# What Drives Projections of Subtropical Precipitation Decline?

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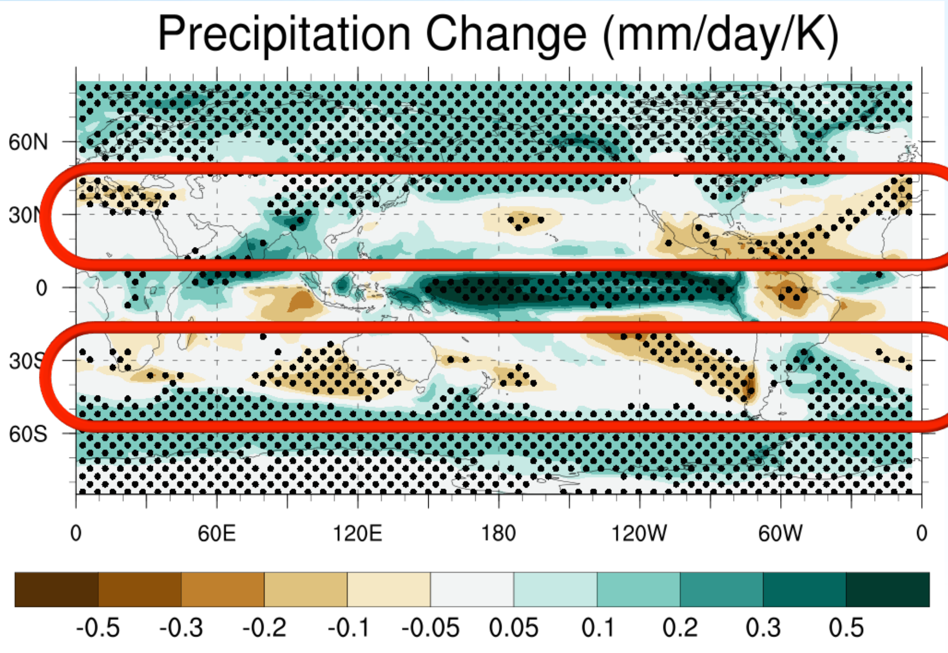
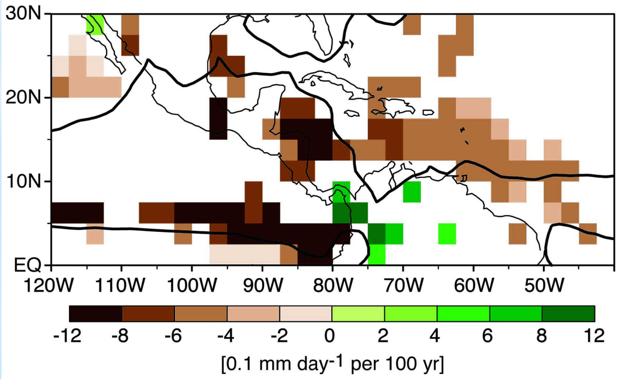
# Precipitation declines in the subtropics.

- Model evidence (1pctCO2)

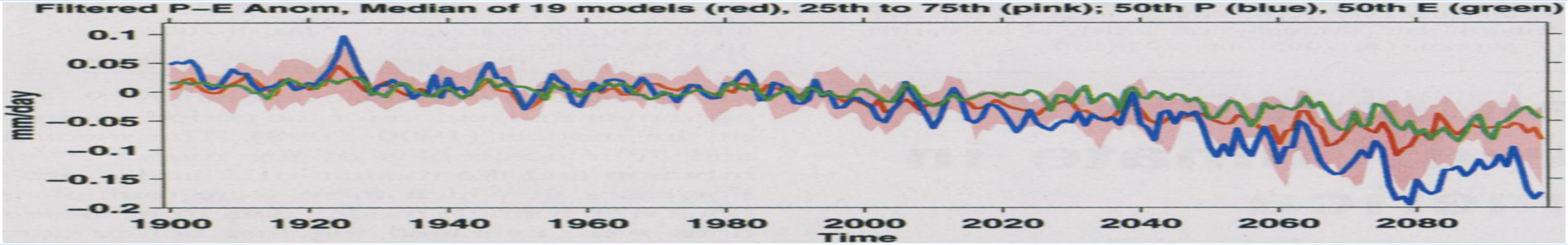



“Dry get Drier”

- Observation (Neelin et al. 2006, *PNAS*)



# Dry getting drier?

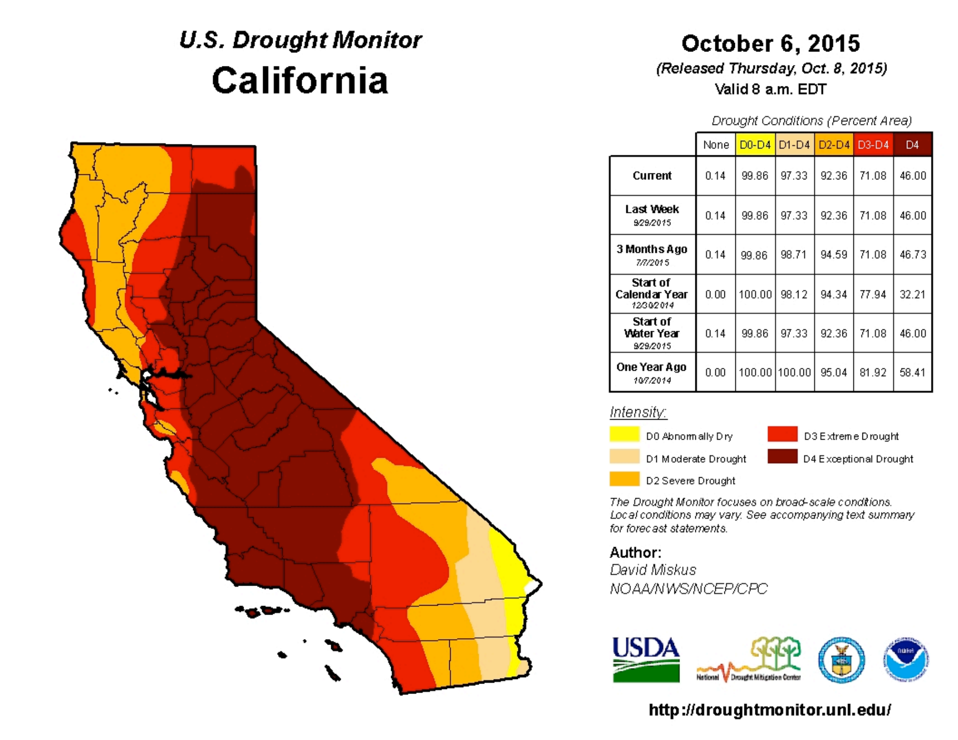



"If these models are correct, the levels of aridity of the recent multi-year drought or the Dust Bowl and the 1950s droughts will become the new climatology of the American Southwest within a time frame of years to decades."

-- Seager et al. 2007, *Science*

# Dry getting drier?

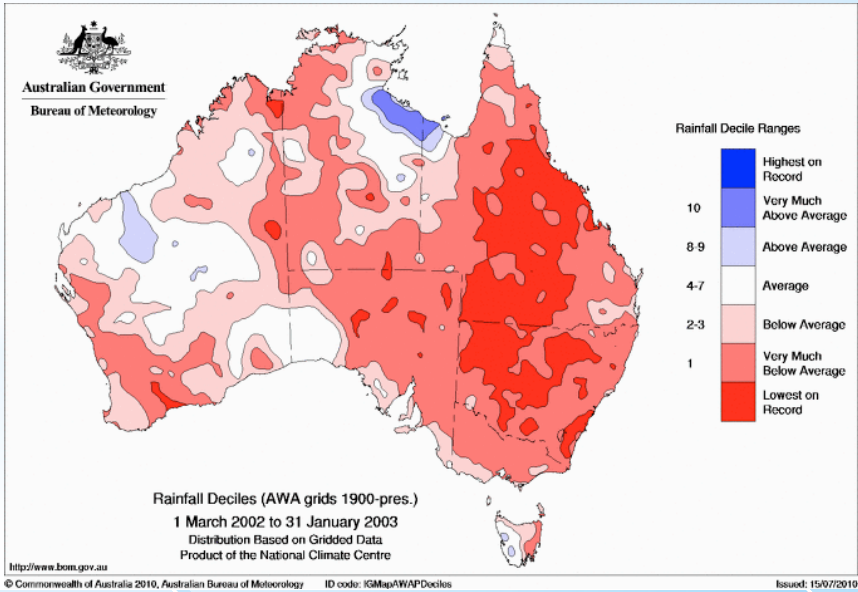
- California Drought (2011-)



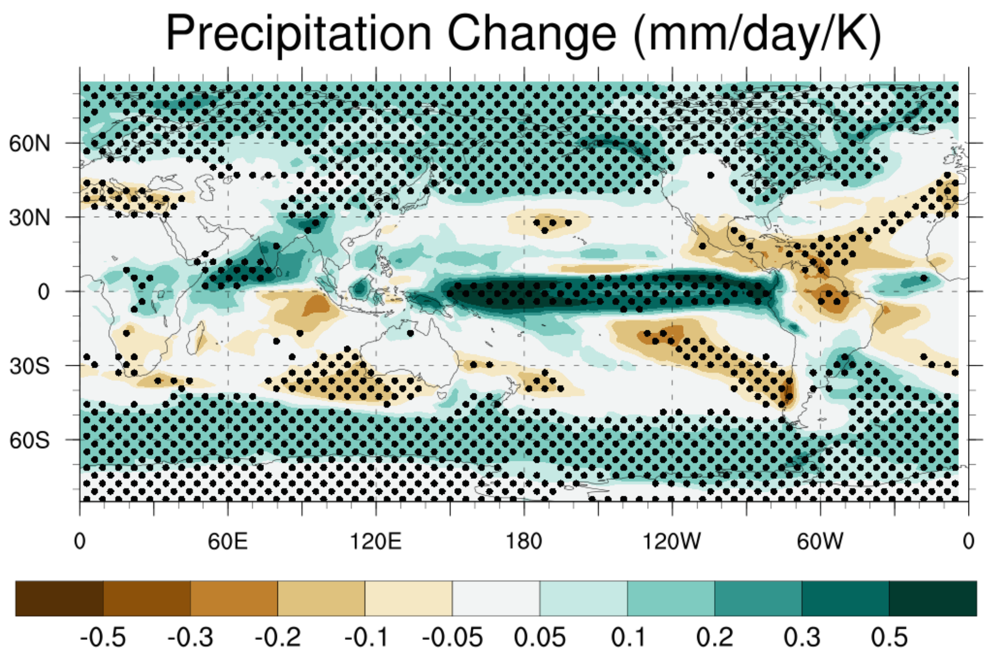

| | None | D0-D4 | D1-D4 | D2-D4 | D3-D4 | D4 |
|---|---|---|---|---|---|---|
| Current | 0.14 | 99.86 | 97.33 | 92.36 | 71.08 | 46.00 |
| Last Week 9/29/2015 | 0.14 | 99.86 | 97.33 | 92.36 | 71.08 | 46.00 |
| 3 Months Ago 7/7/2015 | 0.14 | 99.86 | 98.71 | 94.59 | 71.08 | 46.73 |
| Start of Calendar 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 |



- Australia Drought (1997-2009)



# Dry getting drier?




*Why not land?*

# 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*)

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

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

↓

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

↓ $\delta V \approx 0$

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

↓ $\delta q \approx q \times 7\% / K$

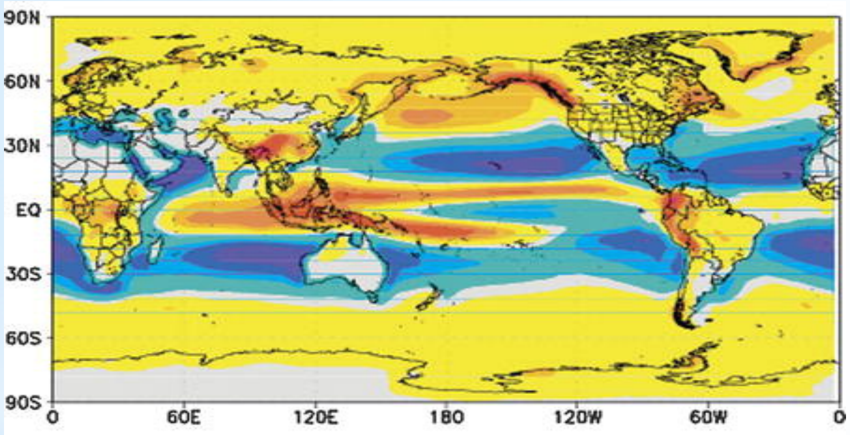
$$\boxed{\delta(P - E)} = -\int \nabla \cdot (q \cdot V) \times 7\% / K = \boxed{(P - E) \times 7\% / K}$$

# What drives the decline?

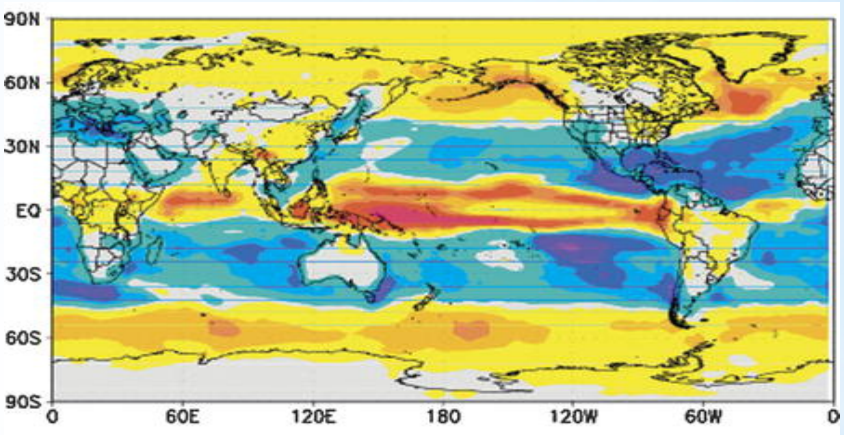
- **"Dry-get-drier"** (Held and Soden 2006, *J. Climate*)

$$\delta(P-E) = (P-E)\times 7\% / K$$

Climatological (P-E)x7%/K




Change in P-E




"Since the changes in precipitation have considerably more structure than the changes in evaporation, this simple picture helps us understand the zonally averaged pattern of precipitation change."

$\longrightarrow$ $\delta P \propto (P-E)$

# What drives the decline?

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

Subtropical precipitation decline

↑

Increased moisture export

↑

Increase in moisture

↑

Global mean warming

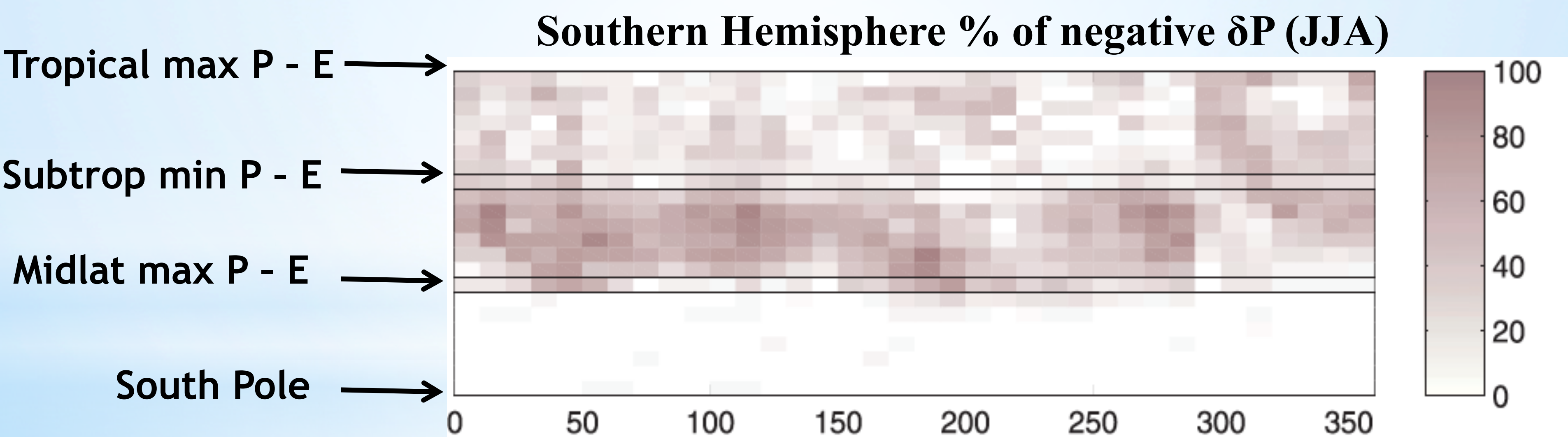
*(a thermodynamic response)*

# What drives the decline?

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

$$\delta P \propto (P - E) \;\; \mathbf{??}$$

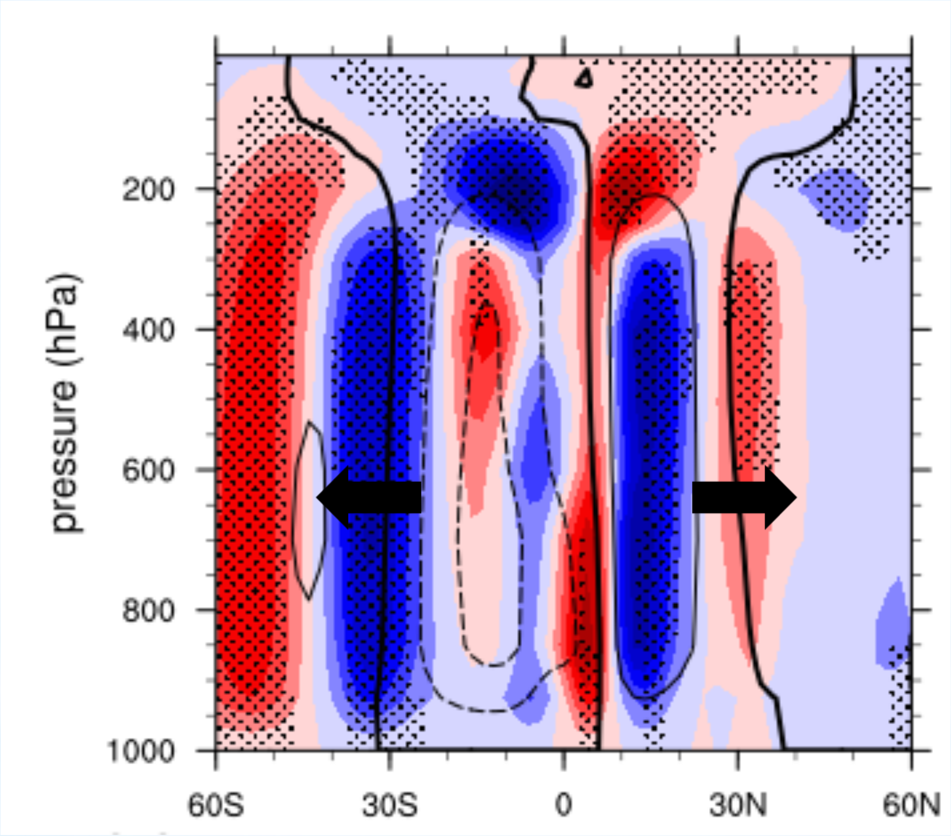
**Most of the decline happens poleward of P-E minima.**



# What drives the decline?

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

**Change in zonal mean stream function**




(He and Soden 2015, *J. Climate*)

# Which one is right?

- "Dry-get-drier"
- Poleward expansion

→ Mean SST warming

(Compo & Sardeshmukh 2009, *C Dyn*; Grise & Polvani 2014, *GRL*; He & Soden 2015, *J Climate*)

*Increasing $CO_2$*

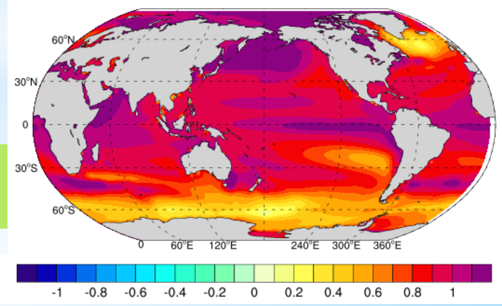
Atmospheric model

Land-sea warming contrast

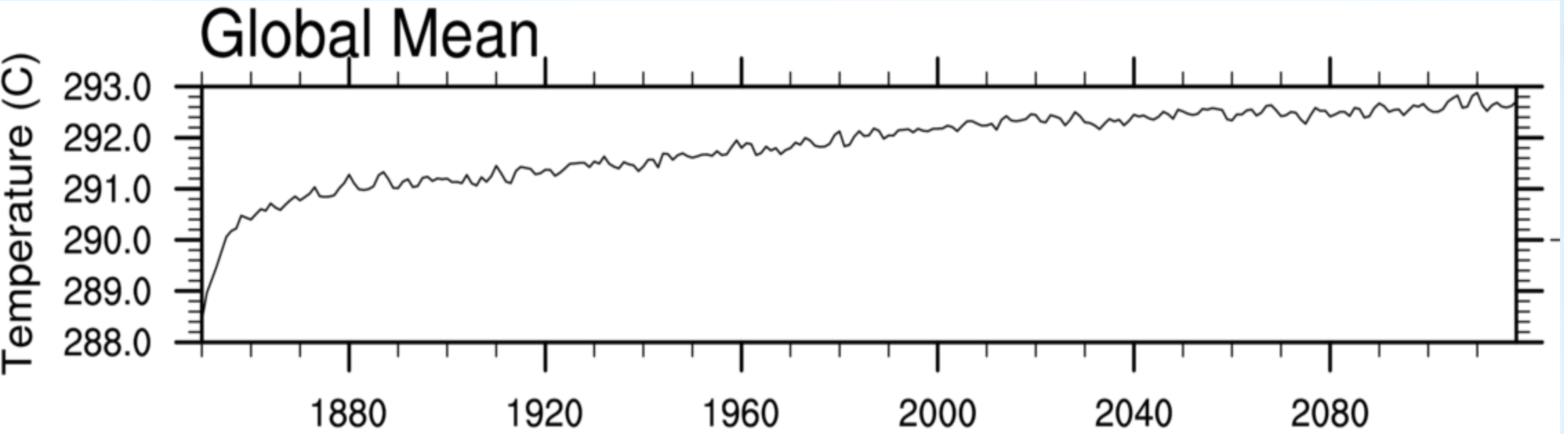
*SST warming*

*Mean SST warming*

*Pattern of SST change*



# *Abrupt4xCO2* (13 CGCMs, CMIP5)

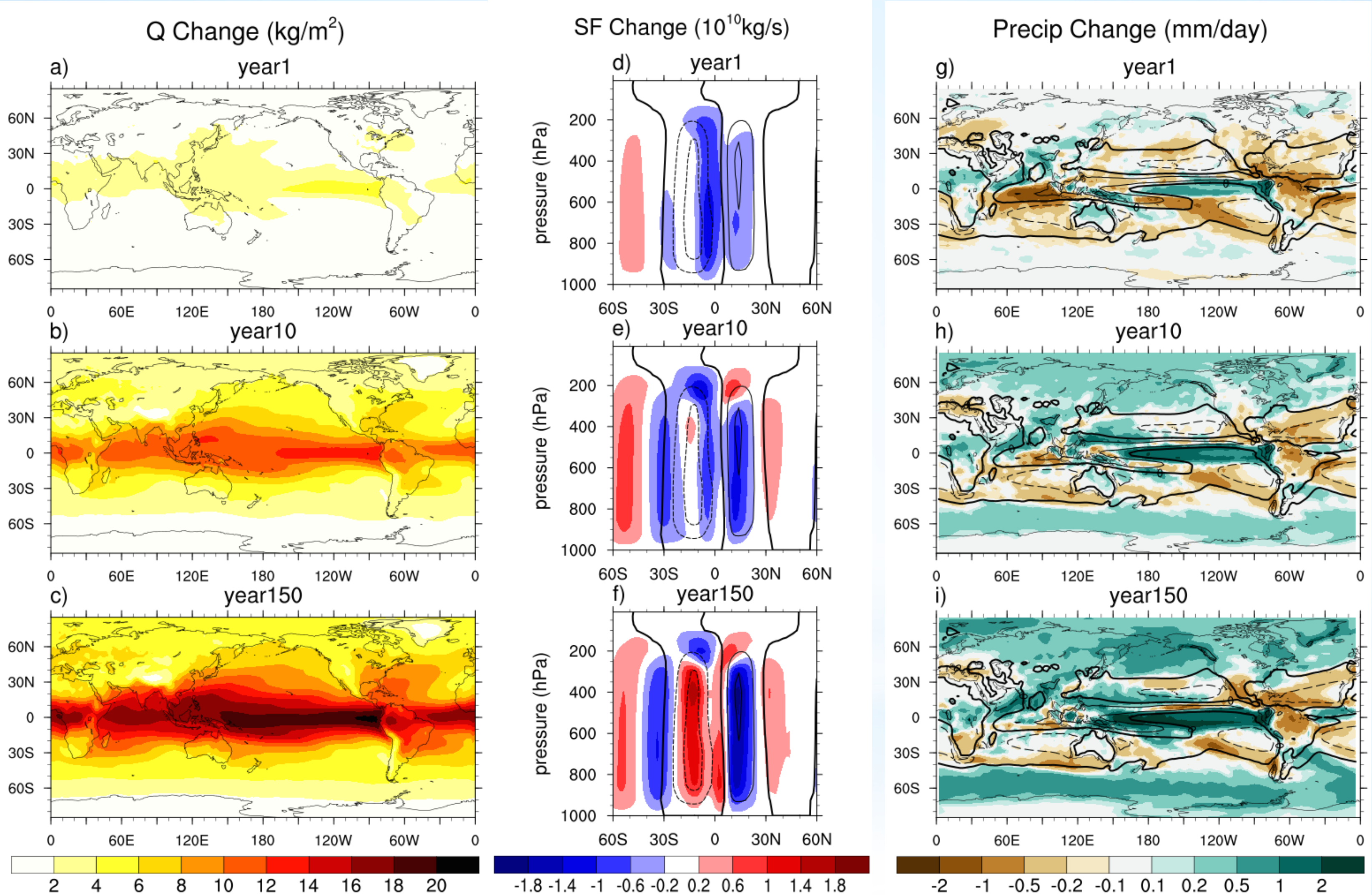



Direct $CO_2$ forcing
Land-sea warming contrast → Fast (1st year)
Pattern of SST change
Mean SST warming → Slow

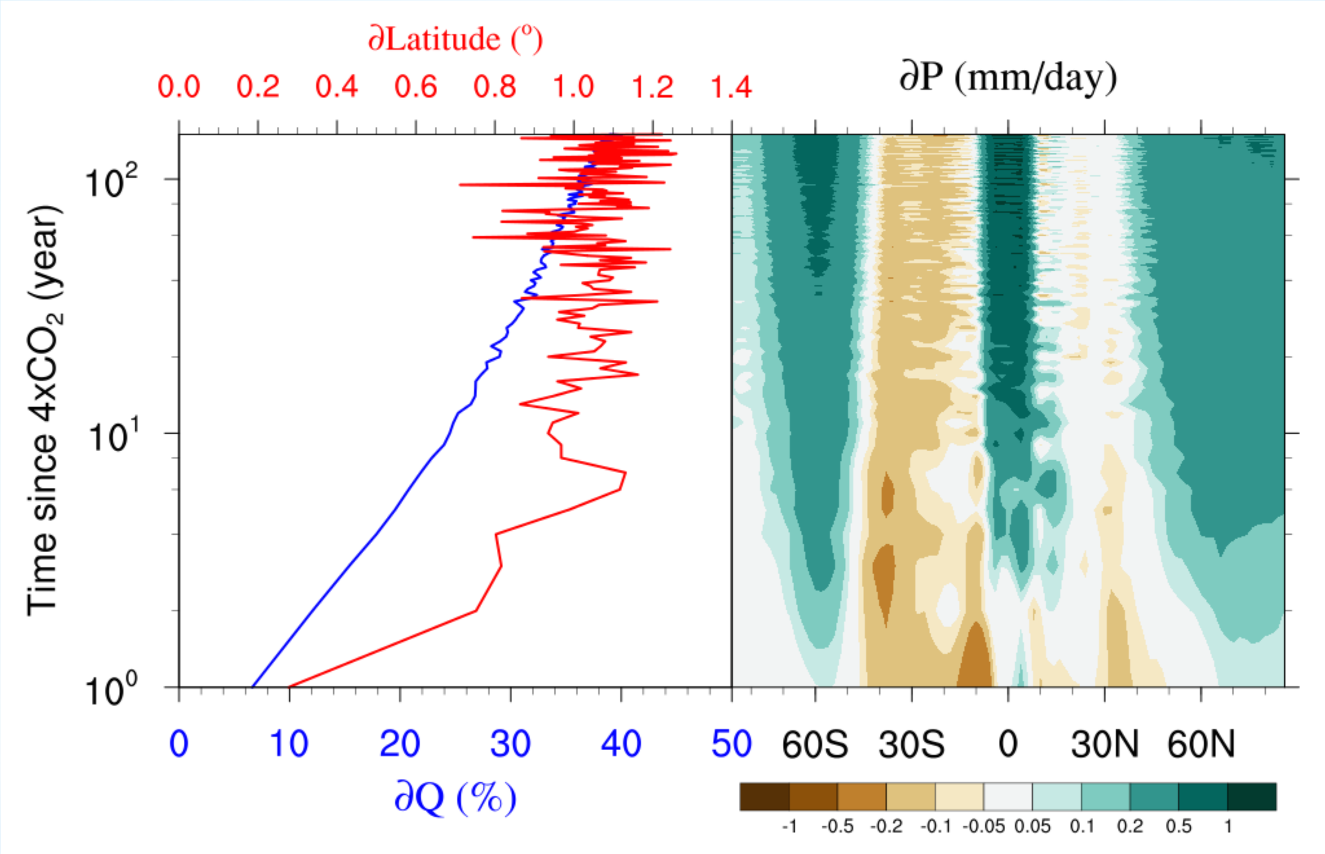
Fast precipitation response in the deep tropics:
Bony et al. 2013 *Nature Geo*; Chadwick et al. 2014 *GRL*

# Fast VS Slow responses

“Dry-get-drier” | Poleward expansion | Fast precipitation decline



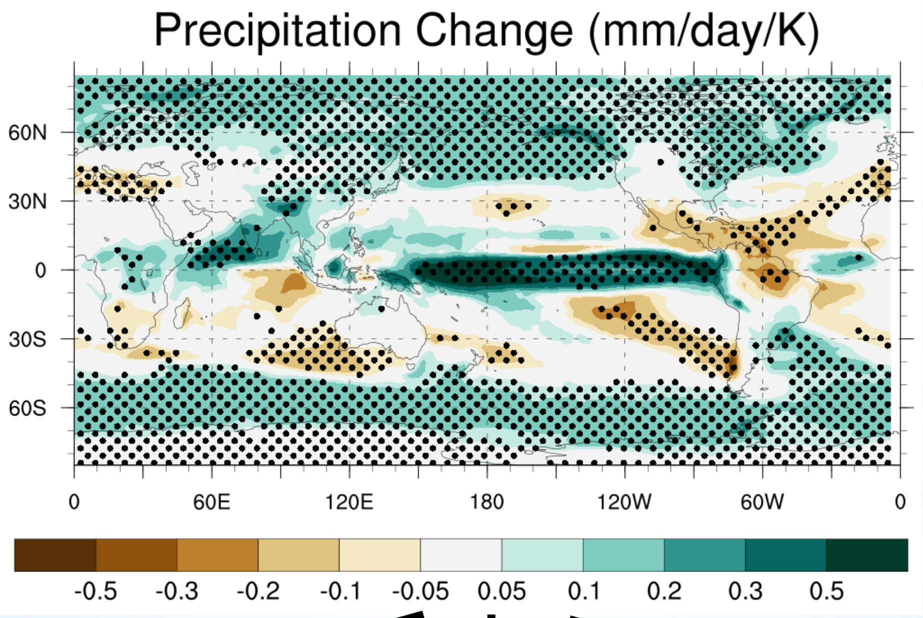
# Fast VS Slow responses




- Neither "Dry-get-drier" nor poleward expansion is required for the subtropical precipitation decline.
- Neither of the two mechanisms contributes substantially to 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

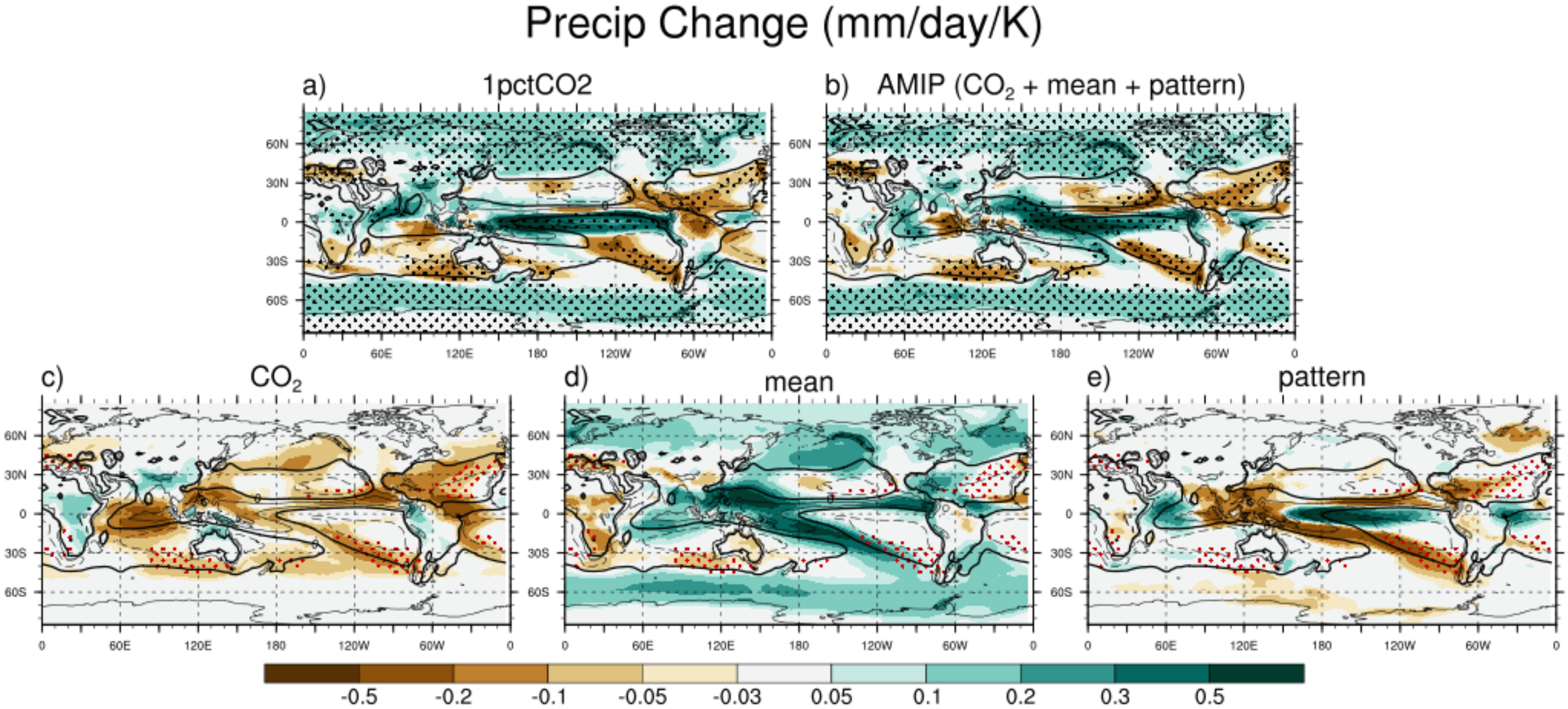
**AMIP_pattern**

Pattern of SST change only

# $CO_2$ VS mean VS pattern

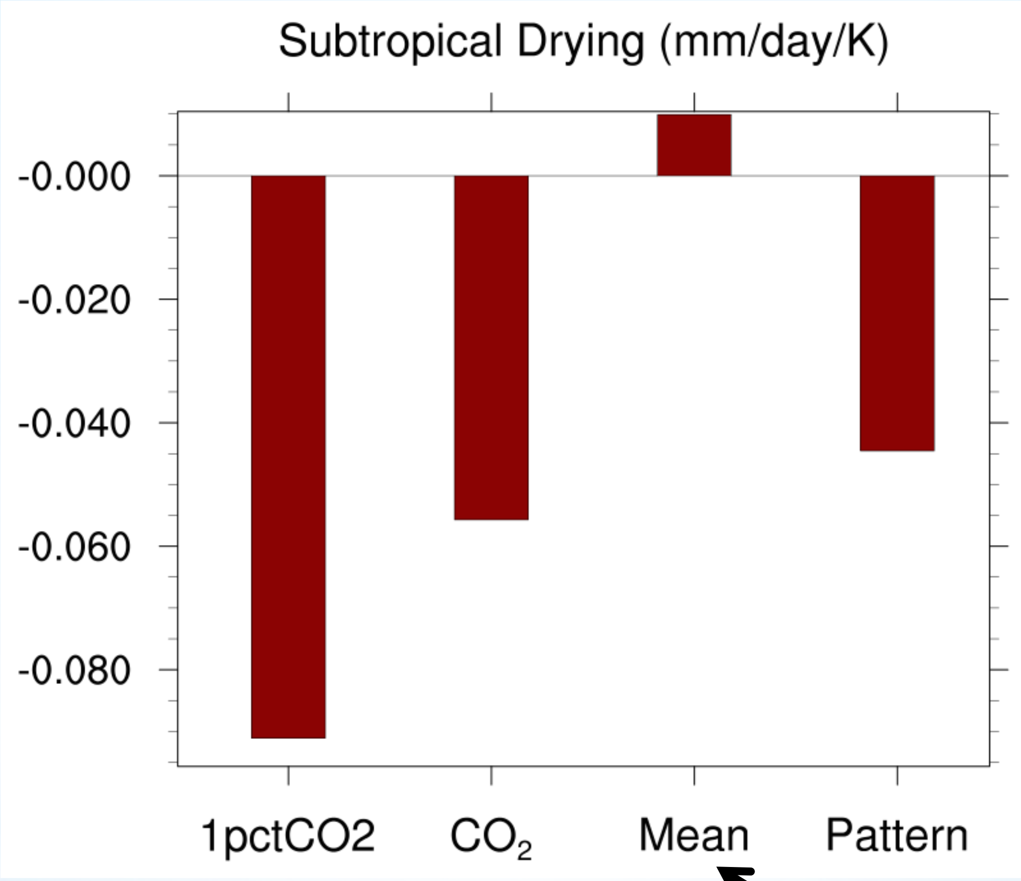
CMIP5 9-model mean

AMIP_pattern = AMIP_future – AMIP_mean




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

# $CO_2$ VS mean VS pattern

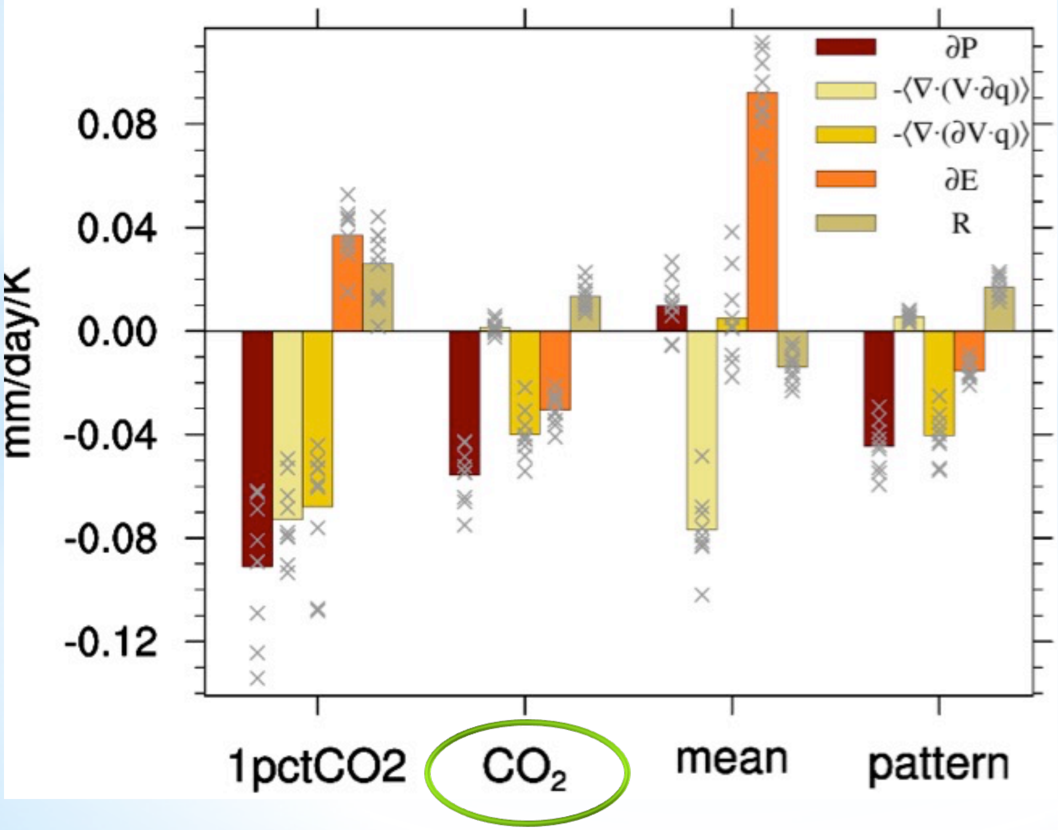



"Dry-get-drier"
& poleward expansion

# $CO_2$ VS mean VS pattern

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

$$\delta P = -\int \nabla\cdot(\delta q \cdot V) - \int \nabla\cdot(q\cdot \delta V) - \int \nabla\cdot(\delta q\cdot\delta V) + \delta E + R$$ (Seager et al. 2010, *J. Climate*)

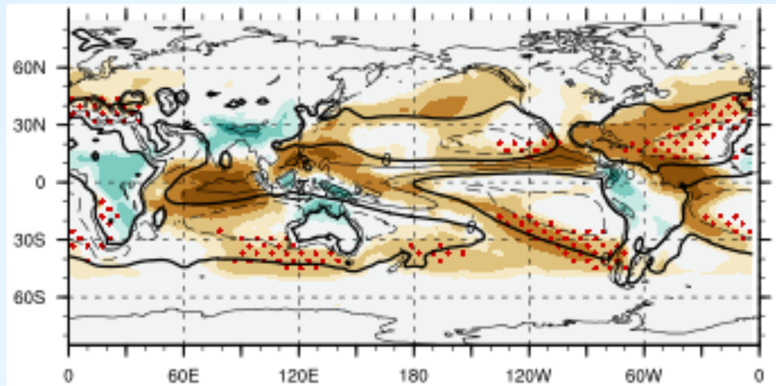



Direct $CO_2$ forcing *(Bony et al. 2013, Nature Geo)*

Land-sea warming contrast *(Chadwick et al. 2014, GRL; He & Soden 2015, J. Climate)*

# Direct $CO_2$ VS Land-sea contrast

δP in AMIP_CO2

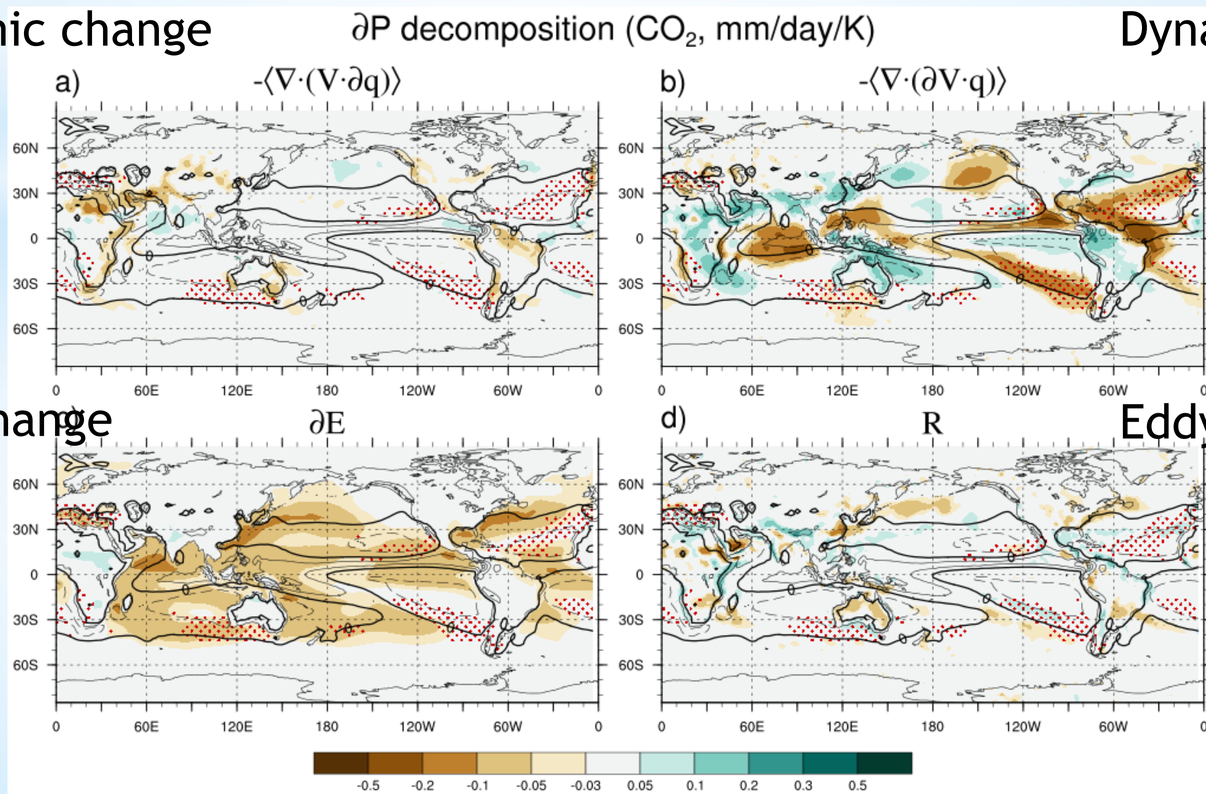



Thermodynamic change

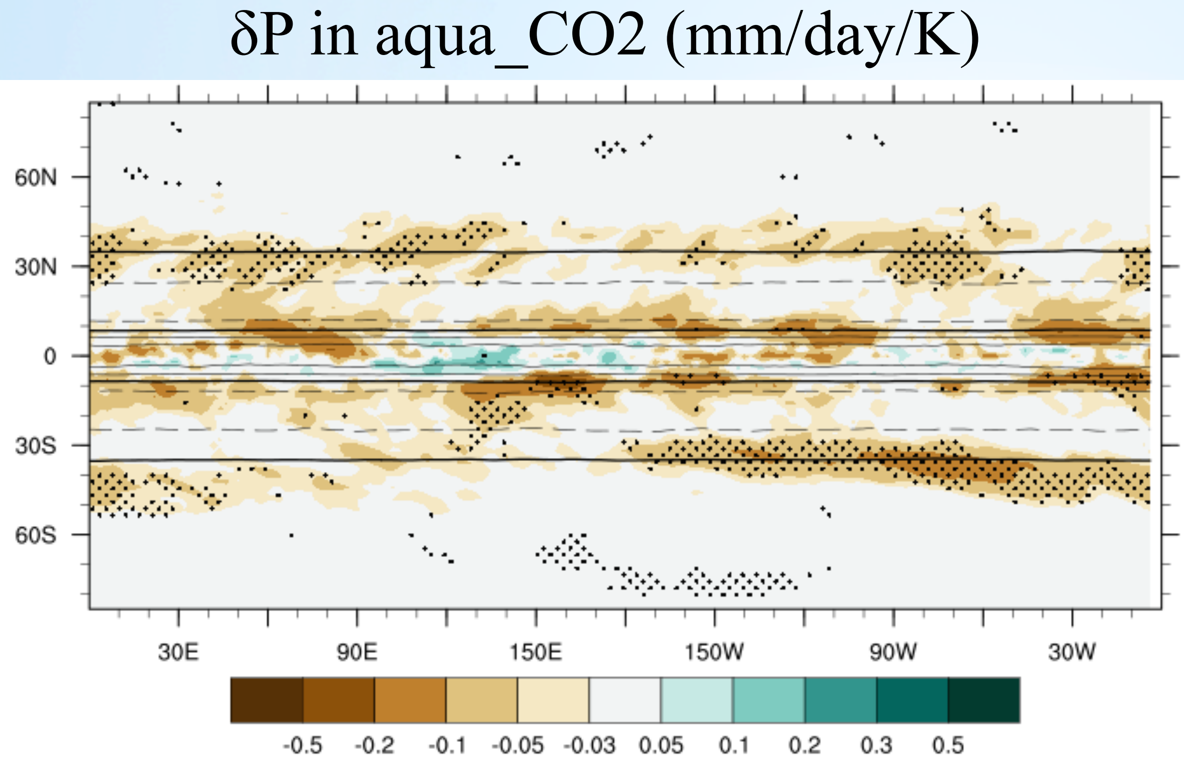
Dynamic change

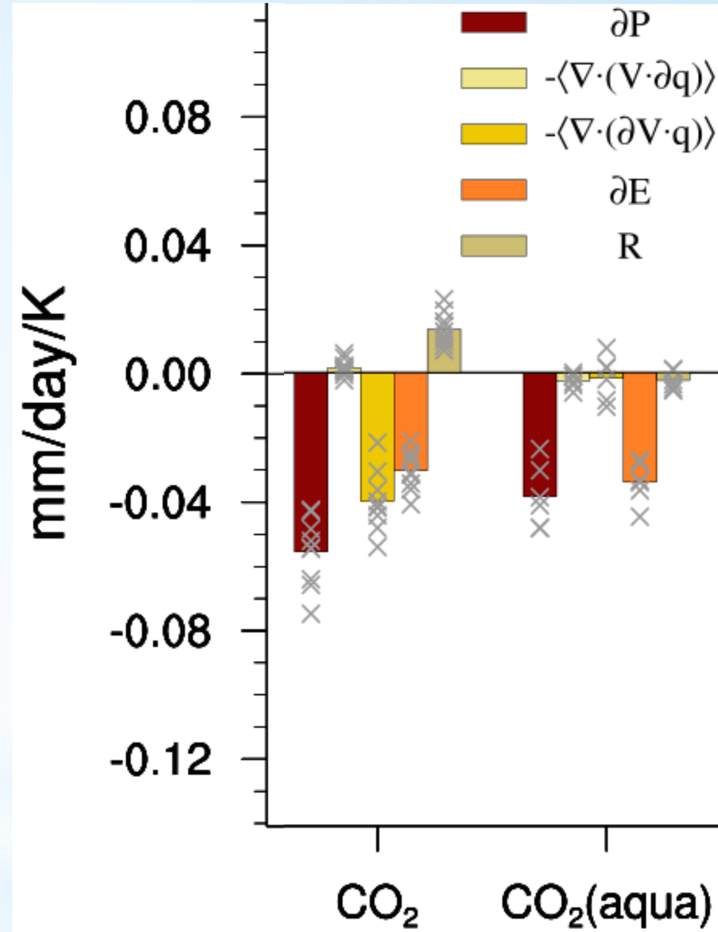
Evaporation change

Eddy transport



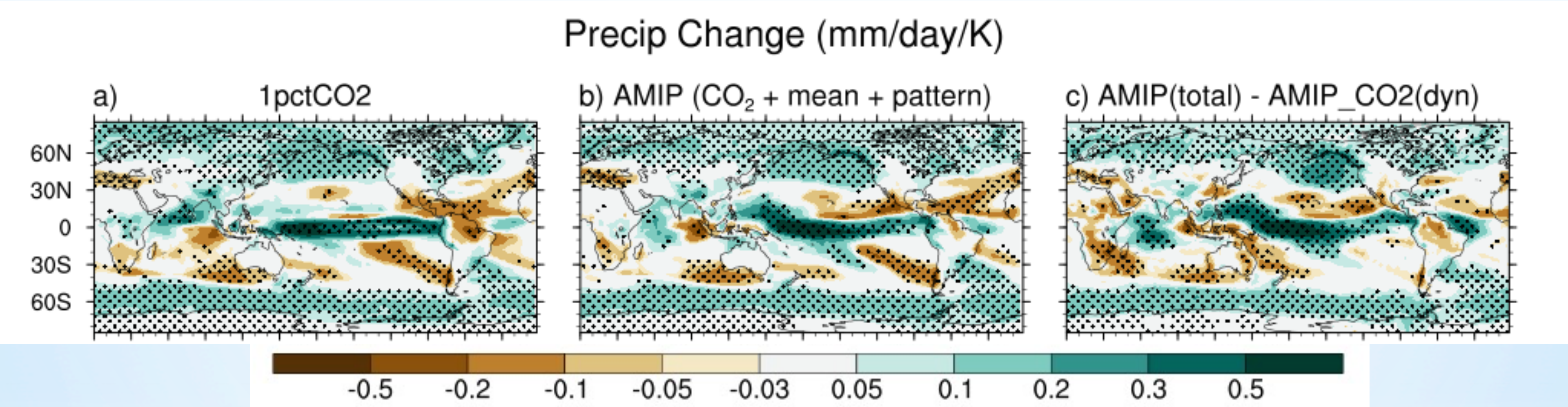
# Direct $CO_2$ VS Land-sea contrast




- Land-sea contrast drives dynamic change.
- Direct $CO_2$ forcing reduces evaporation (He and Soden 2015, *J. Climate*).

# Land-sea warming 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

* Conventional wisdom: “dry-get-drier” and poleward expansion.
* Subtropical precipitation decline is primarily a fast response and does not depend on changes 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.

## References


Bony, S. *et al*. Robust direct effect of carbon dioxide on tropical circulation and regional precipitation. *Nat. Geosci* **6,** 447–451 (2013).

Chadwick, R., Good, P., Andrews, T. and Martin, G. Surface warming patterns drive tropical rainfall pattern responses to CO2 forcing on all timescales. *Geophys. Res. Lett.* **41,** 610-615 (2014).

Grise, K. M. and Polvani, L. M. The response of midlatitude jets to increased CO2: Distinguishing the roles of sea surface temperature and direct radiative forcing.

He, J., and B. J. Soden, 2015: Anthropogenic Weakening of the Tropical Circulation: The Relative Roles of Direct CO2 Forcing and Sea Surface Temperature Change. *J. Clim.*, **28**, 8728–8742, doi:10.1175/JCLI-D-15-0205.1.

Held, I. M., and B. J. Soden, 2006: Robust responses of the hydrological cycle to global warming. *J. Clim.*, **19**, 5686–5699, doi:10.1175/JCLI3990.1.

Neelin, J. D., M. Münnich, H. Su, J. E. Meyerson, and C. E. Holloway, 2006: Tropical drying trends in global warming models and observations. *Proc. Natl. Acad. Sci.*, **103**, 6110–6115, doi:10.1073/pnas.0601798103.

Scheff, J., and D. Frierson, 2012: Twenty-first-century multimodel subtropical precipitation declines are mostly midlatitude shifts. *J. Clim.*, **25**, 4330–4347, doi:10.1175/JCLI-D-11-00393.1.

Seager, R. *et al*. Model projections of an imminent transition to a more arid climate in southwestern North America. *Science* **316,** 1181–1184 (2007).

Seager, R., Naik, N. and Vecchi, G. A. Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. *J. Clim.* **23,** 4651–4668 (2010).


***Thank you*** ☺