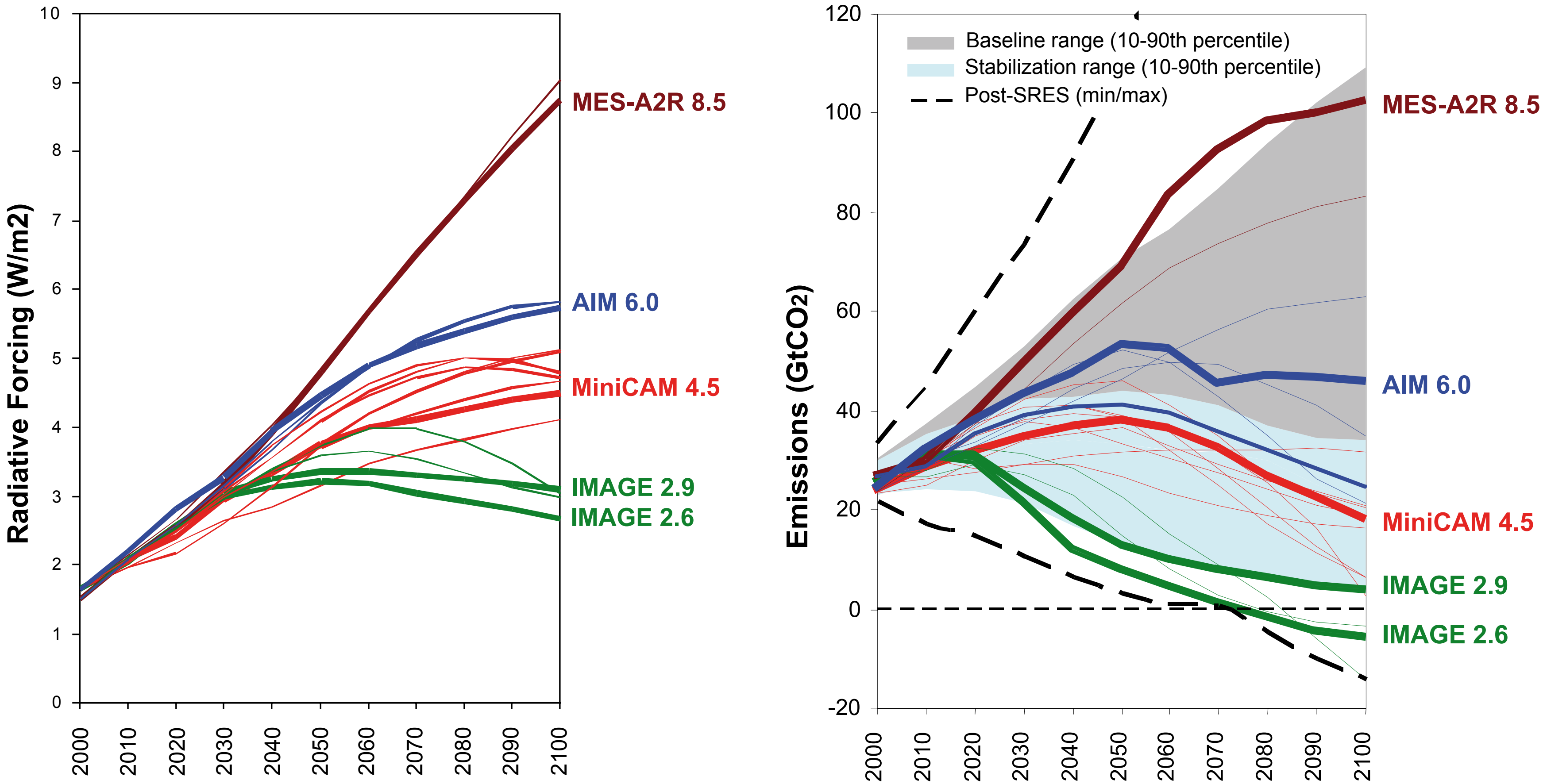


Idealized greenhouse warming experiments



Coupled Model Intercomparison Project 5 (CMIP5)

Model experiments run in support of IPCC-AR5

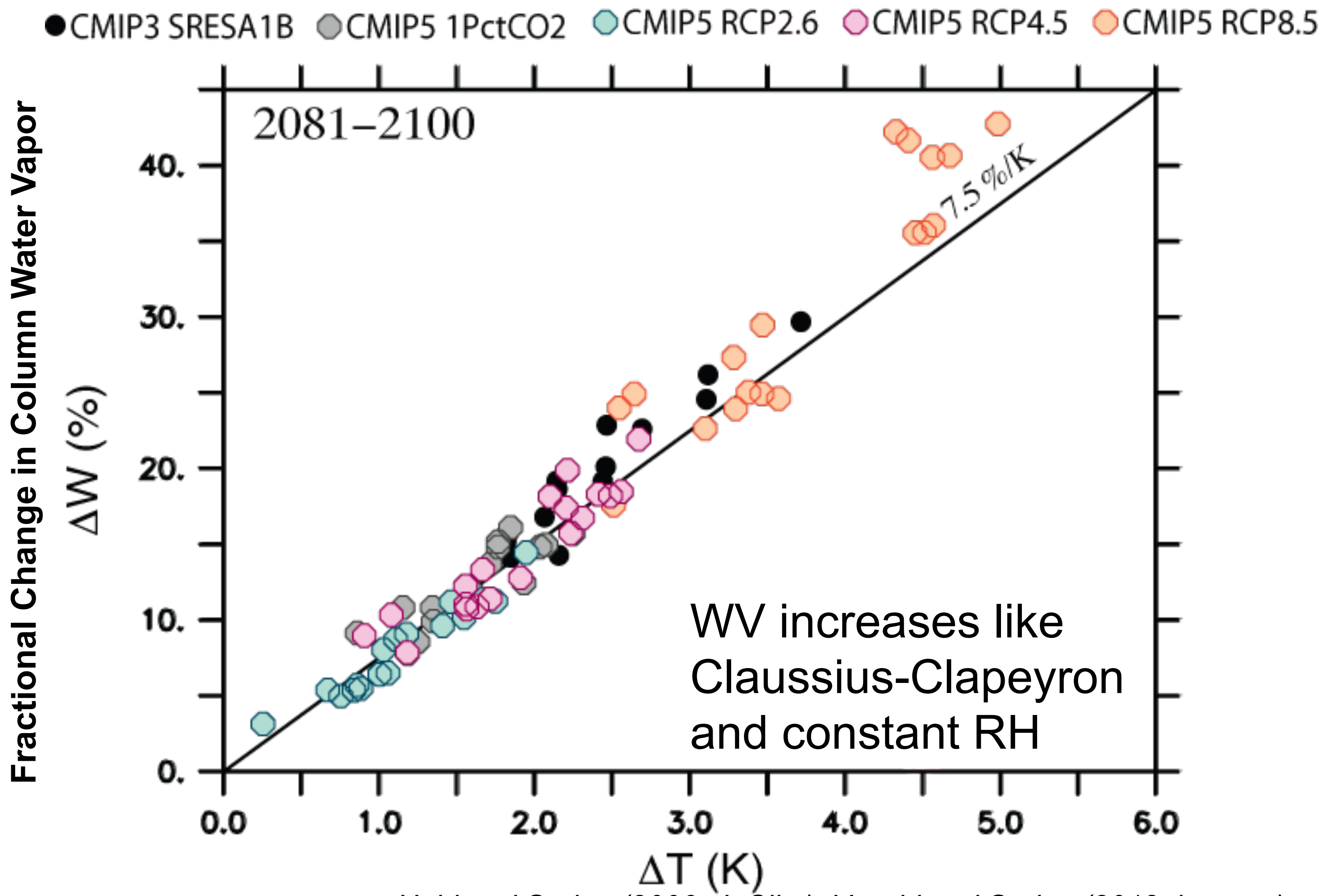


RCPs more than GHG changes: aerosols a big factor.

Moss et al (2008):Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies.

Atmospheric Constraint on Tropical Circulation

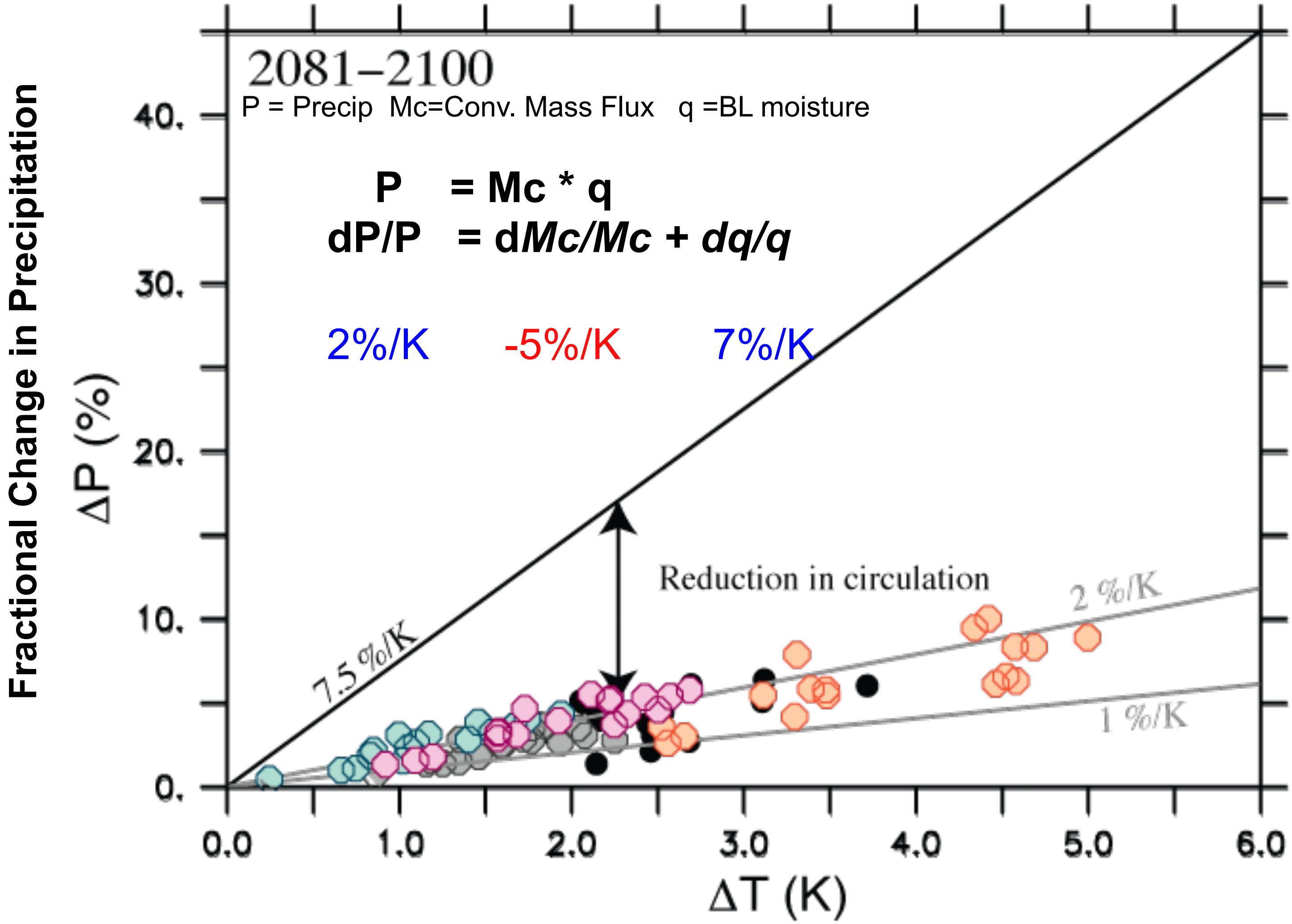
Change in Global Water Vapor at 2100



Held and Soden (2006, J. Clim), Vecchi and Soden (2012, in prep.)

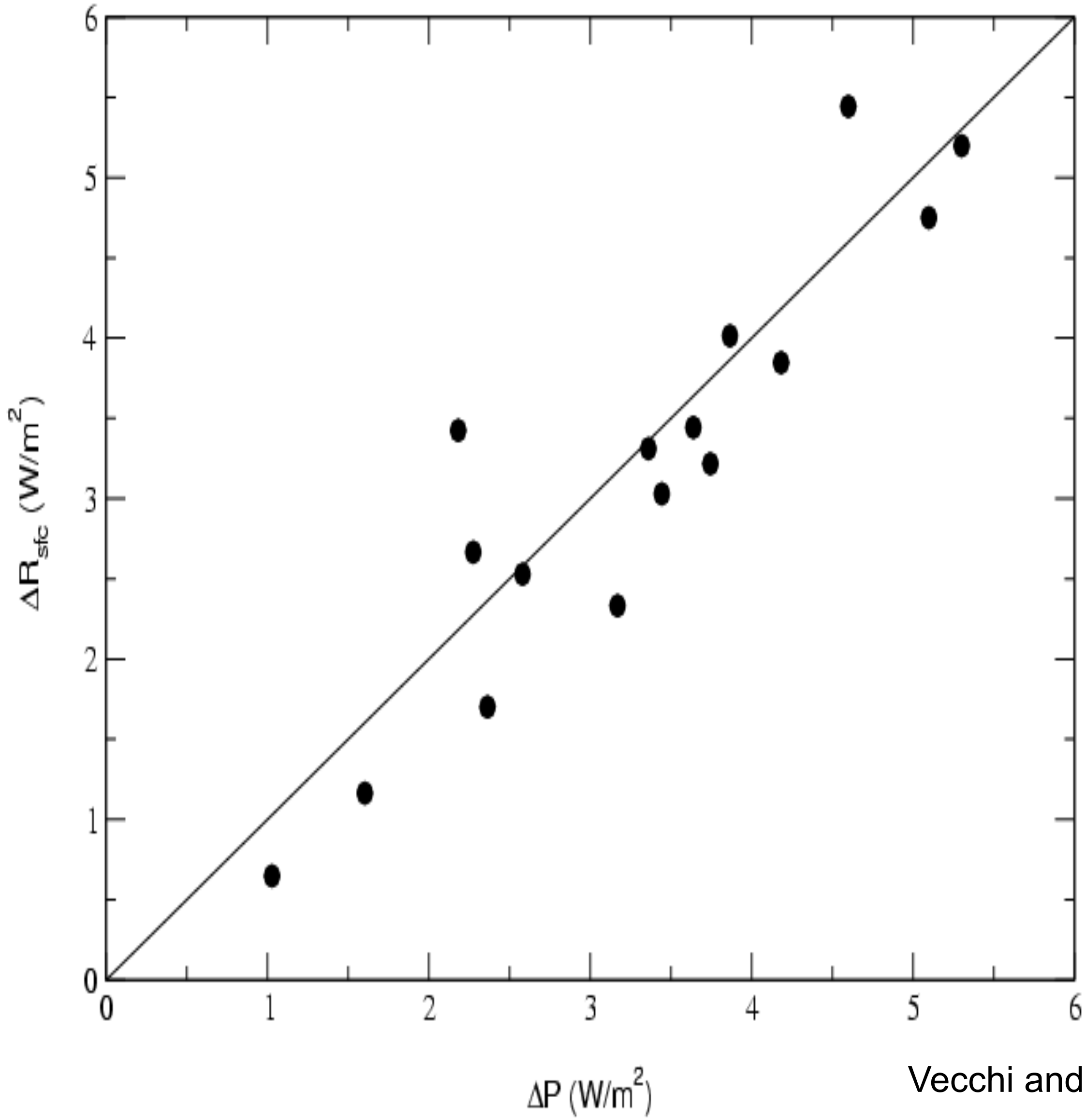
Atmospheric Constraint on Tropical Circulation

Change in Global Precipitation at 2100



Held and Soden 2006, Vecchi and Soden 2012; also: Betts and Ridgway 1989, Knutson and Manabe 1995

Global precipitation scales with surface radiative imbalance



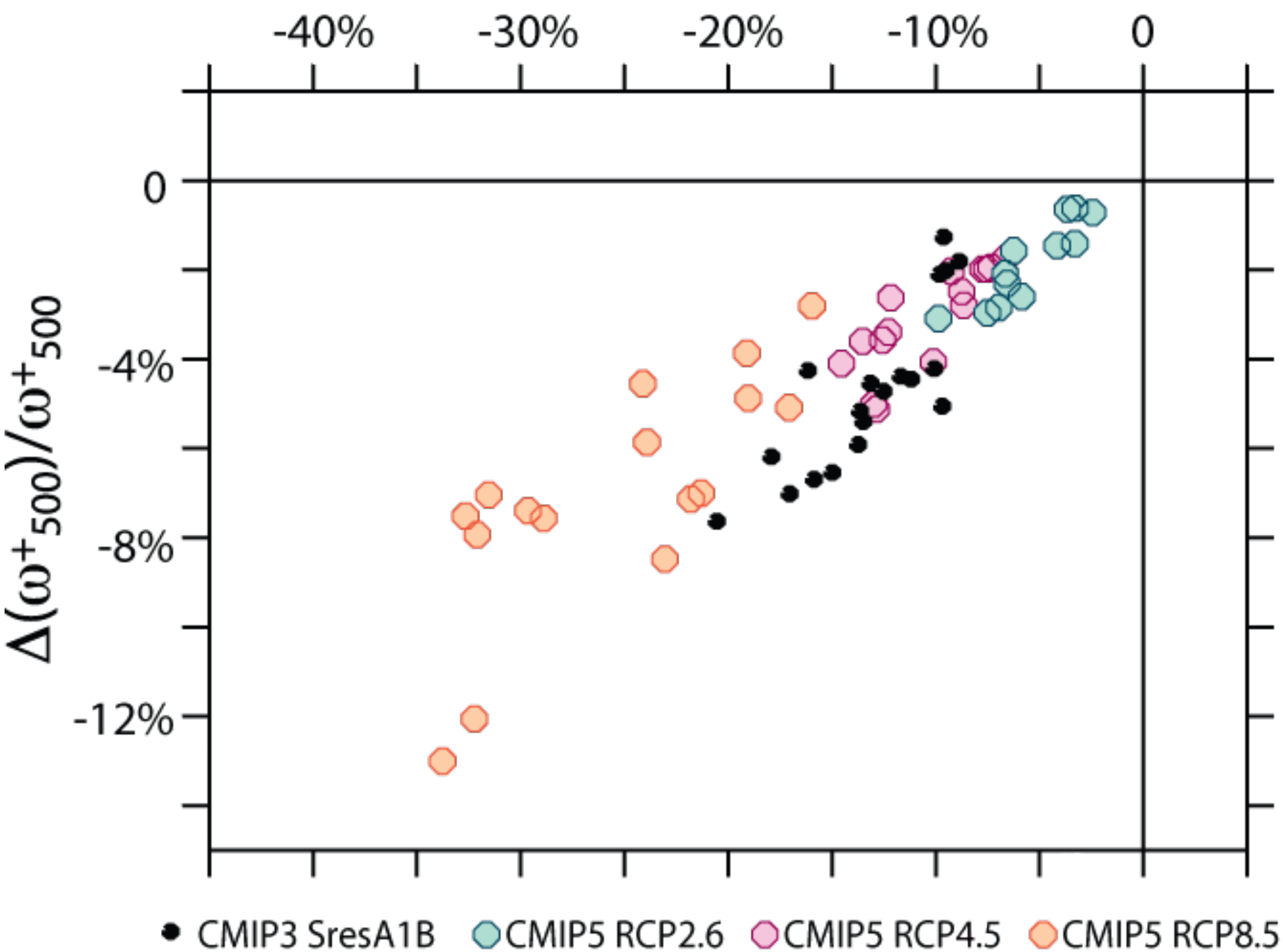
Vecchi and Soden (2007), J.Clim.

CMIP3 Model Global Response to SRESA1B (720 ppm CO_2)

Upward monthly 500 hPa ω vs. mass flux change scaling

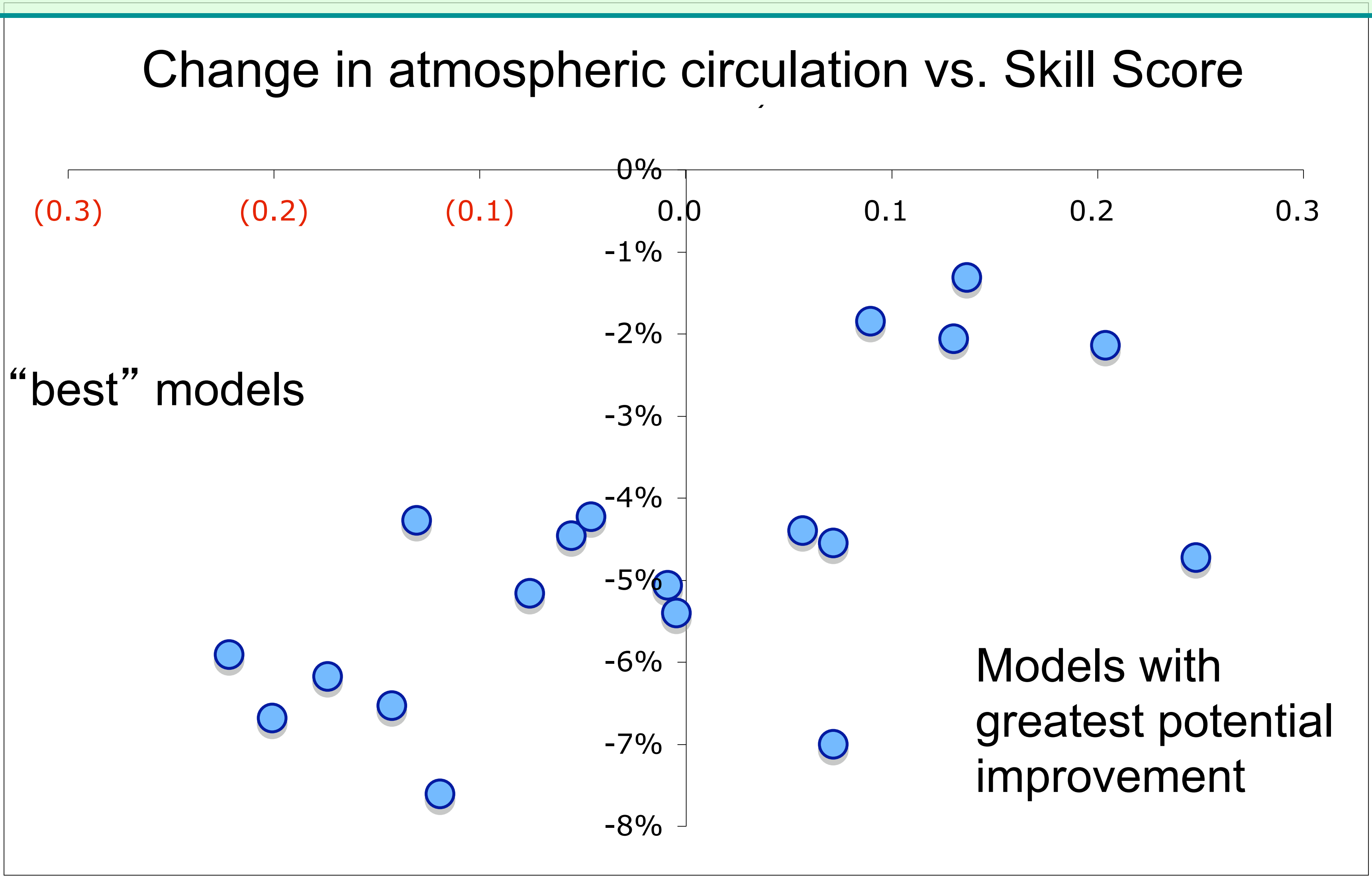
Scaling for circulation change $\Delta(M_c')/M_c' = \Delta P/P - \Delta W/W$

Strength of large-scale circulation



Vecchi and Soden (2007, 2012)

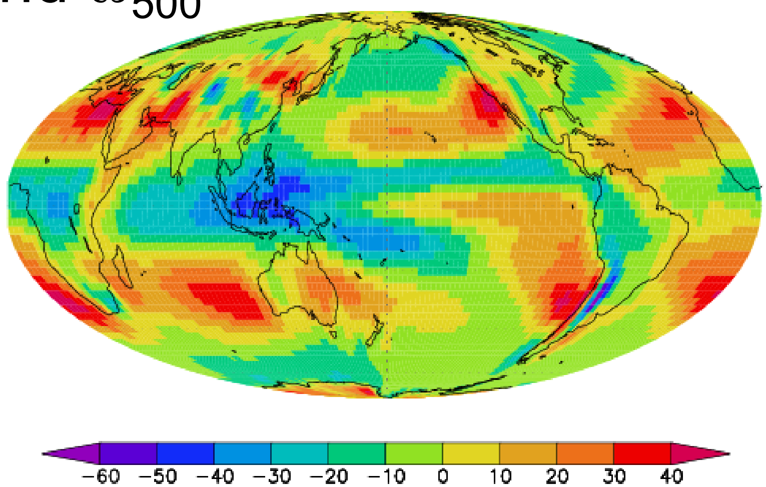
"Best" IPCC-AR4 Models show a large weakening of circulation



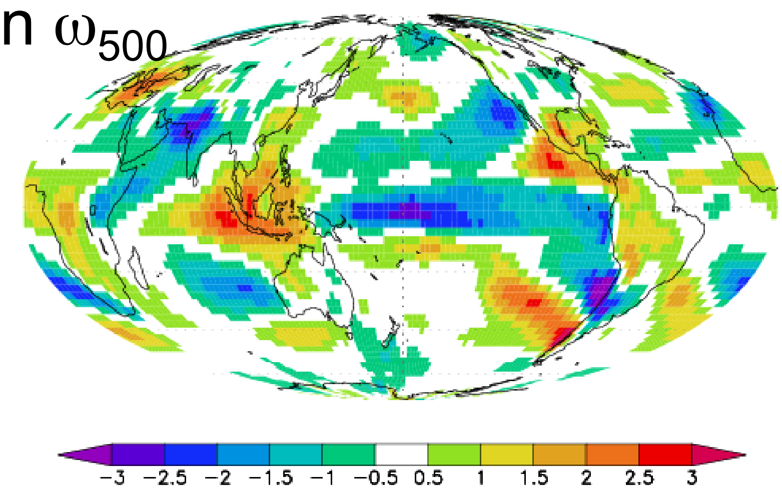
Score from *Reichler and Kim (2008, BAMS)* comparing each model to a wide range of 20th Century observations.

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.

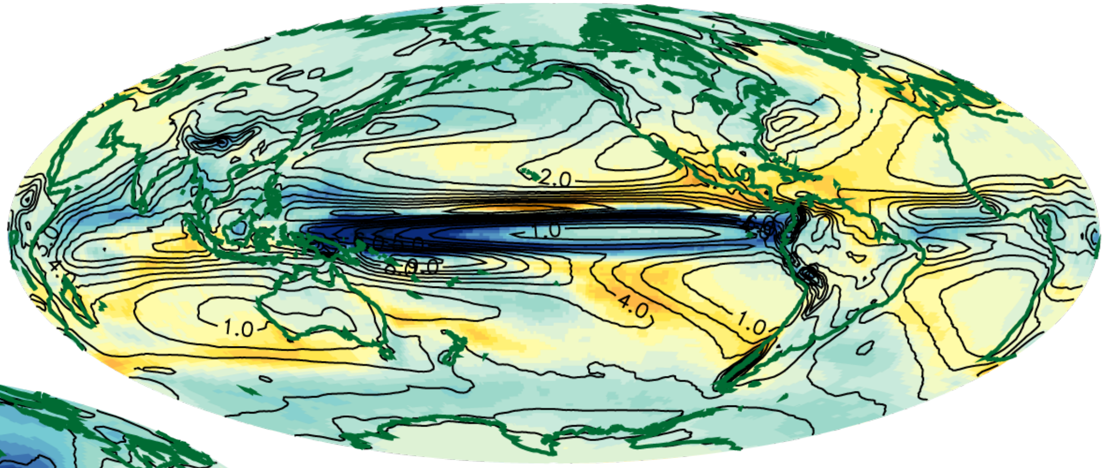
Some "El Niño-like" patterns:
- **Eastward shift of precipitation**
- **Reduction in SST gradient**
- **Reduction in thermocline tilt**

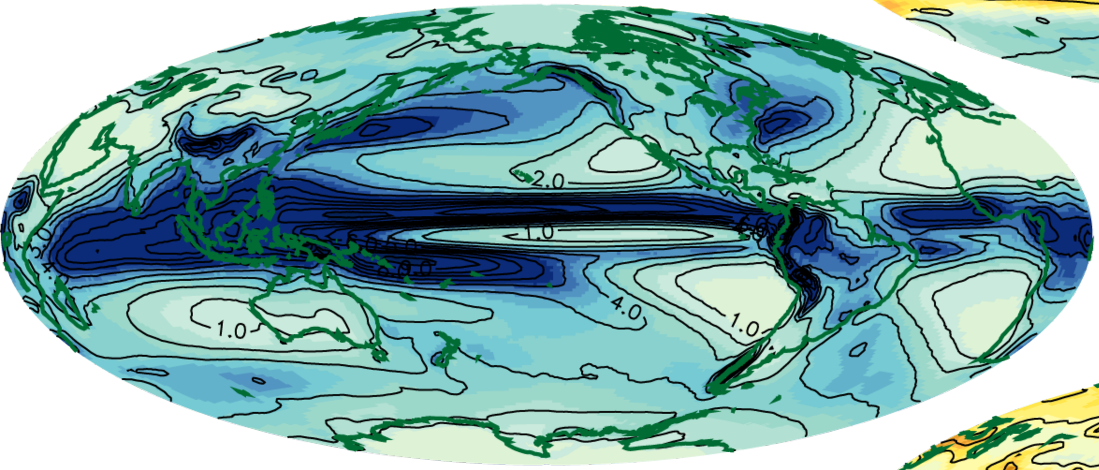
Not "El Niño-like":
- **Ocean changes oppose it**
- **Pacific thermocline shoals**
- **Teleconnections not "El Niño-like" (Lu et al. 2007, 2008; Seager et al. 2007…)**

Vecchi and Soden (2007, J. Clim.; 2012 in prep)

CMIP5 Precipitation Response Reflects Weakening Circulation (see also in CMIP3)

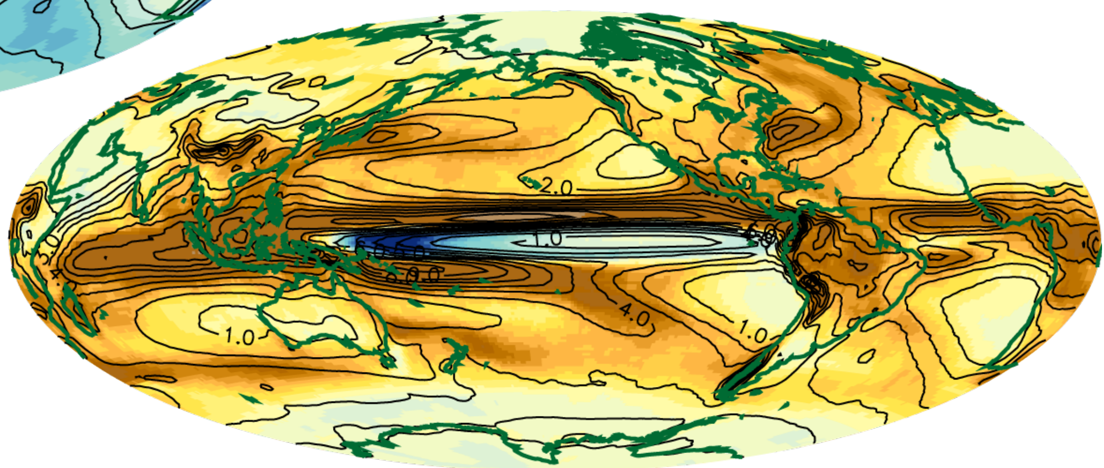
Total CO_2-driven precip. Change (mm/day/K)





Thermodynamic: due to moistening (mm/day/K)

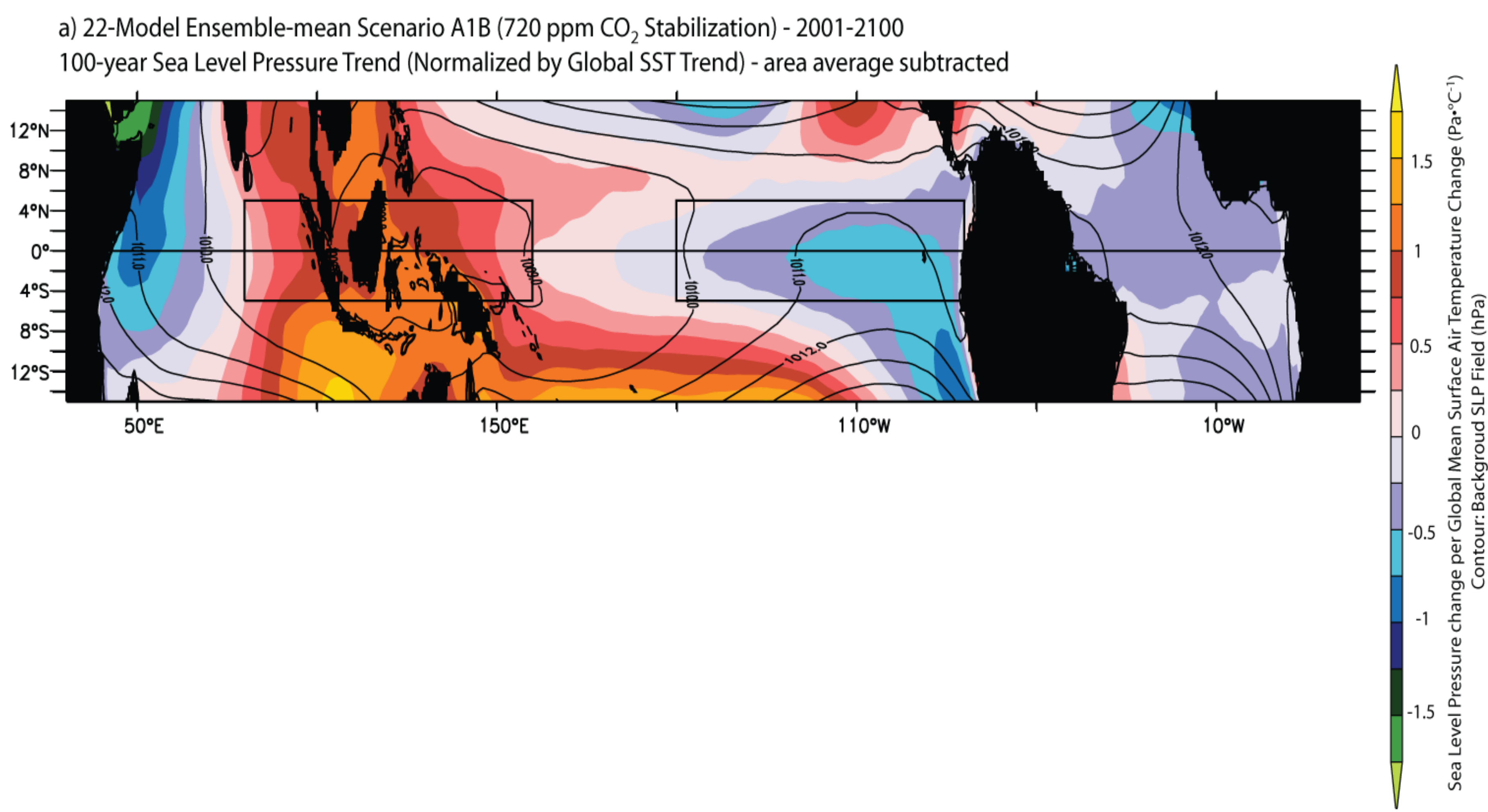
“Dynamic” (mm/day/K): dries everywhere but central Pacific



Vecchi and Soden (2007, 2012)

Near-equatorial Indo-Pacific Zonal SLP gradients decrease

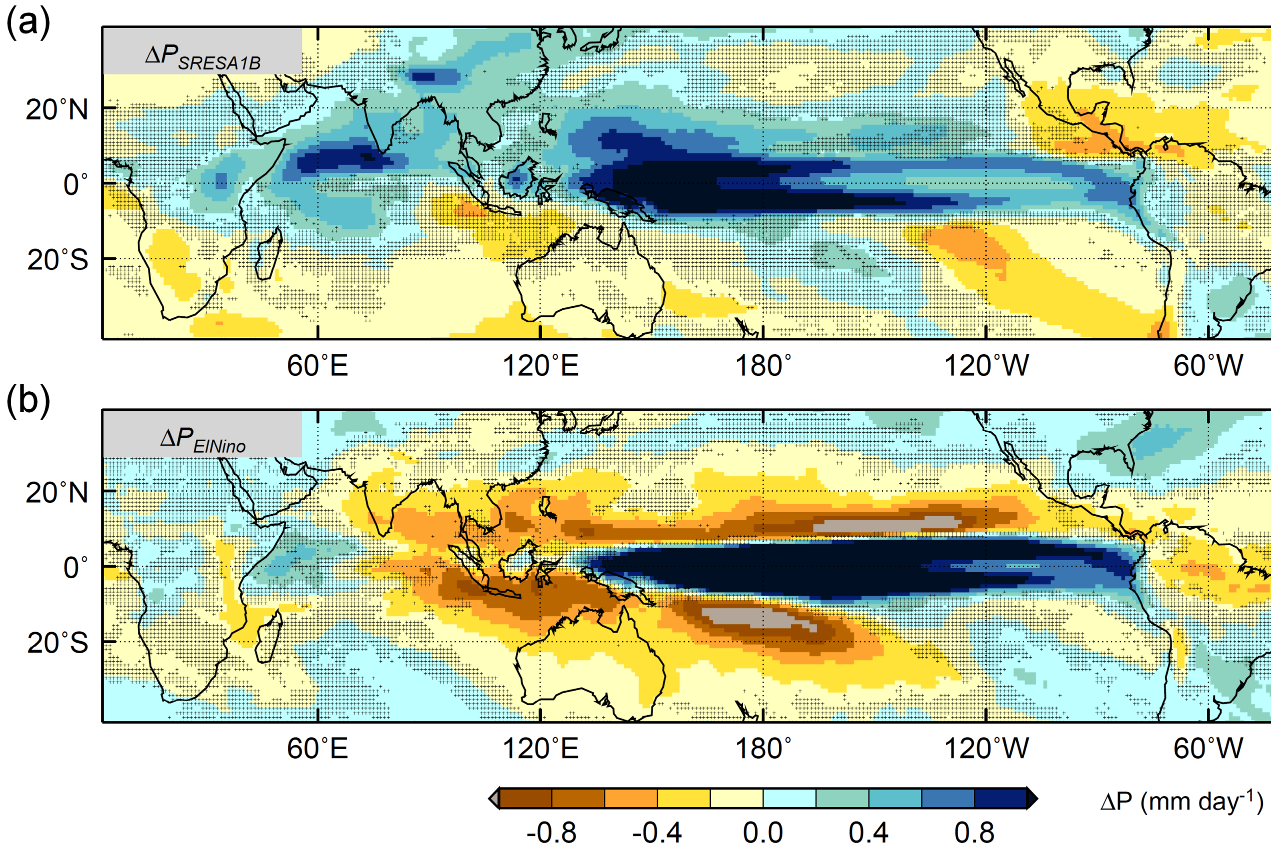
Full ocean GCMs



Vecchi and Soden (2007, J. Clim.)

Precipitation response: CO_2 differs from El Niño

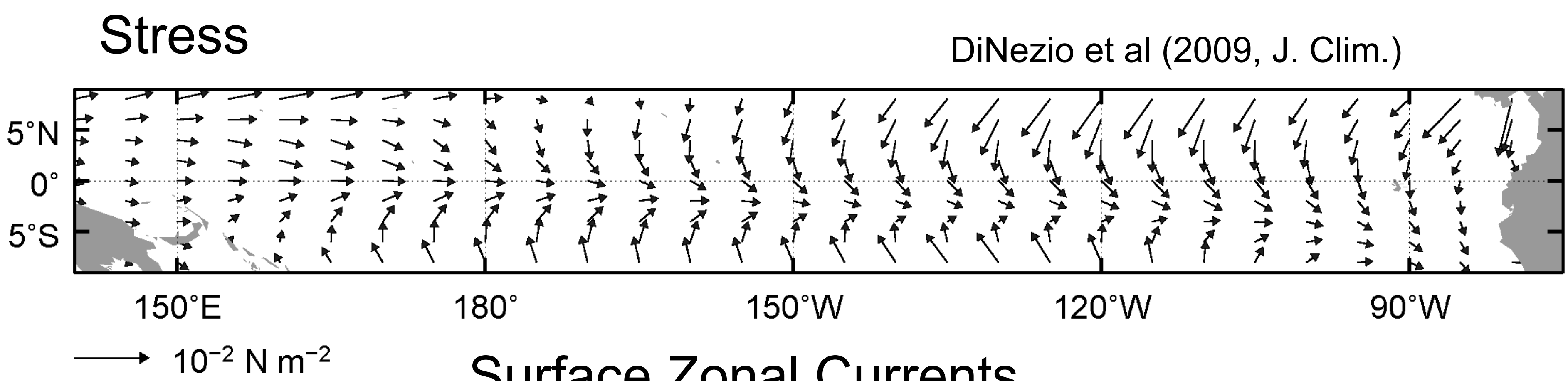
multi-GCM Precipitation response to CO_2



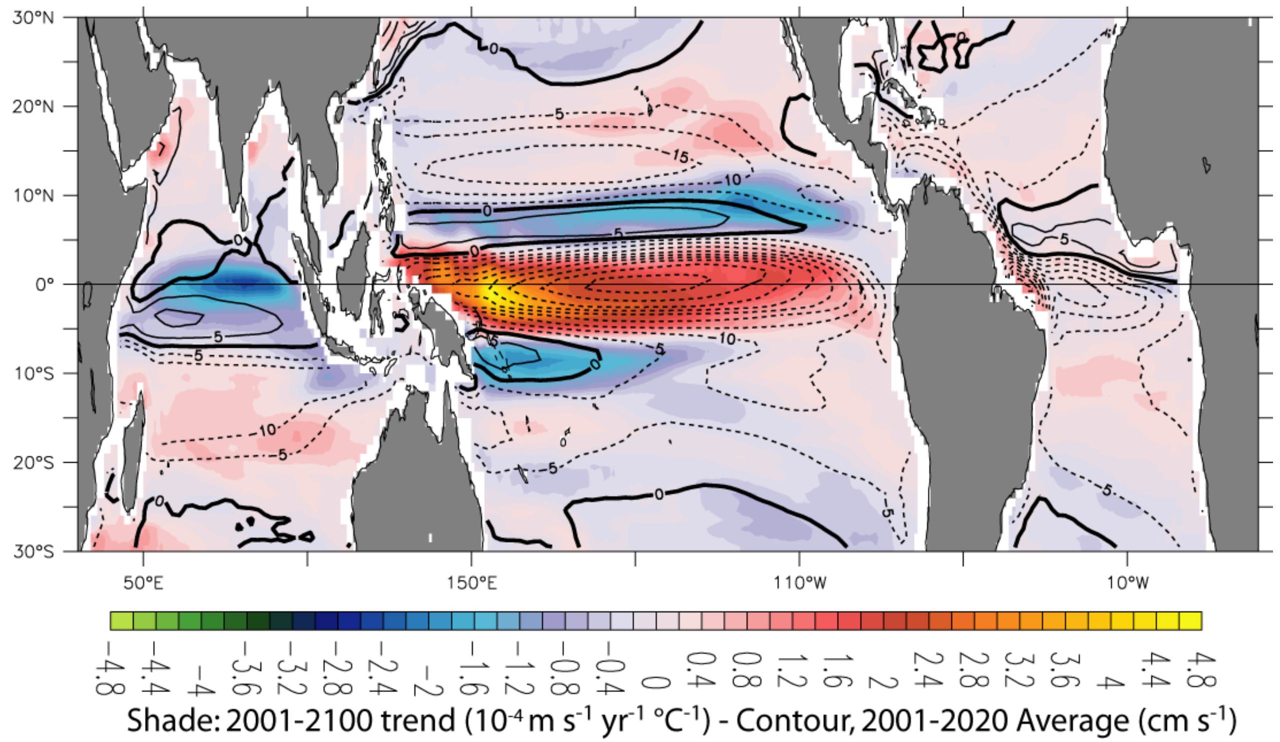
multi-GCM Precipitation response to El Niño

DiNezio, Clement and Vecchi (2010, EOS); Vecchi and Wittenberg (2010, WIRES)

Wind Stress and Currents



Surface Zonal Currents



Vecchi and Soden (2007, J. Clim.)

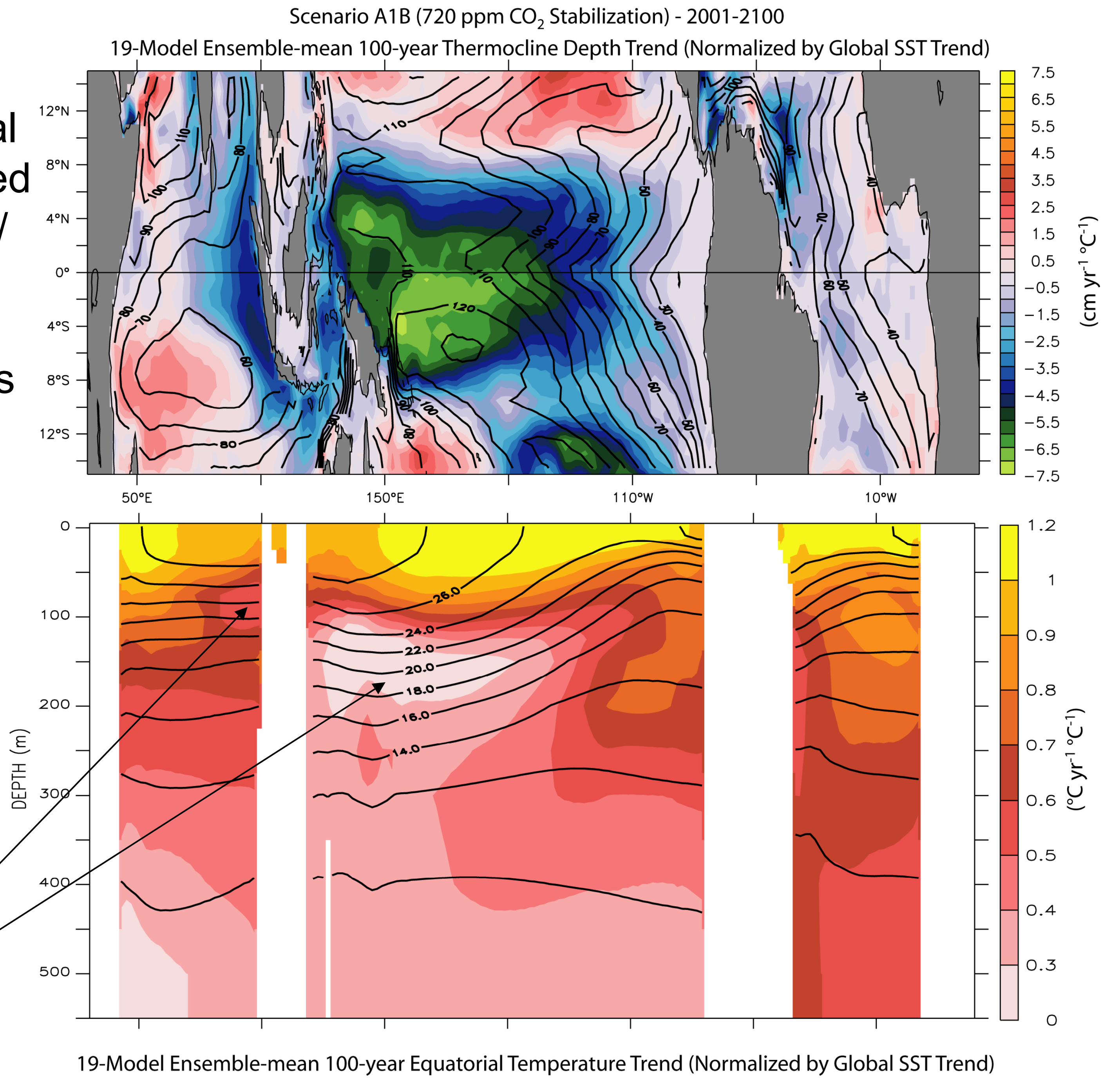
Ensemble-mean response of tropical thermocline (defined as maximum of dT/dz).

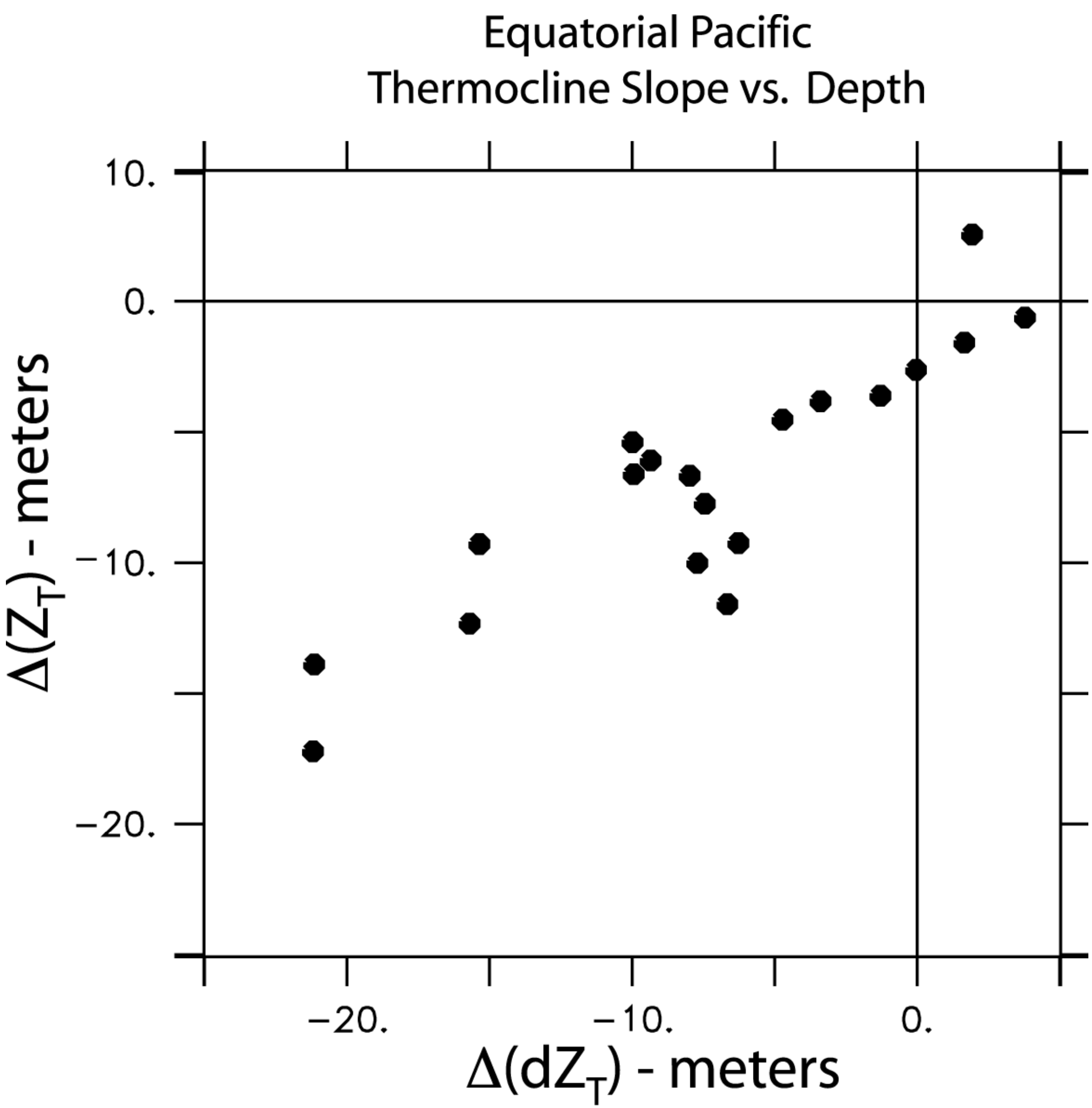
Equatorial Pacific thermocline flattens and shoals.

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)

Outline

- Introduction/background
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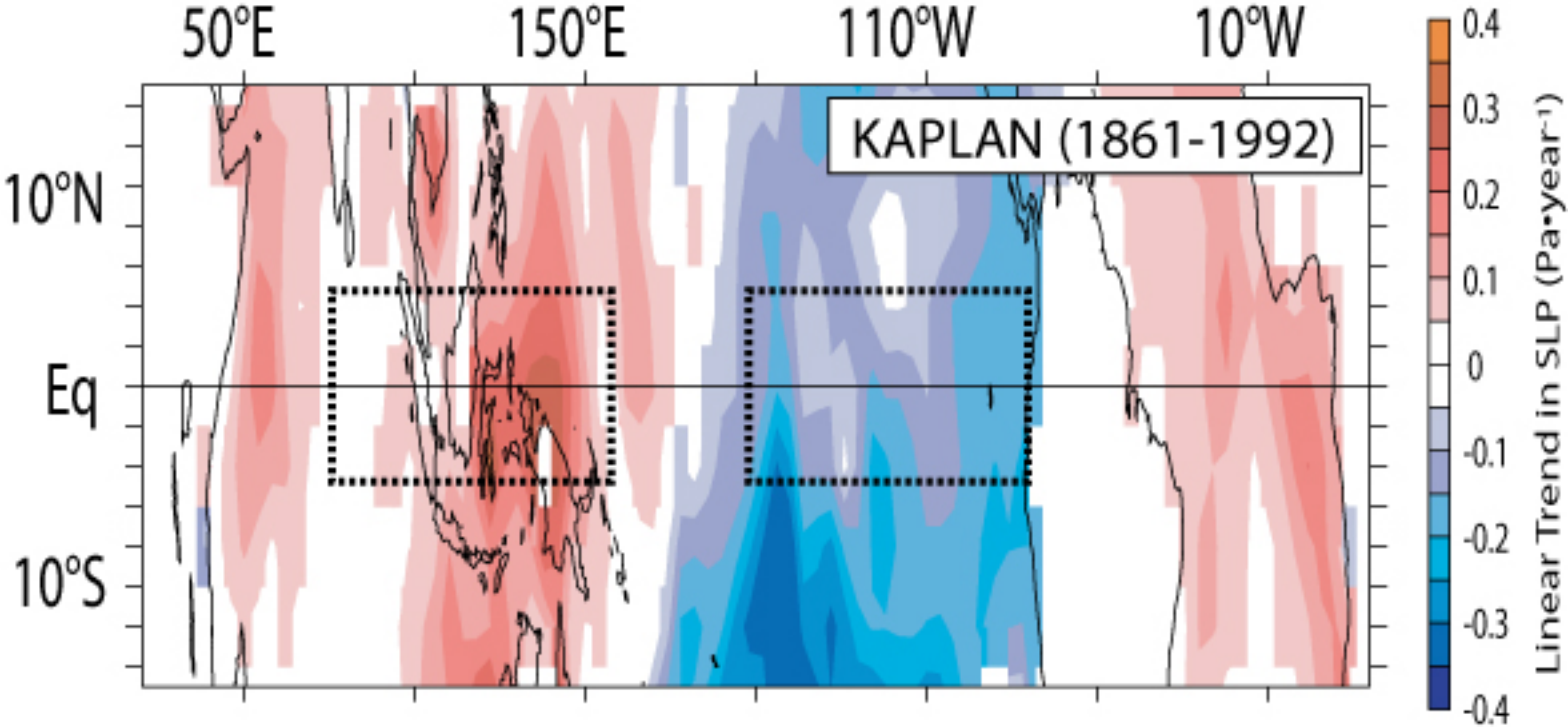
- **Observations**
- Implications

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



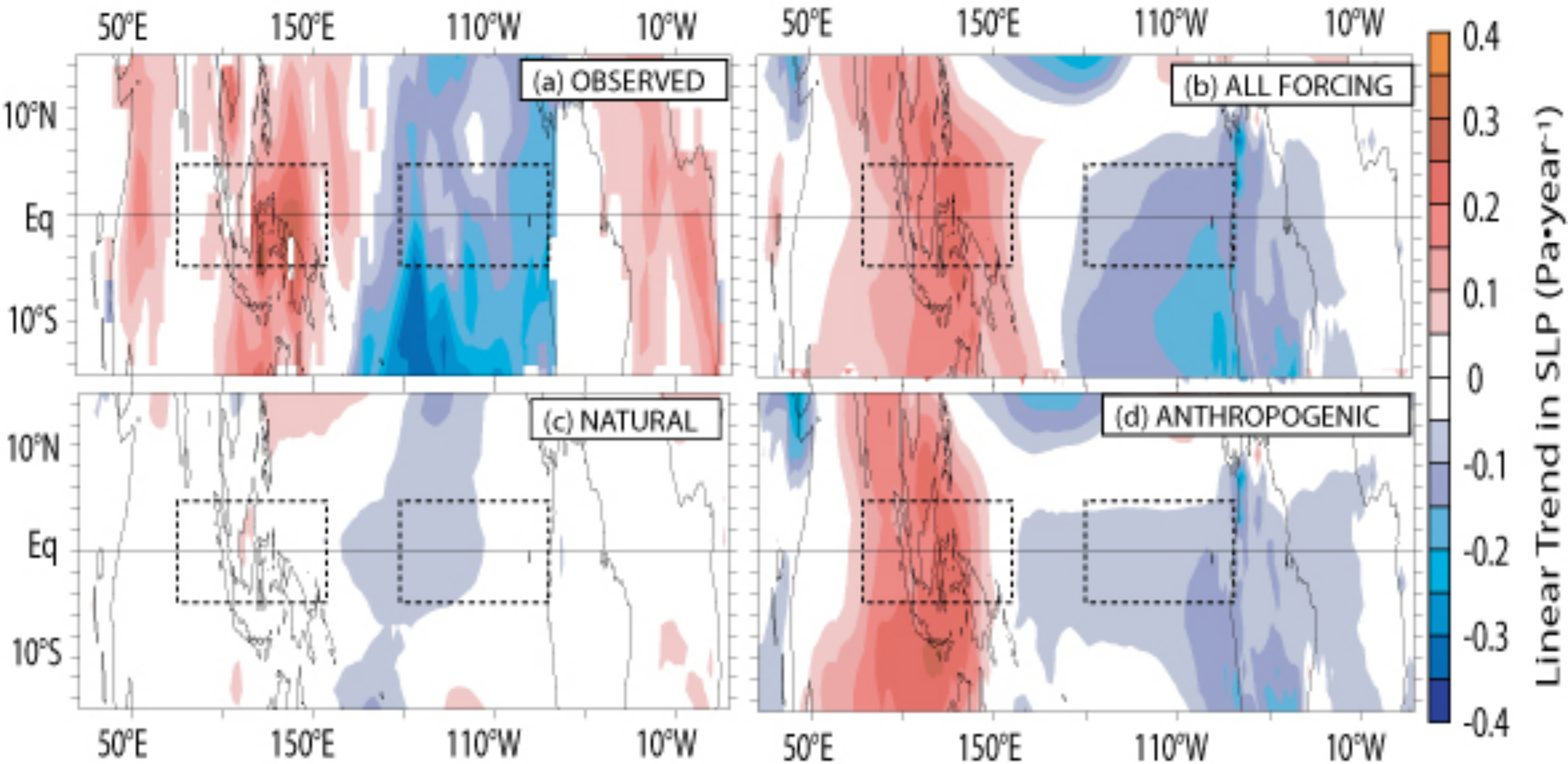
Reduction of E-W SLP gradient across Pacific.

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.

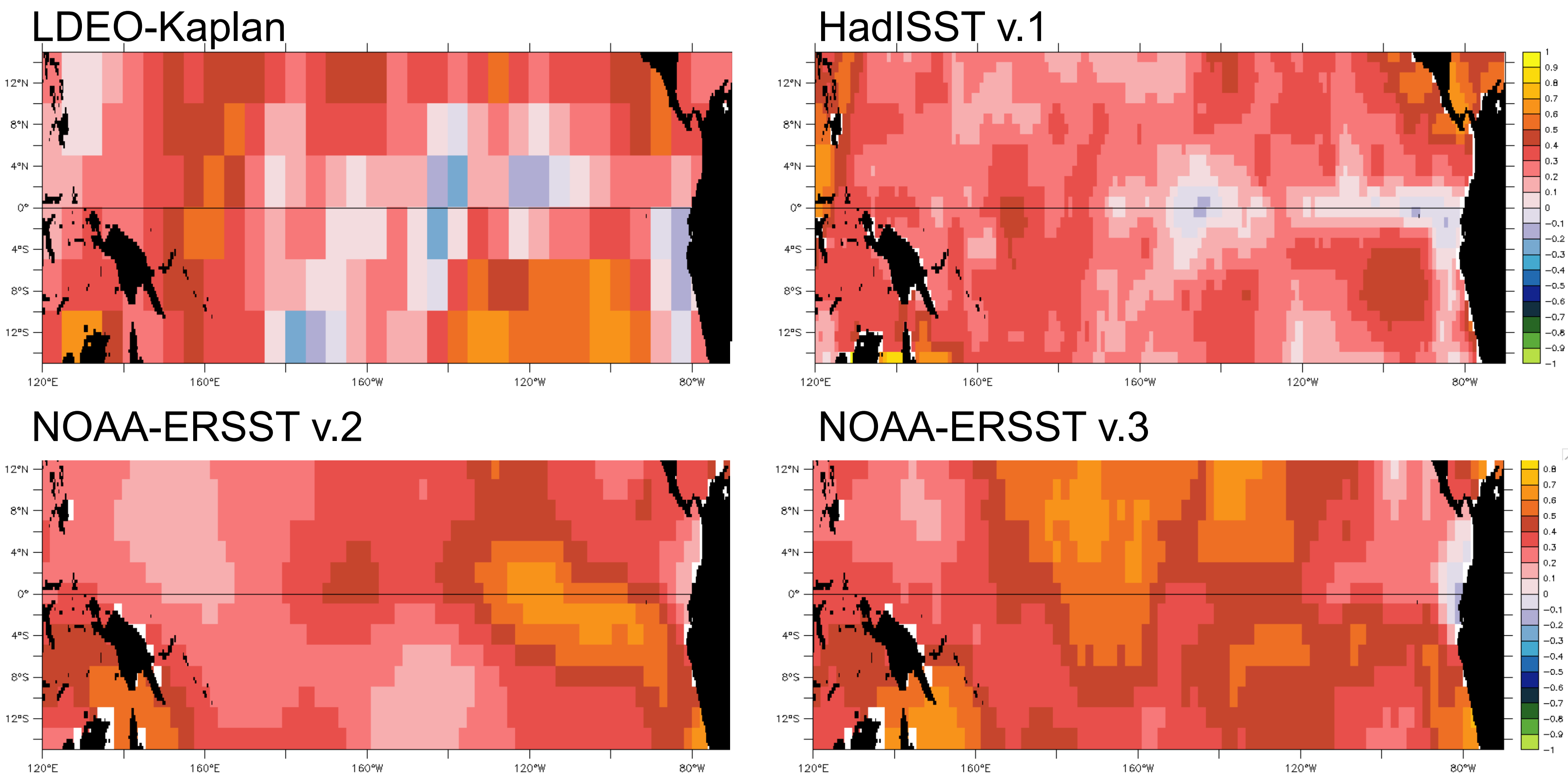


TRENDS COMPUTED 1861-1992

Vecchi et al (2006)

Look at SST?

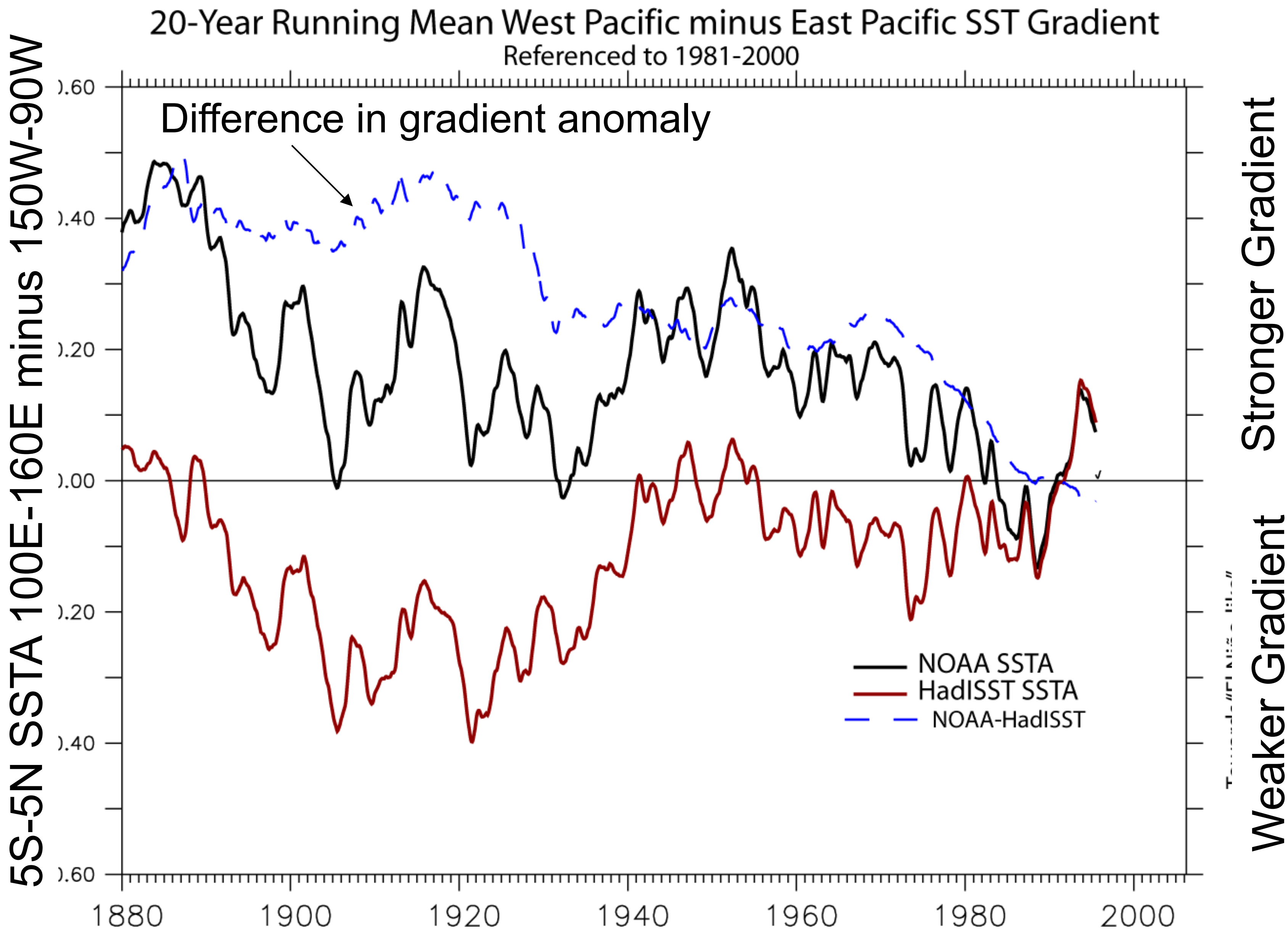
Linear trends (1880-2005) in four SST estimates.



Overall warming seen in all.
Structure dependent on reconsruction.

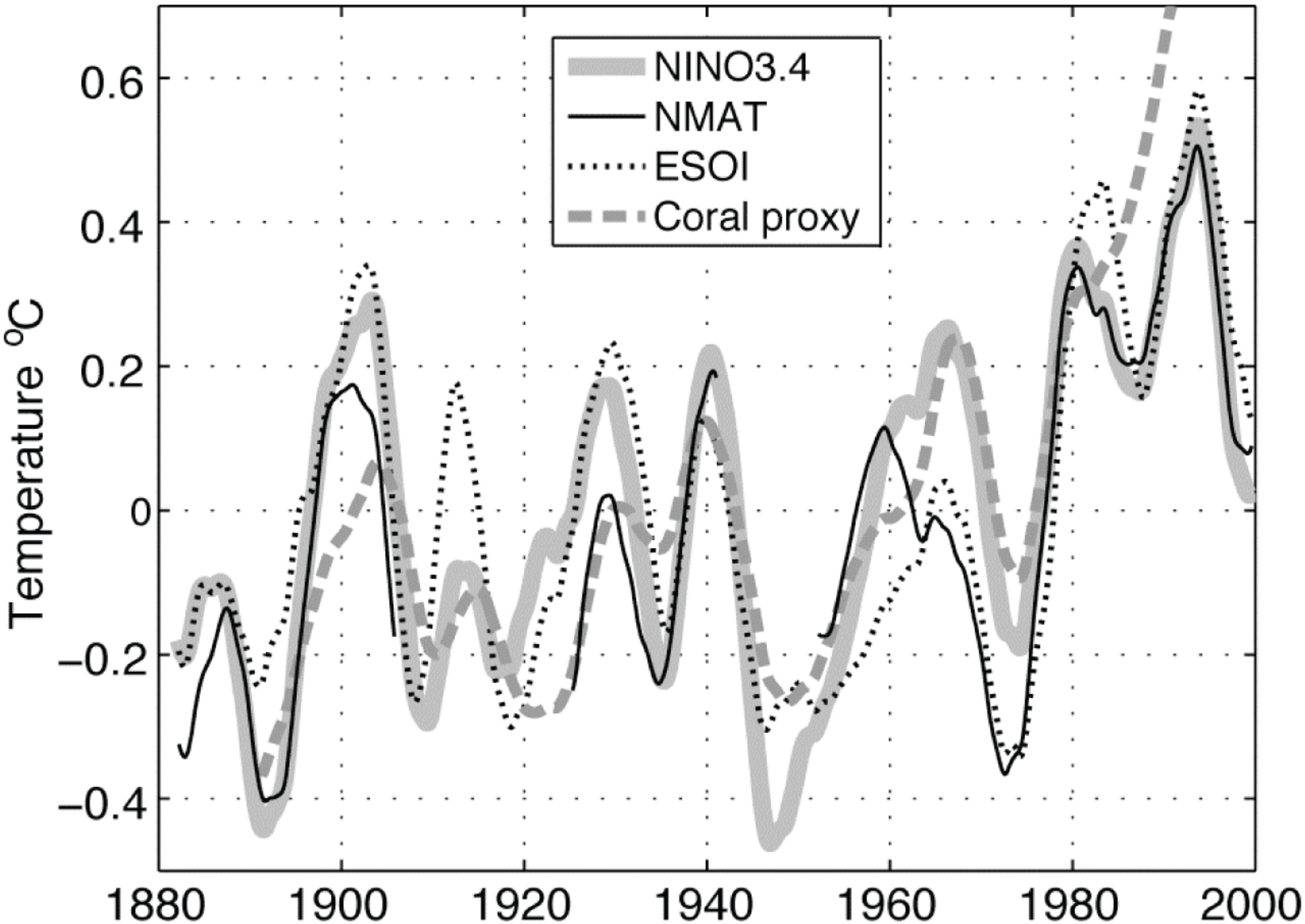
Adapted from Vecchi, Clement and Soden (2008, EOS)

When do differences between SST products emerge?



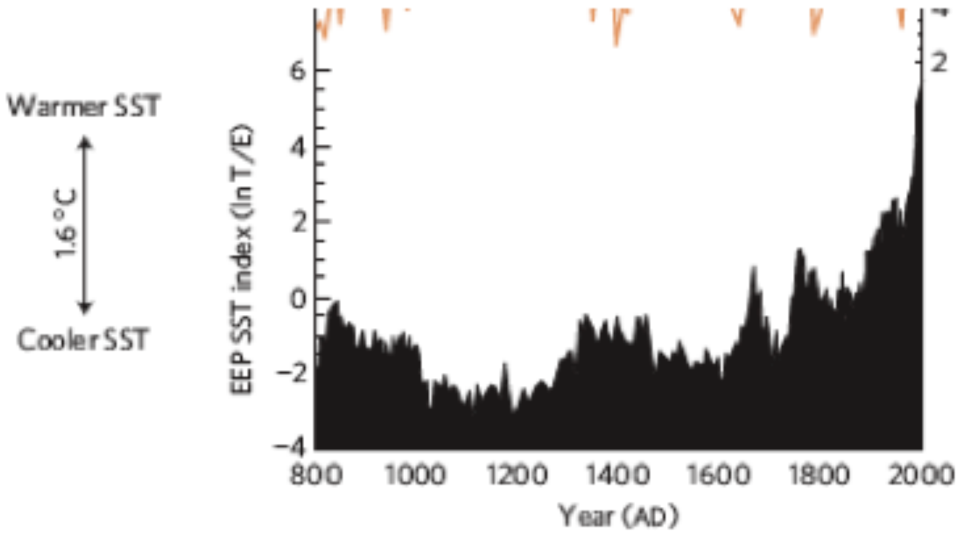
From Vecchi, Clement and Soden (2008, EOS)

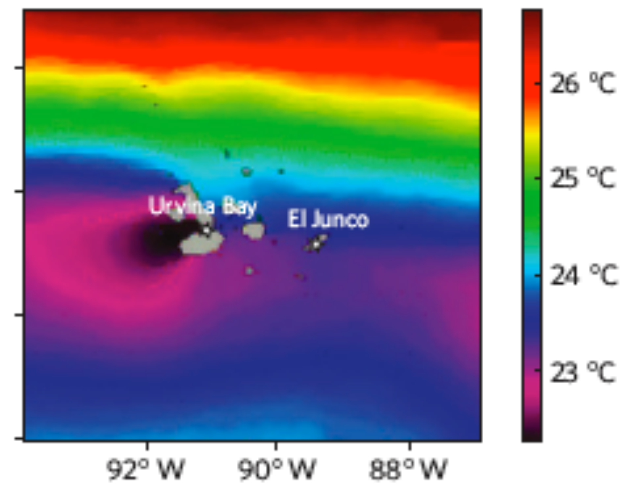
"Pacific-centric" analysis



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

Lake Sediment Record
El Junco Lake, Galapagos



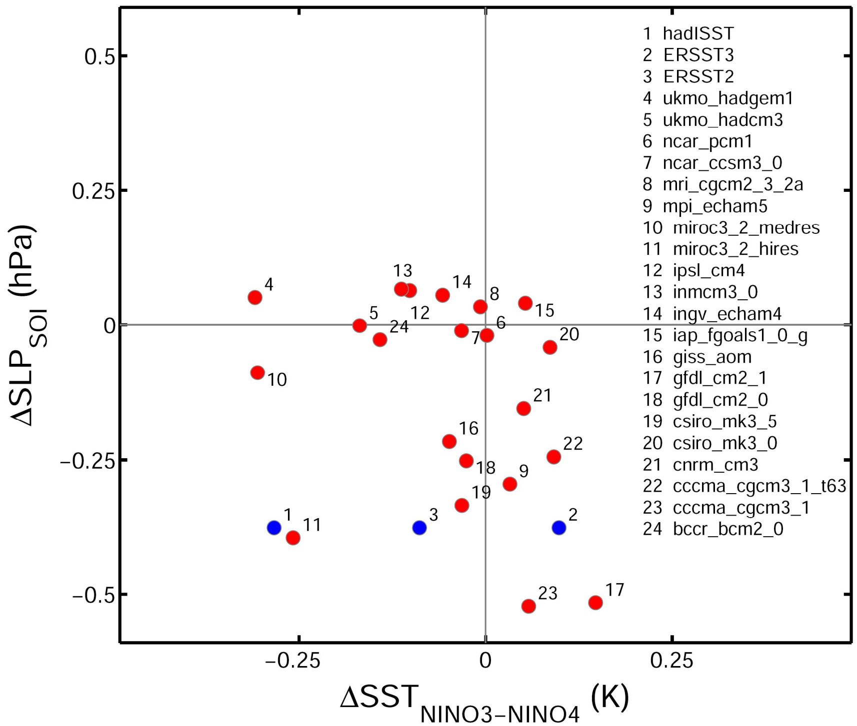


Conroy et al (2009, Nature. Geosci.)

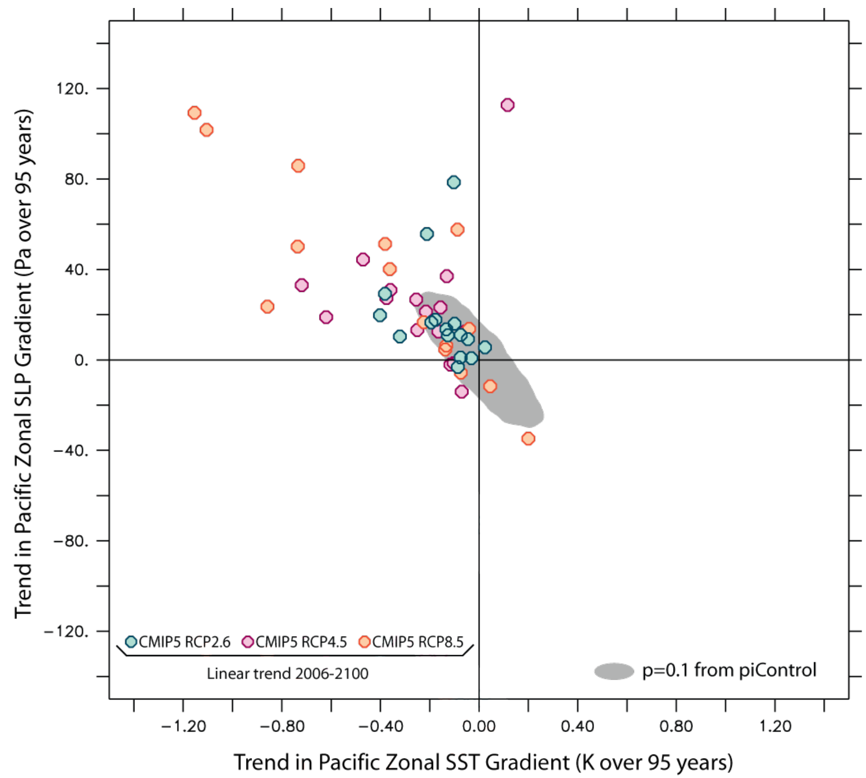
- Indicate warmer(wetter) East Pacific in 20th Century.
- Interpretation of similar records still ongoing (Sachs et al, …)

Gradient of SST vs. Gradient of SLP

- 20th Century CMIP3
- Observed.



CMIP5 21st Century

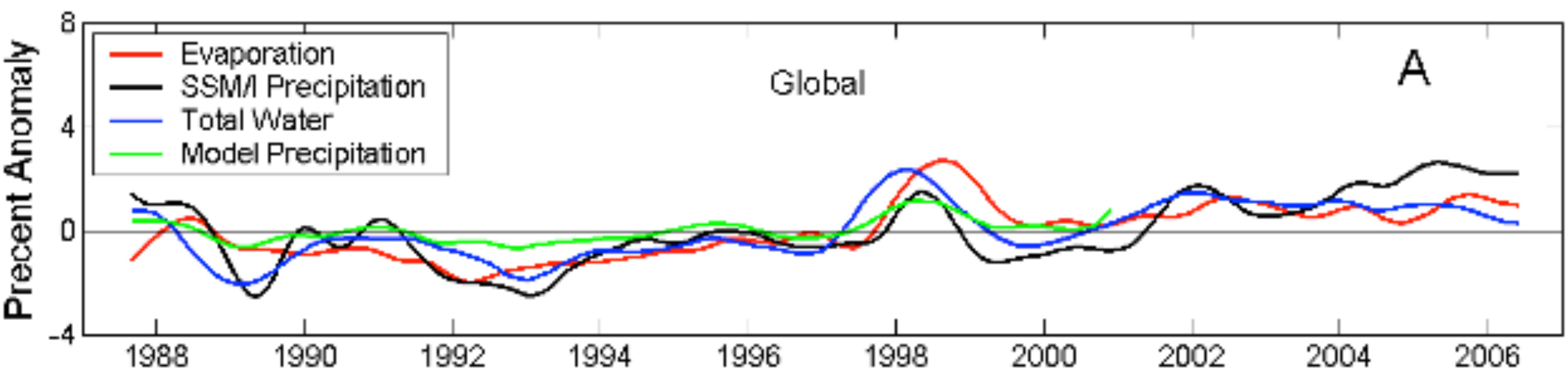


DiNezio, Clement and Vecchi (2010, EOS); *Vecchi and Soden (2012, in prep.)*

SST Gradient not a strong constraint on radiative response of SLP Gradient.

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 larger interannual precip. Variability in SSM/I than in models.
- Can estimates be reconciled?



Wentz et al (2007, Science)

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 includes 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, Wet South Asian Monsoon…

- Both Ocean Thermostat and Weaker Walker present in GCMs

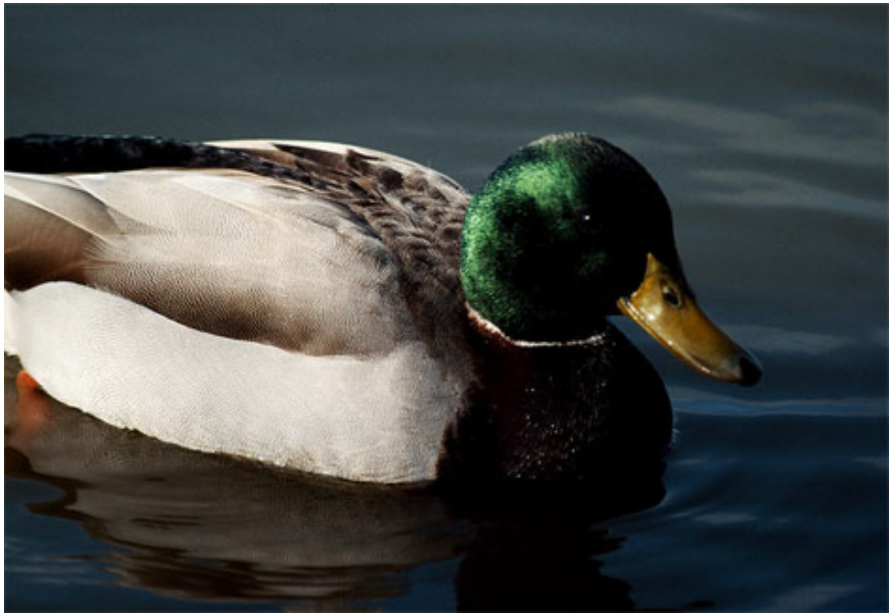
- Observations:
  - SLP indicates Weaker Walker Circulation
  - SST? Discrepancies need to be resolved - proxy data spanning 20th Cy?
  - Mean thermocline depth may be better constraint than SST gradient

- Weaker Walker Cell associated with increased Atlantic wind shear.

“El Niño-like” vs. “La Niña-like”

≠

or



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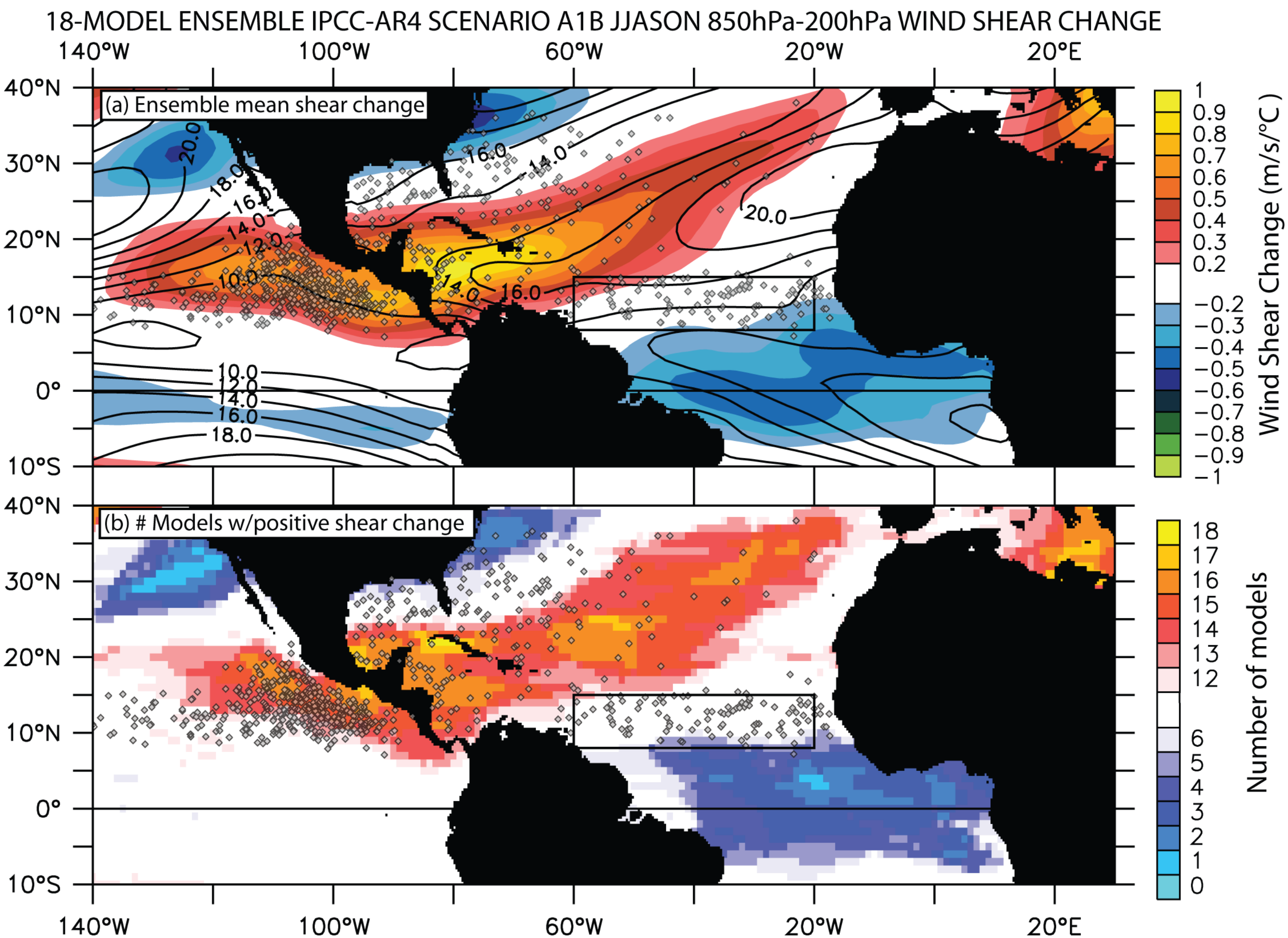
  - Atlantic wind shears
  - ENSO bad analogue for some teleconnections.

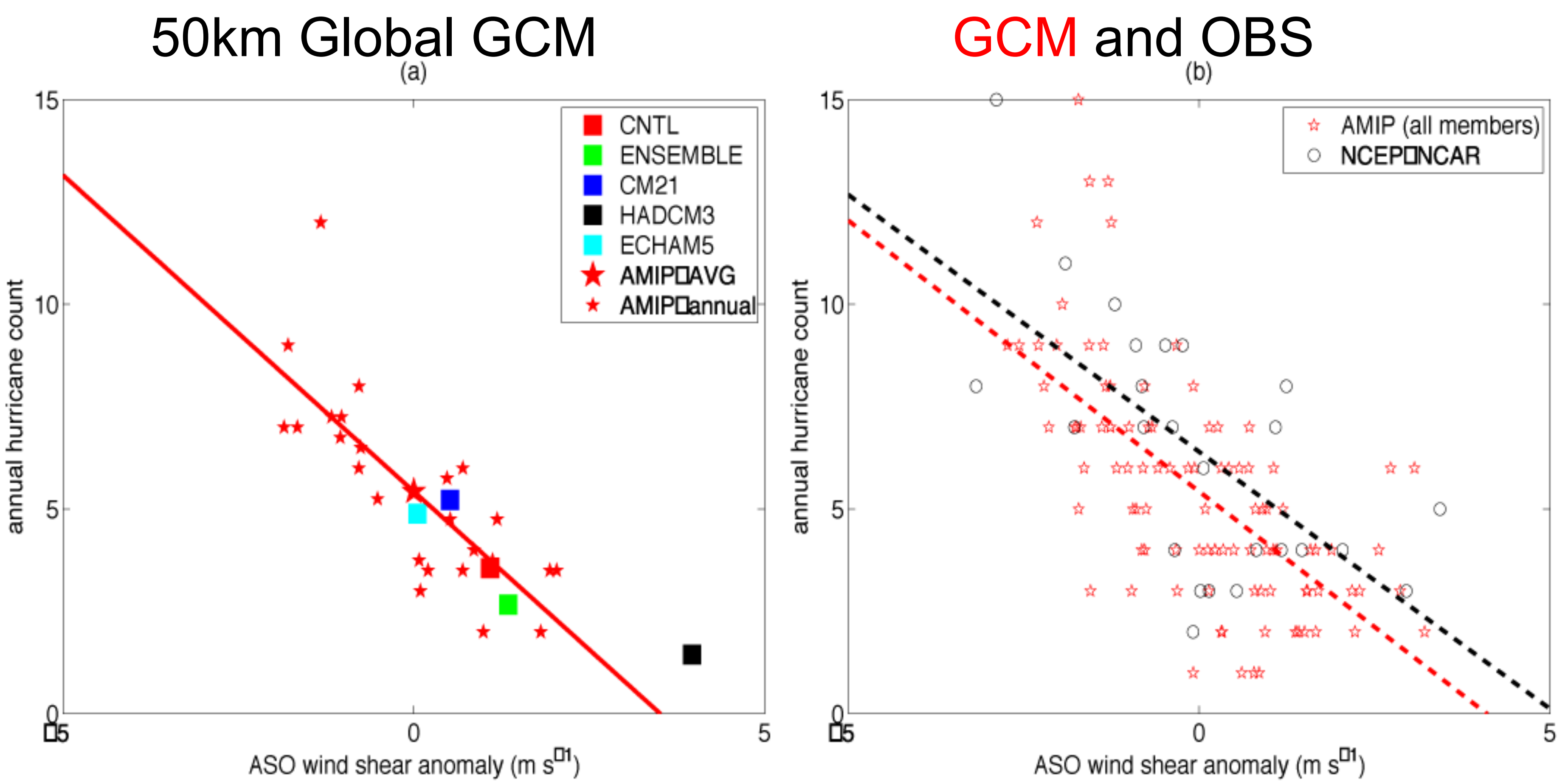
CMIP3 projected 21st Cy vertical wind shear changes



Vecchi and Soden (2007, GRL)

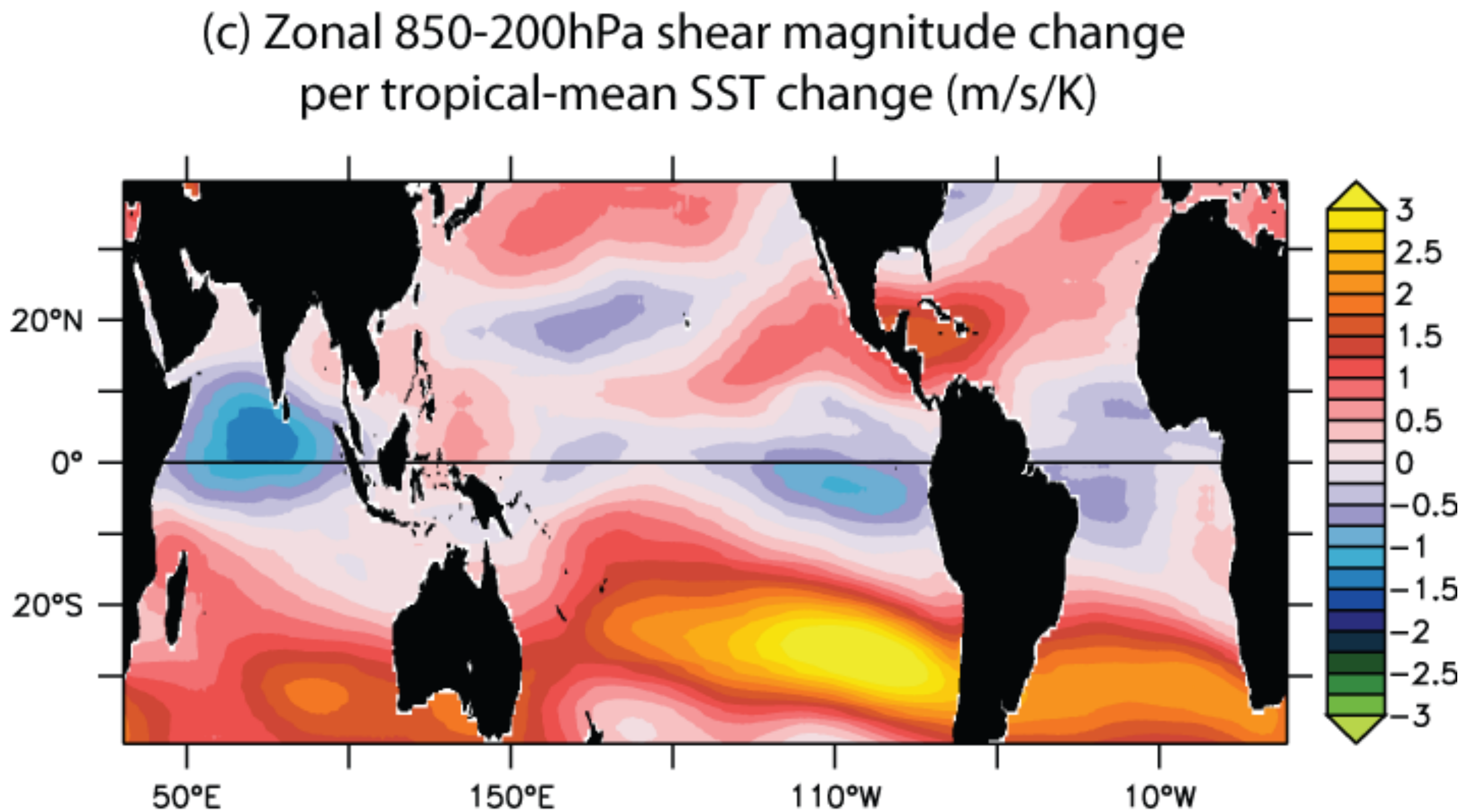
Increased wind shear over much of Tropical Atlantic and eastern Pacific connected to weakening of tropical circulation.

Shear changes and Atlantic hurricane activity



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

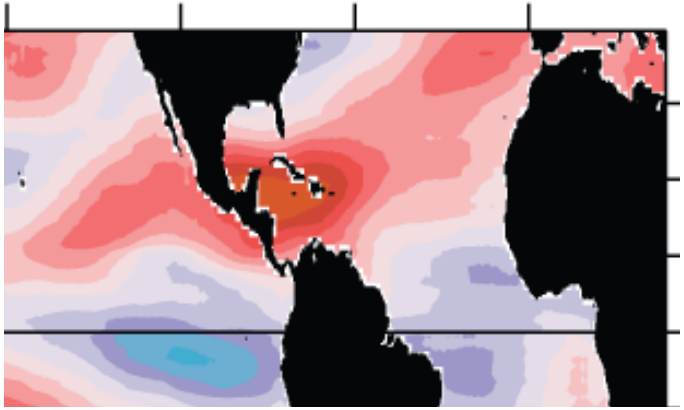
CO_2 increases Atlantic shear in CMIP5 models



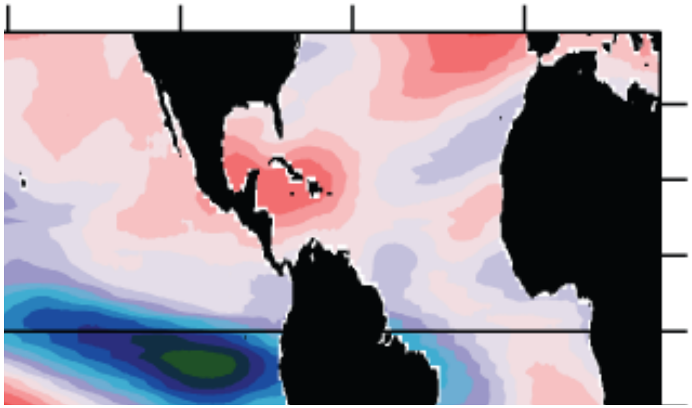
Vecchi and Soden (2012, in prep.)

Aerosols in projections complicate shear response in CMIP5

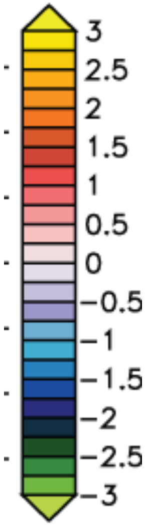
Response to CO_2 only



RCP2.6: strong reduction of aerosols

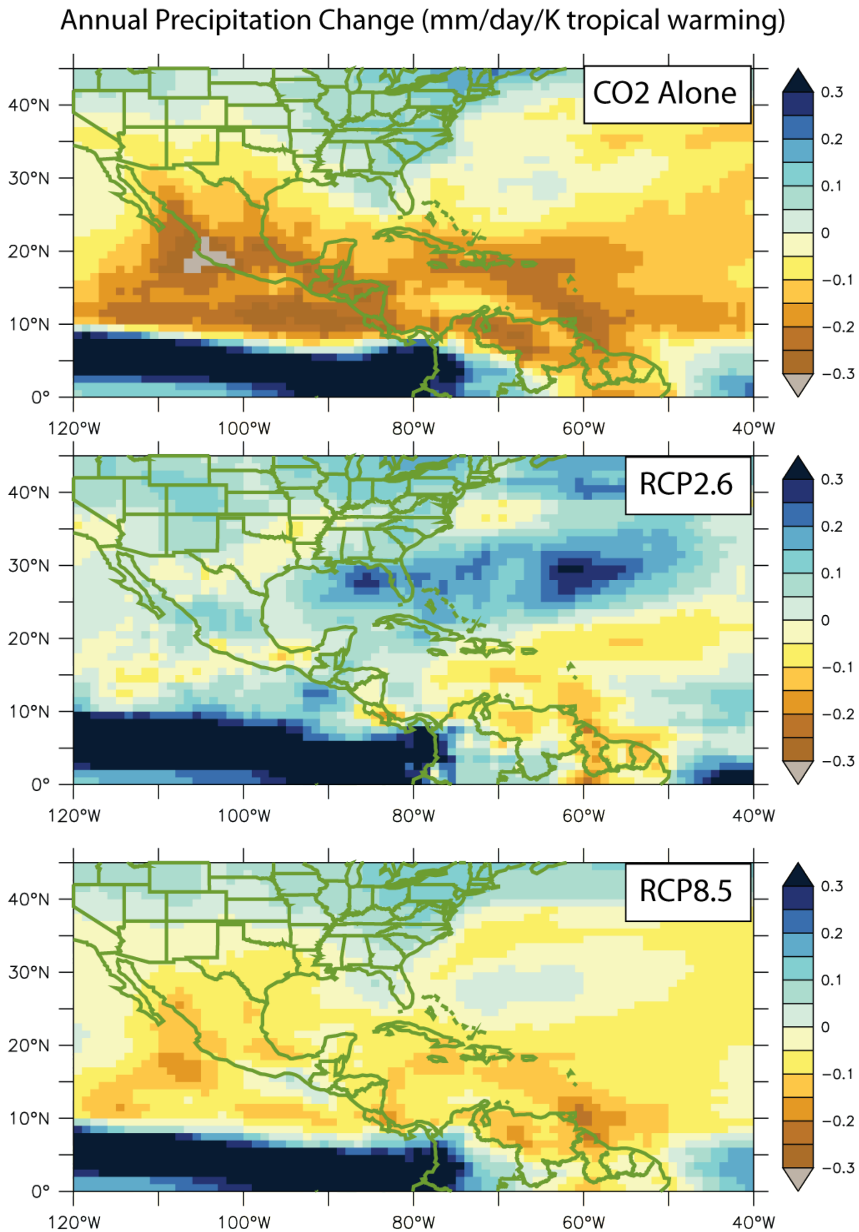


Multi-model shear change per unit tropical SST increase (m/s/K)



Vecchi and Soden (2012, in prep.)

Aerosol impact also evident in precip



CO_2 alone

Weak CO_2 increase
Big aerosol decrease

Large CO_2 increase
Modest aerosol decrease

Vecchi and Soden (2012, in prep.)

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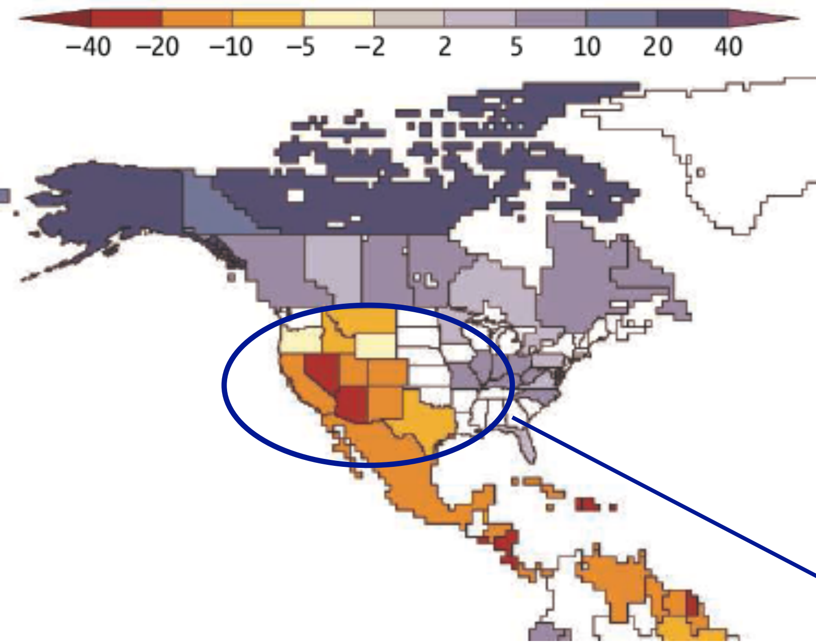
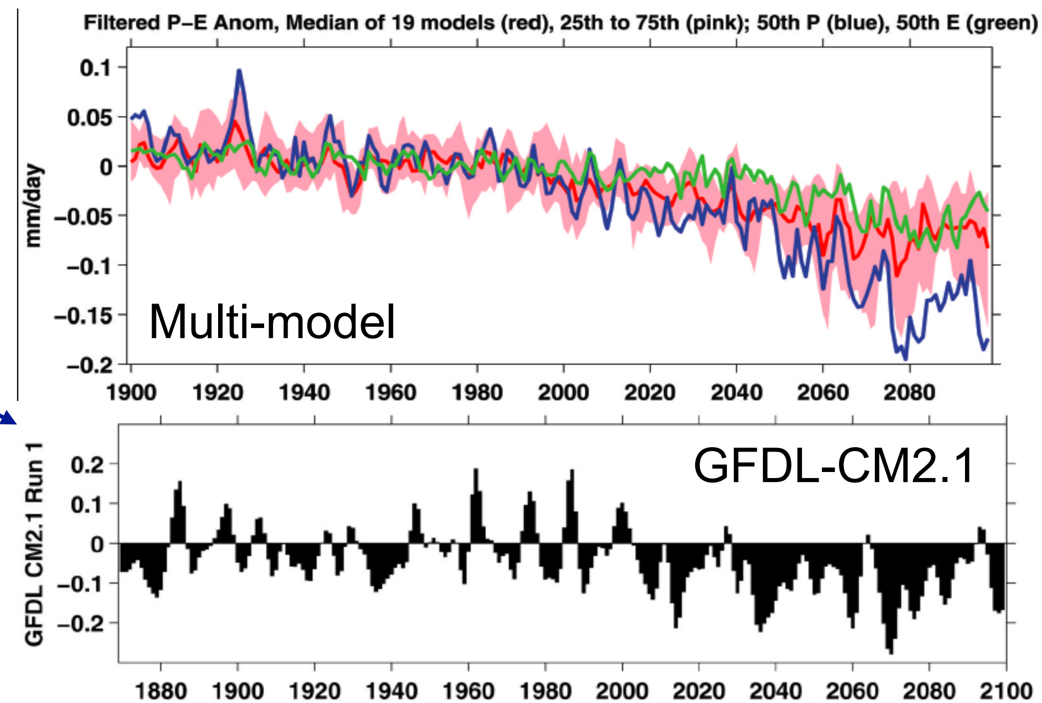
Southwest Drying Projections

21st Century Projected
% Change in Runoff



Milly et al (2008, Science)

Change in SW US Precip. minus Evap.



Seager et al (2007, Science); Seager and Vecchi (2010, PNAS)
Seager, Naik and Vecchi (2010, J. Climate)

SW Drying part of global pattern

SW Drying part of overall drying of subtropics.

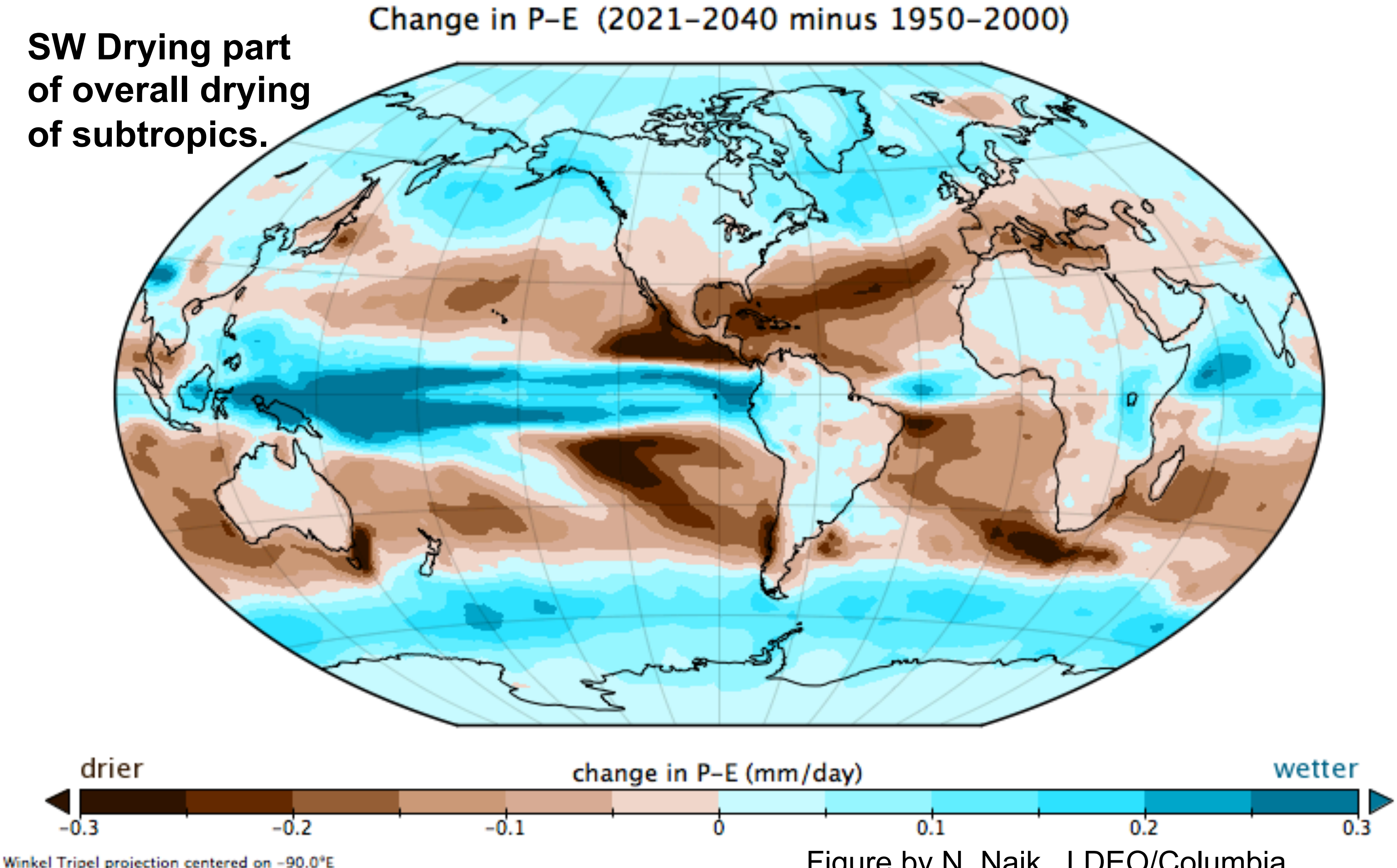


Figure by N. Naik., LDEO/Columbia

Mechanisms for CO_2-Forced Drying

<u>Thermodynamic Control:</u>

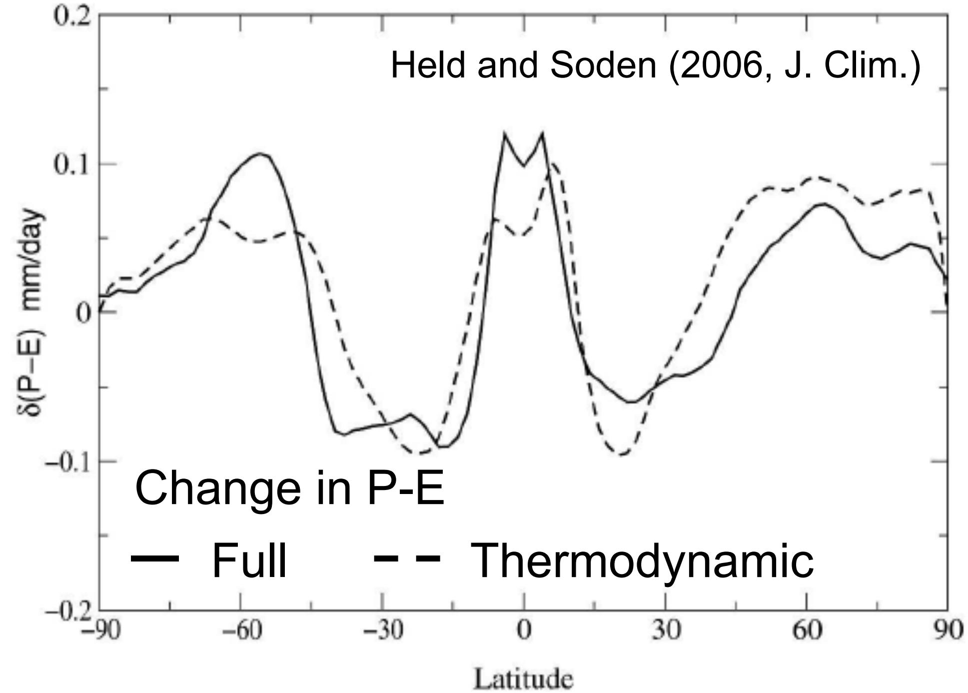
Warming (increase q_{sat})

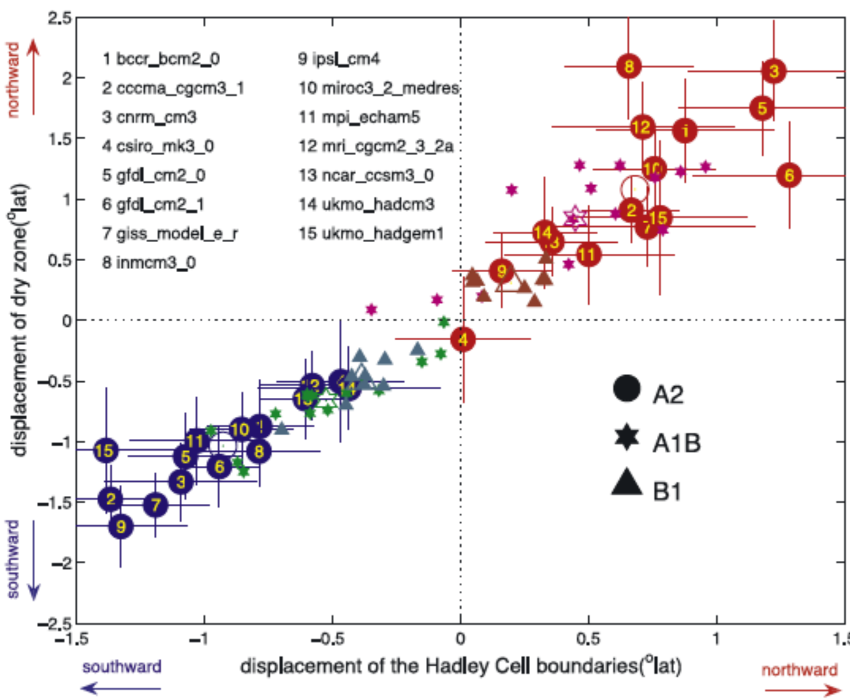
↓

increase atmospheric moisture.

↓

increase moisture flux divergence/ convergence.





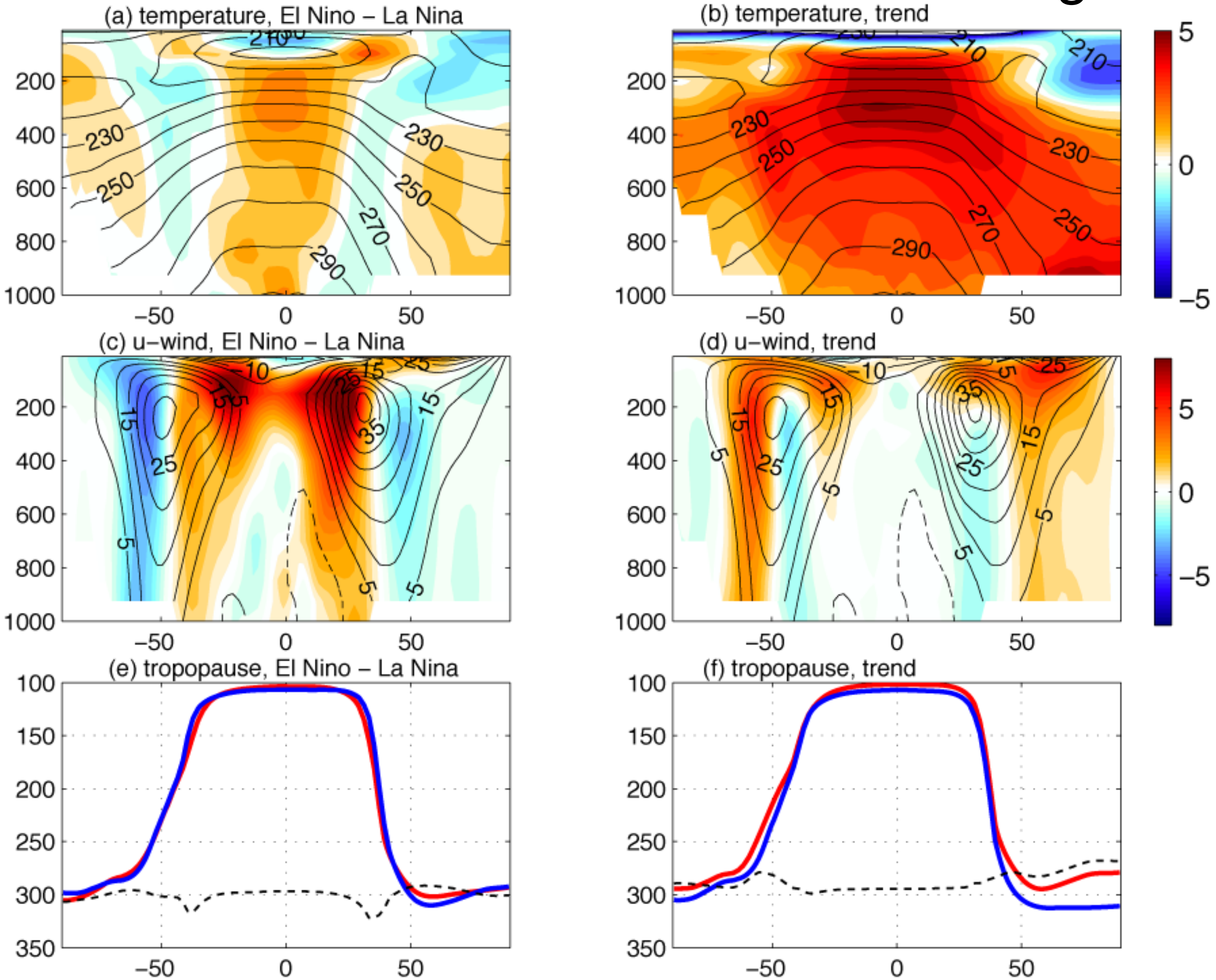
<u>Circulation Changes:</u>

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

Lu, Vecchi and Reichler (2007, GRL)

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 includes 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, Wet South Asian Monsoon…

- 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?
  - Mean thermocline depth may be better constraint than SST gradient

- Weaker Walker Cell associated with increased Atlantic wind shear.

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