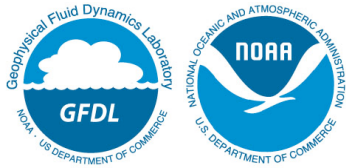


# Tropical Response to Warming: Oceanic and Atmospheric Feedbacks



G. A. Vecchi, B. J. Soden, A. Clement,  
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.

Gabriel.A.Vecchi@noaa.gov

# Outline

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

# From IPCC-AR4

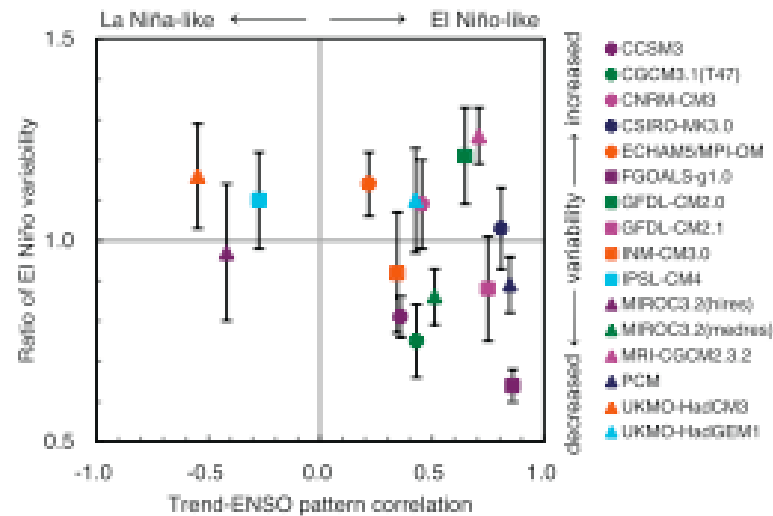


Figure 10.16. Base state change in average tropical Pacific SSTs and change in El Niño variability simulated by AGCMs (see Table 8.1 for model details). The base

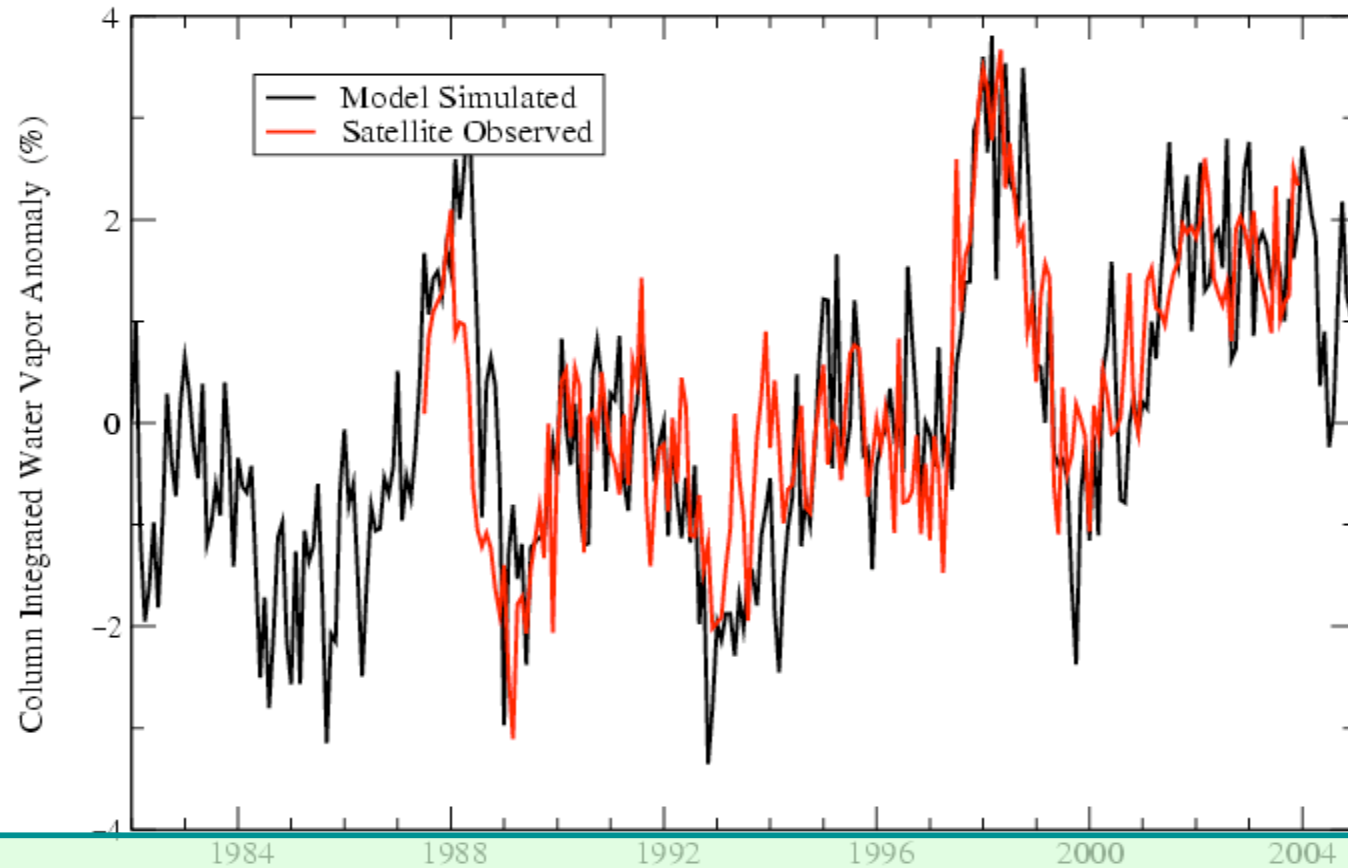
“In summary, the multi-model mean projects a weak shift towards conditions which may be described as ‘El Niño-like’, with SSTs in the central and eastern equatorial Pacific warming more than those in the west, and with an eastward shift in mean precipitation, associated with weaker tropical circulations.”

*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)**

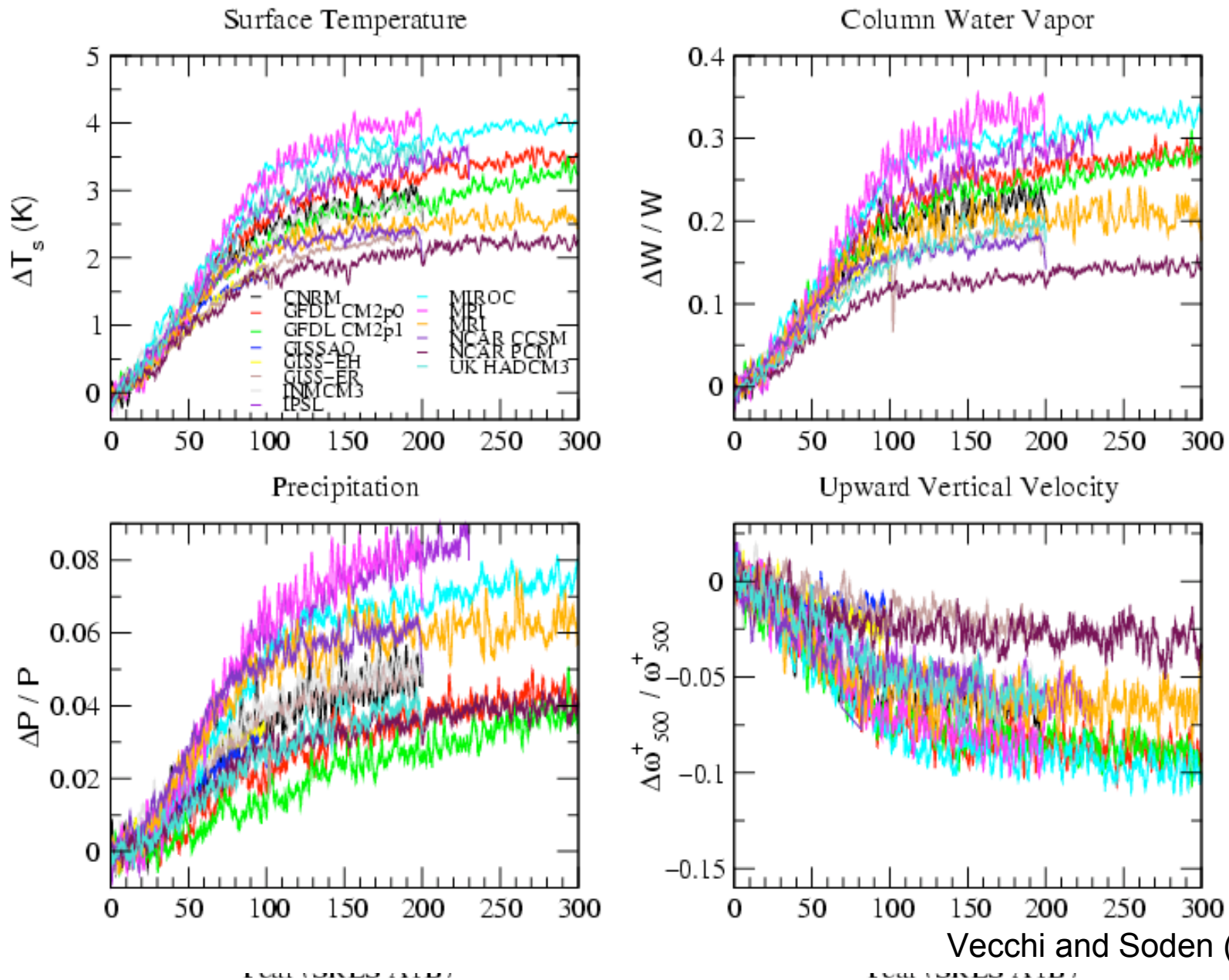
Held and Soden (2006, J. Clim)

# 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<sub>2</sub> Stabilization)



Vecchi and Soden (2007, J. Clim.)

# Outline

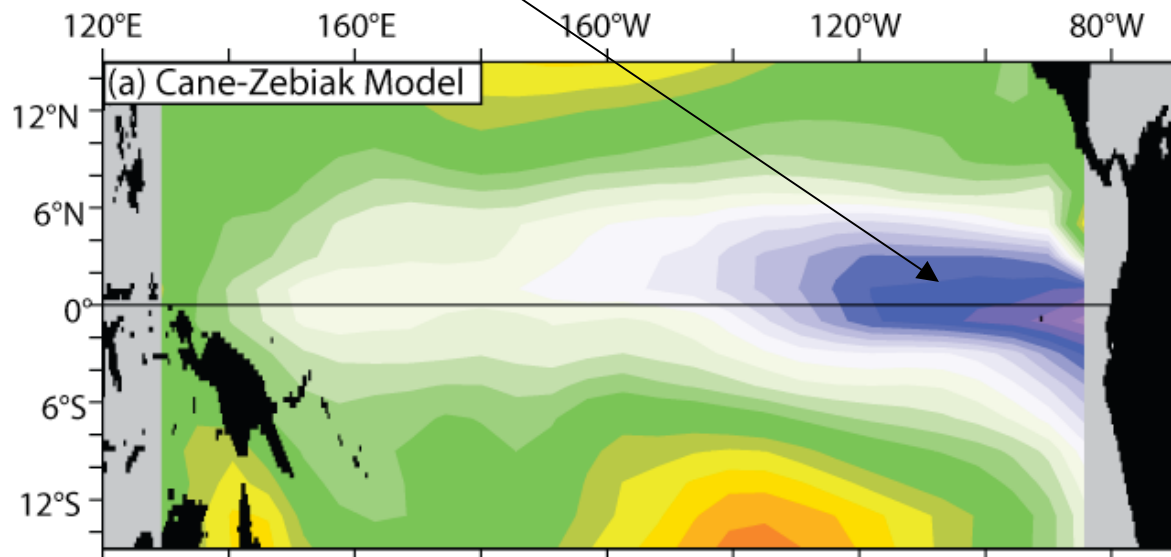
- Introduction/background
- **Theory**
  - Oceanic constraint
  - Atmospheric constraint
- Modeling
- Observations
- Implications (time permitting)



# Ocean Dynamical Thermostat

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

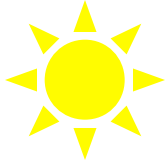
- In warming world, tropical ocean thermal stratification increases.
- Thus, upwelling zones warm more slowly than rest - upwell (c)older water.
- Coupled (Bjerkes) feedbacks.
- “La Niña-like” response.



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

# Simplified view of atmospheric water/energy balance

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

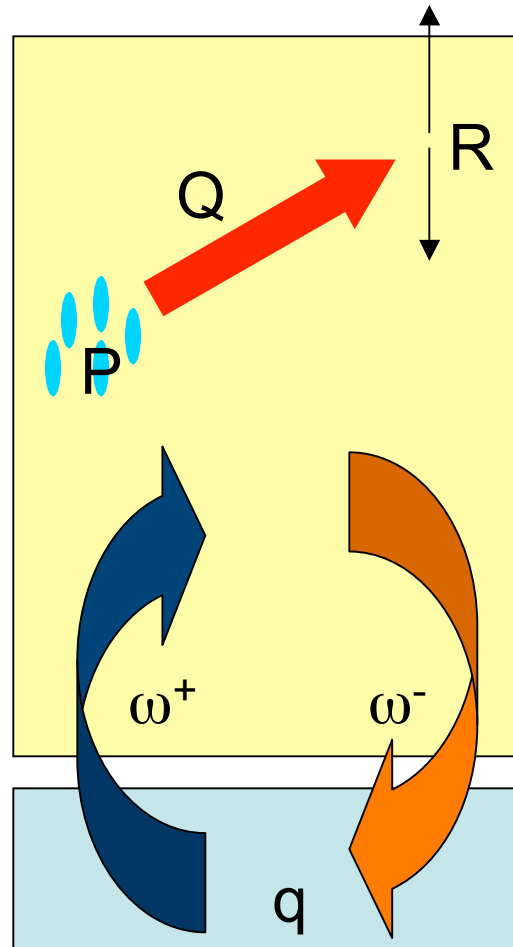


(4) Moist air condenses, heats troposphere, and precipitates.

$$Q = L_v \cdot P$$

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

(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)

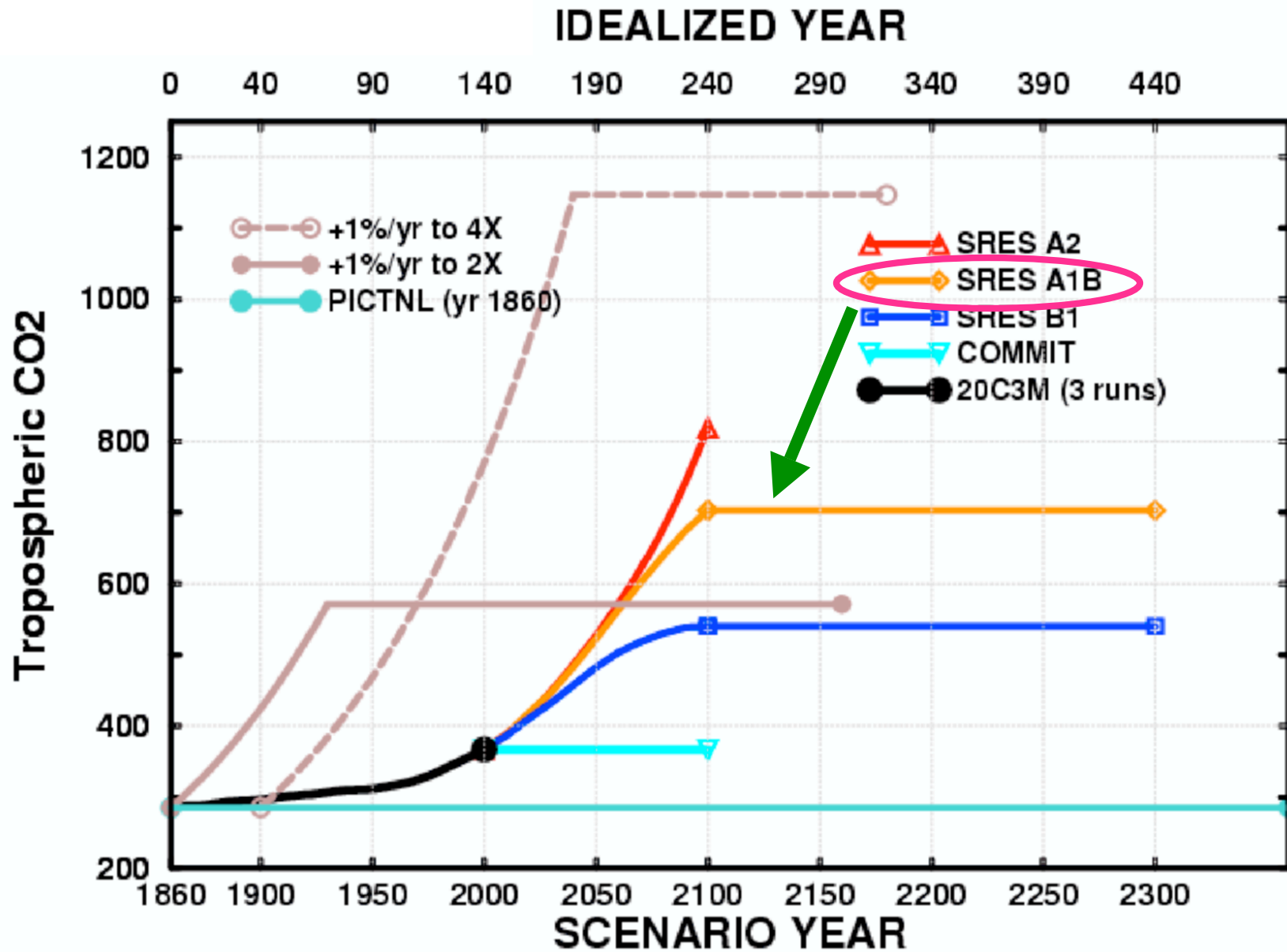
$$R \propto P = q \cdot \omega^+ \longrightarrow dR/R = dP/P = dq/q + d\omega^+/\omega^+$$

- Assume small change in  $rh$ 
  - Thus,  $q$  increases like Clausius-Clapeyron ( $\sim 7\%$  per K)
- Water flux constrained by precipitation
- Precipitation constrained by radiation
  - Radiation changes more slowly than C.-C.
- **Since  $dP/P < dq/q$ , circulation ( $\omega^+$ ) must weaken.**
- Walker Circulation weakens? “El Niño-like”?

# Outline

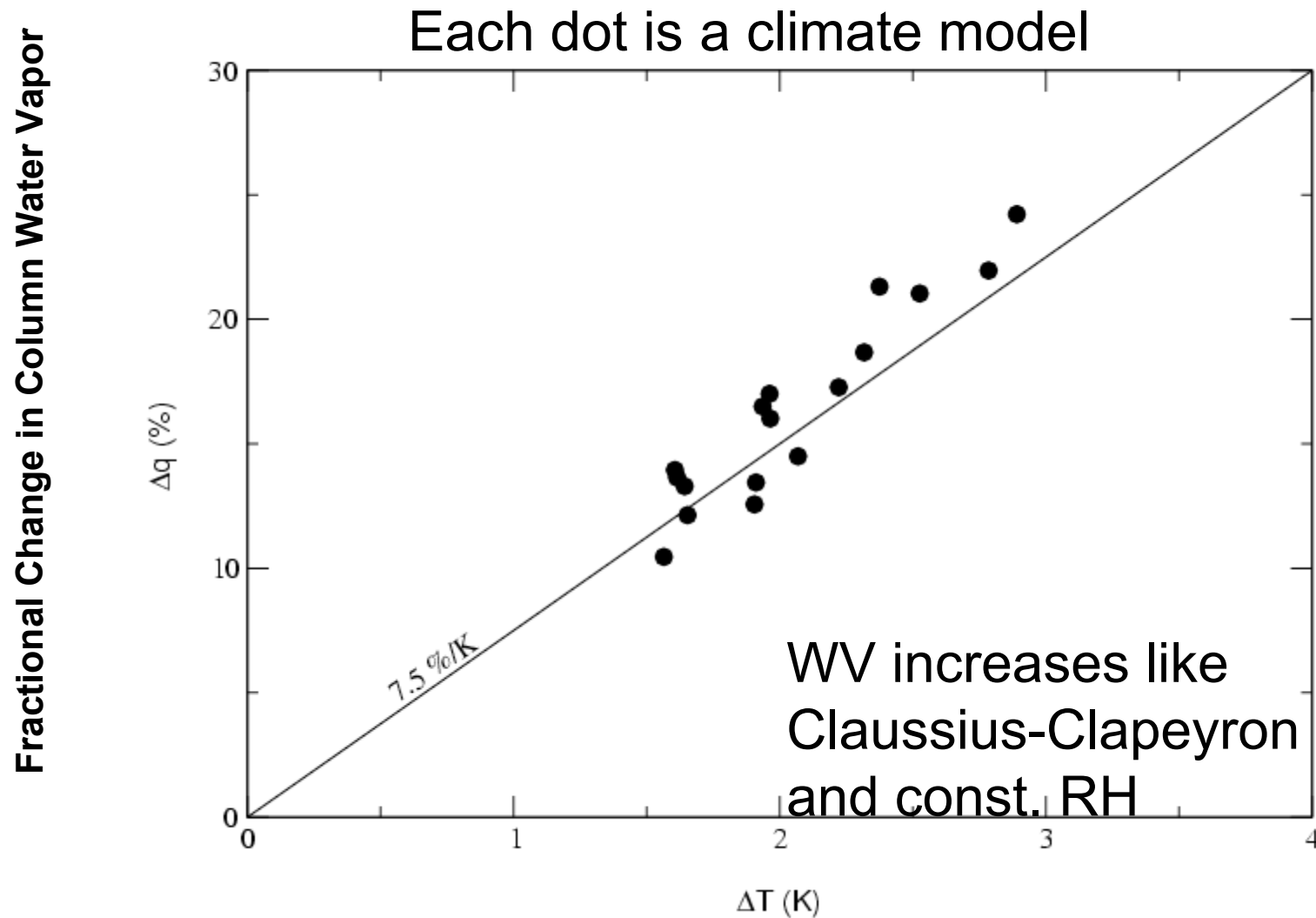
- Introduction/background
- Theory
- **Numerical Modeling**  
explore IPCC-AR4/CMIP3 model database.
- Observations
- Implications

# Idealized greenhouse warming experiments



# Atmospheric Constraint on Tropical Circulation

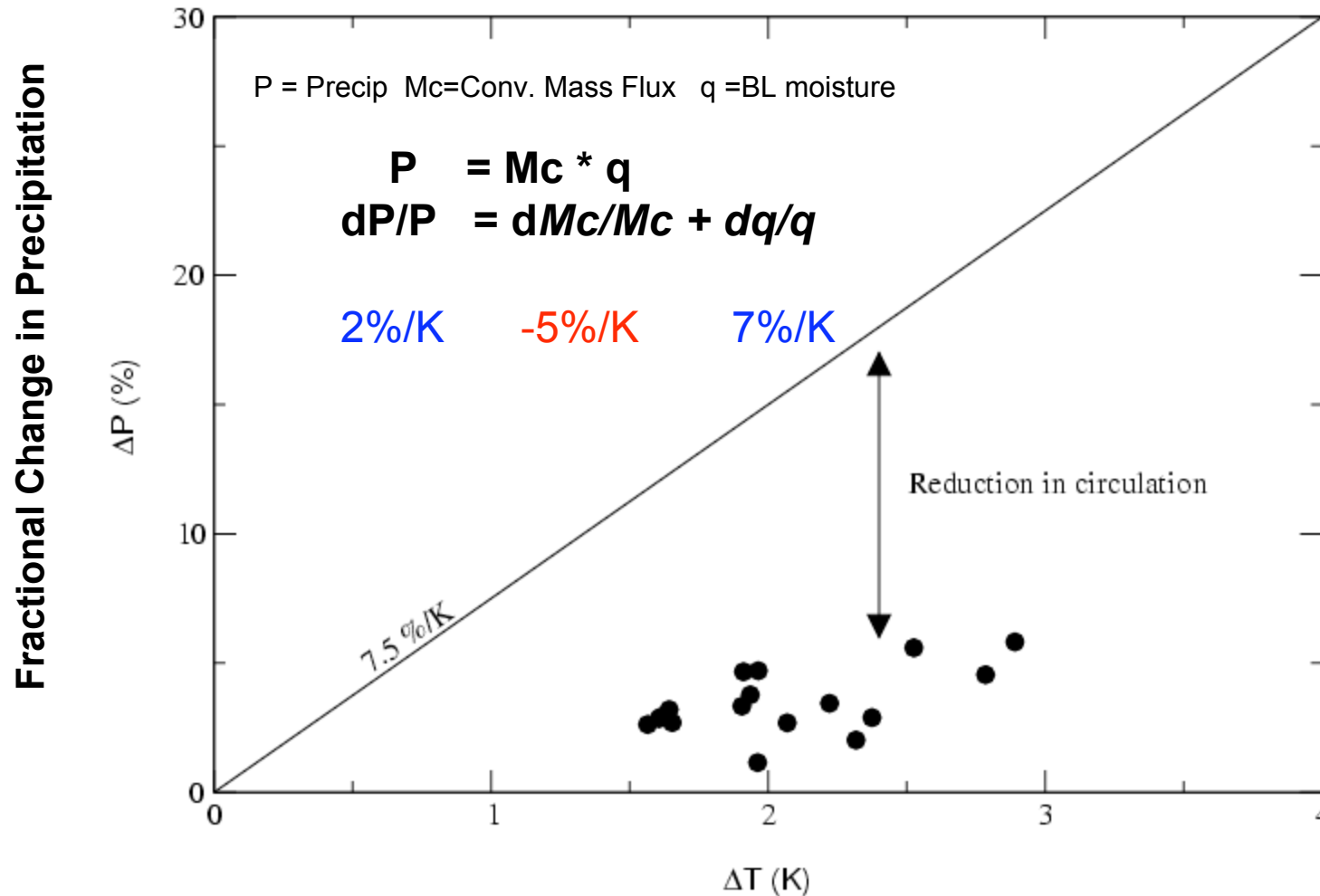
## Change in Global Water Vapor at 2100



Held and Soden (2006, J. Clim)

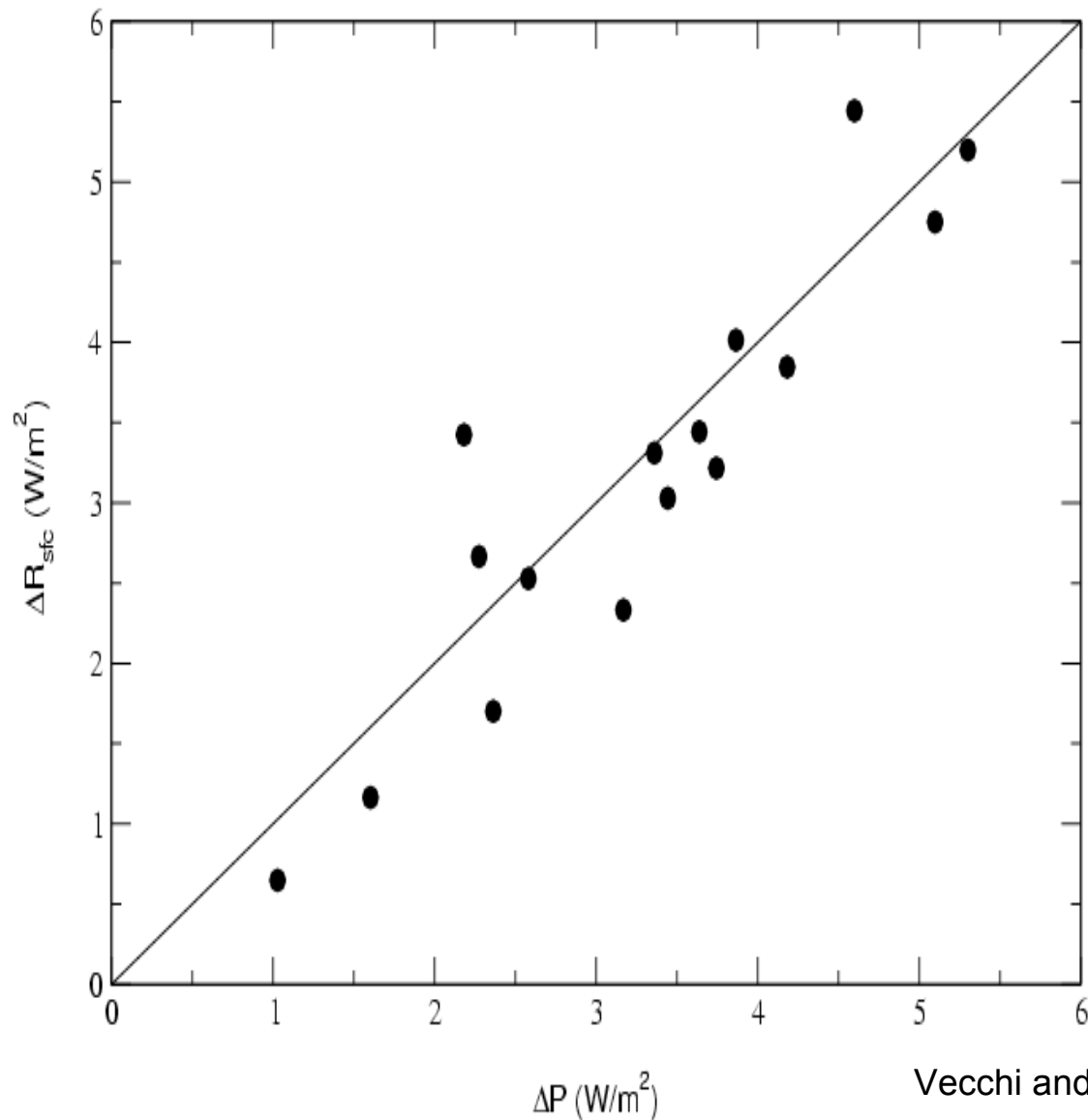
# Atmospheric Constraint on Tropical Circulation

## 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



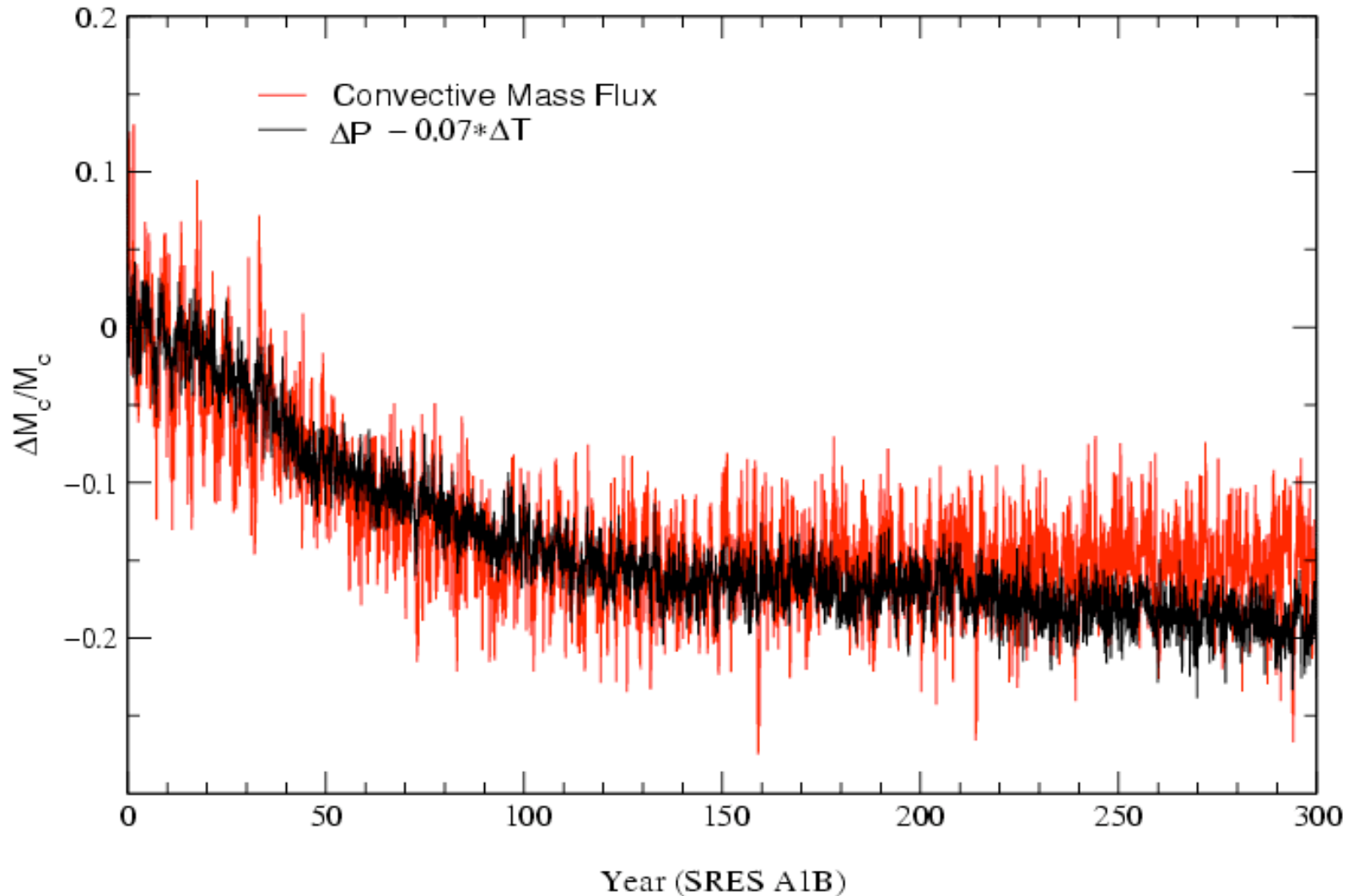
Vecchi and Soden (2007), J.Clim.

IPCC AR4 Model Global Response to SRESA1B (720 ppm CO<sub>2</sub>)

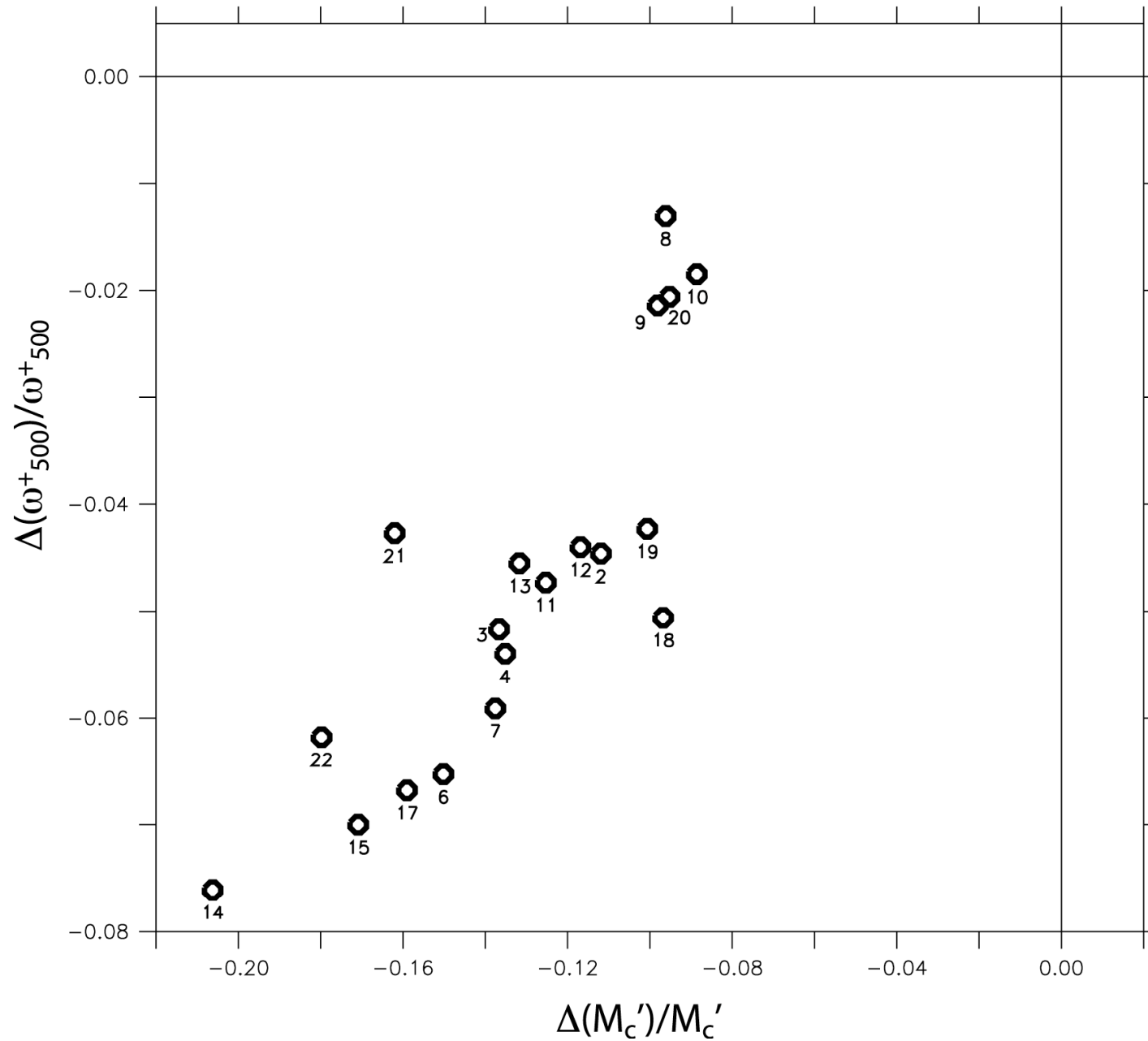


In GFDL CM2.1, convective mass flux changes track theoretical estimate.

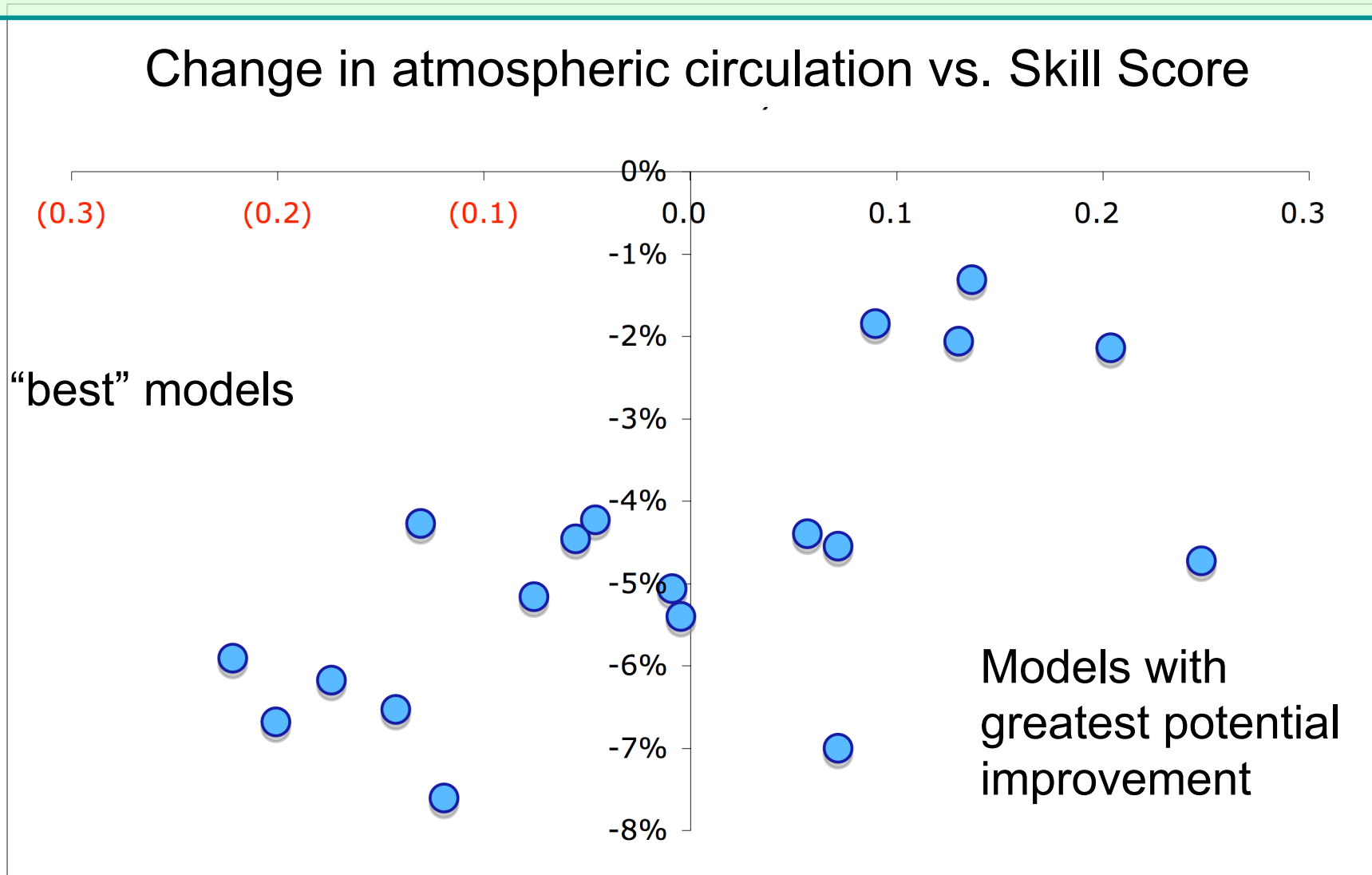
GFDL CM2p1



# Upward 500 hPa $\omega$ vs. estimated convective mass flux



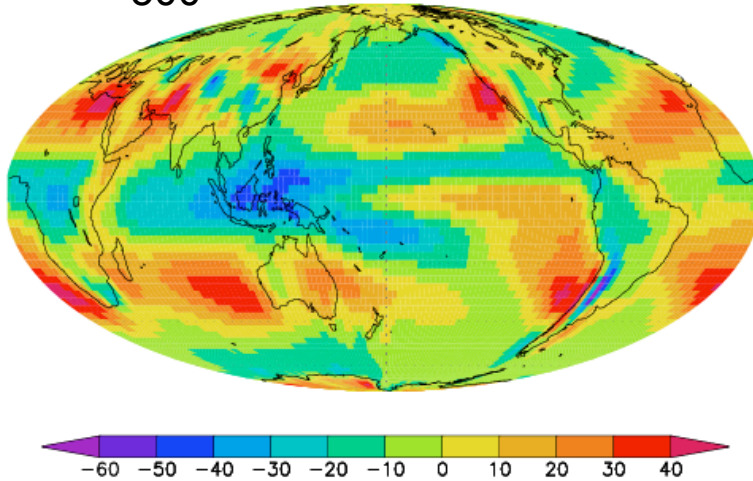
## “Best” IPCC-AR4 Models show a large weakening of circulation



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  $\omega_{500}$



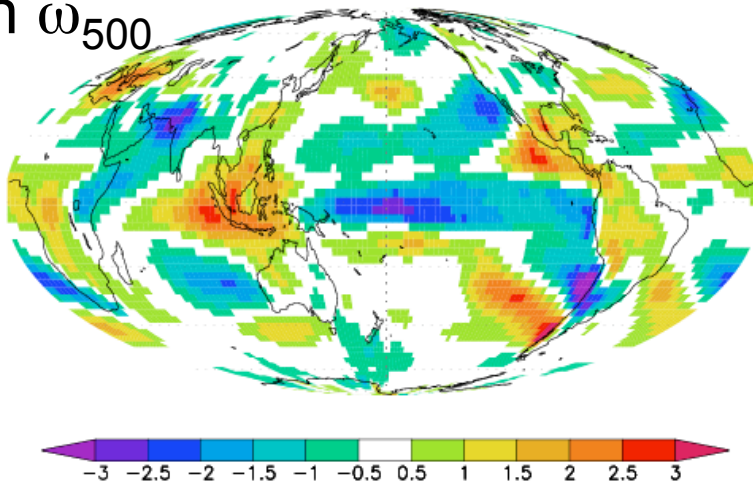
Changes in vertical velocity oppose mean state (except Central Pacific)

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

Change in  $\omega_{500}$



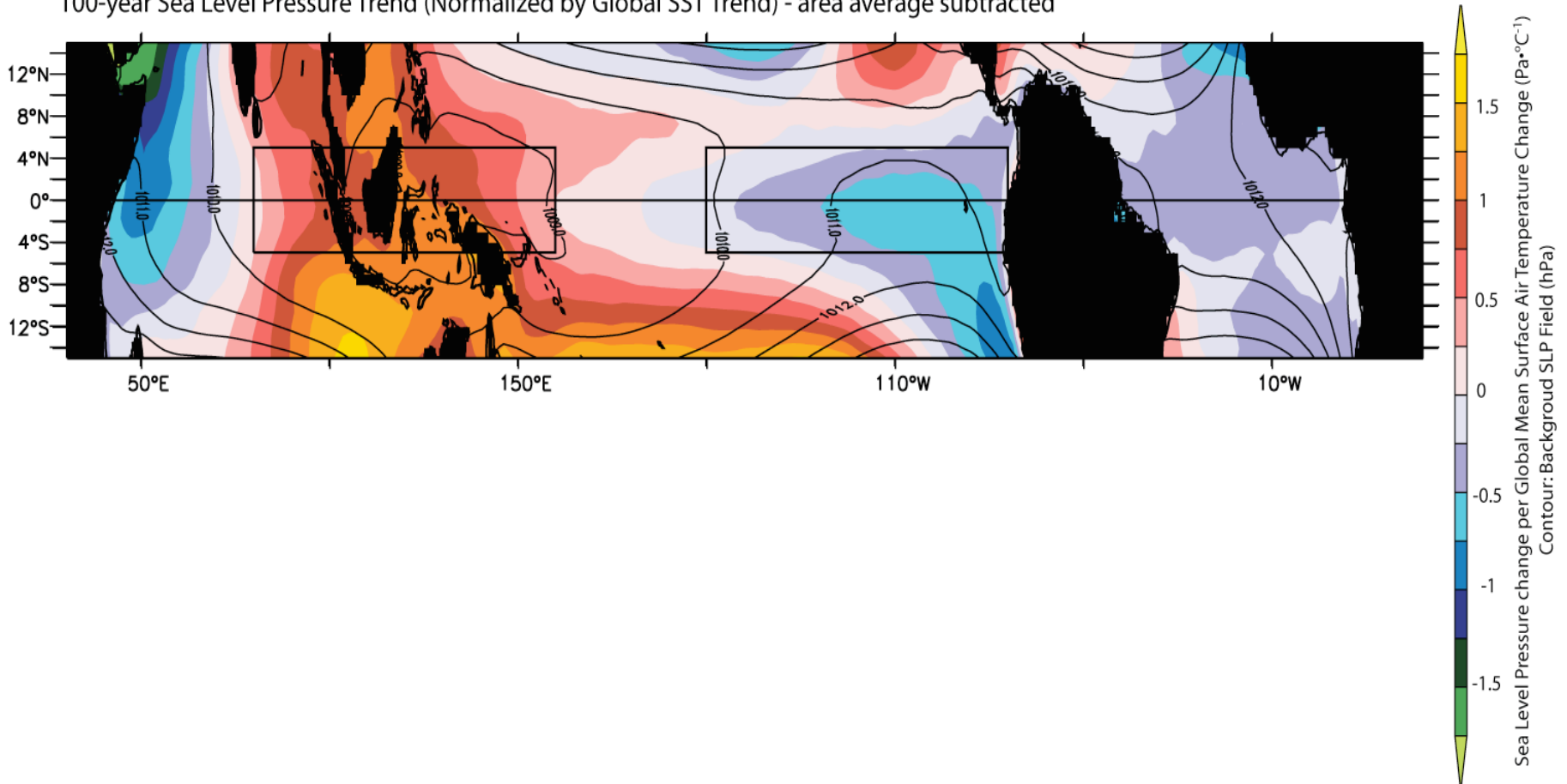
Not “El Niño-like”:

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

# Near-equatorial Indo-Pacific Zonal SLP gradients decrease

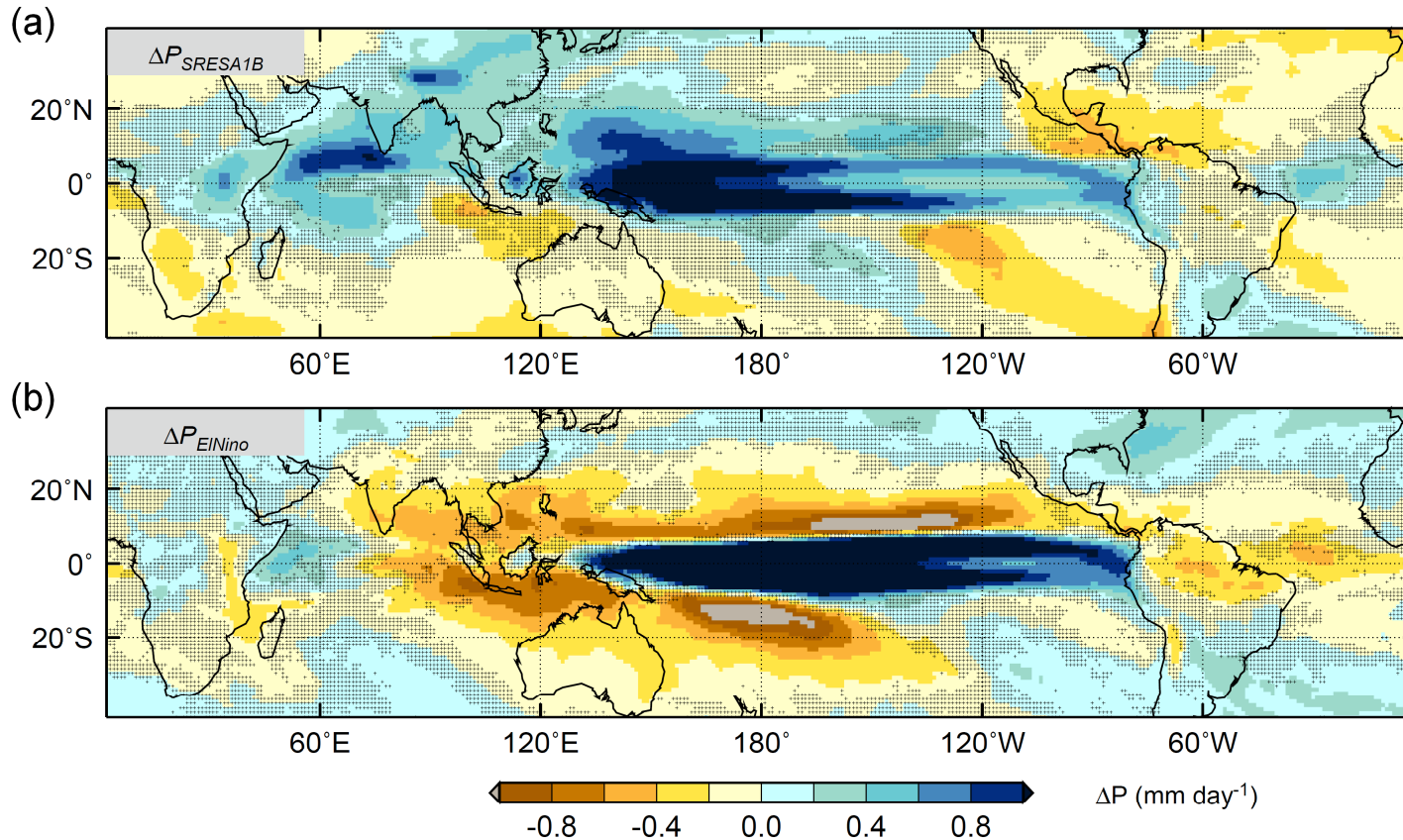
Full ocean GCMS

a) 22-Model Ensemble-mean Scenario A1B (720 ppm CO<sub>2</sub> Stabilization) - 2001-2100  
100-year Sea Level Pressure Trend (Normalized by Global SST Trend) - area average subtracted



# Precipitation response: CO<sub>2</sub> and El Niño

multi-GCM Precipitation response to CO<sub>2</sub>



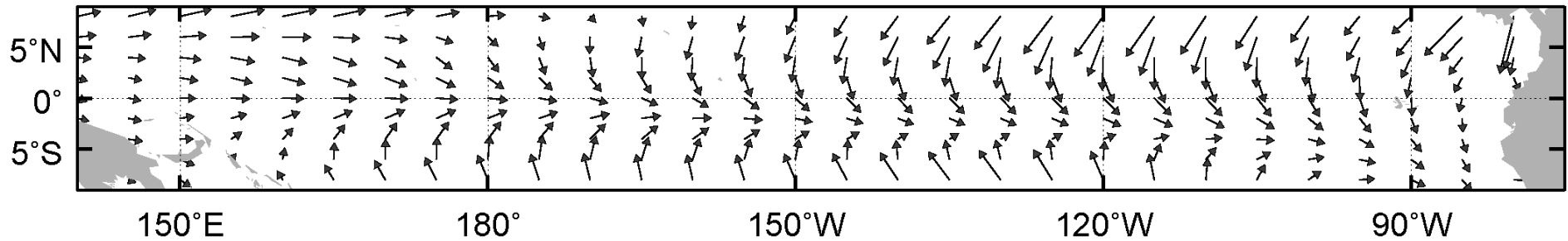
multi-GCM Precipitation response to El Niño

*DiNezio, Clement and Vecchi (2009, Submitted)*

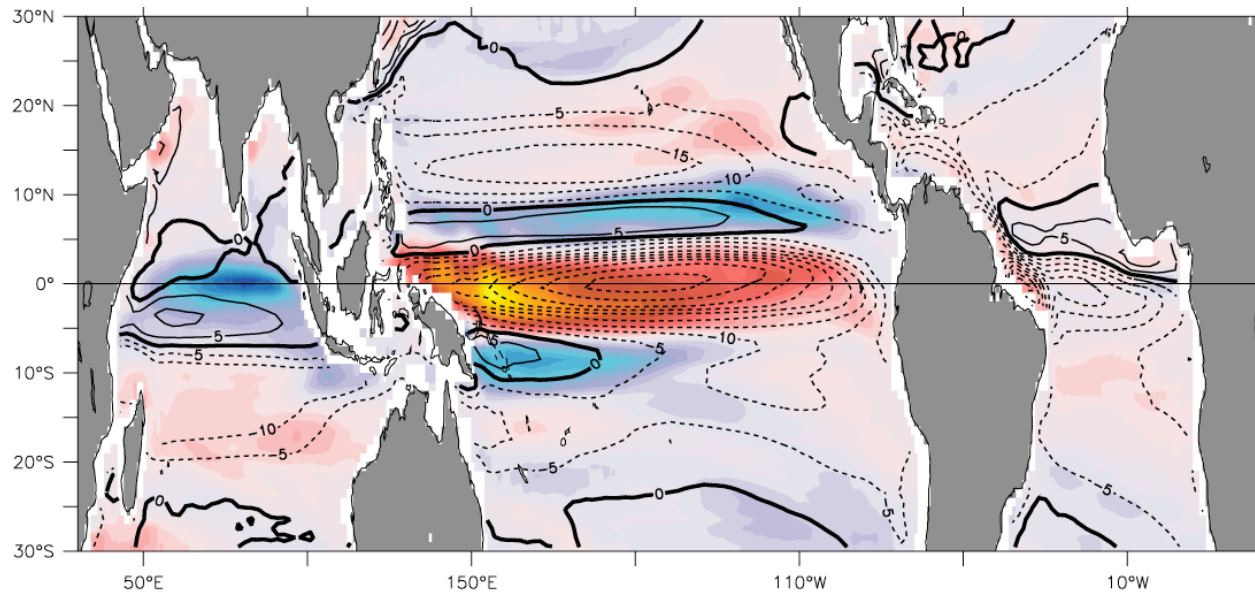
# Wind Stress and Currents

## Stress

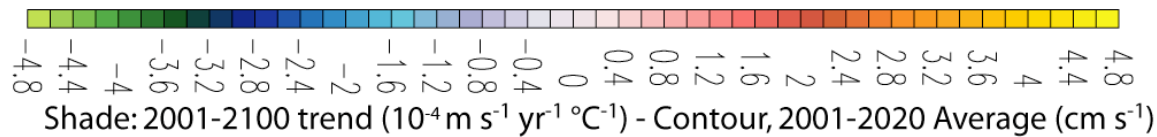
DiNezio et al (2009, J. Clim.)



## Surface Zonal Currents



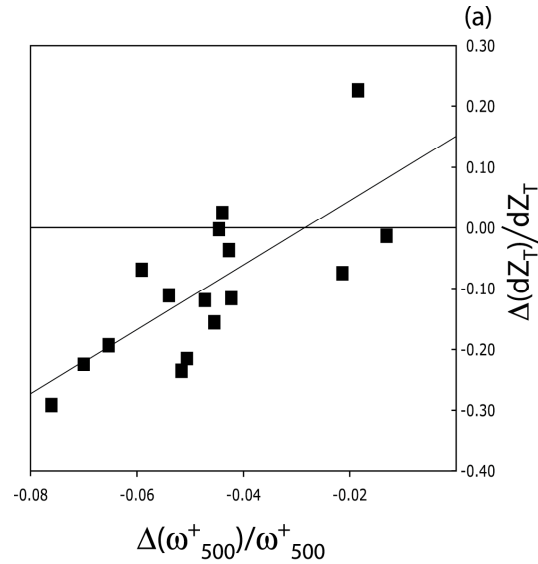
Vecchi and Soden  
(2007, J. Clim.)



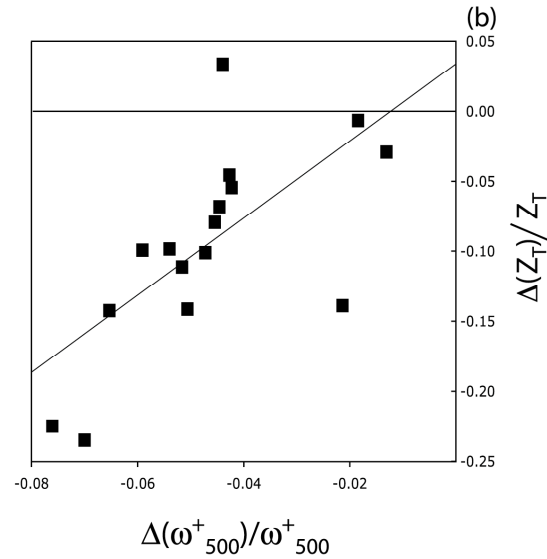


# Many projected tropical ocean changes scale with slowing atmospheric circulation.

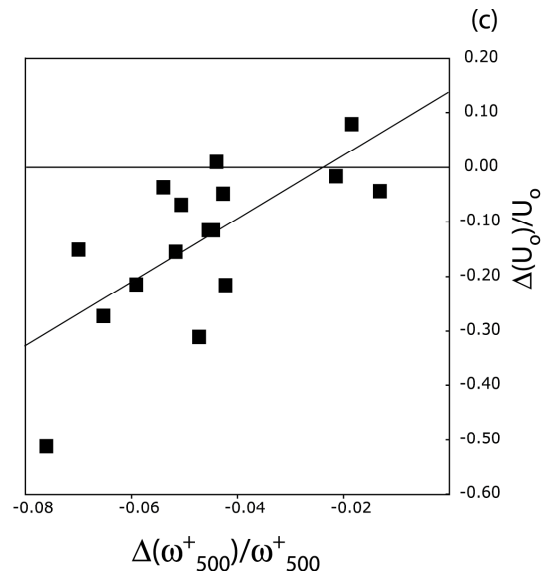
Equatorial Pacific  
thermocline slope



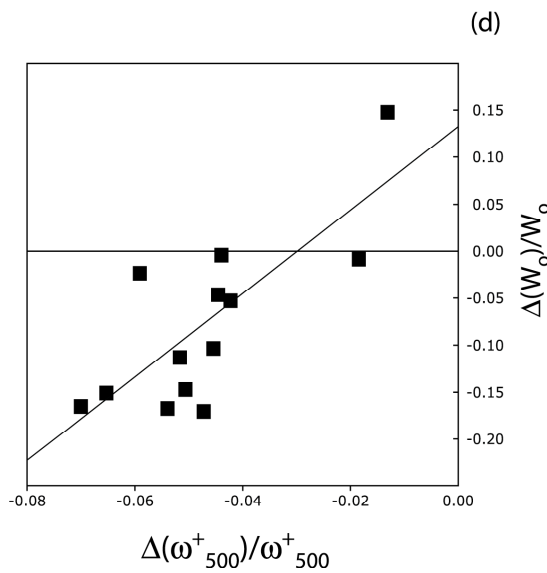
Equatorial Pacific  
thermocline depth



Equatorial Pacific  
surface zonal current



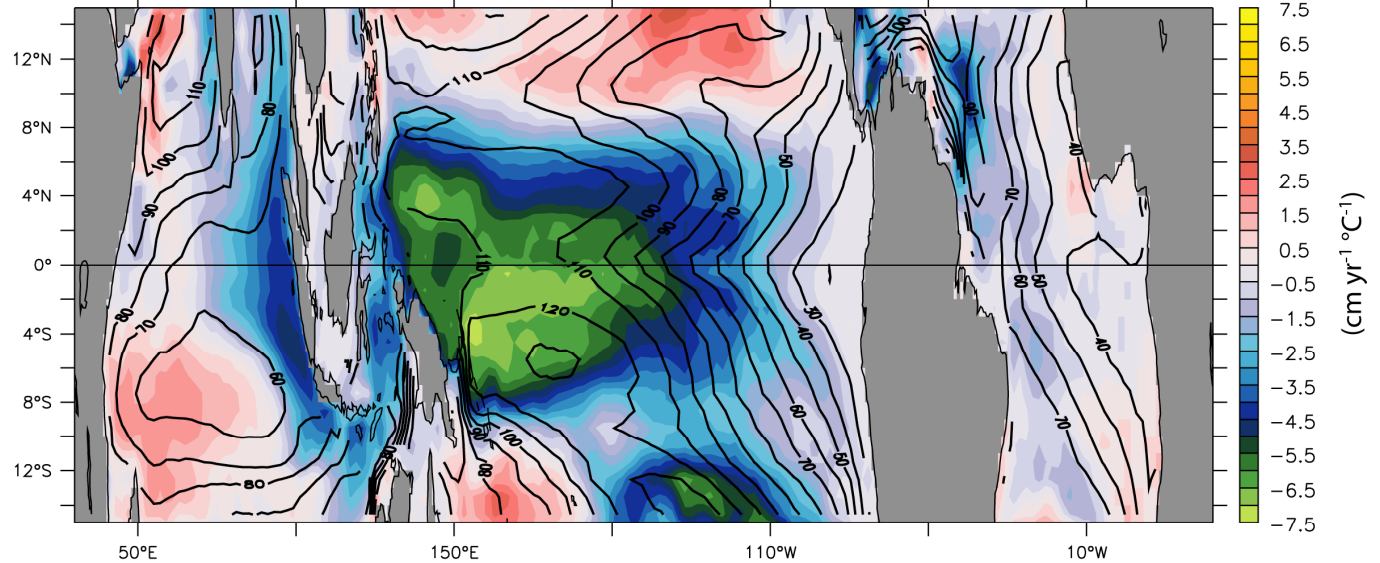
Equatorial Pacific  
vertical velocity





Scenario A1B (720 ppm CO<sub>2</sub> Stabilization) - 2001-2100

19-Model Ensemble-mean 100-year Thermocline Depth Trend (Normalized by Global SST Trend)

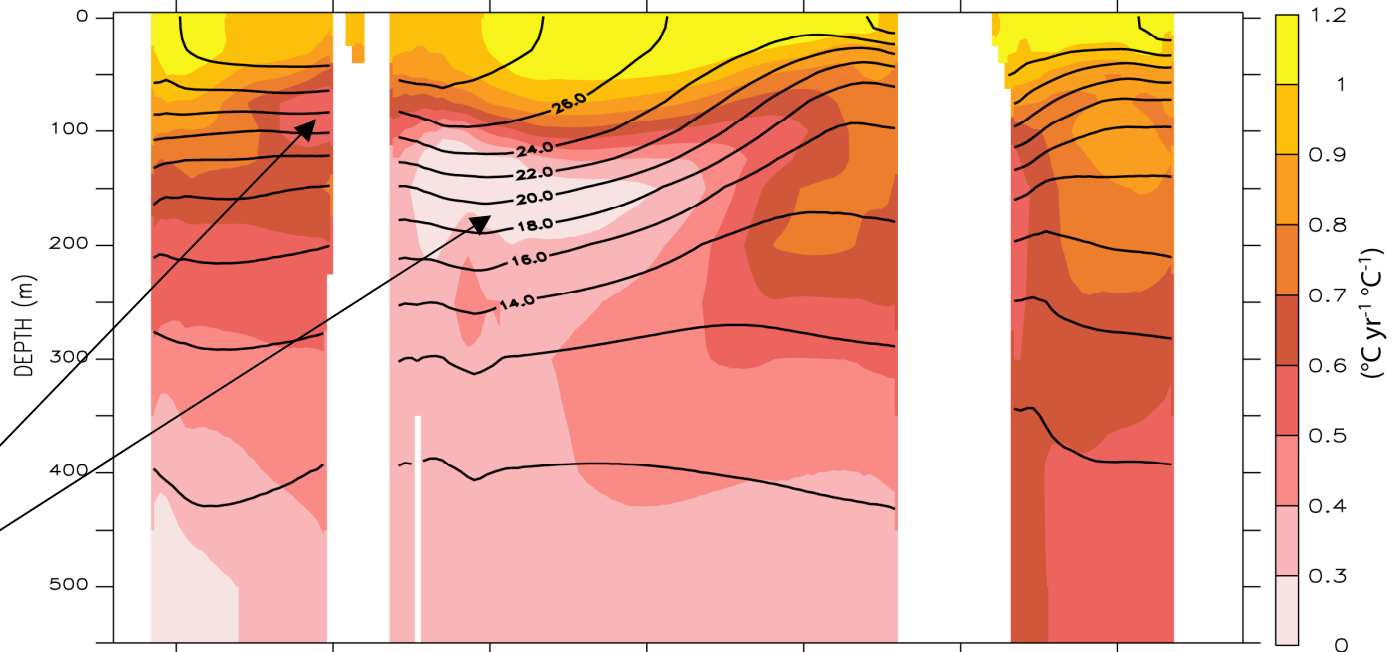


Ensemble-mean response of tropical thermocline (defined as maximum of  $dT/dz$ ). Equatorial Pacific thermocline flattens and shoals.

Ensemble-mean response of equatorial subsurface temperatures.

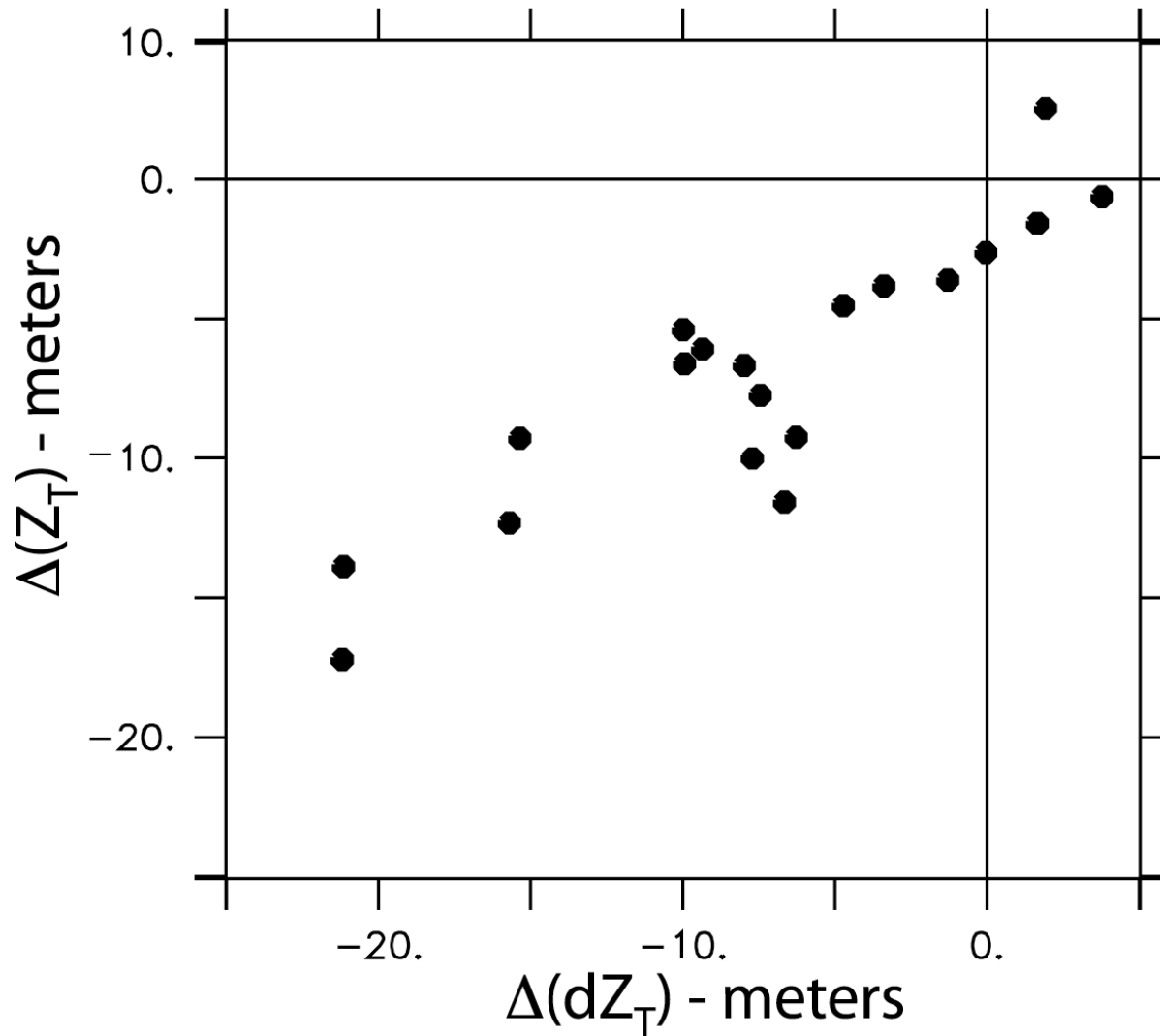
Increased thermal stratification.

Minimum in warming



19-Model Ensemble-mean 100-year Equatorial Temperature Trend (Normalized by Global SST Trend)

Equatorial Pacific  
Thermocline Slope vs. Depth



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)

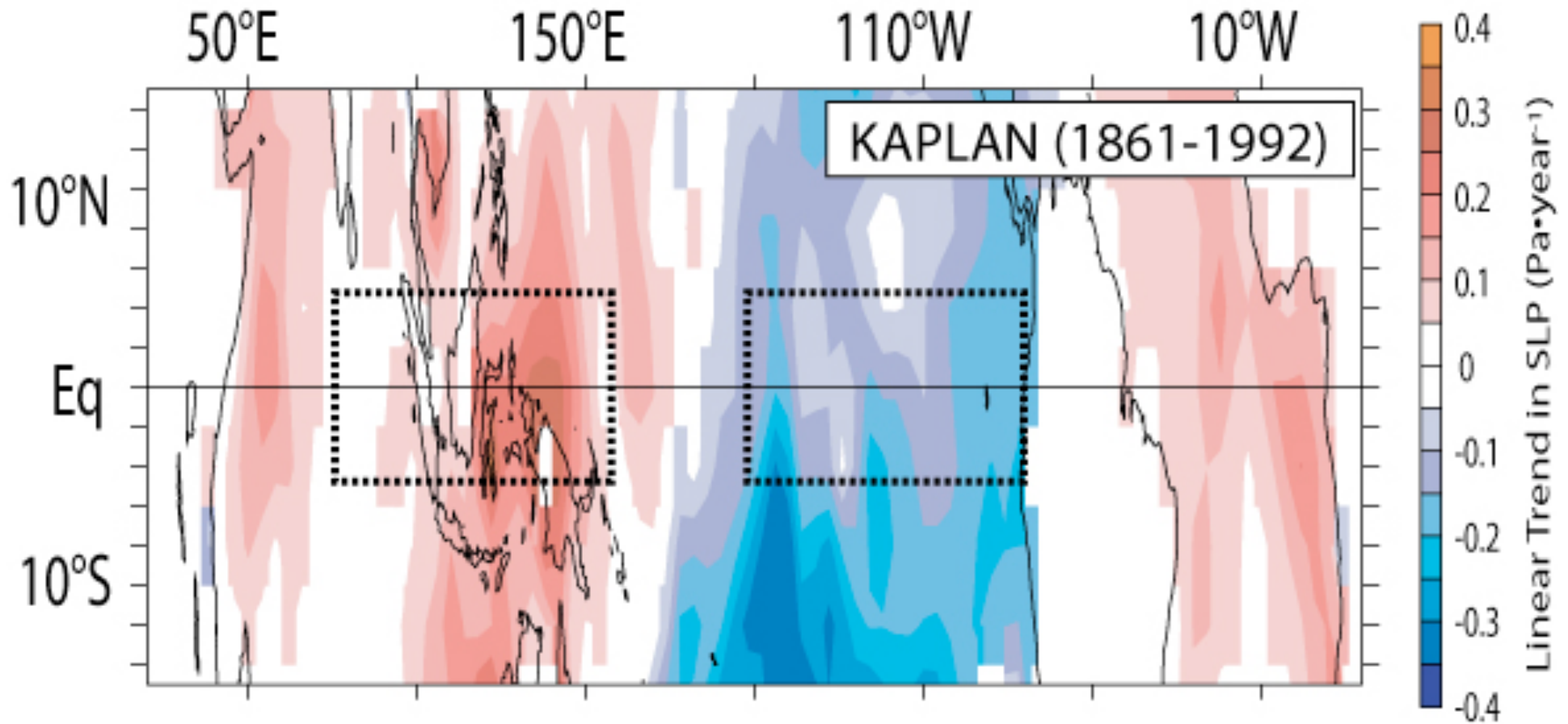
# Outline

- Introduction/background
- Theory
- Numerical Modeling
- **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.

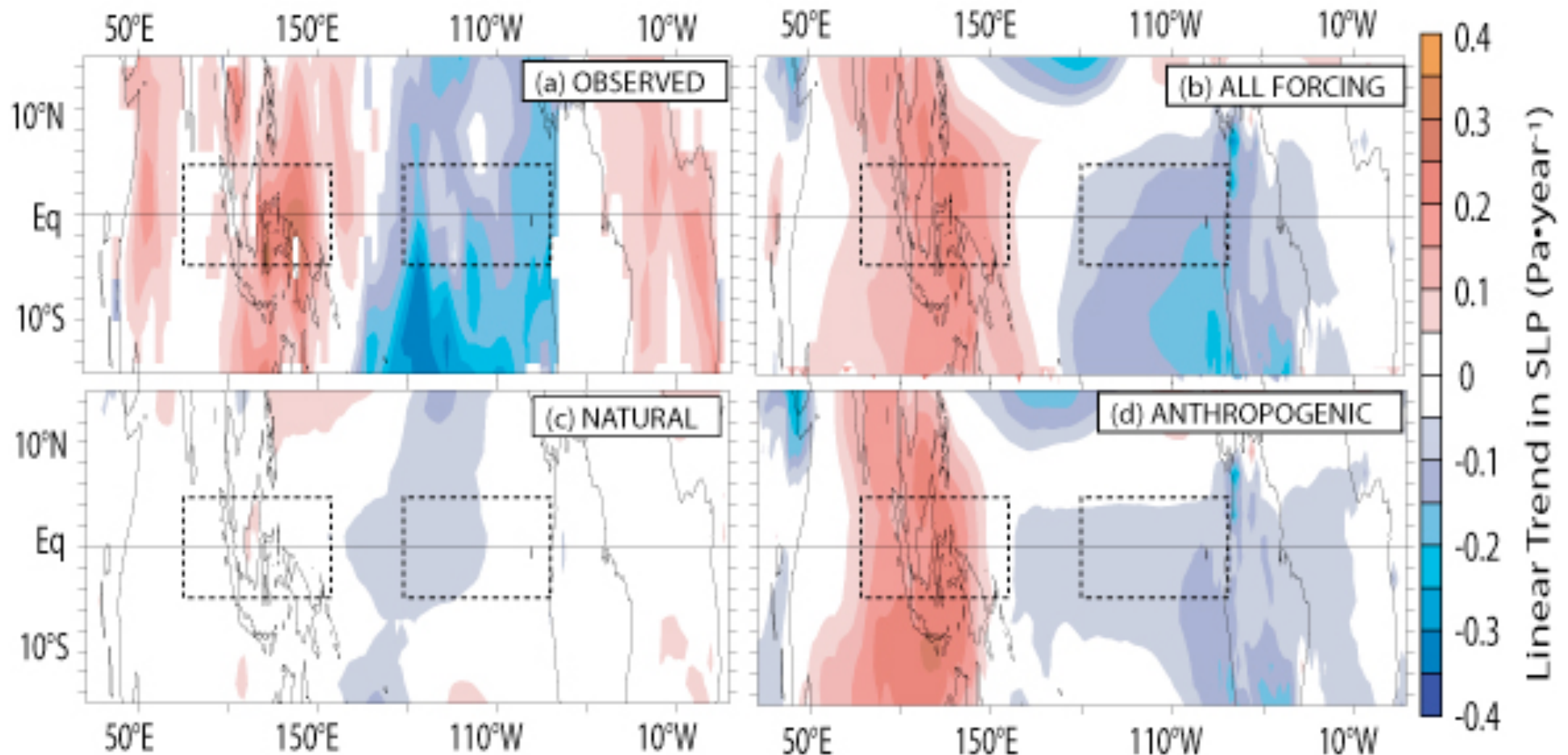
# Linear trend in Kaplan SLP reconstruction



Reduction of E-W SLP gradient across Pacific.  
Consistent with weakening of Walker circulation.

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

Linear trends in SLP weak with natural forcing.



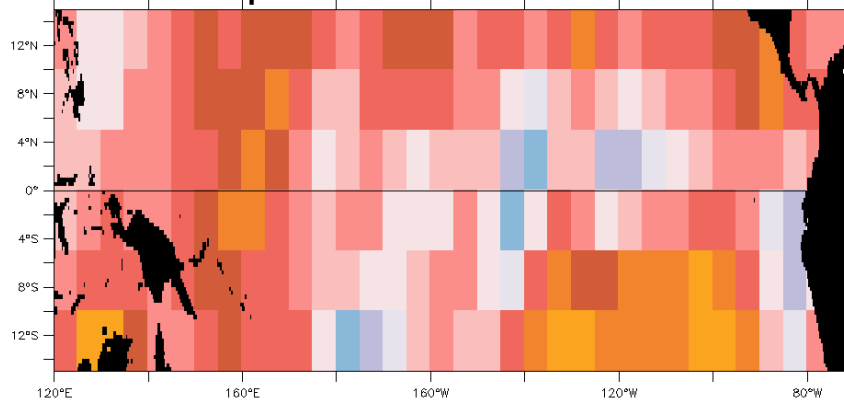
TRENDS COMPUTED 1861-1992

Vecchi et al (2006)

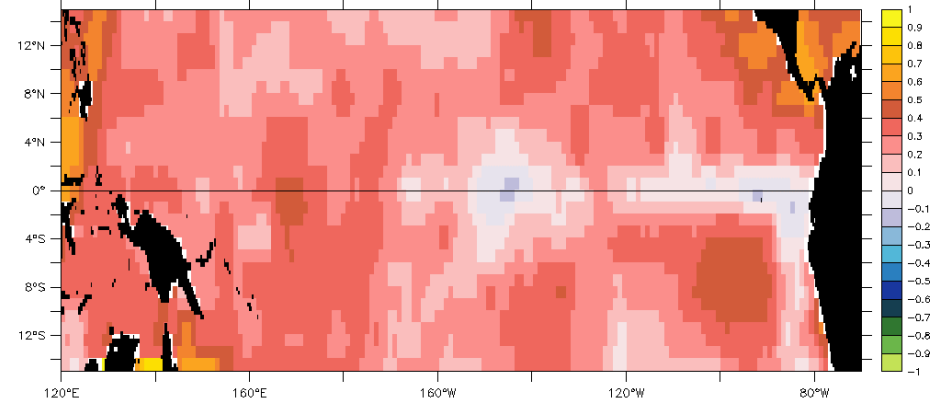
# Look at SST?

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

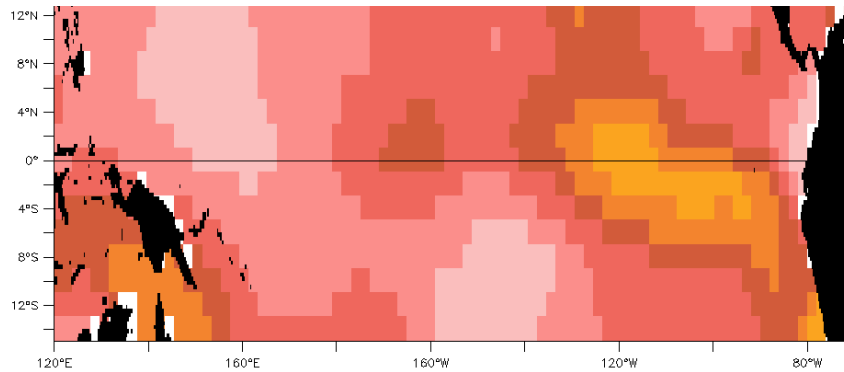
LDEO-Kaplan



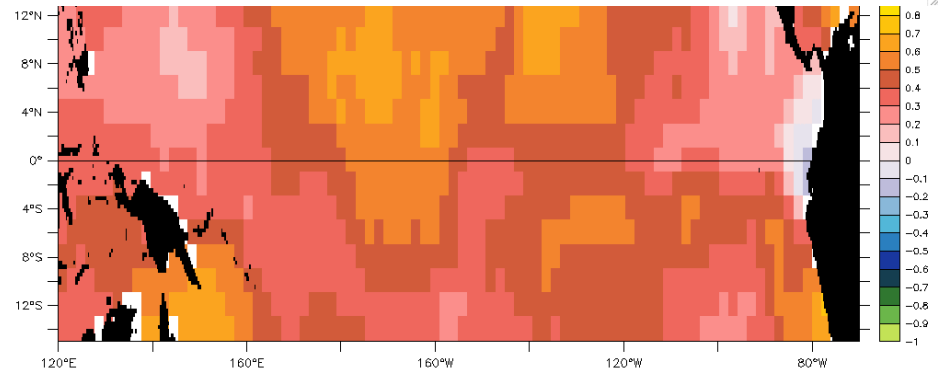
HadISST v.1



NOAA-ERSST v.2



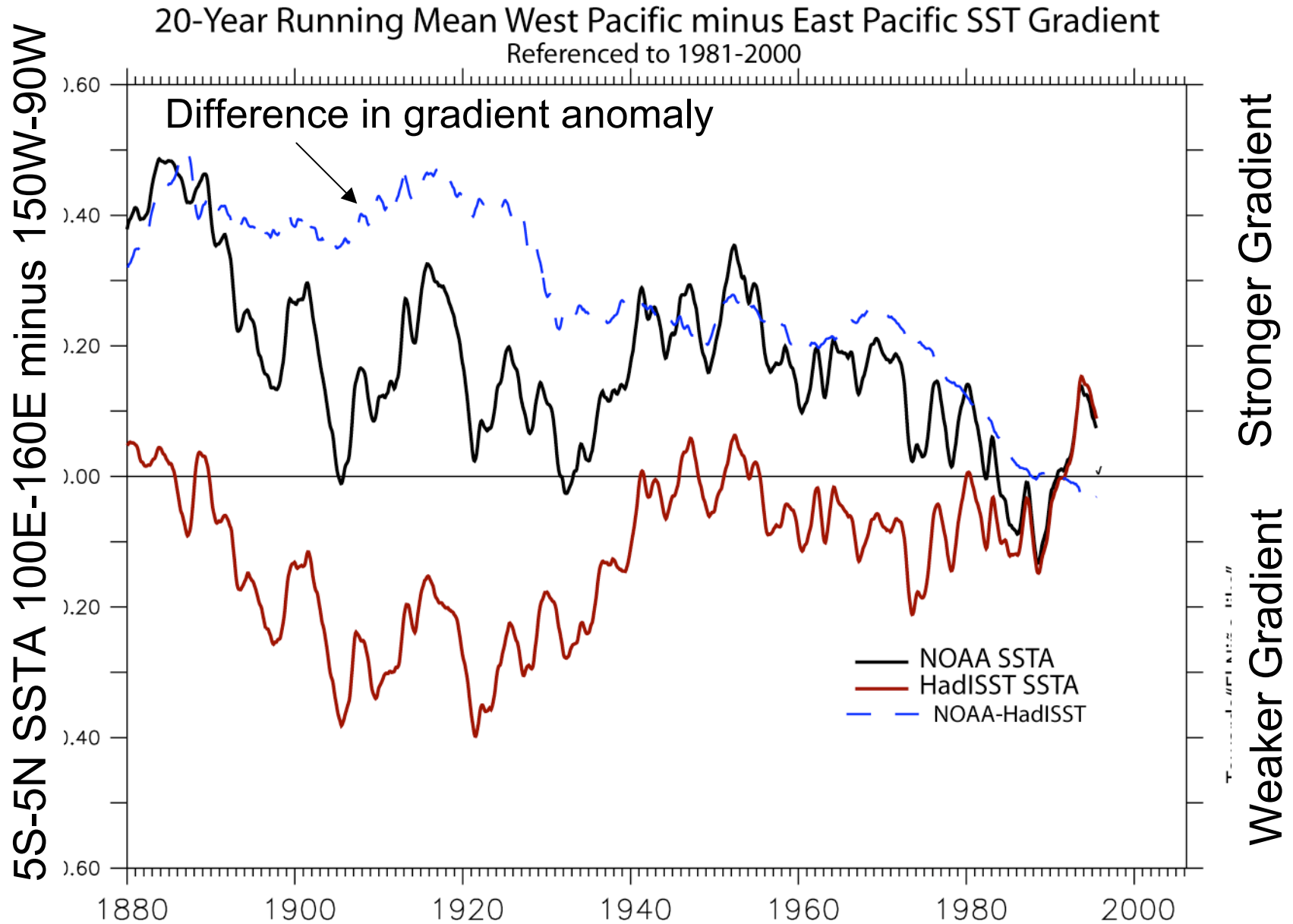
NOAA-ERSST v.3



Overall warming seen in all.  
Structure dependent on reconstruction.

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

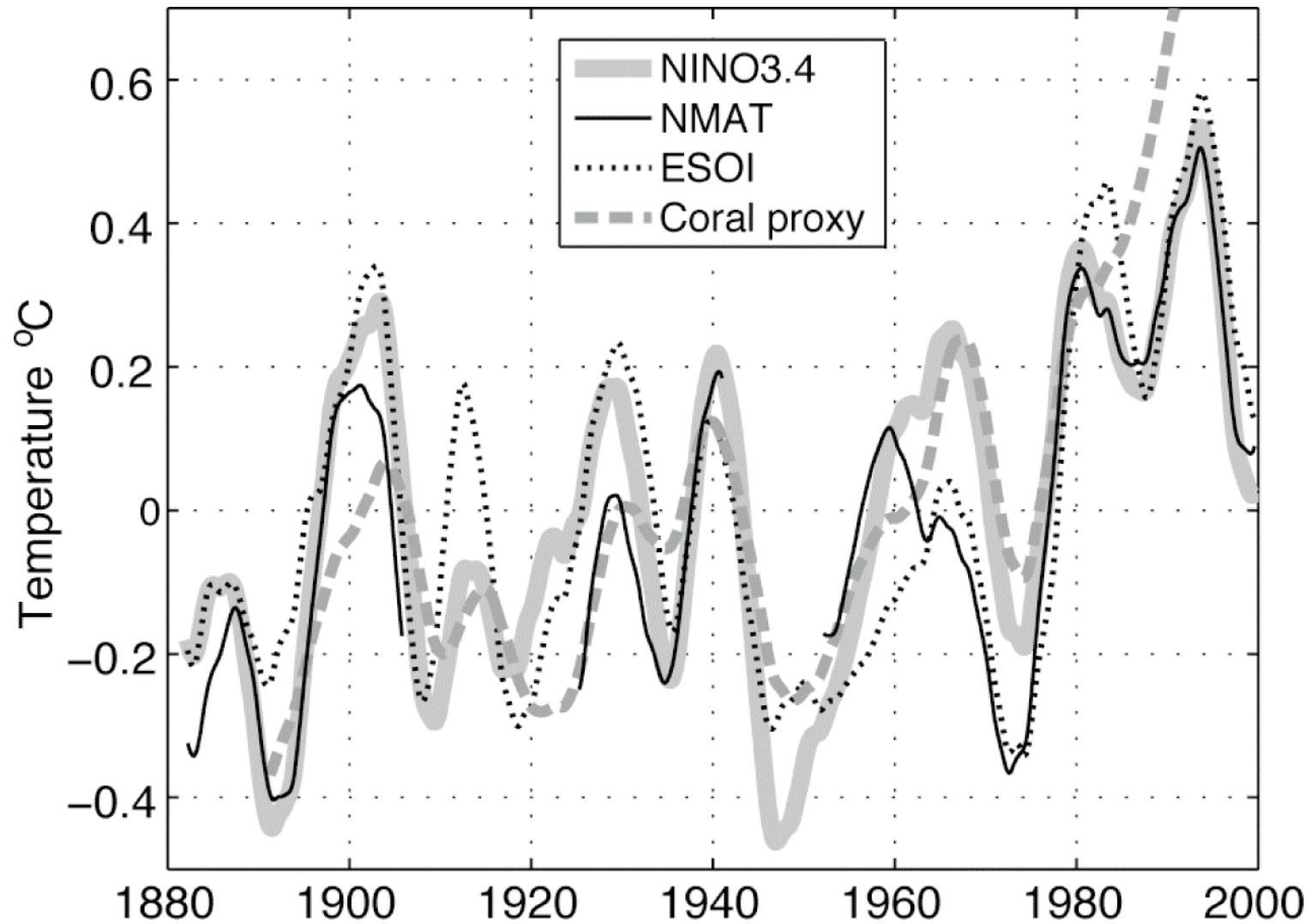
# When do differences between SST products emerge?



From Vecchi, Clement and Soden (2008, EOS)

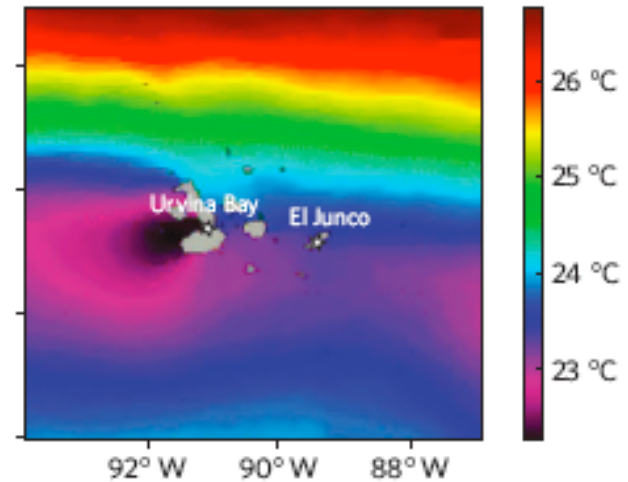
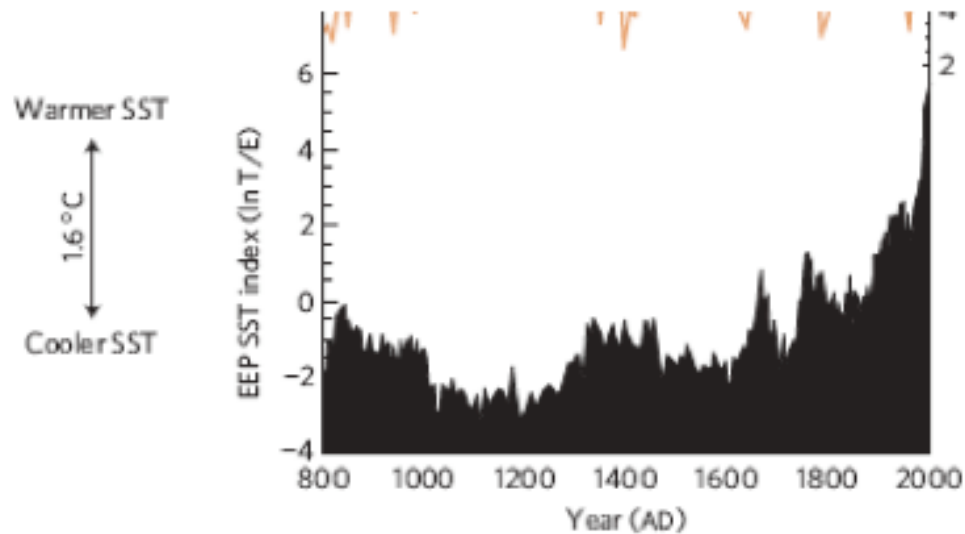


# New “Pacific-centric” analysis



*Bunge & Clarke (2009, J. Climate) “A verified estimation...since 1877”*

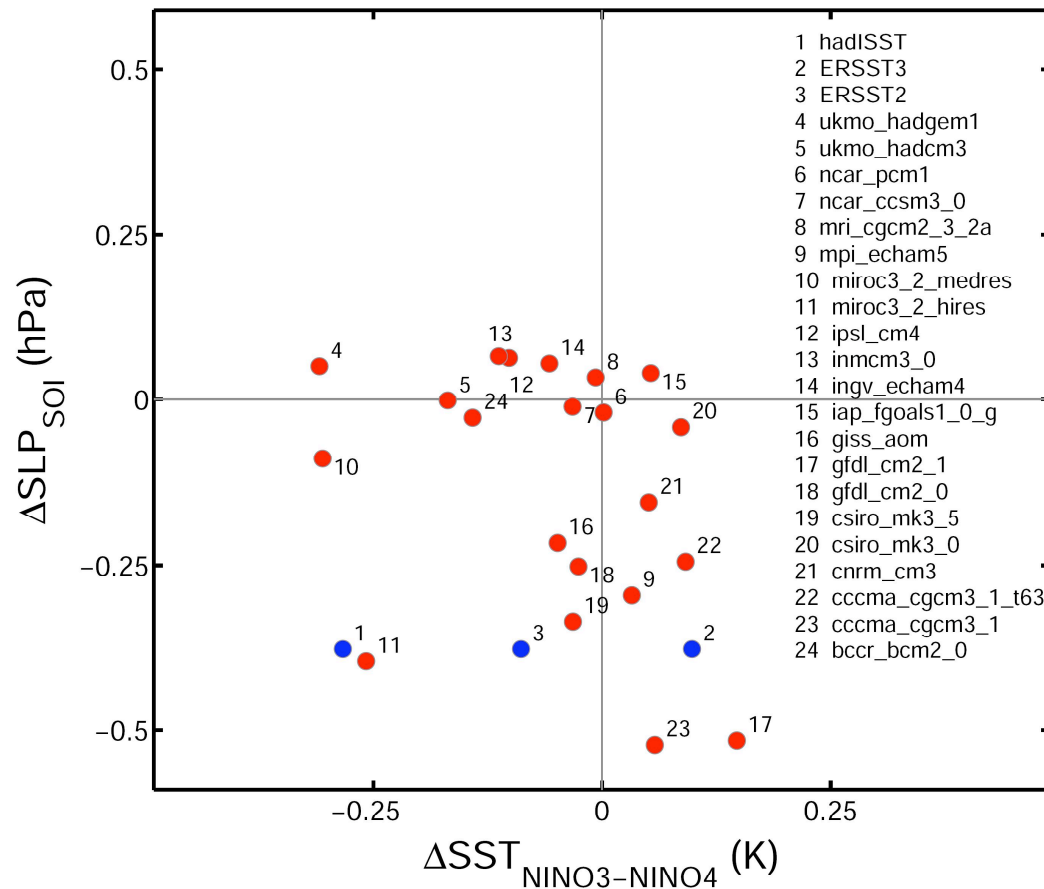
# Lake Sediment Record El Junco Lake, Galapagos



*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.

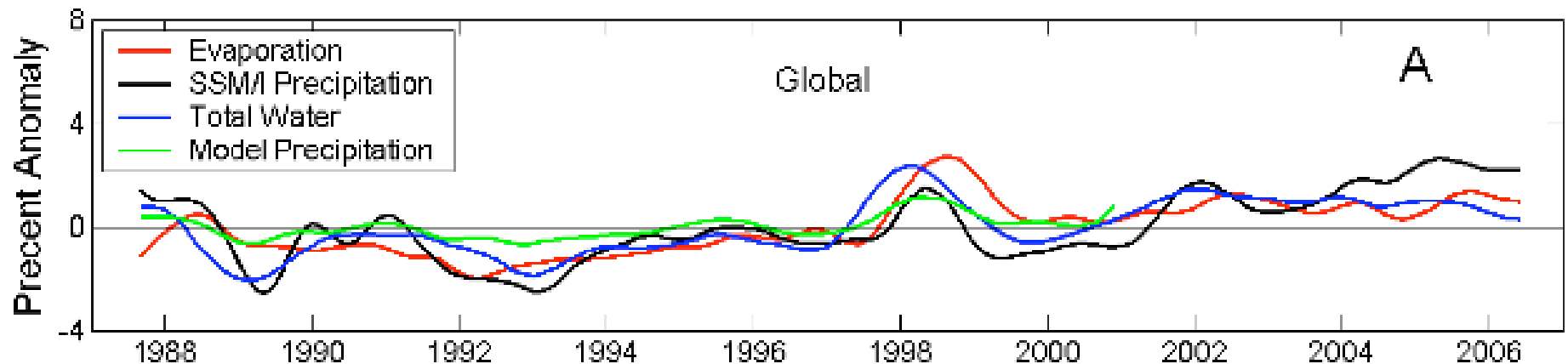
SST Gradient not a strong constraint on models.

## Coral Proxy data

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

# Satellite-estimated Precipitation

- Wentz et al (2007, Science) find a  **$\sim 6.5\%/^{\circ}\text{C}$  ( $\pm 2.5\%/^{\circ}\text{C}$ )** increase in global SSM/I precipitation 1987-2006.
- GCMs give  **$\sim 2\%/^{\circ}\text{C}$** .
- Soden (2000, J. Clim.) finds large interannual precip. Variability in SSM/I than in models.
- Can estimates be reconciled?



Wentz et al (2007, Science)

# Conclusions

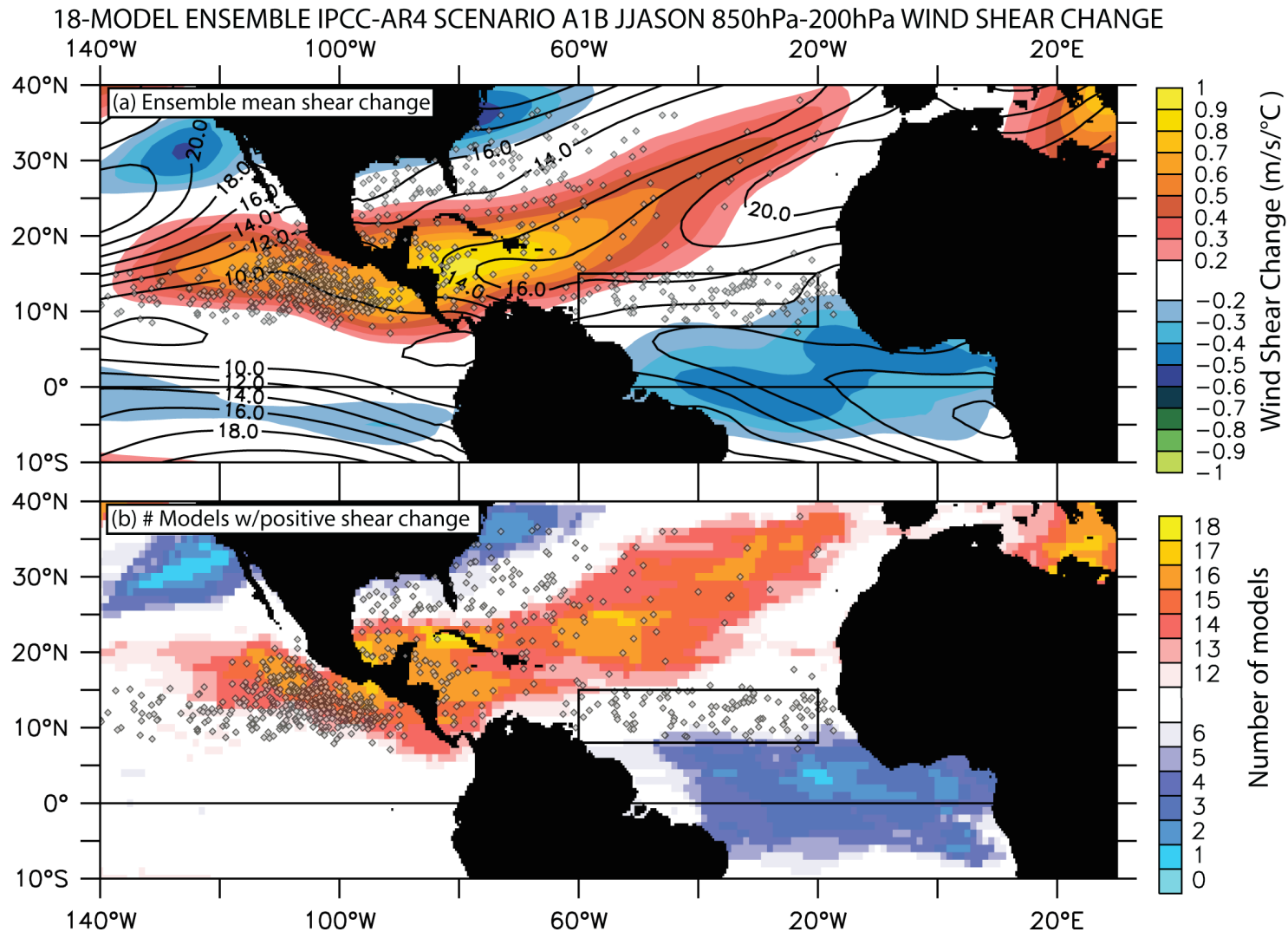
- The weakening of the tropical circulation is a robust projection of all climate models.
  - Connected to sub-Claussius-Clapeyron rate of:
    - Increase in radiative cooling
    - Increase in surface radiative imbalance
- The slower circulation is manifest primarily as a weakened Walker Cell.
  - El 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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# Outline

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

# Model projected 21st Cy vertical wind shear changes



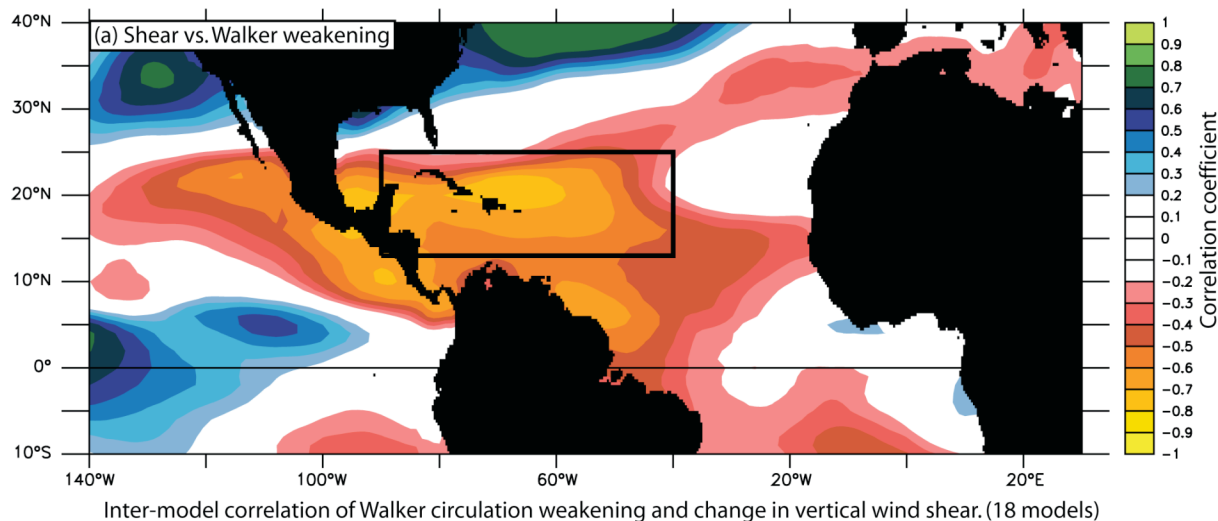
Vecchi and Soden (2007, GRL)

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

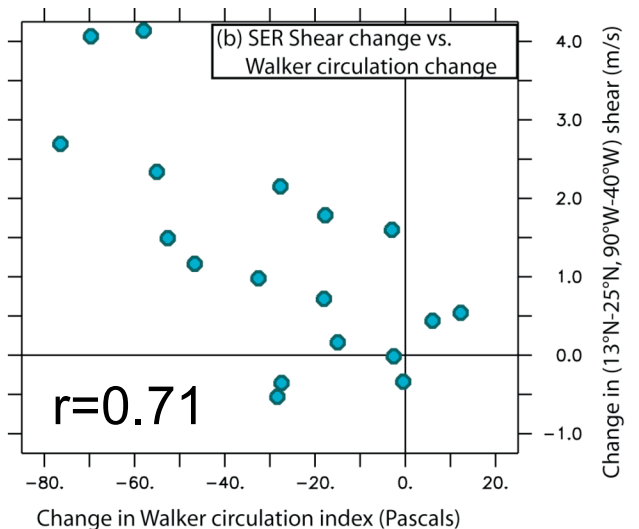


# $V_s$ and Pacific Walker Circulation

Correlation of local shear change with Pacific Walker weakening across models



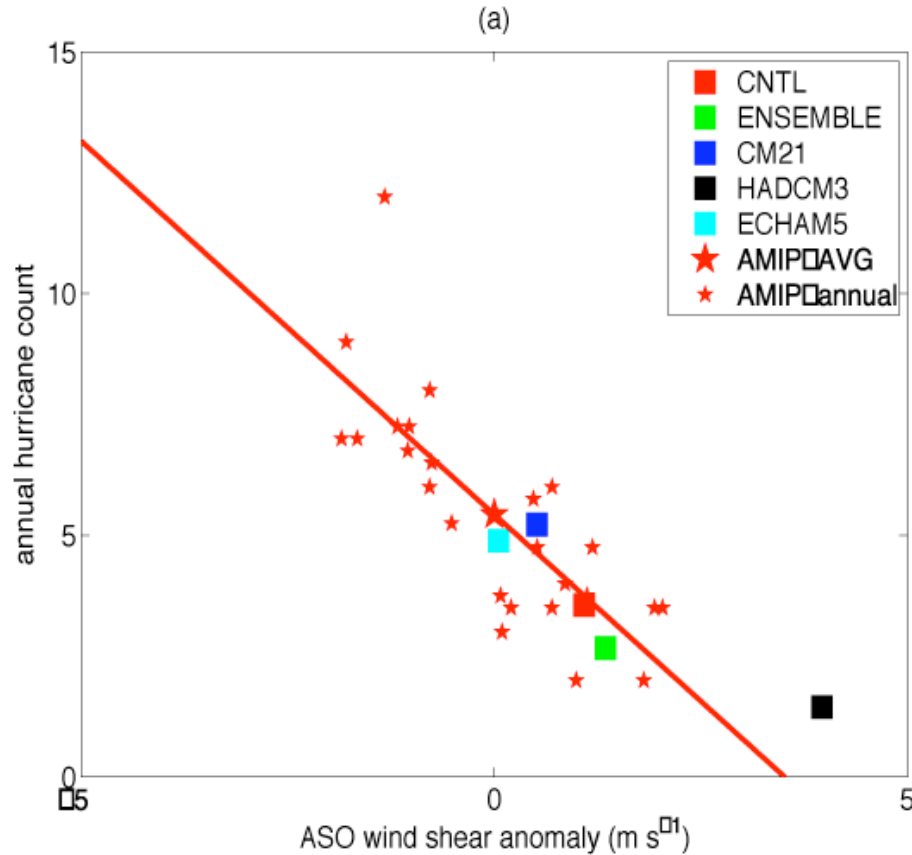
Walker circulation vs. shear change



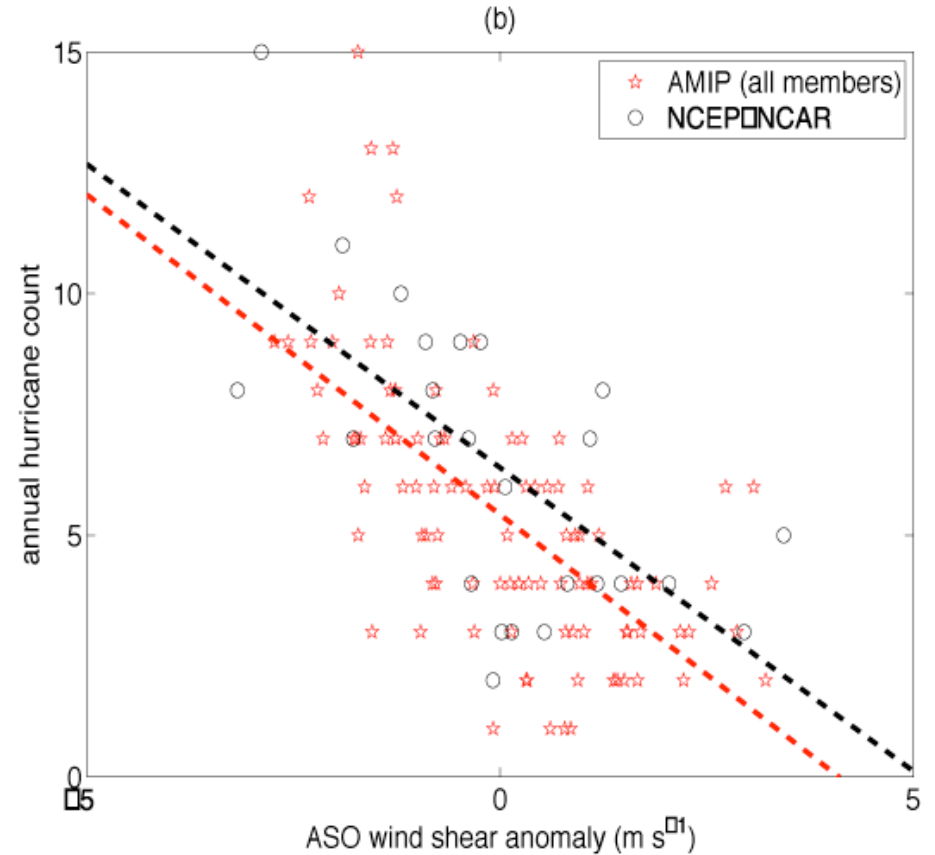
Models with largest Walker weakening have largest shear enhancement.

# Shear changes and Atlantic hurricane activity

50km Global GCM



GCM and OBS



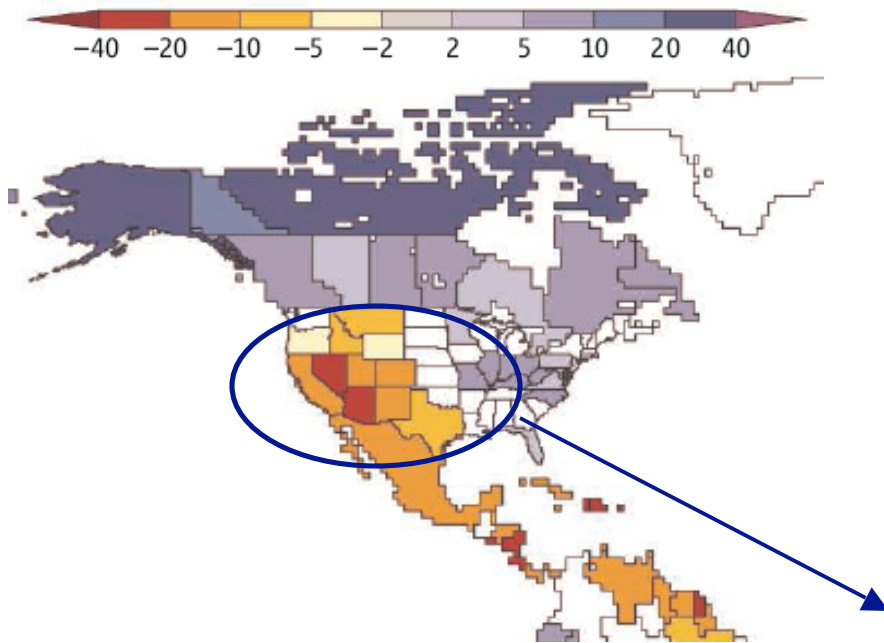
Zhao, Held, Lin and Vecchi (2009, J. Clim.)

# Outline

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

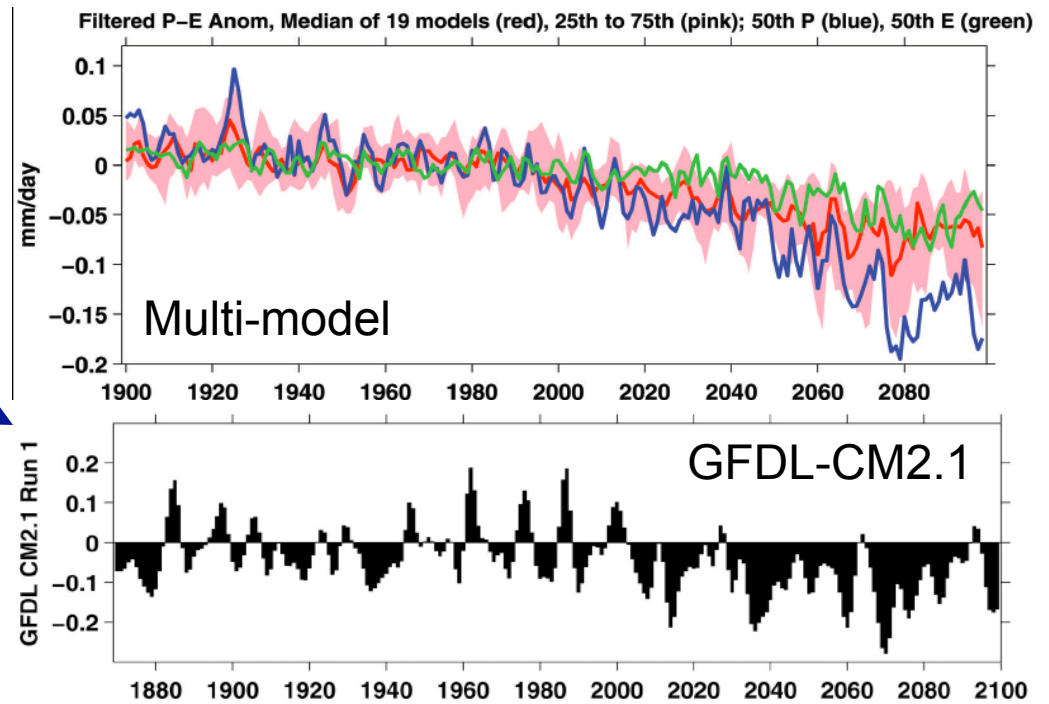
# Southwest Drying Projections

## 21st Century Projected % Change in Runoff



Milly et al (2008, Science)

## Change in SW US Precip. minus Evap.

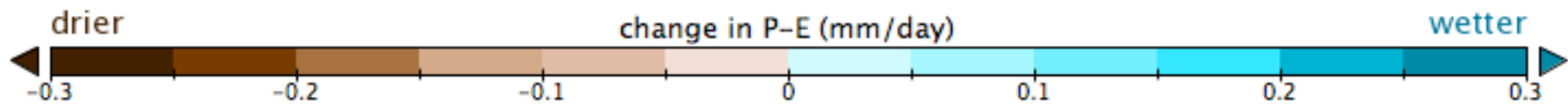
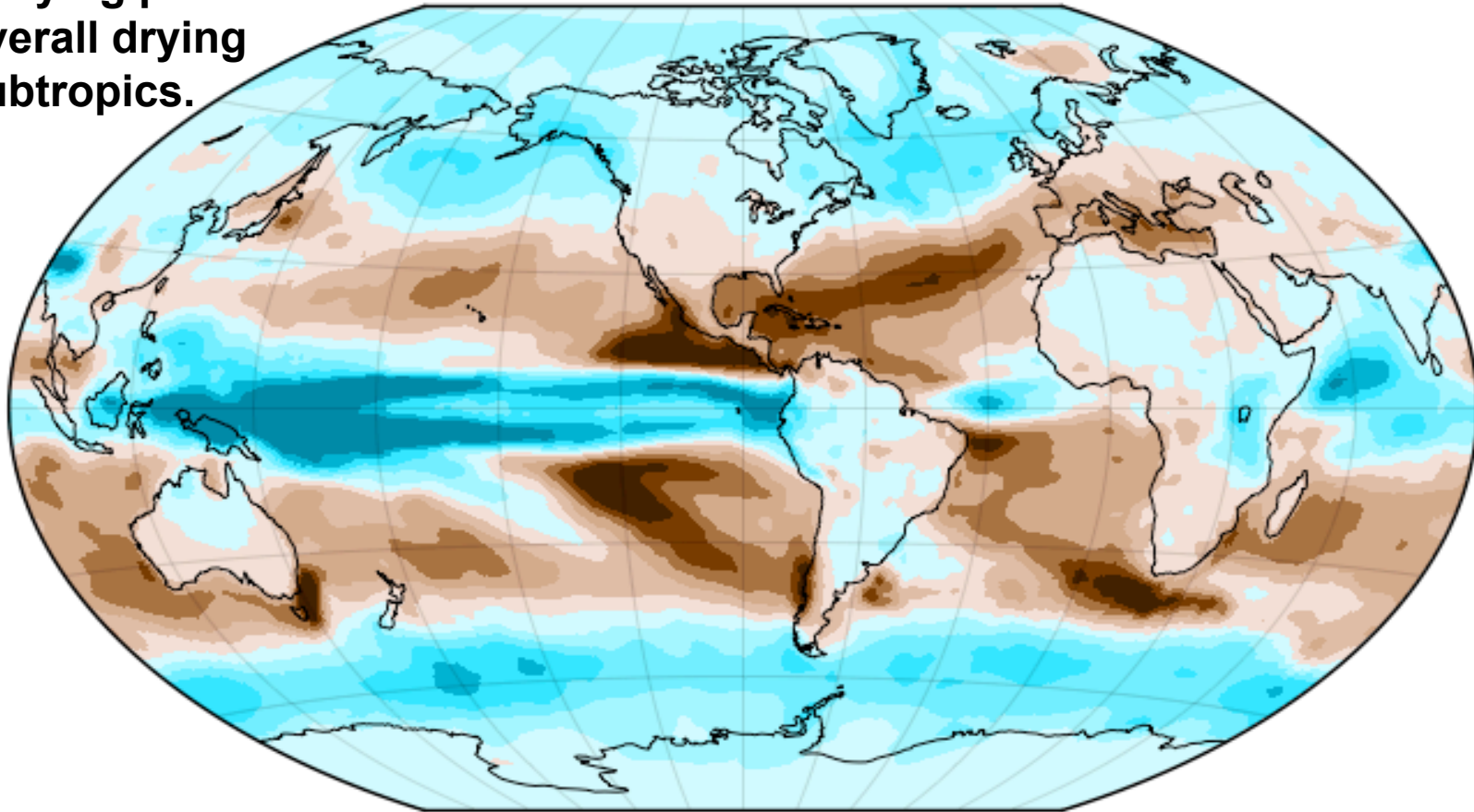


Seager et al (2007, Science)

# SW Drying part of global pattern

SW Drying part  
of overall drying  
of subtropics.

Change in P-E (2021-2040 minus 1950-2000)



Winkel Tripel projection centered on -90.0°E

Figure by N. Naik., LDEO/Columbia

# Mechanisms for CO<sub>2</sub>-Forced Drying

## Thermodynamic Control:

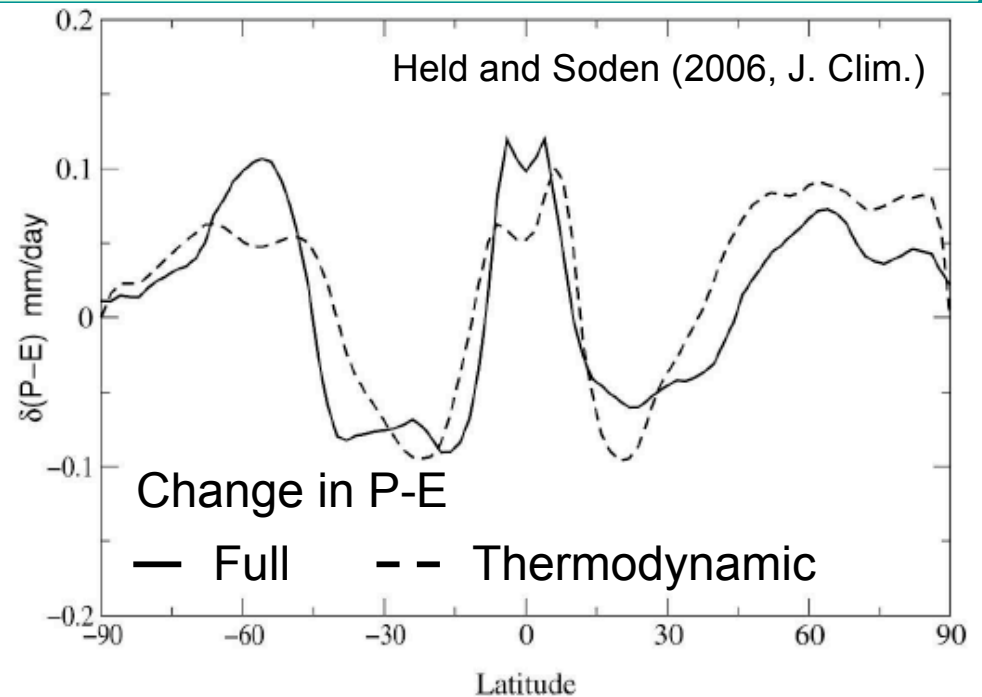
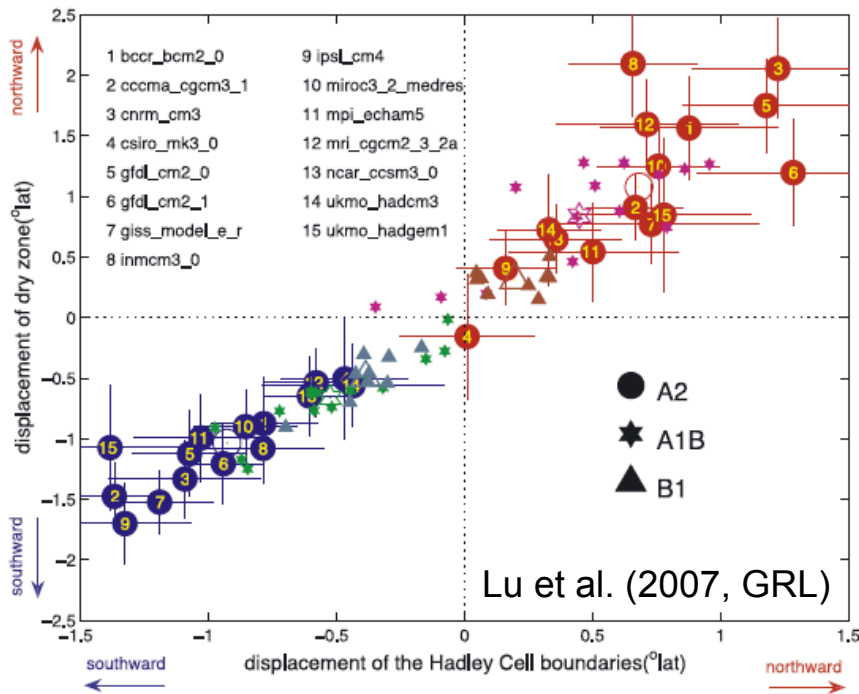
Warming (increase  $q_{\text{sat}}$ )



increase atmospheric moisture.



increase moisture flux divergence/  
convergence.

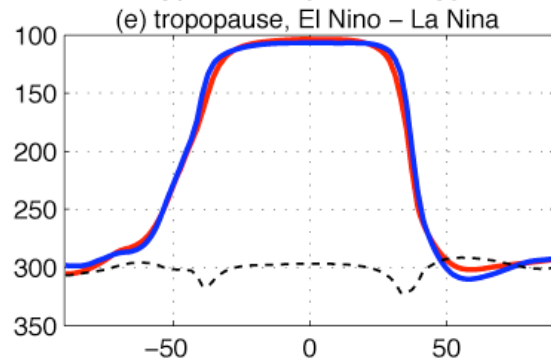
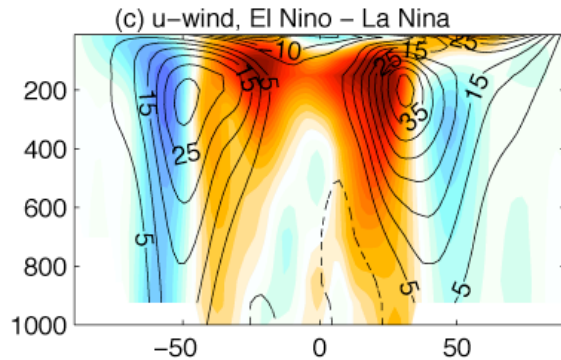
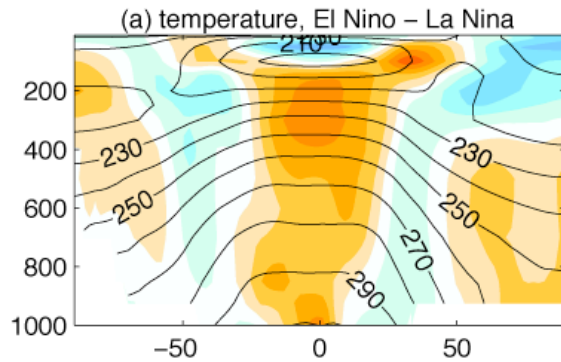


## Circulation Changes:

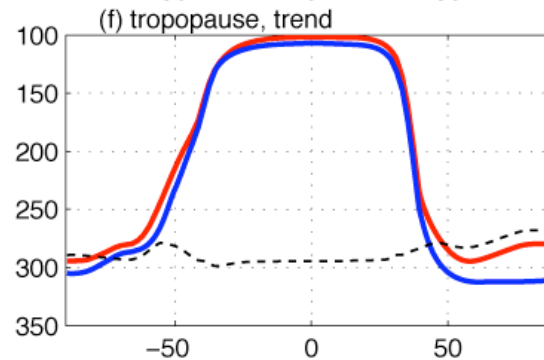
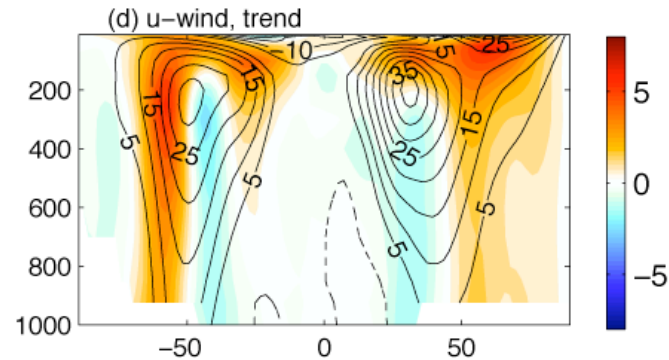
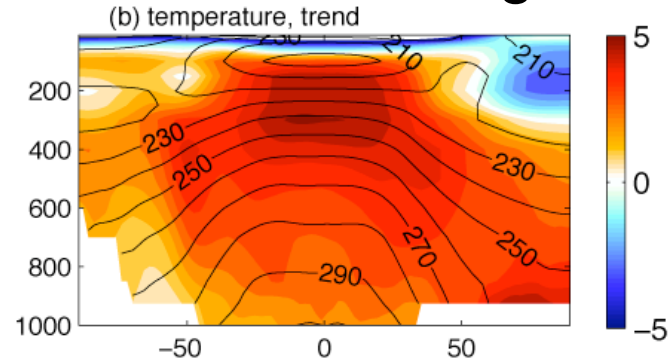
Poleward shift of descending branch of Hadley Circulation is associated with a poleward shift of dry zones.

# 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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