

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

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- What are expected responses of the tropical climate system to a warming climate?
 - Weakening of tropical circulation.
 - Ocean Feedbacks.
- “El Niño-like” and “La Niña-like” climate change?
Neither
- For which response is there observational evidence?

Broader Objective

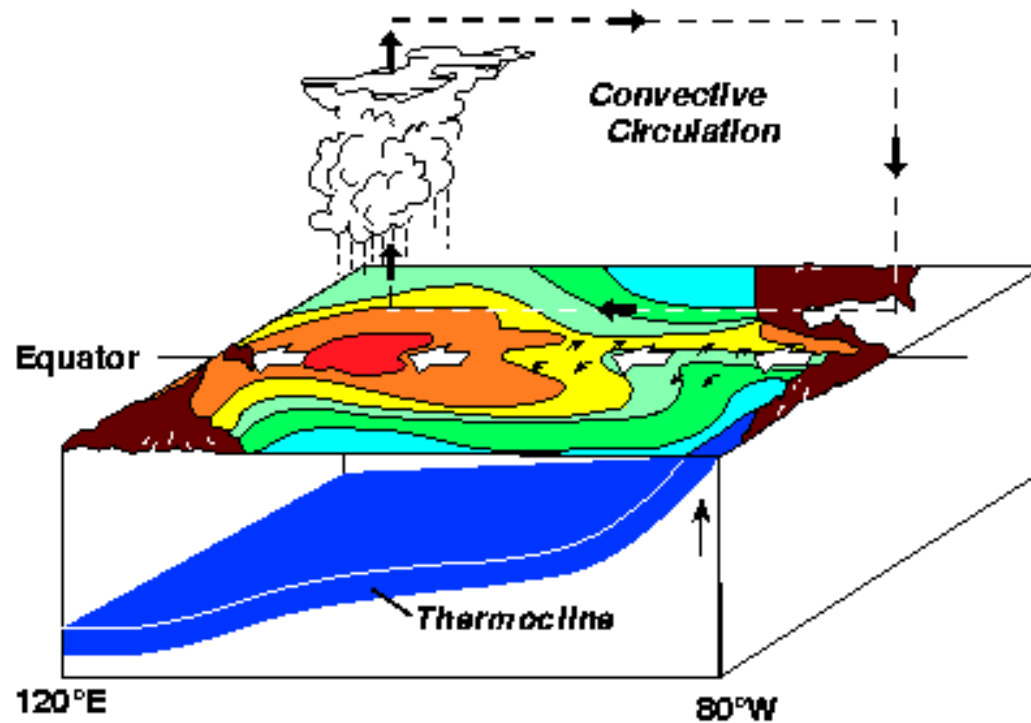
- 1) Identify those aspects of tropical climate change that are:
 - Consistent across a large number of models
 - Are supported by simple physical arguments

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

Outline

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

Normal Conditions



Positive coupled ocean-atmosphere feedbacks drive the growth of El Niño.

El Niño Conditions

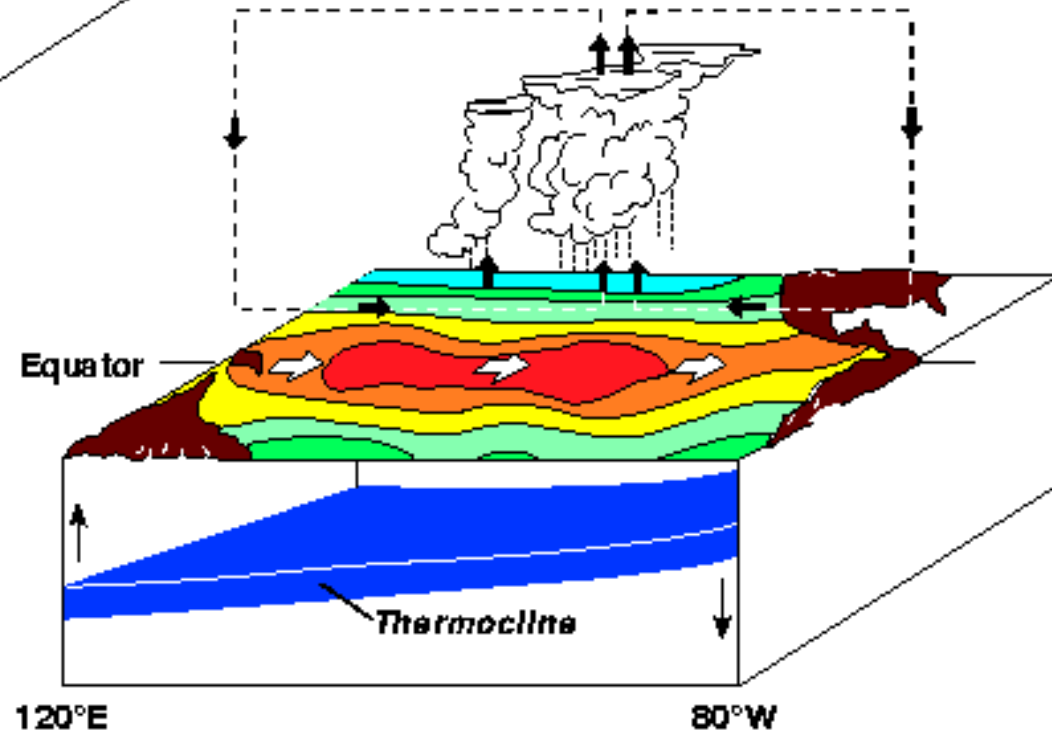
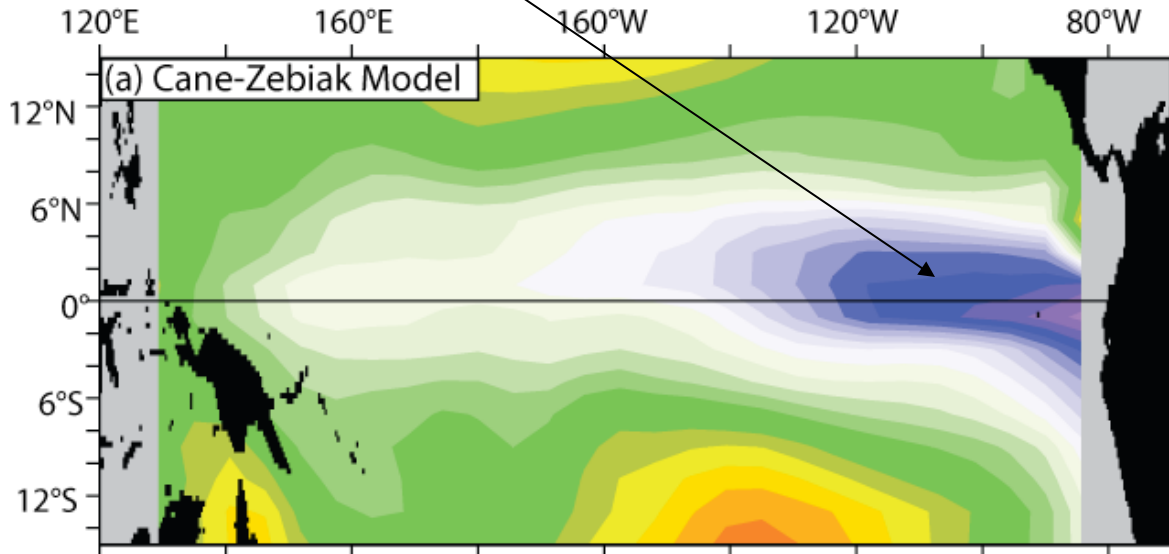


Figure: NOAA

Ocean Dynamical Thermostat

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

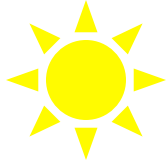
- In warming world, tropical ocean thermal stratification increases. dT/dz gets larger, so wdT/dz a larger cooling term.
- Thus, upwelling zones warm more slowly than rest of planet - upwell (c)older water.
- Coupled (Bjerknes) feedbacks.
- “La Niña-like” response.



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

Simplified view of atmospheric water/energy balance

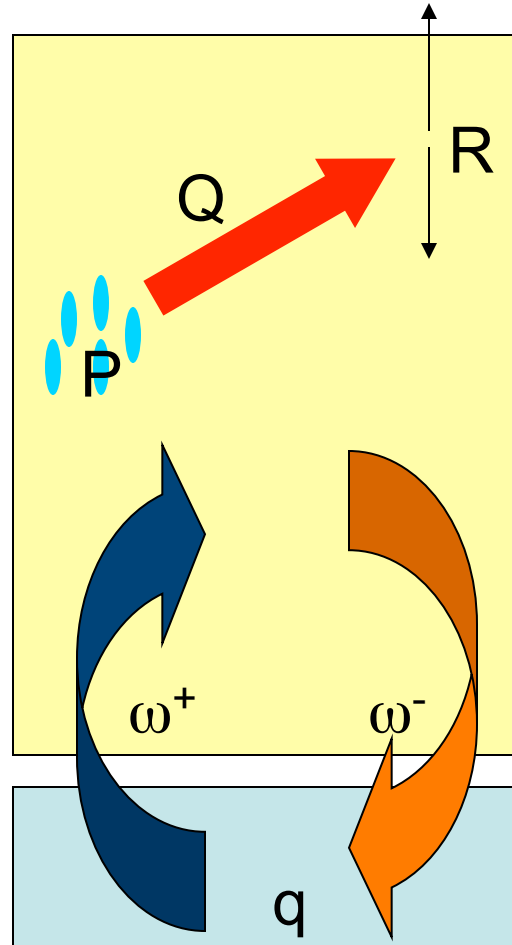
$$R \propto P = q \cdot \omega^+ \longrightarrow dR/R = dP/P = dq/q + d\omega^+/\omega^+$$



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

$$Q = L_v \cdot P$$

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



(5) Energy released from condensation radiates.

$$R = Q$$

Free troposphere

(2) Boundary Layer: moist from evaporation

$$q = rh \cdot q_s$$

Ocean (source of H₂O)

(1) Heated: evaporates/stores

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

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

Thermodynamic constraint on circulation: reduced circulation in warming climate

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

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

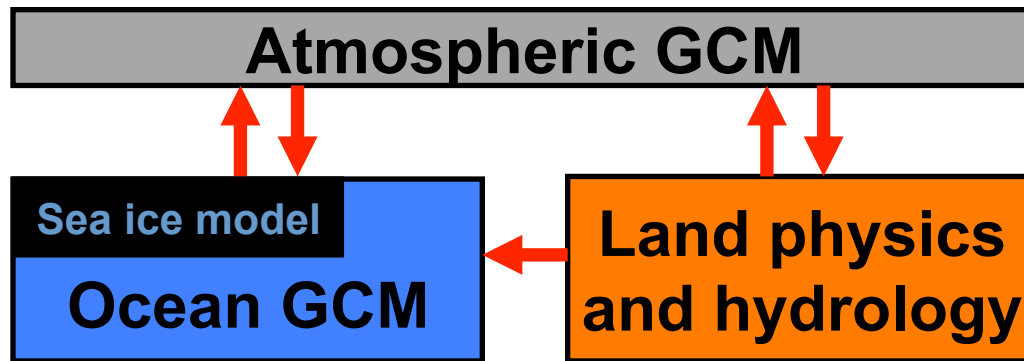
- Assume small change in rh
 - Thus, q increases like Clausius-Clapeyron (7.5-8.5% K⁻¹)
- Water flux constrained by precipitation
- Precipitation constrained by radiation
 - Radiation changes more slowly than C.-C.
- **Since $dP/P < dq/q$, circulation (ω^+) must weaken.**
- Walker Circulation weakens? “El Niño-like”?

Outline

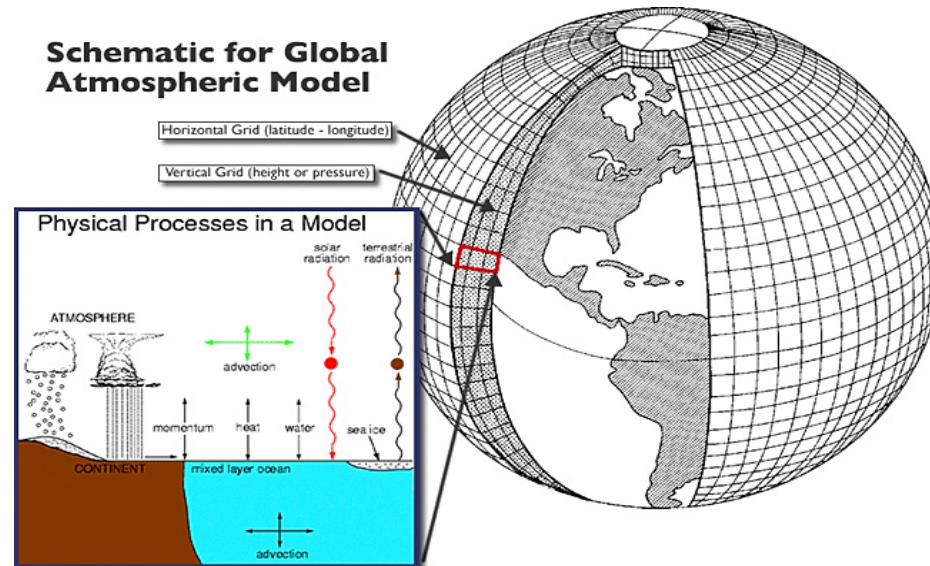
- Theory
- **Numerical Modeling**
explore CMIP3/IPCC-AR4 & CMIP5/IPCC-AR5 databases.
- Observations
- Implications

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.



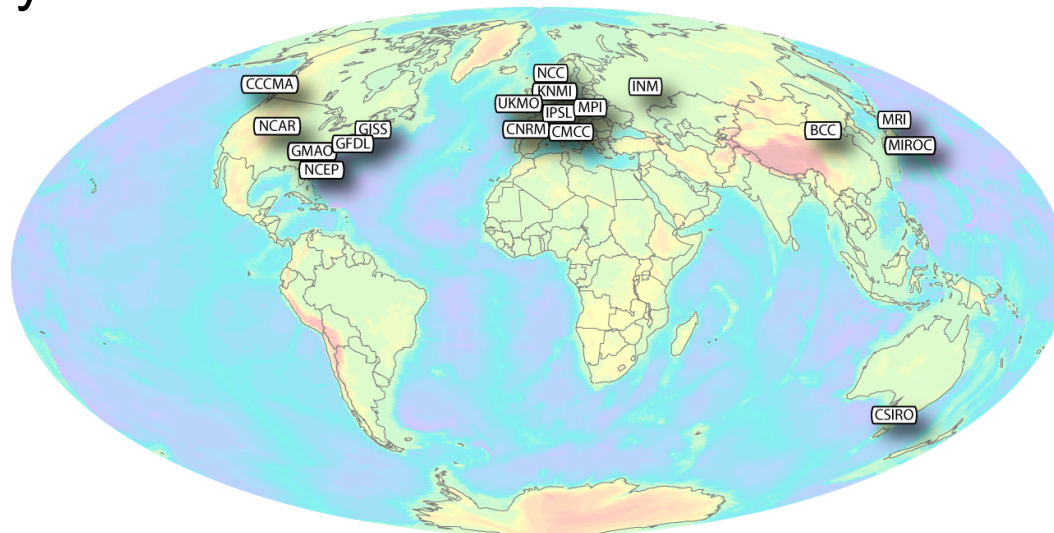
Coupled Model Inter-comparison Projects (CMIP3 & CMIP5)

Taylor et al. (2012)

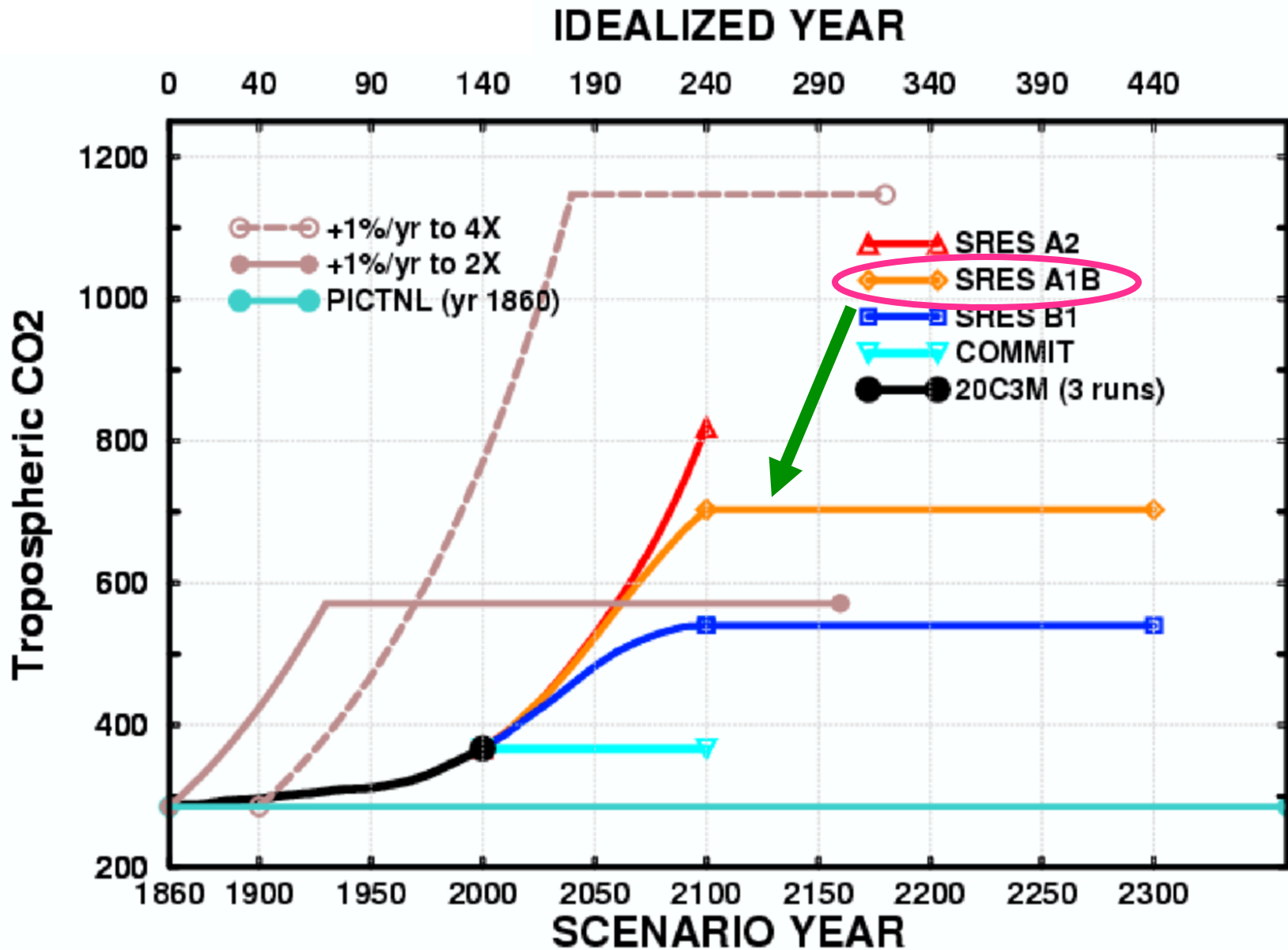
- Coordinated GCM experiments to address key issues in climate science:

Paleoclimate, response to CO₂, aerosols, volcanoes, high-resolution, decadal predictability, earth-system modeling, geoengineering...

- Around 20 centers worldwide
- CMIP3 (assessed in IPCC-AR4) finalized mid-2000s, data still quite useful
- CMIP5 (to be assessed in IPCC-AR5) in “analysis” phase: data publicly available

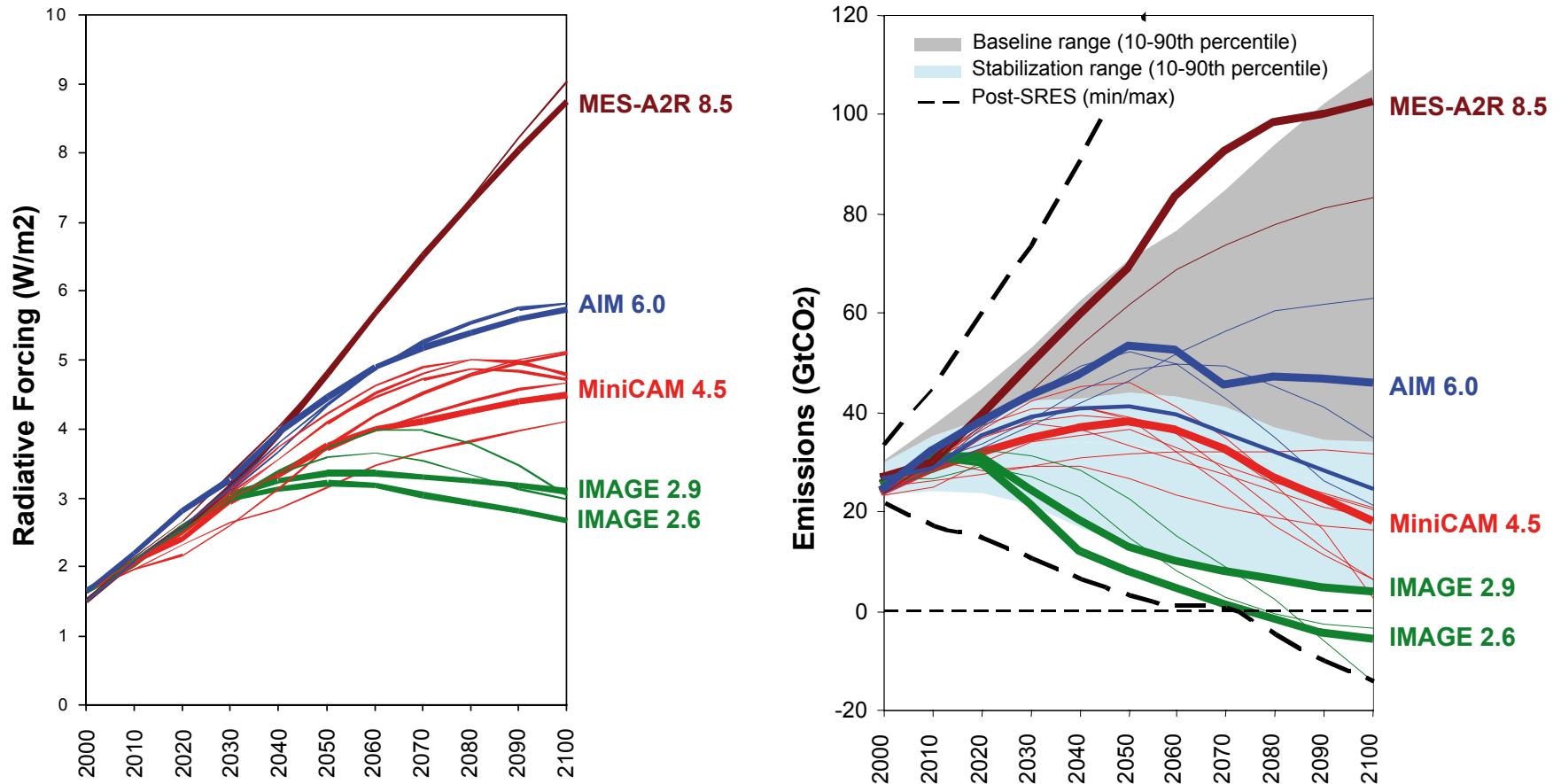


Idealized greenhouse warming experiments



Coupled Model Intercomparison Project 5 (CMIP5)

Model experiments run in support of IPCC-AR5

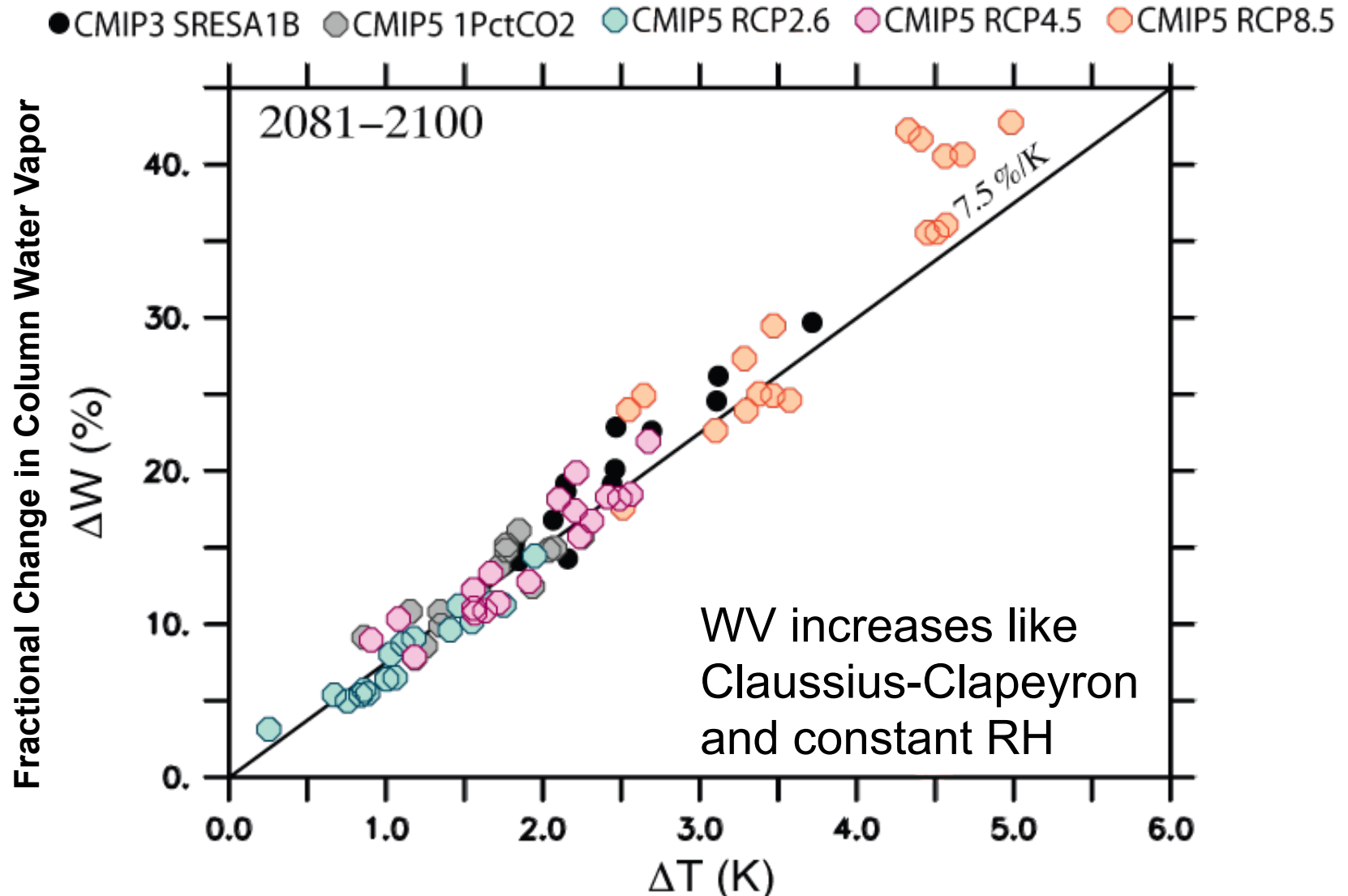


RCPs more than GHG changes: aerosols a big factor.

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

Atmospheric Constraint on Tropical Circulation

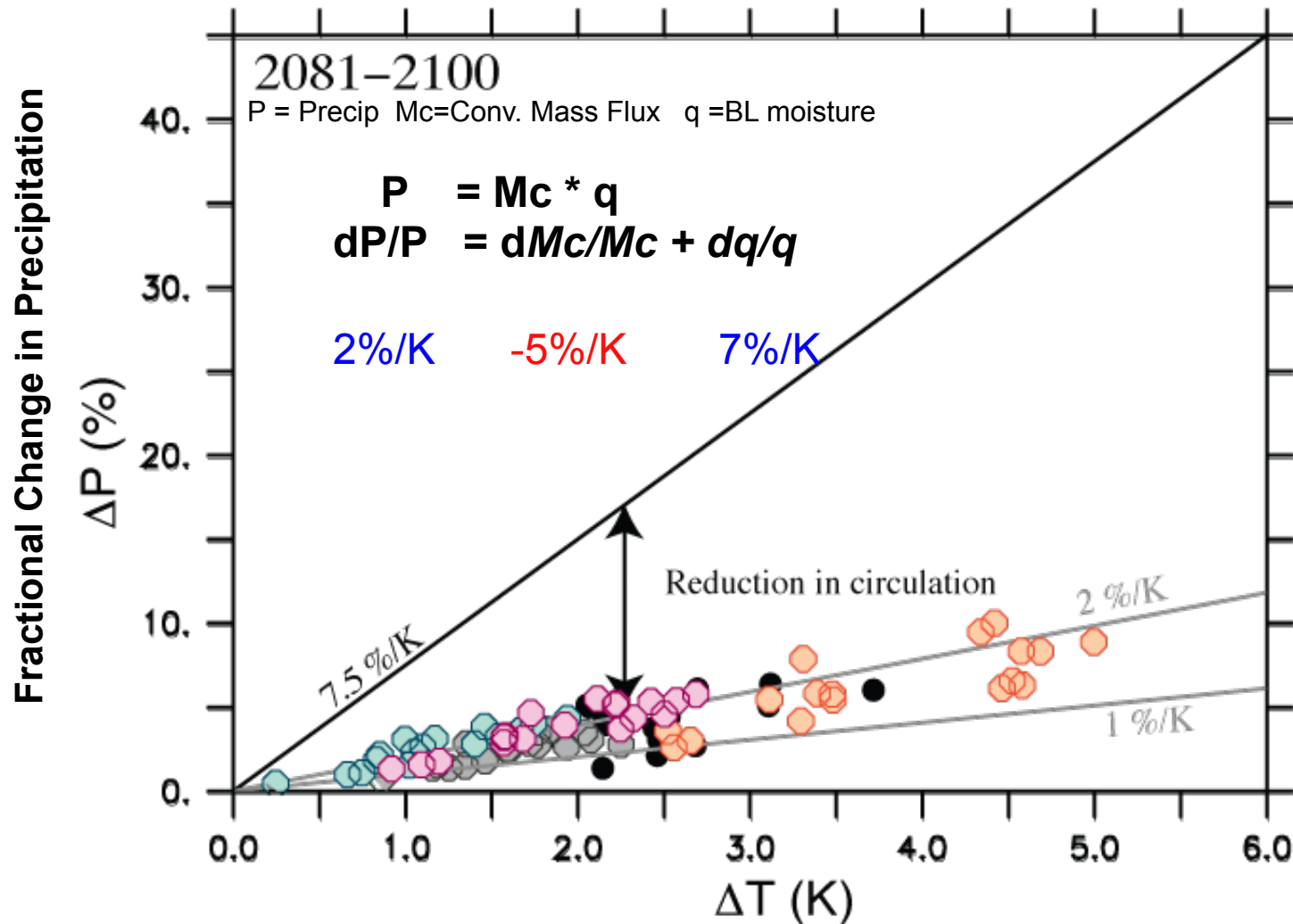
Change in Global Water Vapor at 2100



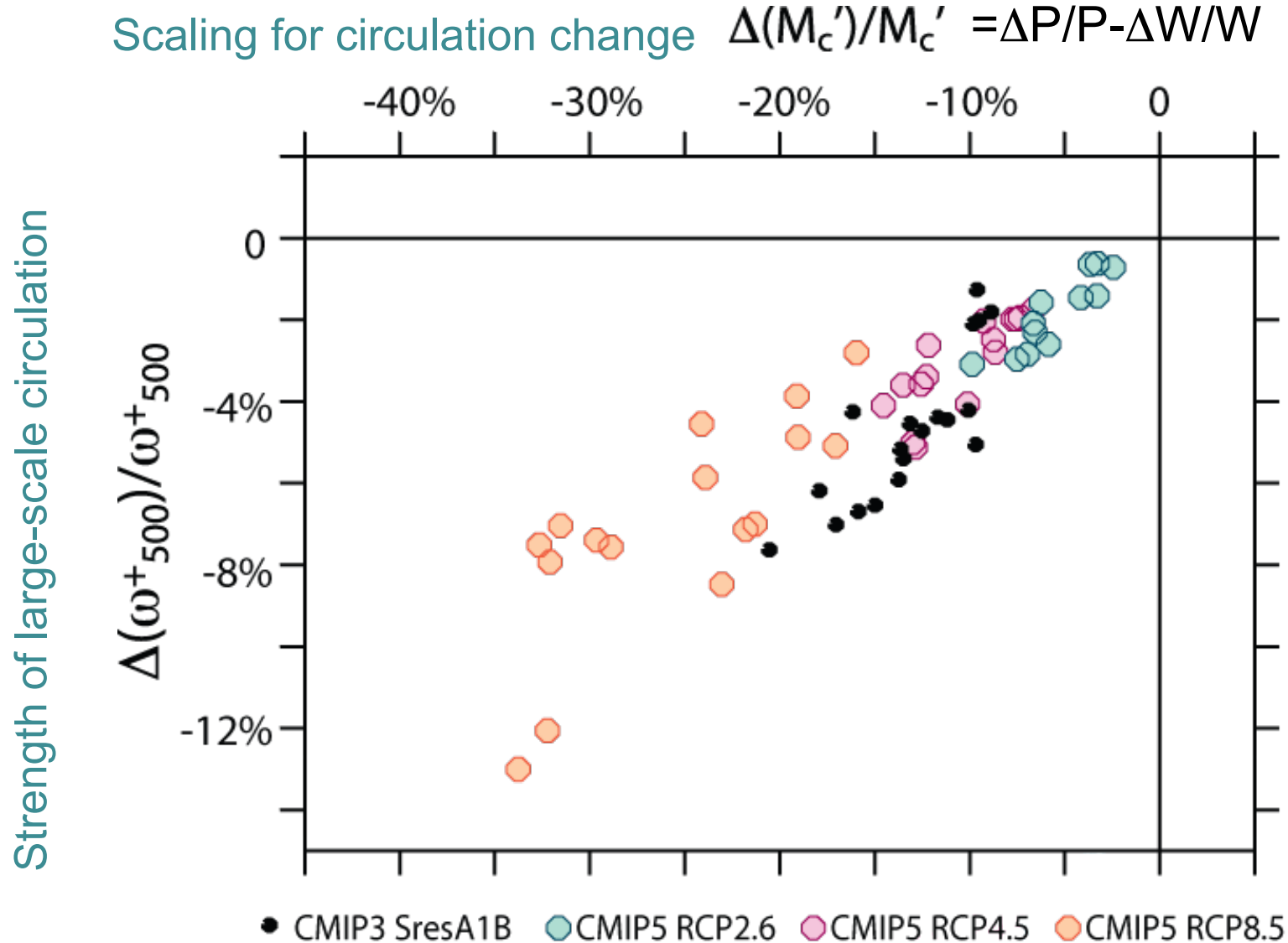
Held and Soden (2006, *J. Clim.*), Vecchi et al. (2012, *in prep.*)

Atmospheric Constraint on Tropical Circulation

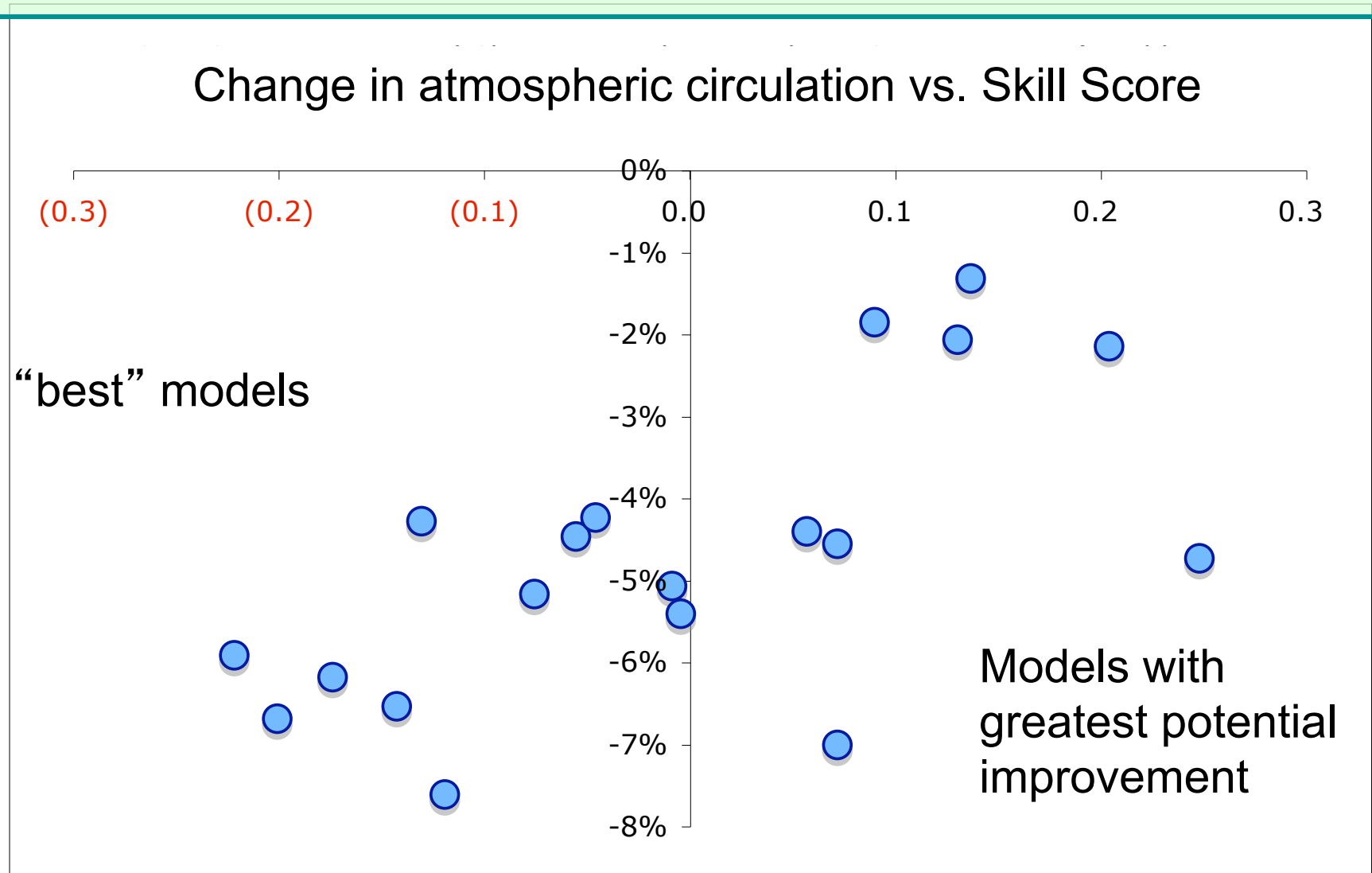
Change in Global Precipitation at 2100



Upward monthly 500 hPa ω vs. mass flux change scaling



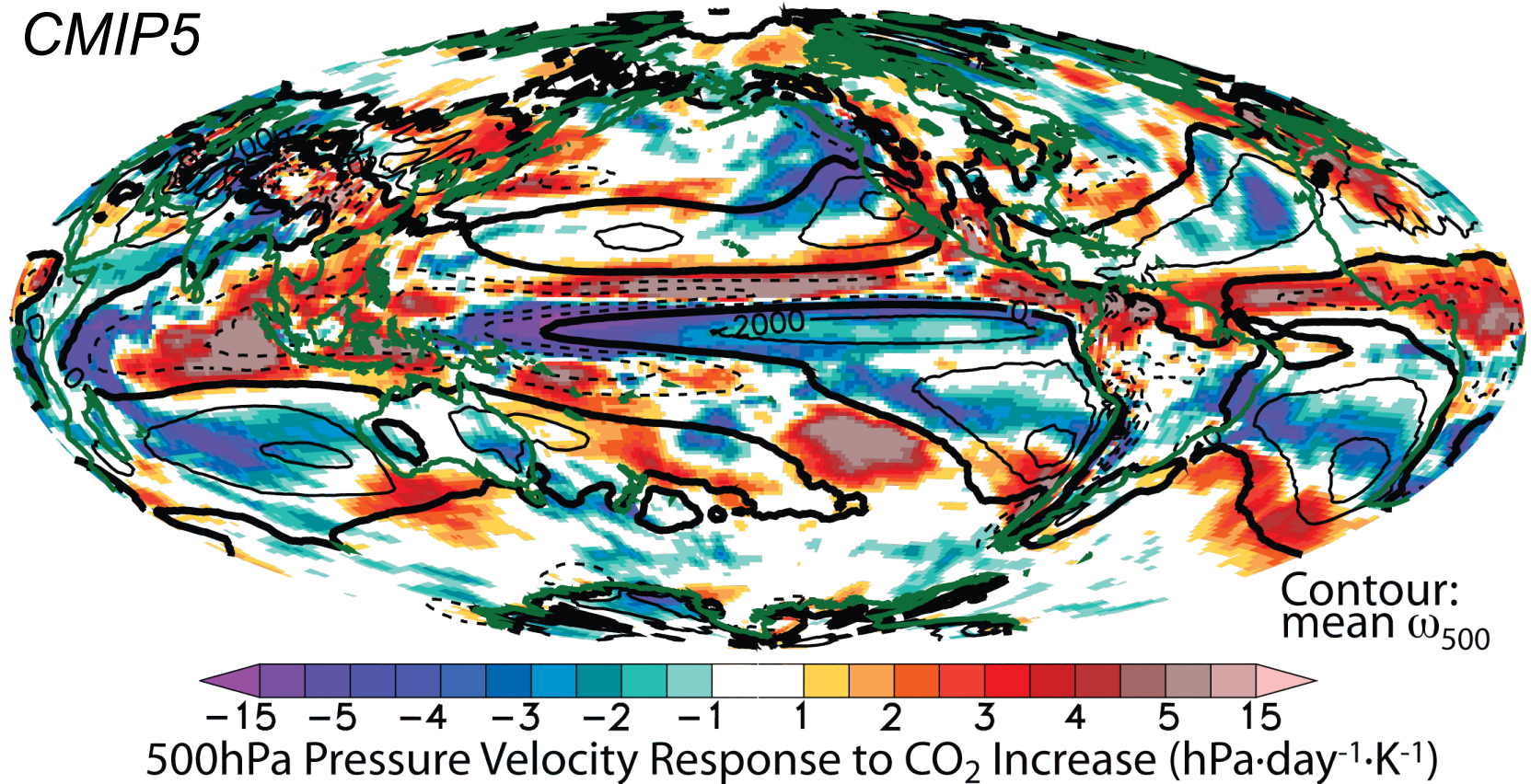
“Best” CMIP3/IPCC-AR4 Models show a large weakening of circulation



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

ω_{500} changes act to oppose mean

CMIP5



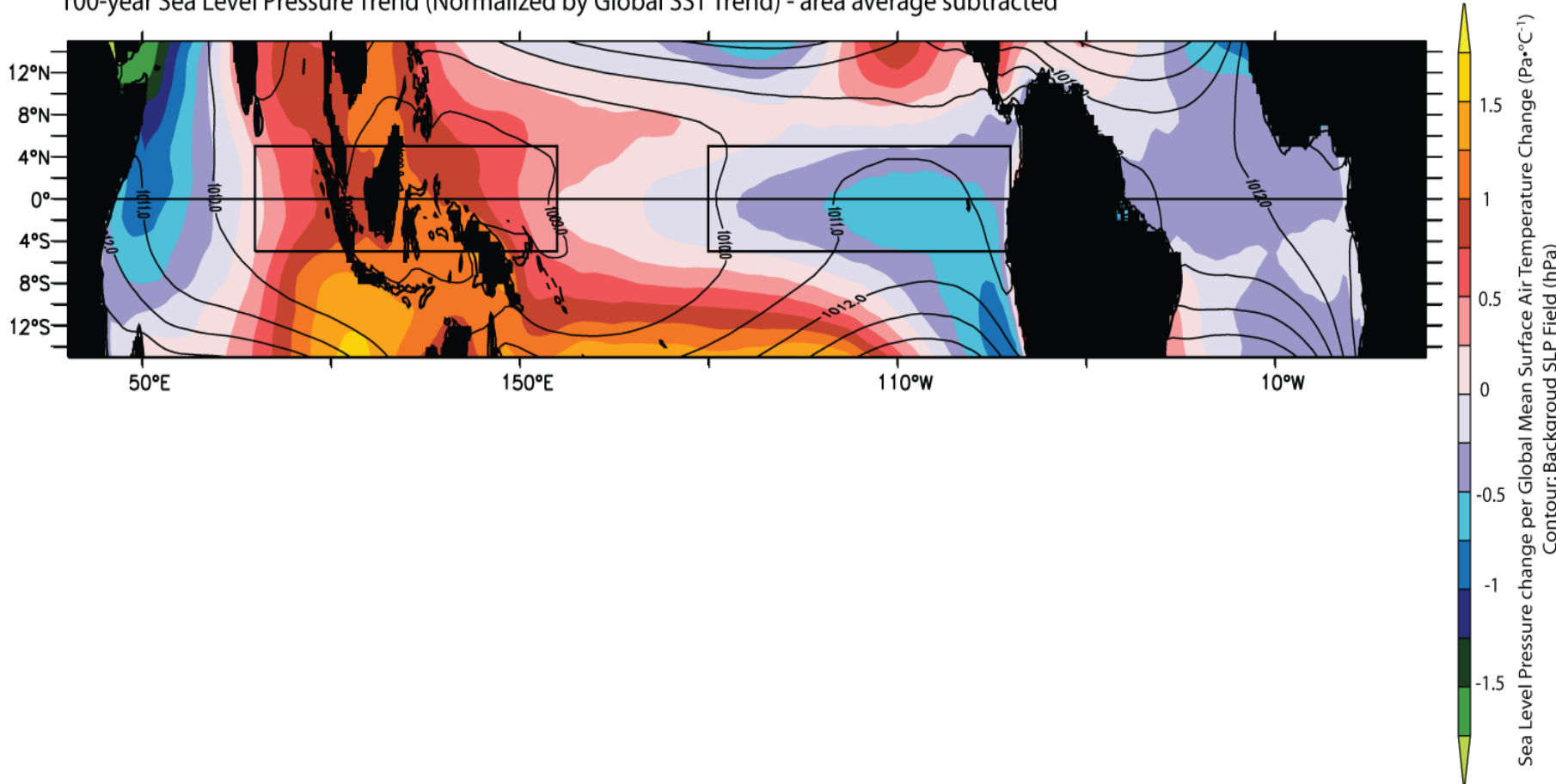
Vecchi et al. (2012, in prep.)

Looks like CMIP3 response (e.g., Vecchi and Soden 2007.a)

Tropical Pacific Response

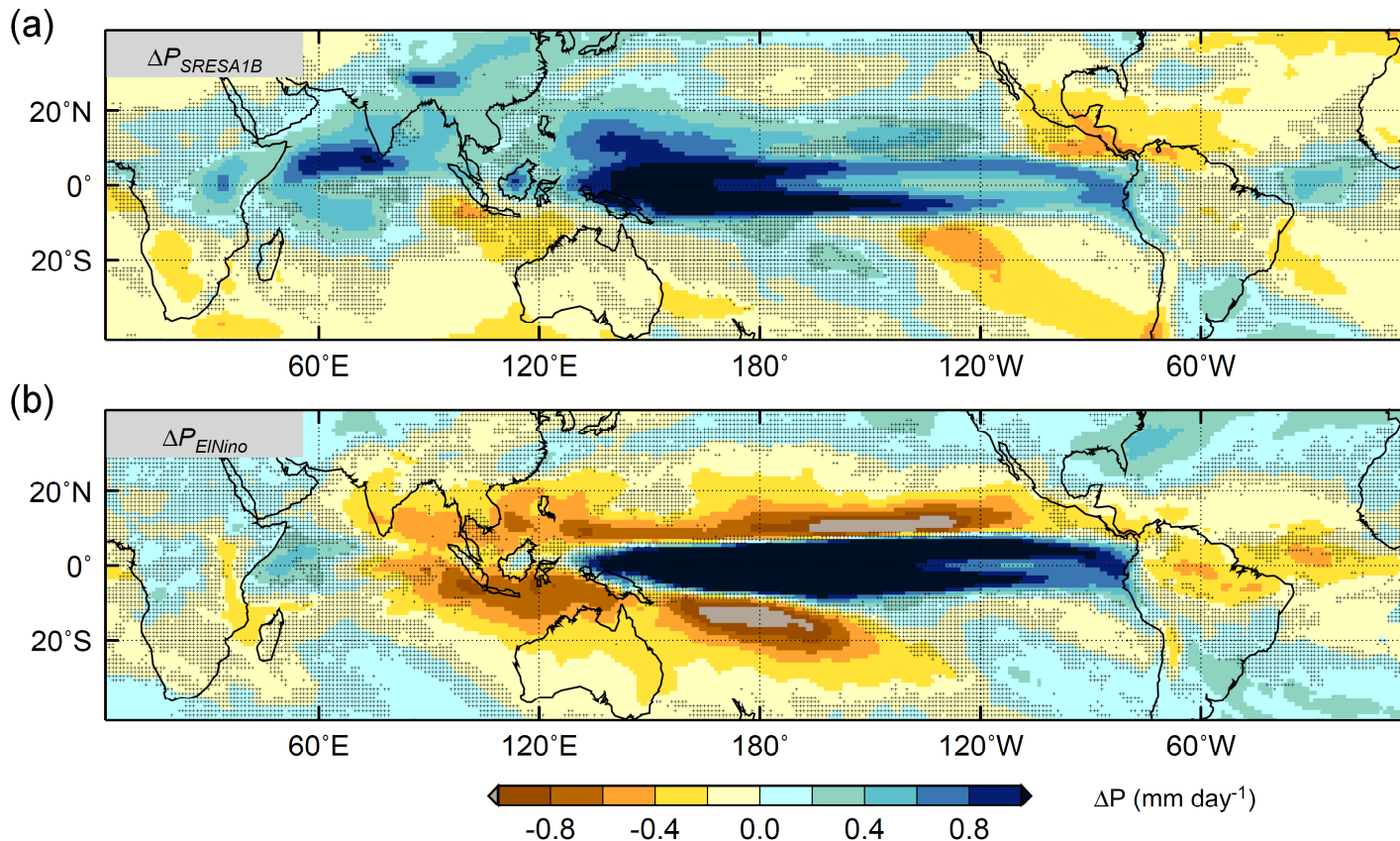
Near-equatorial Indo-Pacific Zonal SLP gradients decrease

a) 22-Model Ensemble-mean Scenario A1B (720 ppm CO₂ Stabilization) - 2001-2100
100-year Sea Level Pressure Trend (Normalized by Global SST Trend) - area average subtracted



Precipitation response: CO₂ differs from El Niño

multi-GCM Precipitation response to CO₂



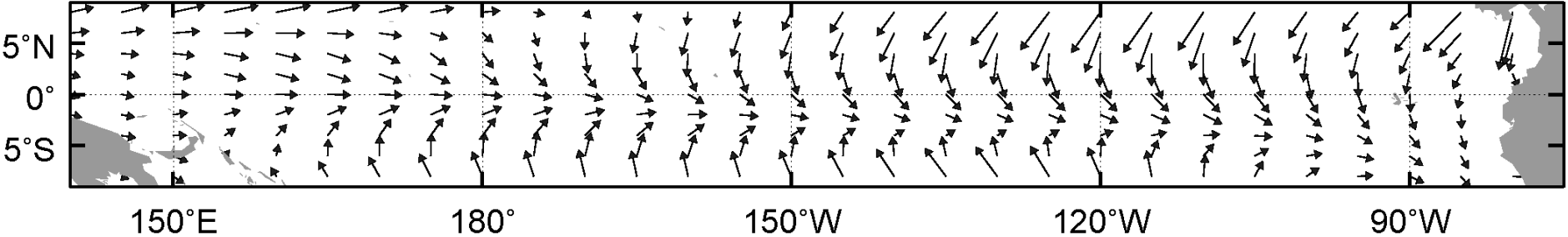
multi-GCM Precipitation response to El Niño

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

Reduced equatorial wind stress and currents reflect weaker Walker circulation

Stress

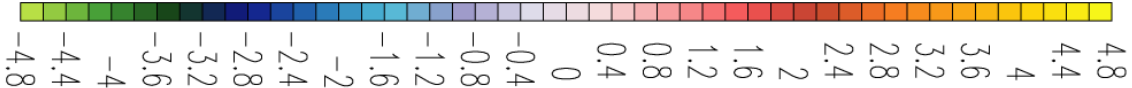
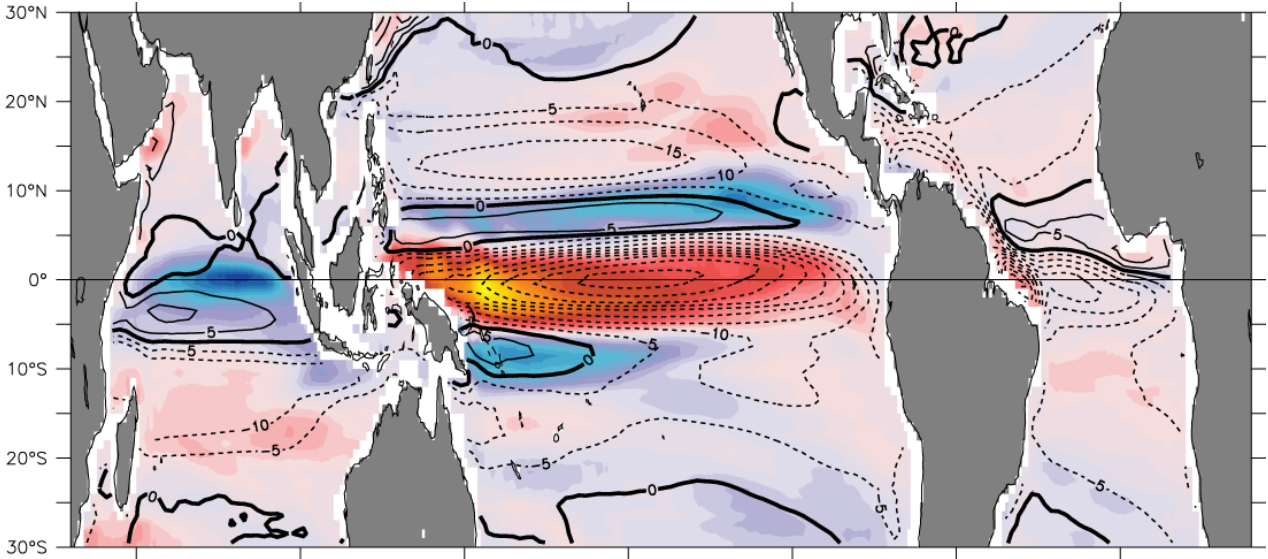
DiNezio et al (2009, J. Clim.)



→ 10^{-2} N m^{-2}

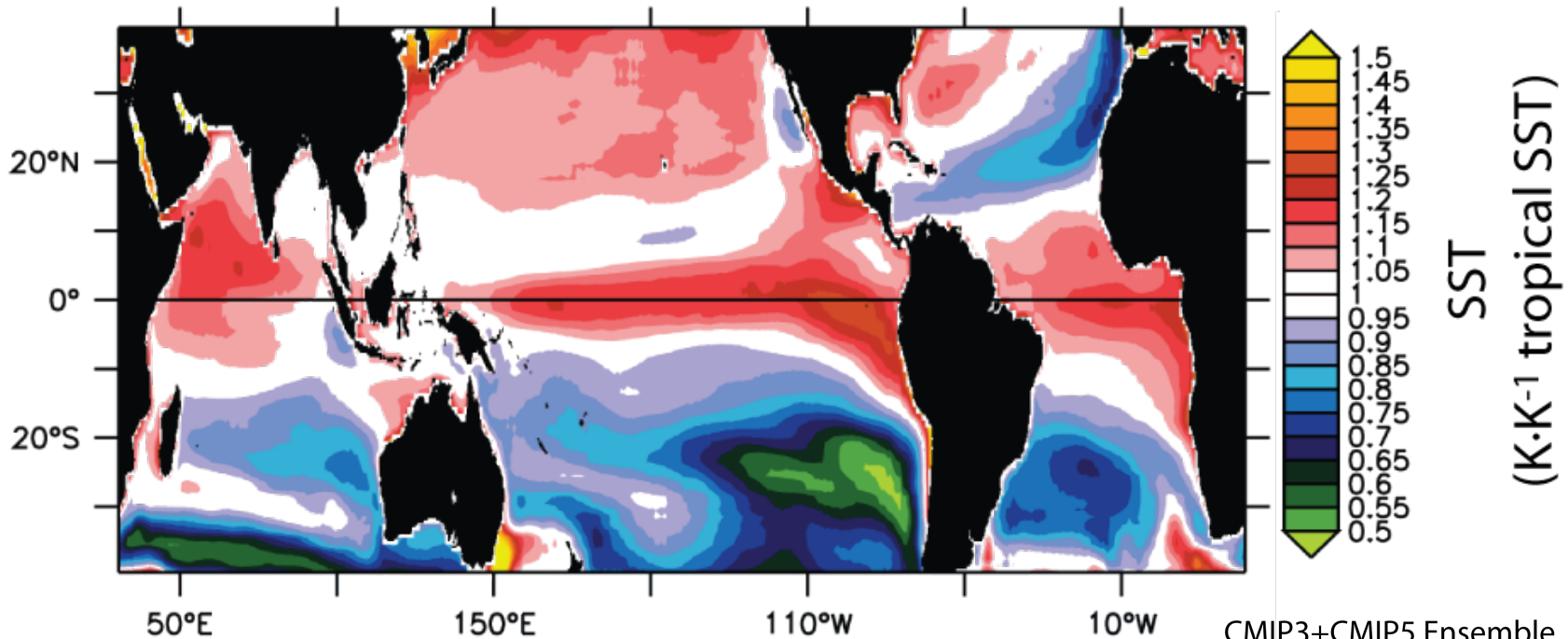
Surface Zonal Currents

Vecchi and Soden (2007, J. Clim.)



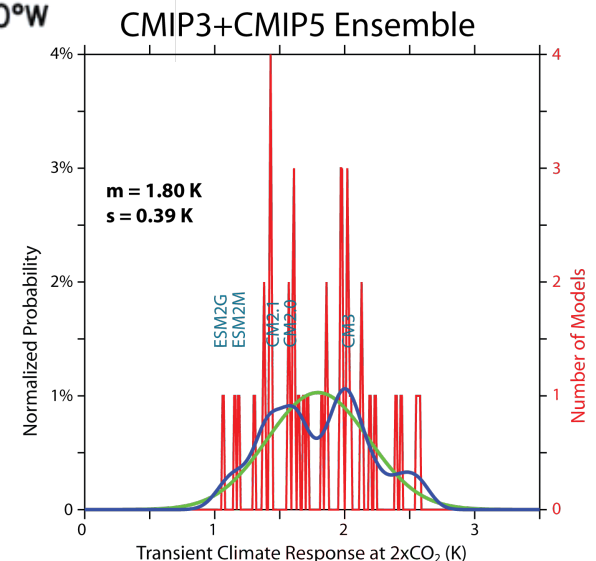
Shade: 2001-2100 trend ($10^4 \text{ m s}^{-1} \text{ yr}^{-1} \text{ } ^\circ\text{C}^{-1}$) - Contour, 2001-2020 Average (cm s^{-1})

Tropical SST response to CO₂ doubling in CMIP5 GCMs

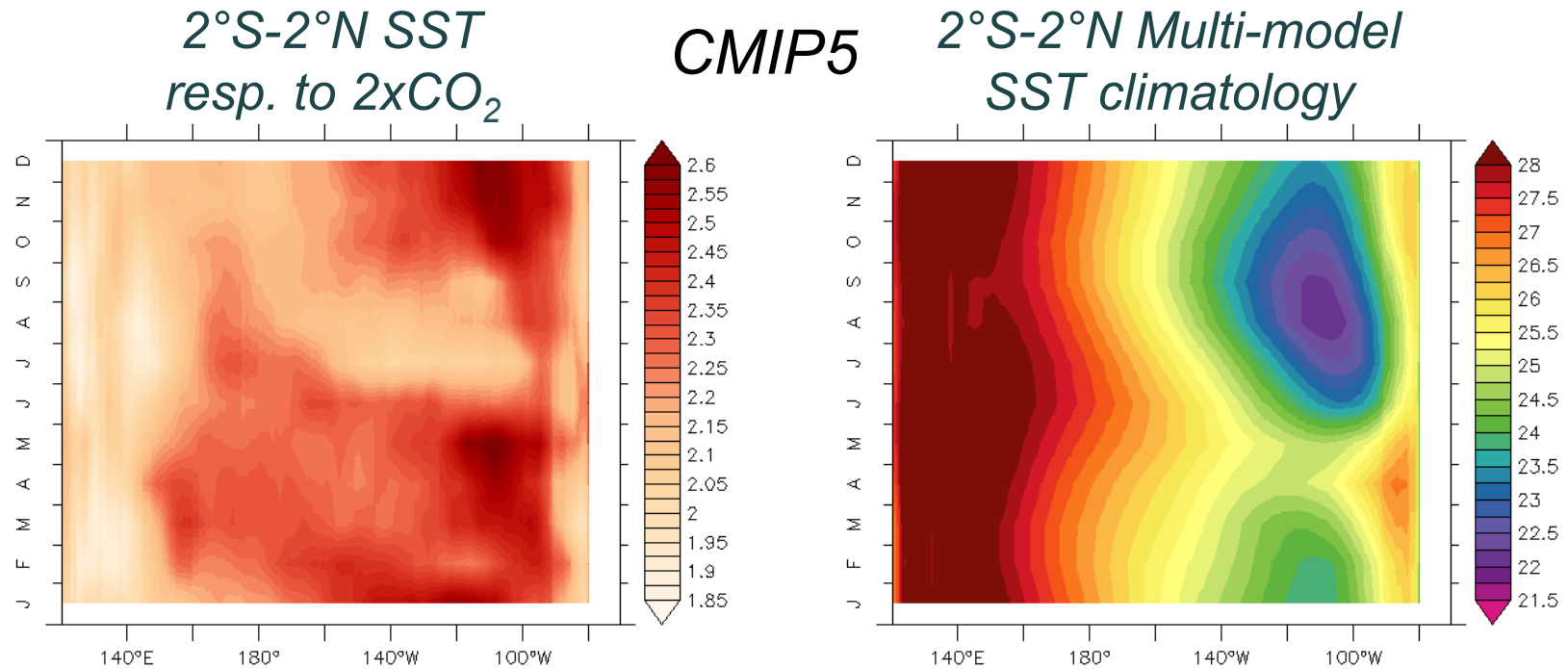


CMIP3+CMIP5 distribution
of tropical-mean SST change

Vecchi et al. (2012, in prep.)



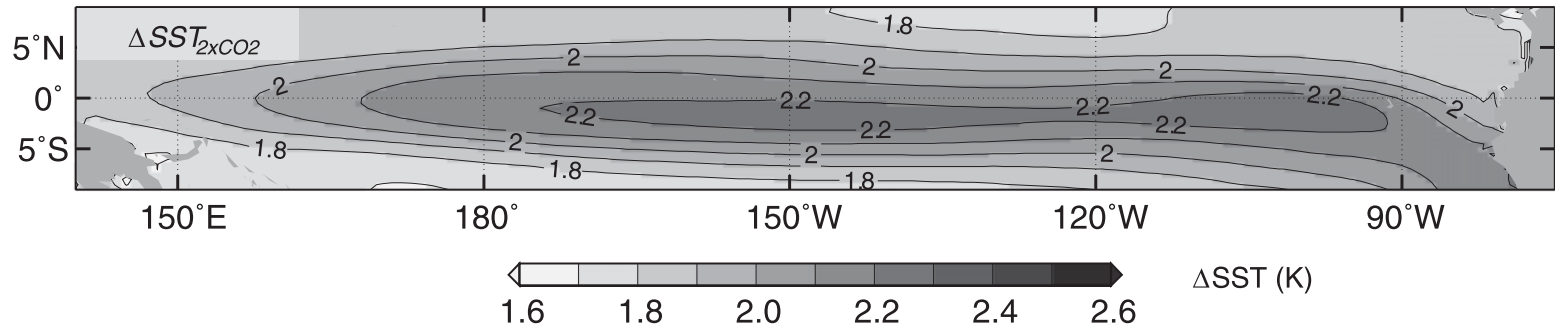
Equatorial Pacific SST response to CO₂ shows annual cycle:
smallest during peak upwelling season



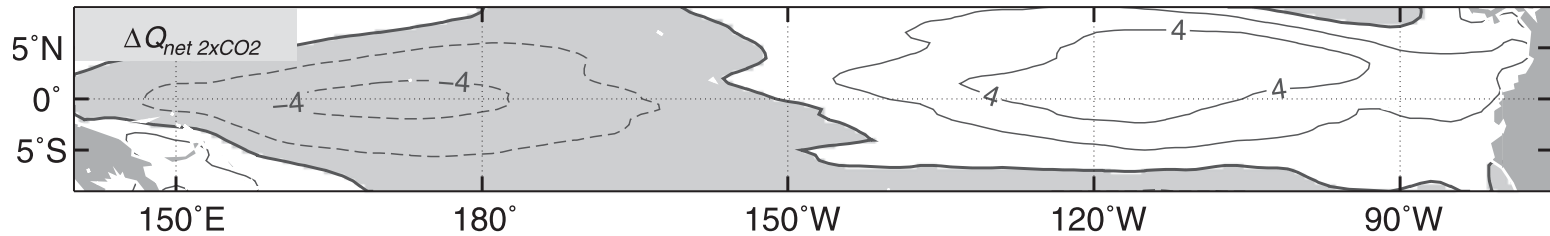
*Evidence of Clement et al. Ocean Dynamical Thermostat: $\langle w \rangle dT'/dz$
In peak upwelling season $\langle w \rangle$ largest, so damping of warming largest.*

Response of CMIP3 multi-model ensemble to 2xCO₂

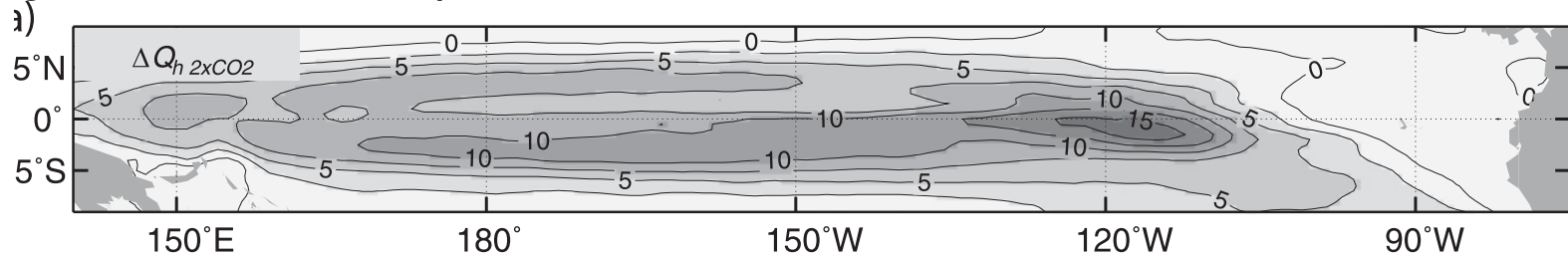
Change in SST



Change in surface heat flux



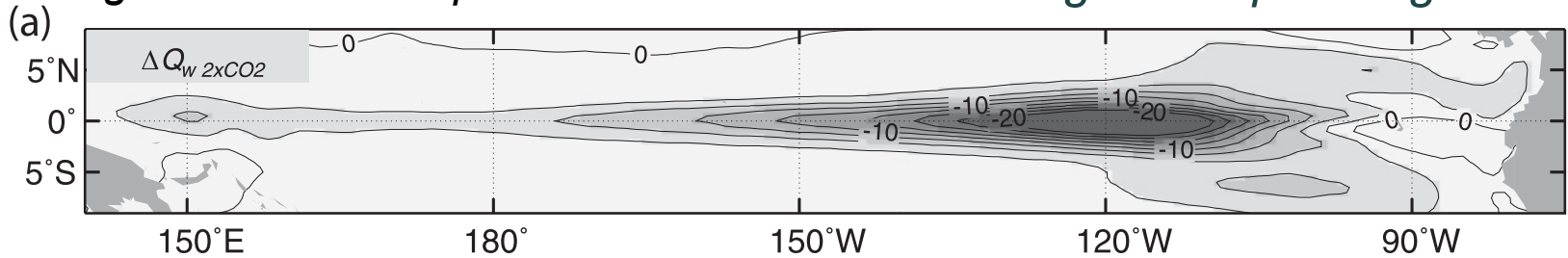
Change in horizontal temp. advection



Response of CMIP3 multi-model ensemble to 2xCO₂

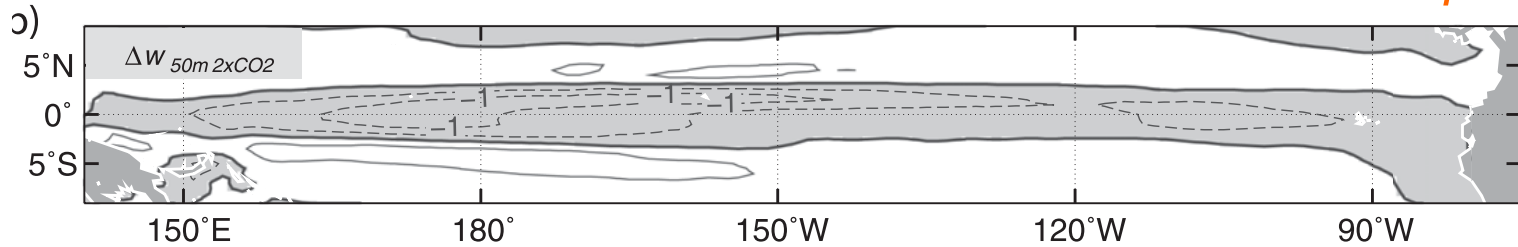
Change in vertical temperature advection

Cooling from upwelling increases

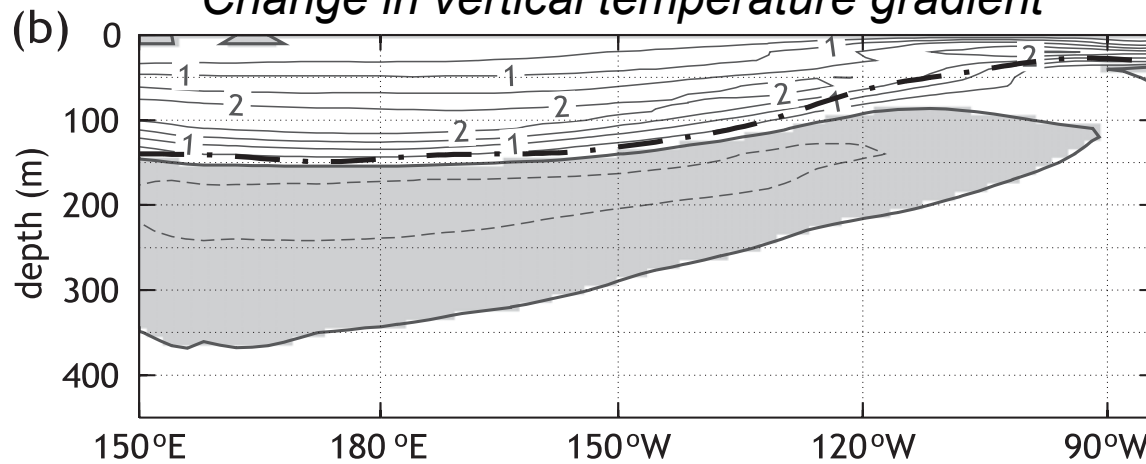


Change in 50m upwelling velocity

Weaker Walker reduces upwelling



Change in vertical temperature gradient

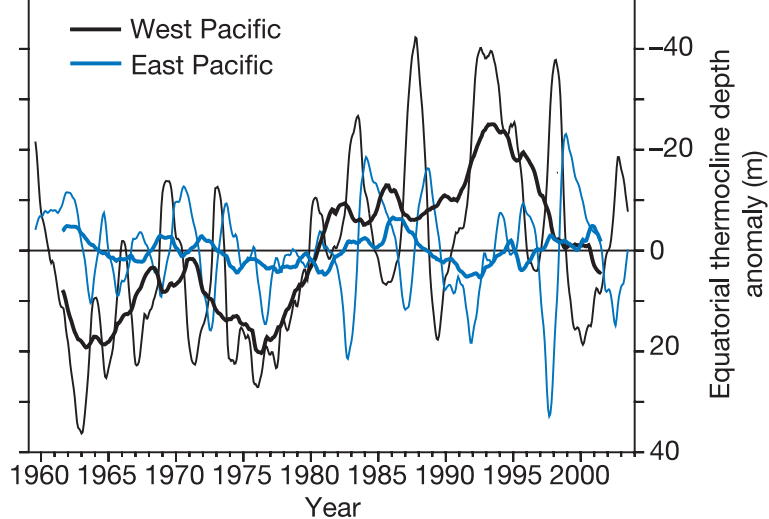
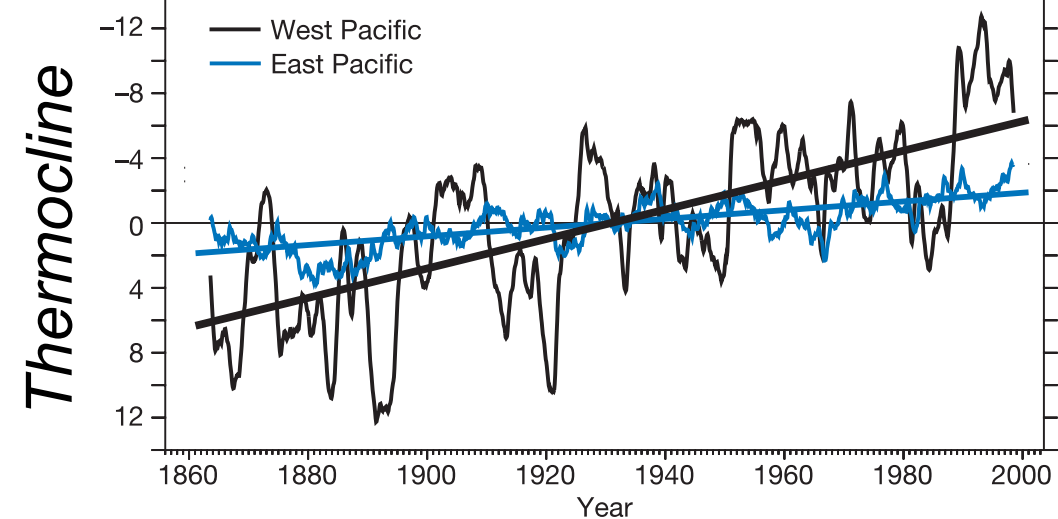
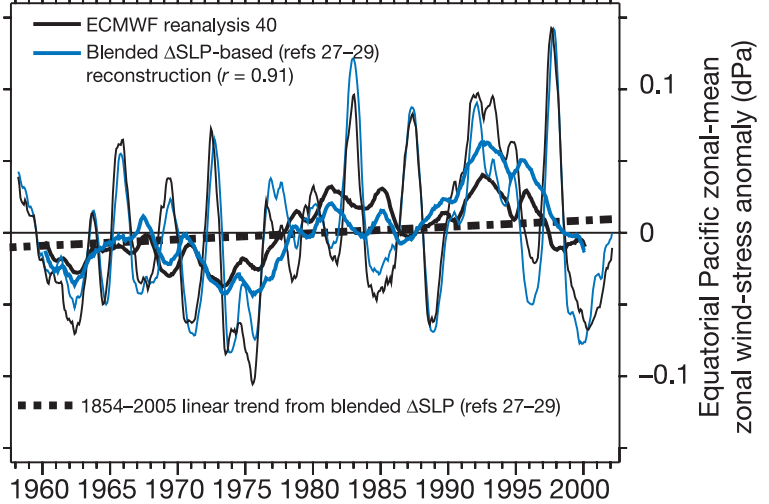
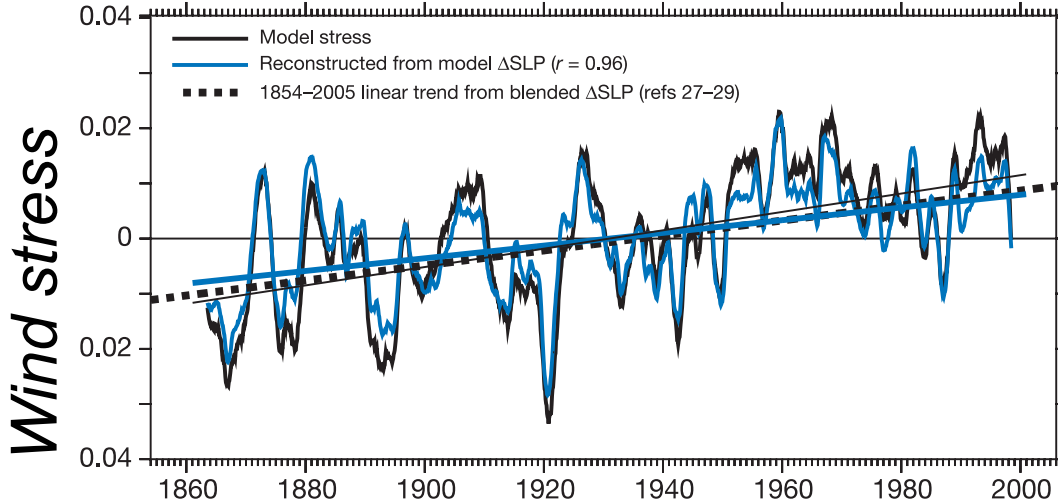


Stratification increases

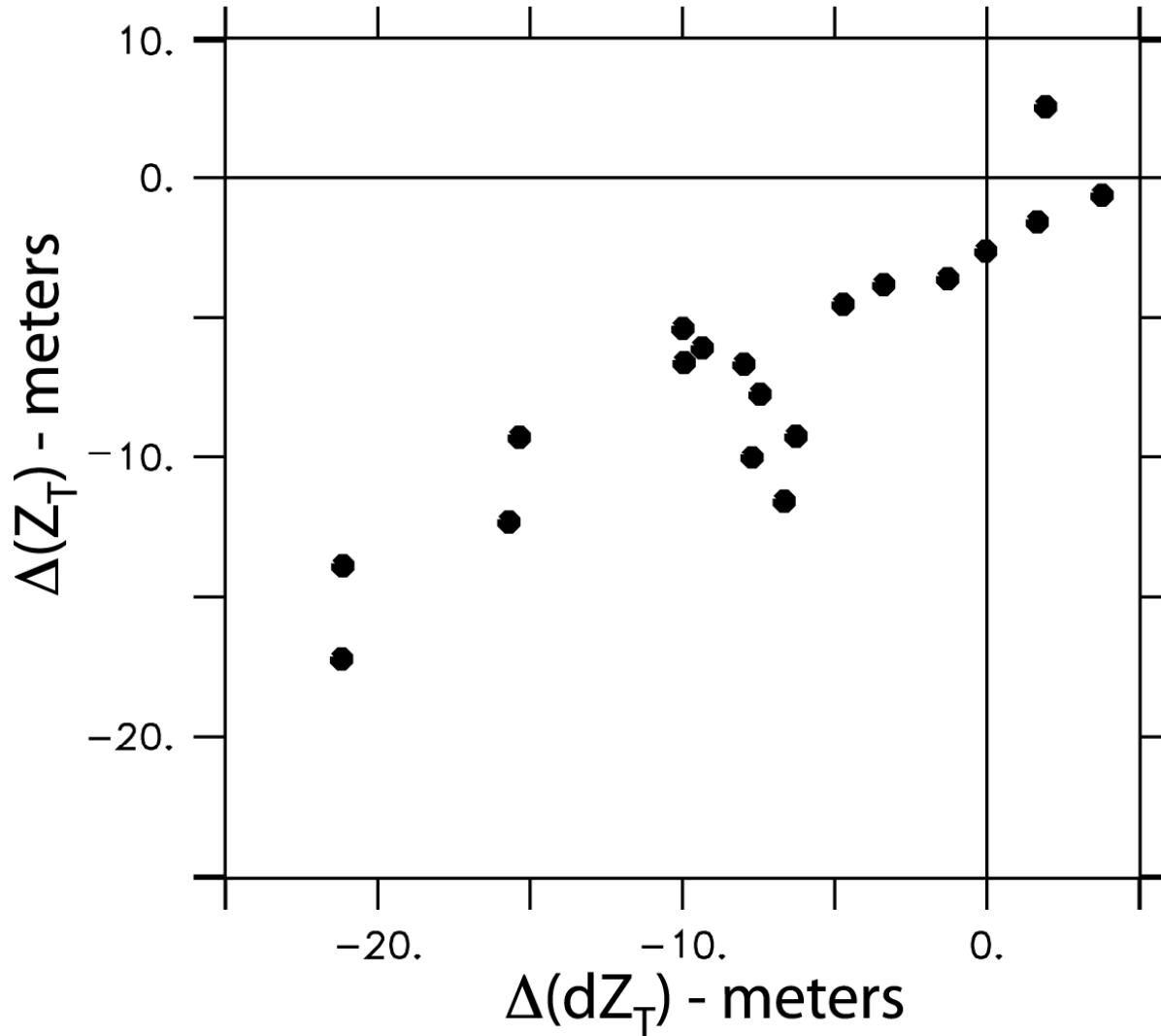
On interannual timescales: east and west Pacific t'cline respond to τ^x
On multi-year to decadal: east Pacific thermocline response is small.

CGCM

Obs. estimates



Equatorial Pacific
Thermocline Slope vs. Depth

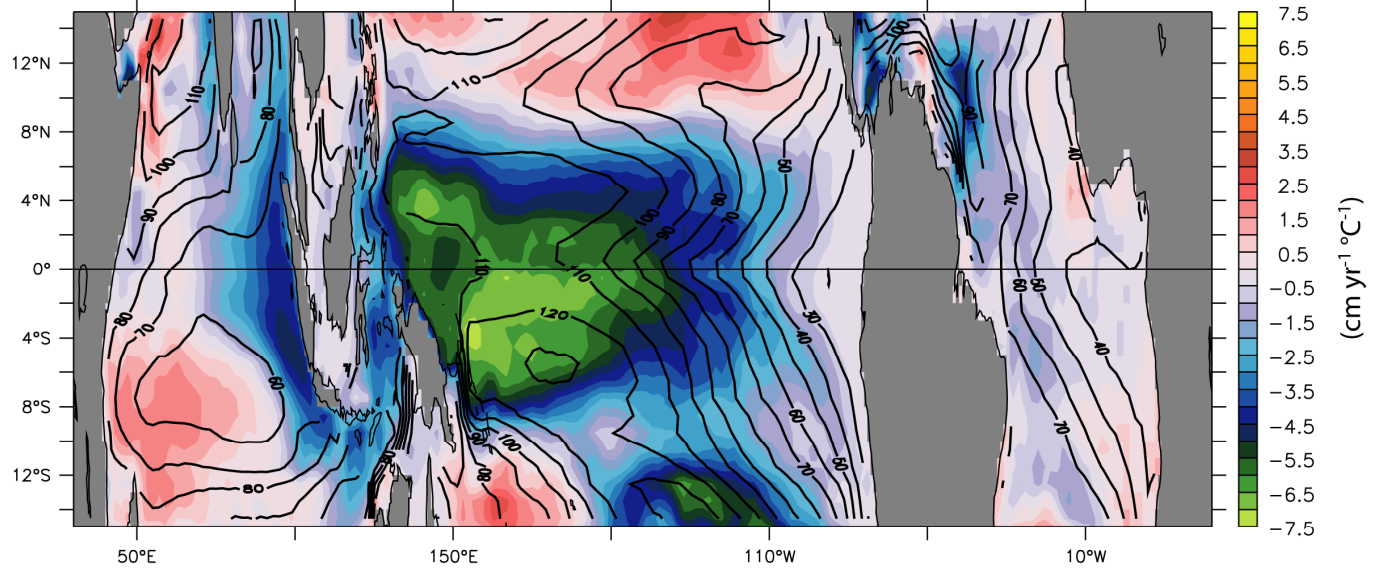


Changes in thermocline depth scale with changes in thermocline slope.

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

Scenario A1B (720 ppm CO₂ Stabilization) - 2001-2100

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

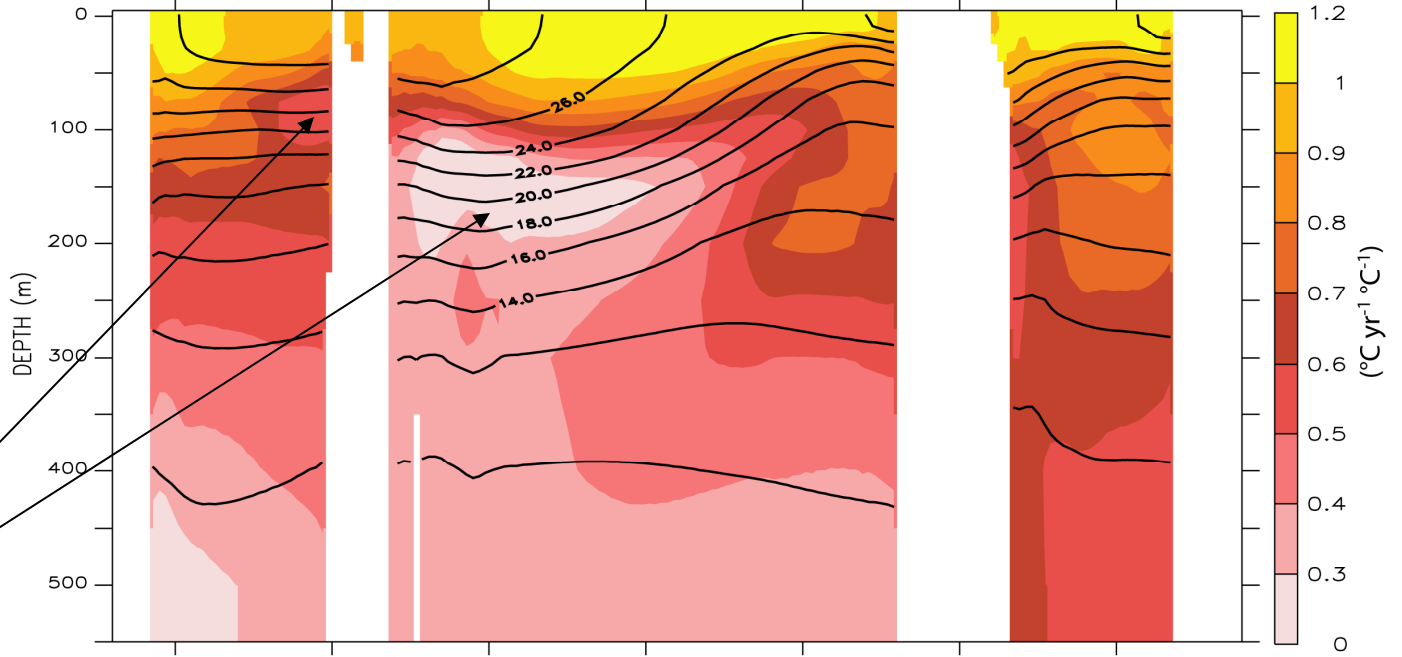


Equatorial Pacific
thermocline flattens
and shoals ->
Shallow in west

Ensemble-mean
response of
equatorial
subsurface
temperatures.

Increased thermal
stratification.

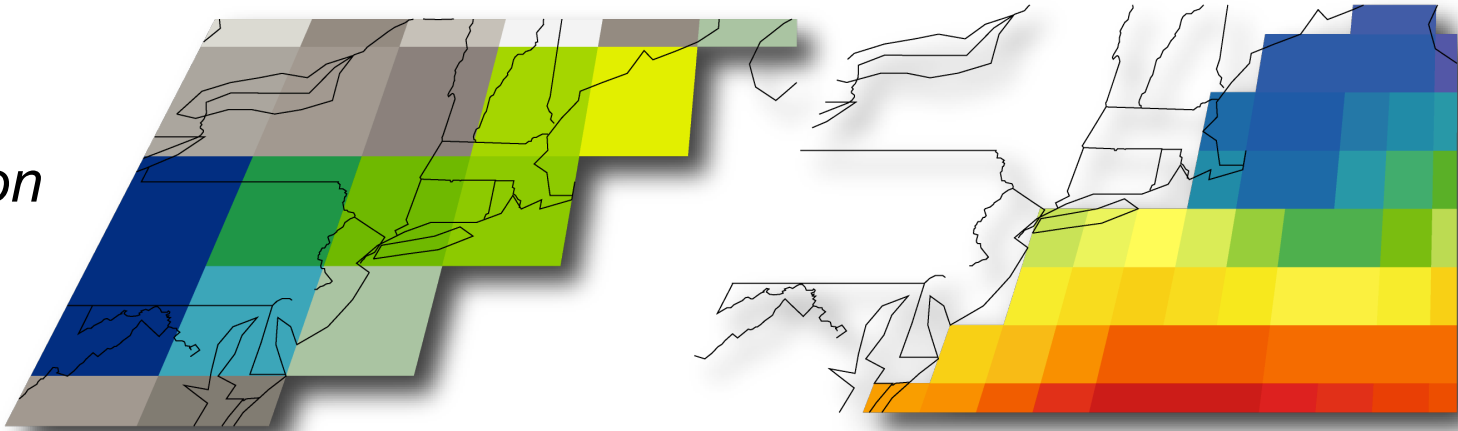
Minimum in
warming



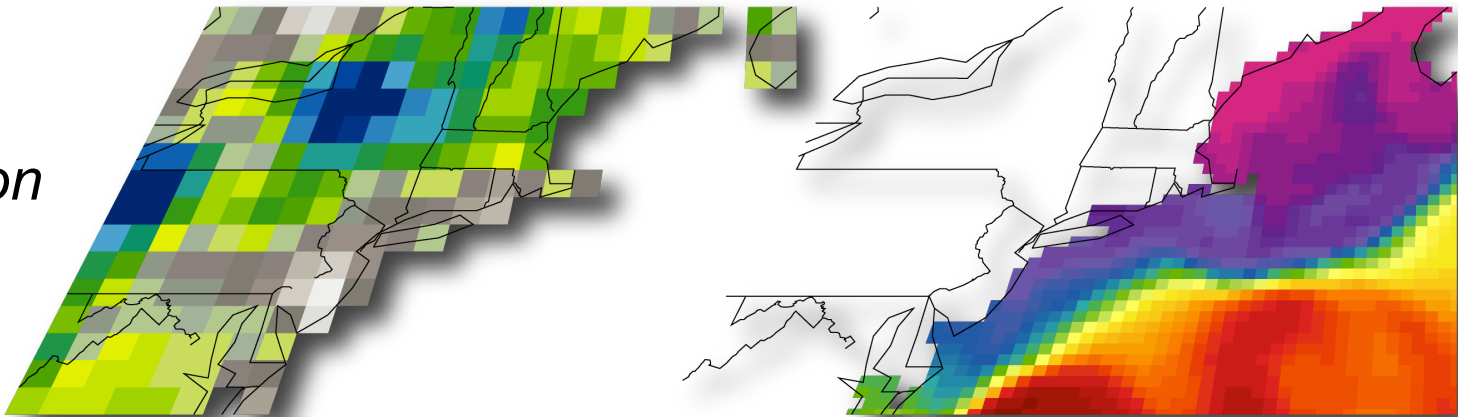
19-Model Ensemble-mean 100-year Equatorial Temperature Trend (Normalized by Global SST Trend)

Resolution (computer power) limits ability to represent processes and phenomena

*Medium
resolution
(CM2.1)*



*High
resolution
(CM2.5)*

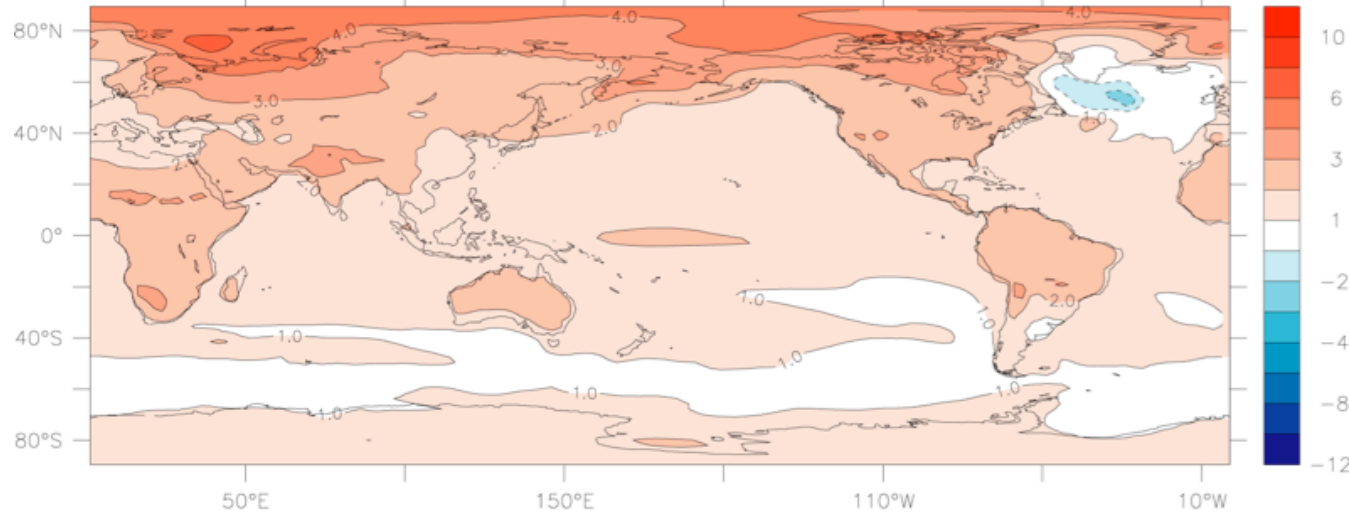


Precipitation

Ocean temp.

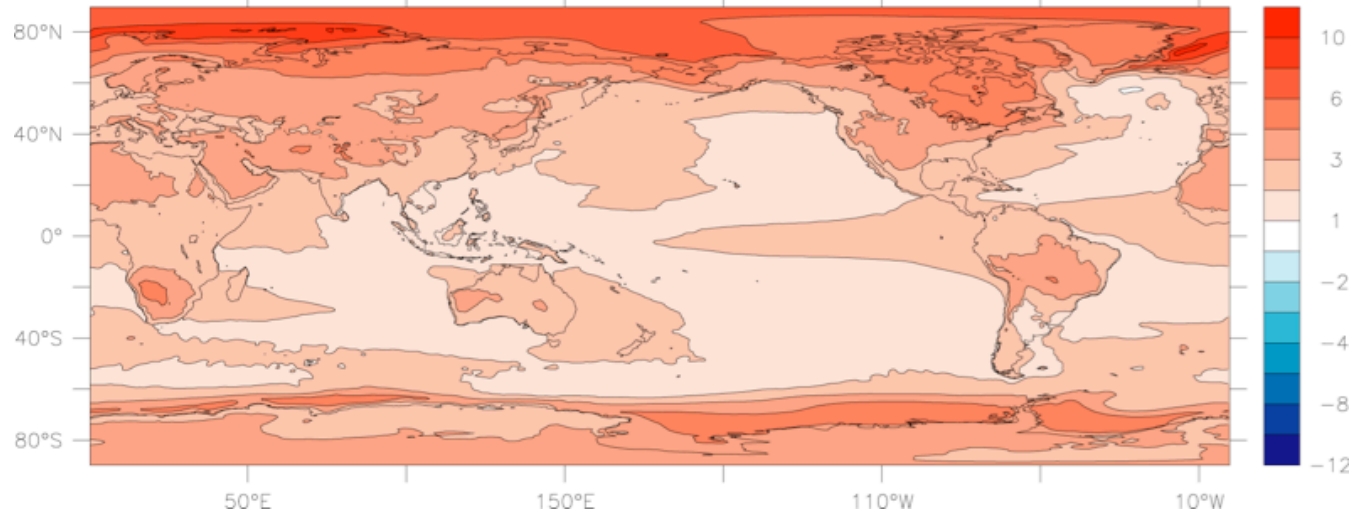
Global Surface Temperature Response to 2xCO₂

**CM2.1
(lo-res)**



*1° ocean
2-2.5° atm.*

**CM2.5
(hi-res)**



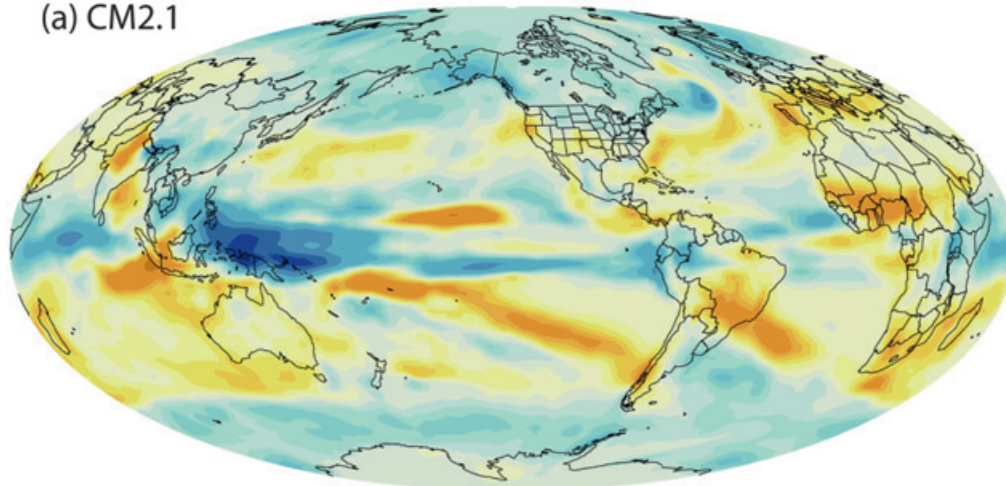
*0.25° ocean
0.5° atm.*

Delworth et al (2012)

“El Niño-ness” of high-res model’s SST response does not translate to remote precipitation

CM2.1
(lo-res)

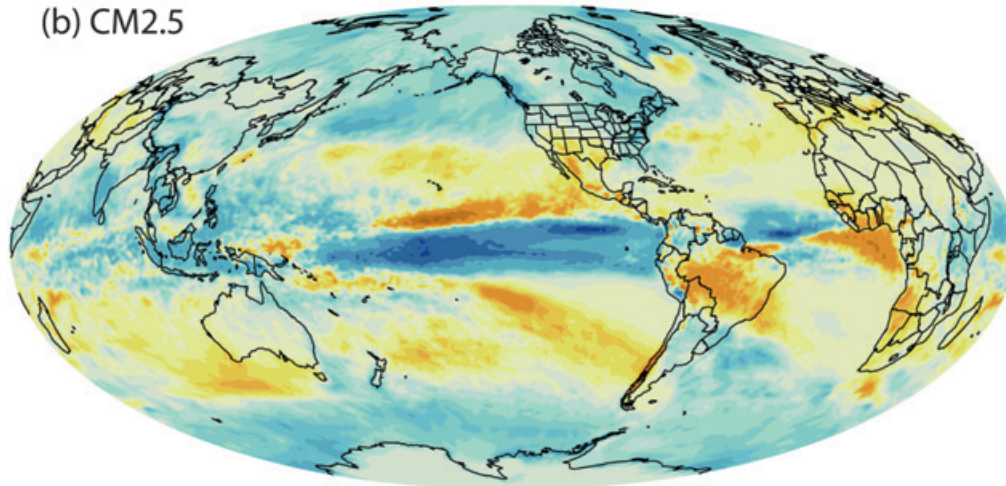
(a) CM2.1



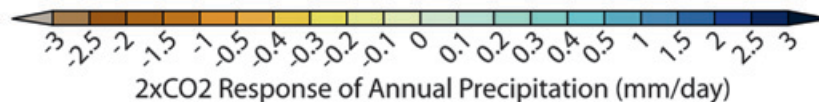
1° ocean
2-2.5° atm.

CM2.5
(hi-res)

(b) CM2.5



0.25° ocean
0.5° atm.



Delworth et al (2012)

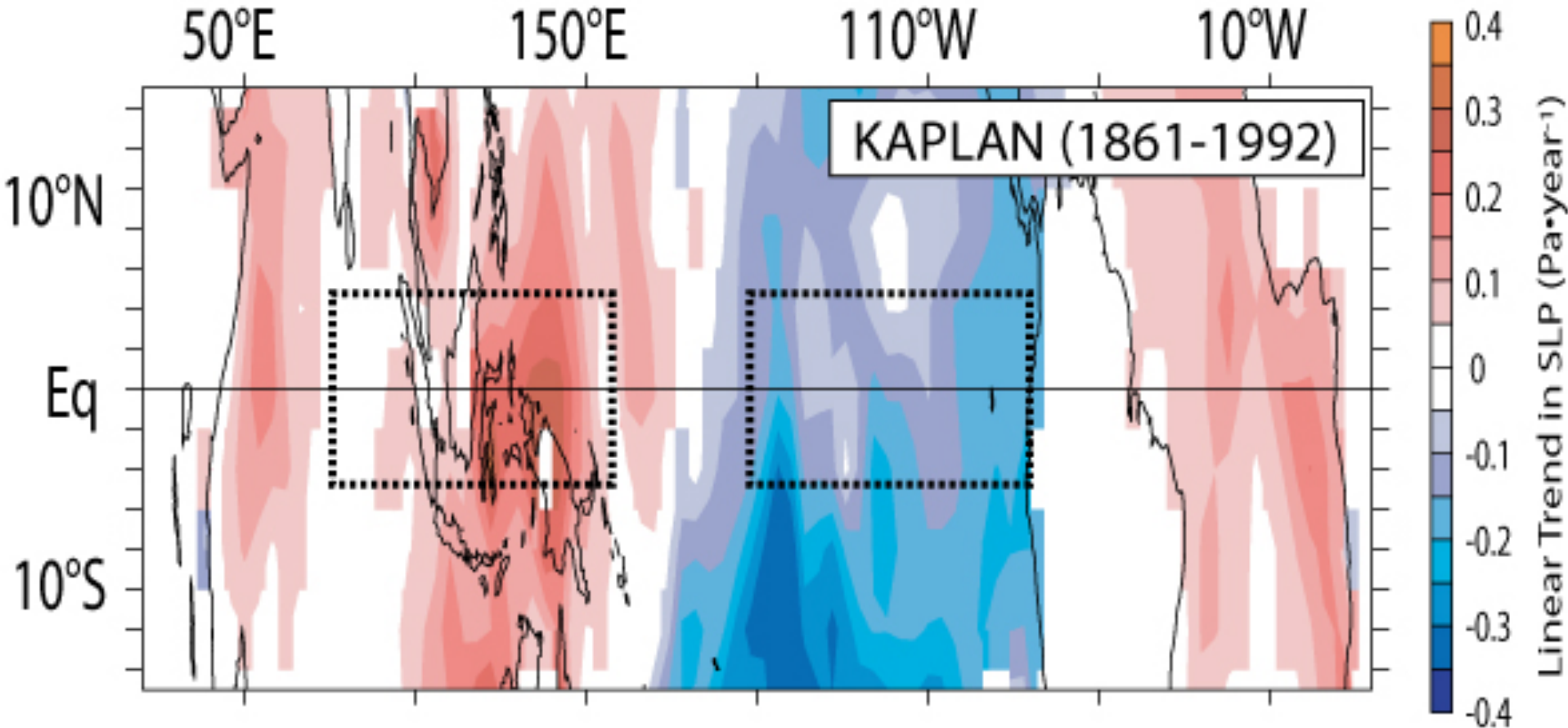
Outline

- 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

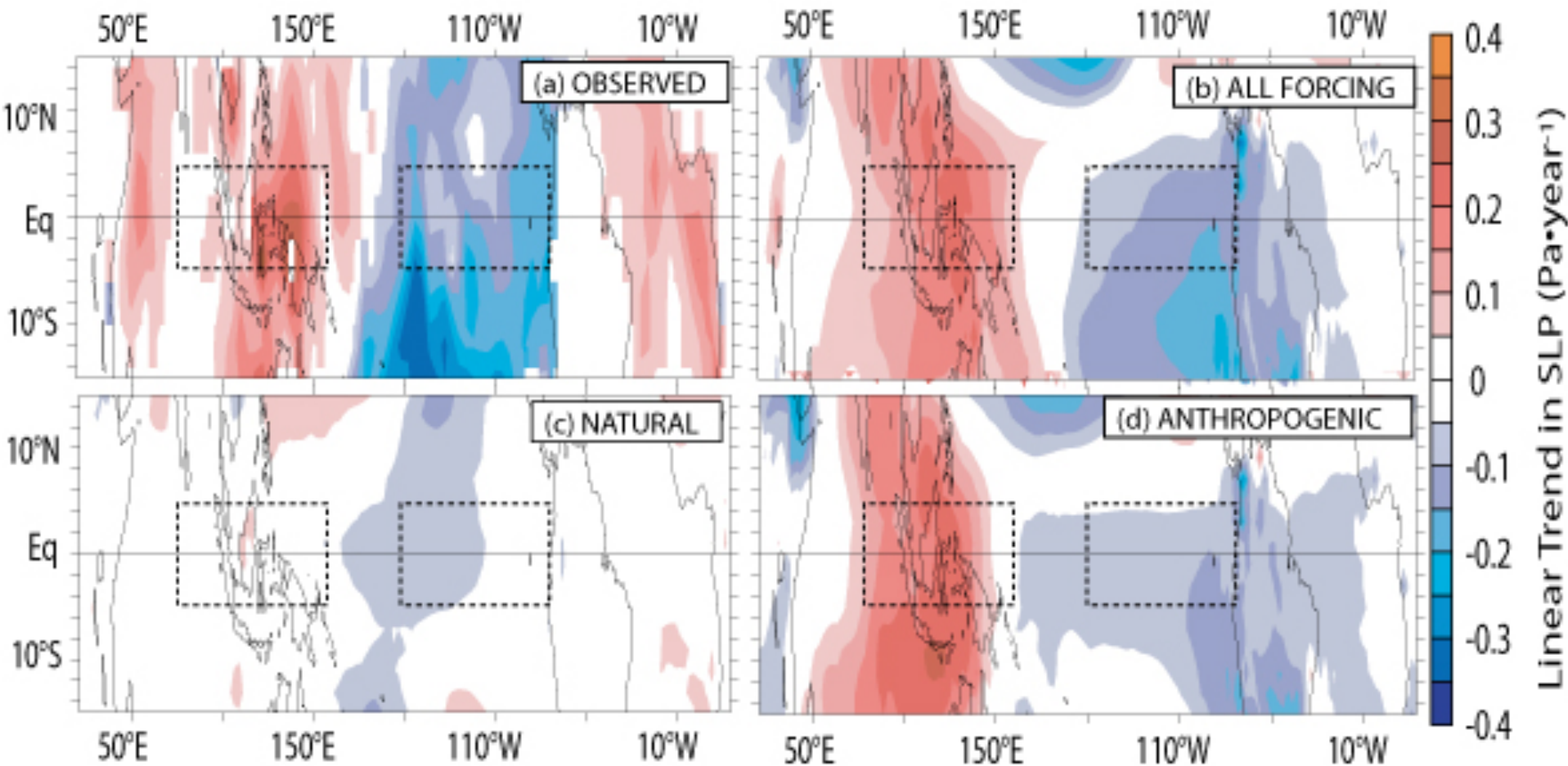


Reduction of E-W SLP gradient across Pacific.

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.

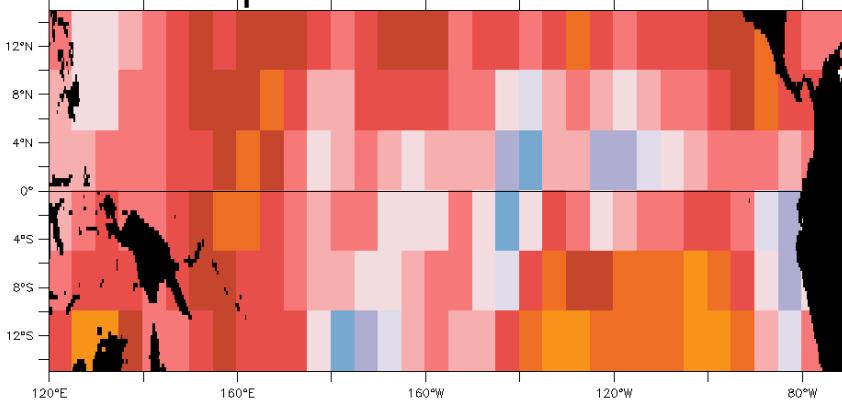


TRENDS COMPUTED 1861-1992

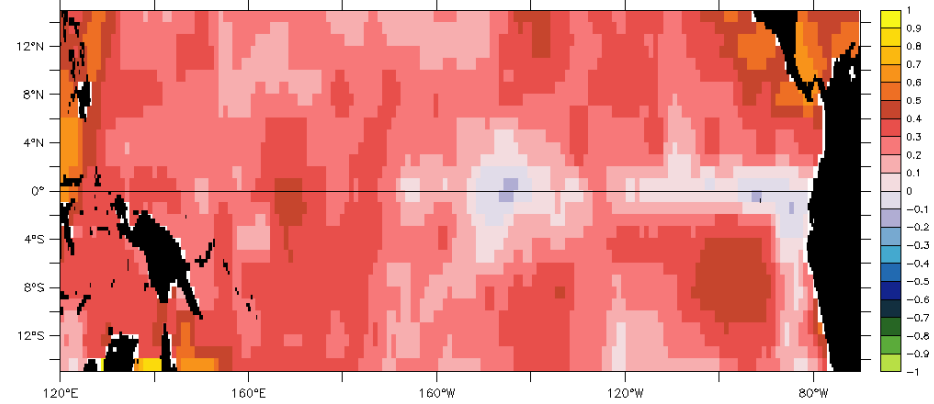
Look at SST?

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

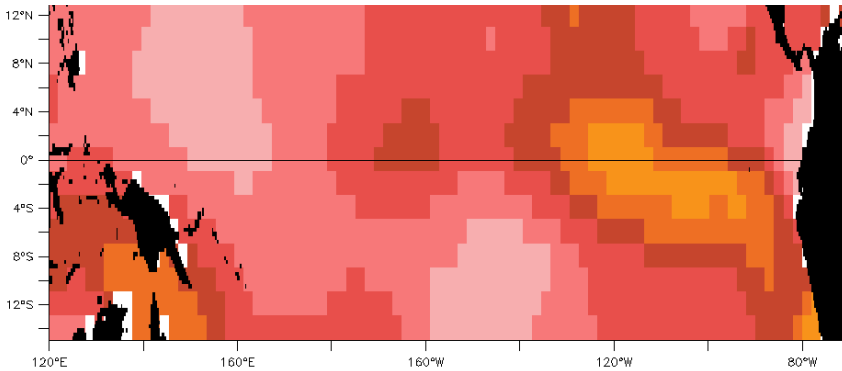
LDEO-Kaplan



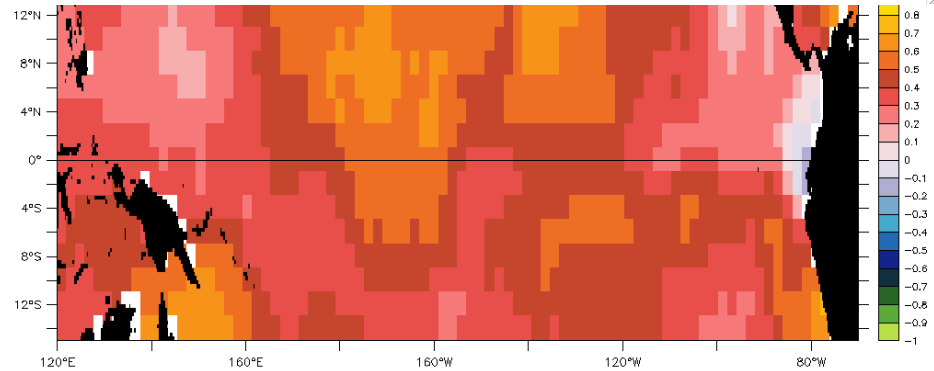
HadISST v.1



NOAA-ERSST v.2

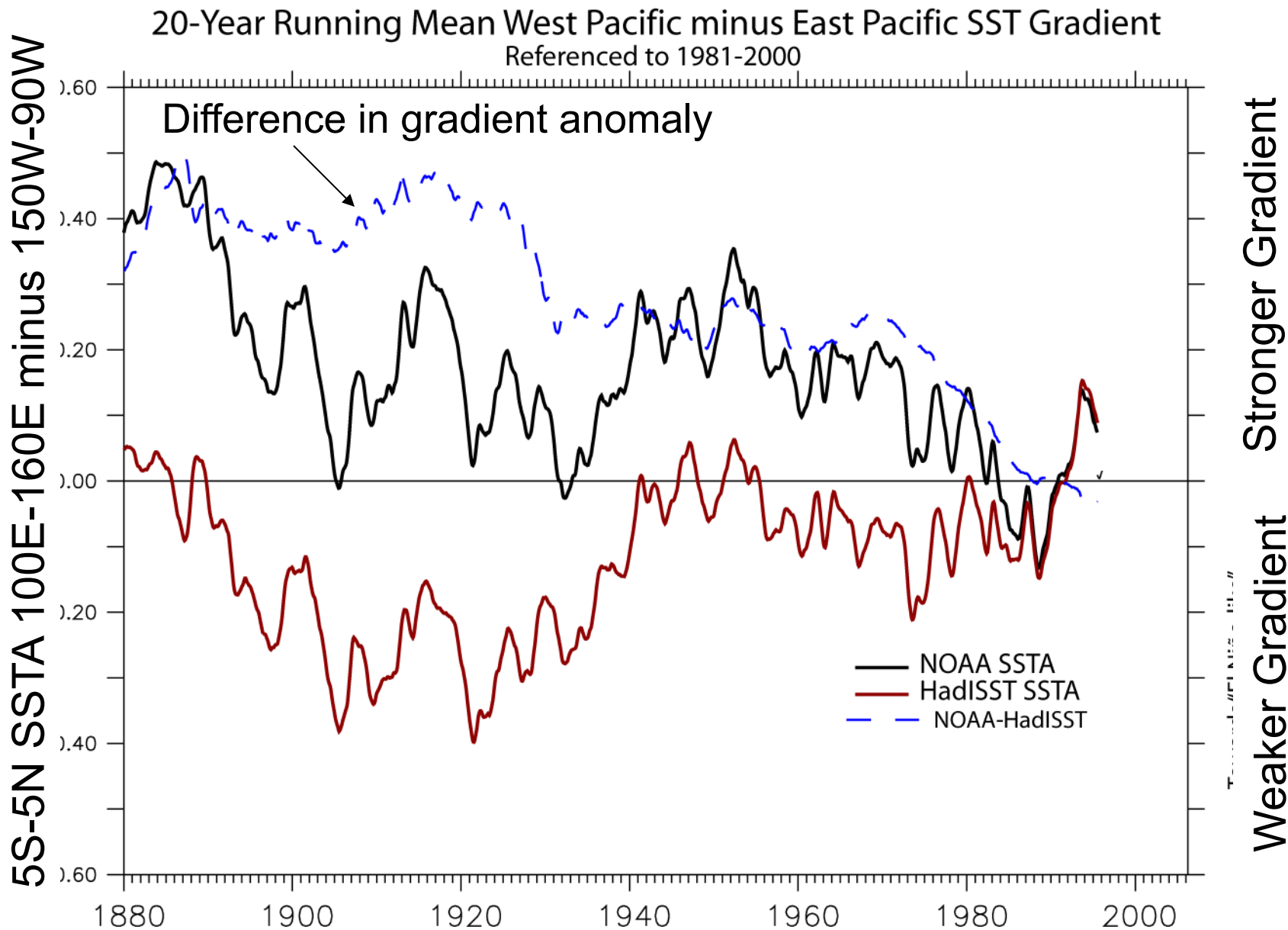


NOAA-ERSST v.3



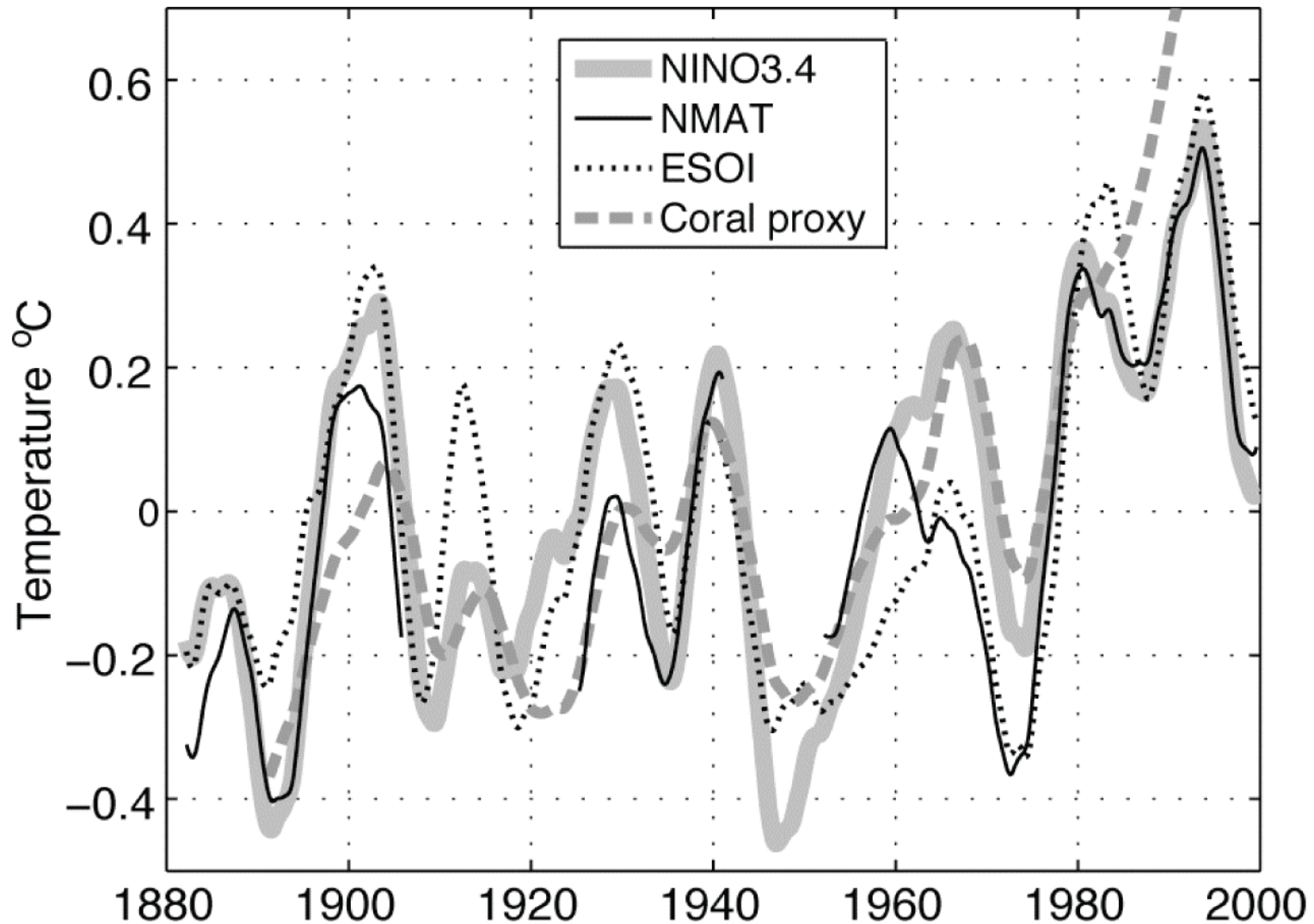
Overall warming seen in all.
Structure dependent on reconstruction.

When do differences between SST products emerge?



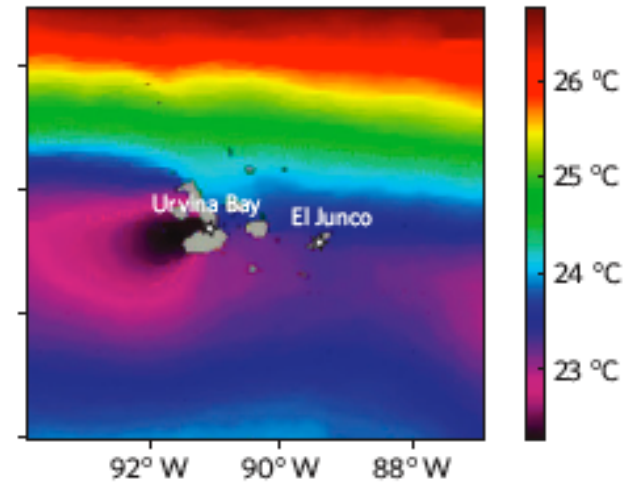
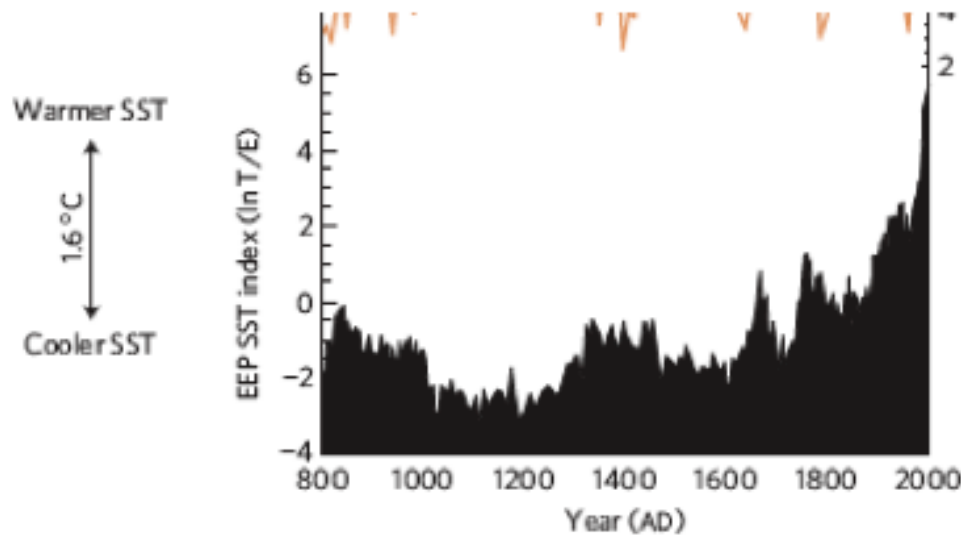
From Vecchi, Clement and Soden (2008, EOS)

“Pacific-centric” analysis



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

Lake Sediment Record El Junco Lake, Galapagos

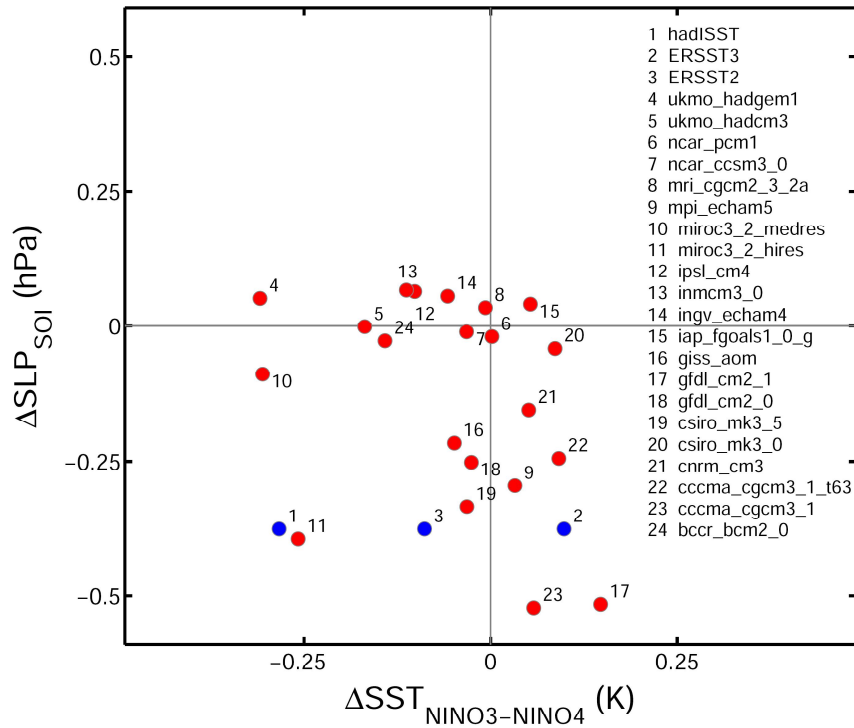


Conroy et al (2009, Nature. Geosci.)

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

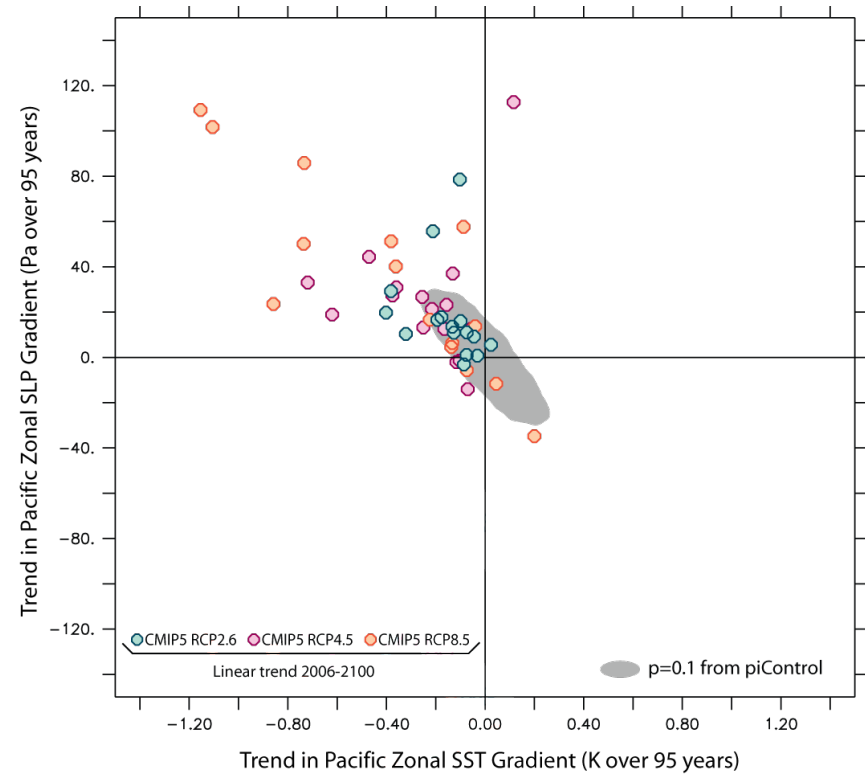
SST Gradient not a strong constraint on radiative response of SLP Gradient.

- 20th Century CMIP3
- Observed.



DiNezio, Clement and Vecchi (2010, EOS);

CMIP5 21st Century

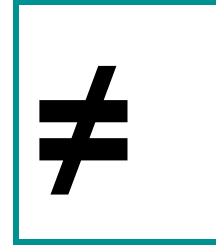


Vecchi et al. (2012, in prep.)

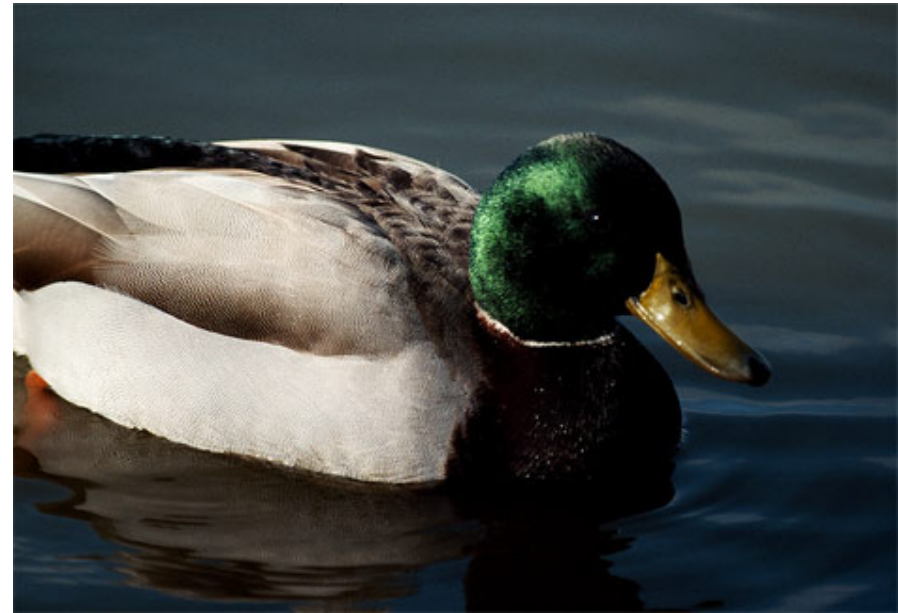
Conclusions

- 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”



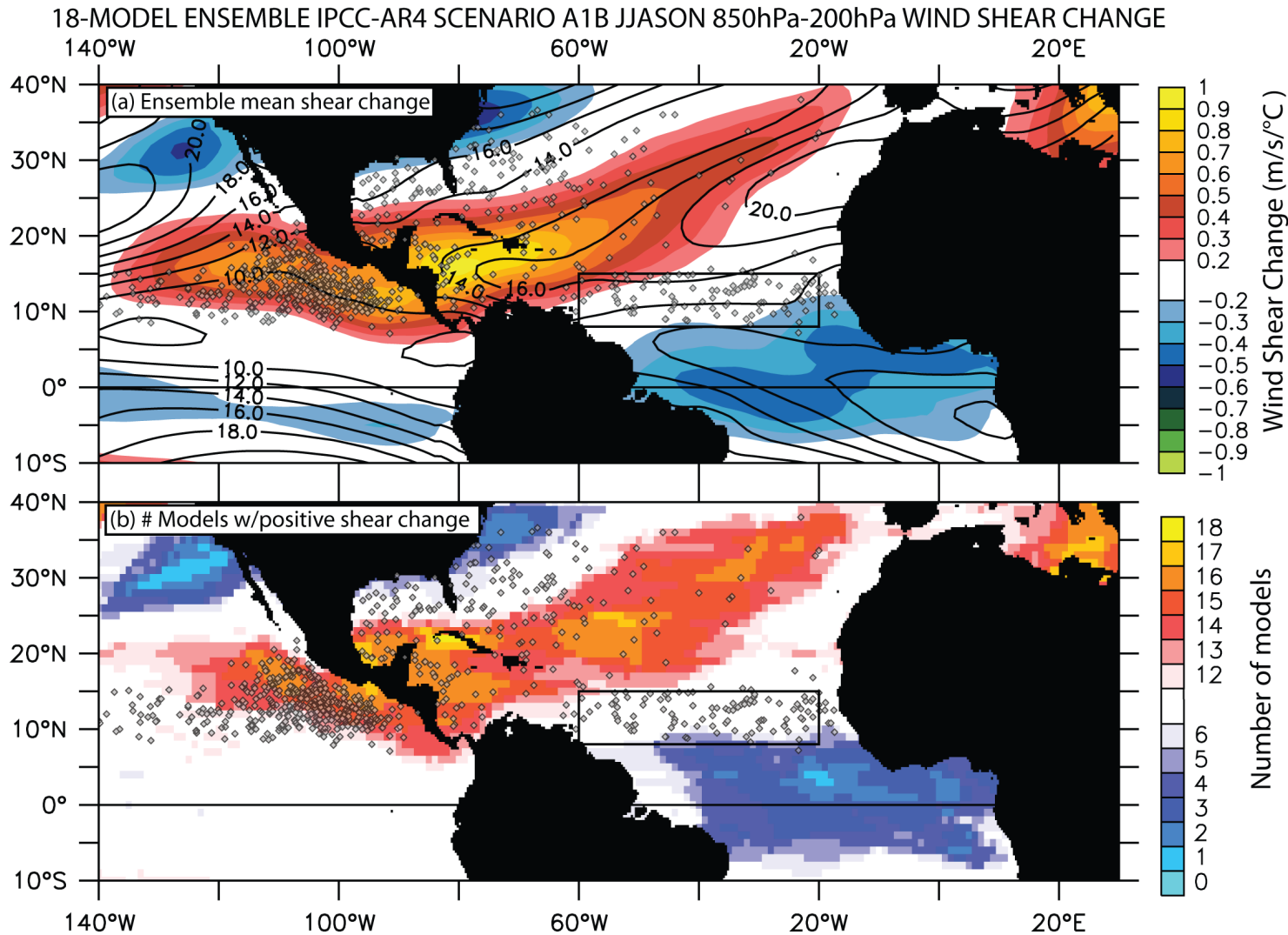
or



Outline

- Theory
- Numerical Modeling
- Observations
- **Implications:**
 - Atlantic wind shears
 - ENSO bad analogue for some teleconnections.

CMIP3 projected 21st Cy vertical wind shear changes

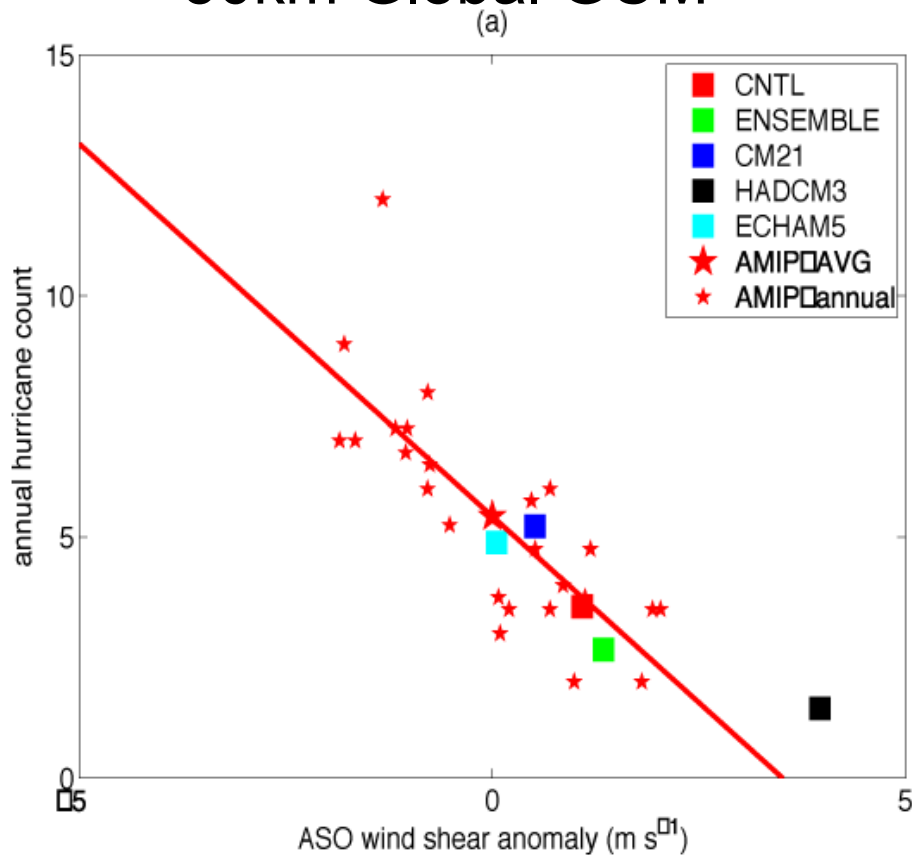


Vecchi and Soden (2007, GRL)

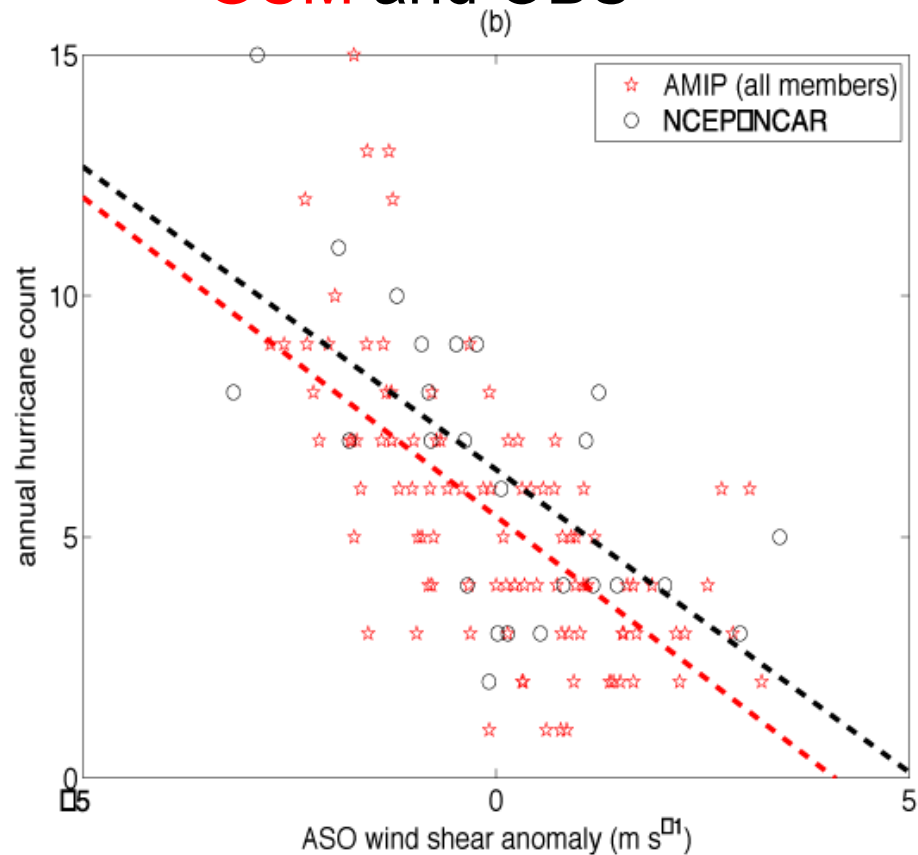
Increased wind shear over much of Tropical Atlantic and eastern Pacific connected to weakening of tropical circulation.

Shear changes and Atlantic hurricane activity

50km Global GCM



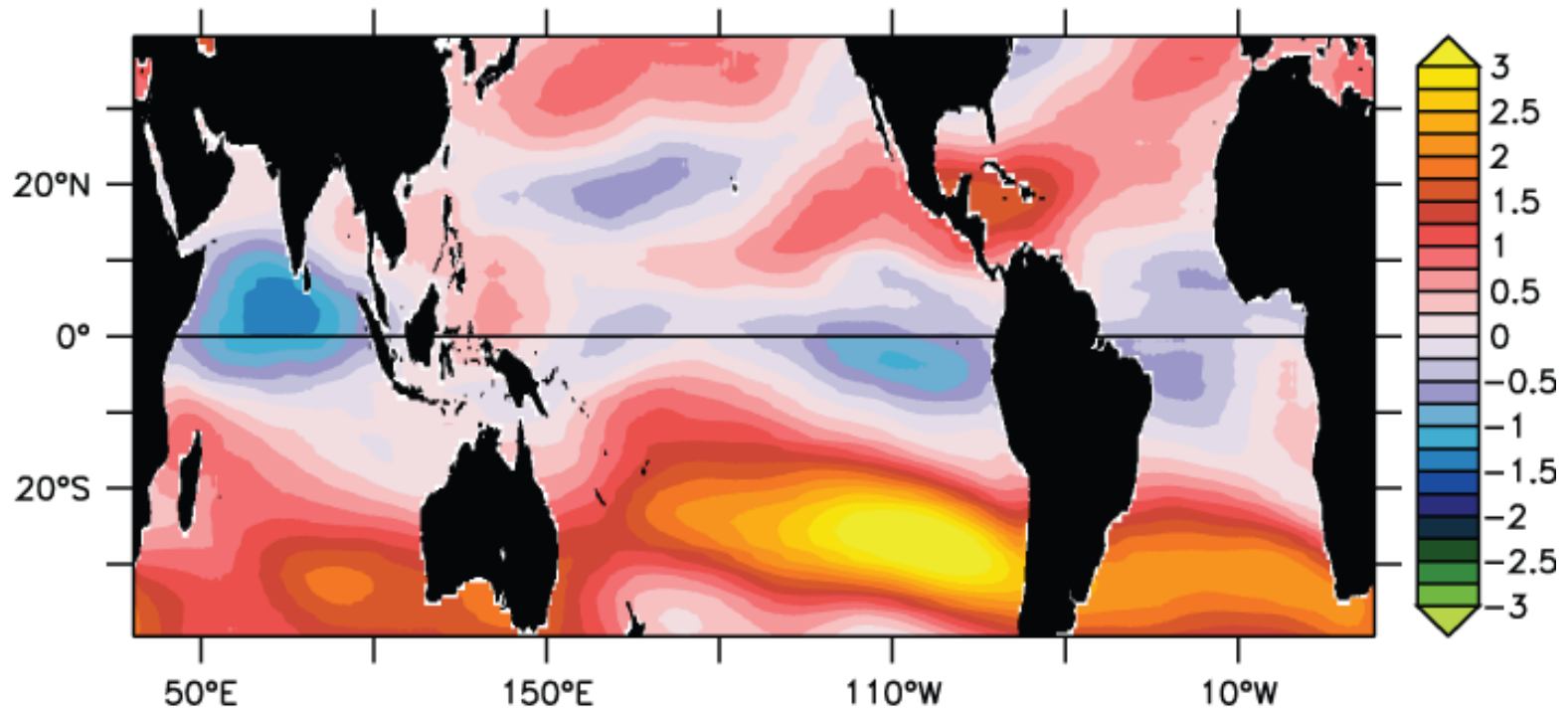
GCM and OBS



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

CO₂ increases Atlantic shear in CMIP5 models

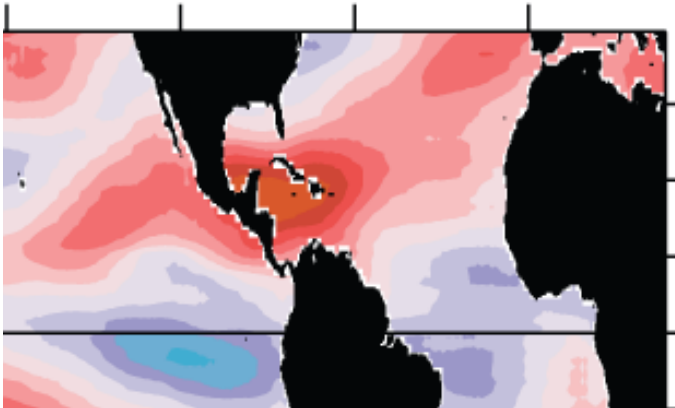
(c) Zonal 850-200hPa shear magnitude change per tropical-mean SST change (m/s/K)



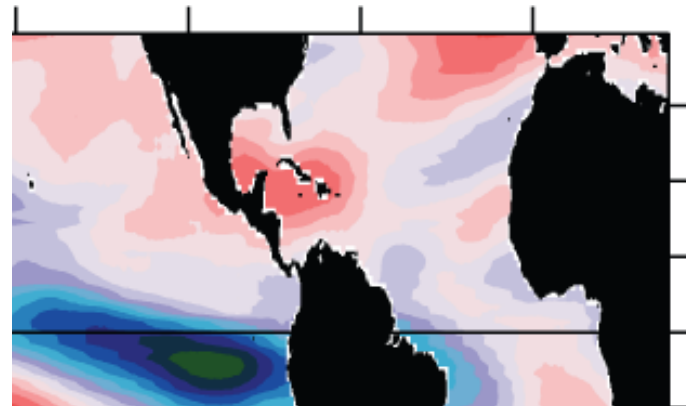
Vecchi and Soden (2012, in prep.)

Aerosols in projections complicate shear response in CMIP5

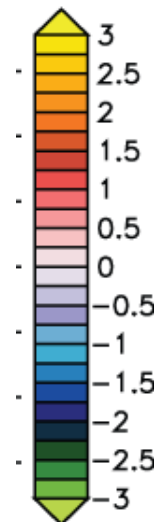
Response to CO₂ only



RCP2.6: strong reduction of aerosols



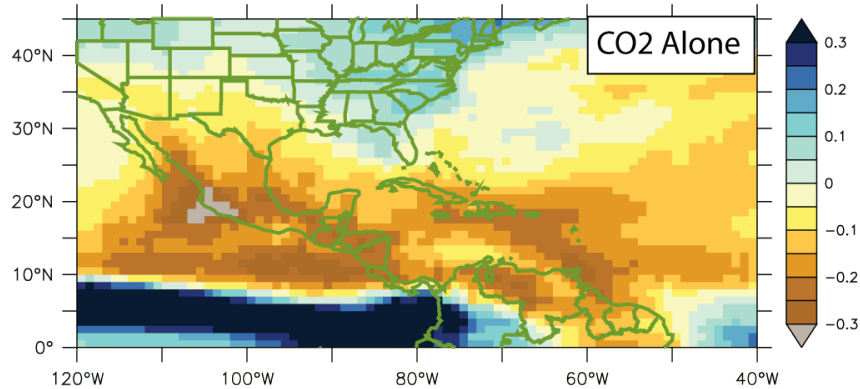
*Multi-model
shear change
per unit tropical
SST increase
(m/s/K)*



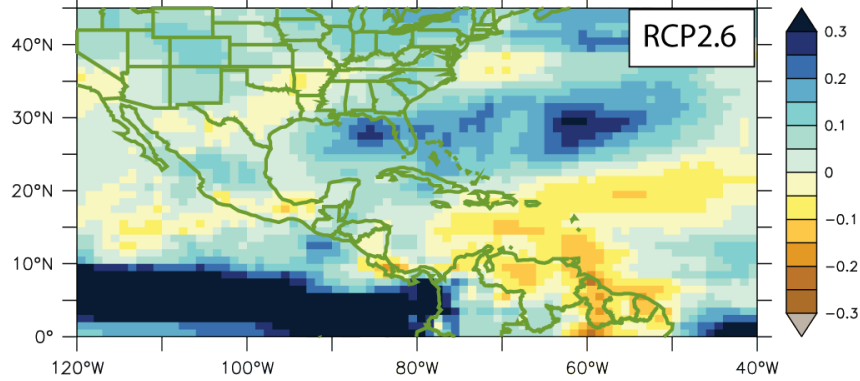
Vecchi and Soden (2012, in prep.)

Aerosol impact also evident in precip

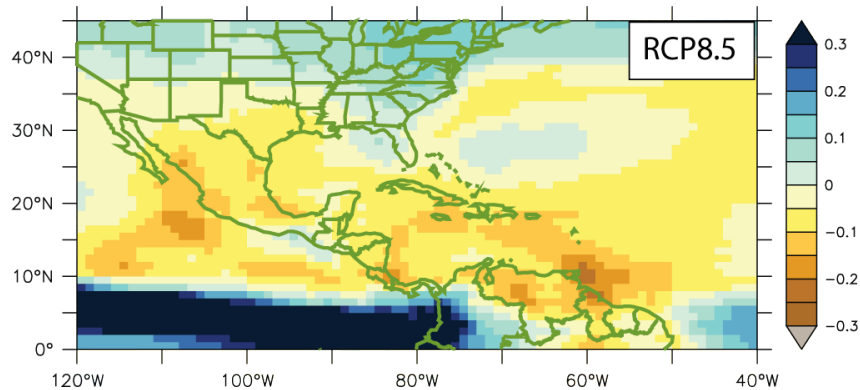
Annual Precipitation Change (mm/day/K tropical warming)



CO₂ alone



*Weak CO₂ increase
Big aerosol decrease*



*Large CO₂ increase
Modest aerosol decrease*

Conclusions

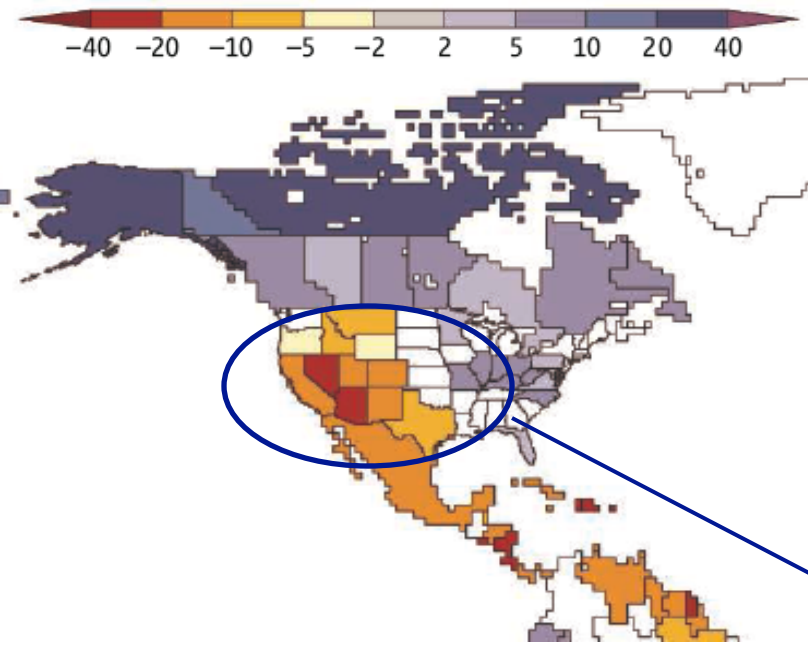
- The weakening of the tropical circulation is a robust projection of all climate models.
 - Connected to sub-Claussius-Clapeyron rate of:
 - Increase in radiative cooling
 - Increase in surface radiative imbalance
- The slower circulation includes a weakened Walker Cell.
 - El Niño bad analogue for 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.

Outline

- Theory
- Numerical Modeling
- Observations
- **Implications:**
 - Atlantic wind shears
 - **ENSO bad analogue for some teleconnections.**

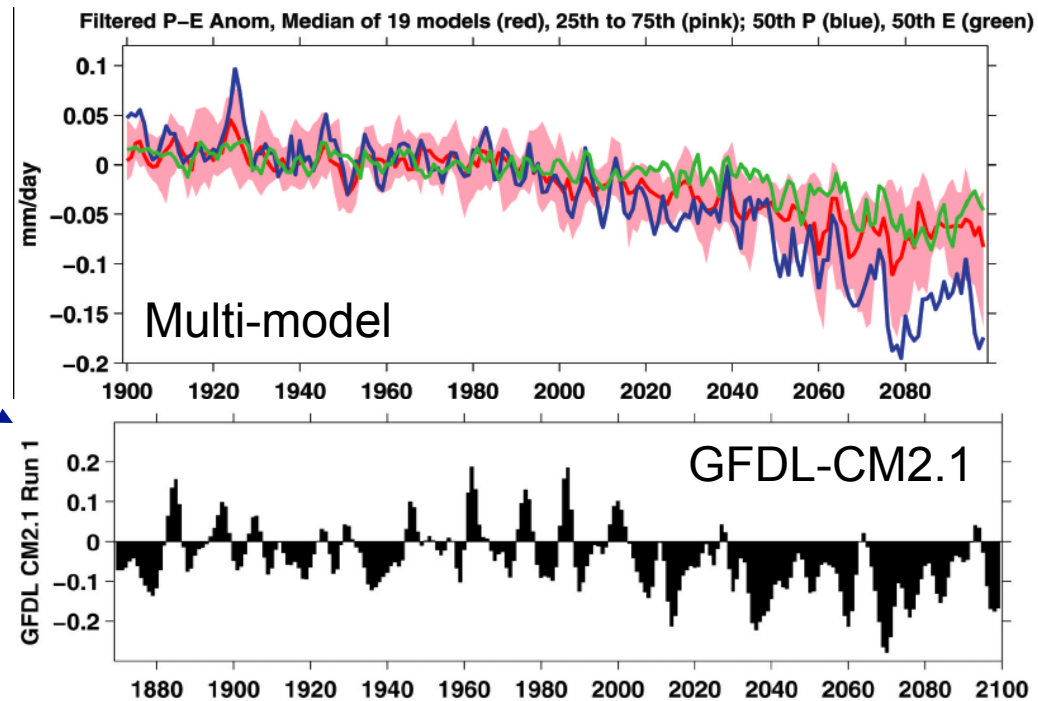
Southwest Drying Projections

21st Century Projected % Change in Runoff



Milly et al (2008, Science)

Change in SW US Precip. minus Evap.

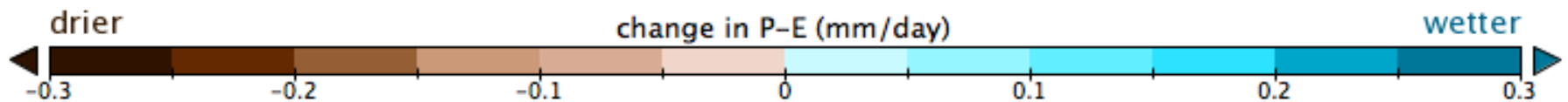
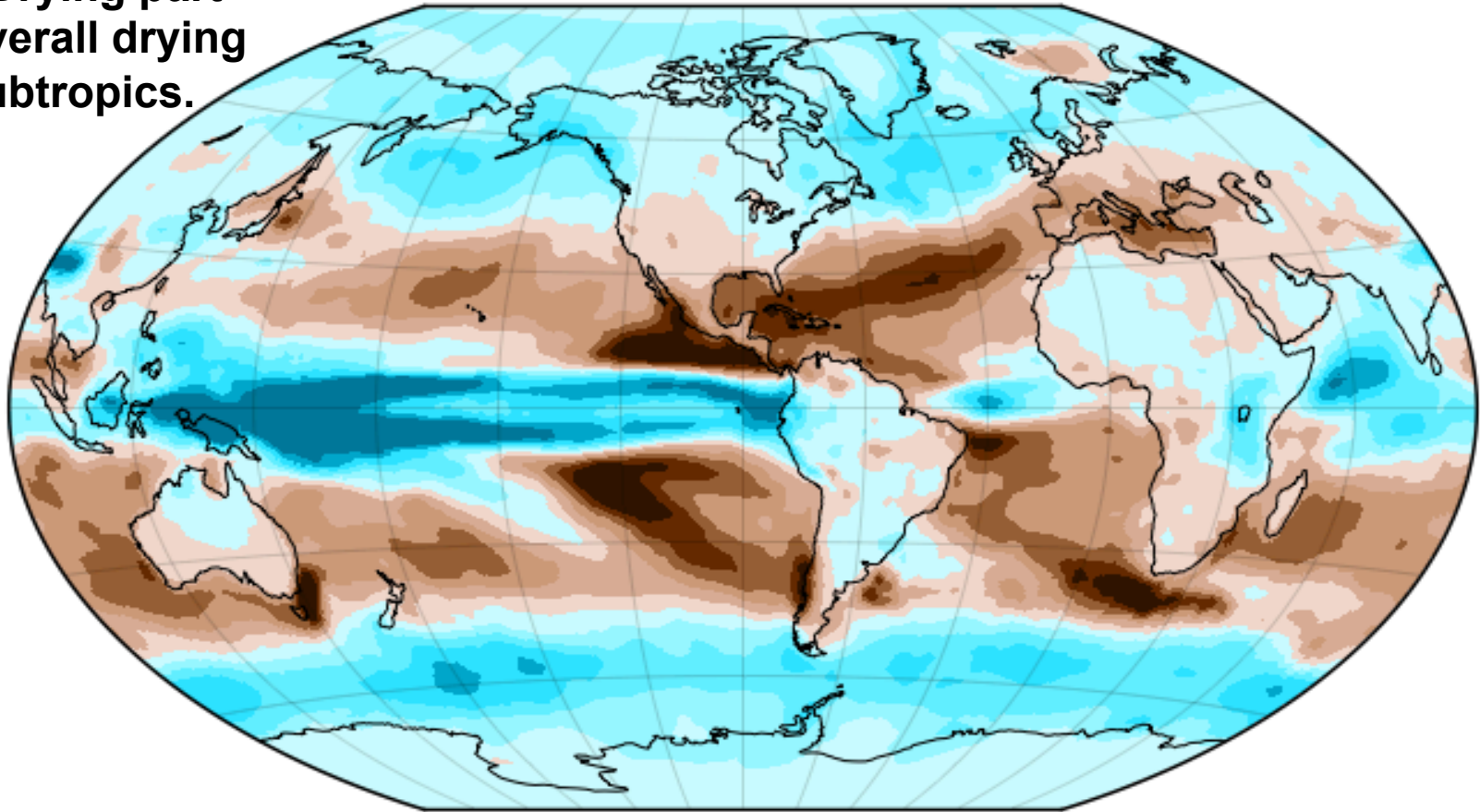


*Seager et al (2007, Science); Seager and Vecchi (2010, PNAS)
Seager, Naik and Vecchi (2010, J. Climate)*

SW Drying part of global pattern

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

SW Drying part
of overall drying
of subtropics.



Winkel Tripel projection centered on -90.0°E

Figure by N. Naik., LDEO/Columbia

Mechanisms for CO₂-Forced Drying

Thermodynamic Control:

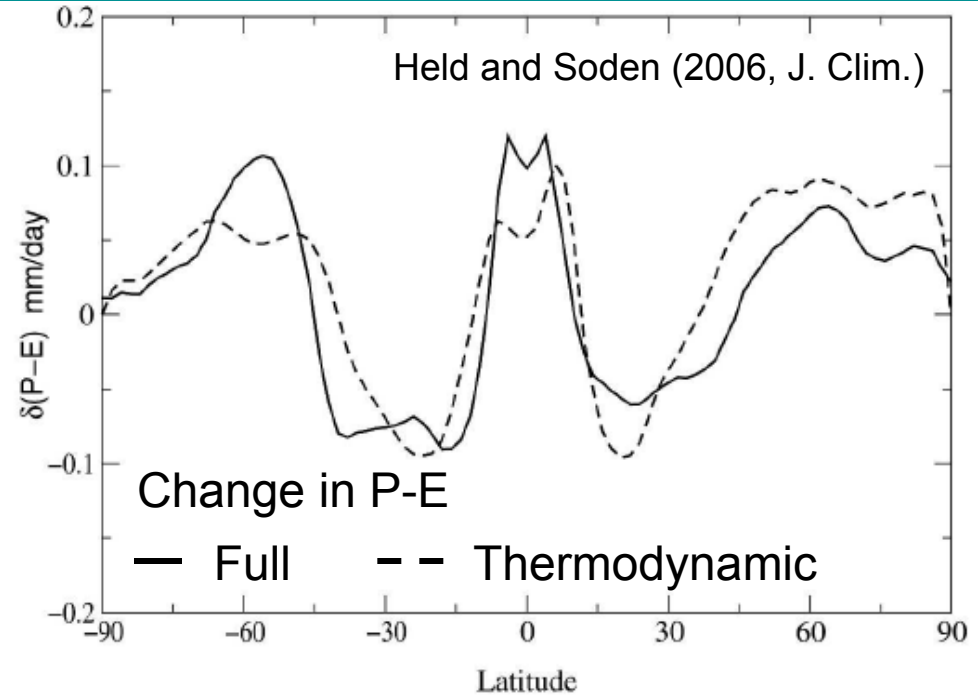
Warming (increase q_{sat})



increase atmospheric moisture.

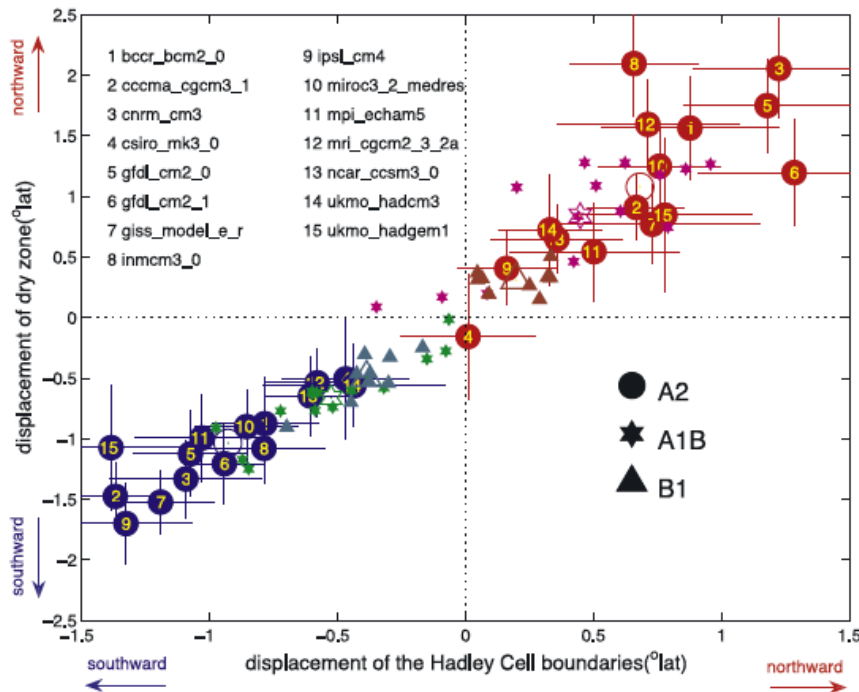


increase moisture flux divergence/
convergence.



Circulation Changes:

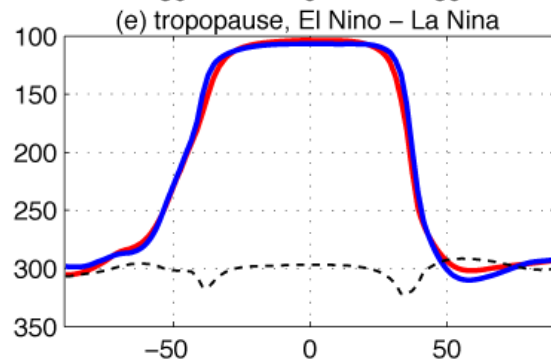
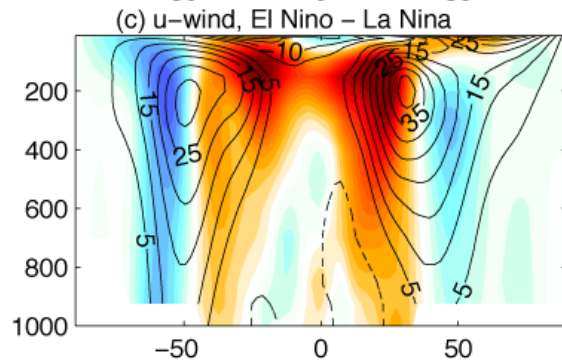
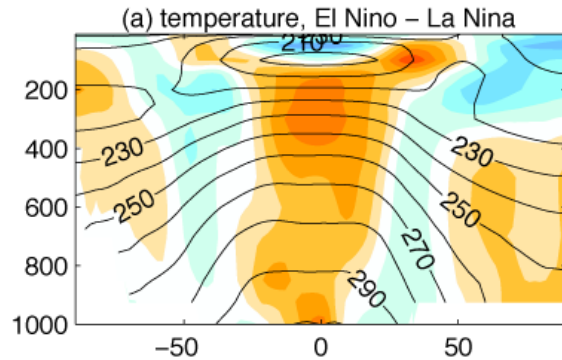
Poleward shift of descending branch of Hadley Circulation is associated with a poleward shift of dry zones.



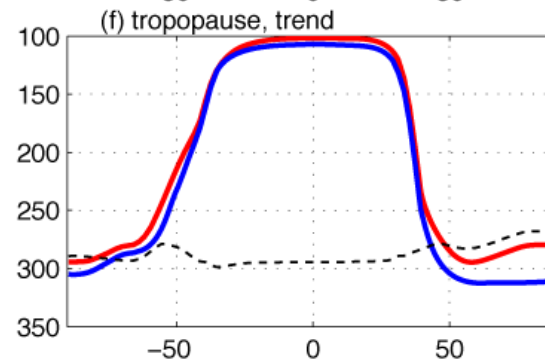
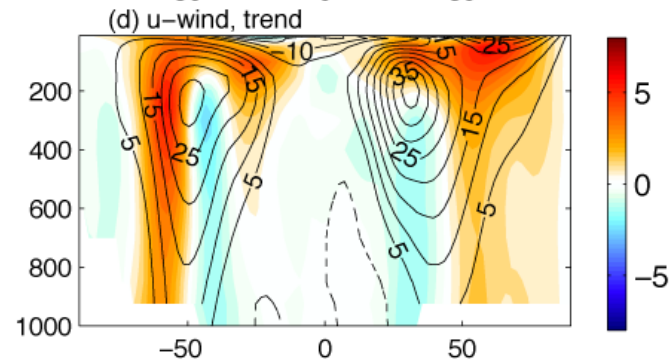
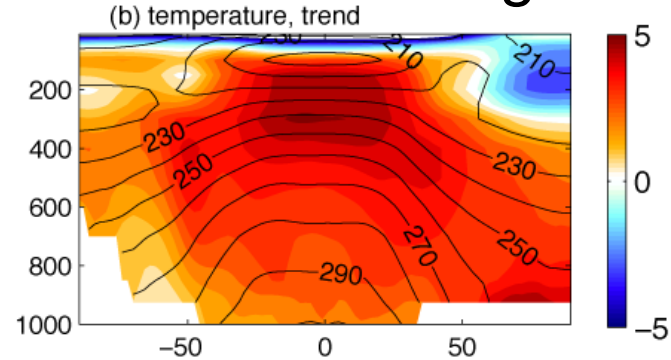
Lu, Vecchi and Reichler (2007, GRL)

Zonal-mean response not “El Niño-like”

ENSO



Global warming



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

Conclusions

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