# Mechanisms of Regional Precipitation Change from Anthropogenic Forcing

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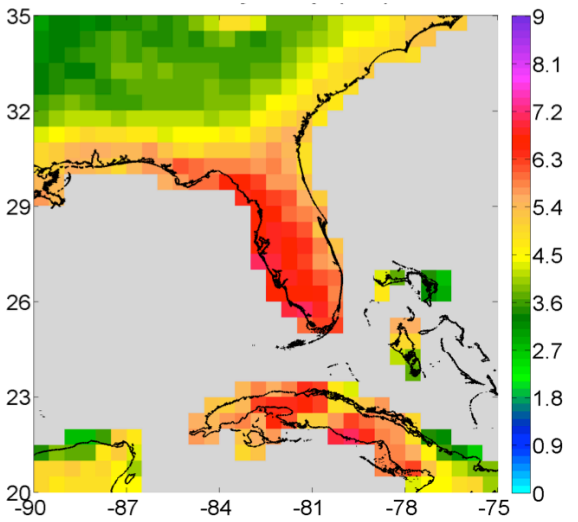
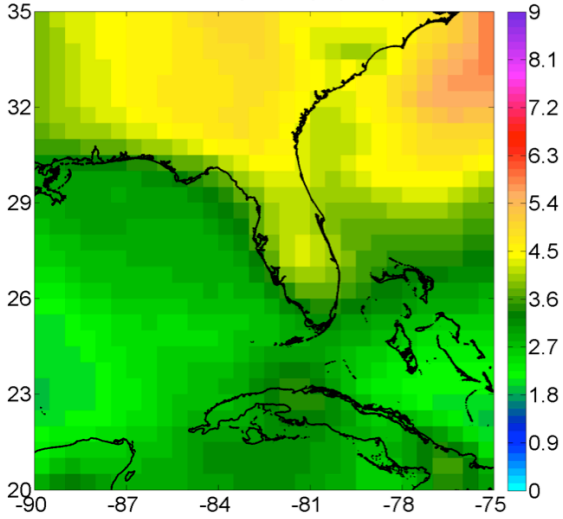
# Challenges in regional precipitation simulation

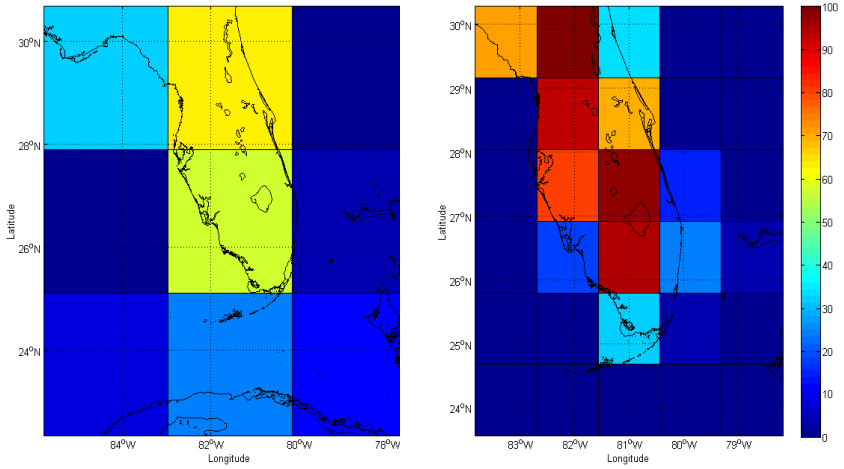
GPCC v5 JJA Rainfall (mm/d)




CMIP5 JJA Rainfall (mm/d)




## Low Model Resolution




Courtesy Roque V. Cespedes (UM)

# Can we use High Resolution "time-slice" Experiments?

High resolution atmosphere-only models forced with projected changes in SST from CGCMs

1. Is **"two-way" coupling** important for regional climate change?

2. Is **details of SST change** important for regional precipitation change?

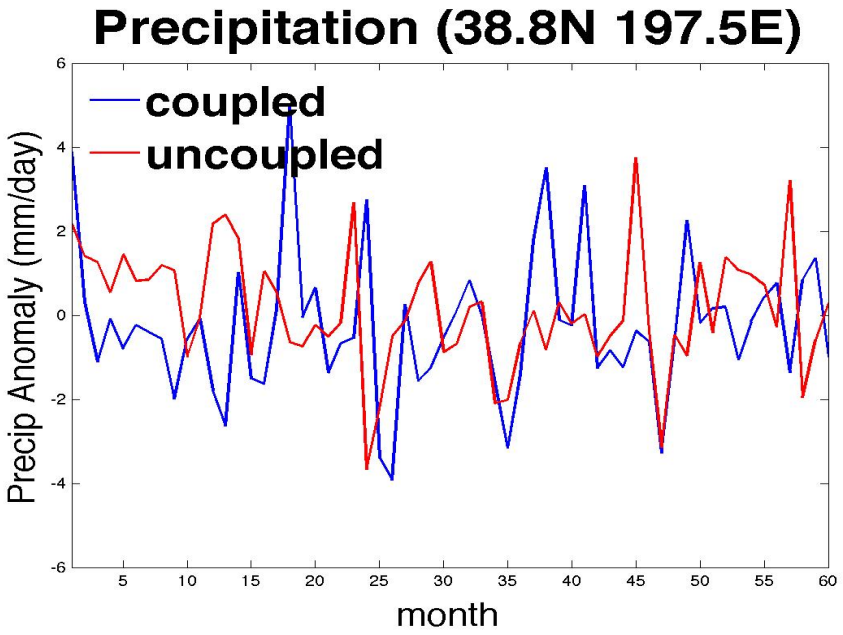
3. Are we getting realistic regional climate change from **CGCMs**?

4. What are some practical ways forward?

- **Fast & slow** precipitation responses in the subtropics and extratropics.

# Impact of Two-way Coupling

Two-way Coupling is **important** for **natural climate variability**.



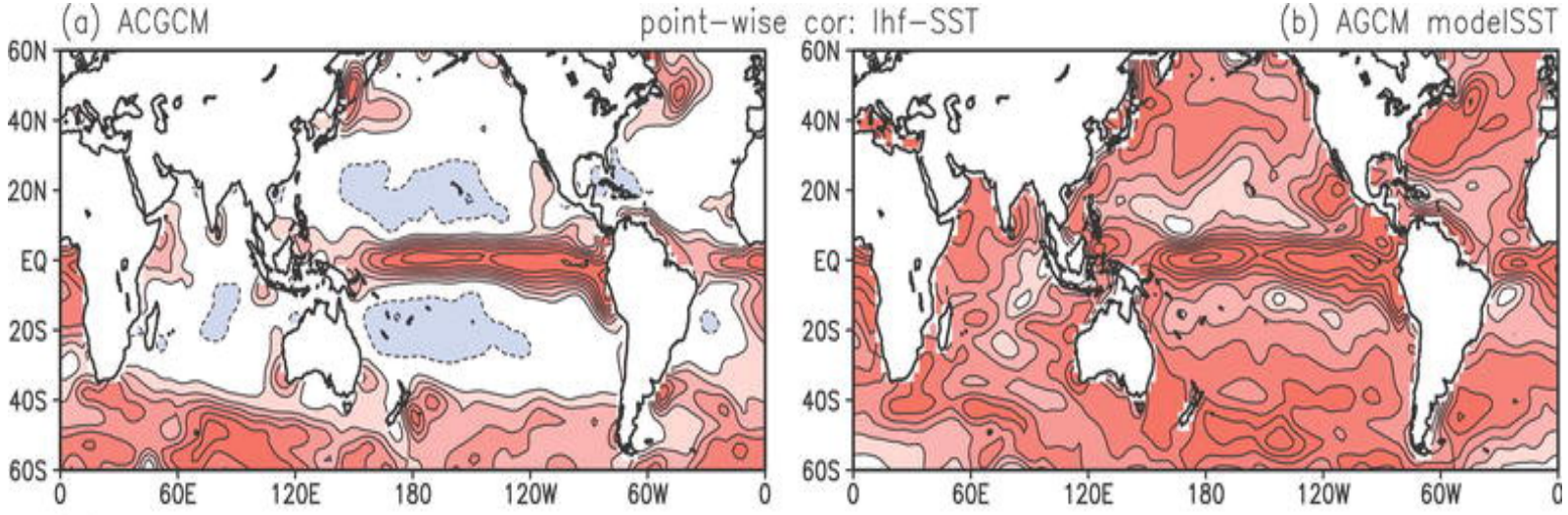

Lack of coupling leads to inconsistency b/w atmos and ocean.

# Impact of Two-way Coupling

The importance of two-way coupling for **natural climate variability** is well documented.

(e.g., Barsugli and Battisti 1998; Wang et al. 2005; Wu et al. 2006)

**coupled** **VS** **uncoupled**




(Wu et al. 2006)

**What about anthropogenic climate change?**

# Impact of Two-way Coupling

**Compare coupled and uncoupled simulations that have the same atmospheric model and SST & sea ice.**

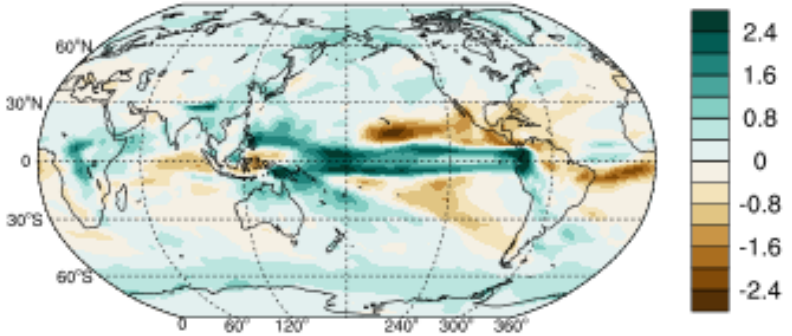
**Model:** CESM
**Resolution:** approximately 2º for atmosphere & land and 1º for ocean

**Simulations:**
**CGCM, 1pctCO2**
**AGCM, 1pctCO2** (SST and sea ice from CGCM 1pctCO2)
**CGCM, pre-industrial**
**AGCM, pre-industrial** (SST and sea ice from CGCM pre-industrial)

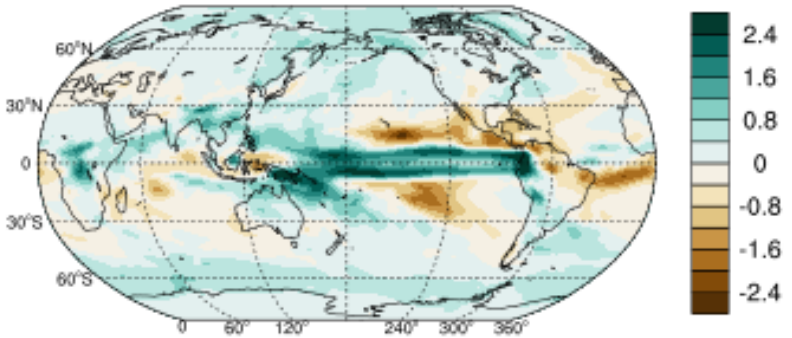
**Run time:** 150 years
**Climate change:** 10-year epoch difference

# Impact of Two-way Coupling

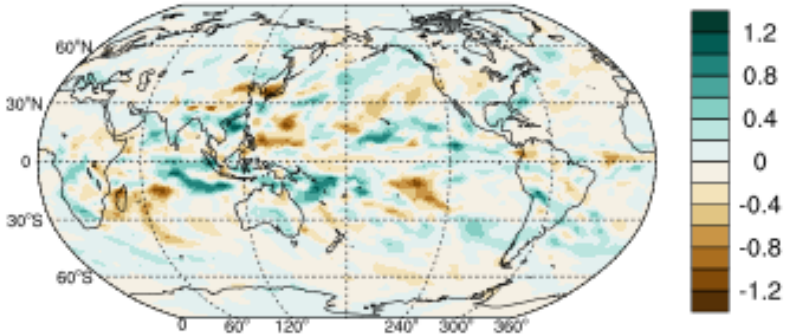
CGCM ΔP 4xCO$_2$ (last10yr - first10yr)

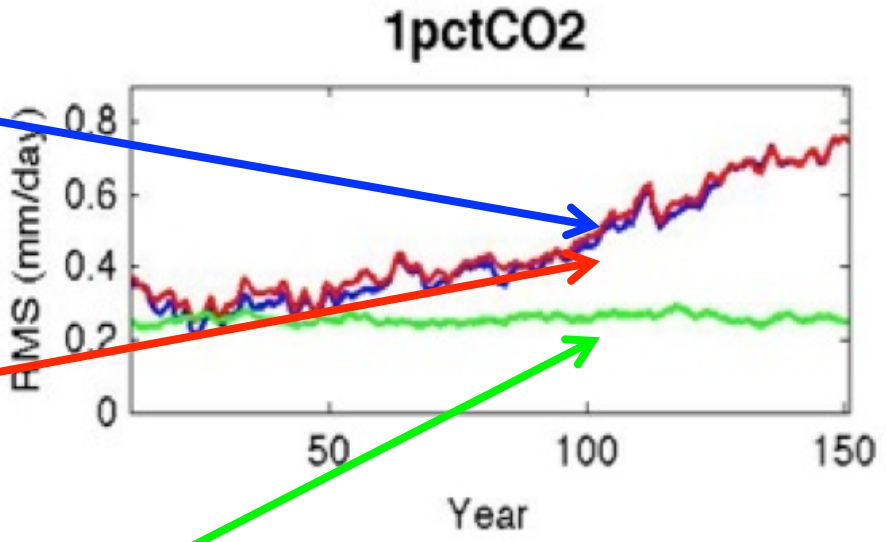



AGCM ΔP 4xCO$_2$ (last10yr - first10yr)



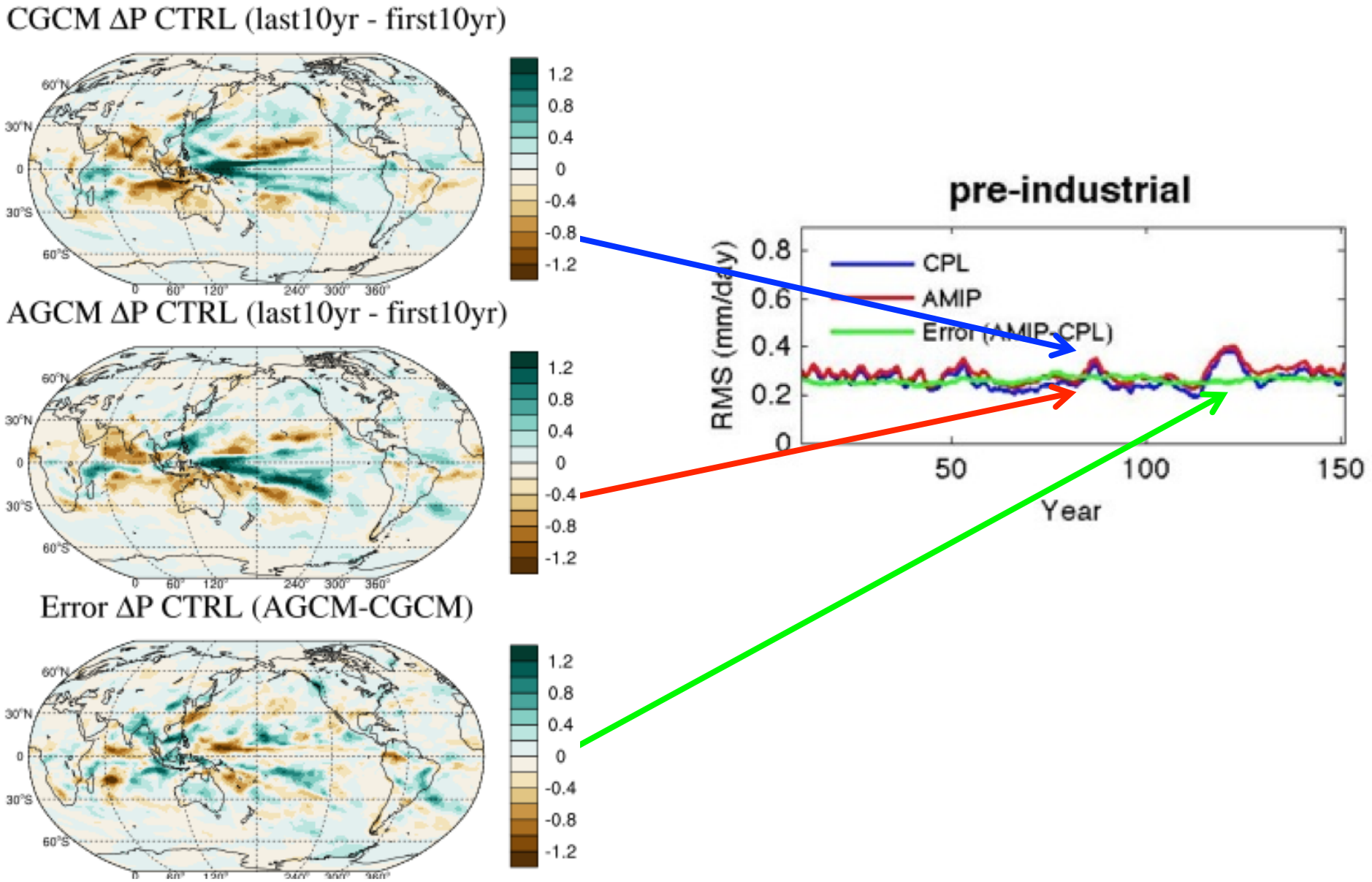

Error ΔP 4xCO$_2$ (AGCM-CGCM)



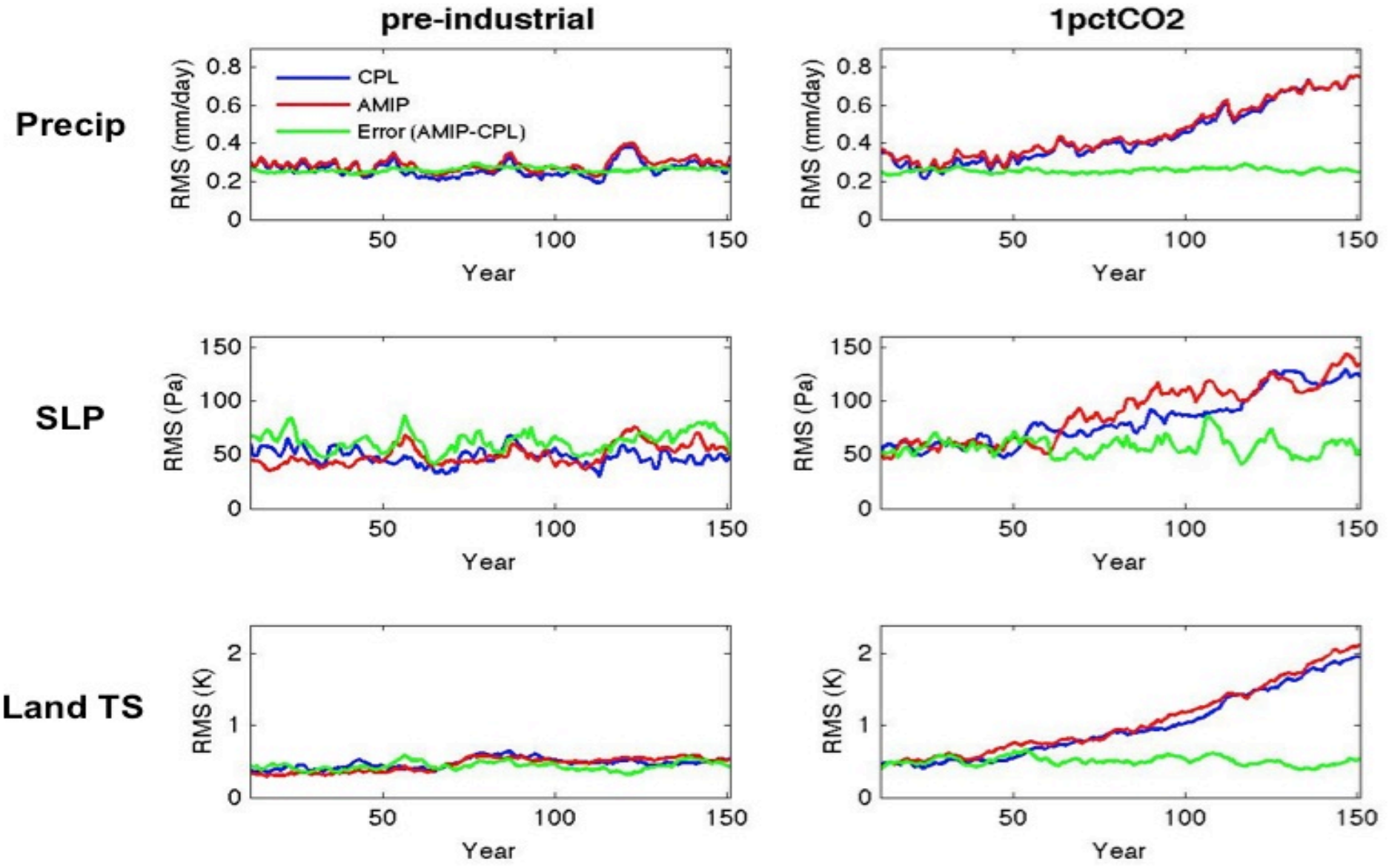




Error due to lack of two-way coupling is independent of external forcing.

# Impact of Two-way Coupling



# Impact of Two-way Coupling

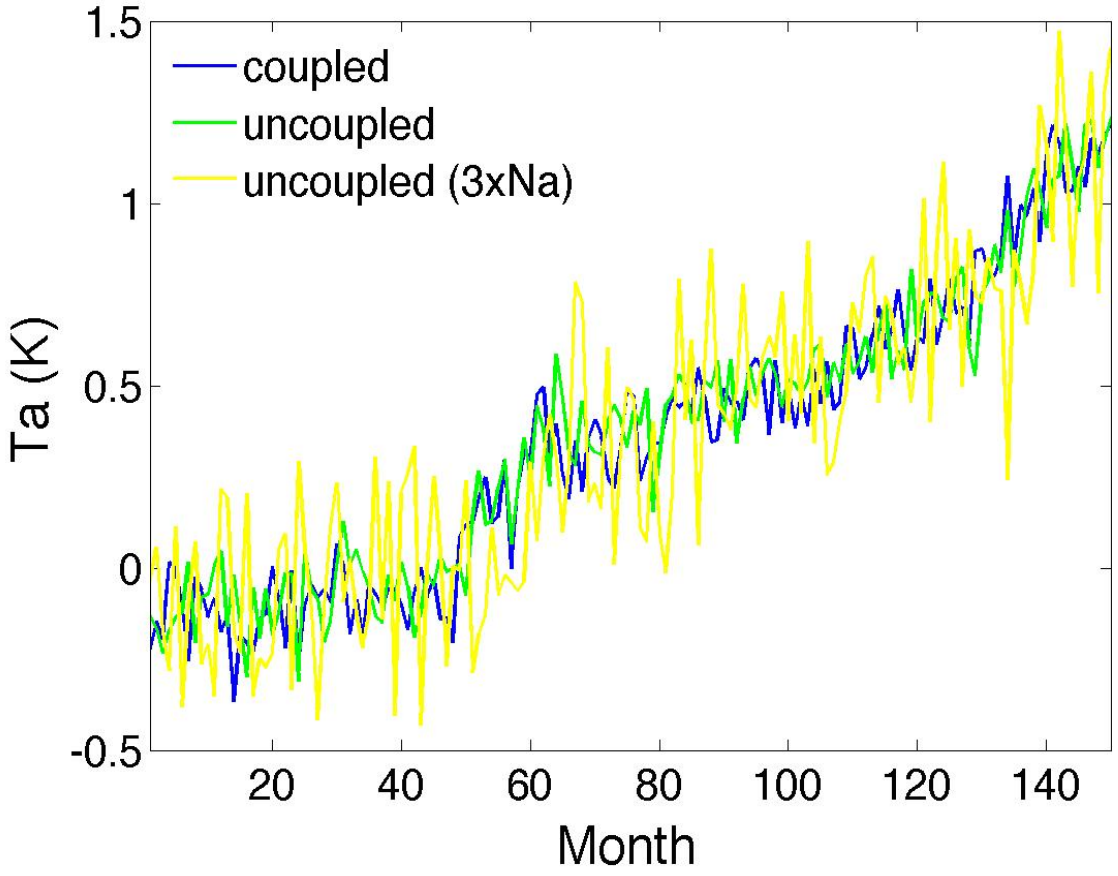


# Impact of Two-way Coupling

$$\frac{dTa}{dt} = \lambda_A (SST - Ta) + F_A + N_A$$

$$\frac{dSST}{dt} = \lambda_O (Ta - SST) + F_O$$

***Ta: air temperature***
***SST: sea surface temperature***
***λ: air-sea interaction coefficient***
$\lambda_A = 23.9 \times 10^{-7}\ s^{-1}$
$\lambda_O = 12.7 \times 10^{-8}\ s^{-1}$
***F: radiative forcing and damping***
$F_A = -1.62\ W/m^2$
$F_O = 2.10\ W/m^2$
***$N_A$: Stochastic forcing (white noise)***
$std(N_A) = 0.2K/6days$
***timestep=6days***



1. **Is "two-way" coupling important for regional climate change? No***

2. **Is details of SST change important for regional precipitation change?**

3. **Are we getting realistic regional climate change from CGCMs?**

4. **What are some practical ways forward?**

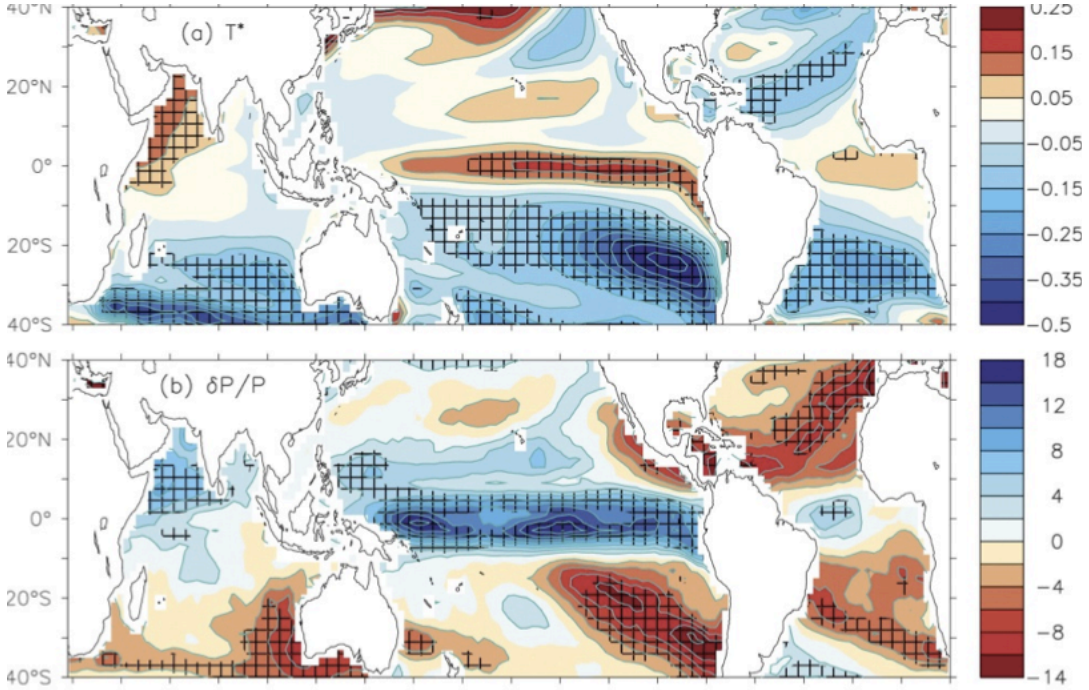
# Pattern of SST Change

Over **ocean**: "warmer-get-wetter"

(e.g., Xie et al. 2010; Ma and Xie 2013; Chadwick et al. 2013; Kent et al. 2015)

Relative SST change

precip change




Ma and Xie (2013)

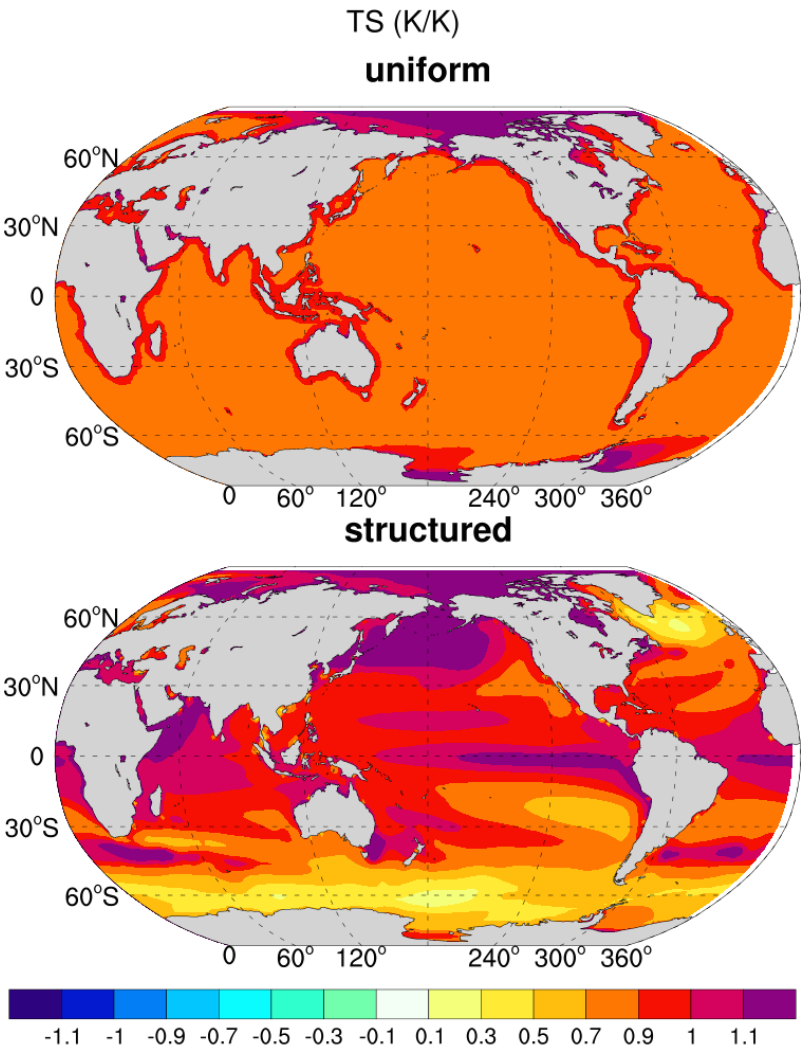
Is the pattern of ΔSST important for precipitation change over **land?**

# Pattern of SST Change

Model Output: CMIP5 (9 models)

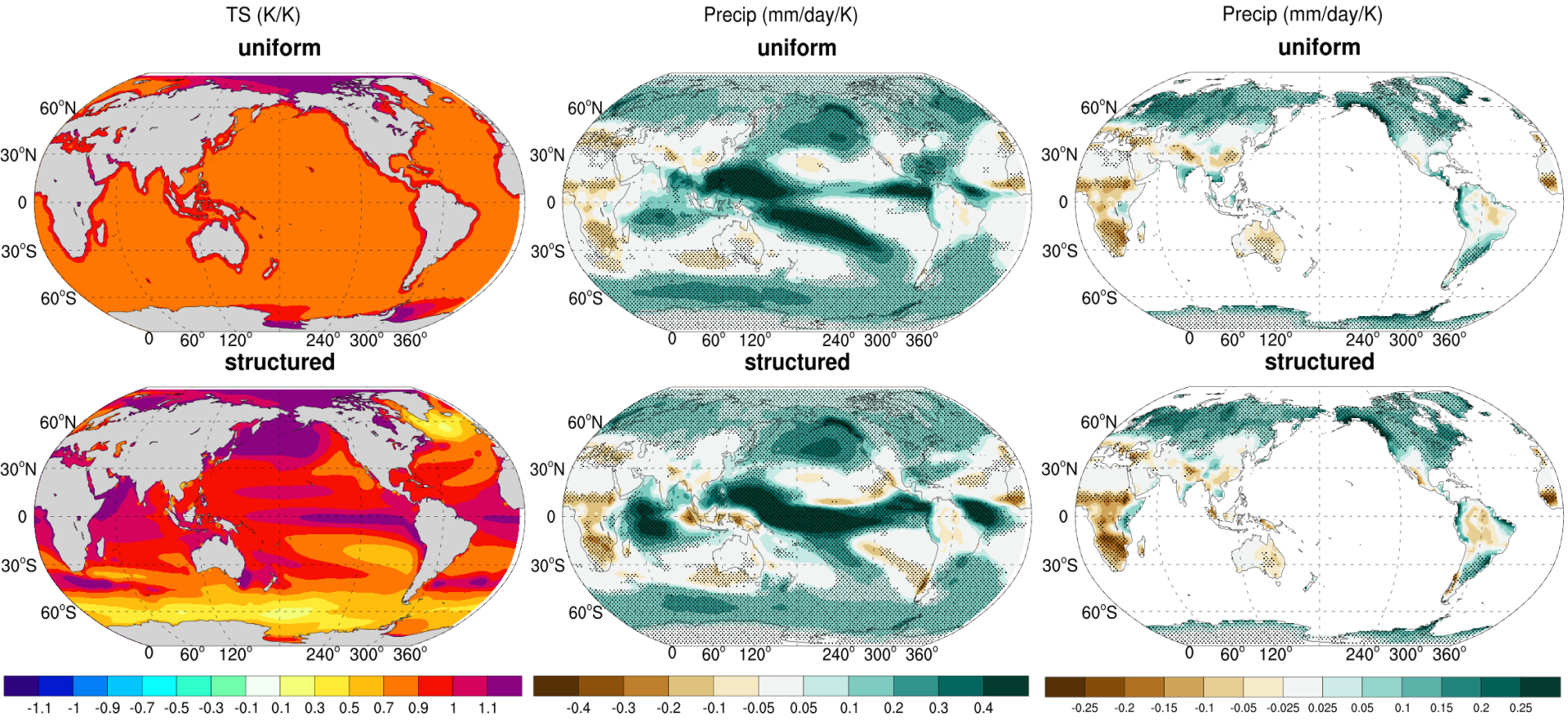
Experiments:

- AMIP control
  (1979~2008 obs SST)
- **Uniform Warming**
  (+4K)
- **Structured warming**
  (ΔSST at 4x$CO_2$)




Changes are normalized by each model's global mean TS change.

# Pattern of SST Change




**Land precipitation is insensitive to the pattern of SST change.**

# Pattern of SST Change

Tropical ΔSST can impact land remotely through

**Rossby Wave** Propagation

(e.g., Sardeshmukh and Hoskins 1988; Ting and Sardeshmukh 1993; Schneider et al. 2003)

Rossby Wave Source (**RWS**)

$$\frac{\partial \varsigma}{\partial t} + V_\psi \cdot \nabla \varsigma = -\varsigma \cdot D - V_\chi \cdot \nabla \varsigma$$

$$\downarrow$$

$$RWS' = (-\varsigma \cdot D - V_\chi \cdot \nabla \varsigma)'$$

$$\downarrow$$

$$RWS' = -\varsigma' \cdot D - \varsigma \cdot D' - \varsigma' \cdot D' - V_\chi' \cdot \nabla \varsigma - V_\chi \cdot \nabla \varsigma' - V_\chi' \cdot \nabla \varsigma'$$

$$\downarrow$$

$$RWS' = -\varsigma \cdot D'$$

Absolute Vorticity

Changes in upper-level divergence

$\varsigma$ Absolute vorticity

$V_\psi$ Rotational wind

$D$ Divergence

$V_\chi$ Divergent wind

# Pattern of SST Change

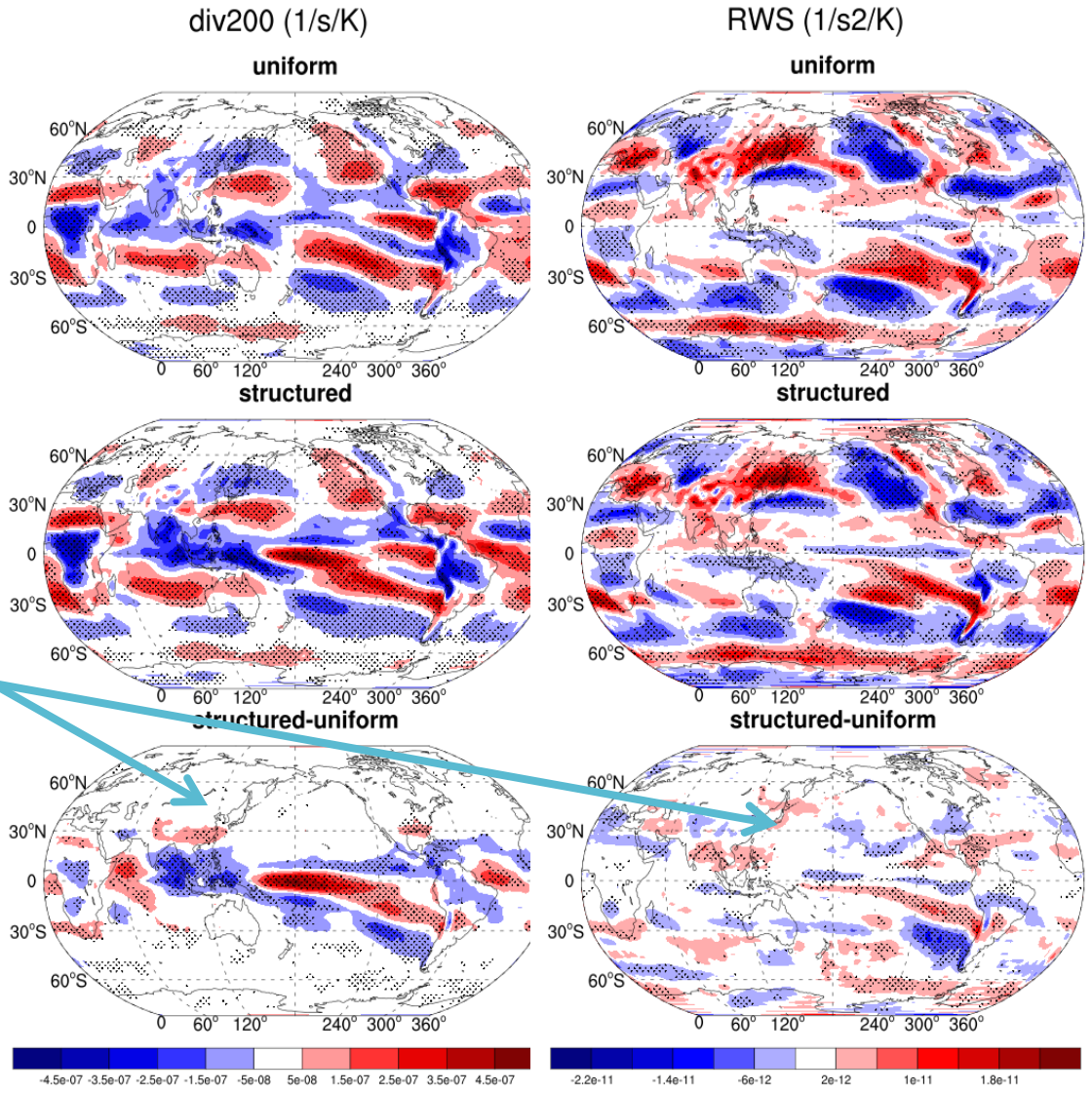
tropical ΔSST ---> land
**Rossby Wave** Propagation

Absolute Vorticity

Changes in upper-level divergence

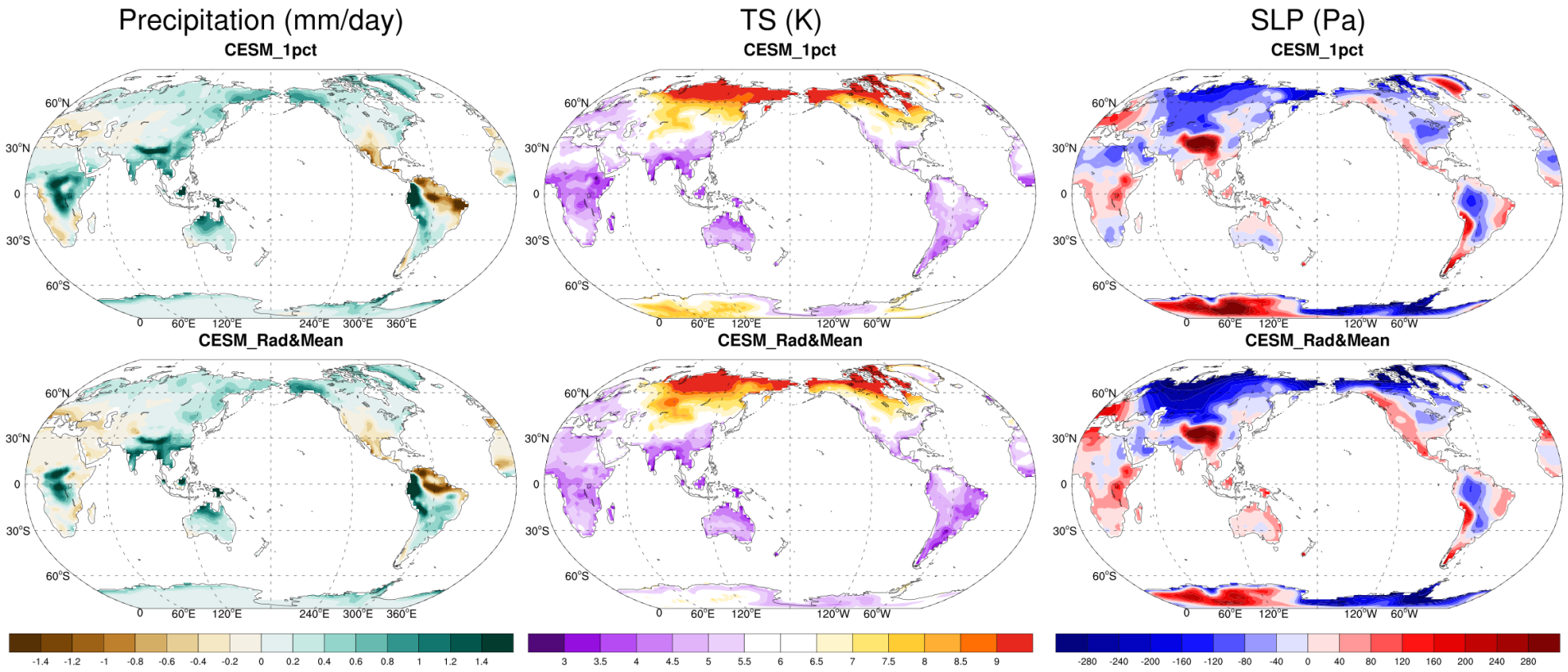
$$RWS' = -\varsigma \cdot D'$$

Very little Rossby Waves are generated by the pattern of ΔSST.



# Pattern of SST Change

We can simulate land climate change using AGCM forced with **only increased $CO_2$ and a uniform warming.**
(results from CESM)




corr=0.86 (pr), 0.95 (TS), 0.85 (SLP)

1. Is “two-way” coupling important for regional precipitation change? No*

2. Is details of SST change important for regional precipitation change? Not for land*

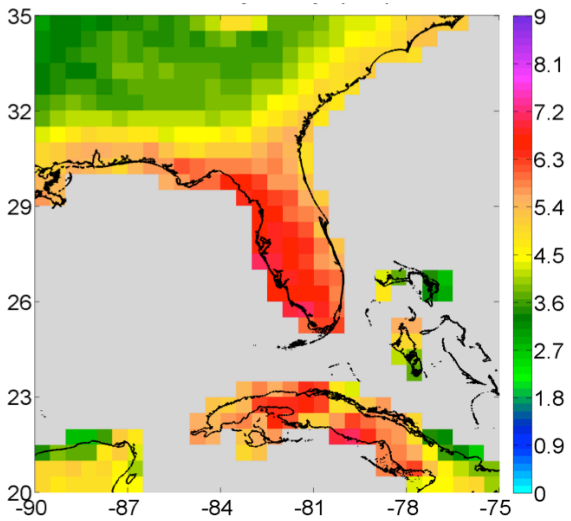
3. Are we getting realistic regional climate change from CGCMs?

4. What are some practical ways forward?

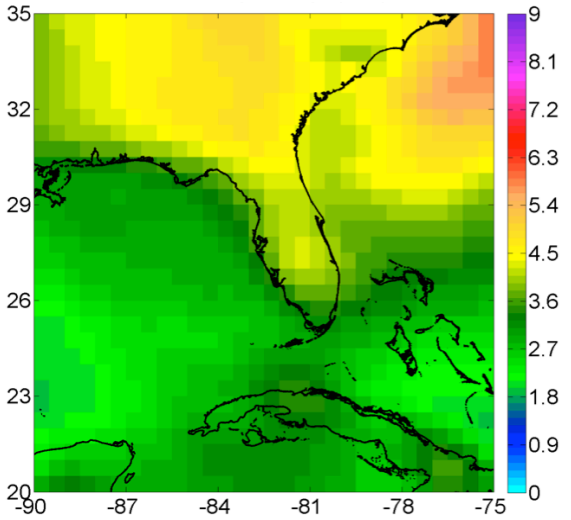
# Climatological Biases

How could we get realistic projections if we could not even simulate the climatology?

GPCC v5 JJA Rainfall

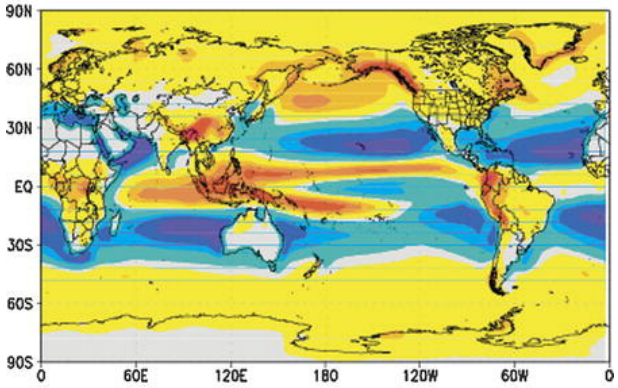



CMIP5 JJA Rainfall

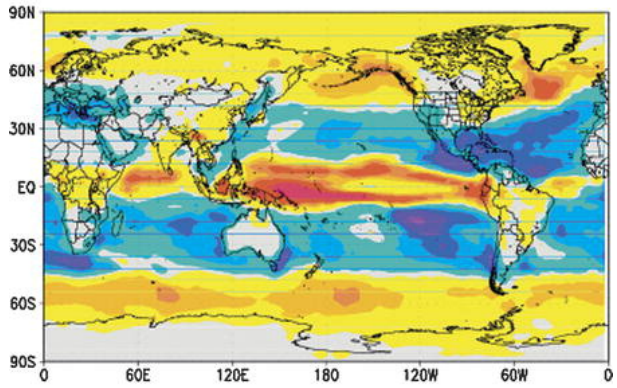



Dependence of precipitation change on climatology "wet-get-wetter" (Held and Soden 2006)

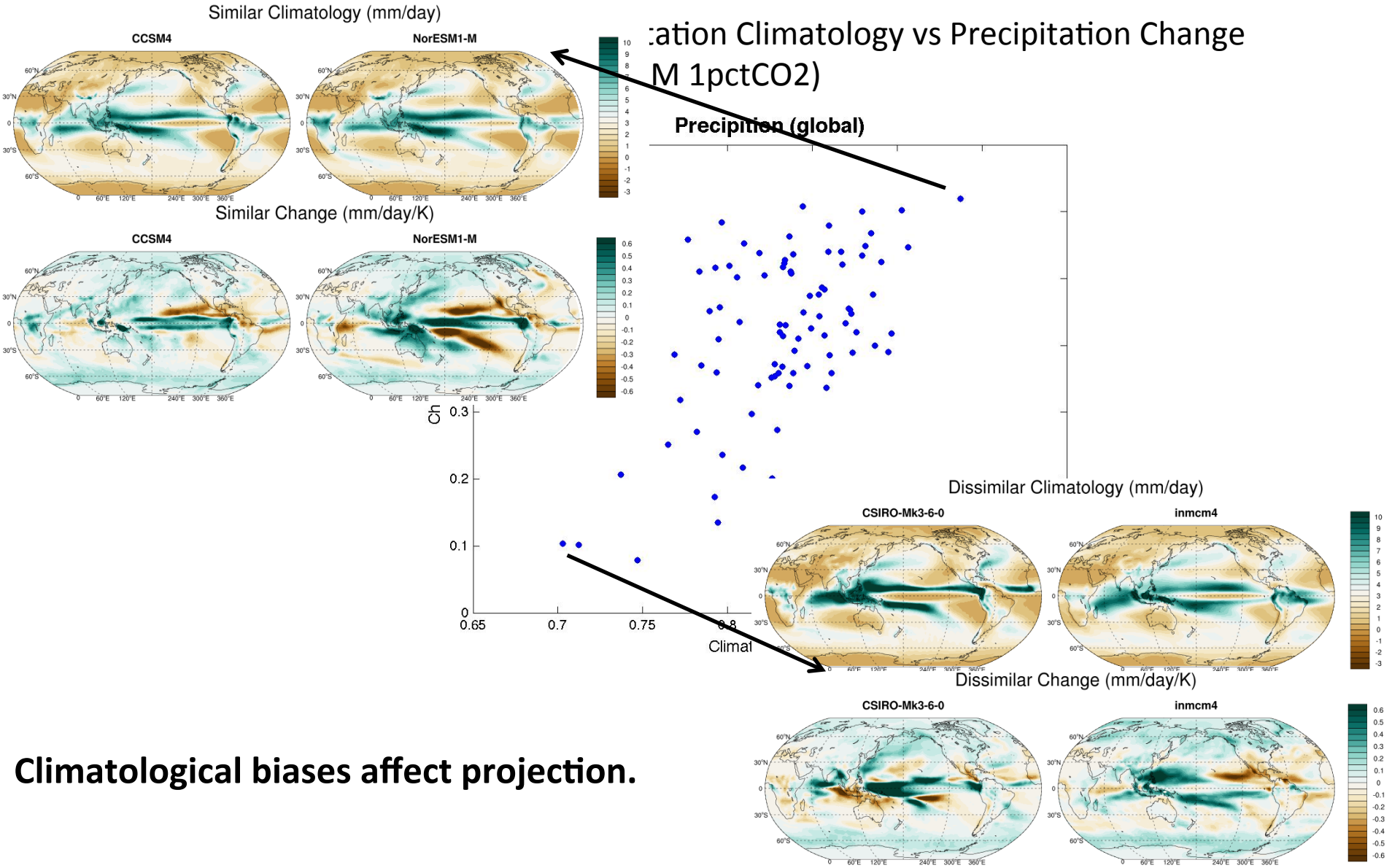
Climatological P-E




Change in P-E



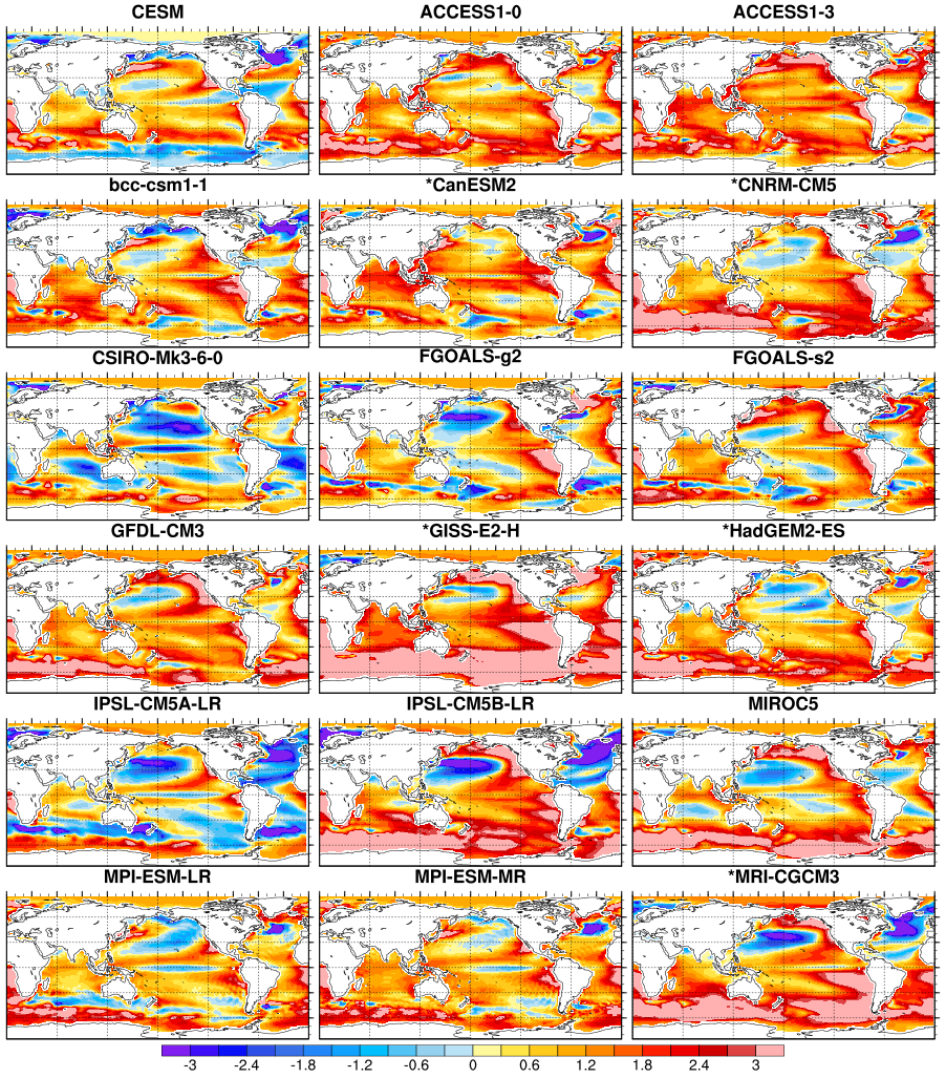
# Climatological Biases




**Climatological biases affect projection.**

# Climatological Biases

## Biases in climatological SST from CMIP5 CGCMs




**Observation:**
Hadley-NOAA/OI (1982-2011)

**CGCMs:**
*Historical (1982-2011)
1pctCO2 (0011-0040)

# Climatological Biases

Model: CESM
Resolution: 2$^{o}$ for the atmosphere

**1. AGCM simulations with *SST climatologies* from observation and CGCMs.**

**ObsSST AGCM**
**VS**
**Coupled CESM**
(1pctCO2)
**modelSST AGCM**
(CanESM2, CNRM-CM5, GISS-E2-H, HadGEM2-ES, MRI-CGCM3)

Same ΔSST,
Different SST climatology.

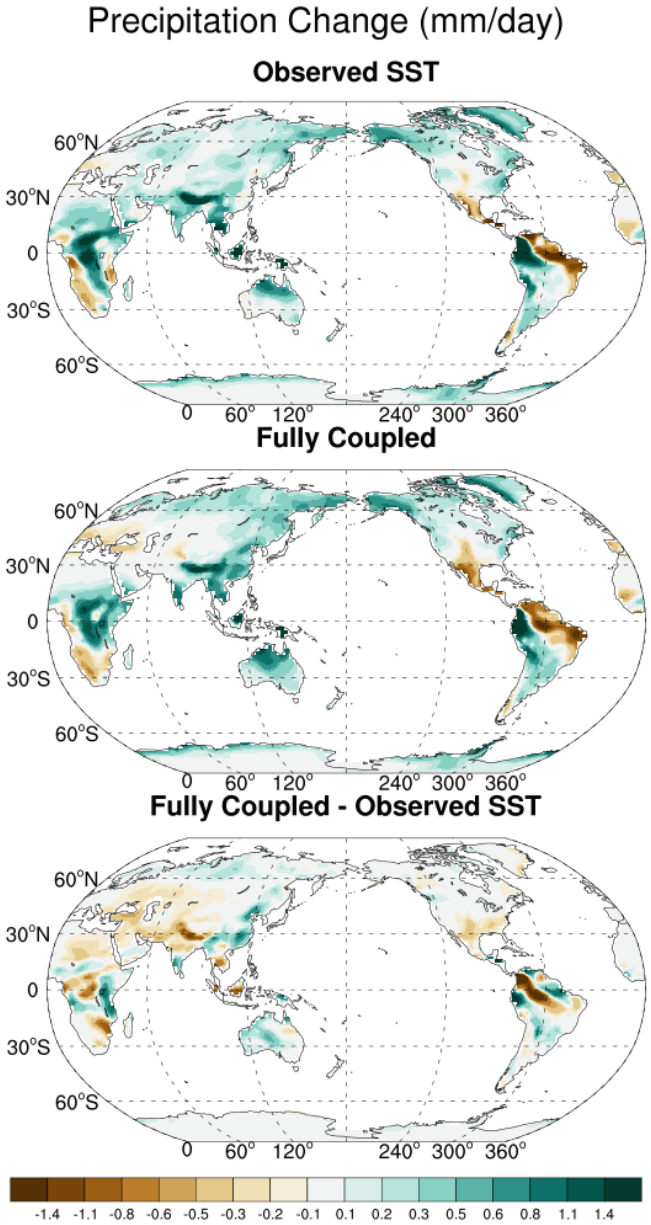
**2. AGCM simulations with *patterns of SST change* from individual CGCMs.**

**Uniform AGCM**
**VS**
**Coupled CESM**
(1pctCO2)
**modelPattern AGCM**
(CanESM2, CNRM-CM5, GISS-E2-H, HadGEM2-ES, MRI-CGCM3)

Same SST climatology,
Different ΔSST.

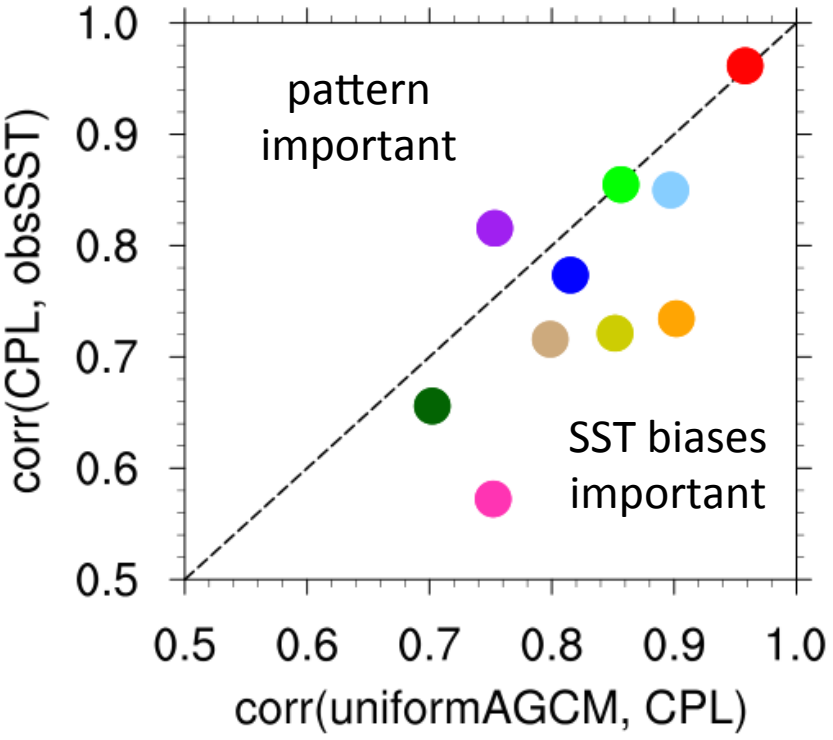
# Climatological Biases

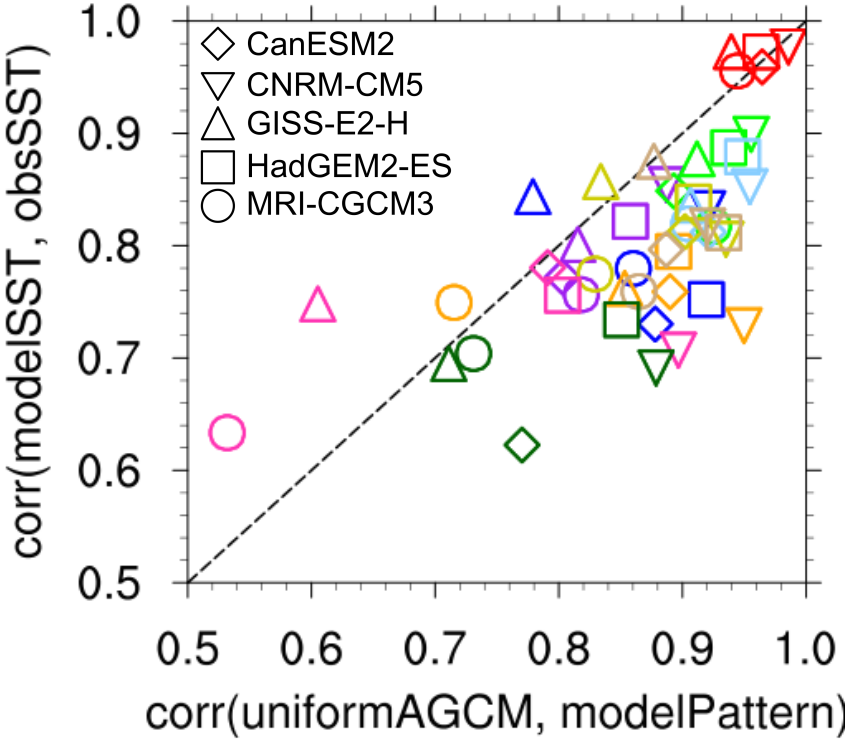
Errors due to biases in climatological SST.



# Climatological Biases

**SST biases VS pattern of ΔSST** (land)




colors: precip TS SLP LH SH cloud $U_{sfc}$ $V_{sfc}$ $U_{500}$ $\omega_{500}$

**SST biases have greater impact than a total removal of pattern of ΔSST (below the diagonal).**

1. Is “two-way” coupling important for regional precipitation change? **No***

2. Is details of SST change important for regional precipitation change? **Not for land***

3. Are we getting realistic regional climate change from CGCMs? **Climatological biases***

4. What are some practical ways forward?

# High-resolution AGCM?

for projecting land climate change

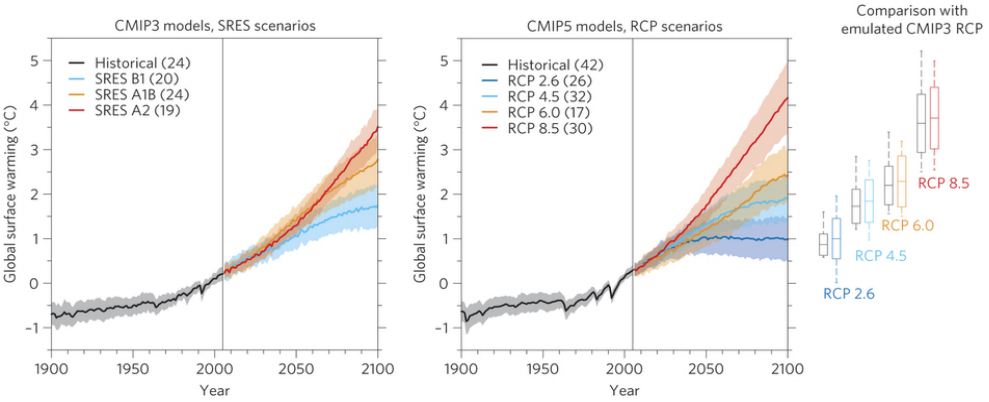
***Pros:***

- Computationally efficient
- Unbiased SST climatology → "best" starting point (precip climatology)

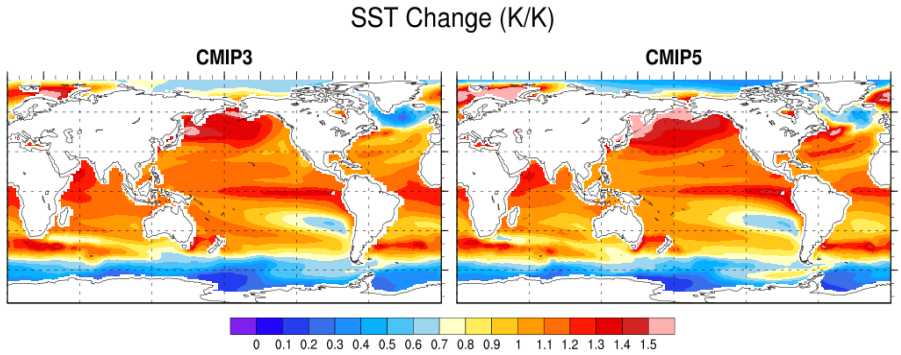
***Con:***

- Can't simulate SST changes directly

*But.. the pattern of ΔSST is not important;*
*ΔSST hasn't changed much from CMIP3 to CMIP5.*




Knutti and Sedláček (2013)

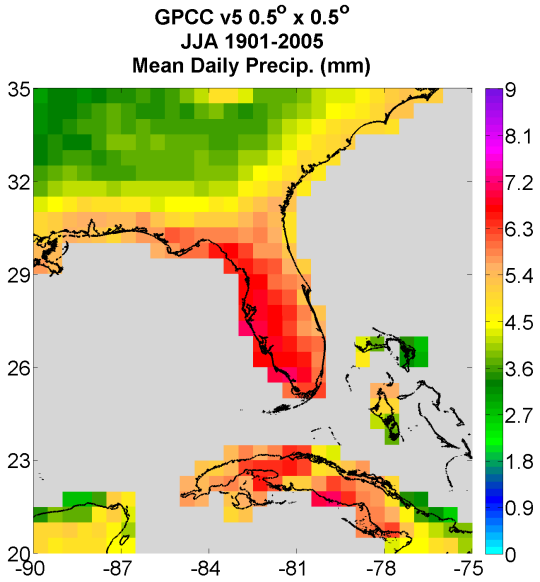


# 1. High-resolution AGCM with observed SST and ensemble mean ΔSST.

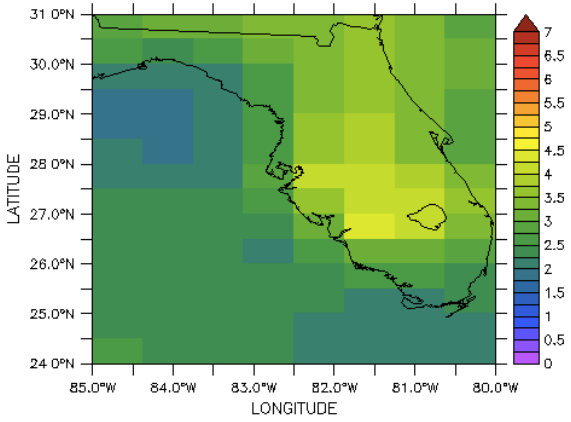
Similar ideas for seasonal predictions (e.g., Jia et al. 2015).

*AGCMs work better without coupling?*

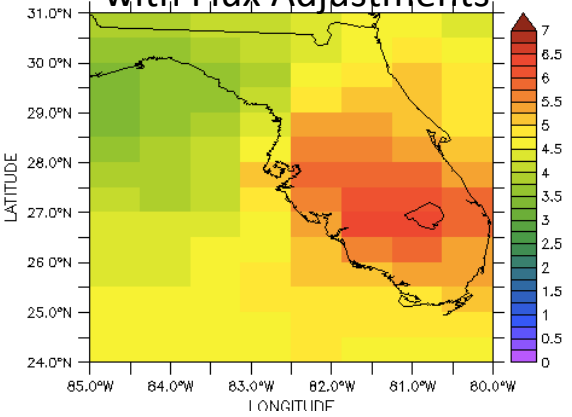
# 2. Flux adjustments?




Coupled GCM (50 km)




Coupled GCM (50 km)
with Flux Adjustments



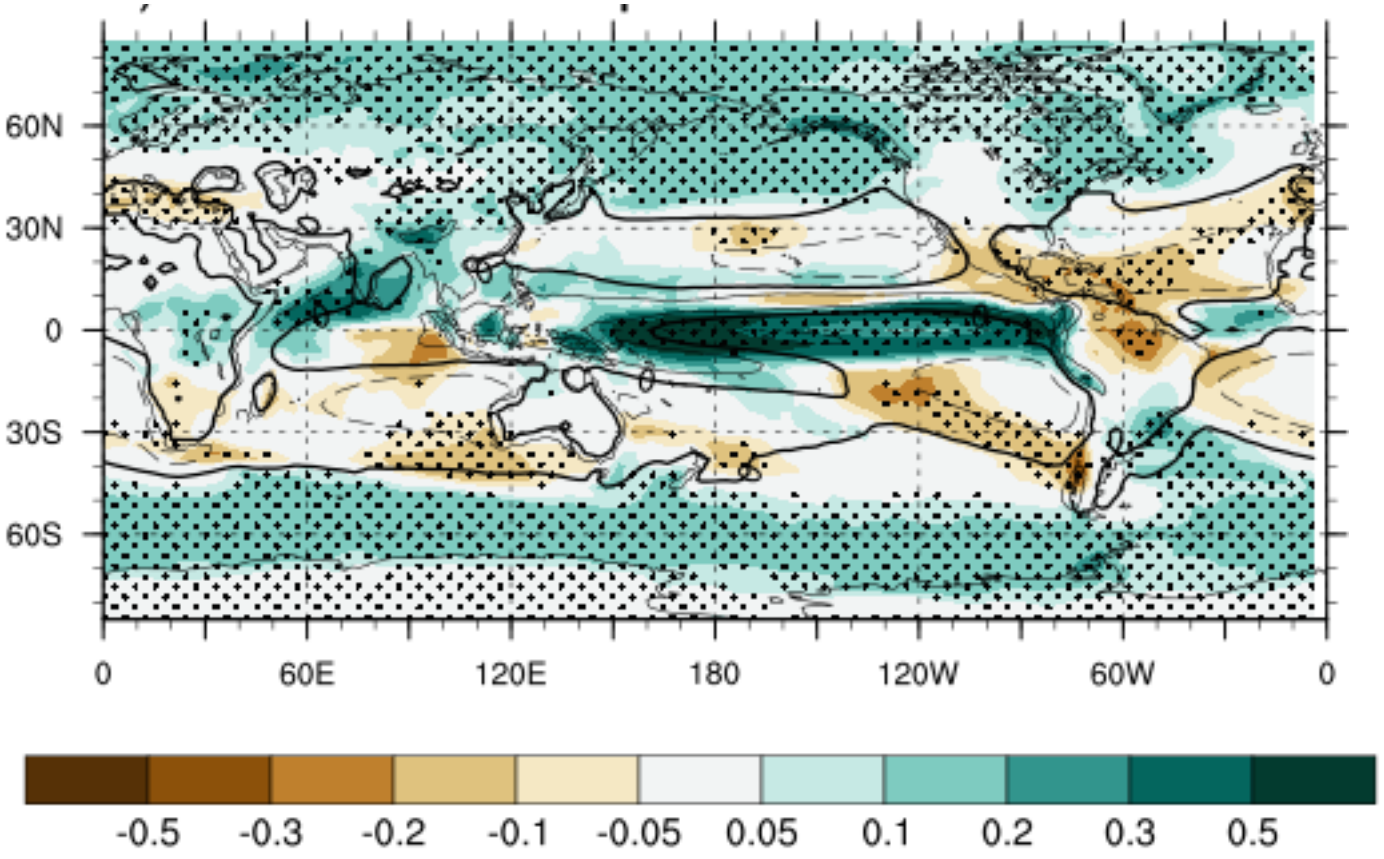
1. Is “two-way” coupling important for regional precipitation change? No*

2. Is details of SST change important for regional precipitation change? Not for land*

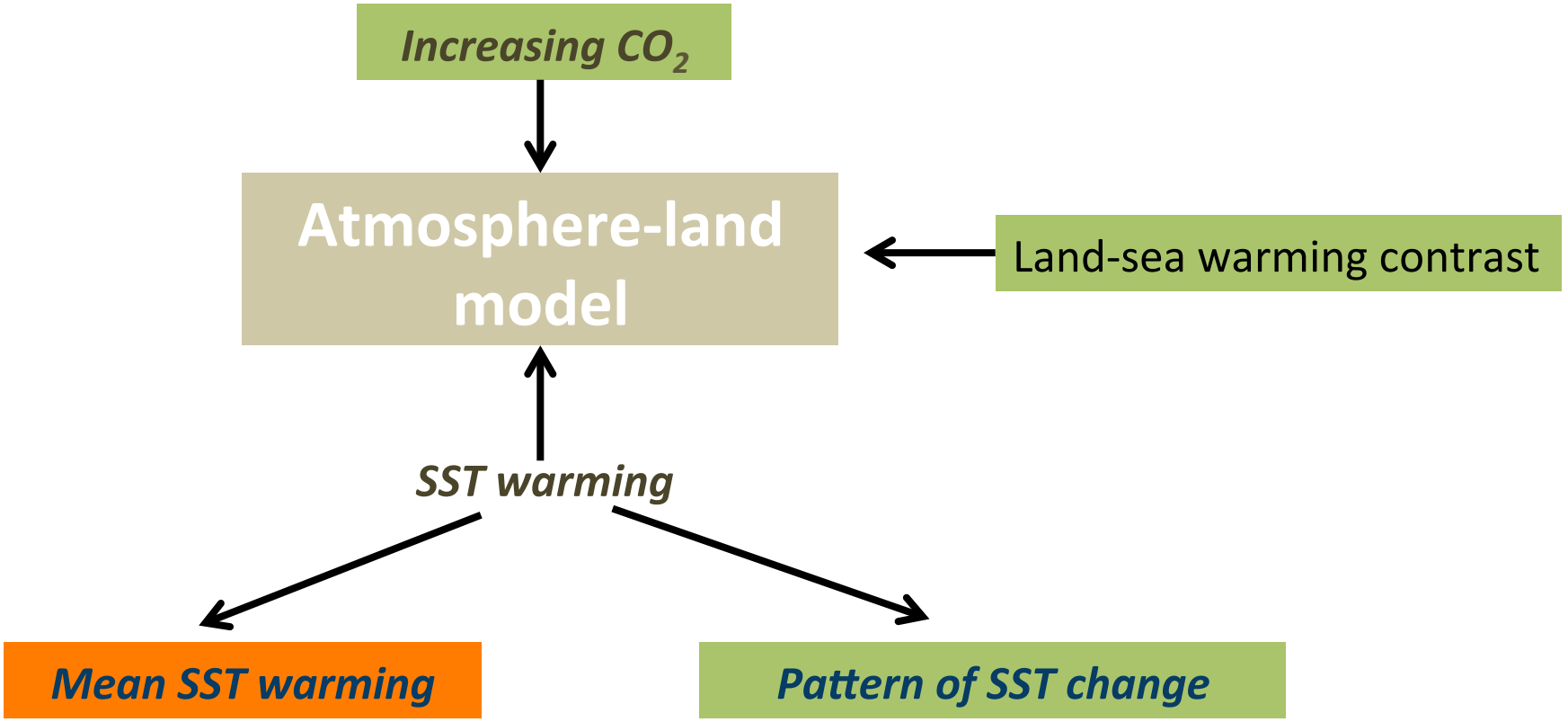
3. Are we getting realistic regional climate change from CGCMs? Climatological biases*

4. What are some practical ways forward?
   HR AGCM? Flux adjustments?

# Physical Mechanisms of Precipitation Changes in the Subtropics and Extratropics

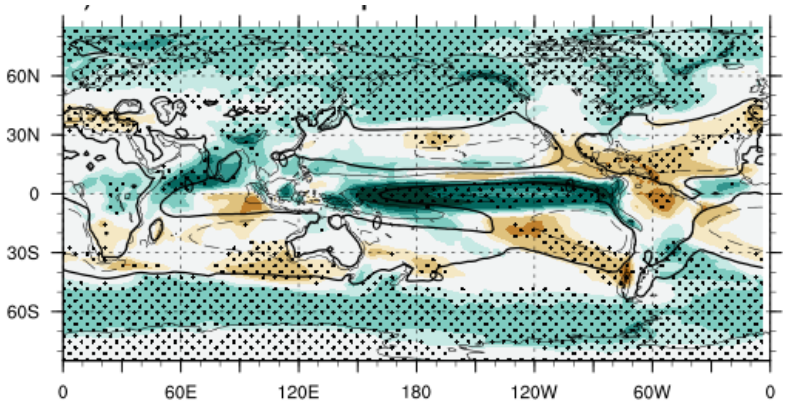


# What drives subtropical and extratropical precipitation changes?




**Fast responses** **VS** **Slow responses**

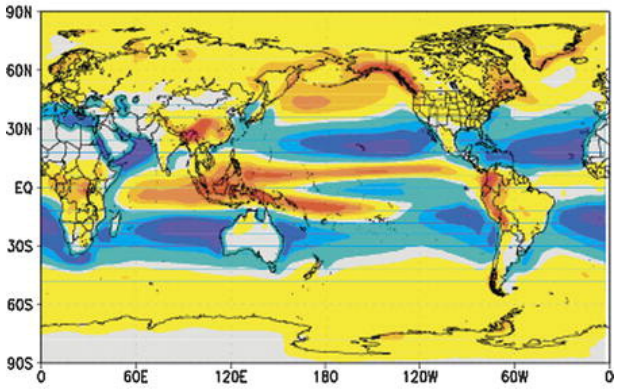
# What do we already know about subtropical and extratropical precipitation changes?



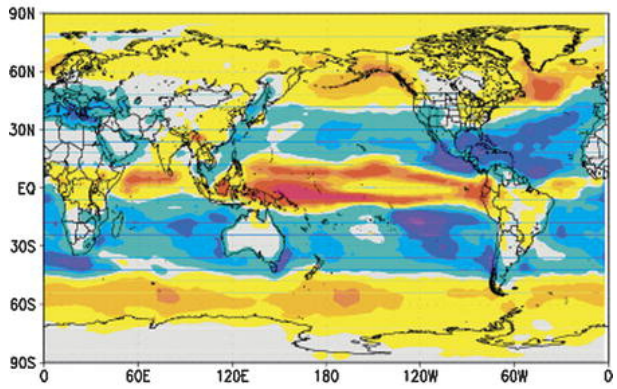

Wet-get-wetter & dry-get-dryer

**Intensification of moisture transport**
(Held & Soden 2006)

Climatological P-E




Change in P-E



*So according to previous studies…*

**Subtropical precipitation decline**
**Extratropical precipitation increase**

↑

**Increase in Moisture**

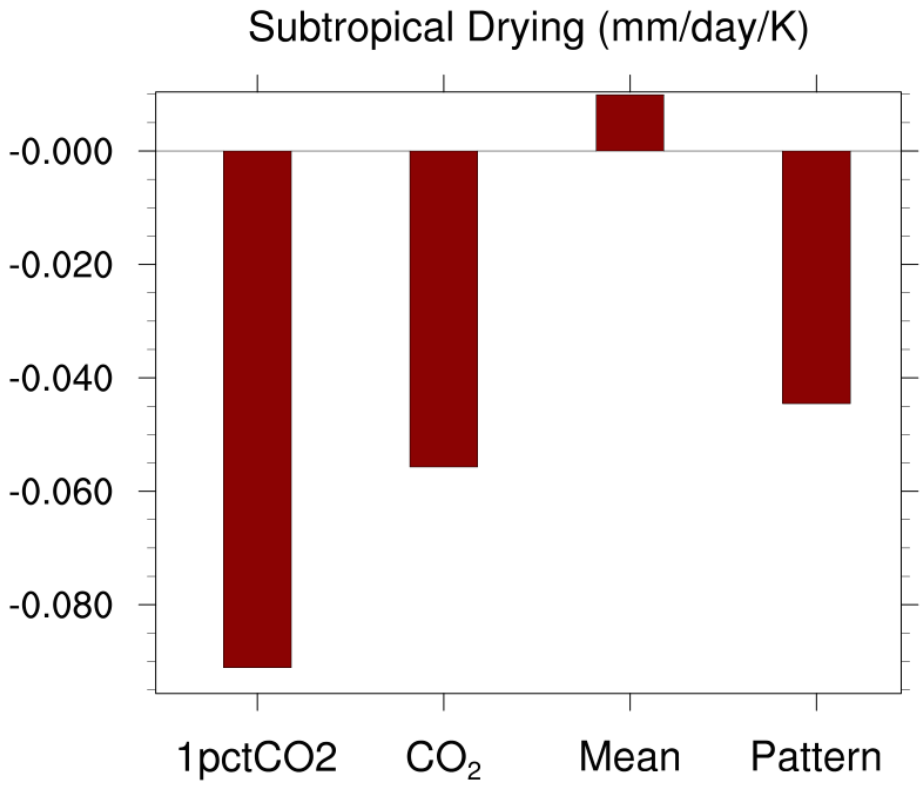
↑

**Global mean SST warming**

# *Actually, subtropical precipitation declines are independent of the mean surface warming…*

Experiments:

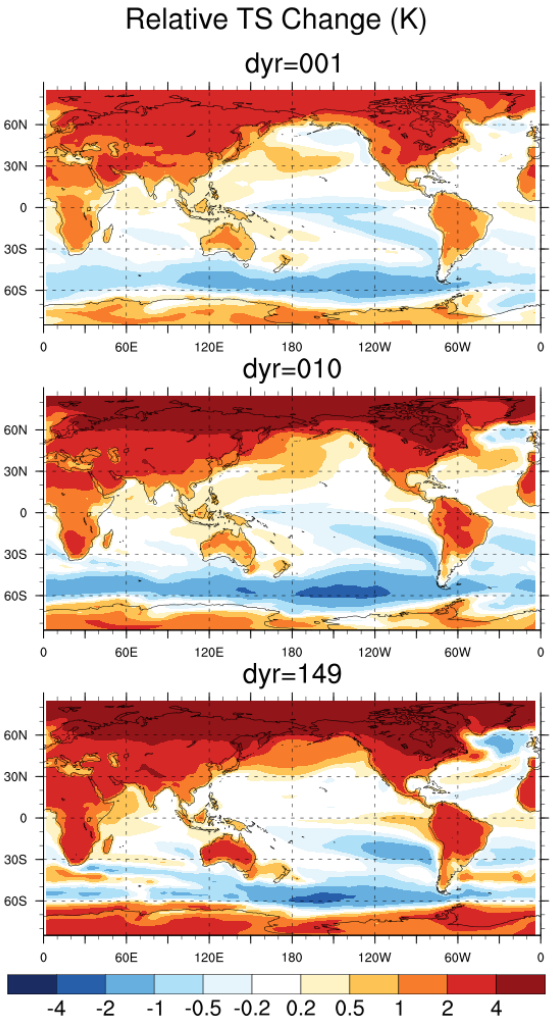
- **Fully coupled**: 1pctCO2 (yr121~140 – yr1~21)
- **$CO_2$ only:** AMIP_CO2 (4x$CO_2$)
- **Mean Warming only:** AMIP_mean (+4K)
- Structured warming: AMIP_future
- **Pattern only:** AMIP_pattern = AMIP_future – AMIP_mean

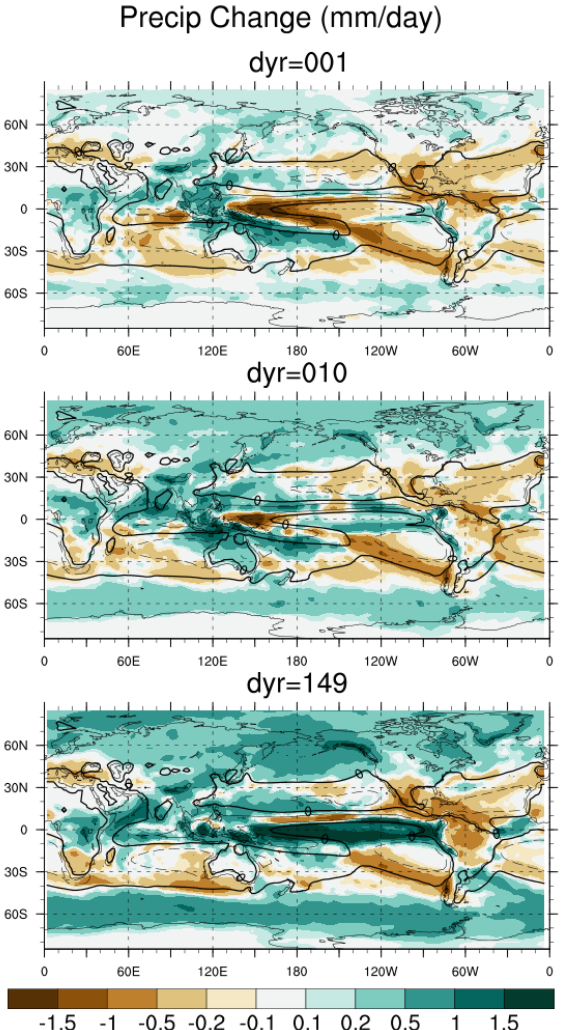


- $CO_2$ radiative forcing
- Land-sea warming contrast → Fast response
- Pattern of SST change

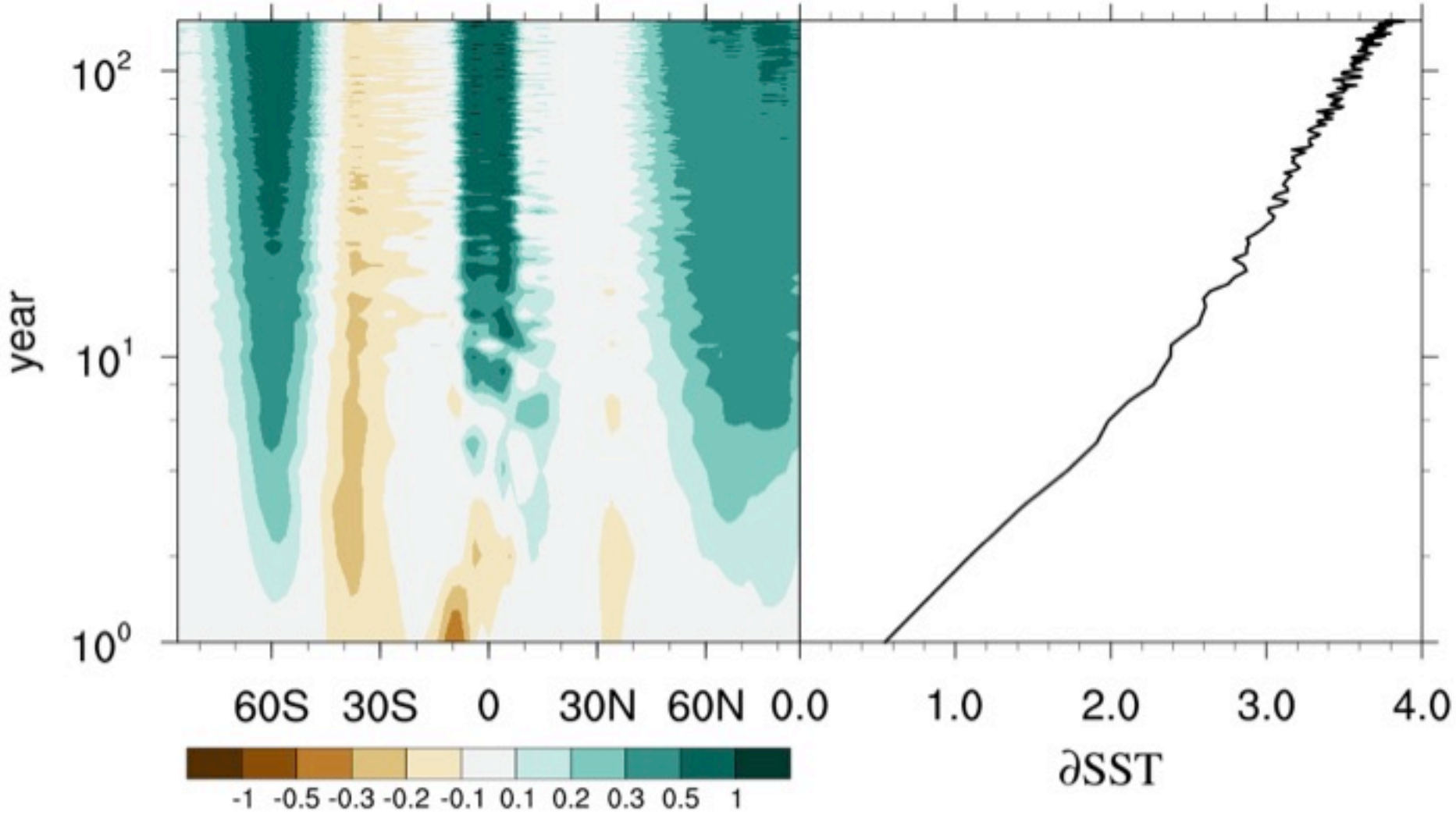
- Mean SST warming → Slow response

***Abrupt4xCO2***



Subtropical precipitation decline is a **fast** response.
Extratropical precipitation increase is a **slow** response.



Experiments:

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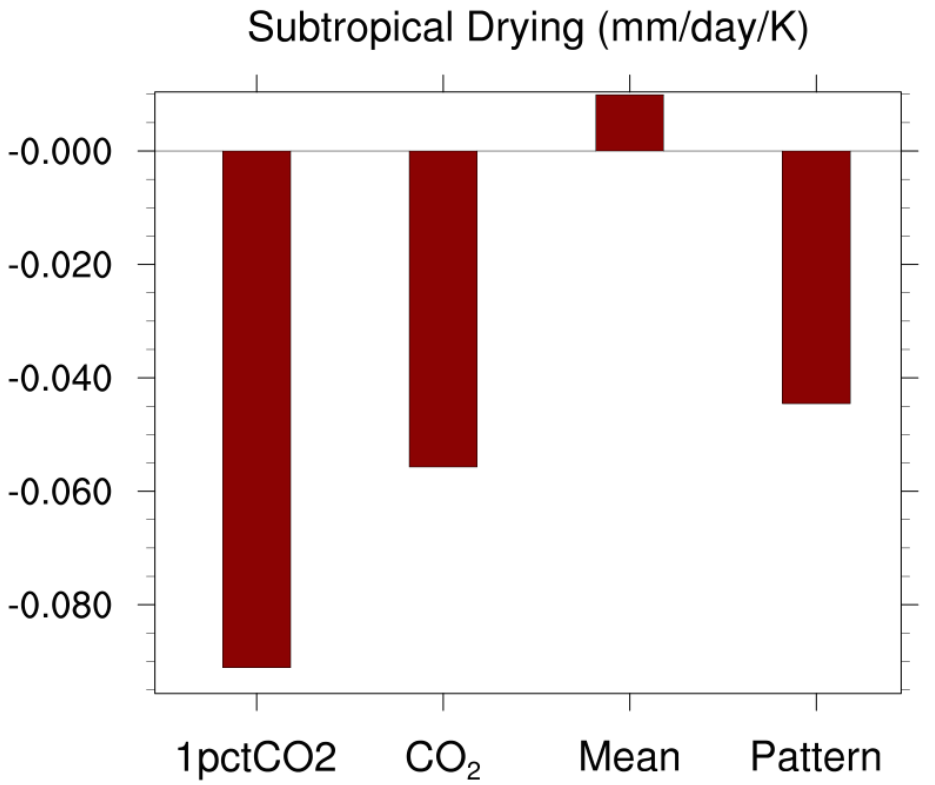
- Structured warming: AMIP_future
- **Pattern only:** AMIP_pattern = AMIP_future – AMIP_mean




**AMIP_CO2:**

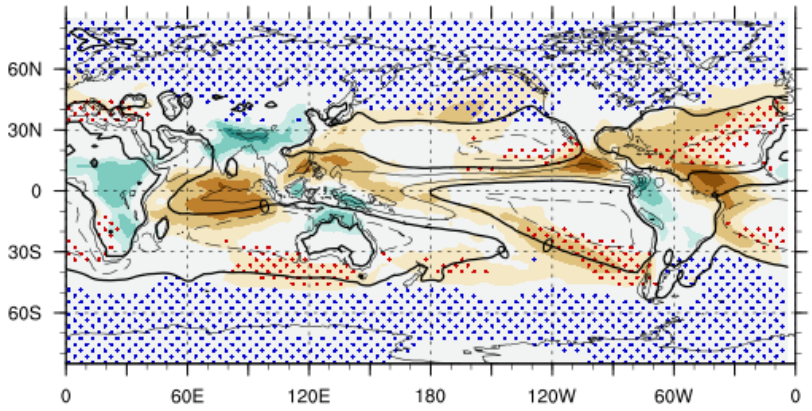
Direct radiative forcing of $CO_2$

Land-sea warming contrast

**aqua_CO2:**

radiative forcing only

δP in AMIP_CO2

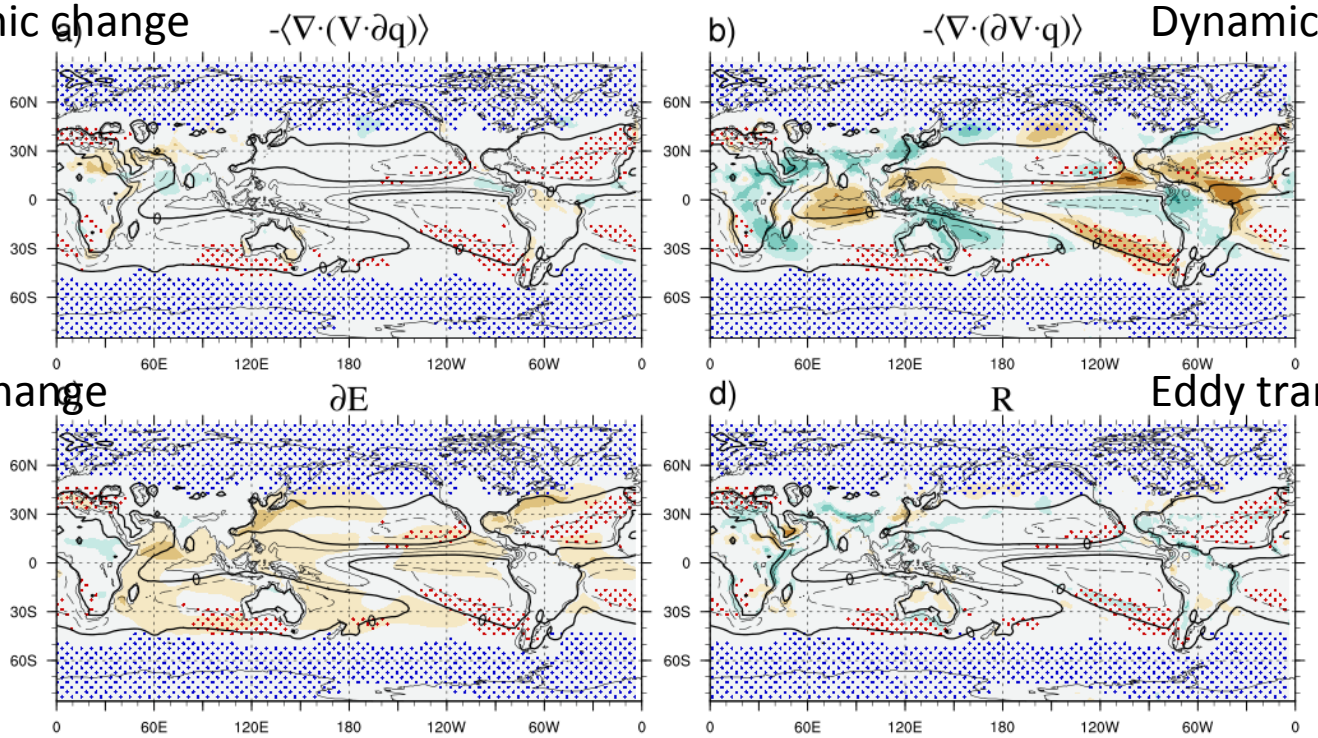



*Stabilization or Land-sea?*

∂P decomposition ($CO_2$, mm/day/K)

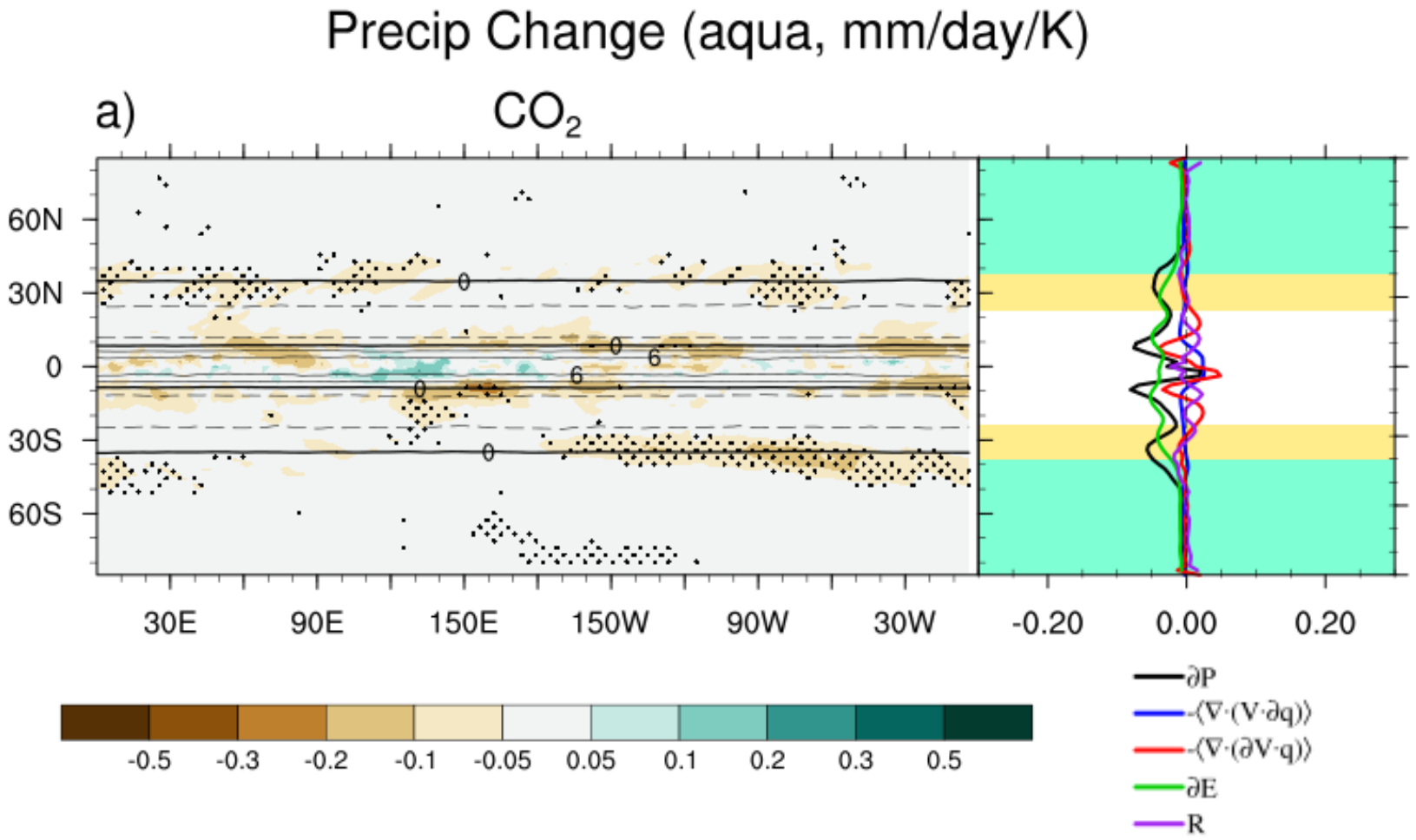
Thermodynamic change

Dynamic change

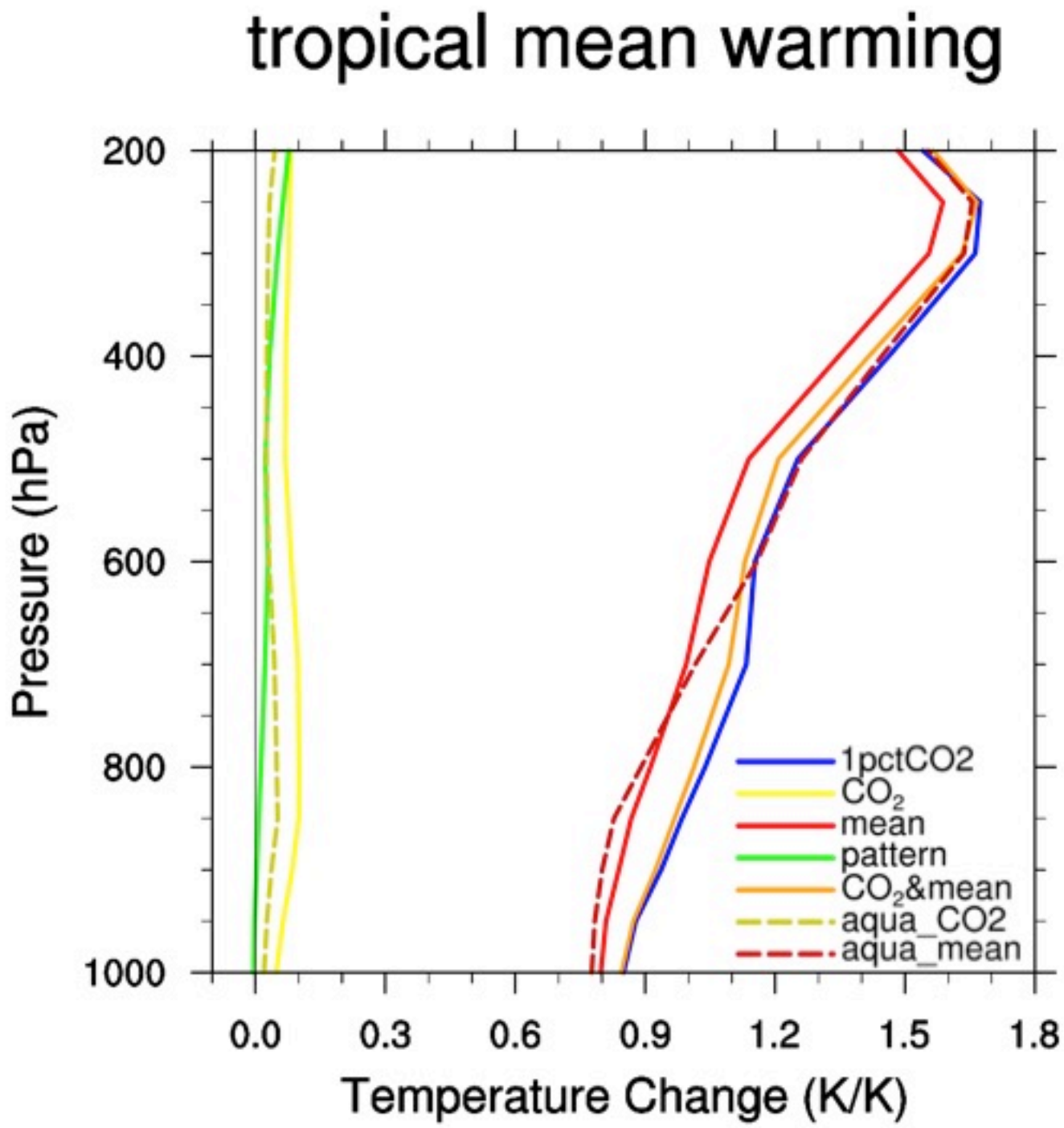



Evaporation change

Eddy transport




The stabilizing effect of $CO_2$ does not weaken convection in the subtropics.


tropical mean warming
200
400
600
800
1000
Pressure (hPa)
0.0
0.3
0.6
0.9
1.2
1.5
1.8
Temperature Change (K/K)
1pctCO2
CO2
mean
pattern
CO2&mean
aqua_CO2
aqua_mean

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***Thank you ☺***