Understanding historical and future change in tropical rainfall

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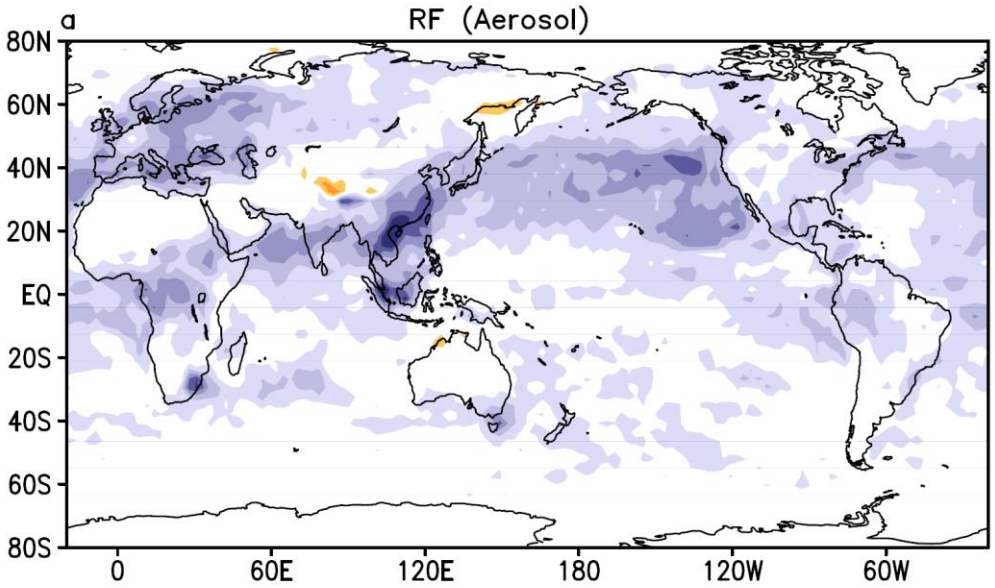
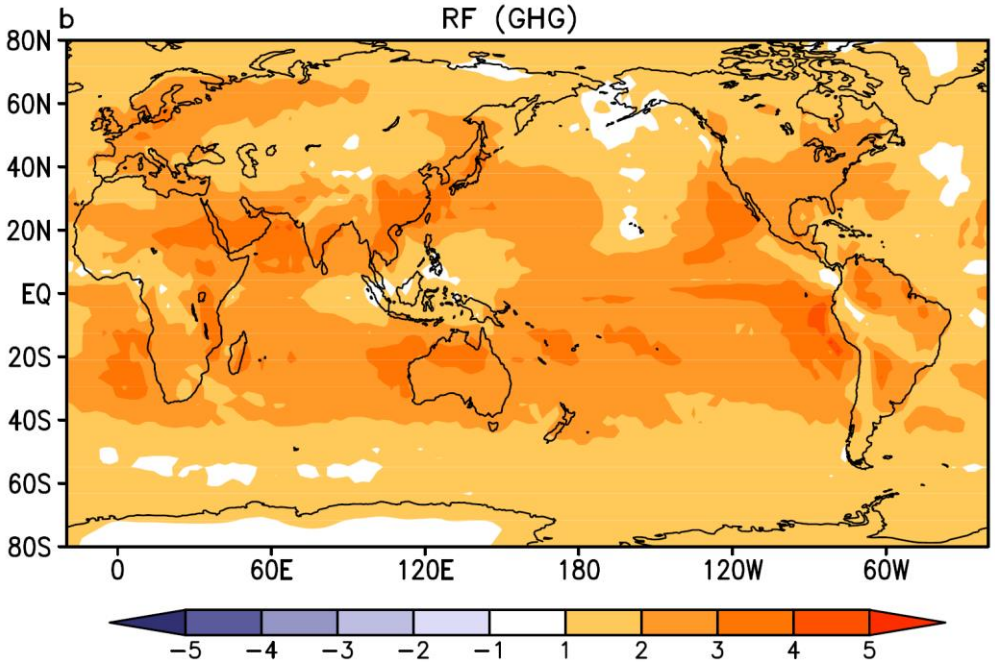
20th century radiative forcing

- **F(aerosol) ~ -0.5 F(CO_2)**
- Atmospheric residence time > 100 years for CO2 but only ~ 1 week for aerosols.
- r(aerosol, GHG) ~ 0.



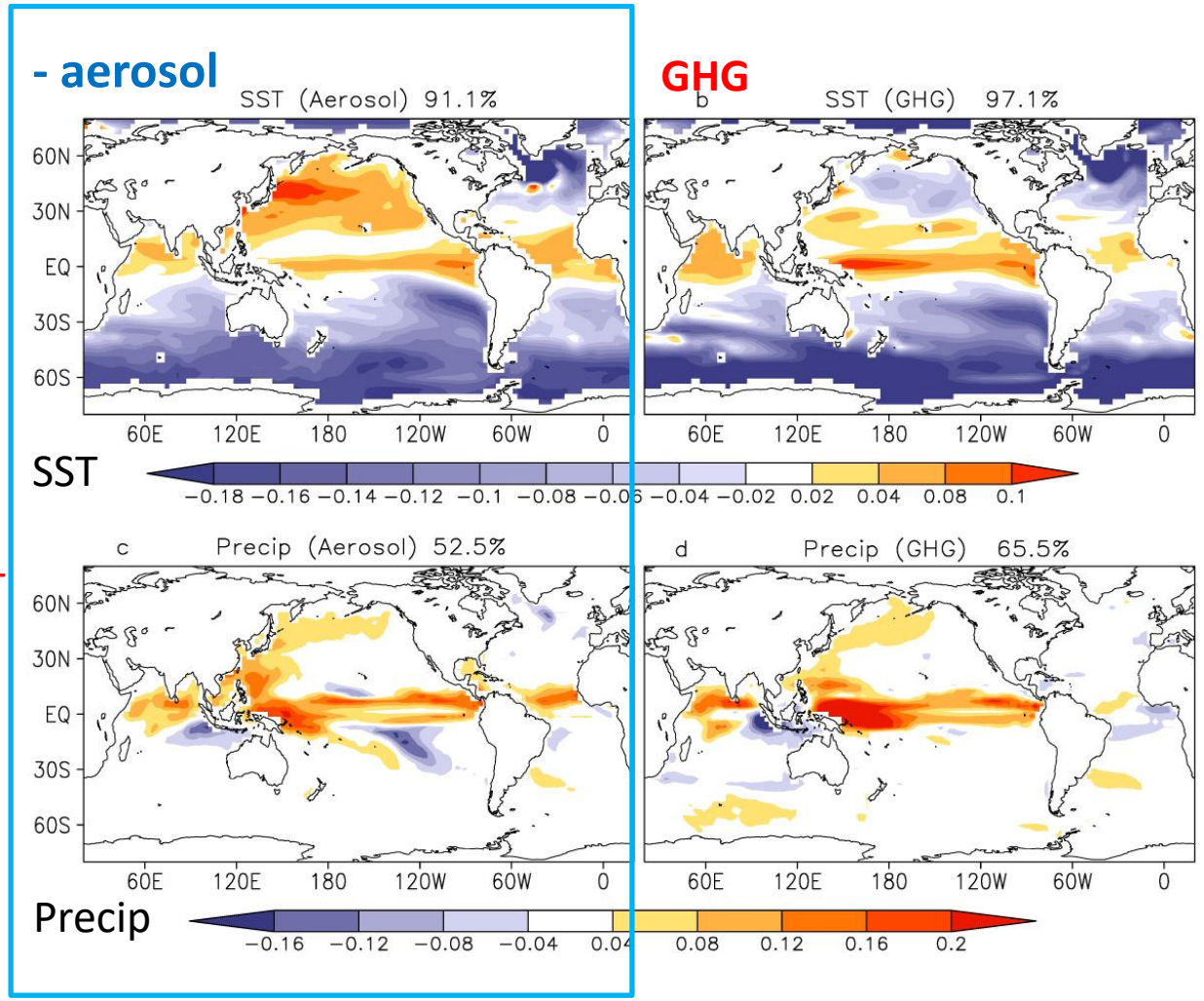


Similar spatial pattern of climate response to aerosol and GHG changes

Relative SST (deviation from tropical mean)

Single-forcing runs

- Peak warming anchors rainfall increase in Eq. Pacific.
- Reduced warming in Southern Hemisphere.

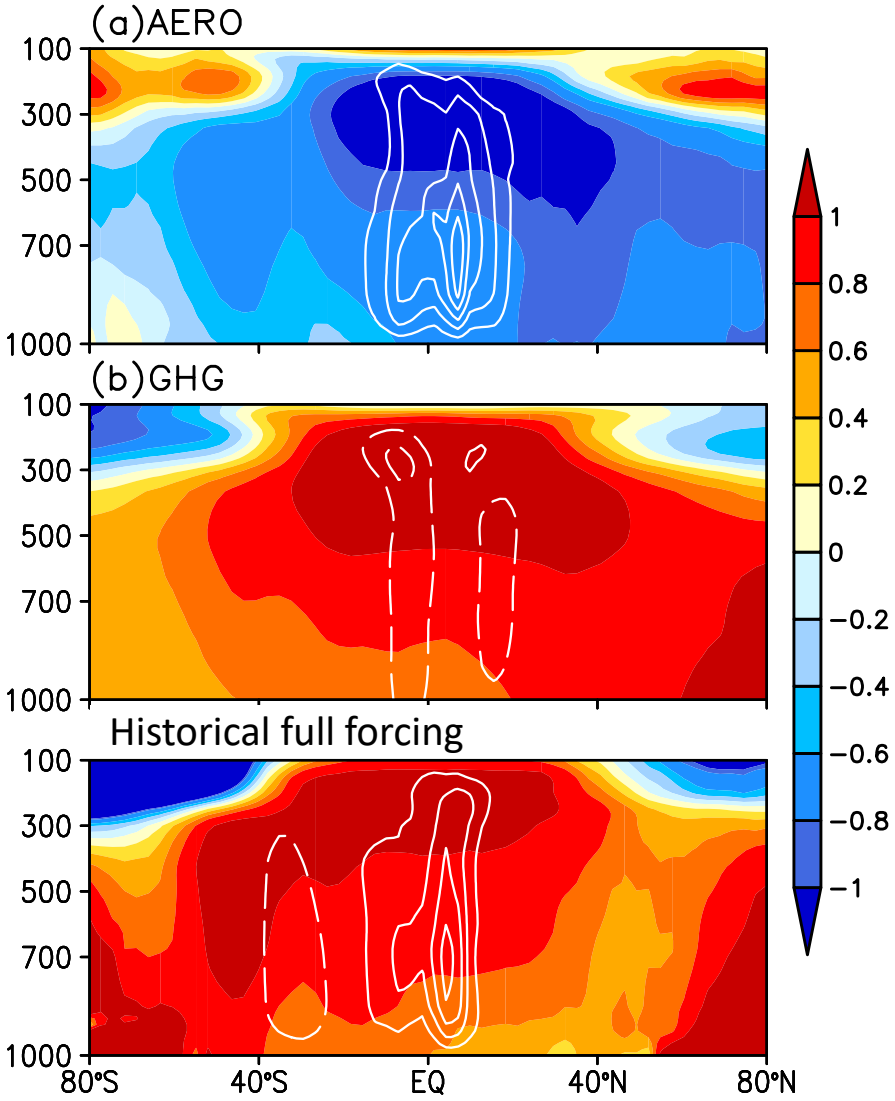


r(aerosol, GHG) = 0.87 for SST
0.67 for precip

Xie, S.-P. et al., 2013: Similar spatial patterns of climate responses to aerosol and greenhouse gas changes. *Nature Geosci.*, 6, 828-832

Disparity

Inter-hemispheric anti-symmetric mode



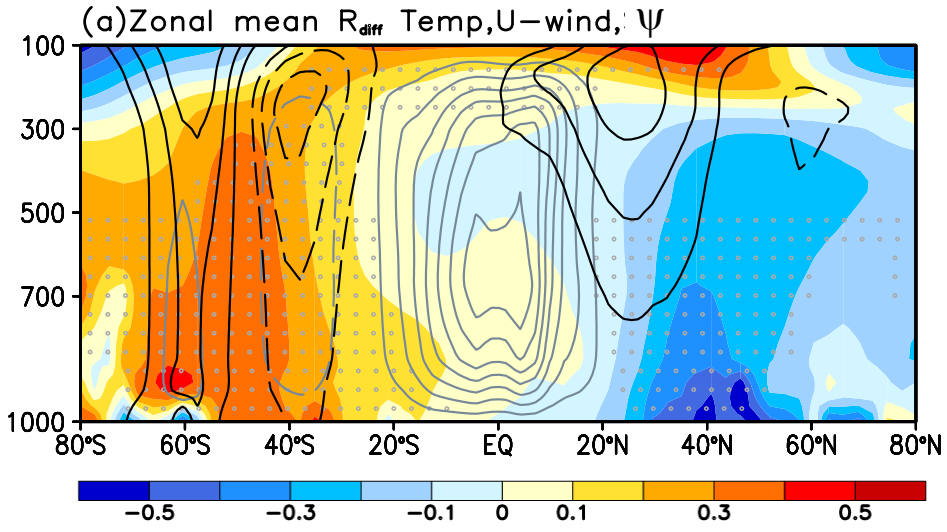
Air Temp. & Hadley Cir.

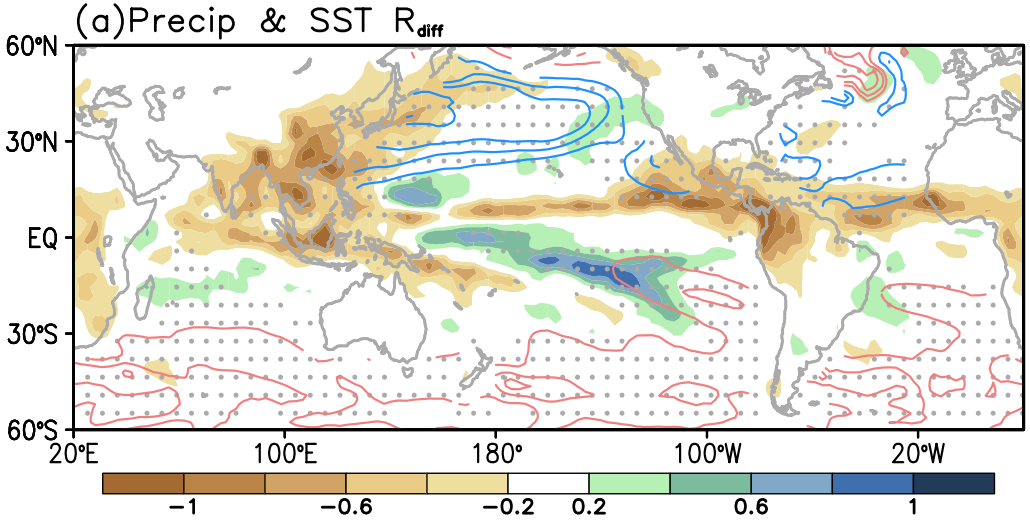
- Aerosols induce a deep cooling structure in the NH mid-latitude.
- TOA radiative forcing drives an anomalous cross-equatorial Hadley circulation. ← Confirmed from ship obs of sfc winds.
- Historically, GHGs dominate global temperature change while aerosols dominate circulation response.

2000-1950 difference normalized by tropical-mean TT

Wang et al. (2016, GRL)

Disparity index





* Normalized to have unit one tropical SST change

$$R_{diff} = R^*_{AERO} - (-R^*_{GHG})$$

Aerosol relative to GHG response:

- Cross-equatorial Hadley circulation
- The westerly jet shifts equatorward in NH, and poleward in SH

- Regional response AA > GHG
- NH-SH asymmetric (SST, ITCZ)
- Drying over East & South Asia

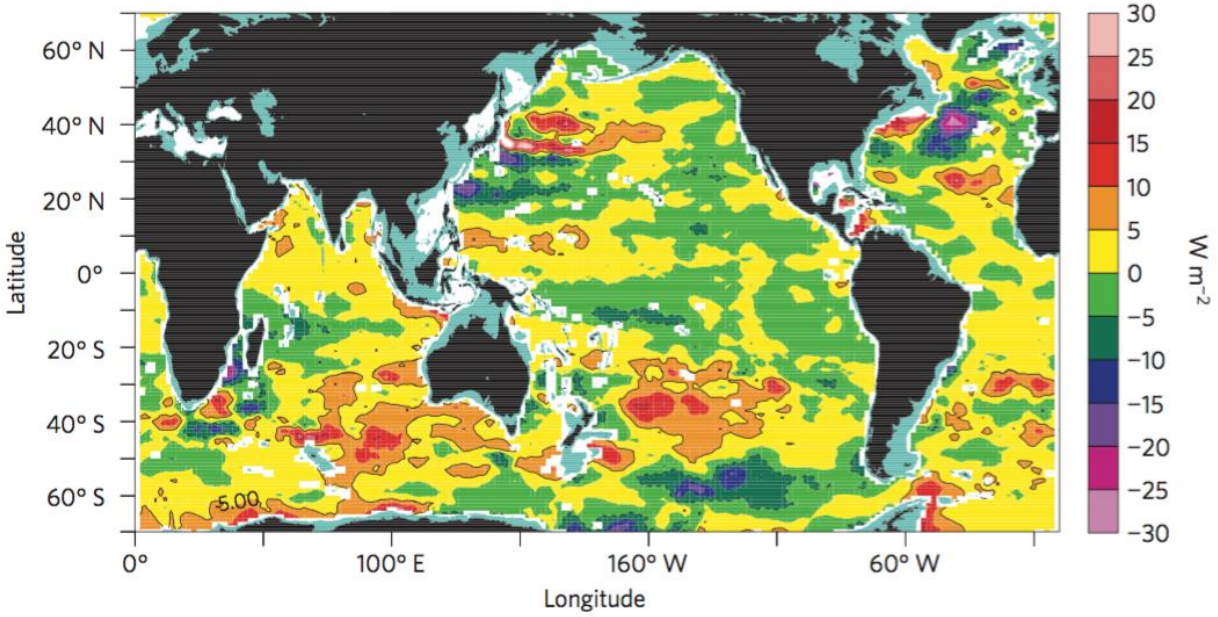
H. Wang et al. (2016, JC)

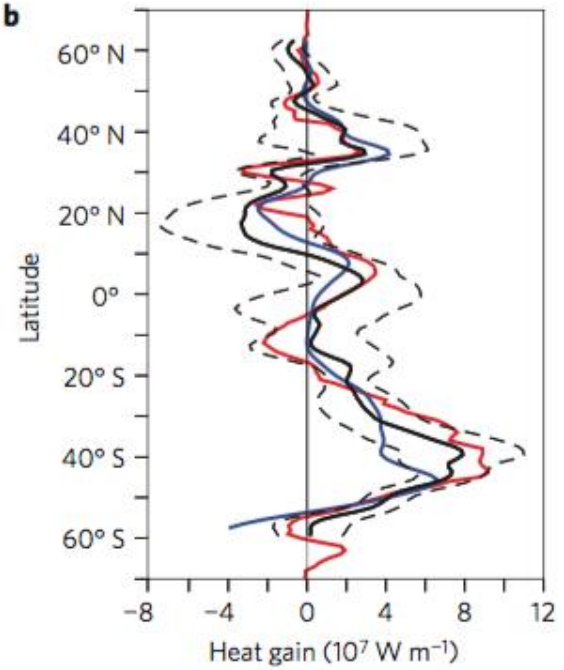
Summary 1

- Robust large-scale structure exists for ocean-mediated slow response to aerosols.
- Surprising similarities b/w GHG and aerosol response:
  - common ocean-atmospheric feedback → spatial resemblance.
  - reduced patterns of rainfall change → difficult to detect.
- Pronounced differences
  - Cross-equatorial Hadley adjustment ← Energy transport theory
  - Decreased summer monsoon rainfall

Uneven ocean heat uptake

Observations





trend in ocean heat content (0-2000m) for 2006 - 13

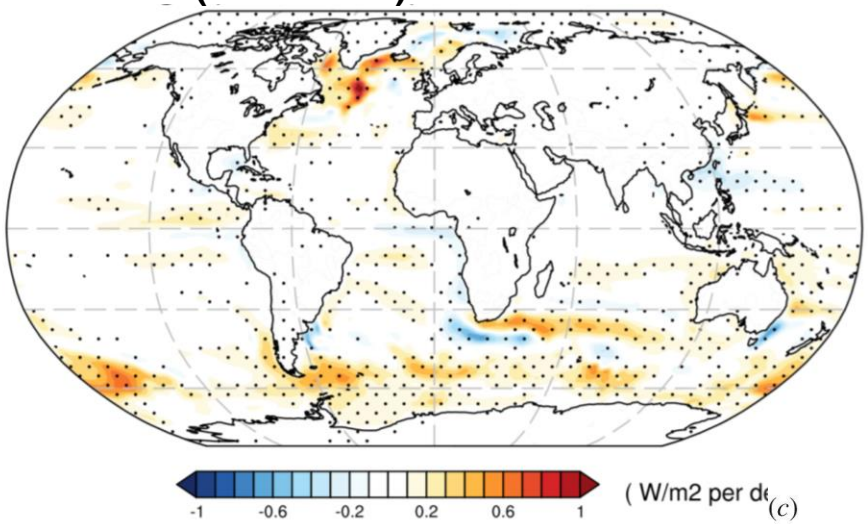
Most of heat gain (67%~98%) occurred in the S.H. extratropical ocean (south of 20˚S)

(Roemmich et al. 2015, Nat Clim Change)

Surface heat flux change

CMIP5 ensemble mean

Historical (1861-2005)



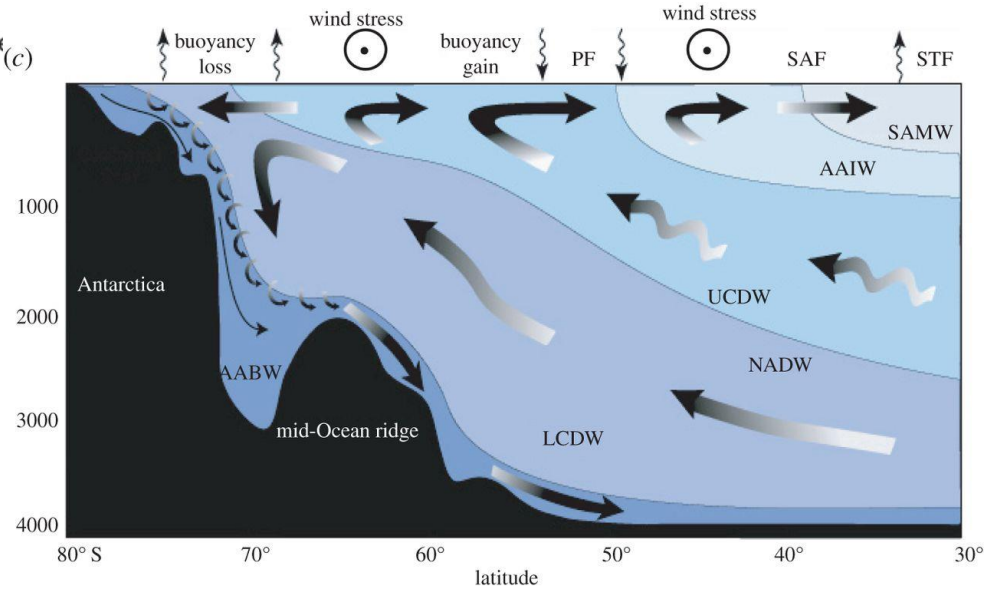
Area-integration over:

NA: 30˚N-70˚N, 80˚W-10˚W
SO: south of 30˚S

Cumulative Heat Uptake over the 20th century:

NA: 6%±39%

SO: 72%±28%



Southern Ocean Heat Uptake

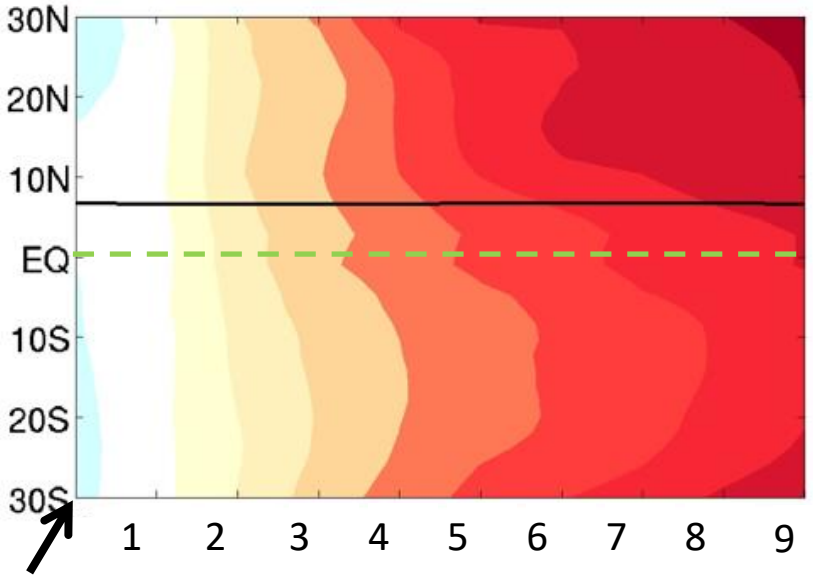
→ **Reduced surface warming**

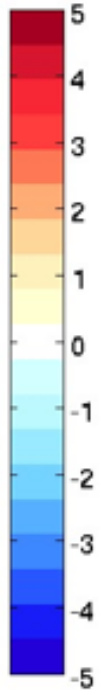
(Bryan et al. 1988; Marshall et al. 2014 …)

CESM 1.2.1
slab ocean model

(1) Control:
50m mixed layer

changes in zonal mean SST

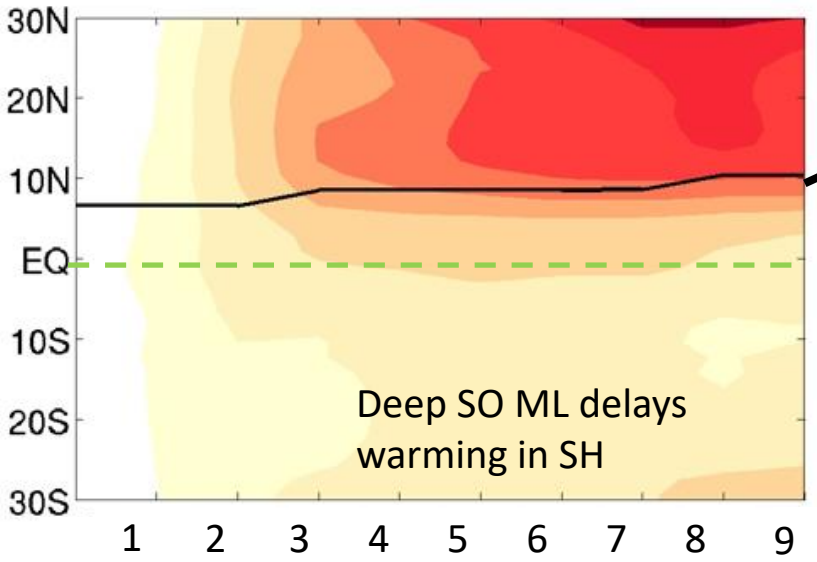




4xCO2

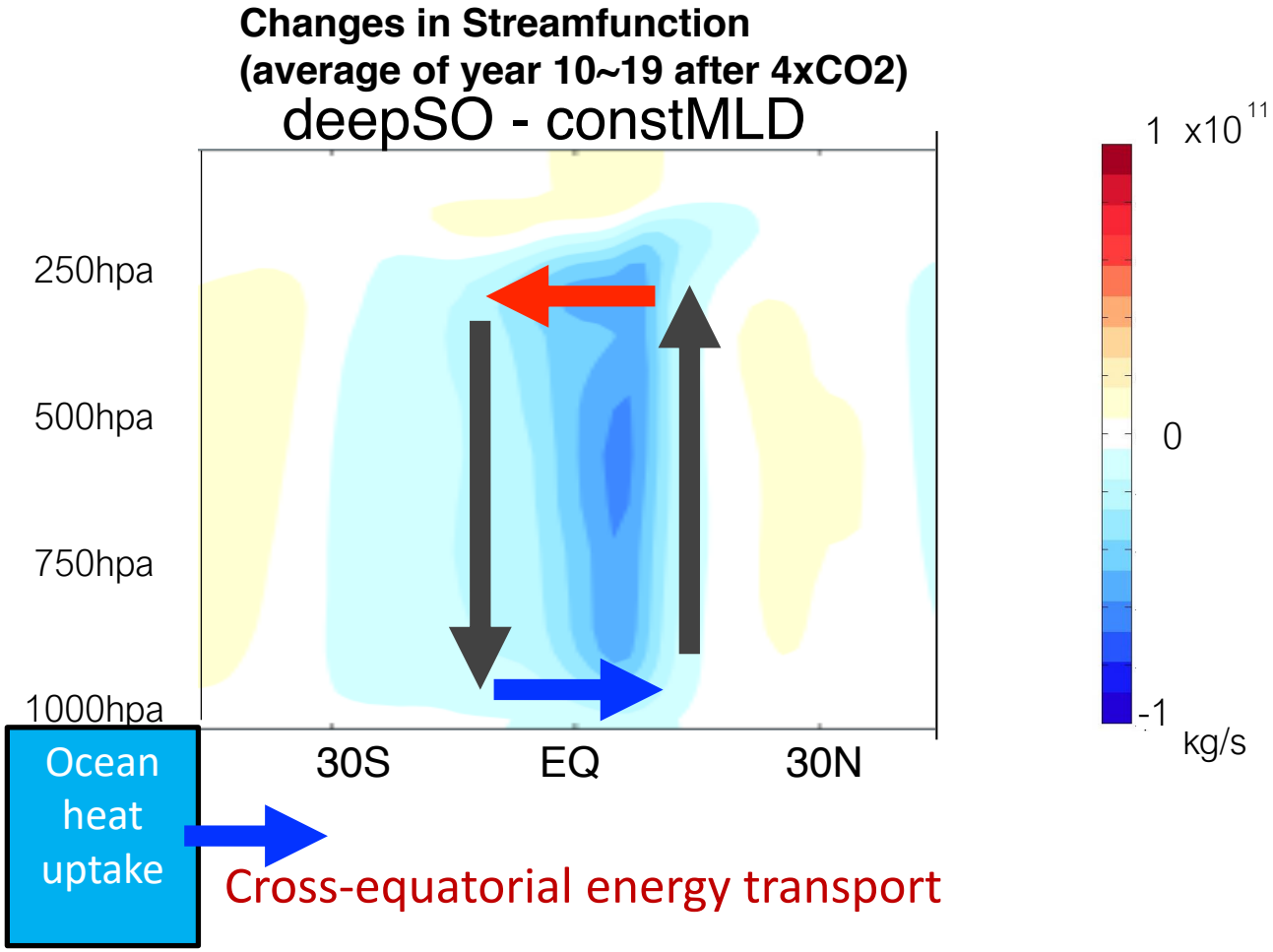
(2) Deep Southern Ocean
(SO) mixed layer:

- 500m in 40~80S,
- 50m elsewhere



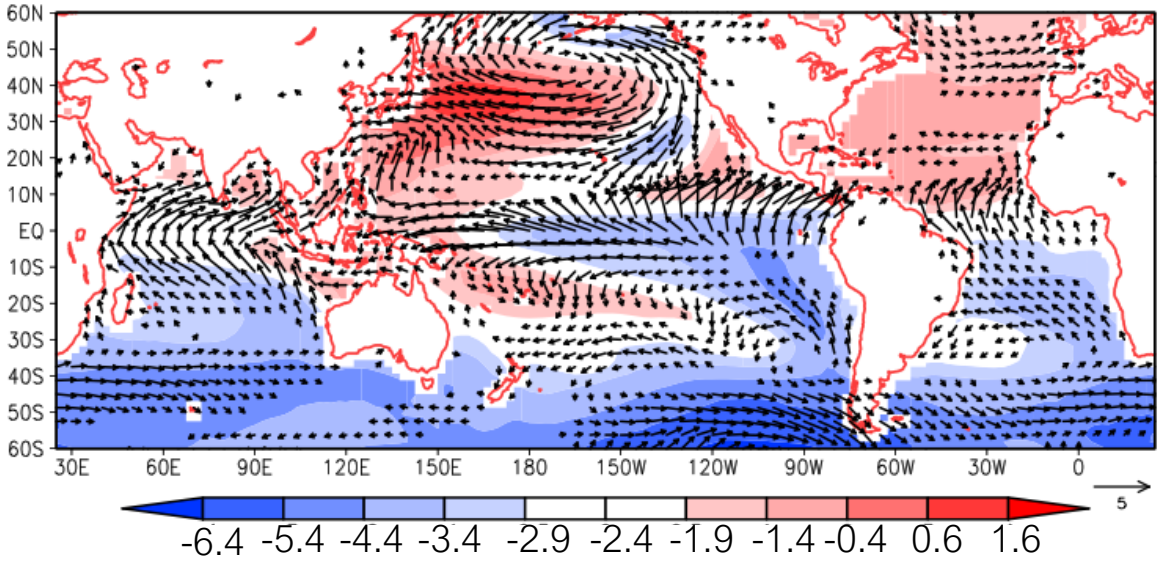
Latitude of max
rainfall shifts north

Y.-T. Hwang et al. (2017, GRL)



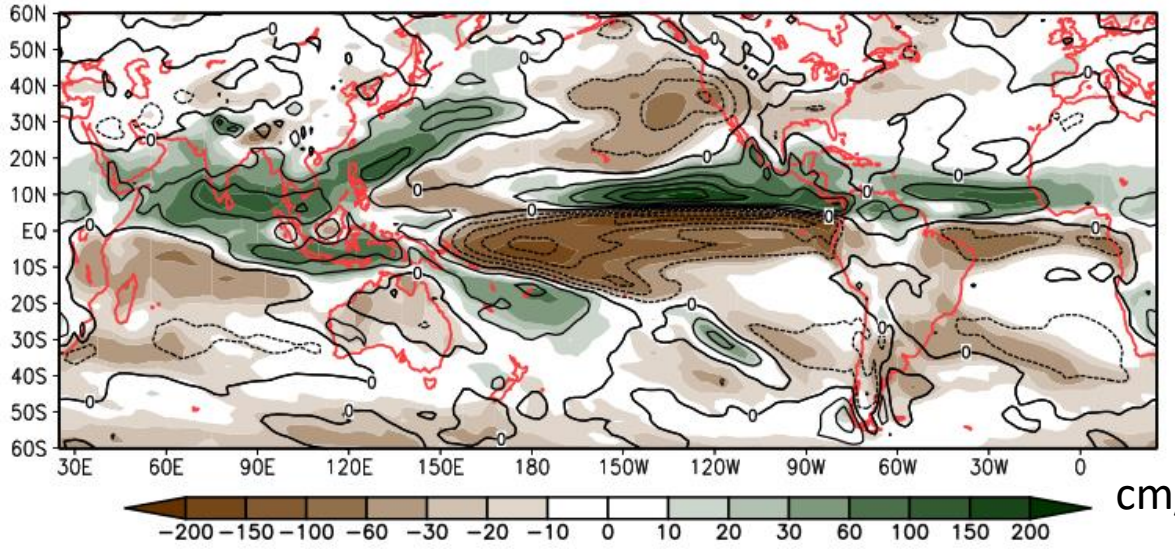
Chiang and Bitz 2005, Kang et al. 2008, 2009; Broccoli et al. 2006, Zhang and Delworth 2005, Frierson and Hwang 2012, Hwang et al. 2013

deepSO – constMLD **Difference (annual mean)**
(year 10~19 after 4xCO2)



SST (shading) &
Sfc Wind (vectors)

Zonal asymmetry: enhanced cooling in SE Pacific



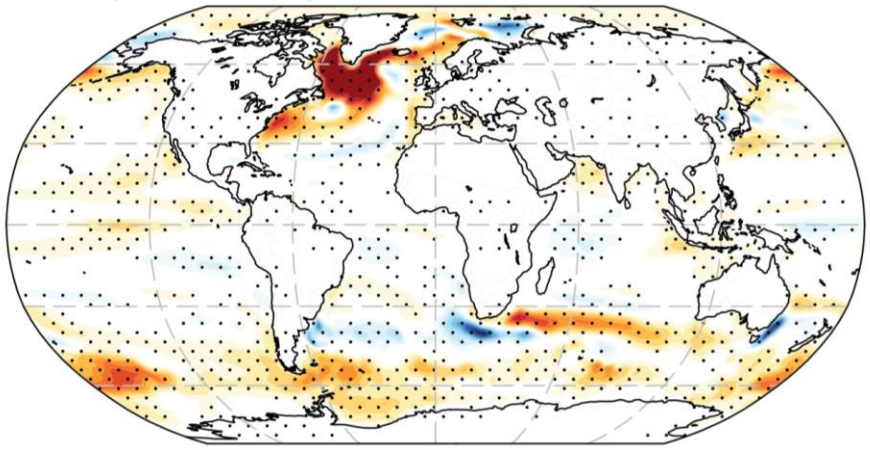
Precipitation

cm/yr

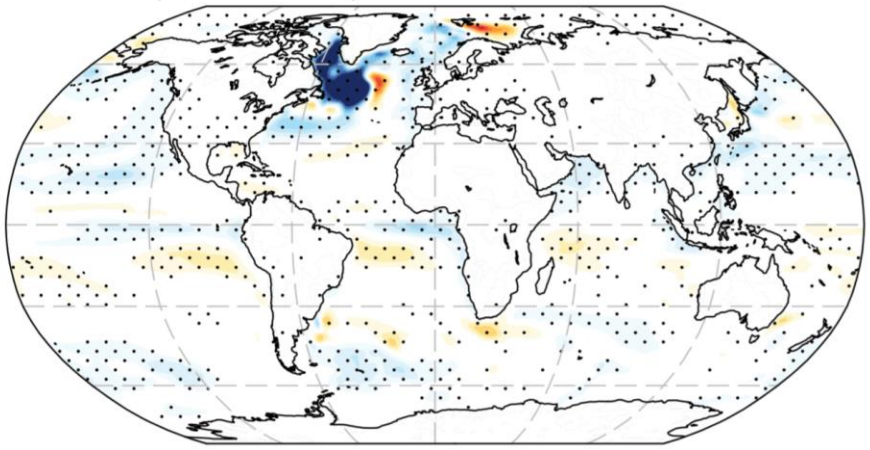
Response of surface heat flux:

CMIP5 ensemble mean

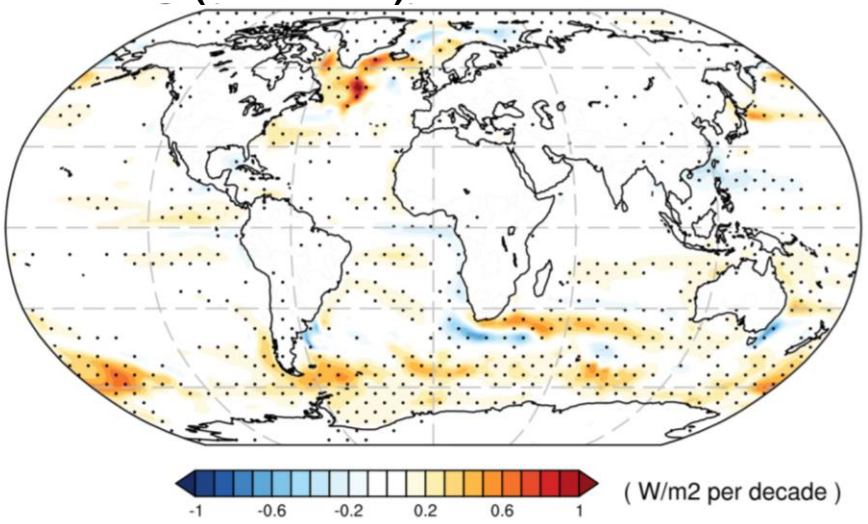
GHG (1861-2005)



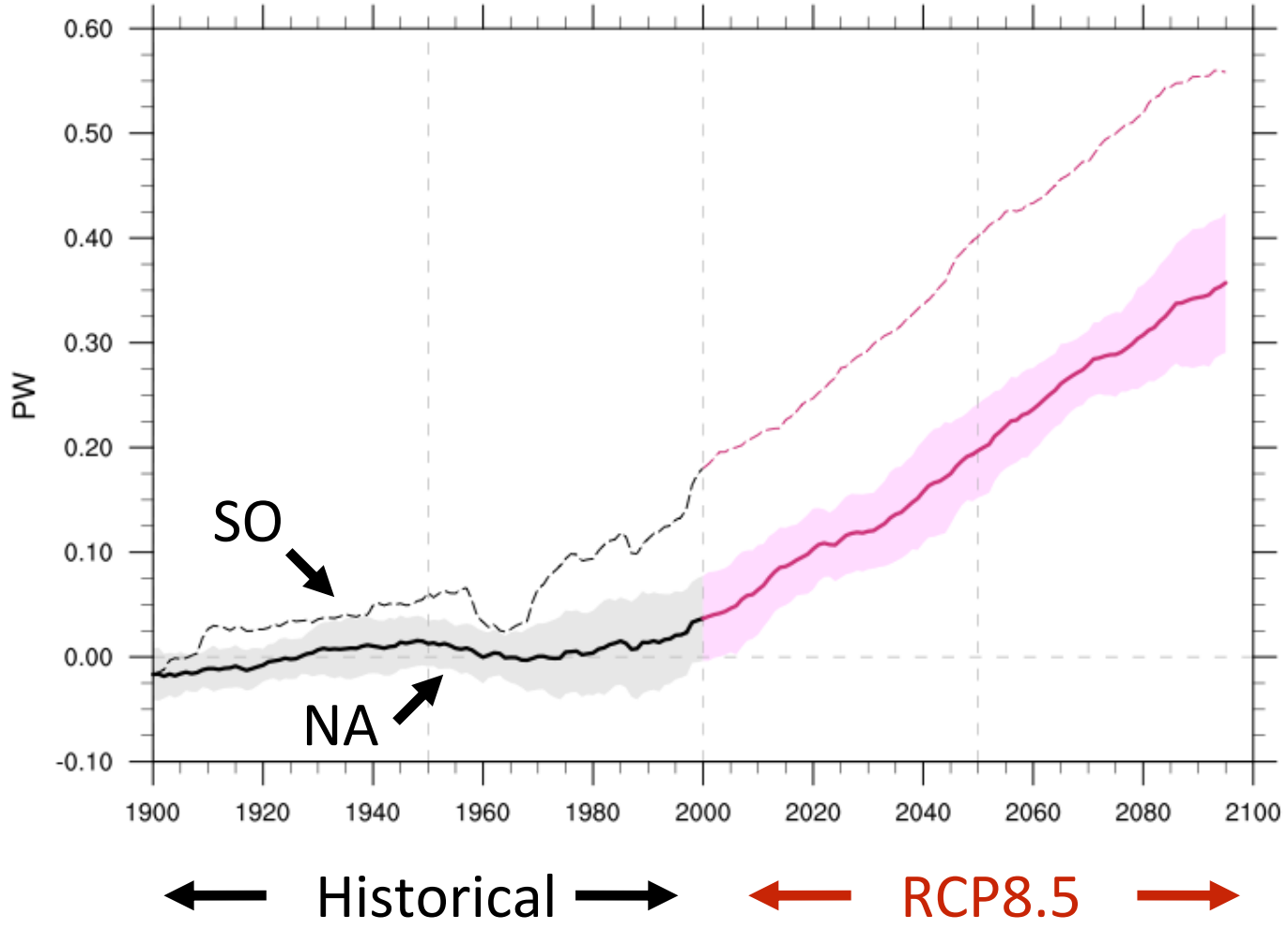
Aerosol (1861-2005)



Historical (1861-2005)



Area-integrated heat flux



Shi, J., S.-P. Xie, and L.D. Tally, 2018: Evolving relative importance of the Southern Ocean and North Atlantic in anthropogenic ocean heat uptake. *J. Climate*, in press.

Summary 2

- Historically, most ocean heat uptake took place in Southern Ocean
- Localized heat uptake drives cross-equatorial Hadley circulation response and reorganization of tropical monsoon/rainfall.
- With anticipated decline in aerosols, the North Atlantic contribution to heat uptake is expected to increase.
  → Further changes in atmospheric circulation/rainfall.