Historical and Future Changes of Tropical Rain Belts: Cloud and Aerosol Processes

Hui Su

Chengxing Zhai[1], Jonathan H. Jiang[1], Longtao Wu[1], J. David Neelin[2], Yuk L. Yung[3]

[1]Jet Propulsion Laboratory, California Institute of Technology
[2]University of California, Los Angeles
[3]California Institute of Technology

WCRP Grand Challenge 2nd Meeting on Monsoons and Tropical Rain Belts
July 2-5, Trieste, Italy

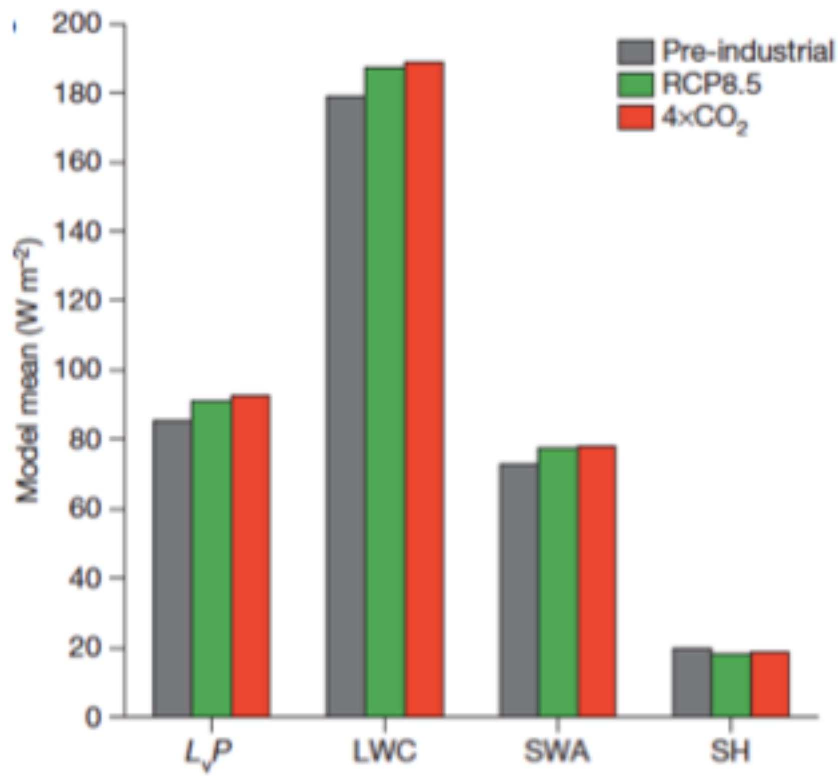
Outline

- Atmospheric energy constraint on global-mean precipitation
- Moist static energy (MSE) framework for tropical circulation
- Observations of tropical rain belt change

Atmospheric Energy Constraint on Global-mean Precipitation

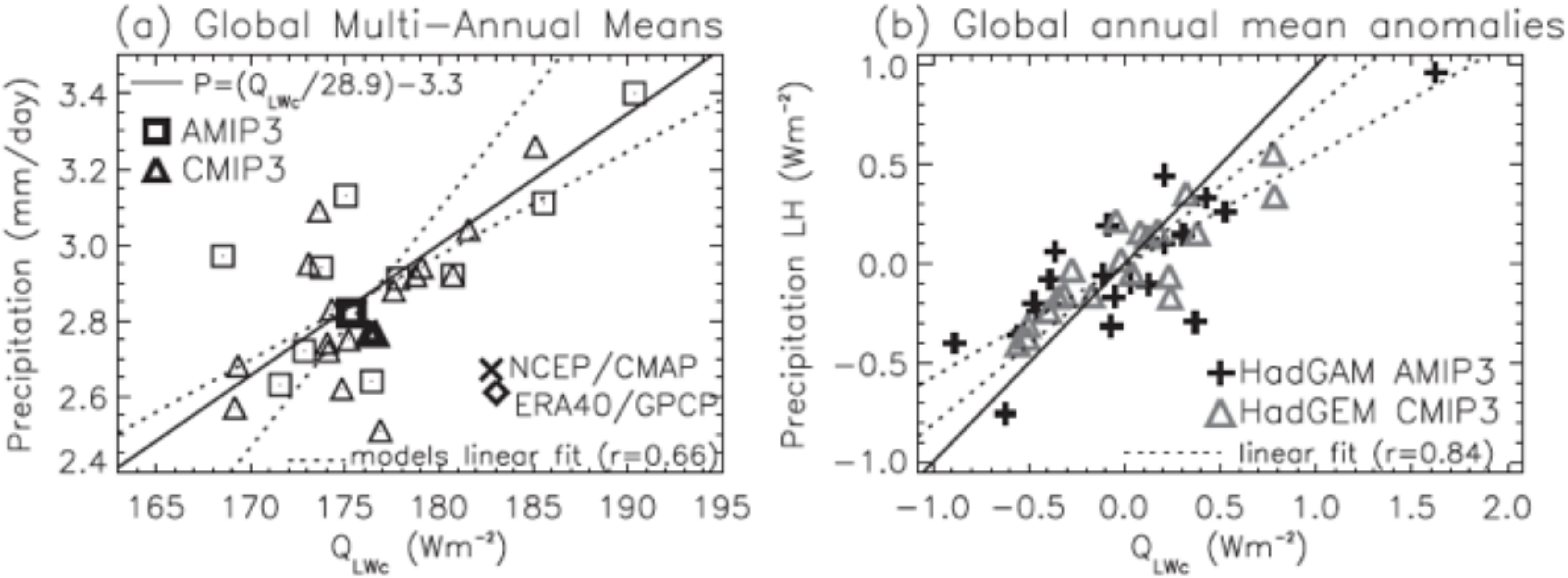
$$L_v P = LWC - SWA - SH$$

Allen and Ingram (2002, Nature)



DeAngelis et al. (2015, Nature)

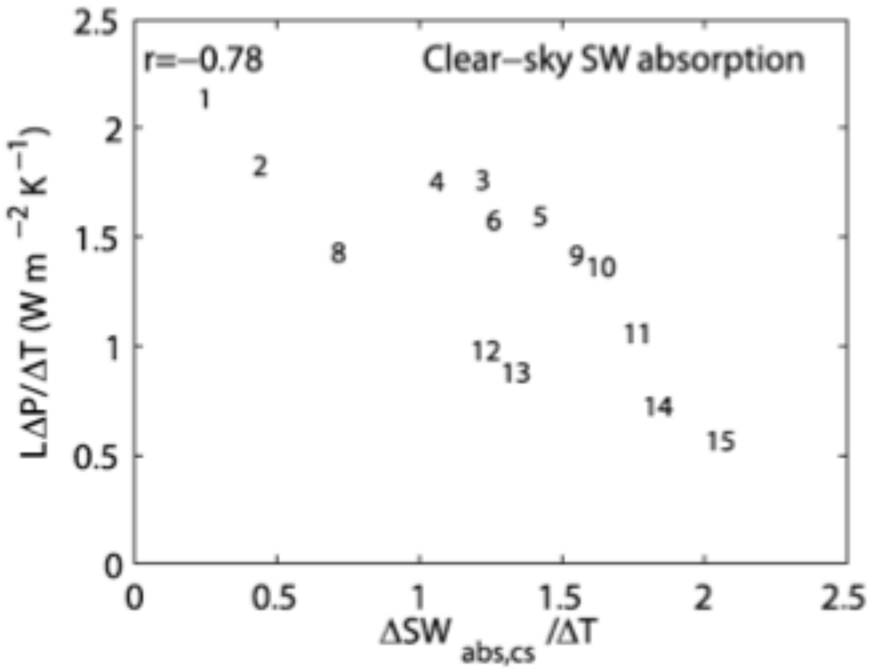
Clear-sky Longwave Radiation



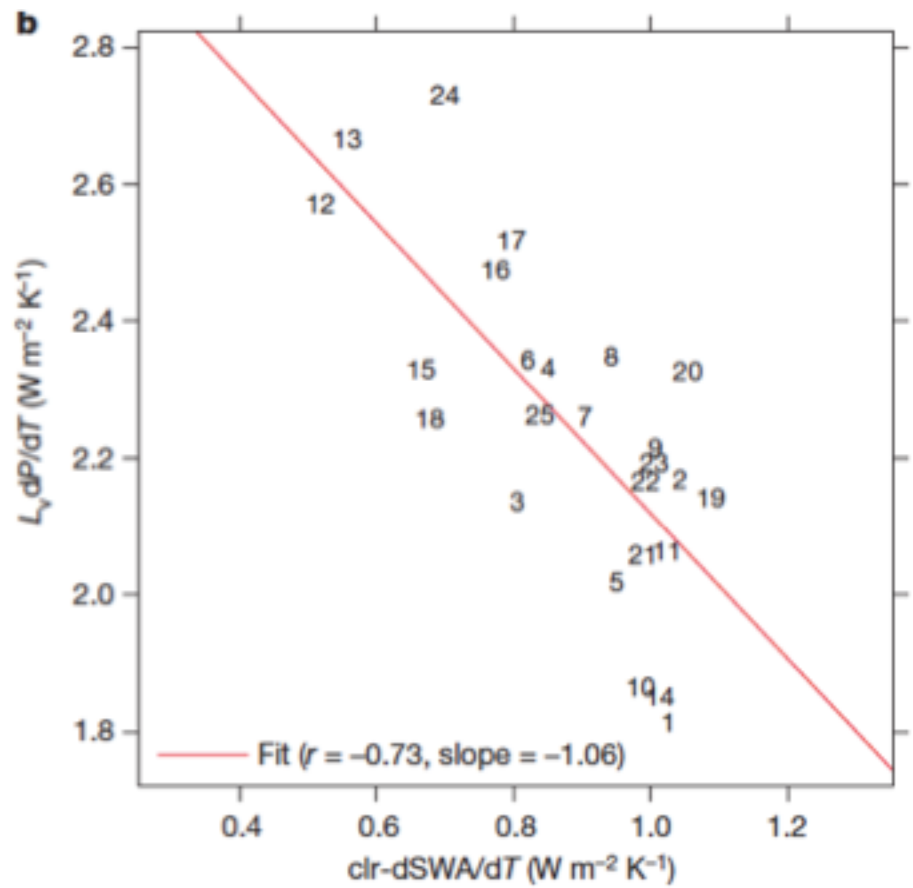
Allan (2009, J. Clim)

LW_C here is clear-sky longwave radiative cooling

Inter-model Spread in Clear-sky Shortwave Absorption



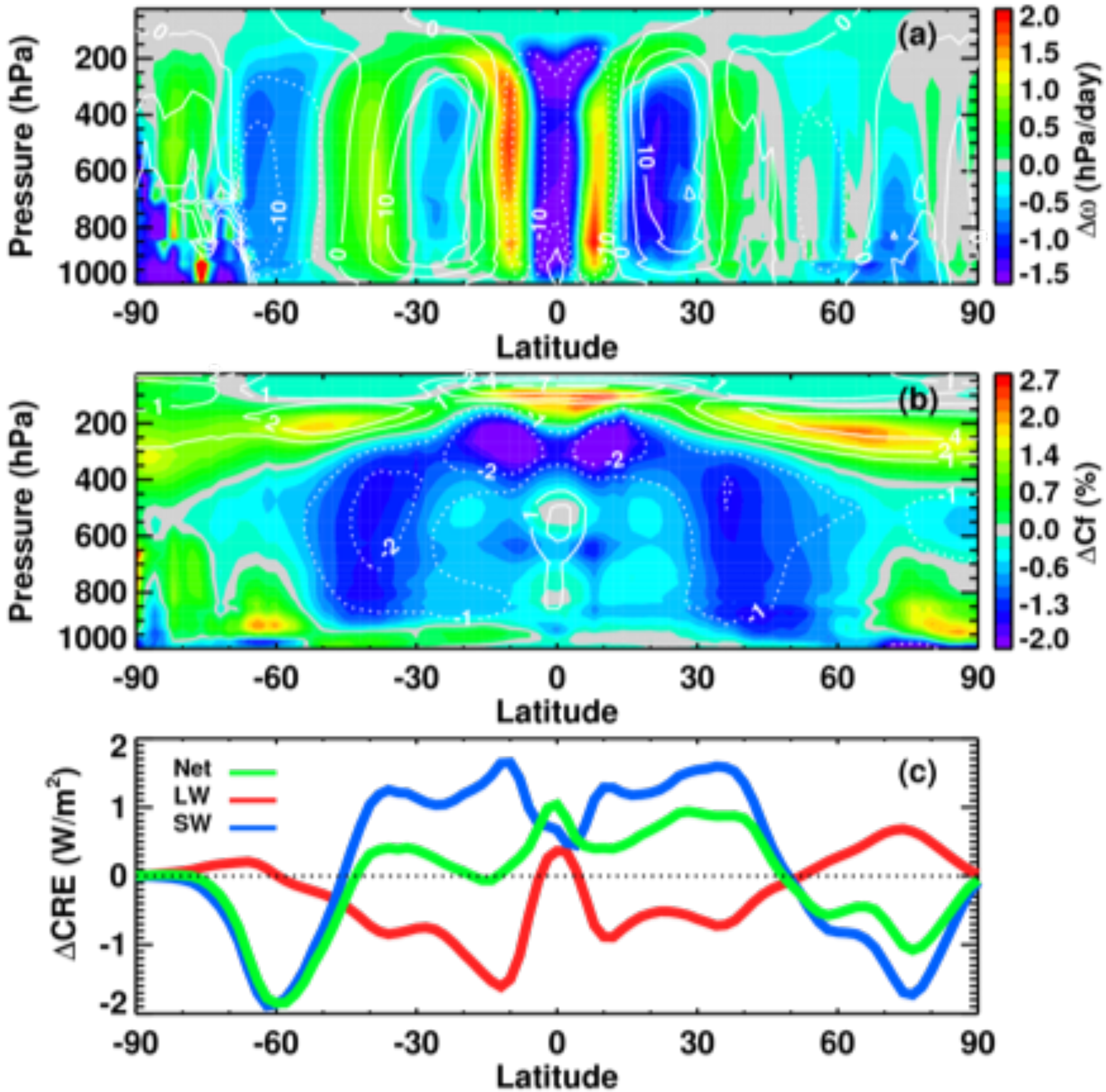
Pendergrass and Hartmann (2012, GRL)



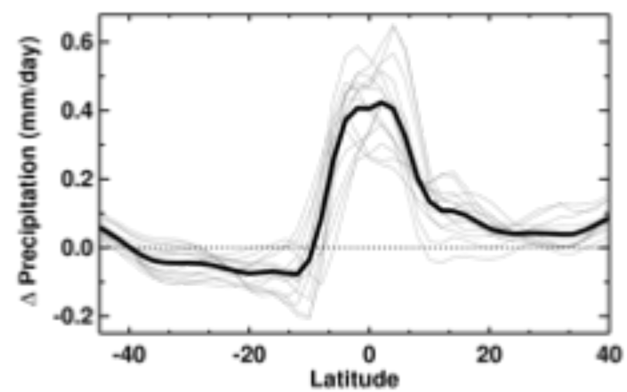
DeAngelis et al. (2015, Nature)

Changes of Hadley Circulation, Cloud Radiative Effects and Precipitation

(Su et al., 2014, JGR)

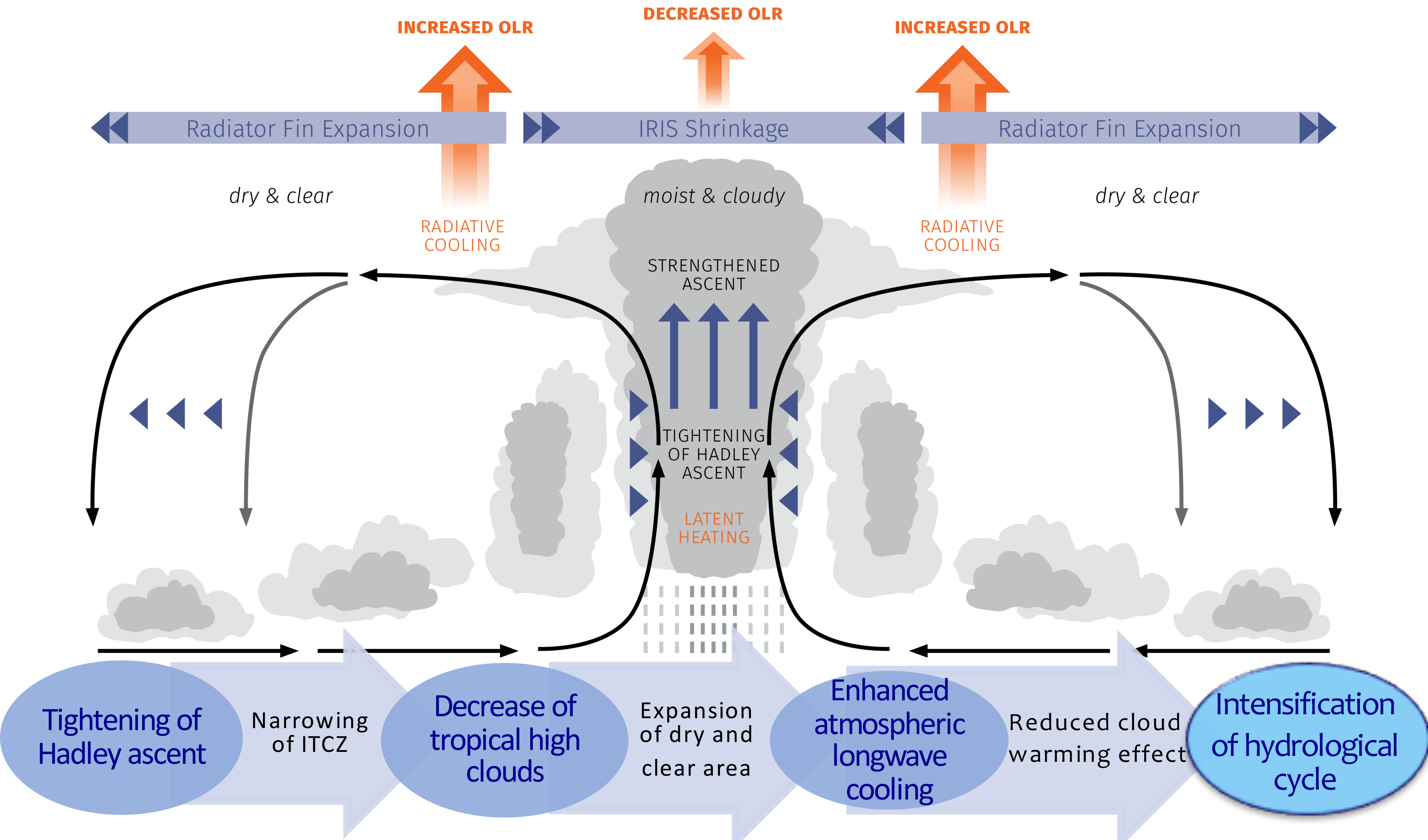


"The Wet Get Wetter, The Dry Get Drier"



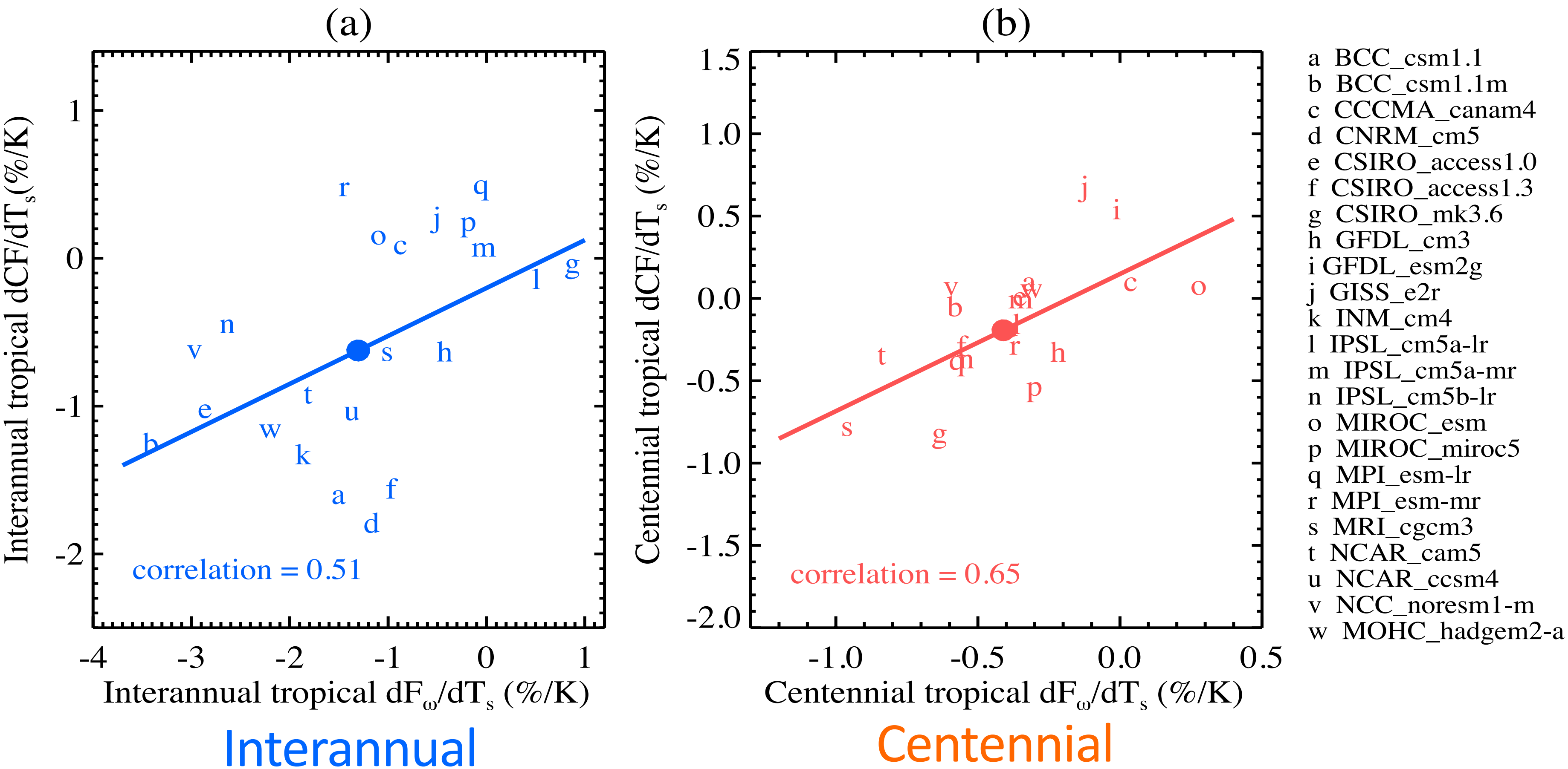
Δ = 2074-2098 in "RCP4.5" – 1980-2004 in "historical run"

Tightening of Tropical Ascent and High Clouds Key to Precipitation Change in a Warmer Climate



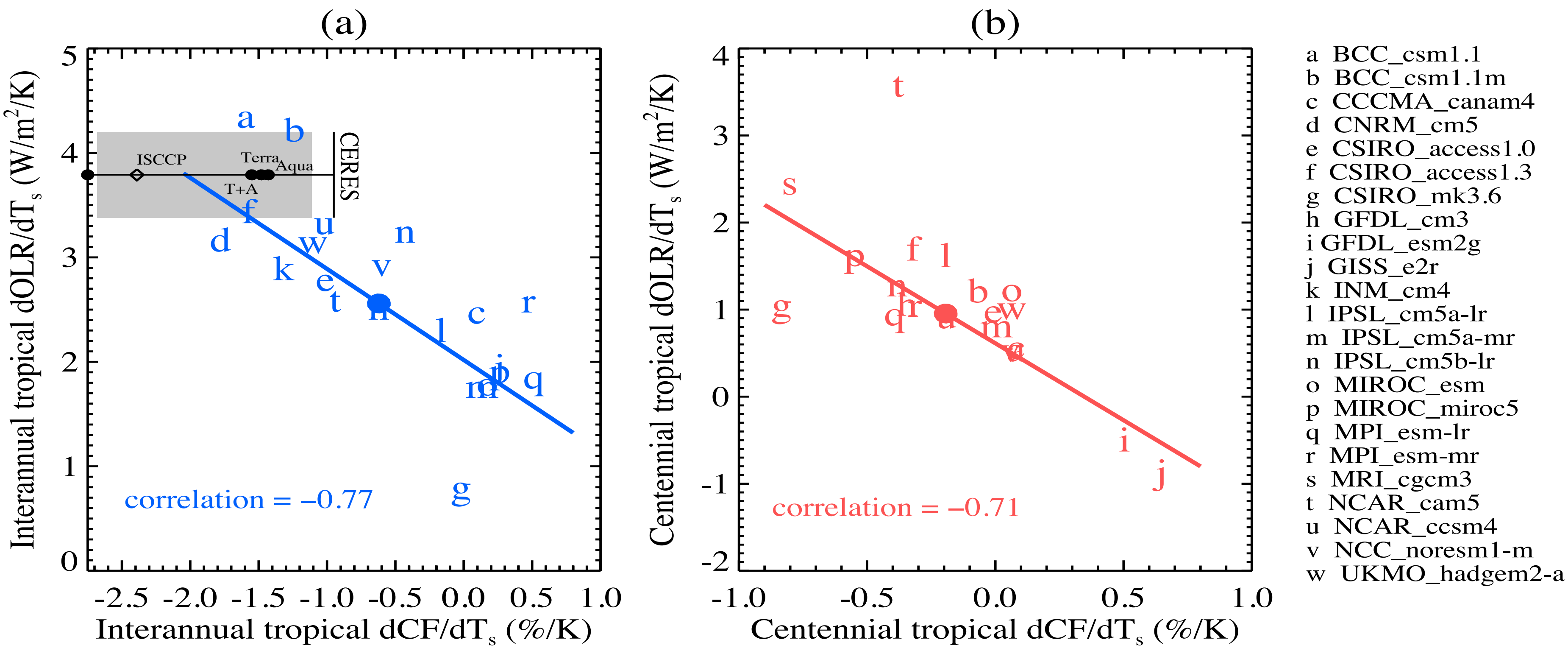
Su et al. (2017, Nature Comm.)

ITCZ Narrowing Linked to High Cloud Reduction



Su et al. (2017, Nature Comm.)

Longwave Effect of High Cloud Reduction

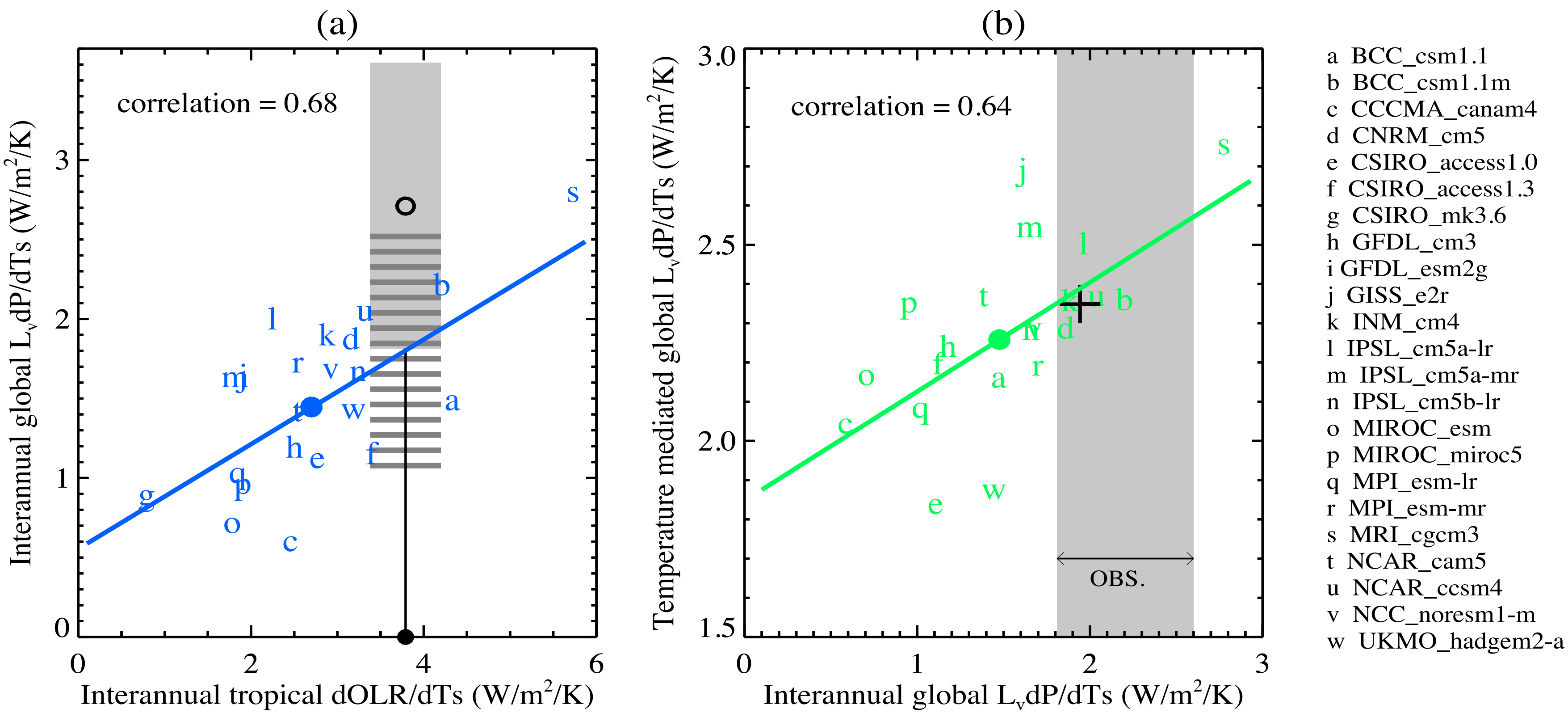


Interannual

Centennial

Su et al. (2017, Nature Comm.)

Observational Constraint on Hydrological Sensitivity



- Observation-based Interannual dP/dTs : 2.1%/K to 3.0%/K
- Observation-constrained hydrological sensitivity: 2.6%/K to 2.9%/K
- The multi-model-mean of the 21 models is 2.6%/K

Su et al. (2017, Nature Comm.)

Moisture Static Energy Budget

$$\partial_t \langle T \rangle + \langle \mathbf{v} \cdot \nabla T \rangle + \langle \omega \partial_p s \rangle = \frac{g}{p_T} (P + R + H)$$

$$\partial_t \langle q \rangle + \langle \mathbf{v} \cdot \nabla q \rangle + \langle \omega \partial_p q \rangle = -\frac{g}{p_T} (P - E)$$

$$\boldsymbol{P = E - \frac{p_T}{g} \langle \mathbf{v} \cdot \nabla q \rangle - \frac{p_T}{g} \langle \omega \partial_p q \rangle}$$

$$\Delta P_{dyn} \approx -\frac{p_T}{g} \langle \Delta\omega \partial_p q \rangle$$

$$\Delta P_{therm} \approx -\frac{p_T}{g} \langle \omega \partial_p \Delta q \rangle$$

Xie et al. (2015, Nature. Clim. Change)

$$\Delta P_{dyn} \propto \Delta\omega$$

Moisture Static Energy Budget

$$\partial_t \langle q + T \rangle + \langle \mathbf{v} \cdot \nabla (q + T) \rangle + \langle \omega \partial_p h \rangle = \frac{g}{p_T} F_{net}$$

$$\boldsymbol{h = T + \phi + q = s + q}$$

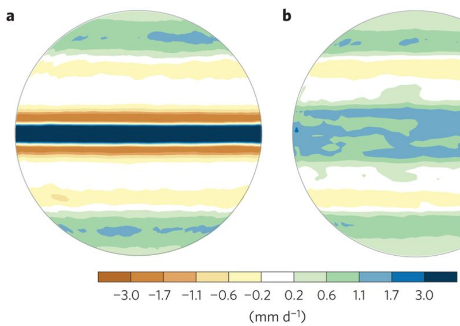
$$F_{net} = R + E + H = (S_t^{\downarrow} - S_t^{\uparrow} - L_t^{\uparrow}) + (S_s^{\uparrow} - S_s^{\downarrow} + L_s^{\uparrow} - L_s^{\downarrow}) + E + H$$

$$\omega(x, y, p, t) = -\Omega 1(p)\, \omega_1 \qquad GMS = \langle \Omega 1 (-\partial_p h) \rangle$$

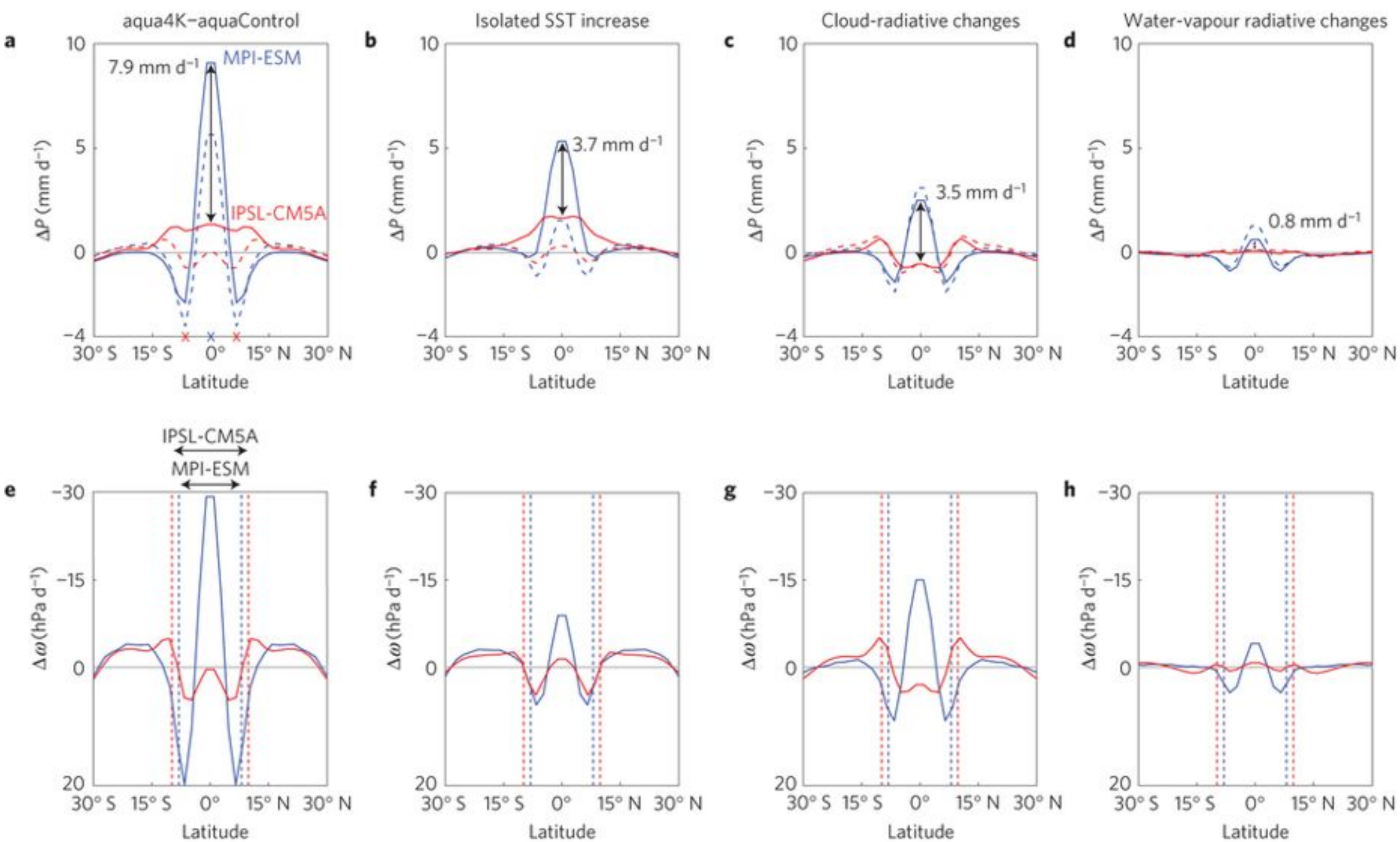
$$\boldsymbol{\omega_1 \approx \frac{g}{p_T} F_{net} / GMS}$$

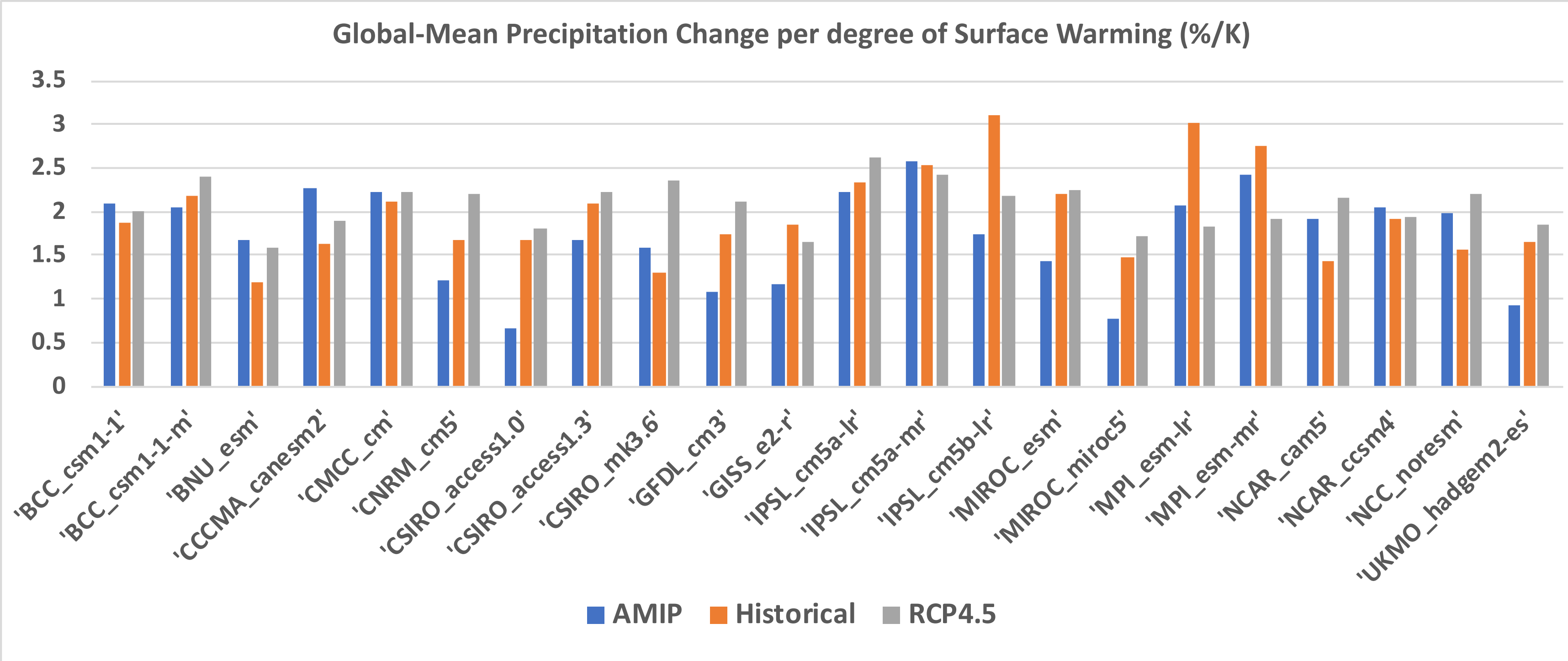
$$\Delta \omega_1 \propto \Delta F_{net}$$

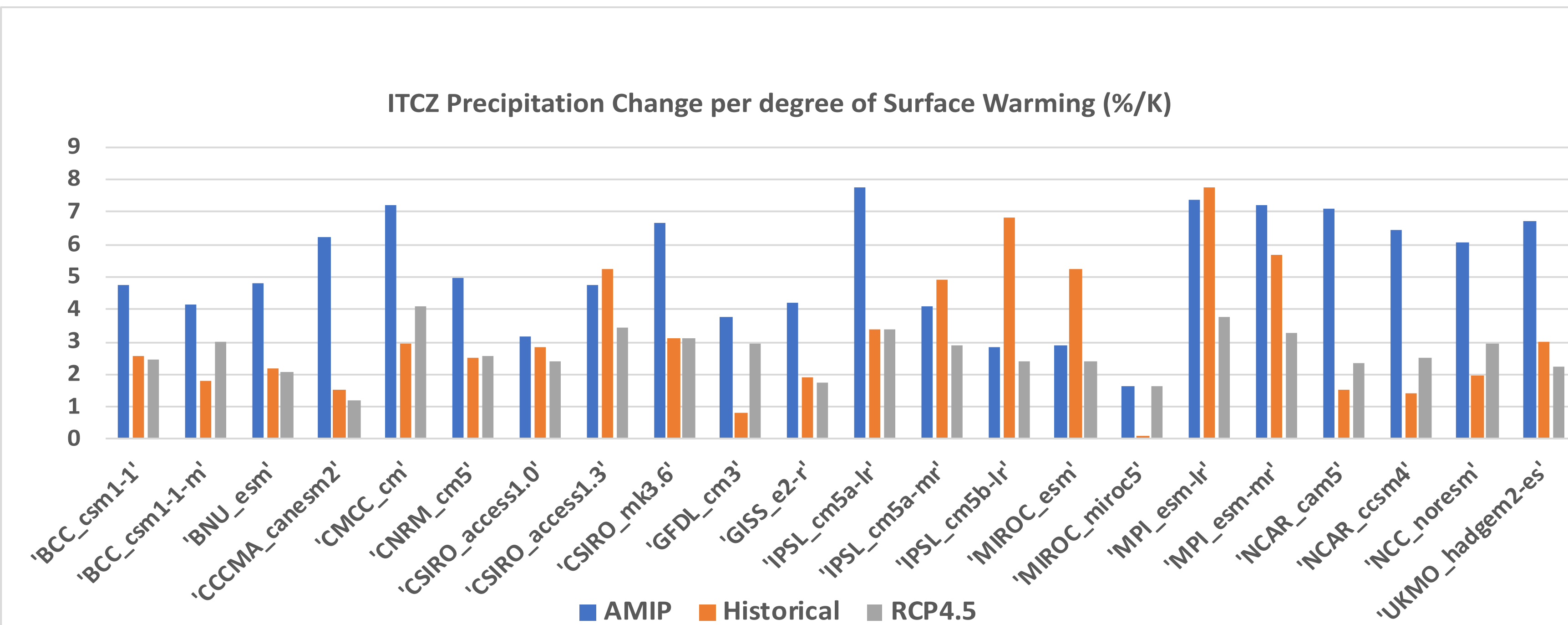
Radiative Changes of Clouds and Water Vapor



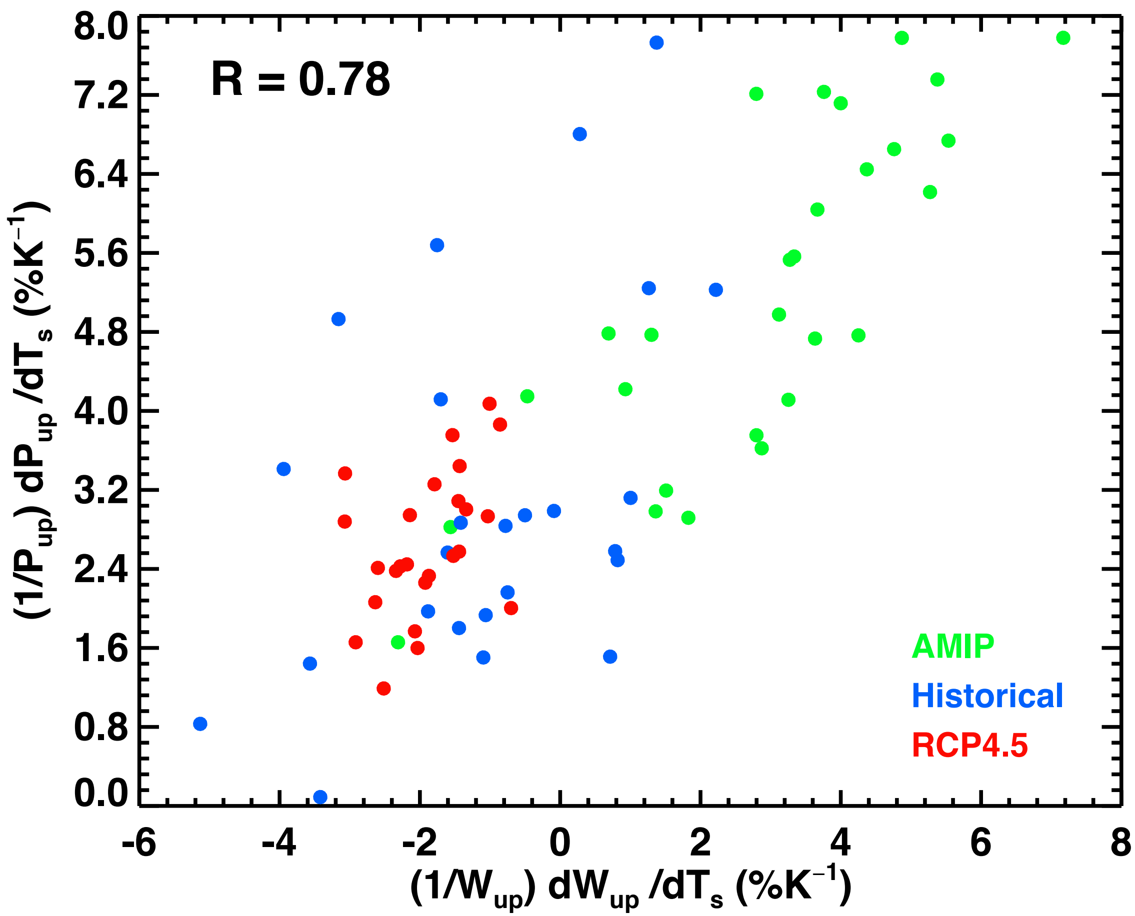
Voigt and Shaw (2015, Nature Geo.)




Global-Mean Precipitation Change per degree of Surface Warming (%/K)
3.5
3
2.5
2
1.5
1
0.5
0
'BCC_csm1-1'
'BCC_csm1-1-m'
'BNU_esm'
'CCCMA_canesm2'
'CMCC_cm'
'CNRM_cm5'
'CSIRO_access1.0'
'CSIRO_access1.3'
'CSIRO_mk3.6'
'GFDL_cm3'
'GISS_e2-r'
'IPSL_cm5a-lr'
'IPSL_cm5a-mr'
'IPSL_cm5b-lr'
'MIROC_esm'
'MIROC_miroc5'
'MPI_esm-lr'
'MPI_esm-mr'
'NCAR_cam5'
'NCAR_ccsm4'
'NCC_noresm'
'UKMO_hadgem2-es'
AMIP
Historical
RCP4.5

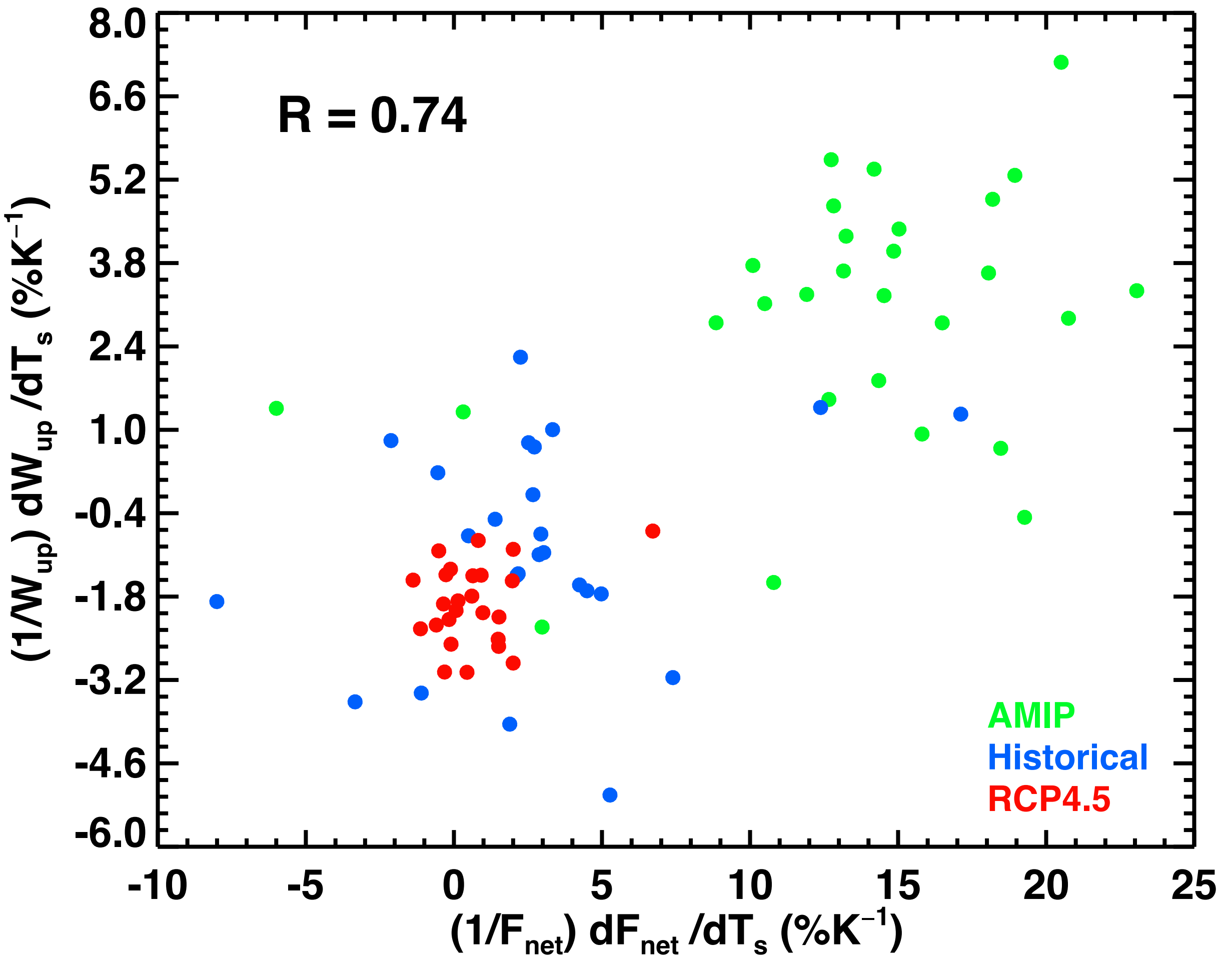

ITCZ Precipitation Change per degree of Surface Warming (%/K)
9
8
7
6
5
4
3
2
1
0
'BCC_csm1-1'
'BCC_csm1-1-m'
'BNU_esm'
'CCCMA_canesm2'
'CMCC_cm'
'CNRM_cm5'
'CSIRO_access1.0'
'CSIRO_access1.3'
'CSIRO_mk3.6'
'GFDL_cm3'
'GISS_e2-r'
'IPSL_cm5a-lr'
'IPSL_cm5a-mr'
'IPSL_cm5b-lr'
'MIROC_esm'
'MIROC_miroc5'
'MPI_esm-lr'
'MPI_esm-mr'
'NCAR_cam5'
'NCAR_ccsm4'
'NCC_noresm'
'UKMO_hadgem2-es'
AMIP
Historical
RCP4.5

Inter-model Spread of Circulation and Precipitation Changes



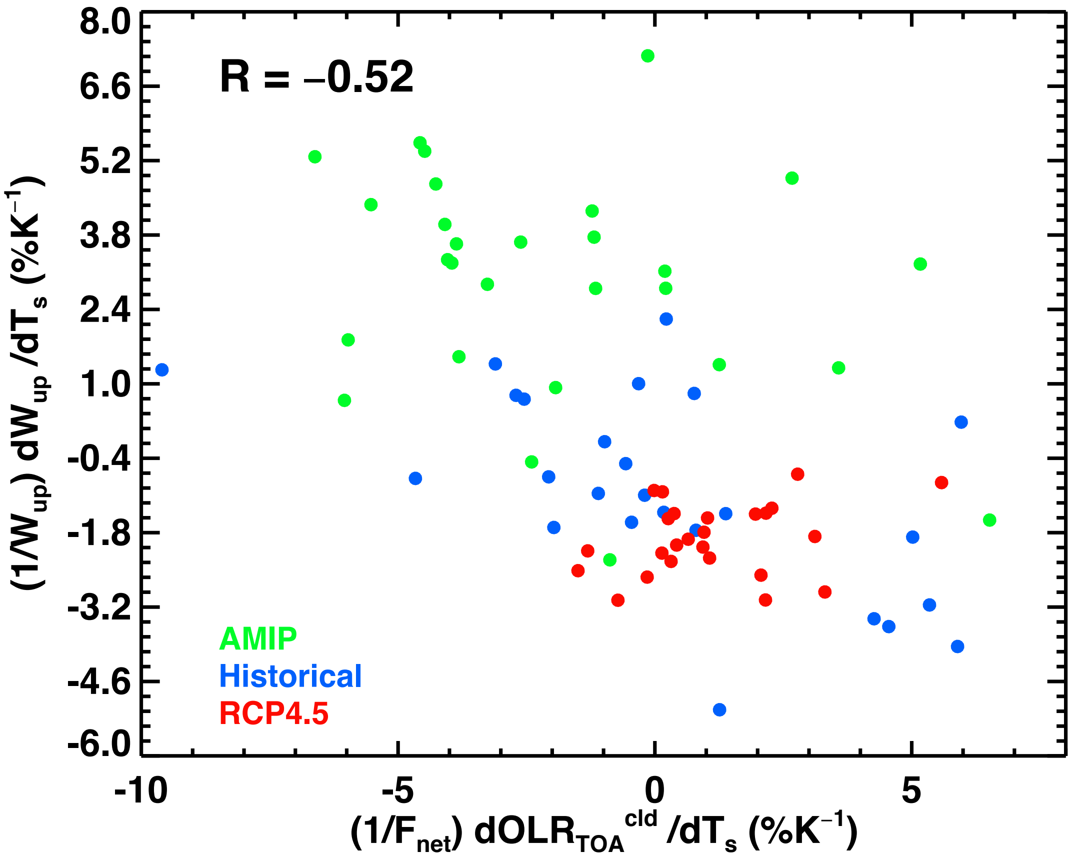
$$\Delta P \propto \Delta\omega_1$$

Energetic Constraint of Tropical Circulation Change



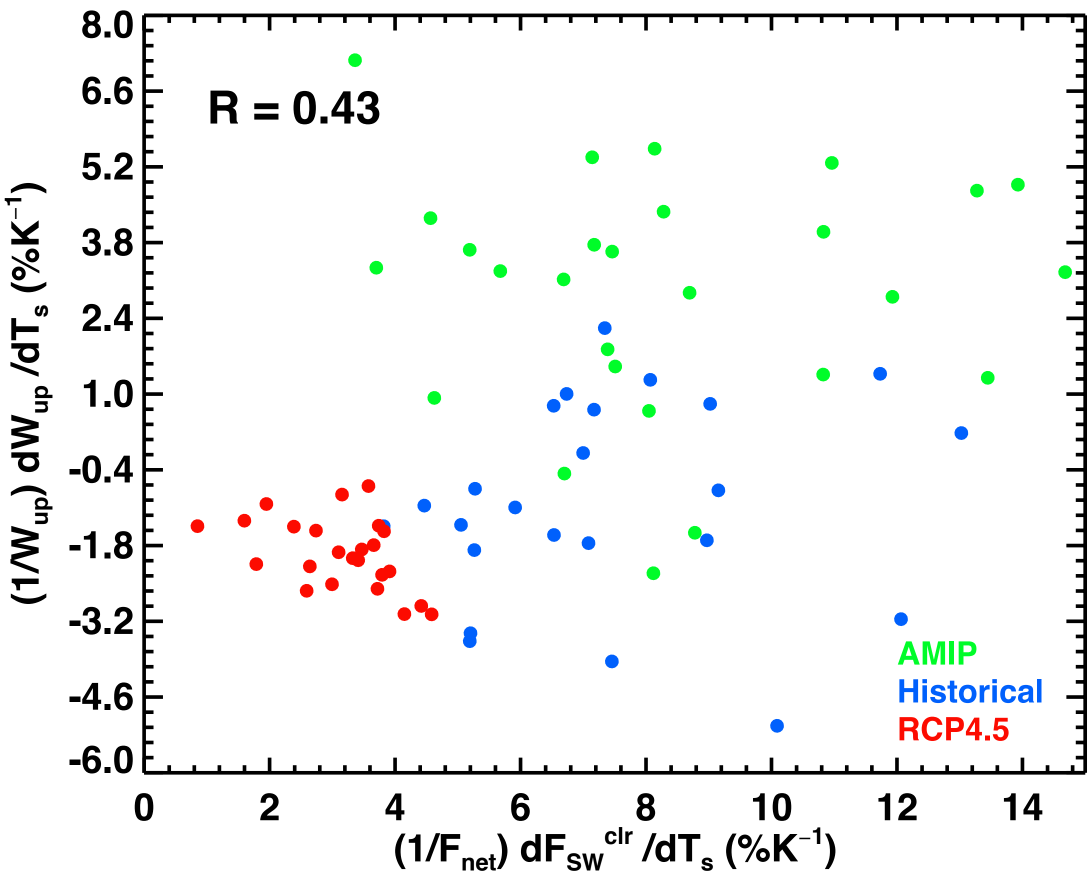
$$\Delta\omega_1 \propto \Delta F_{net}$$

Longwave Cloud Radiative Effect



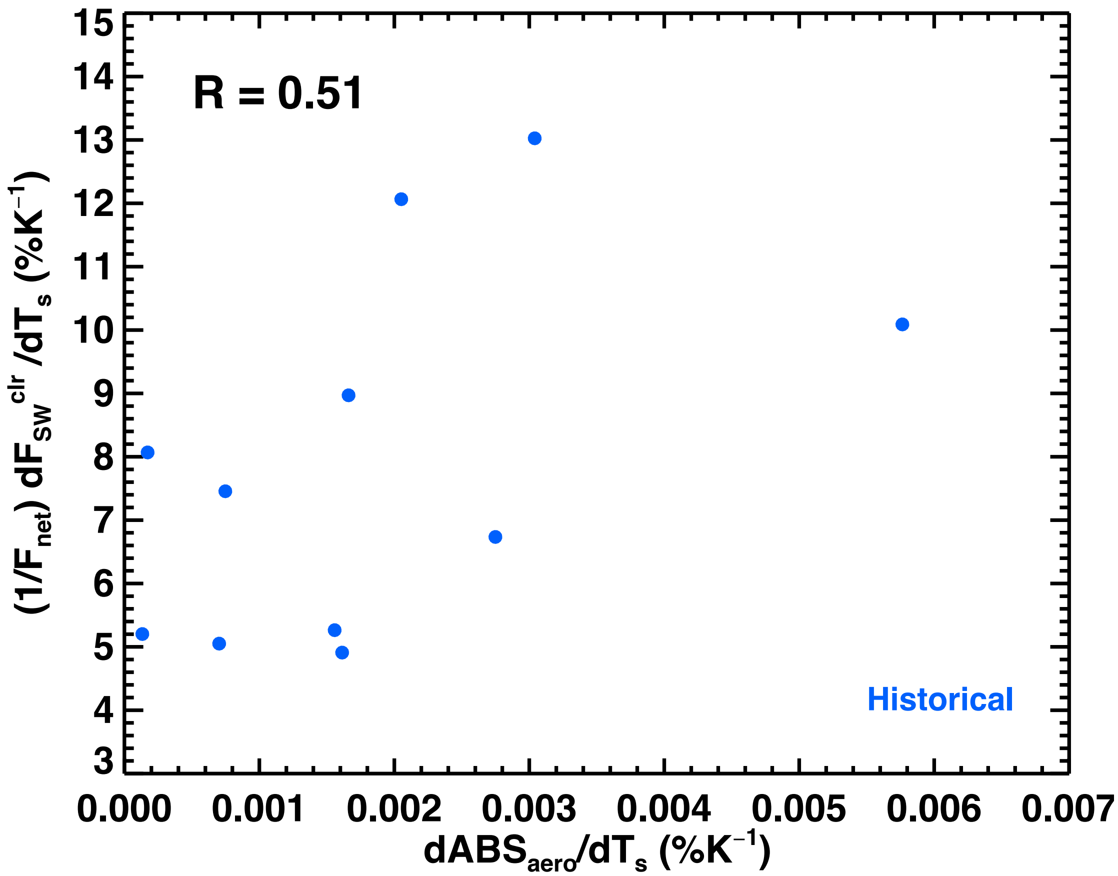
- Less longwave loss at TOA leads to a stronger ascent

Clear-sky Shortwave Absorption

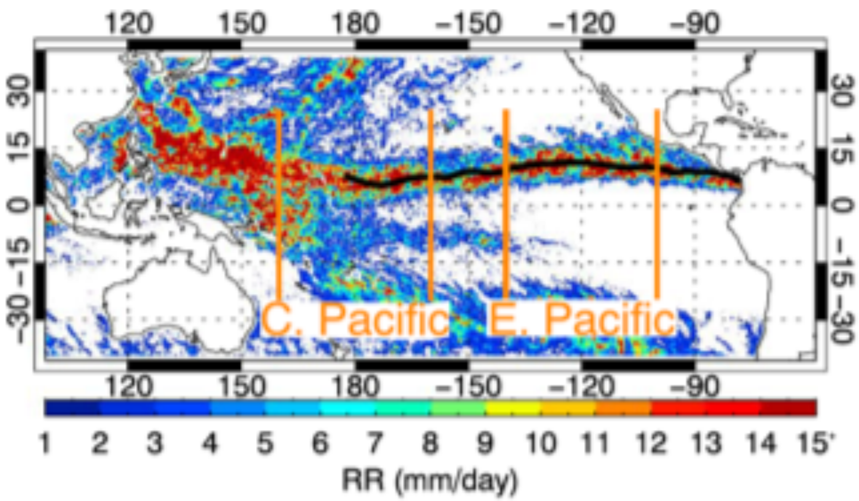


- Greater clear-sky shortwave absorption leads to a stronger ascent

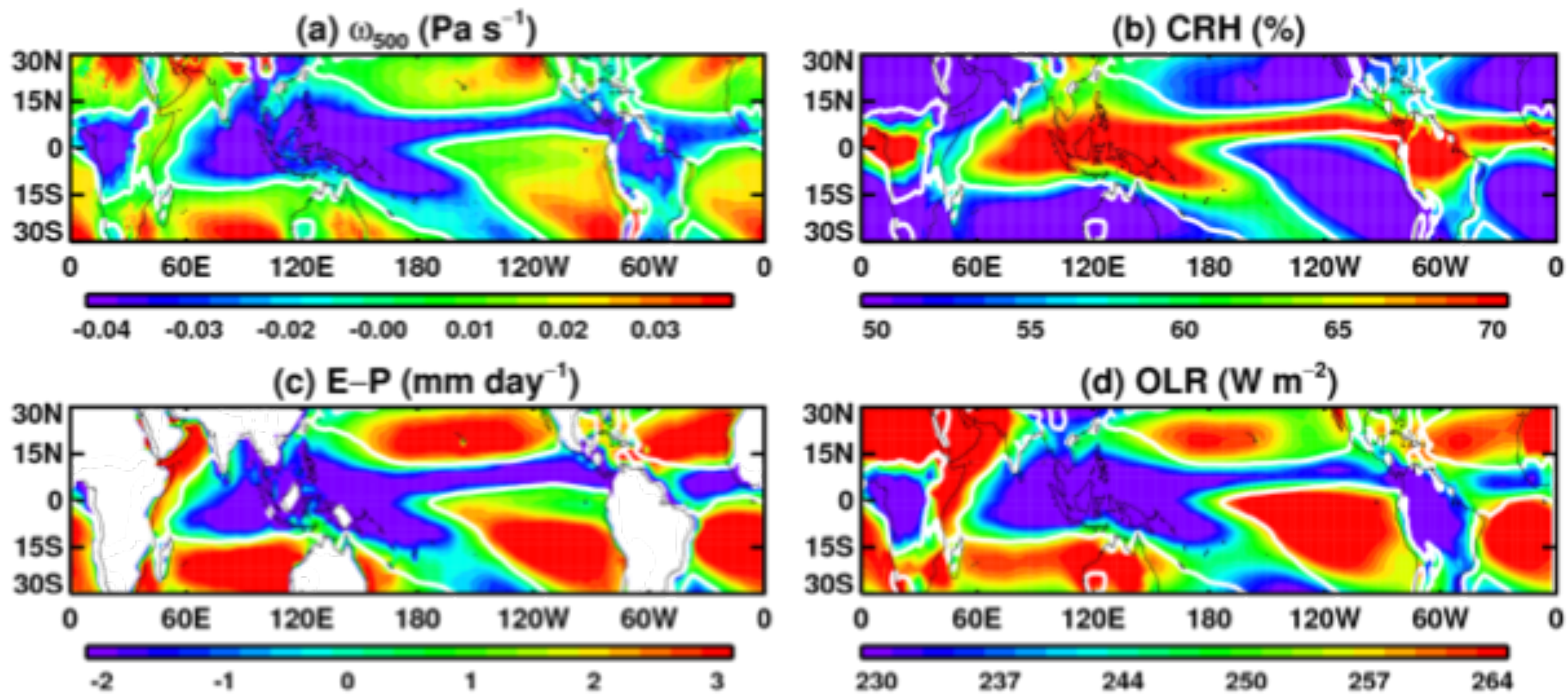
The Role of Absorbing Aerosols



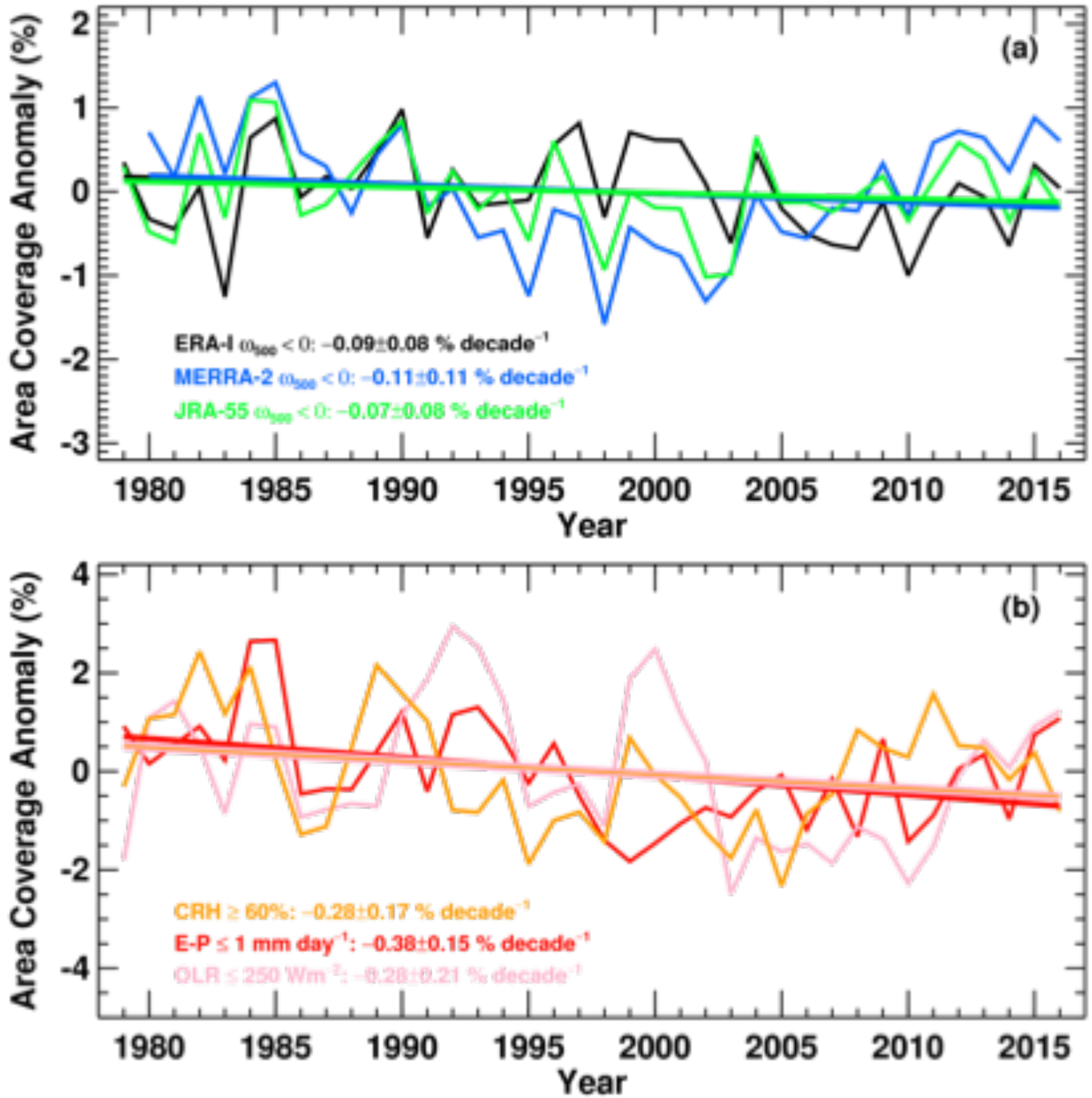
Observed Narrowing of the ITCZ



Wodzicki and Rapp (2016, JGR)

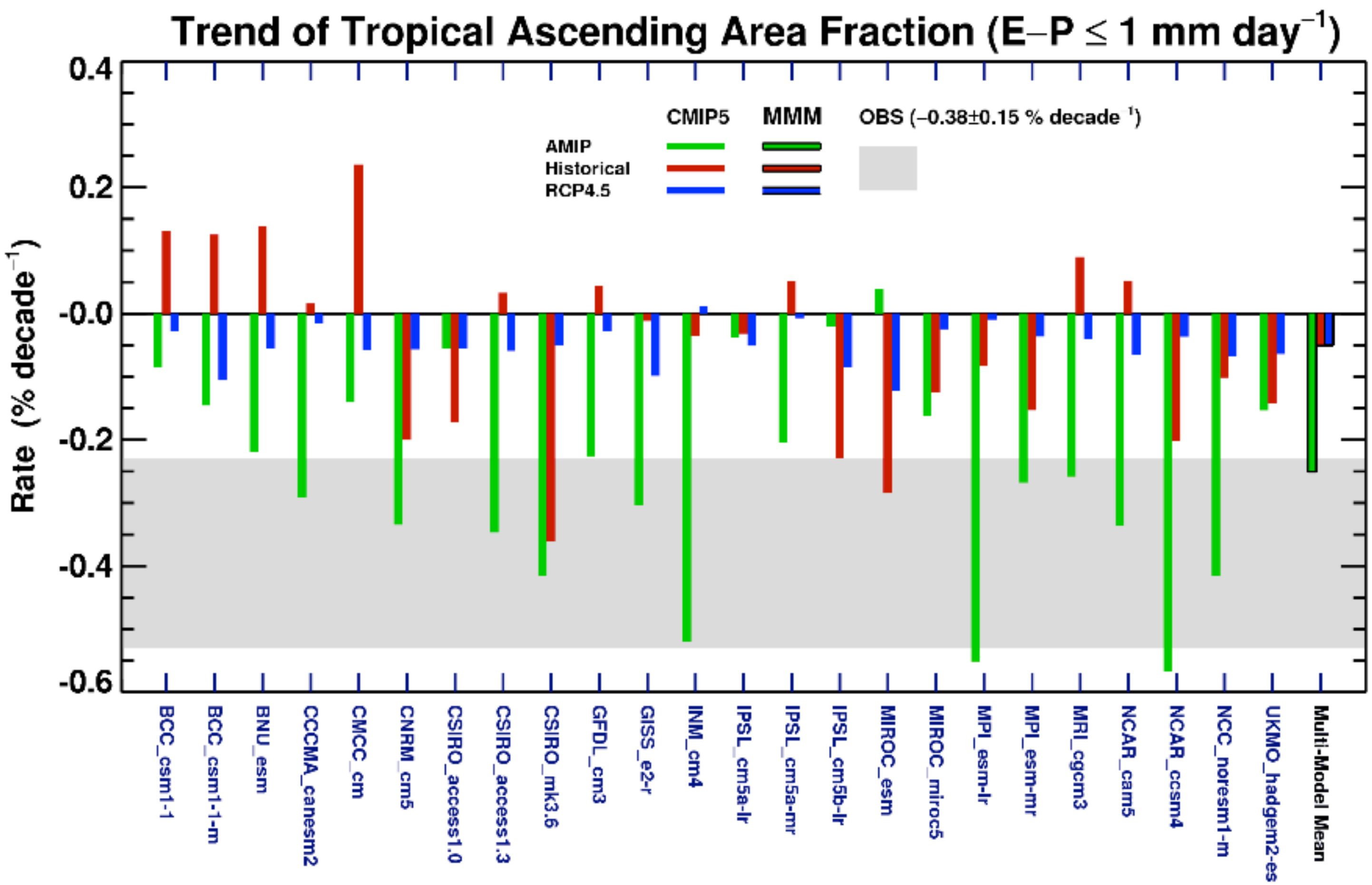


Observed Narrowing of the ITCZ



Su et al. (2018, in prep)

CMIP5 Simulations of the Narrowing



Su et al. (2018, in prep)

Summary

- The changes of the ITCZ intensity and area are strongly constrained by atmospheric energy budget.

- Model diversity in the radiative effects of tropical high clouds and absorbing aerosols contributes significantly to the inter-model spread in the ITCZ intensity and area changes in the past decades.

- Observational evidence of the narrowing of ITCZ is robust.