From IPCC-AR4

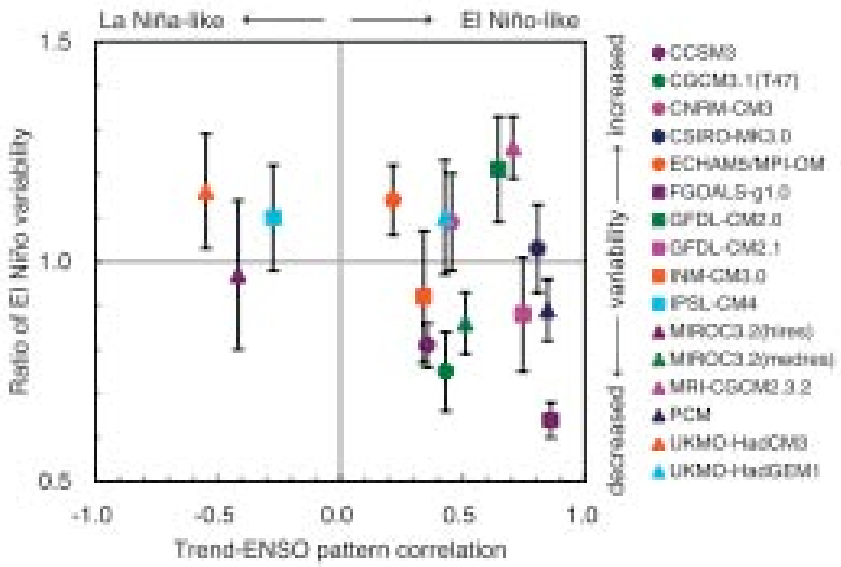


Figure 10.15. *Base state change in average tropical Pacific SSTs and change in El Niño variability simulated by AOGCMs (see Table 8.1 for model details). The base*

"*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

Tropical response to global warming: Mechanisms and analogues.

A. Clement , P. DiNezio, I. Held, J. Lu,
B. J. Soden, G. A. Vecchi, A.T. Wittenberg

- What is character of tropical response to CO_2?
  - "Wet get wetter, dry get drier"
  - Poleward shift of dry zones
  - "La Niña-like" response - oceanic constraint
    (*Clement et al 1996, Cane et al 1997,…)*
  - "Weaker Walker" response - atmospheric constraint
    (*Betts 1989, Knutson and Manabe 1995, Held and Soden 2006, Meehl et al 2007,..*)
- "El Niño-like" Global Warming: really?

  In what senses is this correct?

  In what senses is it incorrect?

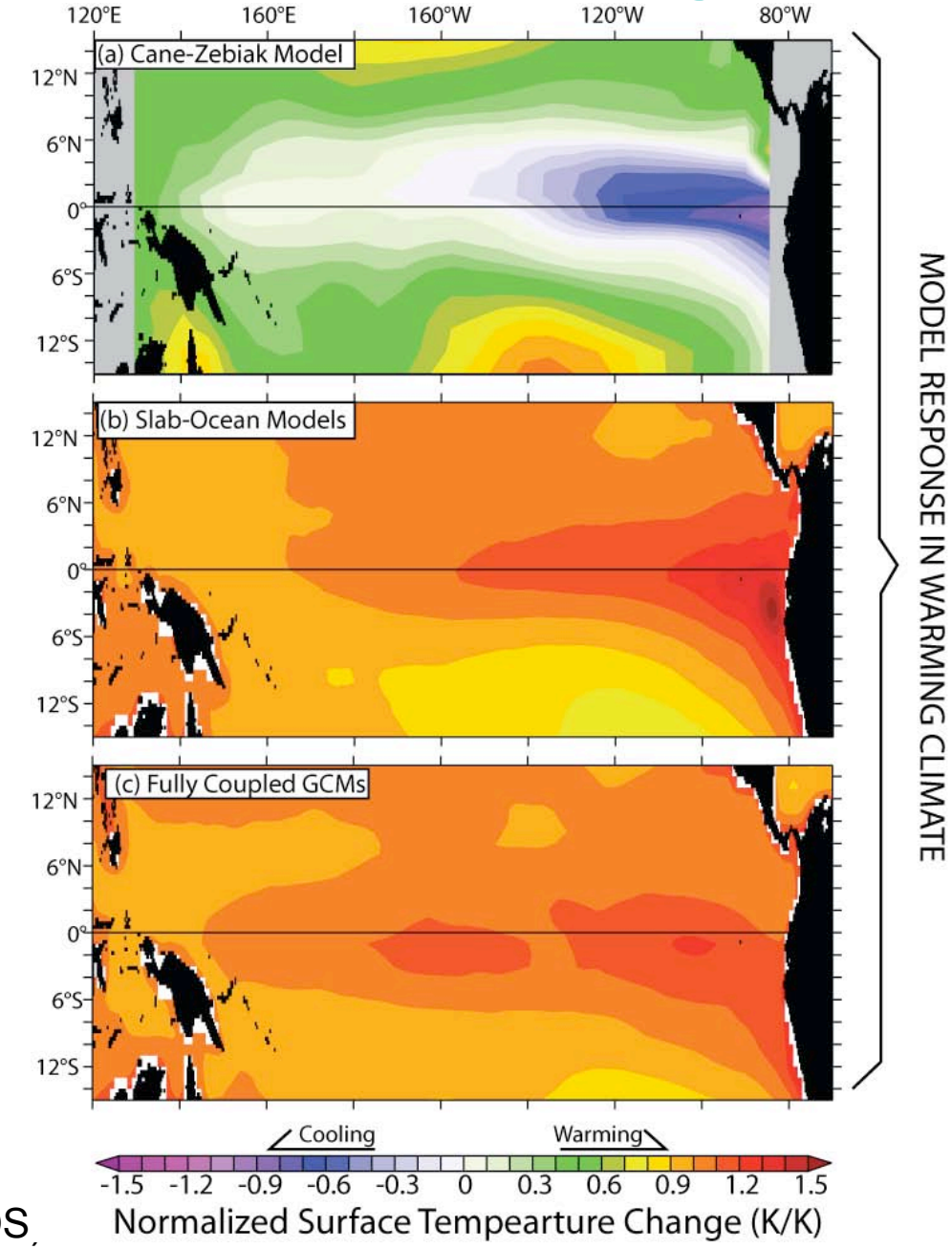
  Weaker tropical circulation.

Modeled SST Response to Heating

Simplified atmosphere
(forced by uniform heating)

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

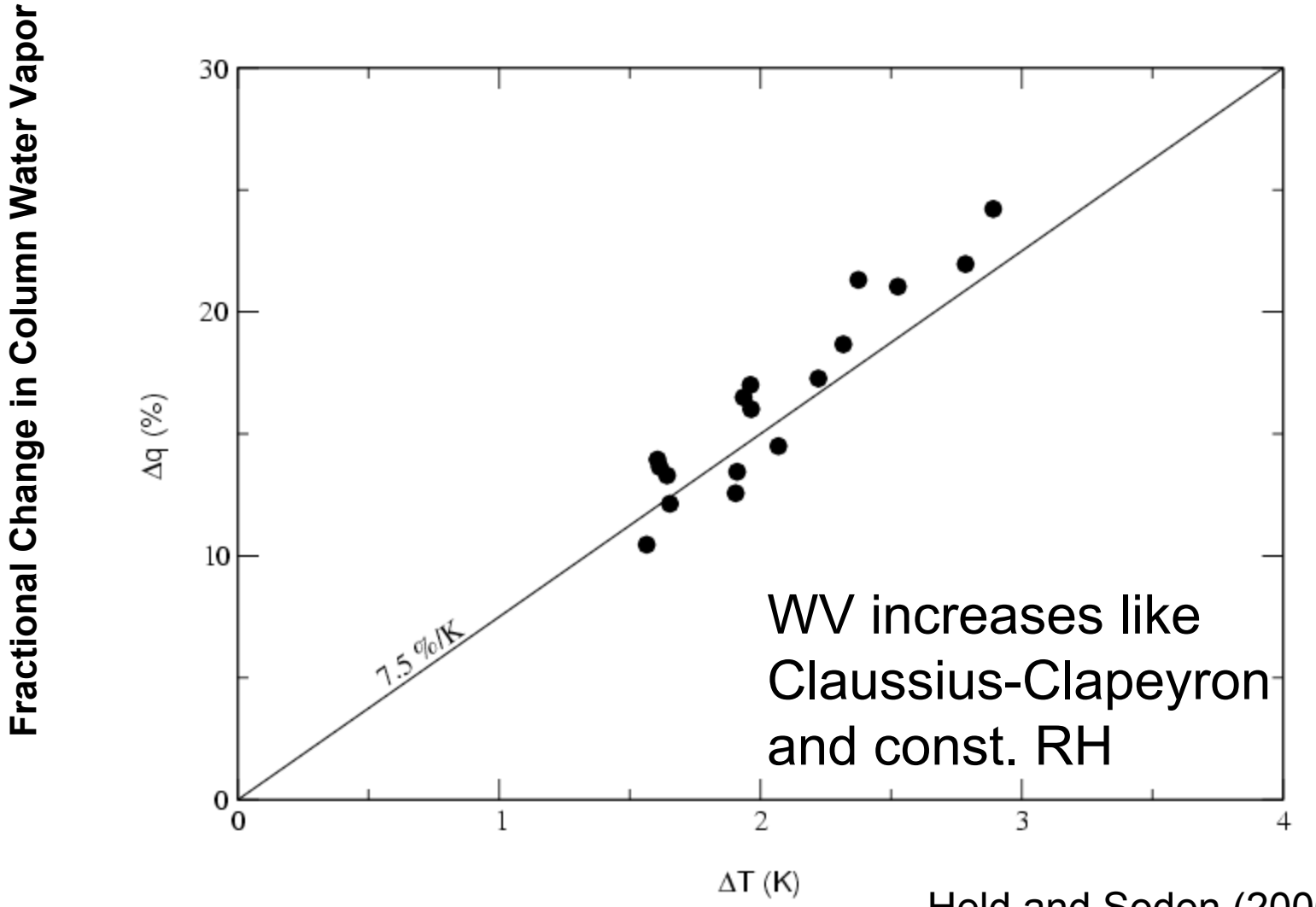
Full-dynamics GCMs
(13 models, doubled-CO_2)



From Vecchi, Clement and Soden (2008, EOS)

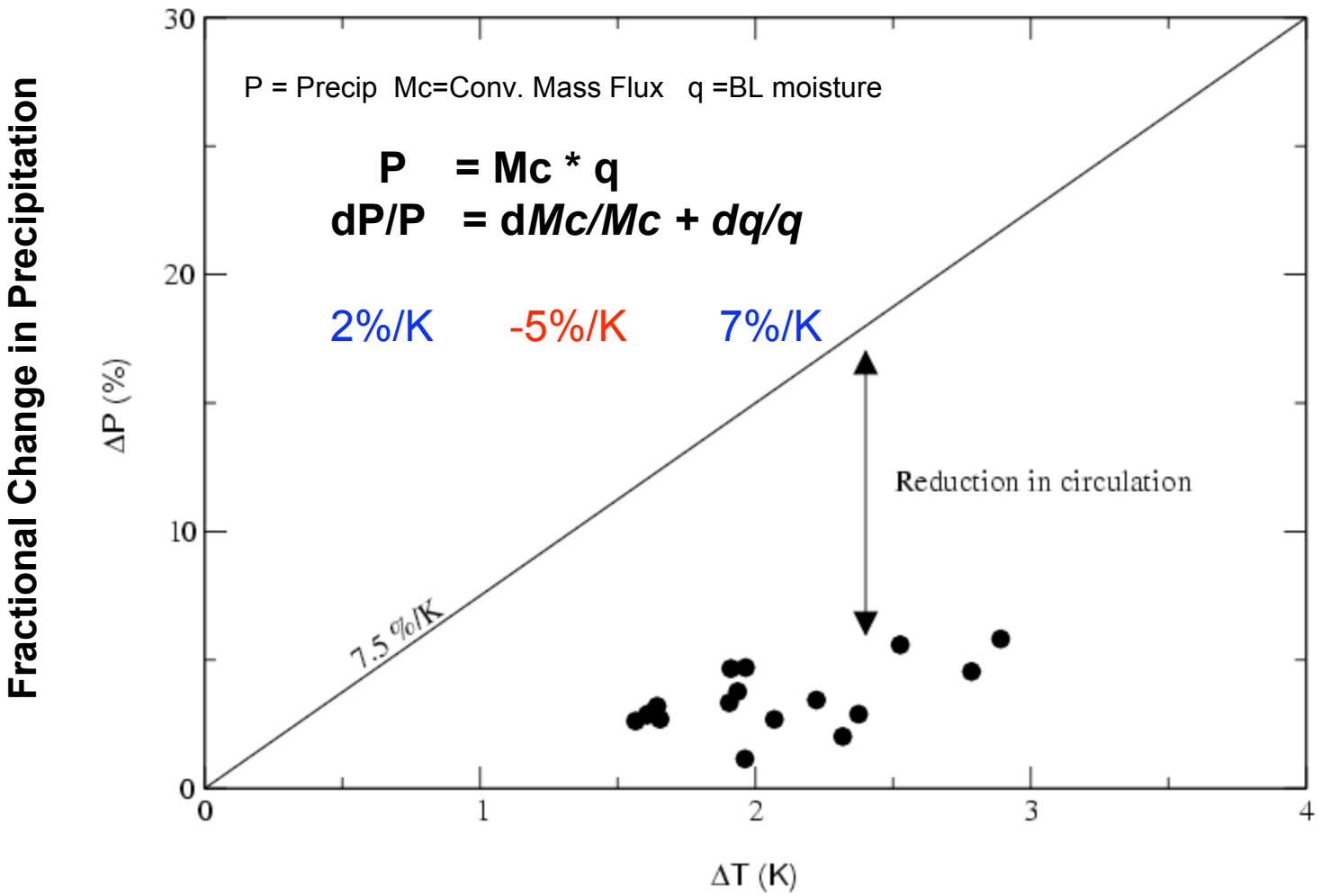
Atmospheric Constraint on Pacific

Change in Global Water Vapor at 2100



Held and Soden (2006, J. Clim)

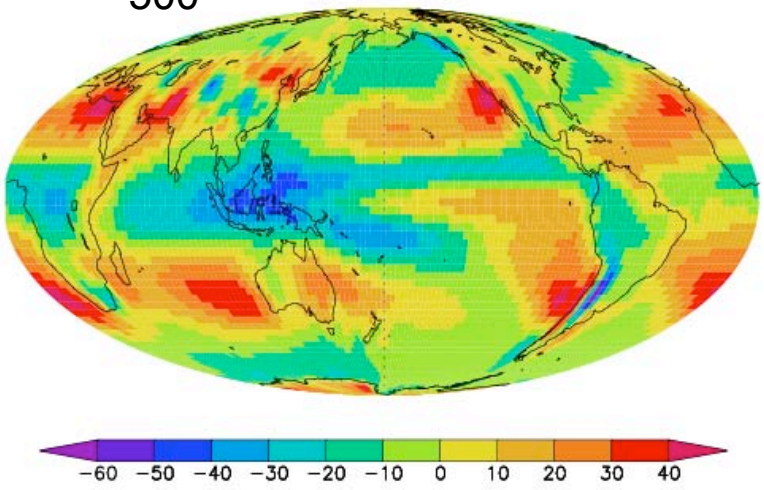
Change in Global Precipitation at 2100



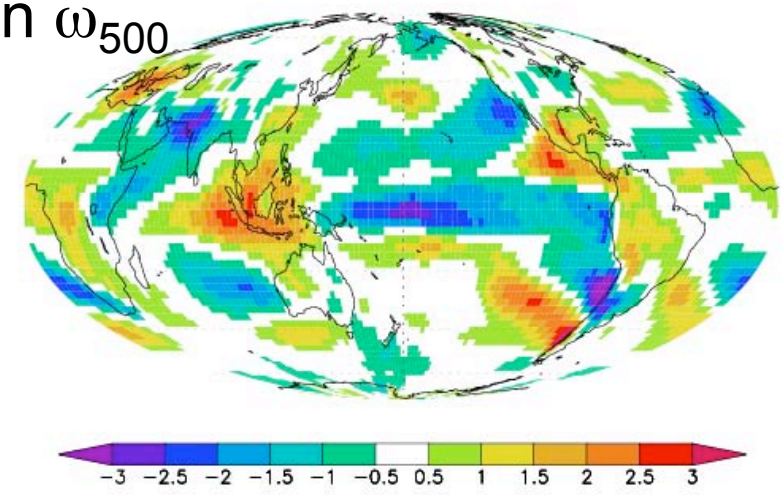
Held and Soden 2006, J. Clim.,
similar arguments: Betts and Ridgway 1989, Knutson and Manabe 1995

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

Background ω_{500}



Change in ω_{500}



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

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

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

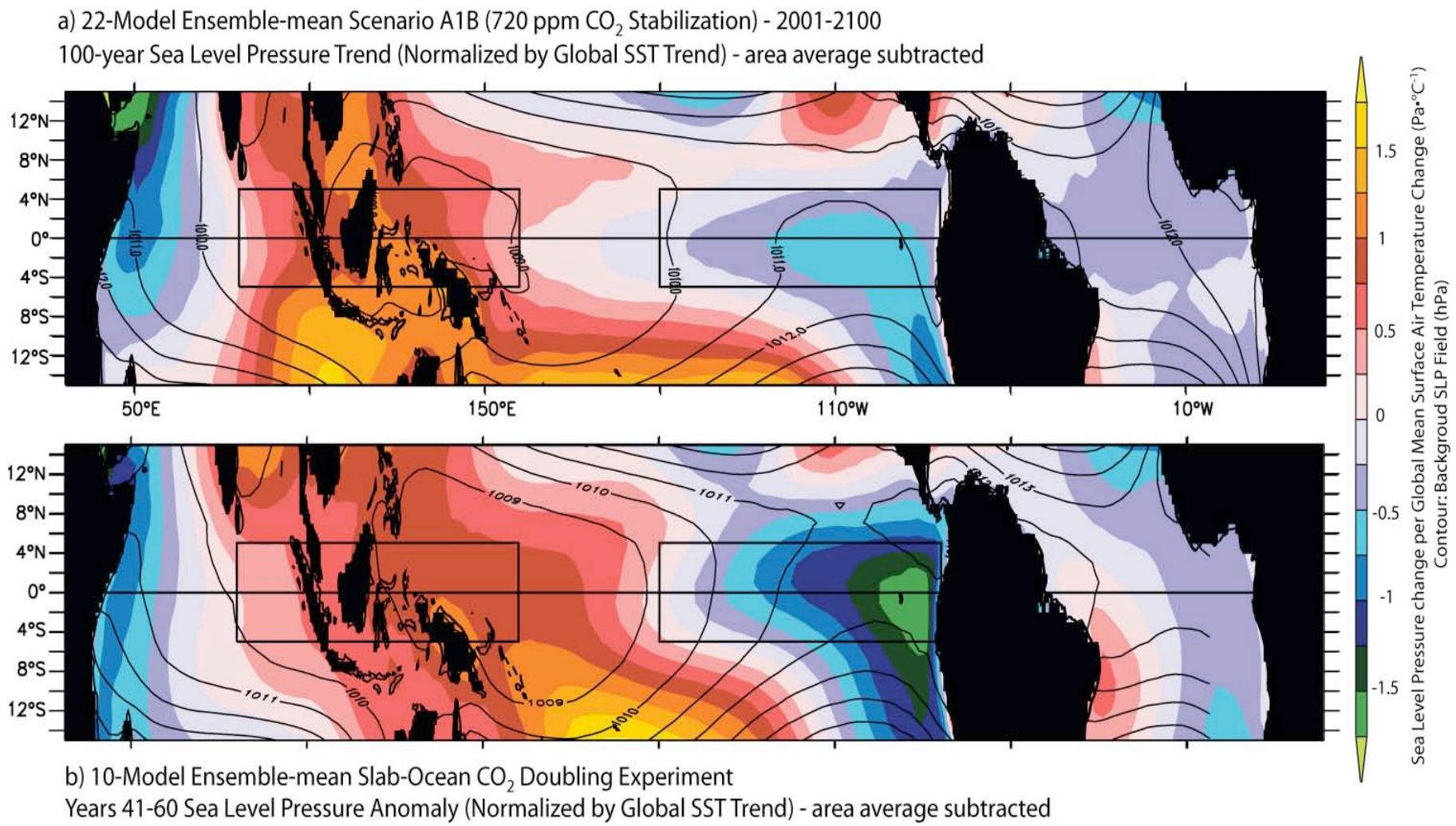
Not "El Niño-like":
- **Ocean changes oppose it**
- **Pacific thermocline shoals**
- **Teleconnections not "El Niño-like" (Lu et al. 2007, 2008; Seager et al. 2007…)**

Vecchi and Soden 2007, J. Clim.

Near-equatorial Indo-Pacific Zonal SLP gradients decrease

Full ocean GCMs

Slab ocean GCMs



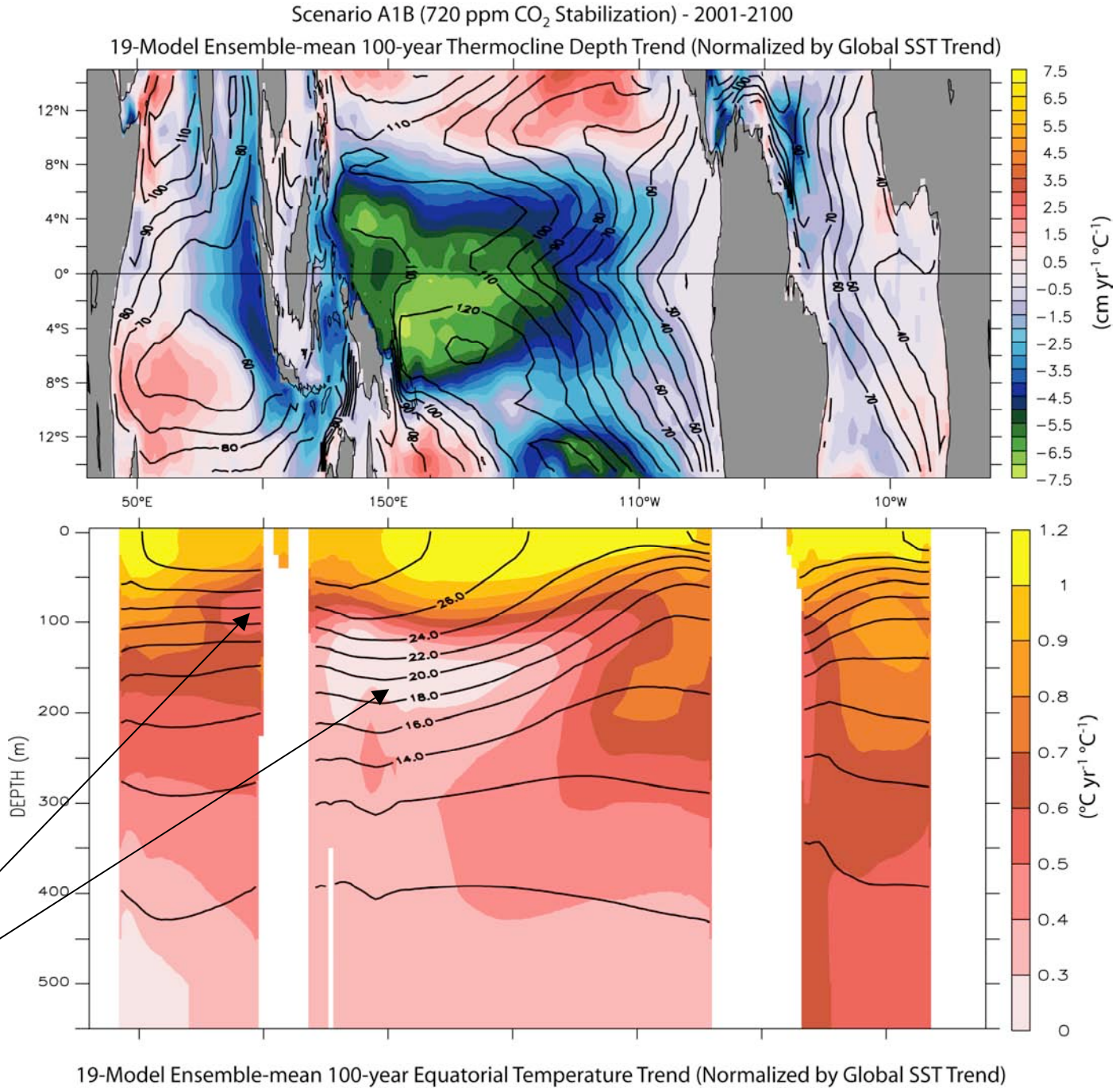
Slab ocean GCM response stronger over Pacific = **Not El Niño**

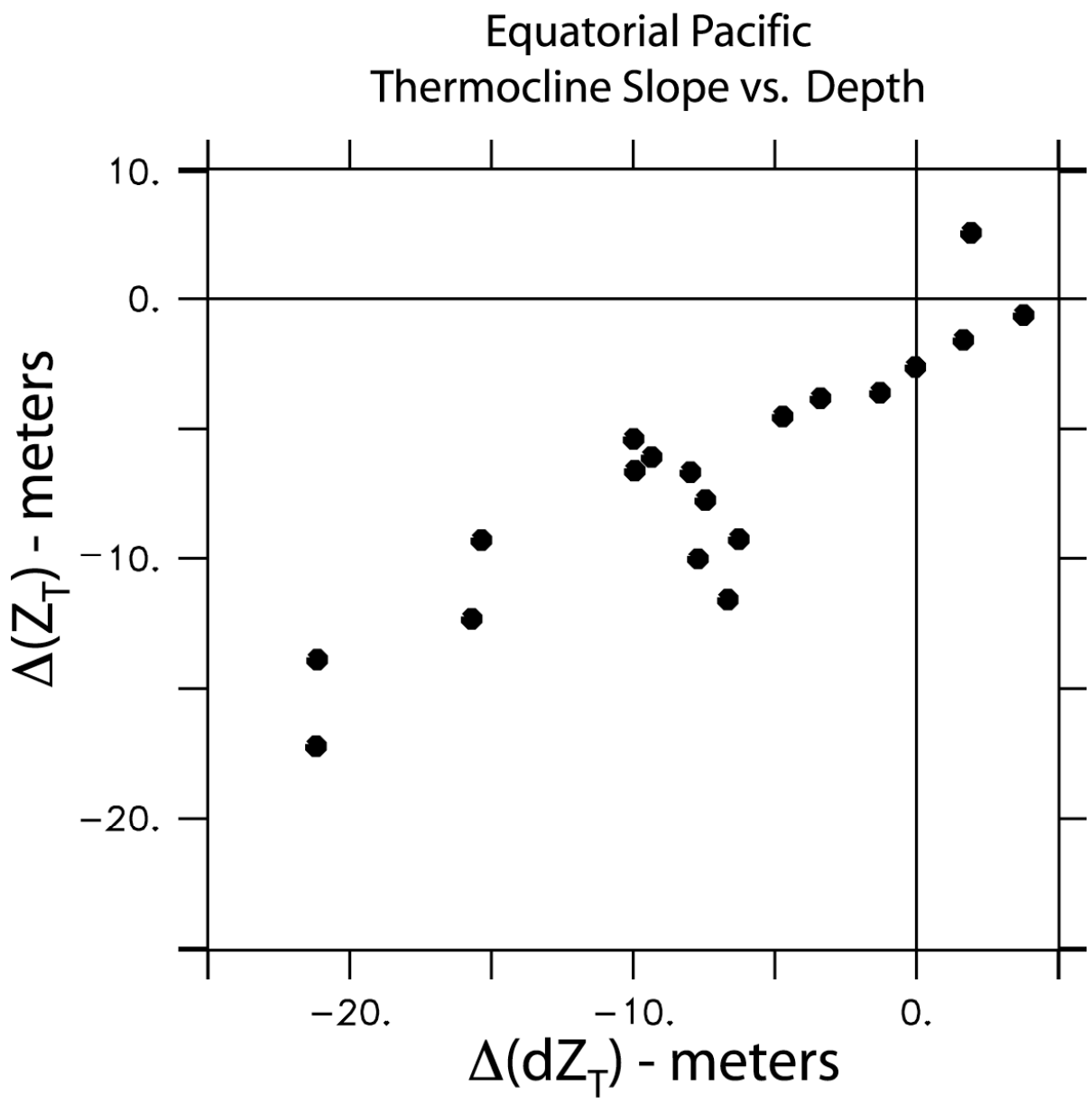
Vecchi and Soden 2007

Equatorial Pacific thermocline flattens and shoals.

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)

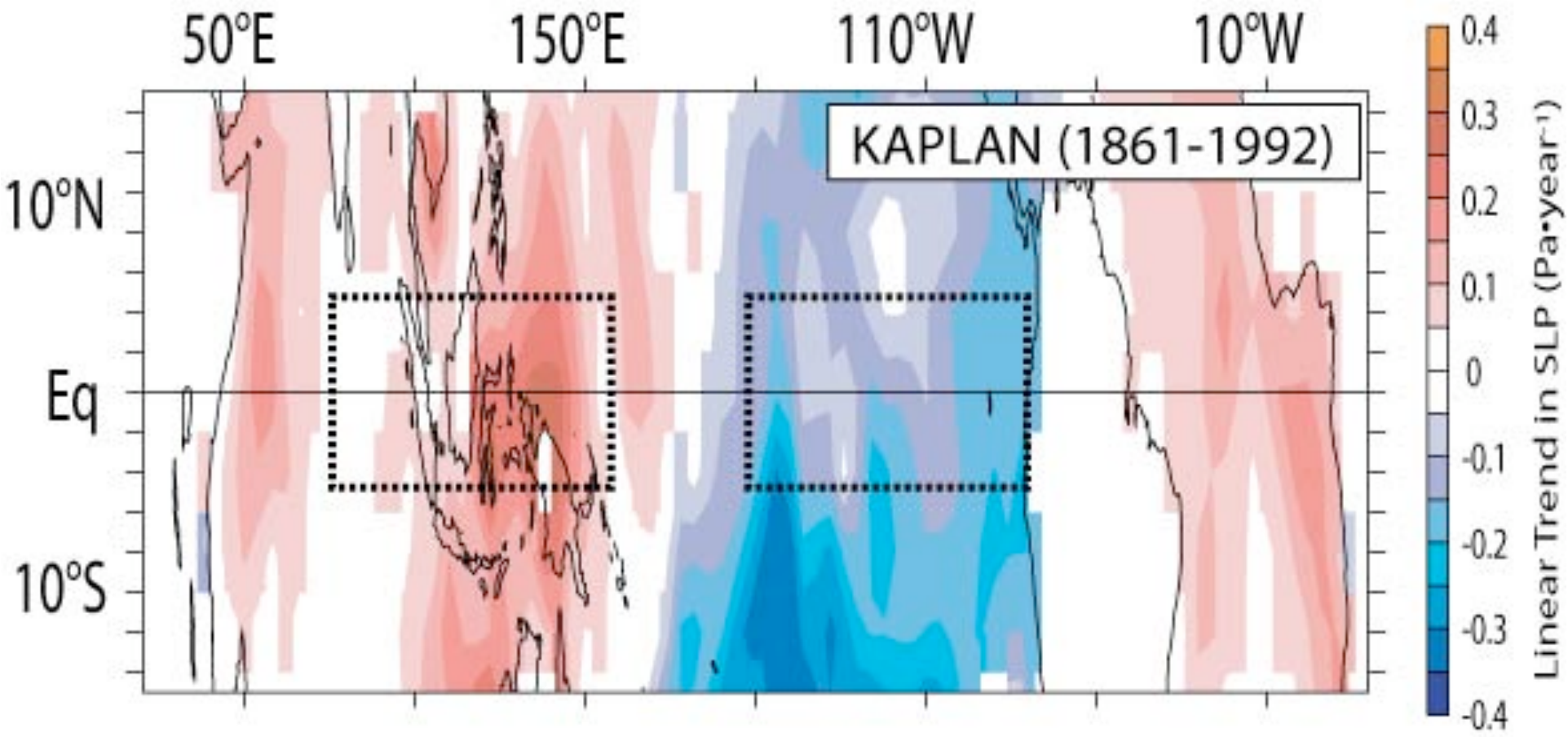
Vecchi and Soden (2007, J. Clim.)

What is observational evidence?

- Sea level pressure: Walker circulation has weakened.

- Sea surface temperature: Depends on dataset you use.

Linear trend in Kaplan SLP reconstruction



Reduction of E-W SLP gradient across Pacific.

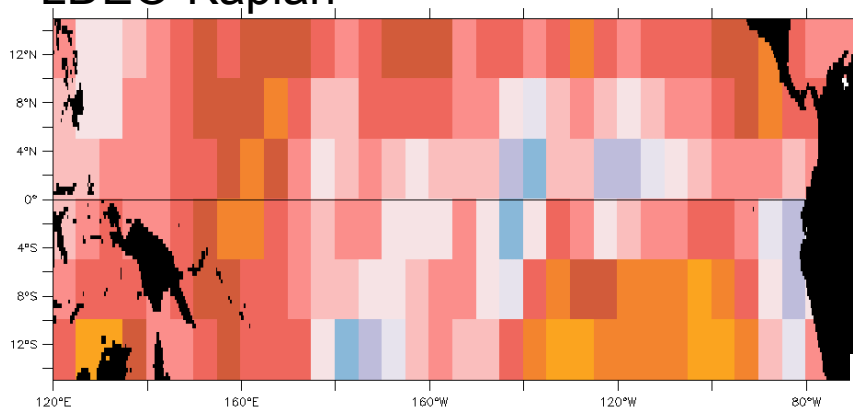
Consistent with weakening of Walker circulation.

Vecchi et al (2006, Nature)

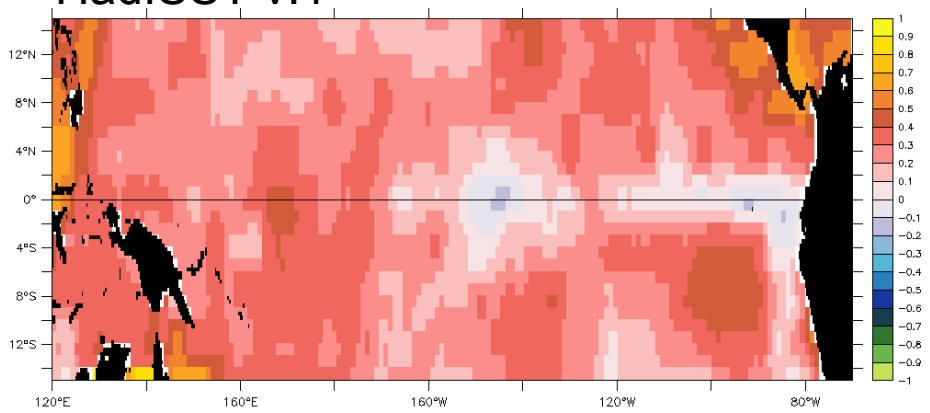
Look at SST?

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

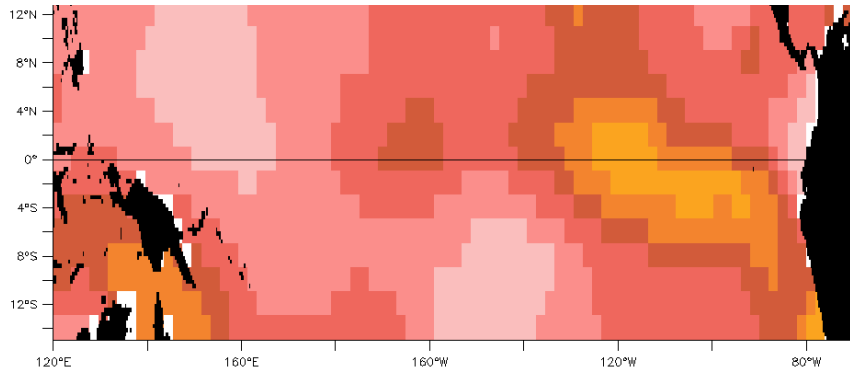
LDEO-Kaplan



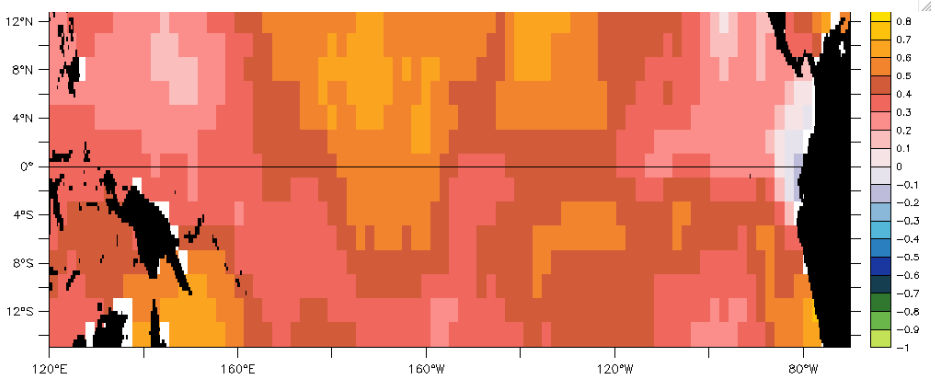
HadISST v.1



NOAA-ERSST v.2



NOAA-ERSST v.3

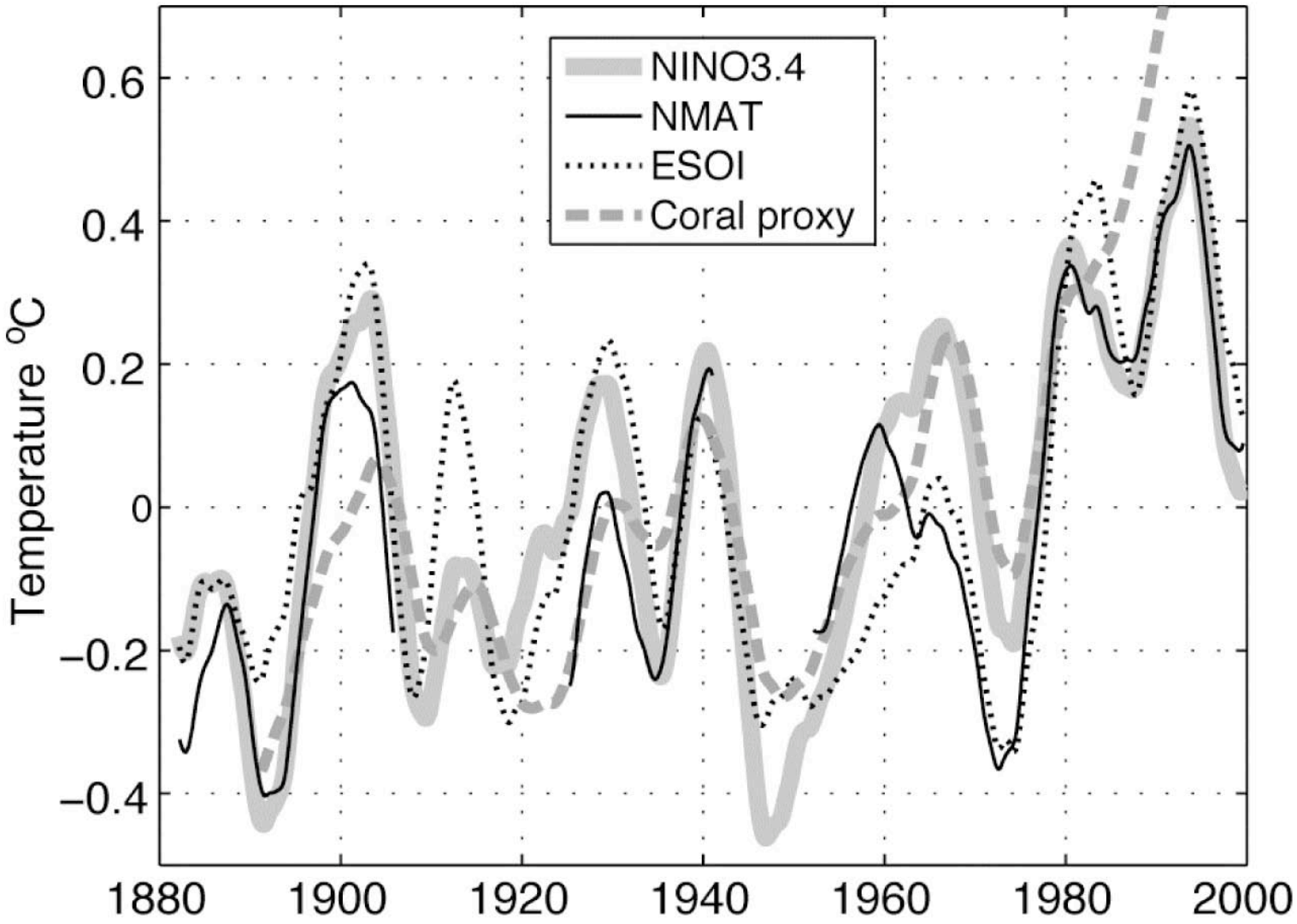


Overall warming seen in all.

Structure dependent on reconsruction.

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

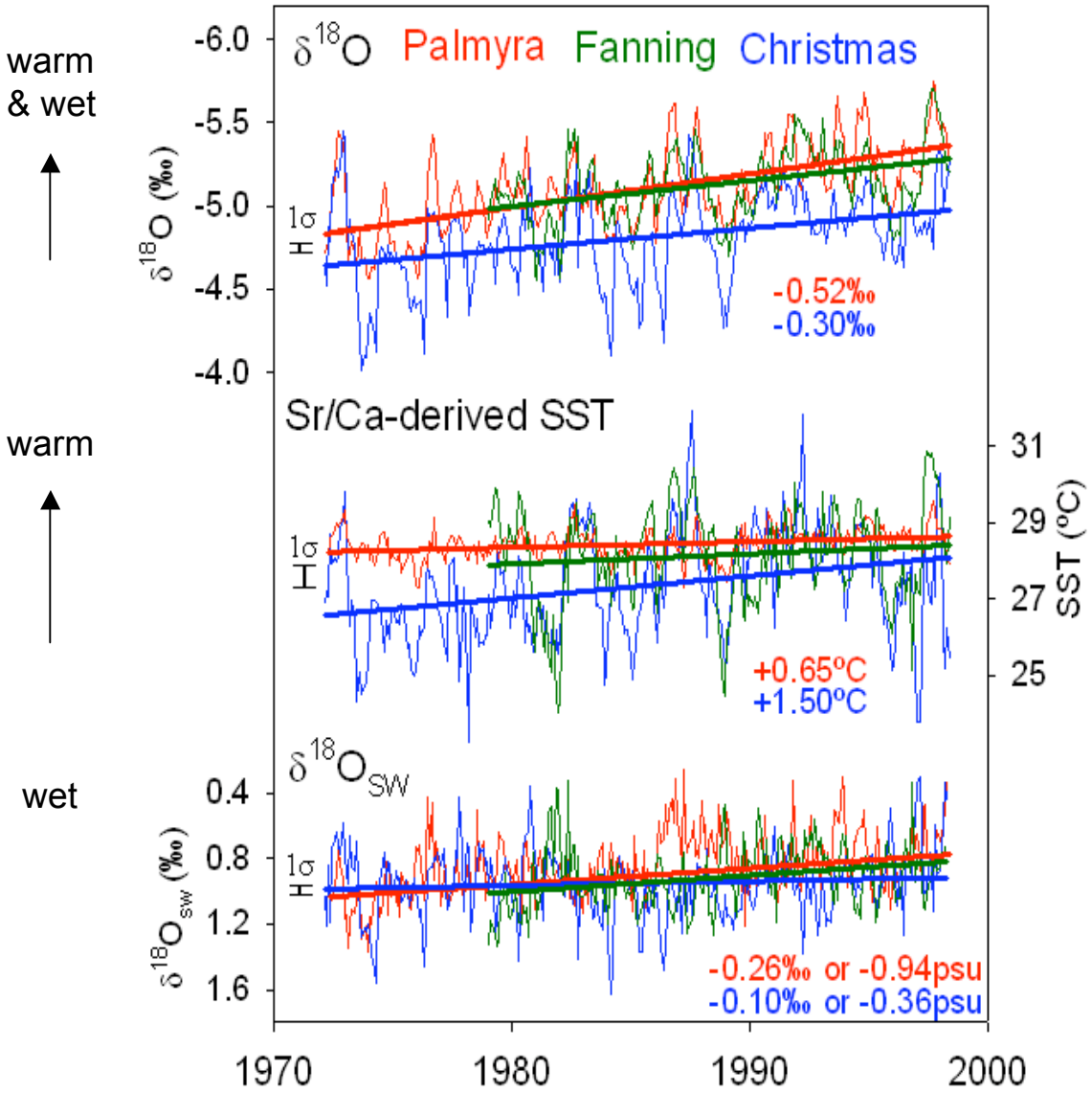
New “Pacific-centric” analysis



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

Coral Proxy data (Nurhati et al 2008, in prep.)

Central Eq. Pacific Warming and Freshening



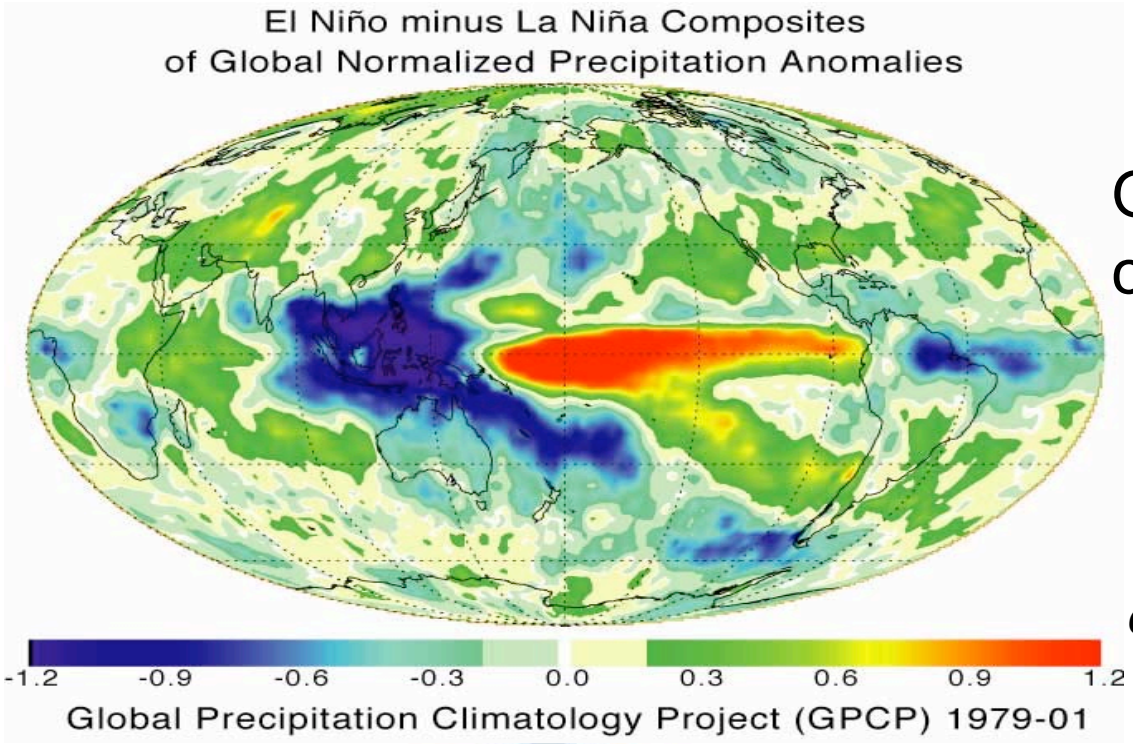
Observations:

- ✓ Warming trend stronger at the equator
- ✓ Freshening trend stronger at Palmyra

Simultaneous warming and freshening in the CTP is consistent with weakened zonal SST gradient in the late 20th century

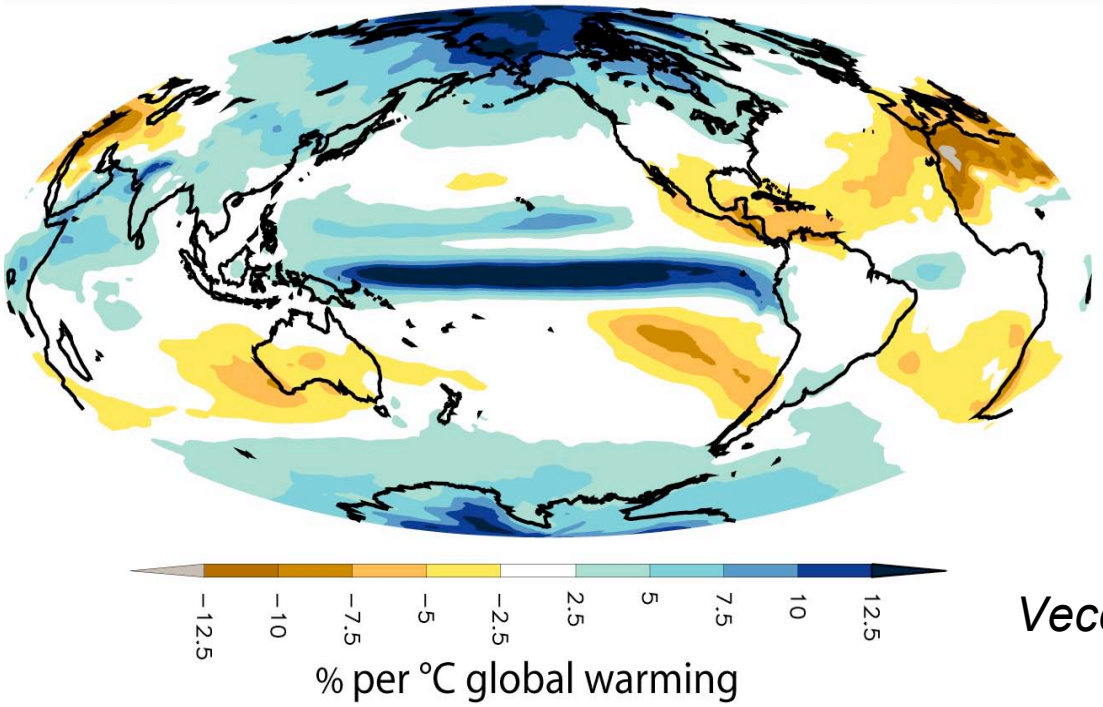
Impacts

To what extent is El Niño a good analogue for drivers of societal impacts (e.g., precipitation, tropical cyclones, etc.)?



Observed El Niño rainfall composite

oceanworld.tamu.edu



Model rainfall response to CO_2 increase.

22-model average

Vecchi and Soden (2007, J. Clim.)

“Wet get wetter, dry get drier”

Held and Soden (2006, J. Clim.)

Drying of subtropics.

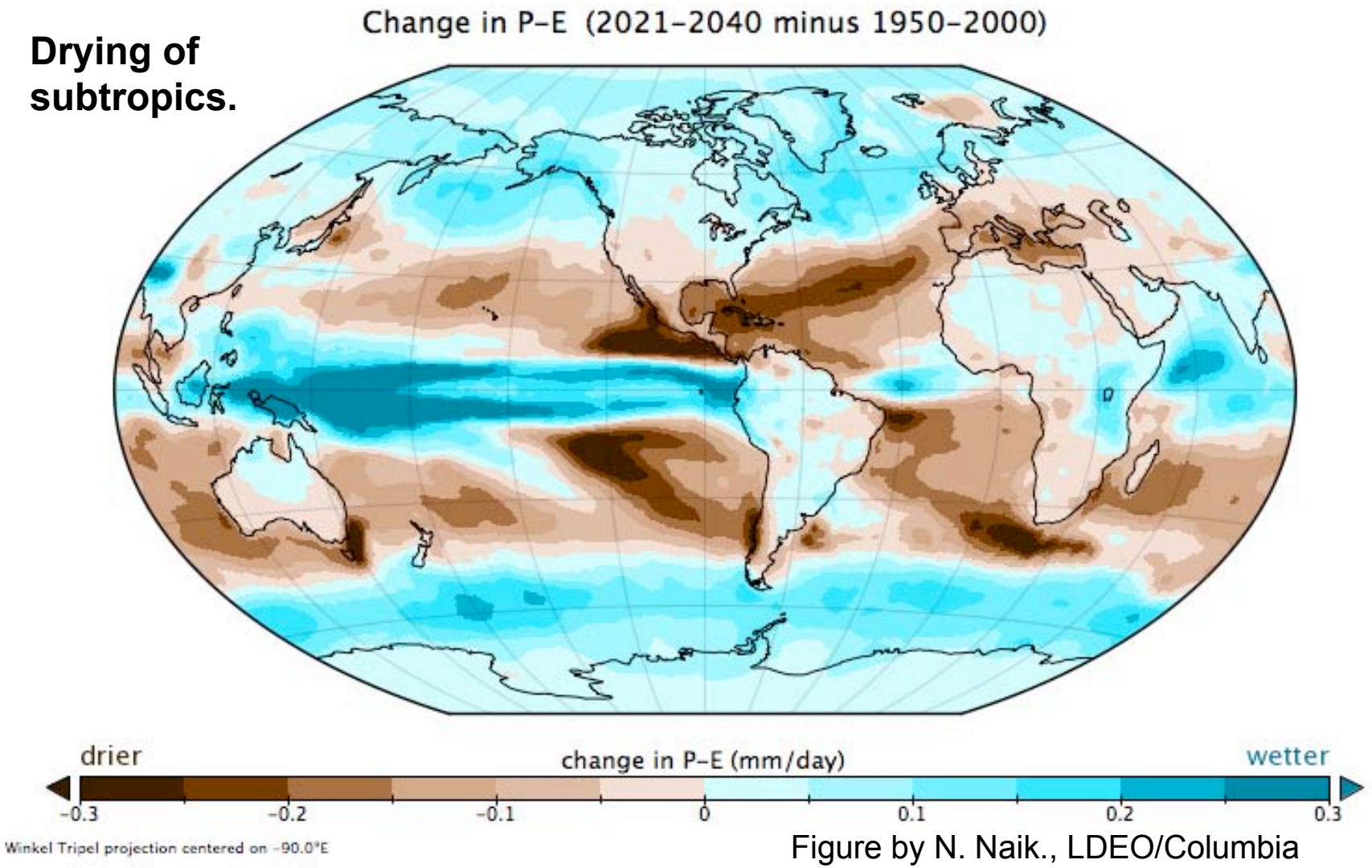


Figure by N. Naik., LDEO/Columbia

$$d(P\text{-}E) = d(\nabla\cdot\underline{\mathbf{u}}q) \approx dq\nabla\cdot\underline{\mathbf{u}} \approx dq_s/q_s\ (P\text{-}E)$$

Mechanisms for CO_2-Forced Drying

Thermodynamic Control:

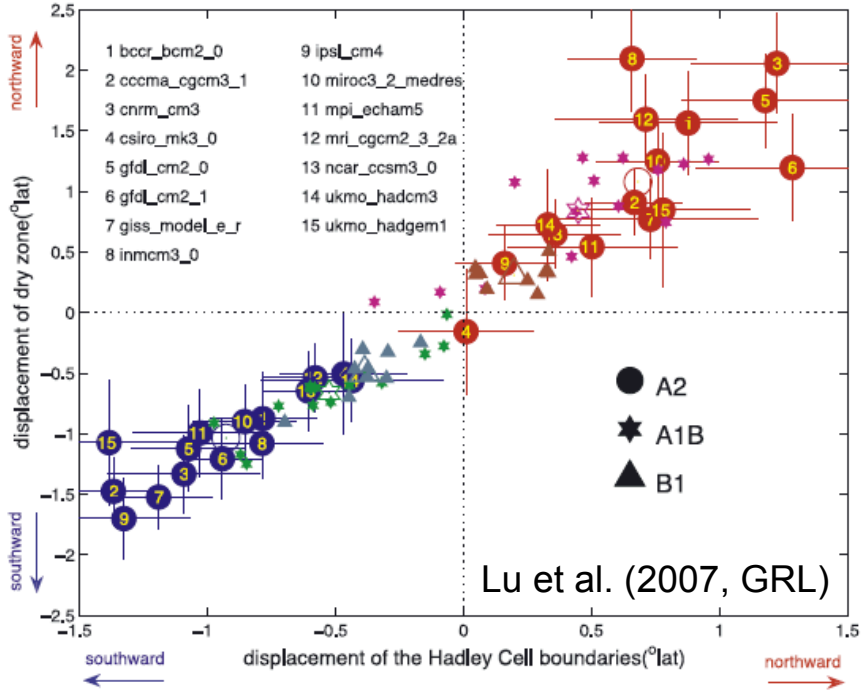
Warming (increase q_{sat})

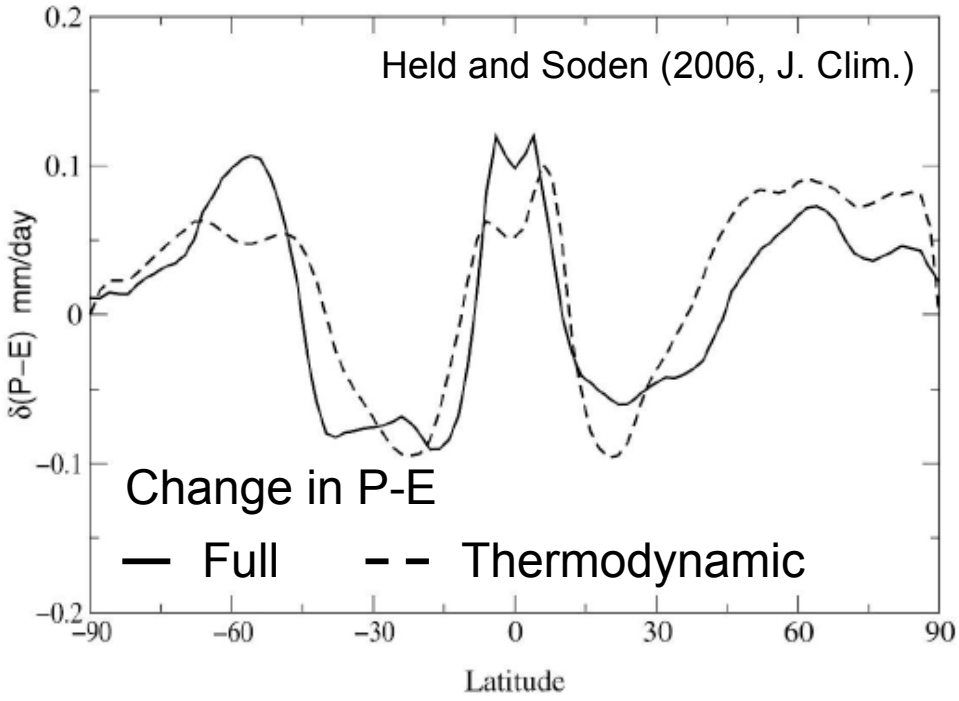
↓

increase atmospheric moisture.

↓

increase moisture flux divergence/ convergence.





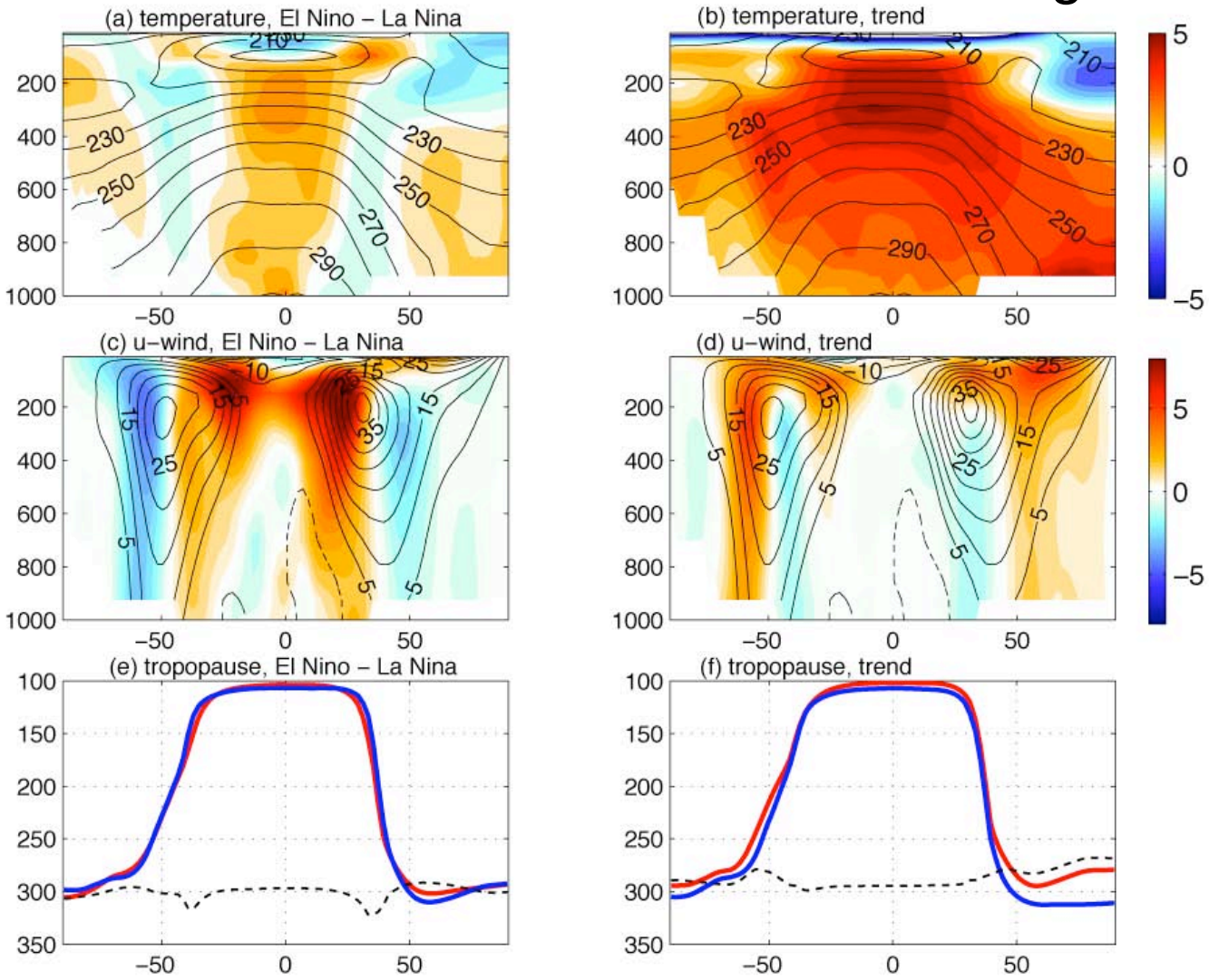
Circulation Changes:

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

Zonal-mean response not “El Niño-like”

ENSO

Global warming



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

Conclusions

- **"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**

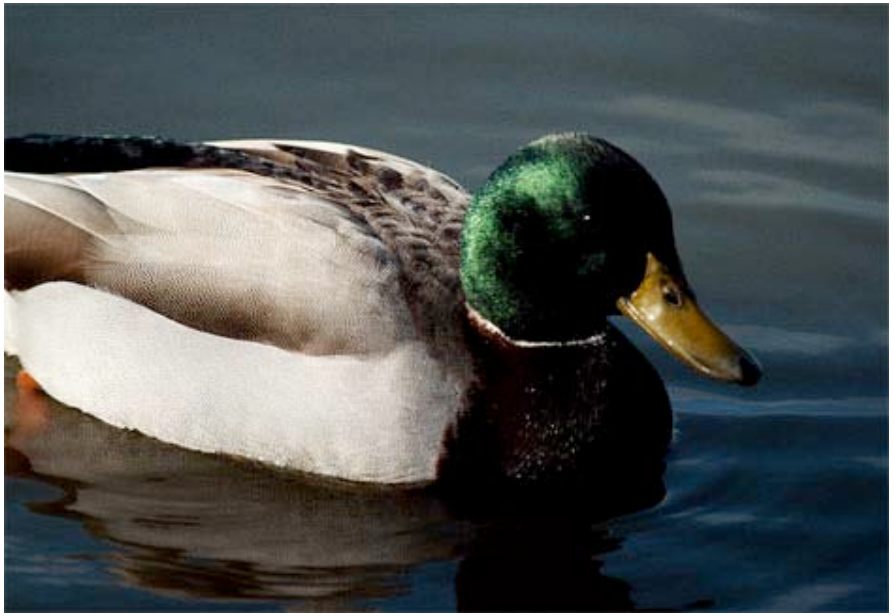
- **Observations**:
  - SLP indicates Weaker Walker Circulation
  - SST? Source of discrepancies needs to be understood

Gabriel.A.Vecchi@noaa.gov

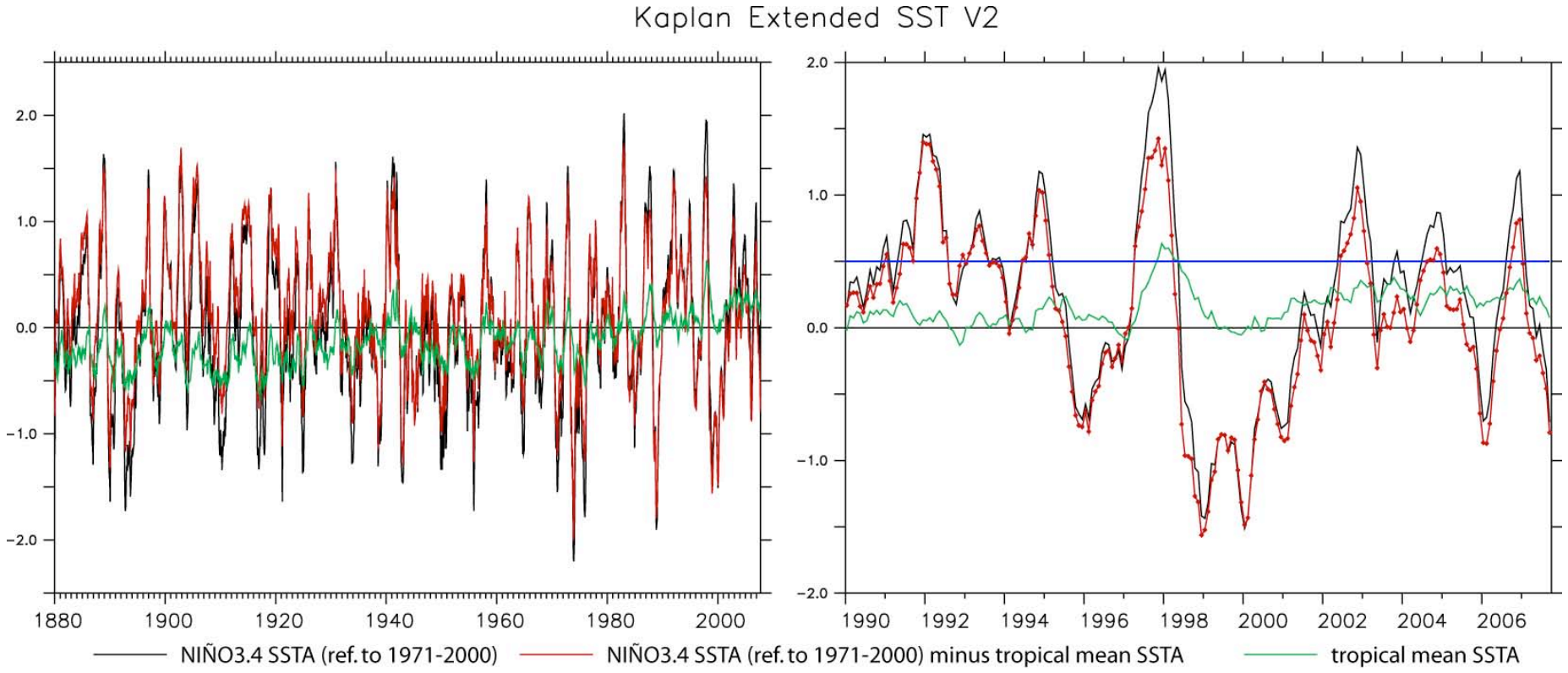
?

≈

or



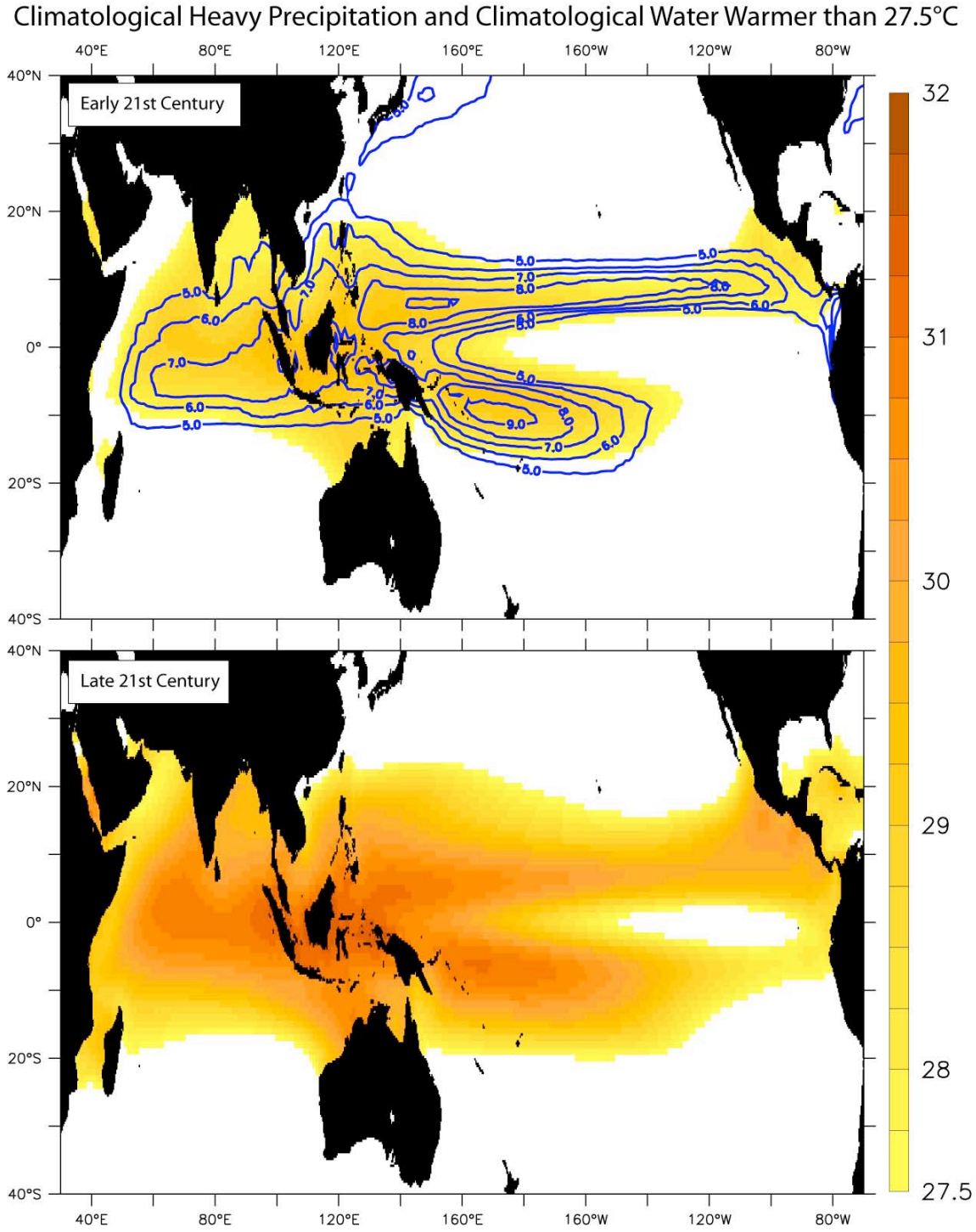
Indices in a Changing Climate: ENSO



- 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”?



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?

References

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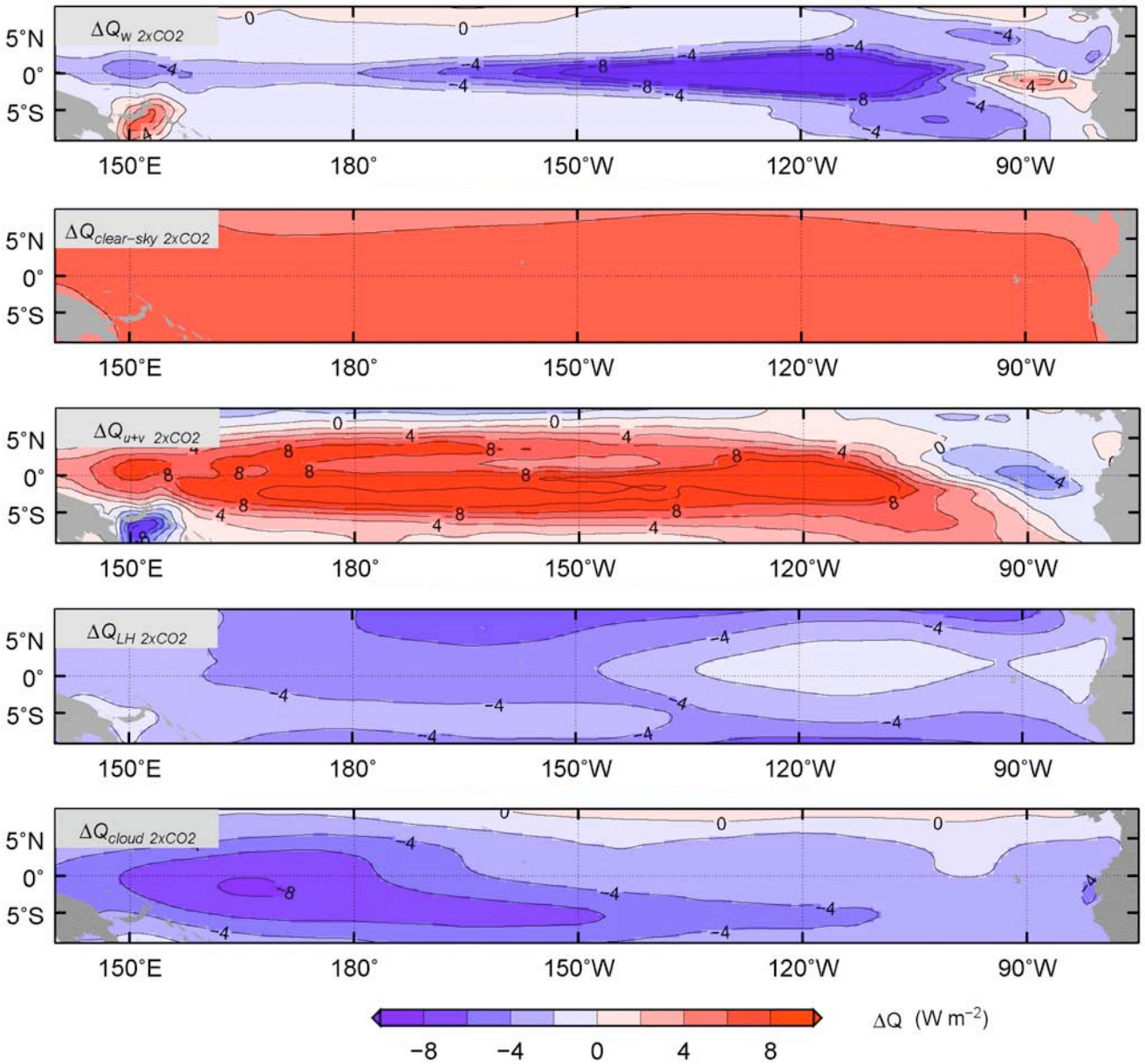
Mixed-layer heat balance in response to GW



Ocean vert.

Clear-sky

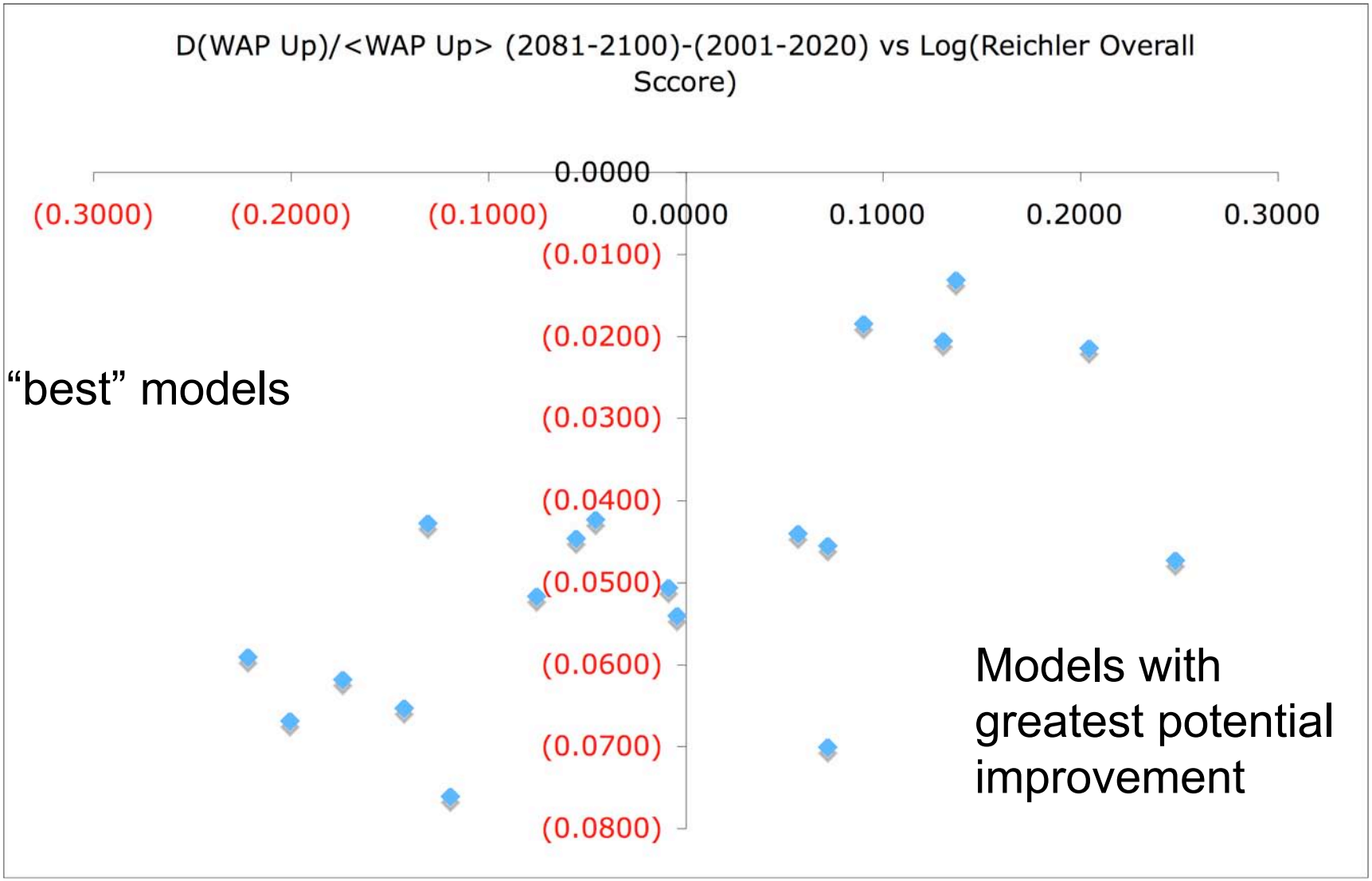
Ocean horiz.

Latent

Clouds

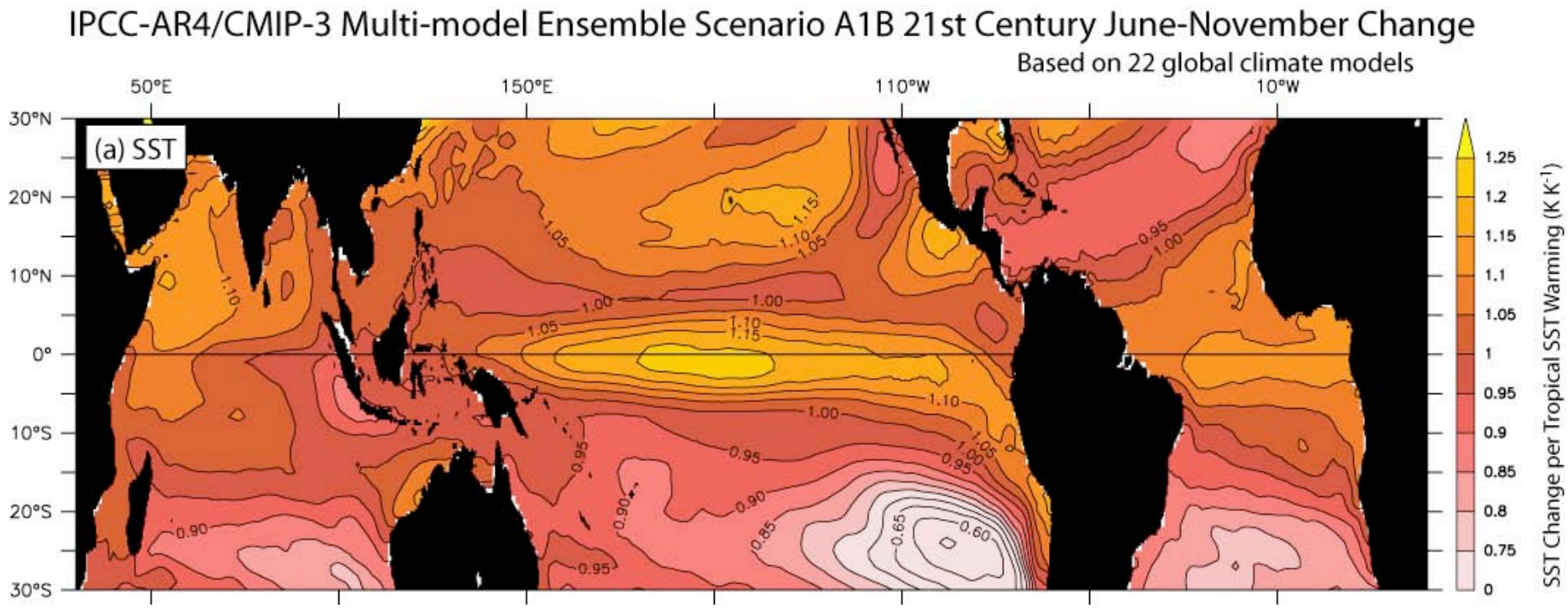
DiNezio et al (2009, J. Clim.) (positive is into the ocean, i.e. heating)

“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.

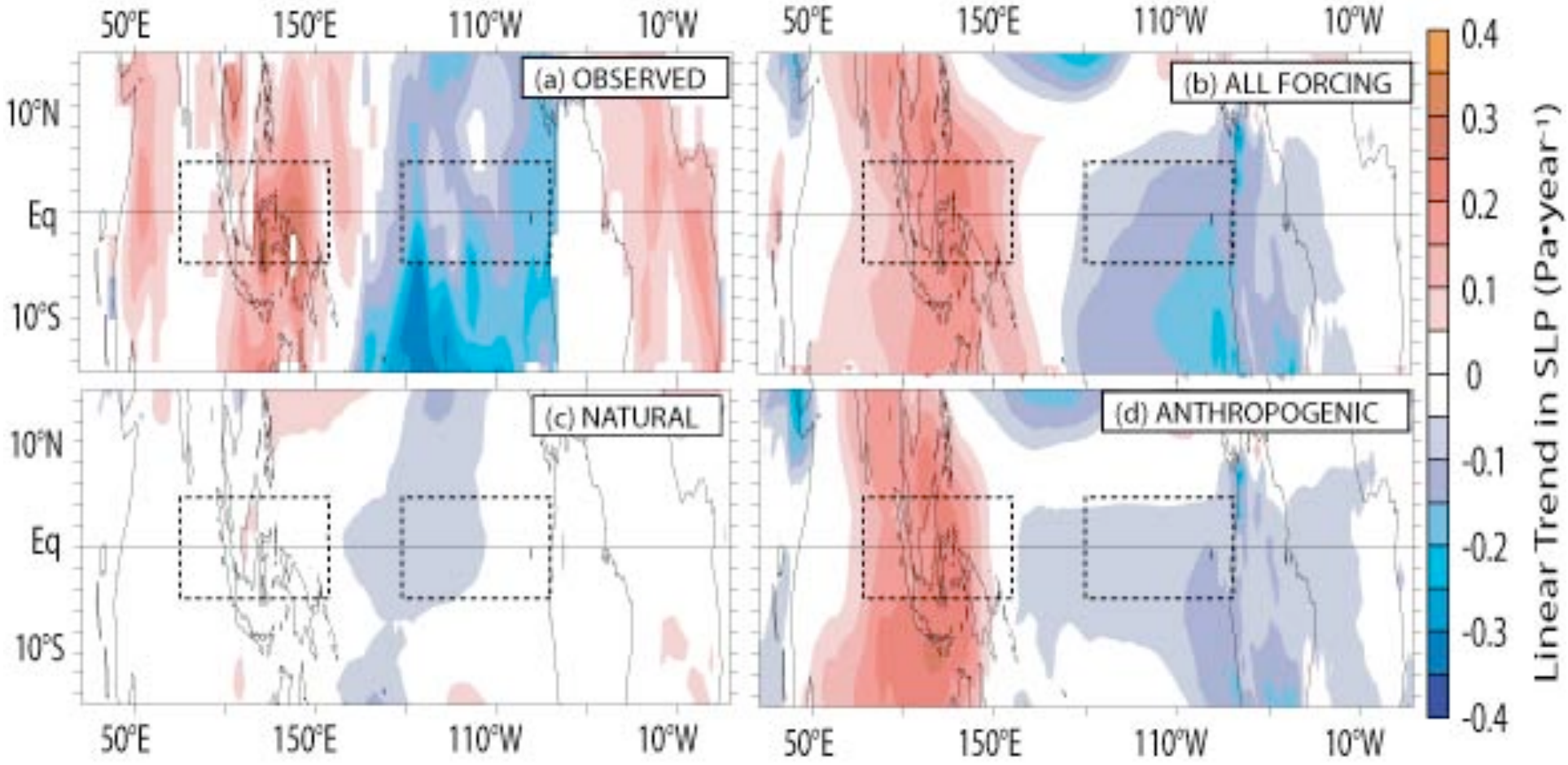
Projected SST Changes (per °C tropical warming)



~20% enhancement of near-Dateline SST warming relative to tropical-mean, in response to CO2 increase.

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

Linear trends in SLP weak with natural forcing.

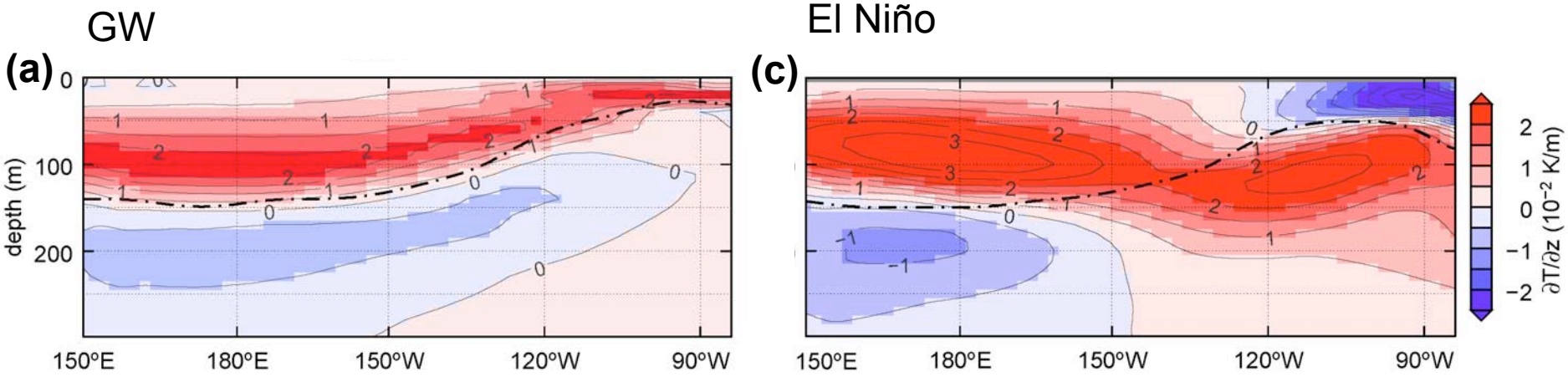


TRENDS COMPUTED 1861-1992

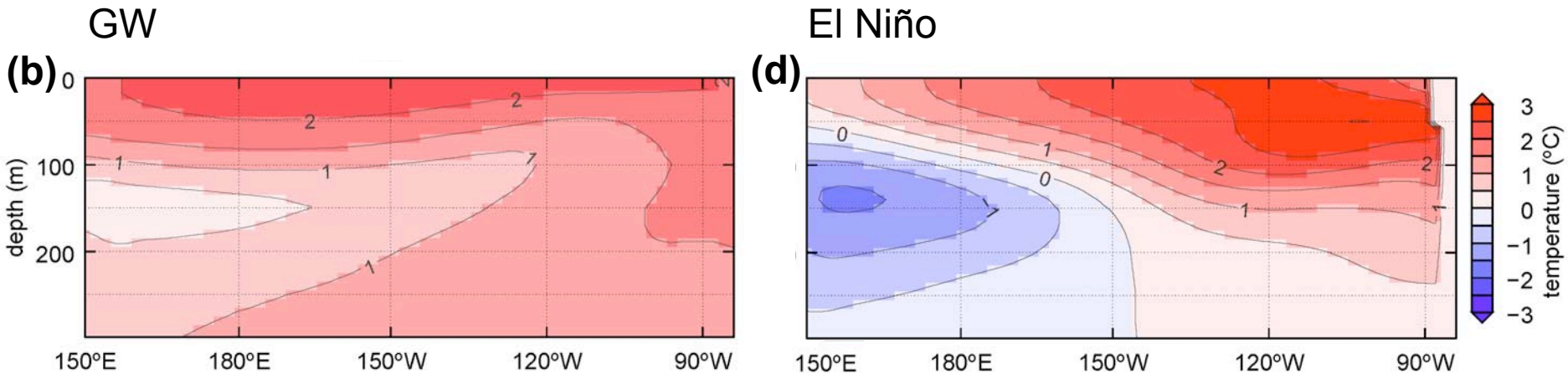
Vecchi et al (2006)

T(z): ENSO vs. GW

Change in Vertical T Gradient



Change in Temperature

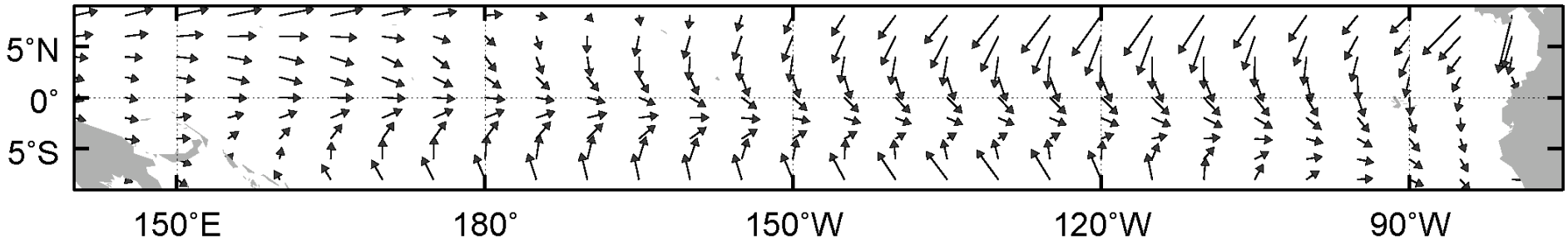


DiNezio et al (2009, J. Clim.)

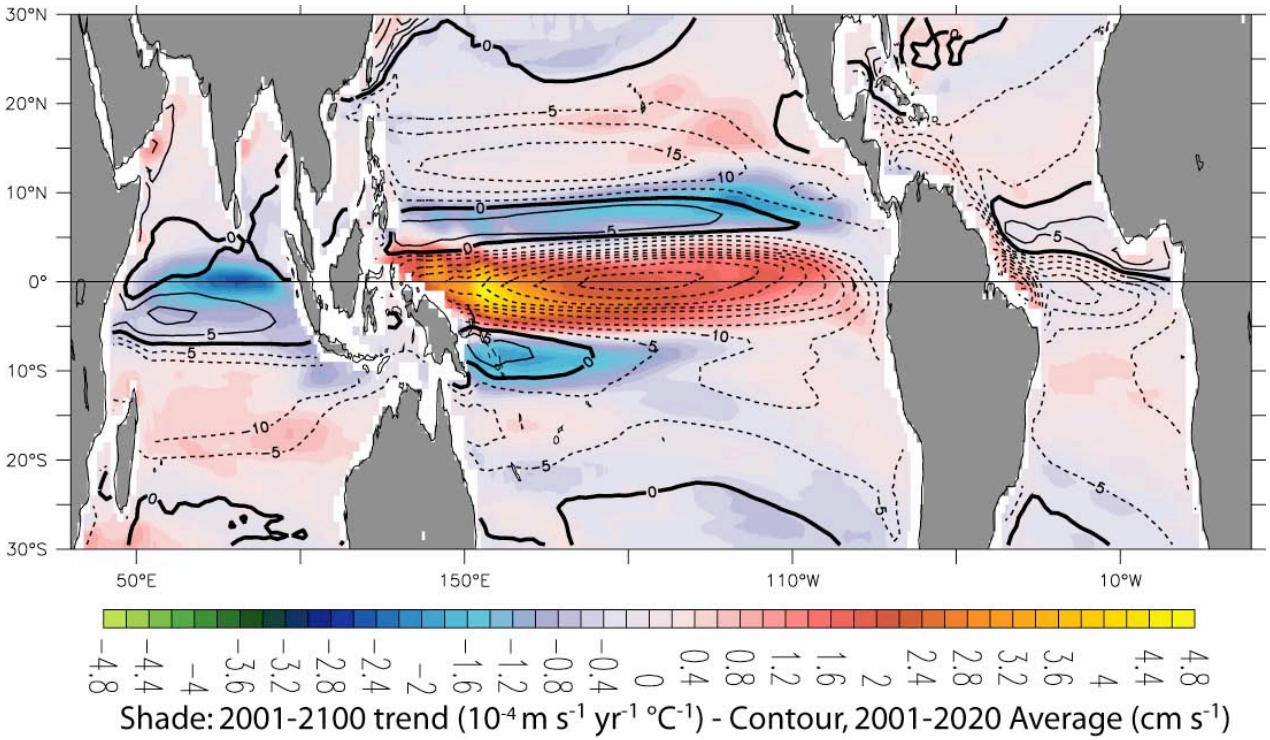
Wind Stress and Currents

Stress

DiNezio et al (2009, J. Clim.)



Surface Zonal Currents



Vecchi and Soden (2007, J. Clim.)