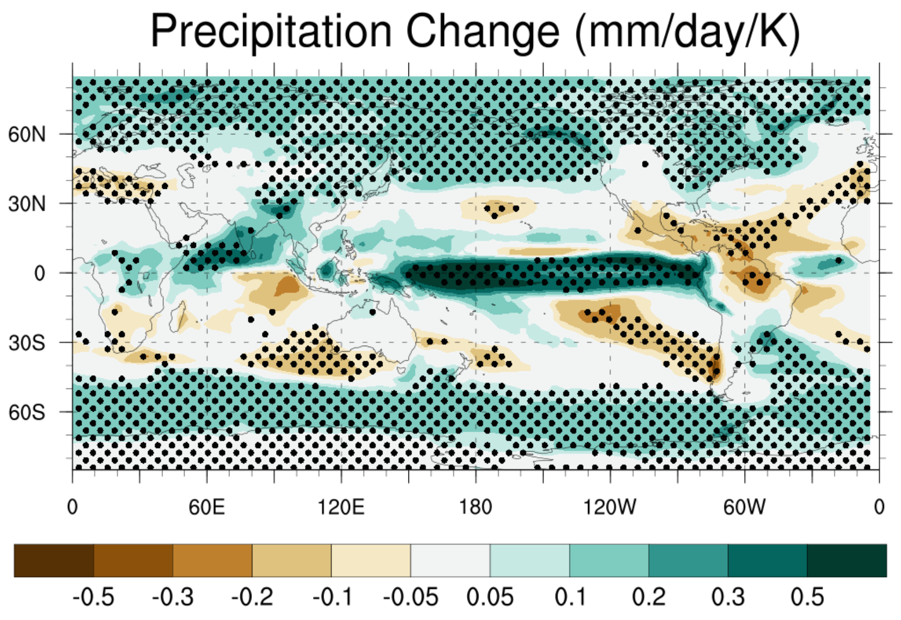
Precipitation Changes and Variability: Some New Perspectives on Current Theories

Jie He

Princeton University

Geophysical Fluid Dynamics Laboratory

Precipitation Changes: Subtropical Drying

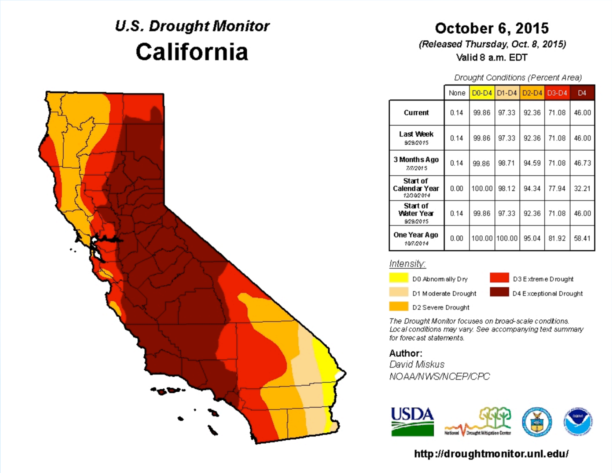


“Dry get drier”

Dry getting drier?

> "If these models are correct, the levels of aridity of the recent multi-year drought or the Dust Bowl will become the new climatology of the American Southwest within a time frame of years to decades."
>
> -- Seager et al. 2007, *Science*

- California Drought (2011-2016)



U.S. Drought Monitor

California

October 6, 2015

(Released Thursday, Oct. 8, 2015)

Valid 8 a.m. EDT

Drought Conditions (Percent Area)

	None	D0-D4	D1-D4	D2-D4	D3-D4	D4
Current	0.14	99.86	97.33	92.36	71.08	46.00
Last Week *9/29/2015*	0.14	99.86	97.33	92.36	71.08	46.00
3 Months Ago *7/7/2015*	0.14	99.86	98.71	94.59	71.08	46.73
Start of Calendar Year *12/30/2014*	0.00	100.00	98.12	94.34	77.94	32.21
Start of Water Year *9/29/2015*	0.14	99.86	97.33	92.36	71.08	46.00
One Year Ago *10/7/2014*	0.00	100.00	100.00	95.04	81.92	58.41

Intensity:

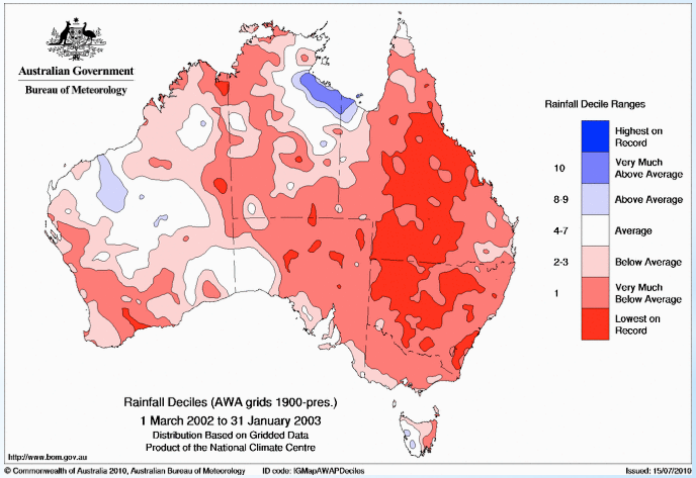
- D0 Abnormally Dry
- D1 Moderate Drought
- D2 Severe Drought
- D3 Extreme Drought
- D4 Exceptional Drought

The Drought Monitor focuses on broad-scale conditions. Local conditions may vary. See accompanying text summary for forecast statements.

Author:
David Miskus
NOAA/NWS/NCEP/CPC

http://droughtmonitor.unl.edu/

- Australia Drought (1997-2009)



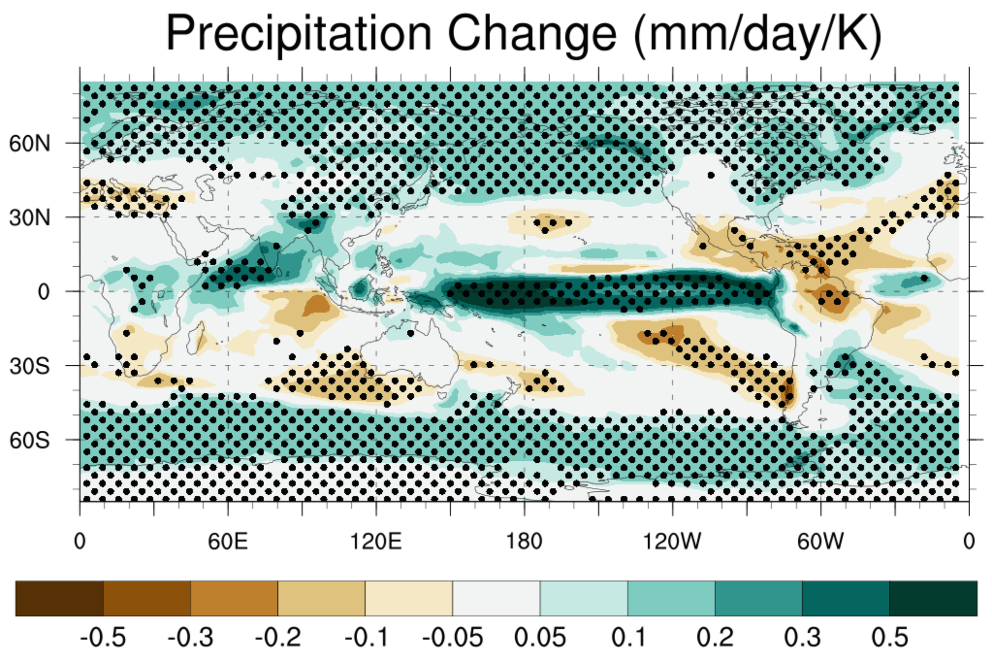
Australian Government
Bureau of Meteorology

Rainfall Deciles (AWA grids 1900-pres.)
1 March 2002 to 31 January 2003
Distribution Based on Gridded Data
Product of the National Climate Centre

http://www.bom.gov.au

© Commonwealth of Australia 2010, Australian Bureau of Meteorology ID code: IGMapAWAPDeciles Issued: 15/07/2010

Dry getting drier?



Only 15% of the robust drying areas are over land.
(Land covers 27% of the subtropics).

What drives the decline?

2 prominent mechanisms:

- **“Dry-get-drier”**
- **Poleward expansion**

What drives the decline?

- **“Dry-get-drier”** (Held and Soden 2006, *J. Climate*)

$$P - E = -\int \nabla \cdot (q \cdot V)$$

$$\partial(P - E) = -\int \nabla \cdot \partial(q \cdot V)$$

$$\Big\downarrow$$

$$\partial(P - E) = -\int \nabla \cdot (\partial q \cdot V) - \int \nabla \cdot (q \cdot \partial V) - \cancel{\int \nabla \cdot (\partial q \cdot \partial V)}$$

$$\Big\downarrow \quad \partial V \approx 0$$

$$\partial(P - E) = -\int \nabla \cdot (\partial q \cdot V)$$

$$\Big\downarrow \quad \boxed{\partial q \approx q \times 7\% / K}$$

$$\partial(P - E) = -\int \nabla \cdot (q \cdot V) \times 7\% / K = (P - E) \times 7\% / K$$

$$\partial P \approx (P - E) \times 7\% / K$$

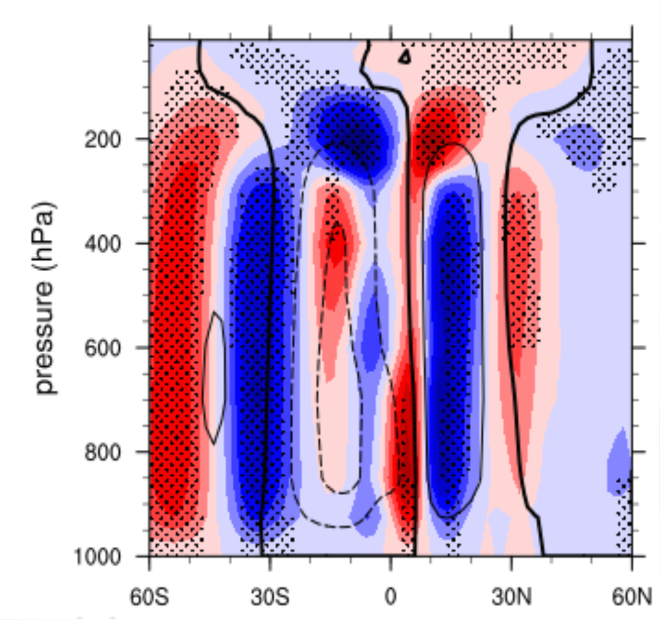
What drives the decline?

- **Poleward expansion** (Scheff and Frierson 2012, *J. Climate; GRL*)

$$\partial P \propto (P - E) \quad ??$$

Most of the decline happens poleward of P-E minima.

Change in zonal mean stream function

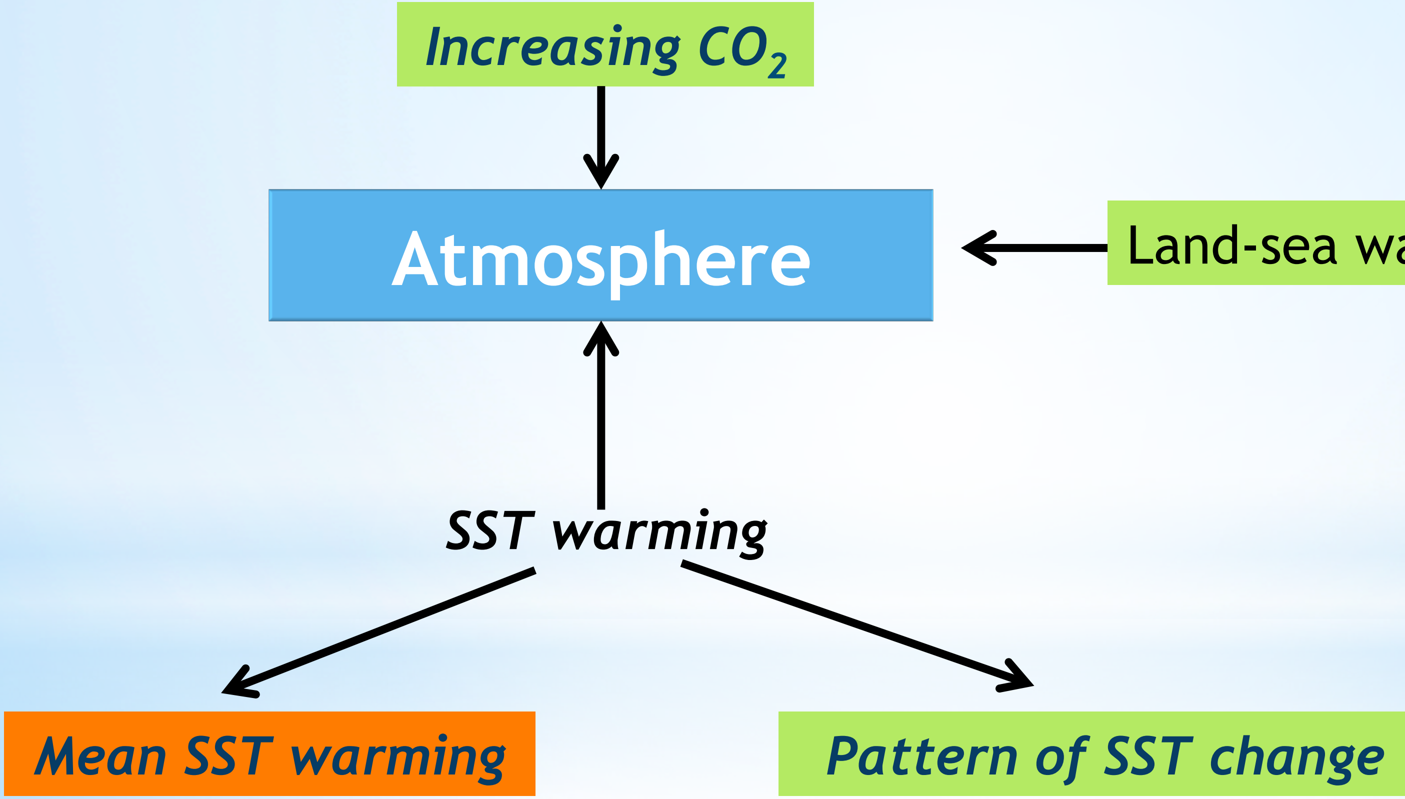


A new perspective

- “Dry-get-drier”
- Poleward expansion

→ Mean SST warming

(Compo & Sardeshmukh 2009, *C Dyn*; Grise & Polvani 2014, *GRL*)



Increasing CO_2

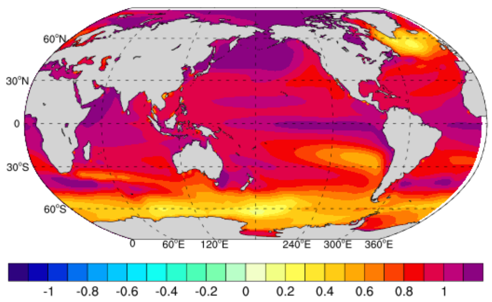
Atmosphere

Land-sea warming contrast

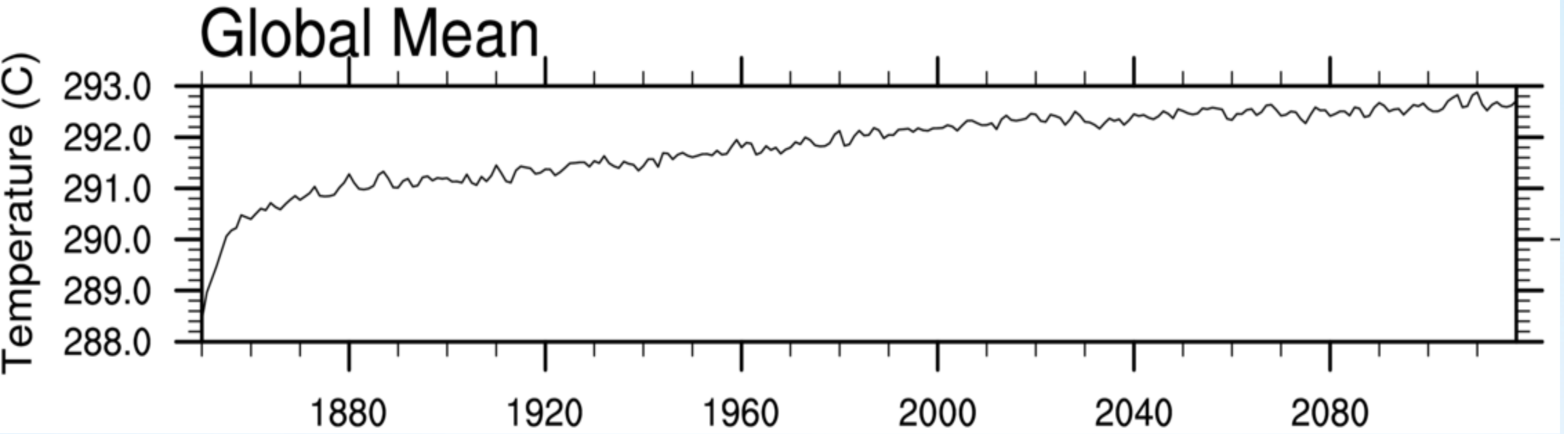
SST warming

Mean SST warming

Pattern of SST change



Abrupt4xCO2 (13 CGCMs, CMIP5)

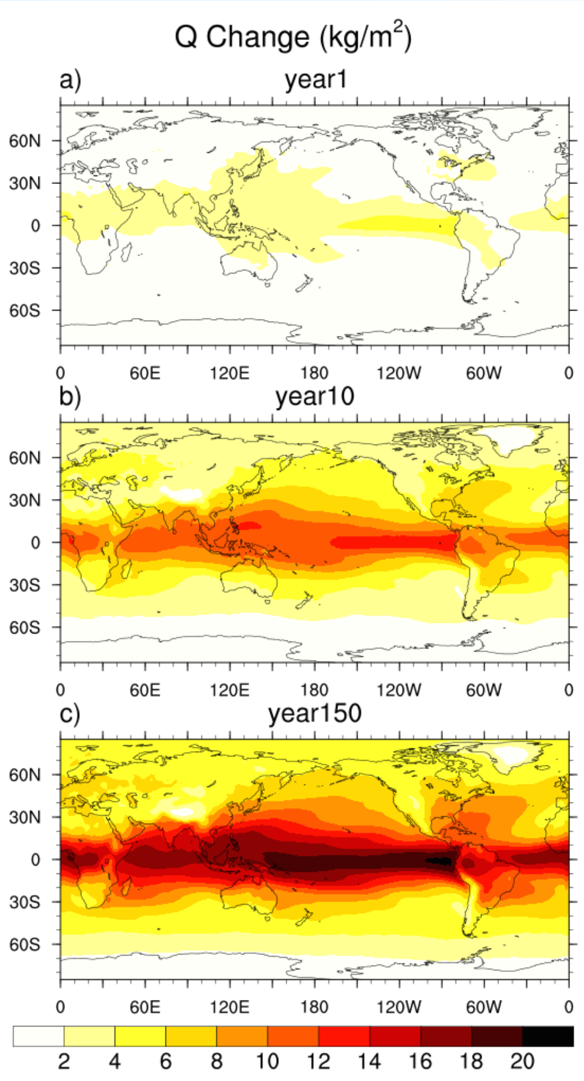


Dry-get-drier
Poleward expansion → Slow

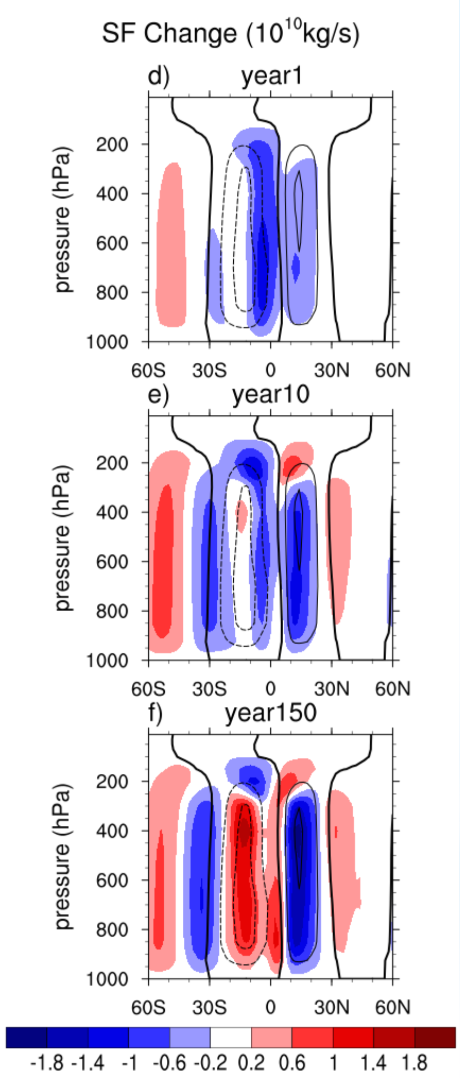
Direct CO_2 forcing
Land-sea warming contrast → Fast (1st year)
Pattern of SST change

Fast VS Slow responses

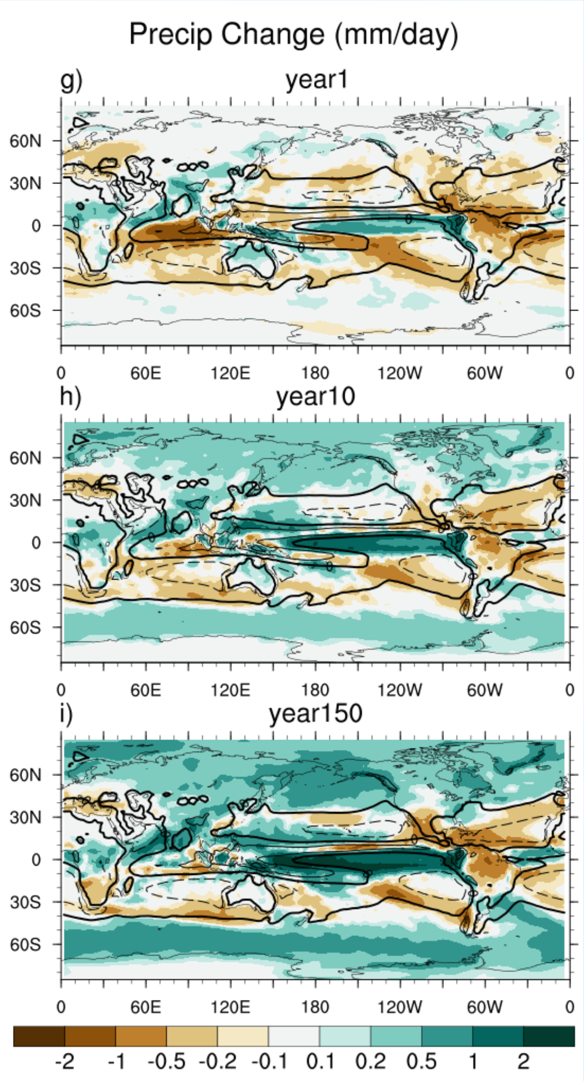
“Dry-get-drier”



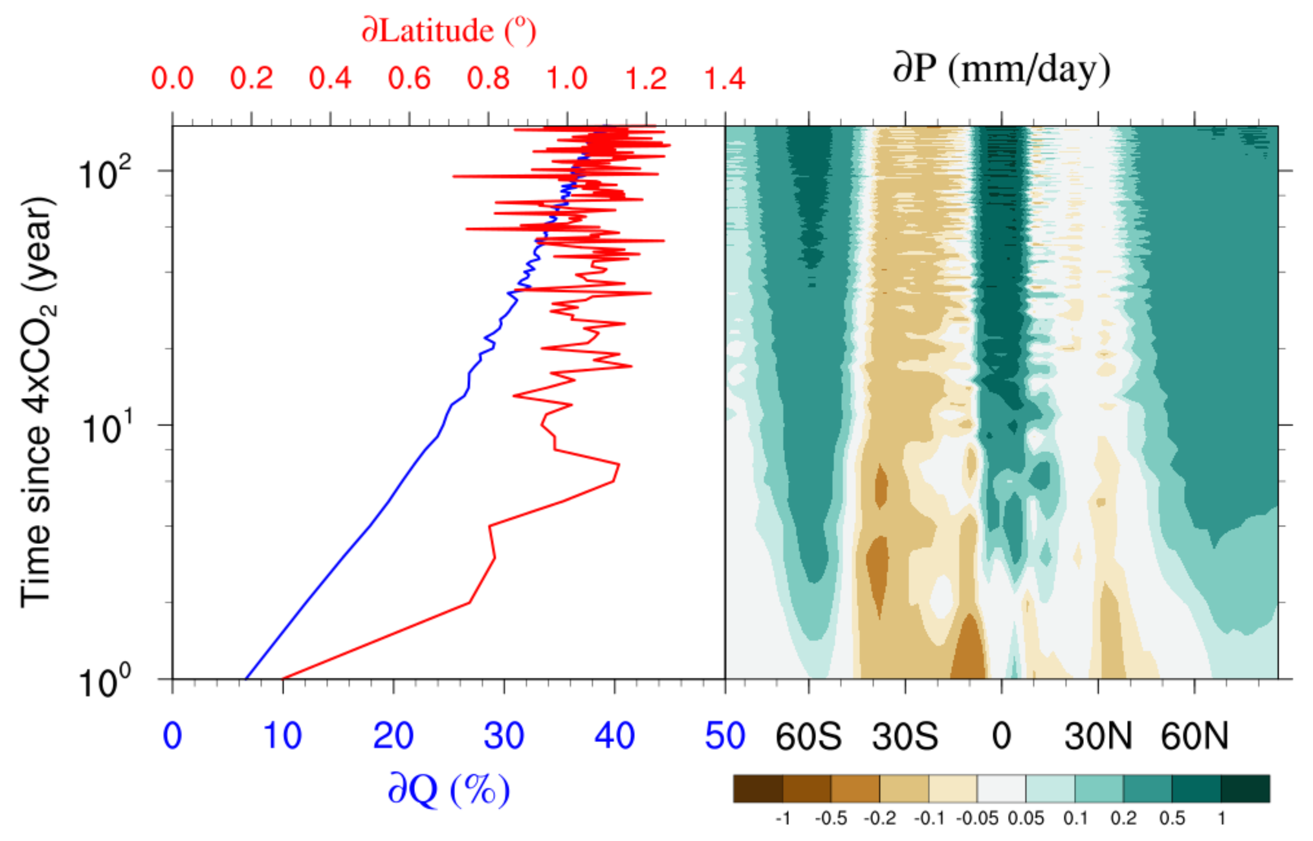
Poleward expansion



Fast precipitation decline



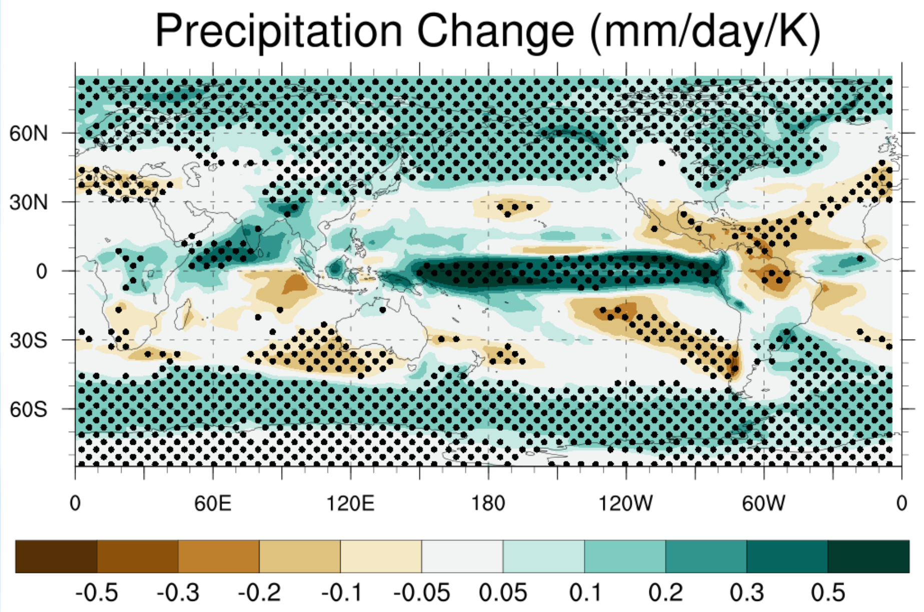
Fast VS Slow responses

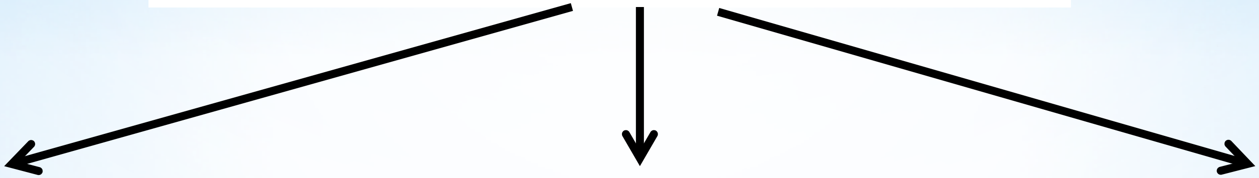


- Neither “Dry-get-drier” nor poleward expansion is required for the subtropical precipitation decline.

A more realistic scenario…

Total Change
(1pctCO2)





$AMIP\_CO_2$

CO_2 + land-sea contrast

AMIP_mean

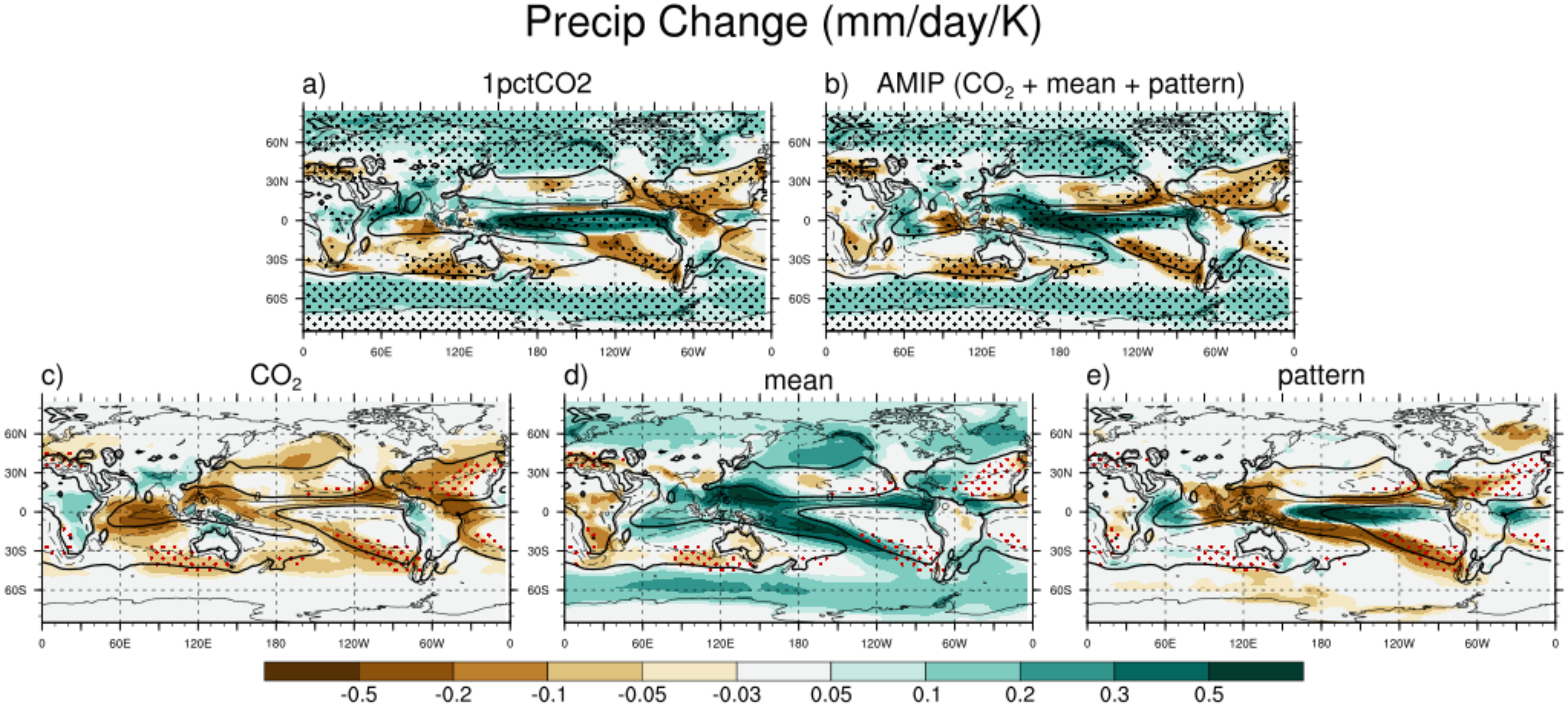
Mean SST warming only

AMIP_pattern

Pattern of SST change only

CO_2 VS mean VS pattern

CMIP5 9-model mean

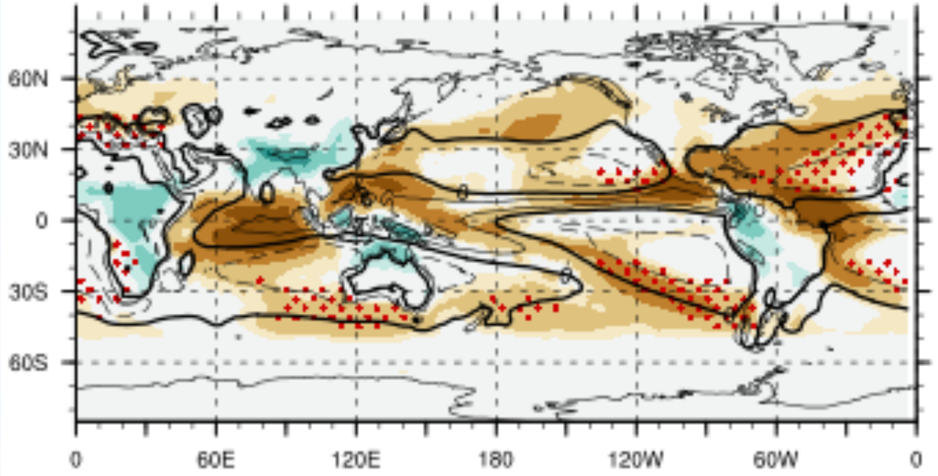


- **Subtropical precipitation decline does not depend on the global mean SST warming.**

Direct CO_2 VS Land-sea contrast

(Bony et al. 2013, Nature Geo)

(Chadwick et al. 2014, GRL)



∂P in AMIP_CO2

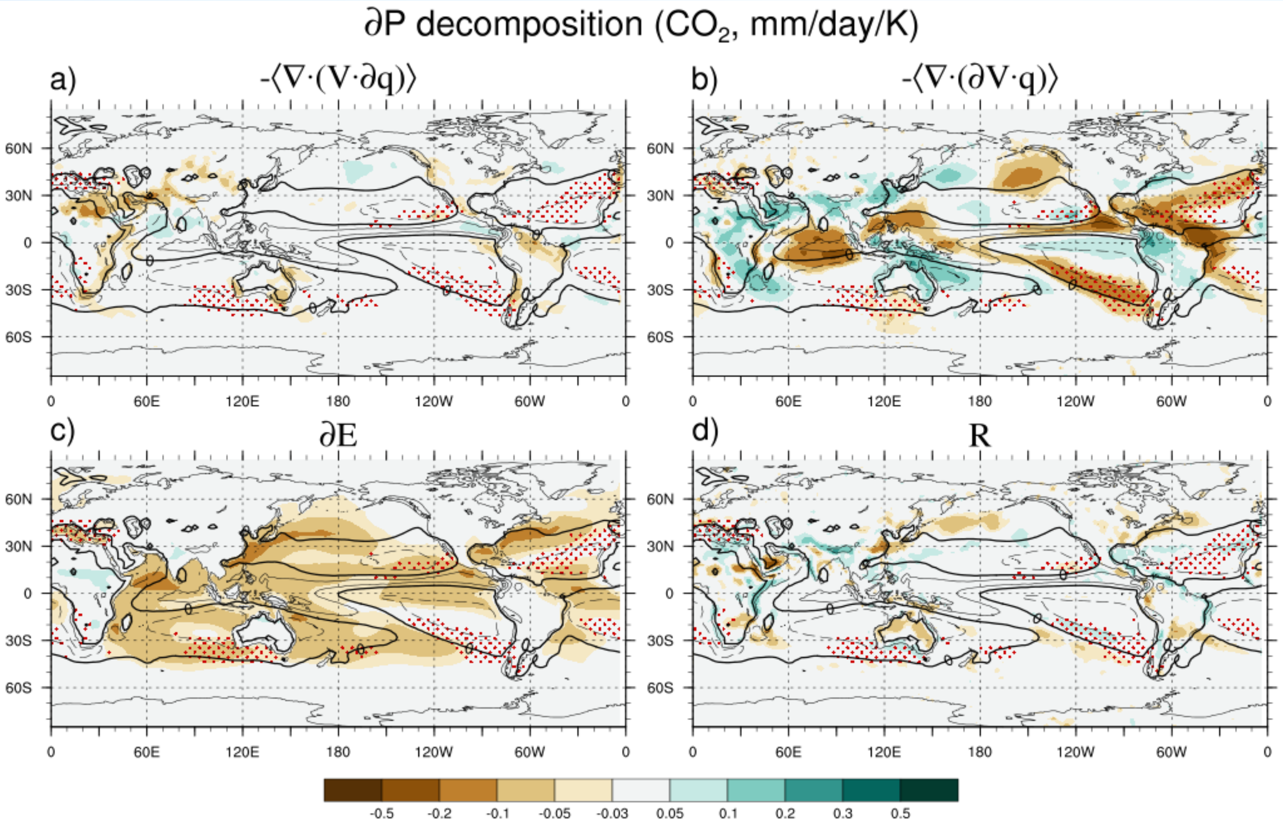
$$\partial(P-E) = -\int \nabla\cdot(\partial q\cdot V) - \int \nabla\cdot(q\cdot\partial V) - \int \cancel{\nabla\cdot(\partial q\cdot\partial V)}$$

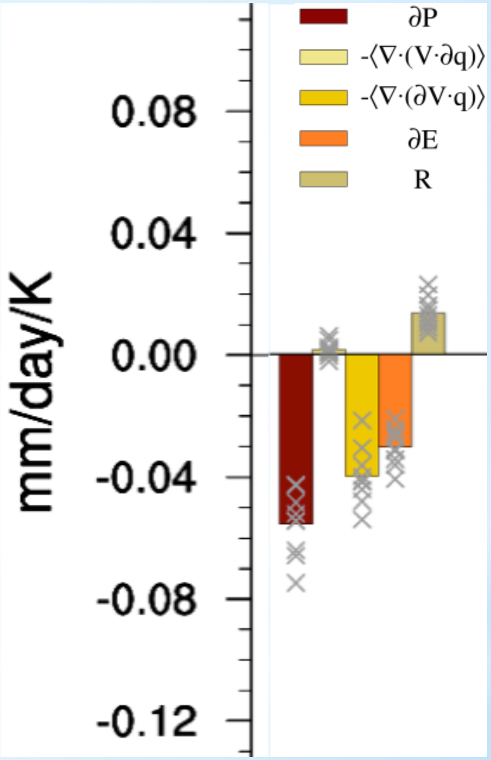
$$\partial P \approx -\int \nabla\cdot(\partial q\cdot V) - \int \nabla\cdot(q\cdot\partial V) + \partial E + R$$

(Seager et al. 2010, *J. Climate*)

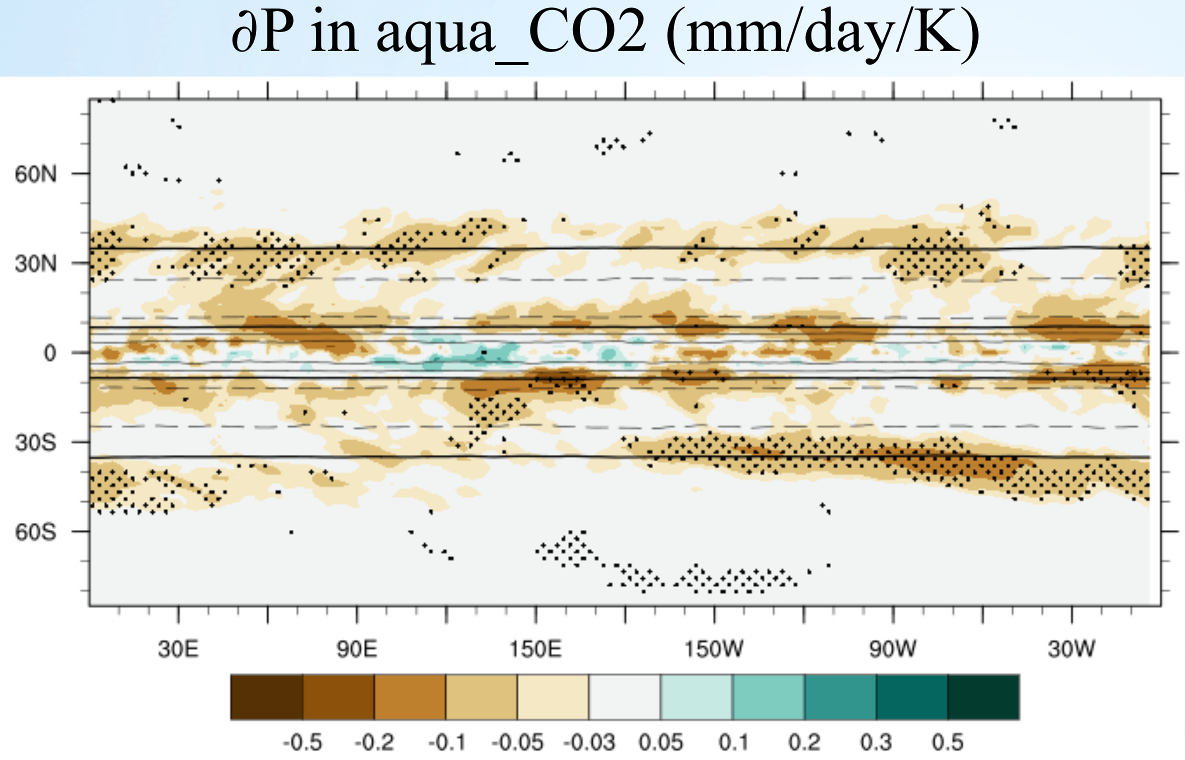
Direct CO_2 VS Land-sea contrast

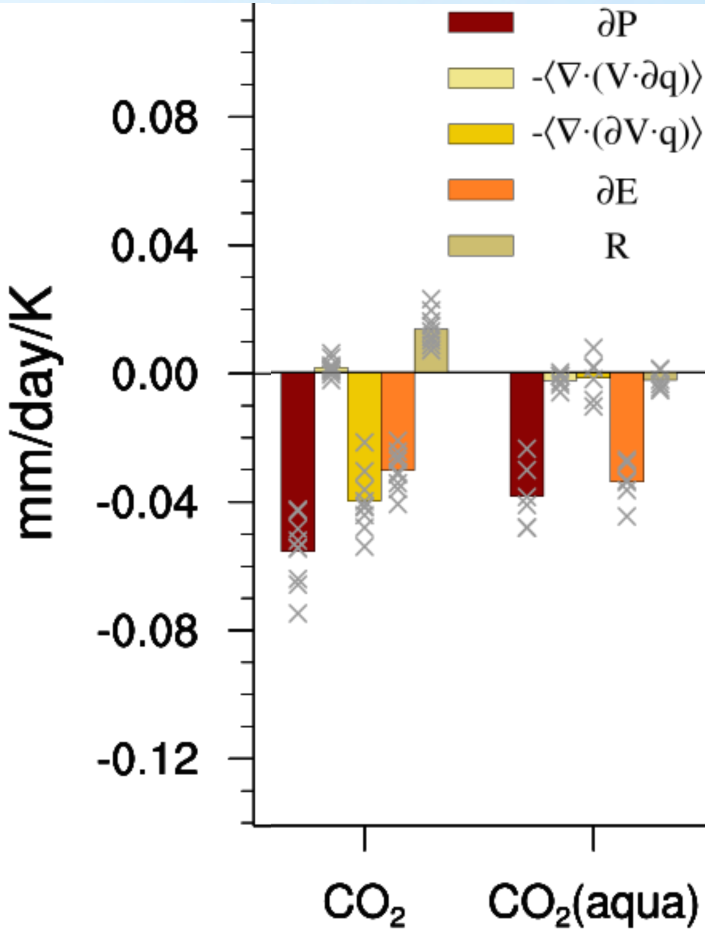
$$\partial P \approx -\int \nabla \cdot (\partial q \cdot V) - \int \nabla \cdot (q \cdot \partial V) + \partial E + R$$





Direct CO_2 VS Land-sea contrast

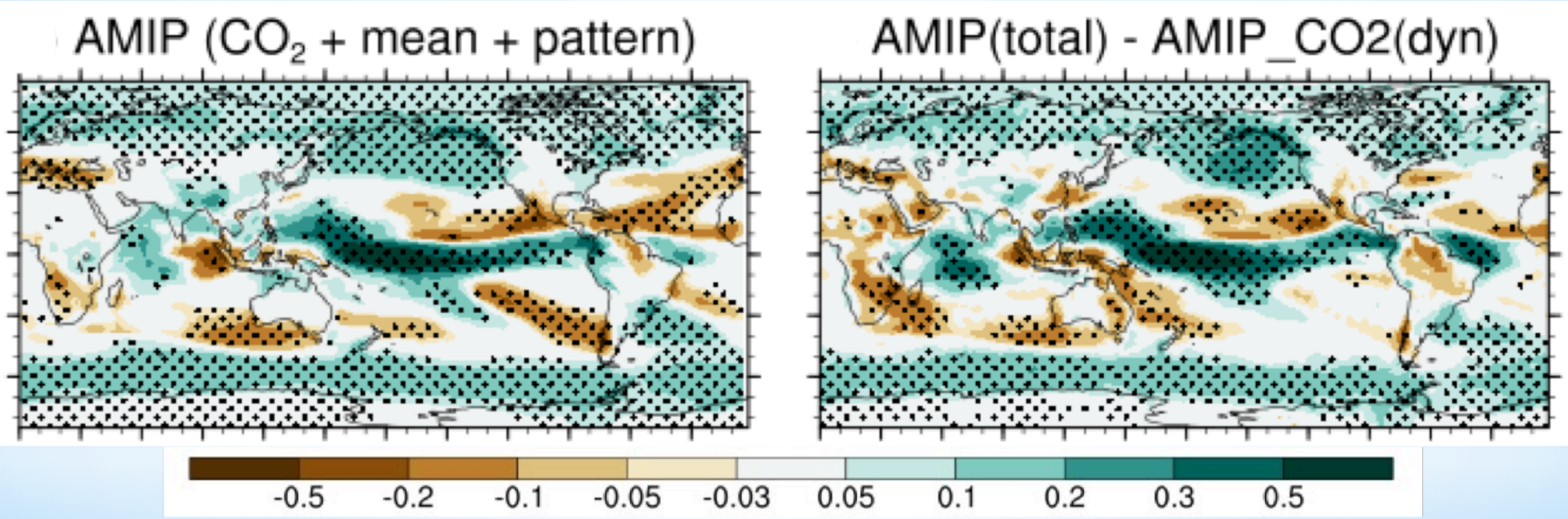

∂P in aqua_CO2 (mm/day/K)



- Land-sea contrast drives dynamic change.
- Direct CO_2 forcing reduces evaporation.

Land-sea warming contrast

Total ∂P **∂P without land-sea contrast**

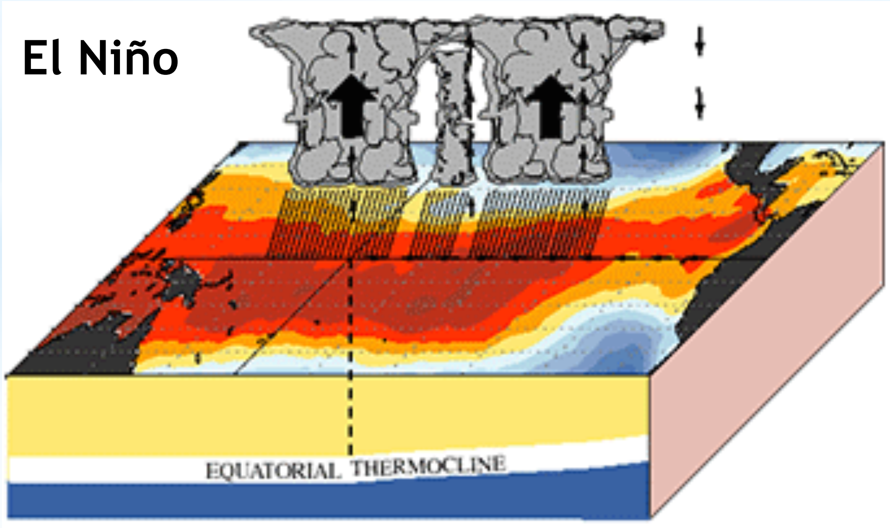


- Land-sea warming contrast drives precipitation decline over ocean but counteracts the precipitation decline over land, which would otherwise happen due to SST change.

Summary I

- Subtropical precipitation decline does not depend on increases in moisture or poleward expansion of the Hadley cell.
- The large-scale subtropical precipitation decline is driven by the land-sea warming contrast, direct CO_2 forcing and, in certain regions, pattern of SST change.
- The land-sea warming contrast drives precipitation decline over subtropical ocean but counteracts the precipitation decline over land.

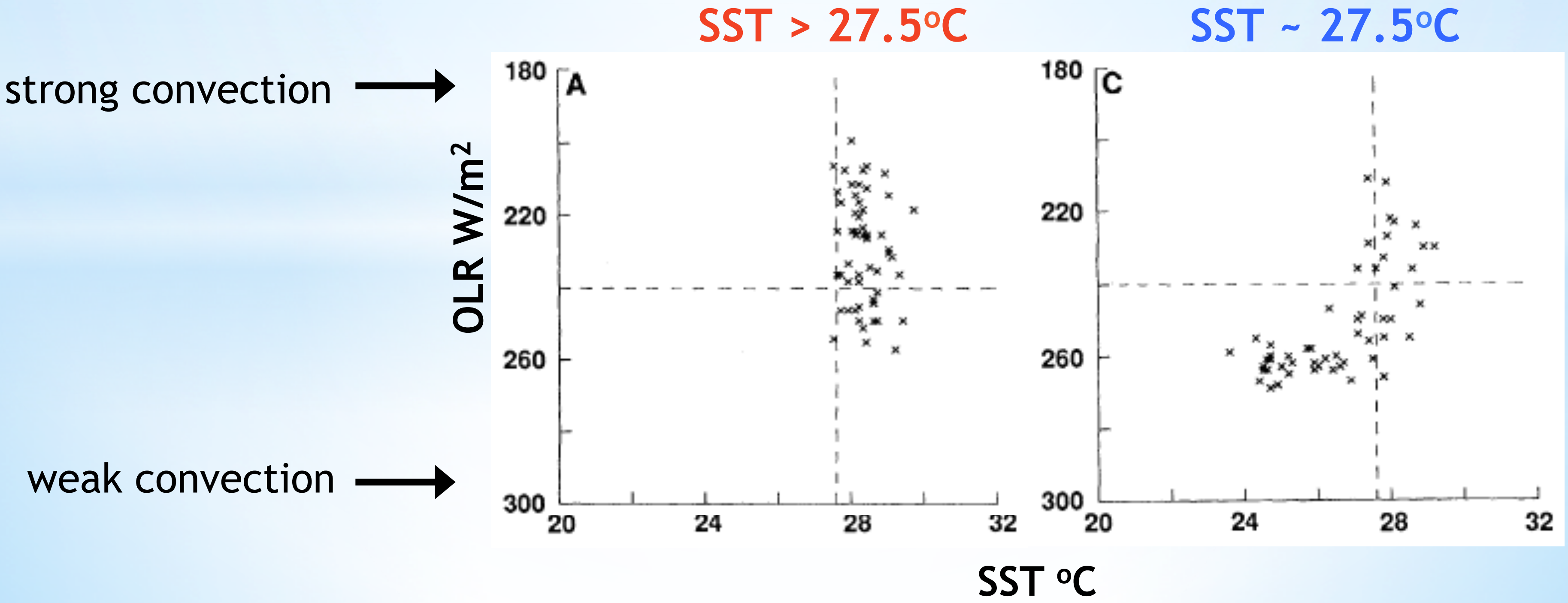
Precipitation Variability:
SST Forcing in the Tropics



http://forum.weatherzone.com.au/ubbthreads.php/topics/1050469/40

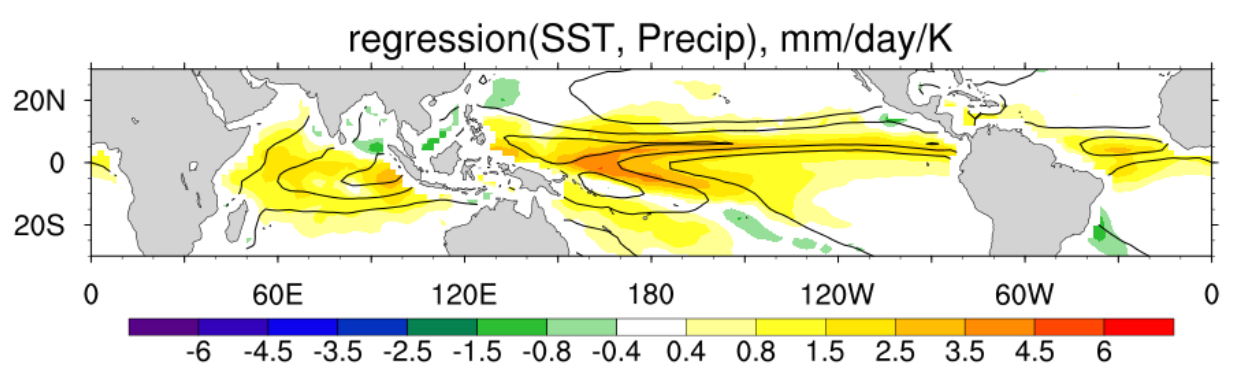
How strong is the SST forcing?

> “Although SSTs in excess of 27.5°C are required for deep convection to occur, the intensity of convection appears to be insensitive to further increases in SST.”
>
> -- Graham and Barnett 1987, *Science*

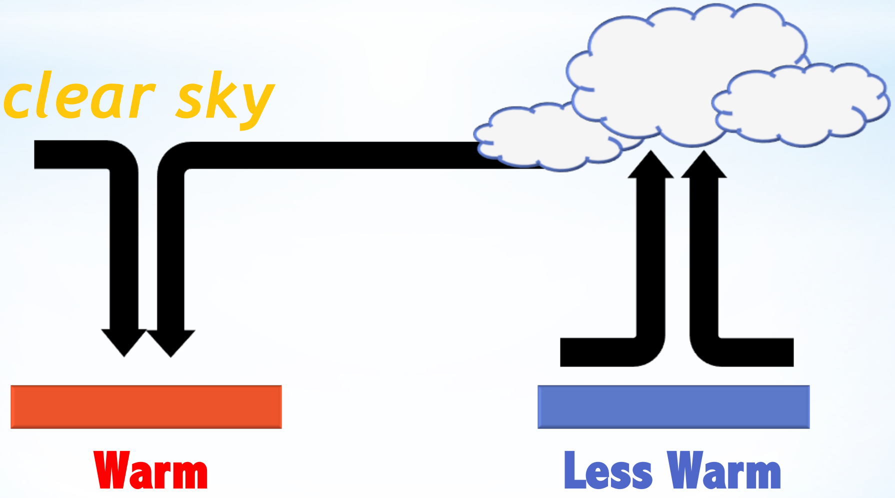


Lack of SST forcing over warm pool?

Waliser and Graham 1993, *J. Climate*; Zhang 1993, *J. Climate*; Waliser 1996 *J. Climate*



Large-scale remote forcing?

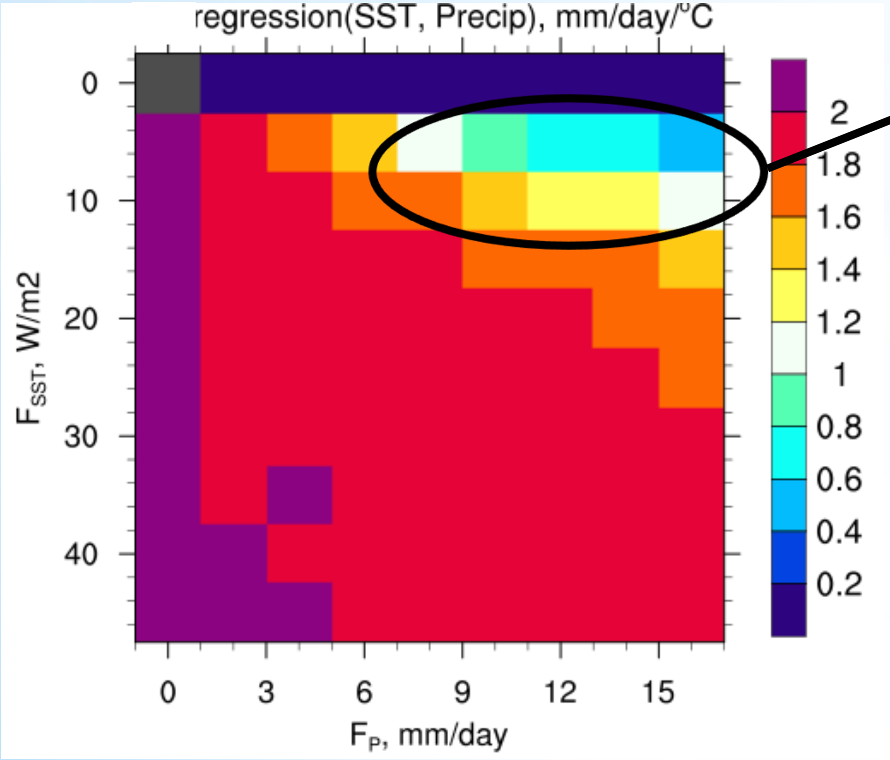


SST forcing in coupled systems

$$P = a \cdot SST + F_P$$

$$\frac{dSST}{dt} = \frac{1}{c_p \rho_w H}(b \cdot P + F_{SST})$$

a=2 (mm/day)/^{o}C; b=-3 (W/m^2)/(mm/day)



If F_P is large and F_{SST} is small (e.g., ITCZ), it would appear in a coupled system that the SST forcing is much less than 2 (mm/day)/K.

SST forcing in an uncoupled system

$$P = a \cdot SST + F_P$$

$$\xcancel{\frac{dSST}{dt} = \frac{1}{c_p \rho_w H}(b \cdot P + F_{SST})}$$

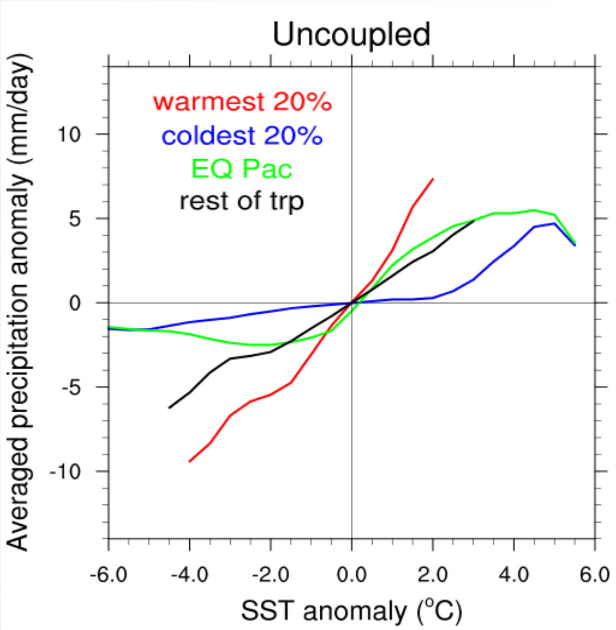
Coupled GFDL-FLOR

$\downarrow$ *SST anomalies*

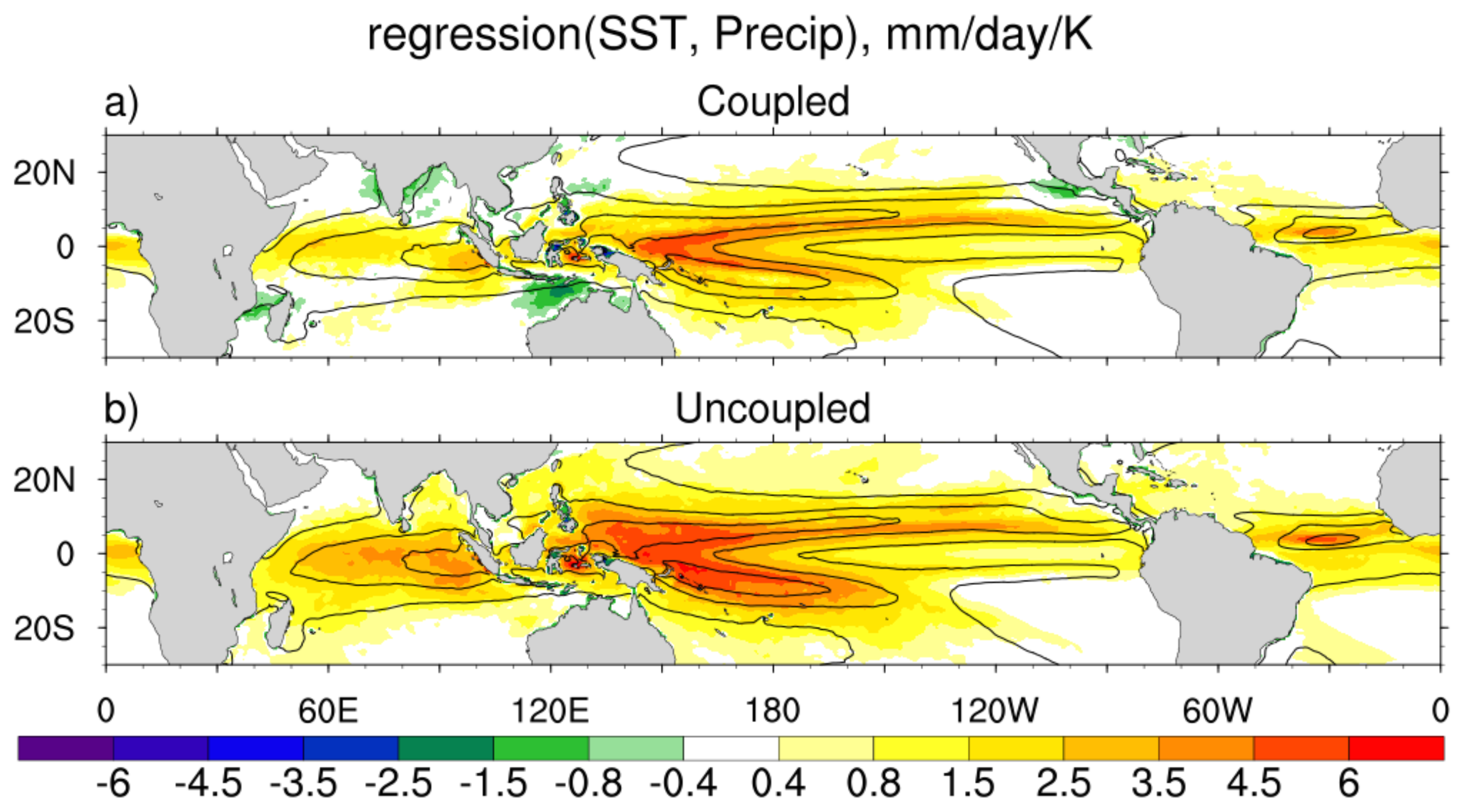
Atmosphere-only GFDL-FLOR

run for 80 years

Assume linearity and solve for regression coefficient, a.

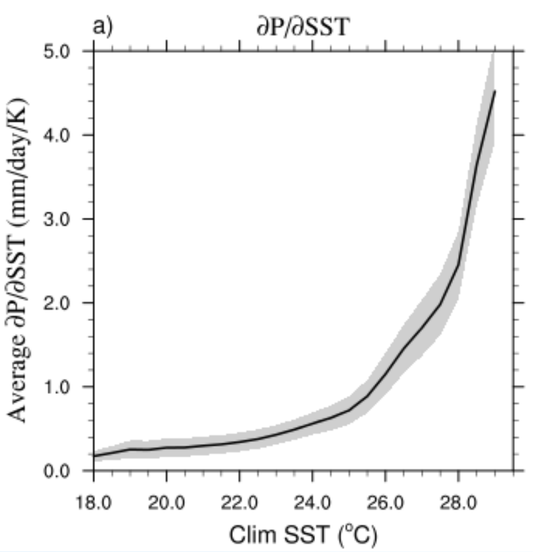


SST forcing in an uncoupled system



- The higher the base SST, the larger the SST forcing.

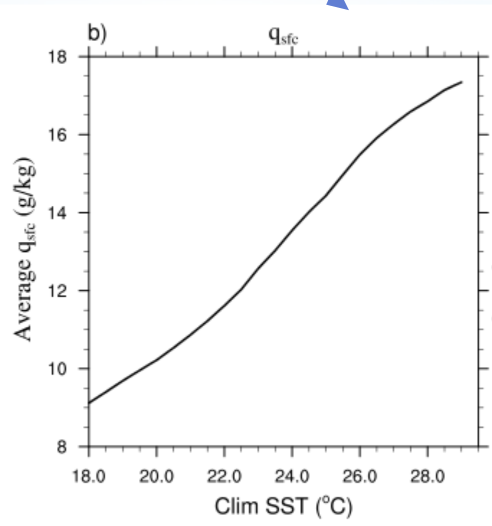
SST forcing in an uncoupled system

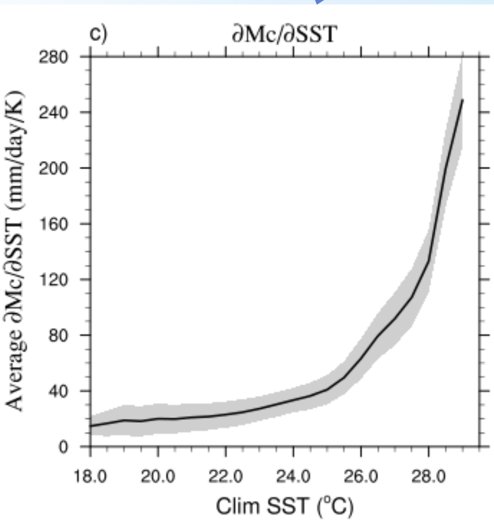


$$P = q_{sfc} \cdot Mc \qquad (Mc = \frac{P}{q_{sfc}})$$

$$\frac{\partial P}{\partial SST} = \frac{\partial P}{\partial q_{sfc}} \cdot \frac{\partial q_{sfc}}{\partial SST} + \frac{\partial P}{\partial Mc} \cdot \frac{\partial Mc}{\partial SST}$$

$$\frac{\partial P}{\partial SST} = \cancel{\overline{\overline{Mc}} \cdot \frac{\partial q_{sfc}}{\partial SST}} + \overline{\overline{q_{sfc}}} \cdot \frac{\partial Mc}{\partial SST}$$





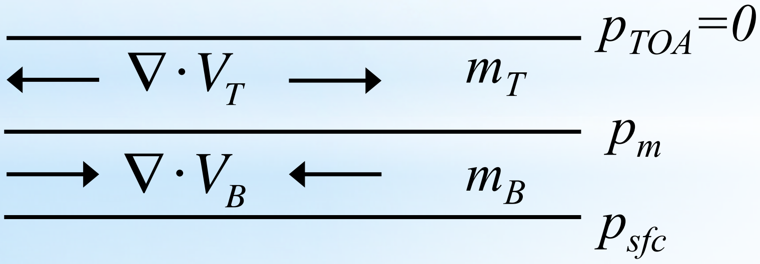
What determines ∂Mc/∂SST?

- **Moist Static Energy Model** (Neelin and Held 1987, *J. Climate*)

$$m = s + L \cdot q \qquad s = C_p \cdot T + \Phi$$

$$\int \nabla \cdot (mV) = F_{sfc} - F_{TOA}$$

$$\int m \cdot (\nabla \cdot V) + \cancel{\int V \cdot (\nabla m)} \approx F_{sfc} - F_{TOA}$$



$$\nabla \cdot V_B = \int_{p_m}^{p_{sfc}} \nabla \cdot V \frac{dp}{g} = -\nabla \cdot V_T$$

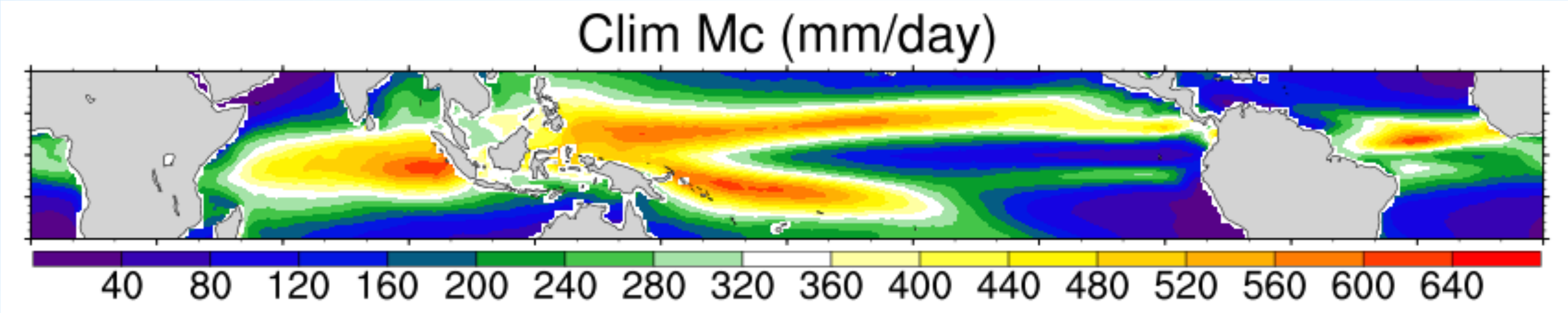
$$\Delta m = m_T - m_B$$

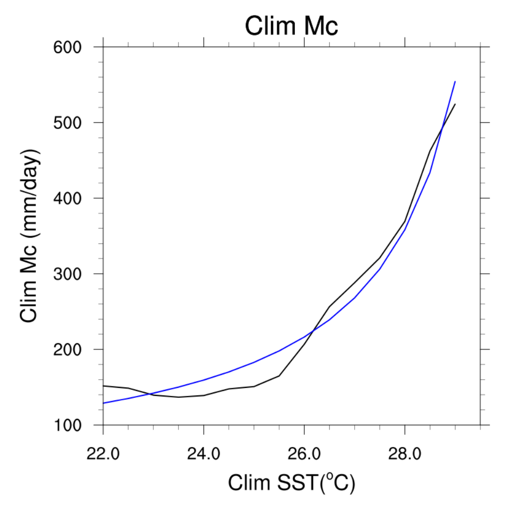
$$-\Delta m \nabla \cdot V_B \approx F_{sfc} - F_{TOA}$$

$$-\nabla \cdot V_B \approx \frac{F_{sfc} - F_{TOA}}{\Delta m}$$

What determines ∂Mc/∂SST?

$$Mc \propto -\nabla \cdot V_B \approx \frac{F_{sfc} - F_{TOA}}{\Delta m}$$





$$Mc \propto \frac{F}{\Delta m} = \frac{F}{s_T + \cancel{L \cdot q_T} - s_B - L \cdot q_B} \approx \frac{F}{\Delta s - L \cdot q_B}$$

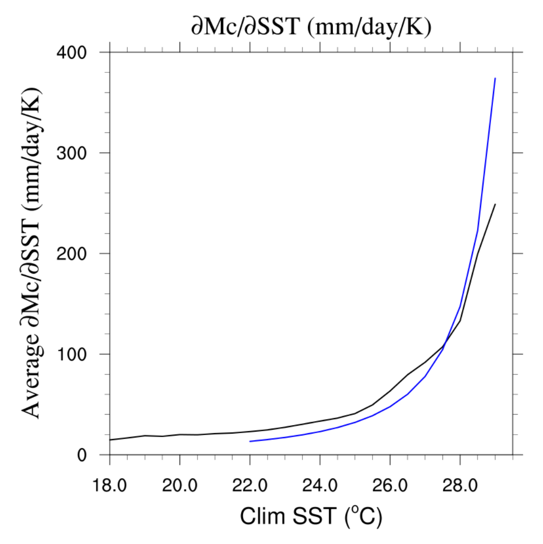
$$q_B = \alpha \cdot q_{sat}(T_B) \approx 80\% \cdot q_{sat}(SST - 1.5^oC)$$

$$\Delta s = 5.0 \times 10^4 J/kg$$

What determines ∂Mc/∂SST?

$$Mc \propto \frac{F}{\Delta s - L \cdot q_B} \qquad \frac{\partial q_B}{\partial SST} = q_B \cdot 7\% / ^o C$$

$$\frac{\partial Mc}{\partial SST} \propto \frac{F \cdot L \cdot q_B \cdot 7\% / ^o C}{(\Delta s - L \cdot q_B)^2}$$



- As the base *SST* increases, $L \cdot q_B$ increases exponentially towards Δs.

Summary II

- Simultaneous SST-convection relationships from coupled systems, including observation, are inadequate for quantifying SST forcing.
- SST forcing of convection is a monotonically increasing function of the base SST.
- Uncoupled simulations can be ideal tools for quantifying SST forcing.

A framework for air-sea interaction

$$P = \frac{\partial P}{\partial SST} \cdot SST + F_P$$

$$LH = \frac{\partial LH}{\partial SST} \cdot SST + F_{LH}$$

$$SH = \frac{\partial SH}{\partial SST} \cdot SST + F_{SH}$$

$$SW = C_{SW} \cdot P$$

$$C_{SW} = regression(P, SW)$$

$$\frac{\partial SST}{\partial t} = \frac{1}{c_p \rho_w H}(SW + LW - LH - SH + F_{SST})$$

- Quantify atmospheric sources of SST variability.

$$LW = \beta \cdot SST - 4 \cdot \alpha \cdot \overline{\overline{SST}}^{3} \cdot SST$$

(Waliser and Graham 1993, *J. Climate*)

ENSO forcing

Tropical SST variability

$$\frac{dSST}{dt} = \frac{1}{c_p \rho_w H}(SW + LW - LH - SH + F_{SST})$$

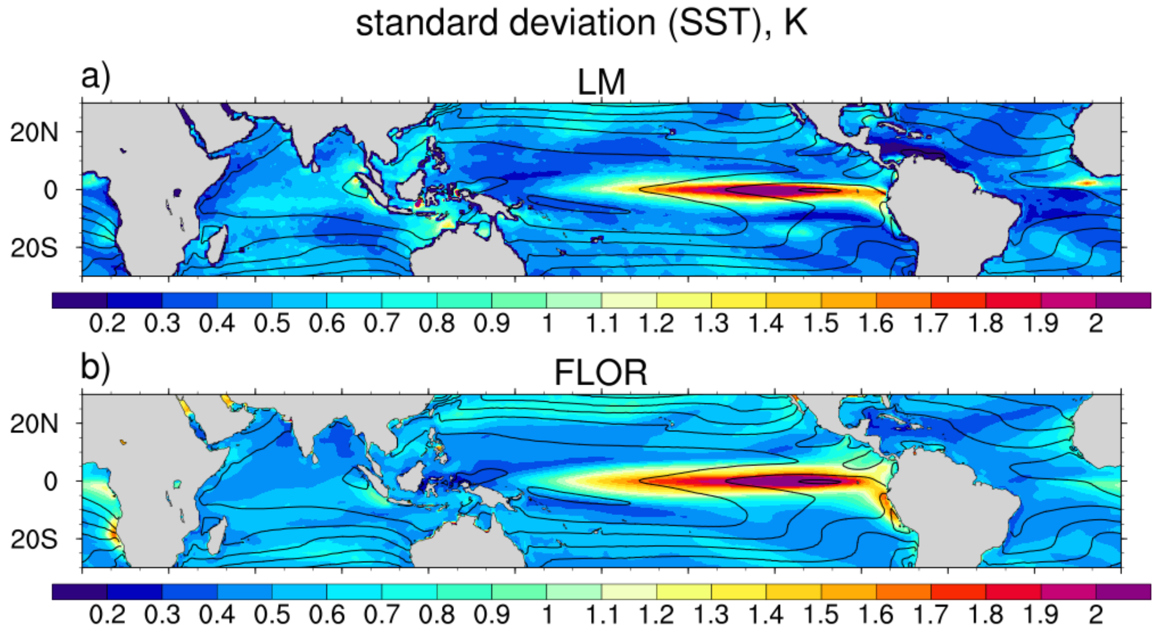
$$P = \frac{\partial P}{\partial SST} \cdot SST + F_P$$

$$LH = \frac{\partial LH}{\partial SST} \cdot SST + F_{LH}$$

$$SH = \frac{\partial SH}{\partial SST} \cdot SST + F_{SH}$$

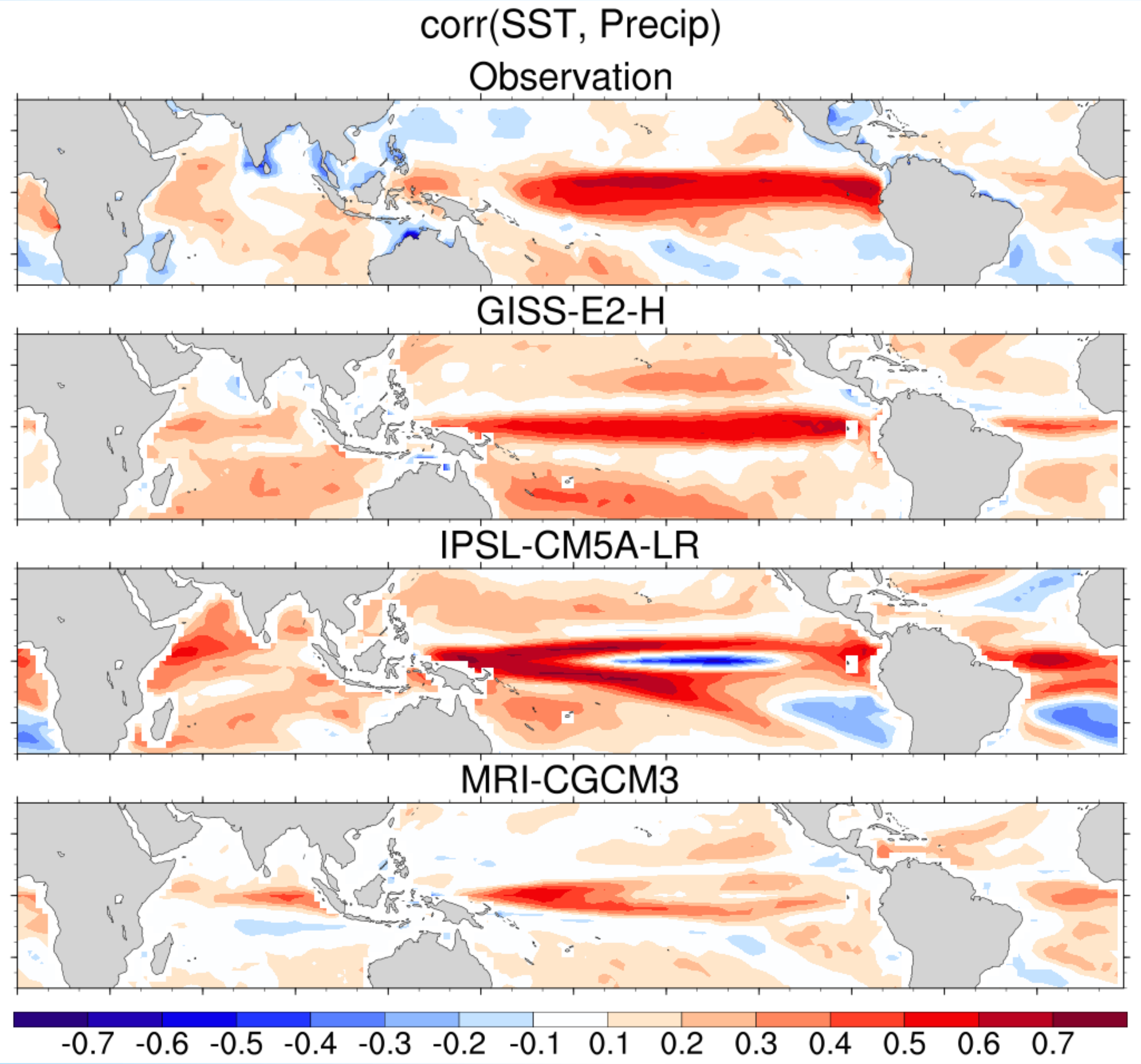
$$LW = \beta \cdot SST - 4 \cdot \alpha \cdot \overline{\overline{SST}}^{3} \cdot SST$$

$$SW = C_{SW} \cdot P$$



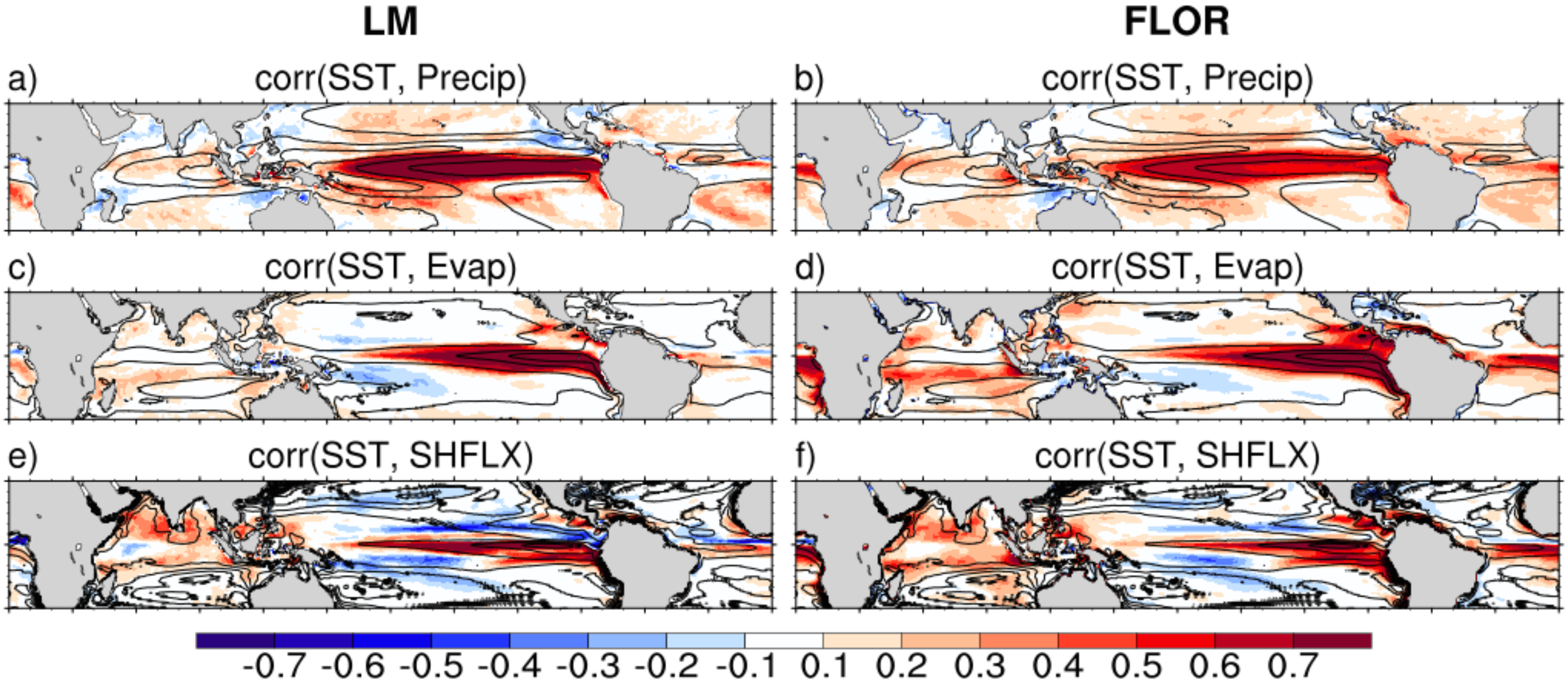
- LM simulates tropical SST variability reasonably well.

Local air-sea relationship



- Large biases in the simulation of air-sea relationship from current CGCMs.

Local air-sea relationship



- LM reasonably represents the local air-sea relationship from the CGCM.

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- The land-sea warming contrast drives precipitation decline over subtropical ocean but counteracts the precipitation decline over land.

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Thank you

References

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