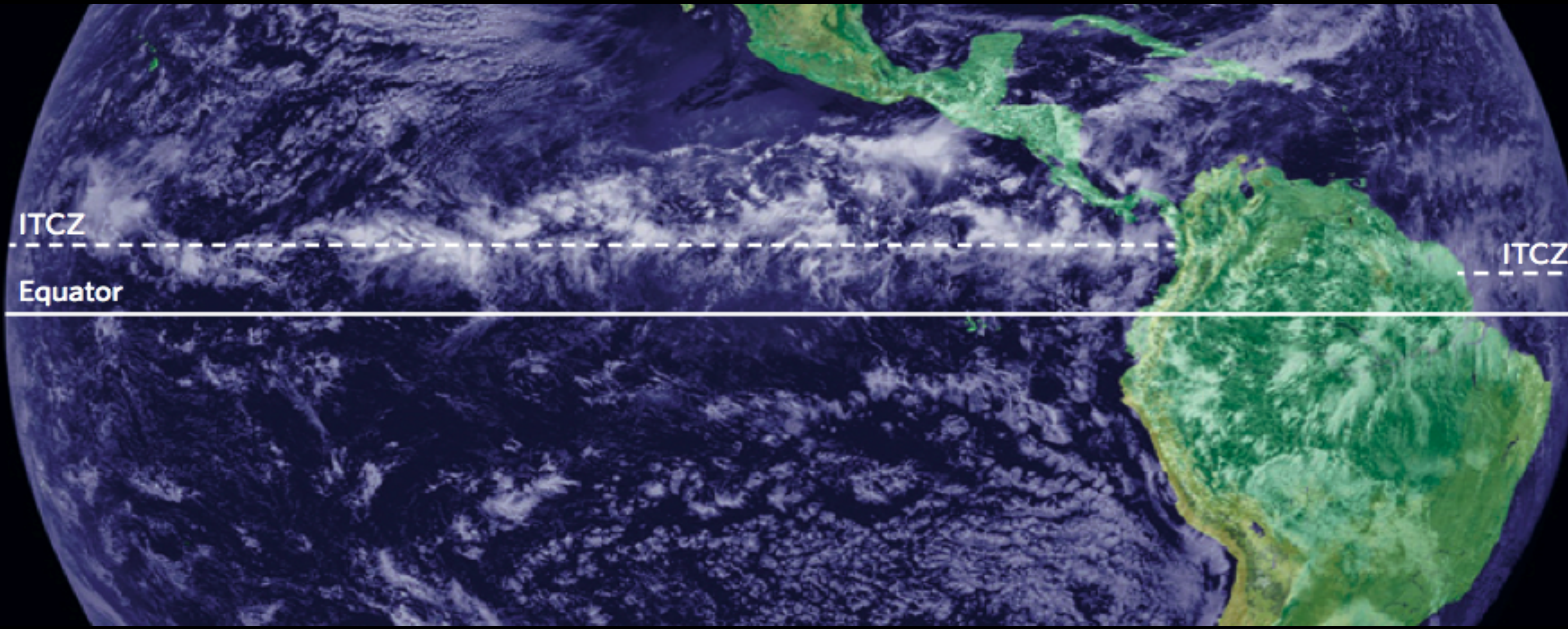
An Interconnected Planet

How Radiation Drives Distant Climate Anomalies



Dargan M. W. Frierson
University of Washington

CERES Workshop, 9-2-15

New Connections

Recent research has uncovered some remarkable new links between radiation and circulation

- The **ozone hole** caused a large shift in the Southern Hemisphere storm tracks
- **Aerosols** affecting climate locally and remotely
- **Vegetation** can change atmospheric circulation patterns
- **Clouds** affect global and regional climate

All these parts of the Earth system have profound interconnections – often unexpected ones

WCRP Grand Challenge

- Clouds, Circulation and Climate Sensitivity
  - Bony, Stevens, Frierson, Jakob, Kageyama, Pincus, Shepherd, Sherwood, Siebesma, Sobel, Watanabe, Webb

- Other current challenges:
  - Changes in cryosphere
  - Climate extremes
  - Regional climate information
  - Regional sea-level rise
  - Water availability

Four Questions

1. What role does convection play in **cloud feedbacks**?
2. What role does **convective aggregation** play in climate?
3. What controls the position, strength and variability of **extratropical storm tracks**?
4. What controls the position, strength, and variability of the **tropical rain belts**?

See Bony et al (2015, Nature Geoscience) for more

Energy Transports

- Zonal mean Earth energy budget

$$\frac{\partial E}{\partial t} = Q_s - Q_l - \frac{\partial F}{\partial y}$$

Change in energy content

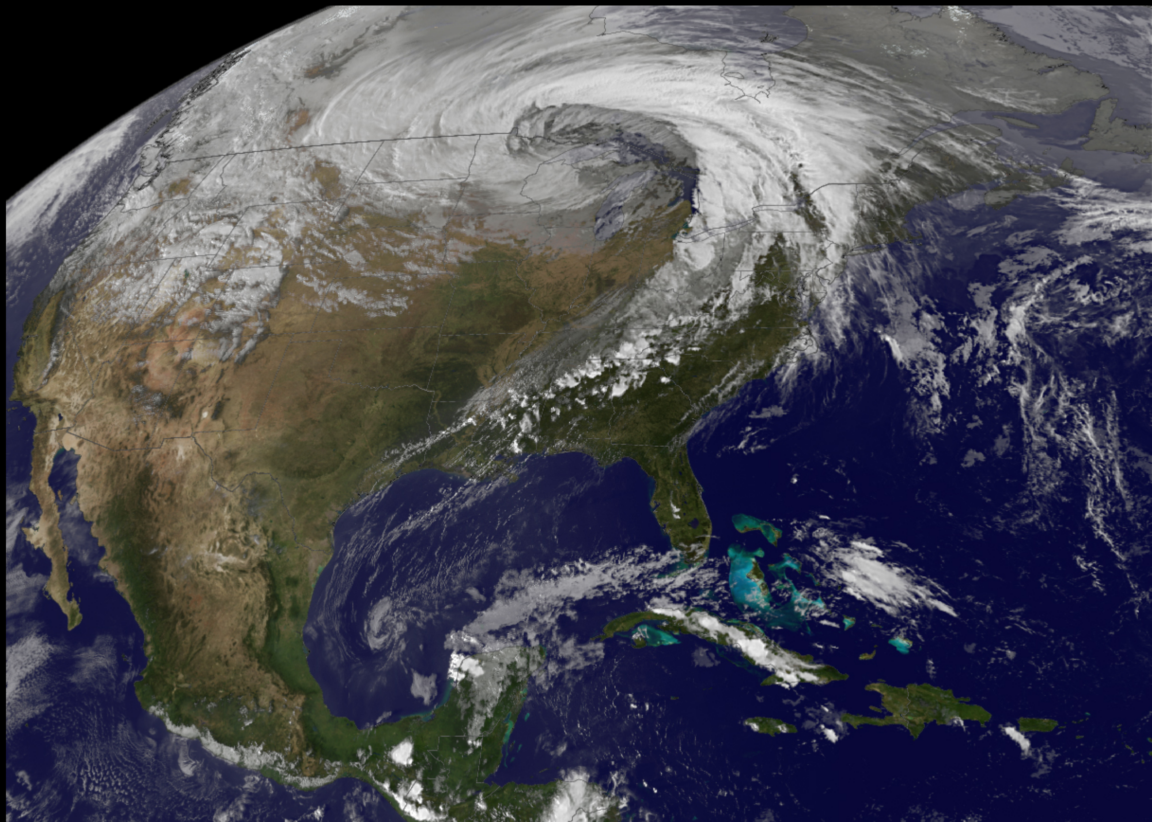
Shortwave radiation

Longwave radiation

Energy transport by atmosphere and ocean

What determines the poleward transport of energy?

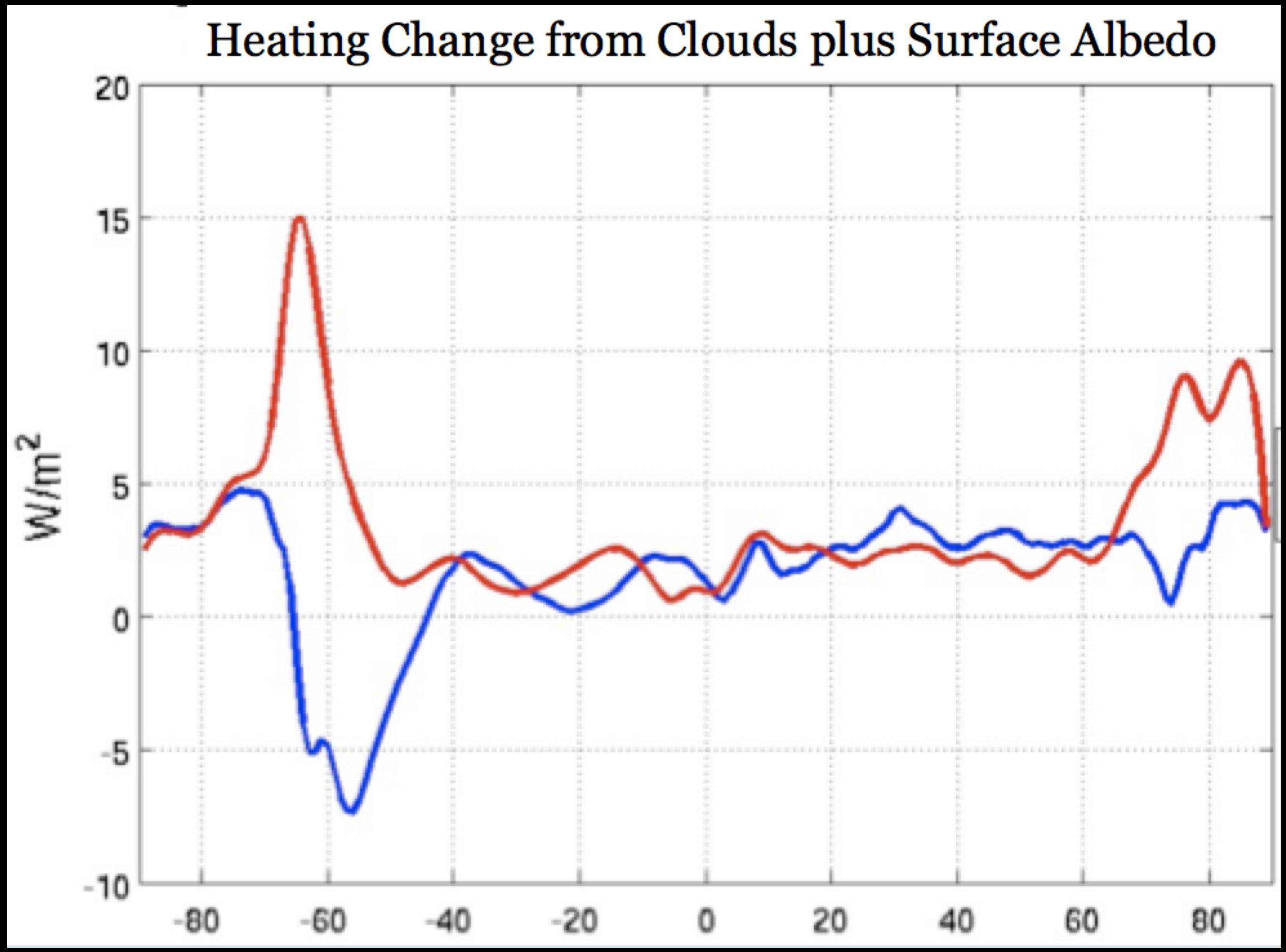
How might this change with global warming?



Our Radiation Revelation

- Early attempts at explaining GCM transports using turbulence theories = fail
- We quickly recognized that radiation was key

Example of heating change w/ doubled CO2 → 15 W/m^2 difference!

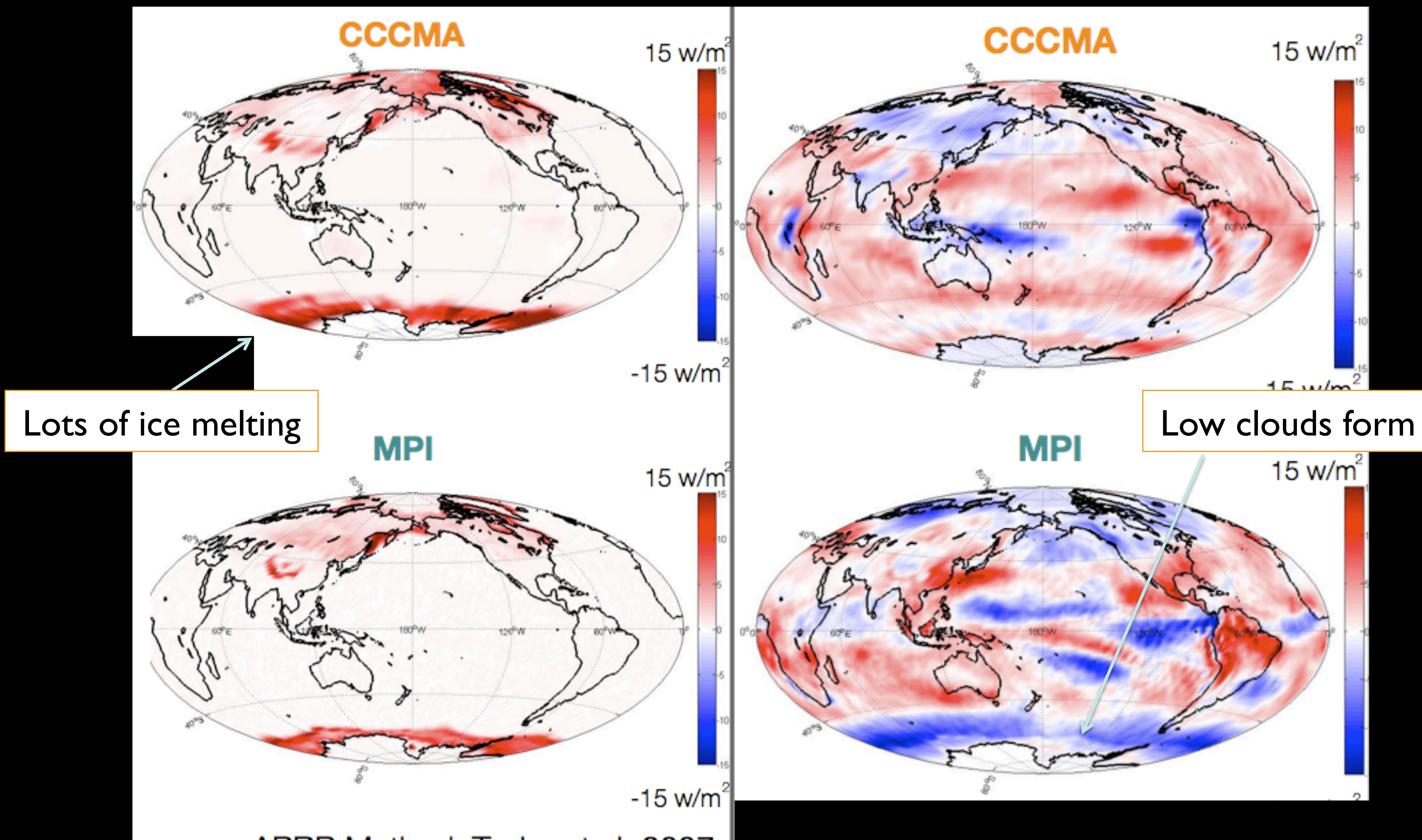


Latitude

CMIP3 slab ocean 2xCO2 exps,
Red = CCCMA, Blue = MPI

Radiative Flux Changes

Surface albedo / Cloud shortwave

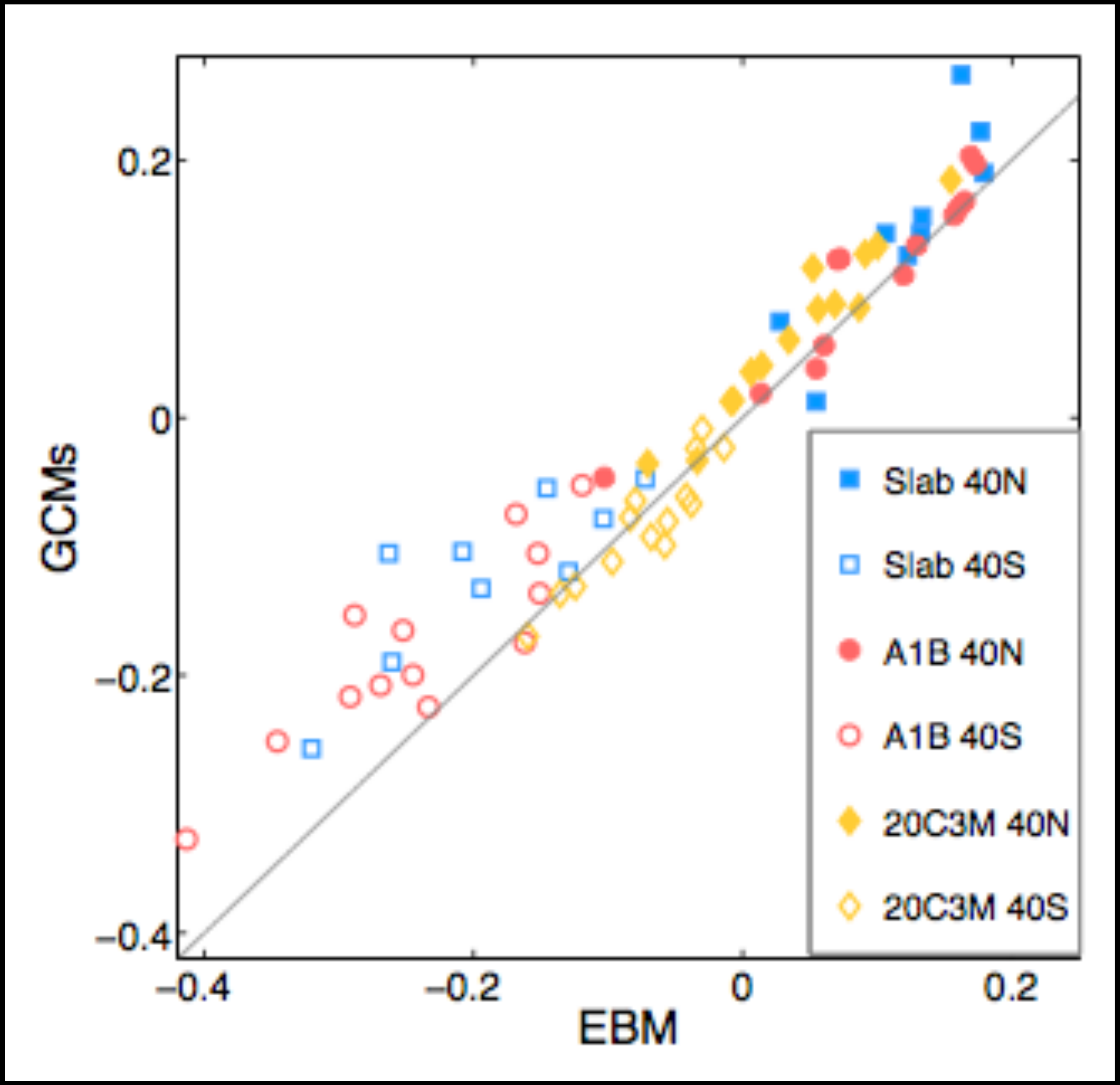


1-D Energy Balance Model for Energy Transports

- Maybe a Budkyo-Sellers-North energy balance model can explain transports??
- **Prescribe latitudinal structure of forcings/ feedbacks**
- Diffuse **moist static energy**
- **Predict**:
  - Energy fluxes
  - Temperature changes
  - Clear sky outgoing radiation changes
- Assumes **constant** diffusivity!

Diffusive Model Performance in Midlatitudes

Midlatitude (40° N/S)



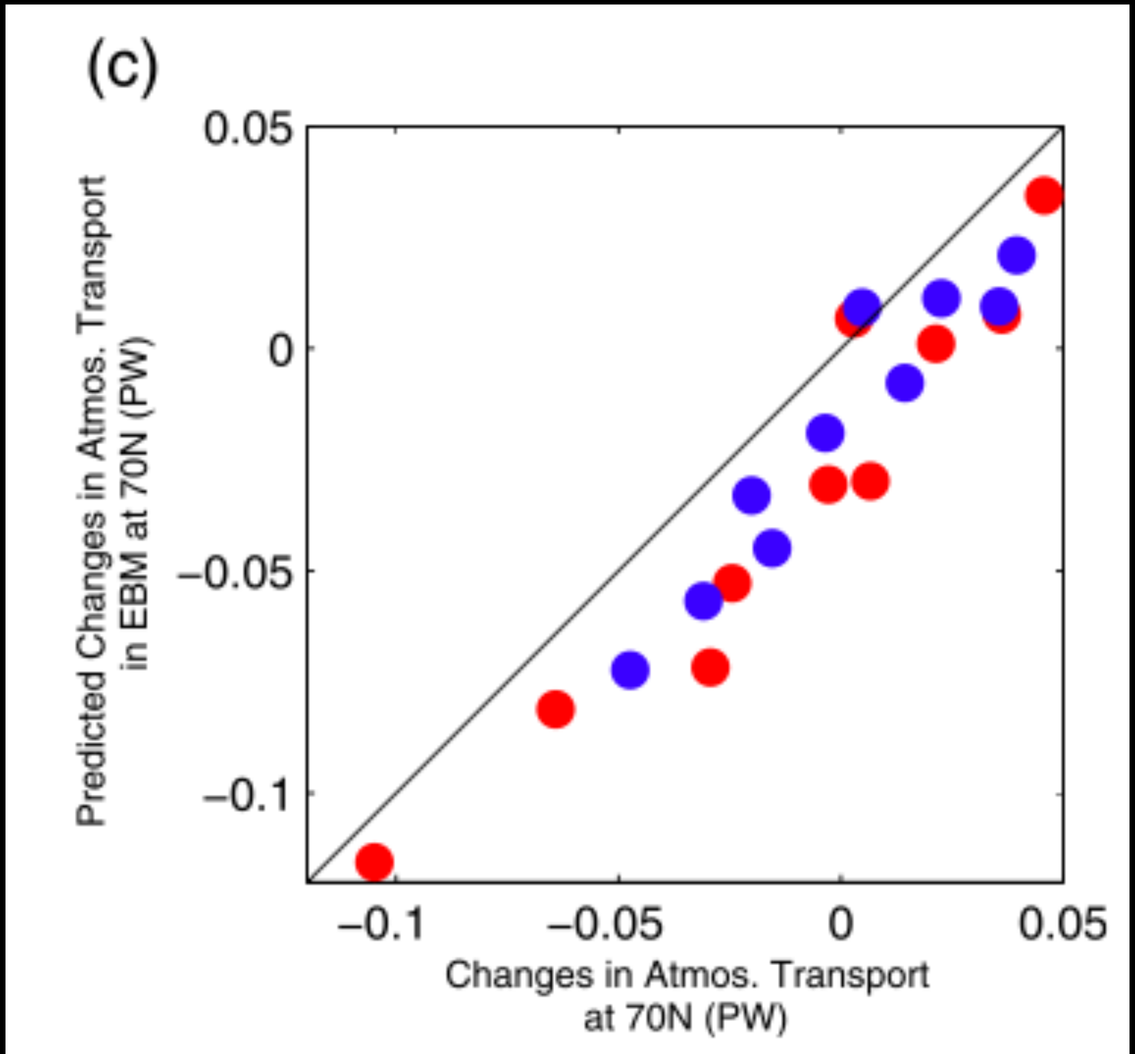
Diffusive model captures most of the variability

Large variances due primarily to differences in cloud responses

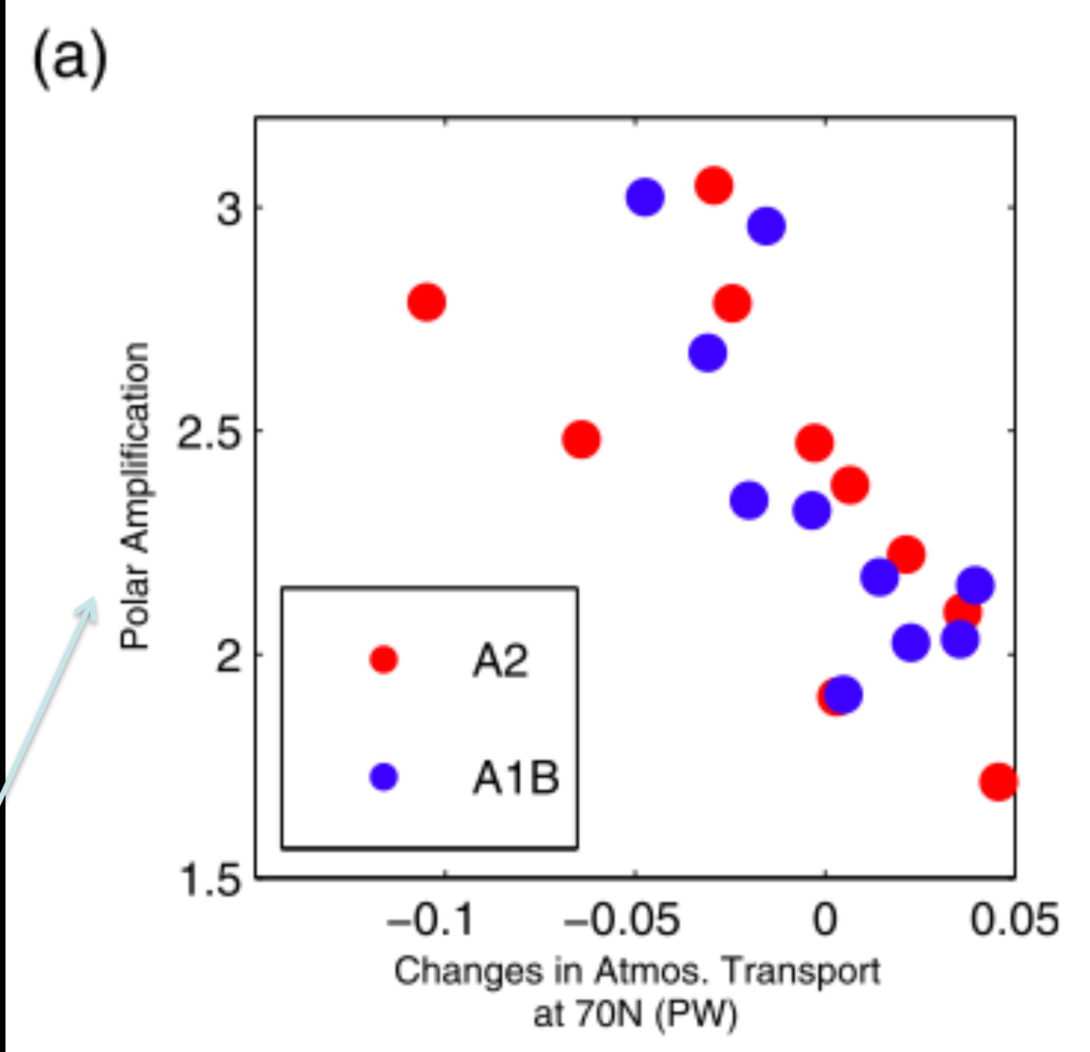
Hwang and Frierson (2010)

Diffusive Model in **High Latitudes**

EBM flux vs actual flux at **70º N**



Polar amplification vs atmospheric flux



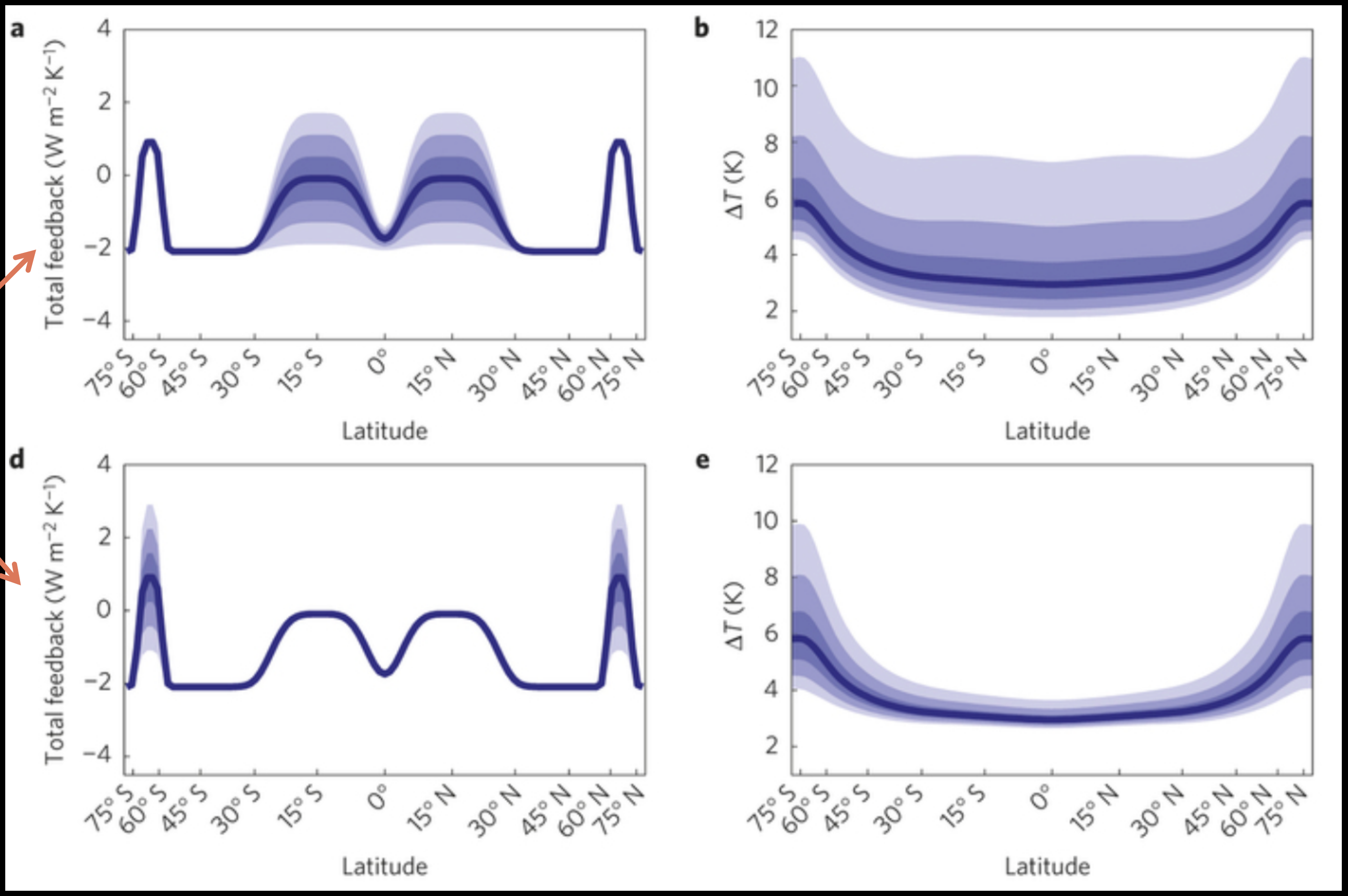
Models with **more** polar amplification have **less** atmospheric heat transport into high latitudes!

From Hwang, Frierson, and Kay (2011, GRL)

Uncertainty in Feedbacks Causes Uncertainty in **Temperature Response**

- Roe, Feldl, Armour, Hwang, & Frierson (2015, Nature Geoscience)

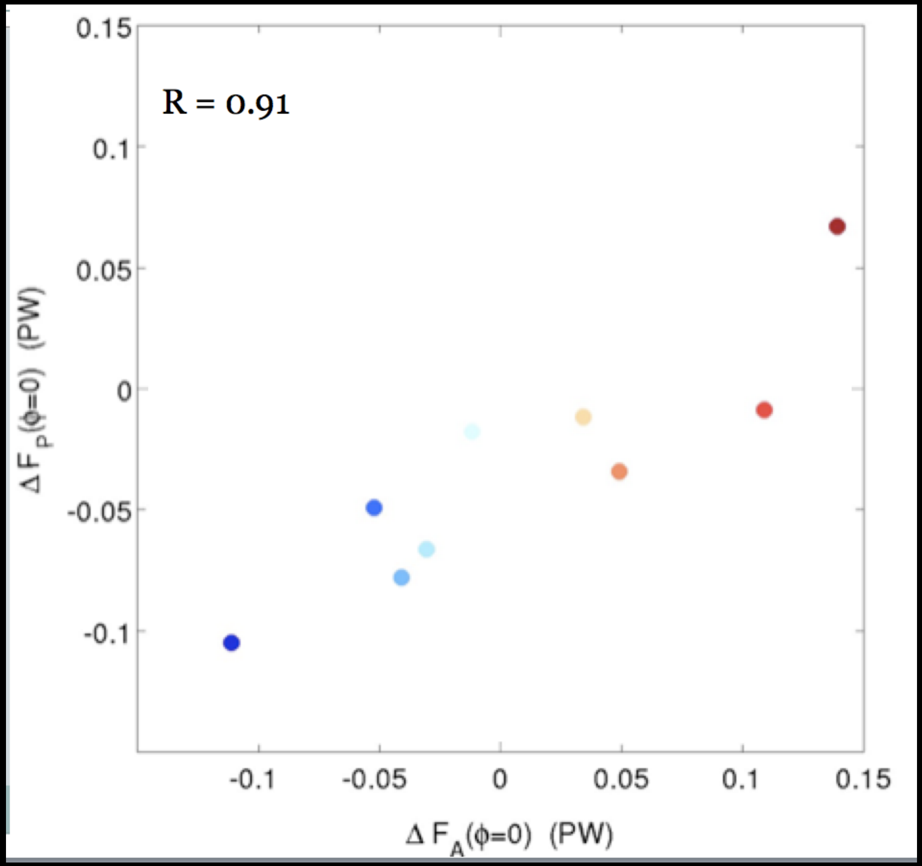
Feedback

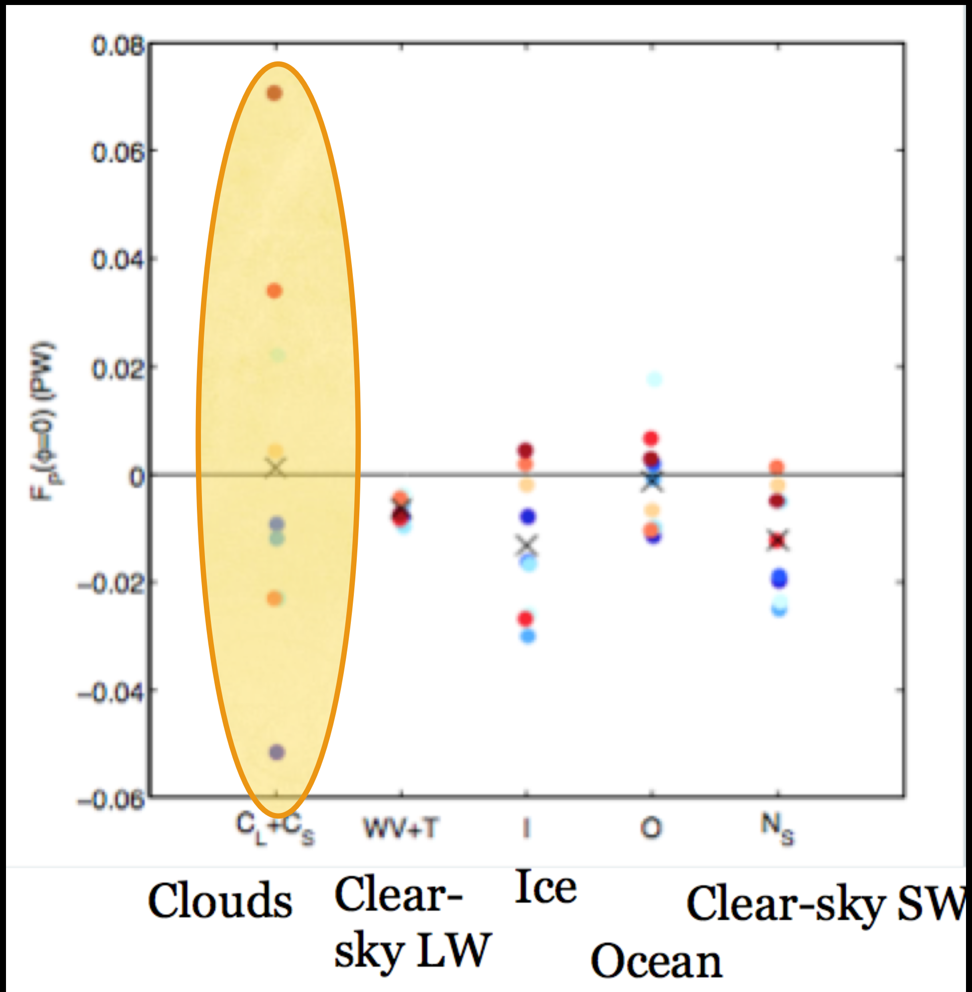


Temperature change

EBM Prediction for Cross-Eq Transport

Our model predicts cross-eq flux too →
Hmm…

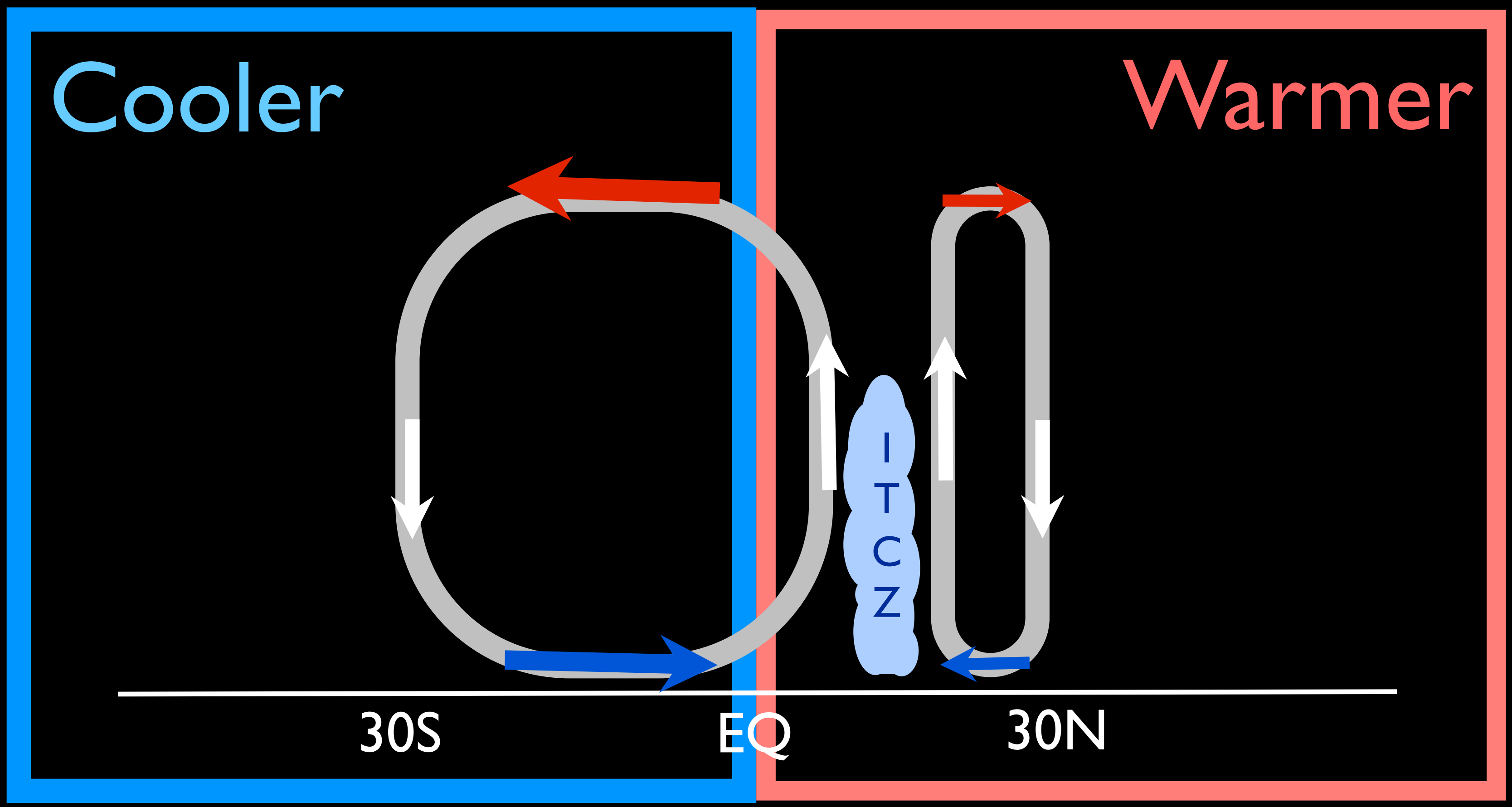




← Its variance is due mostly to clouds

Frierson and Hwang (2012)

Cross-equatorial transport linked to ITCZ precip



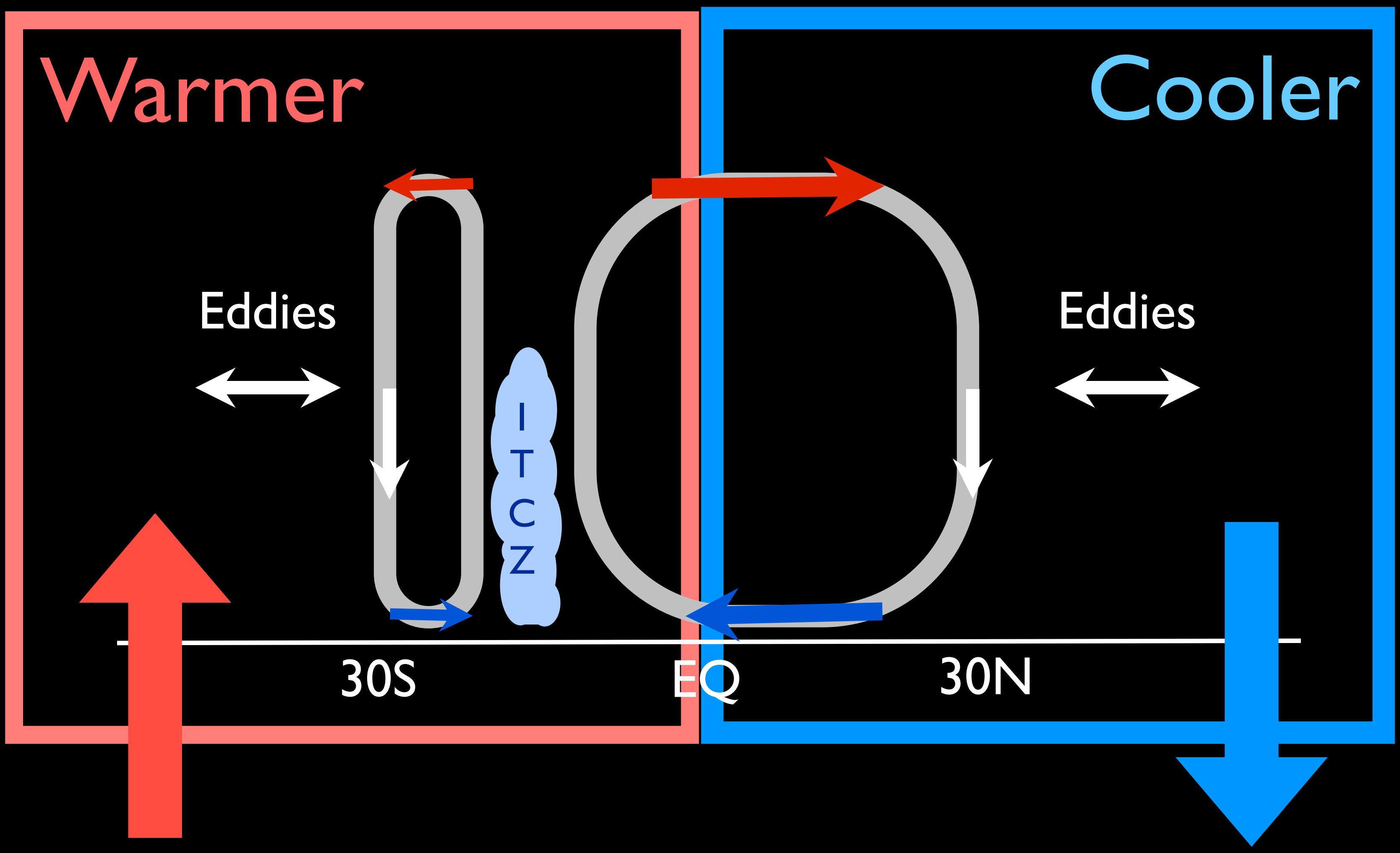
Southern Hemisphere (SH)

Northern Hemisphere (NH)

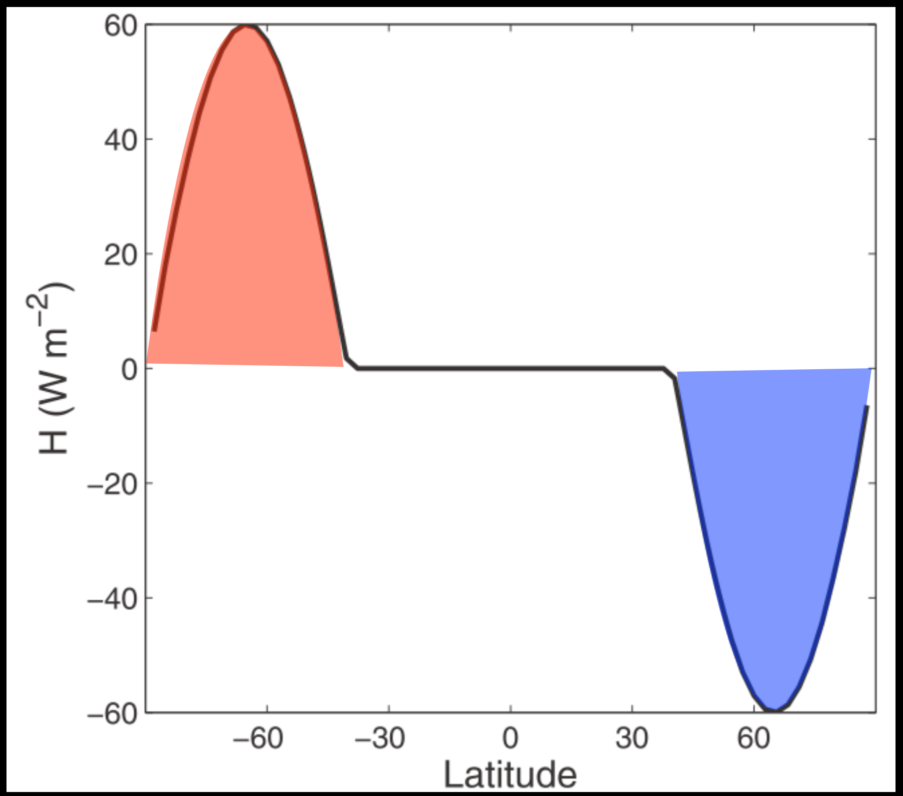
Hadley Cells transport **energy** from **warm** to **cold**, but **moisture** into the **warmer** hemisphere

And they even respond to heating **well outside the tropics**!

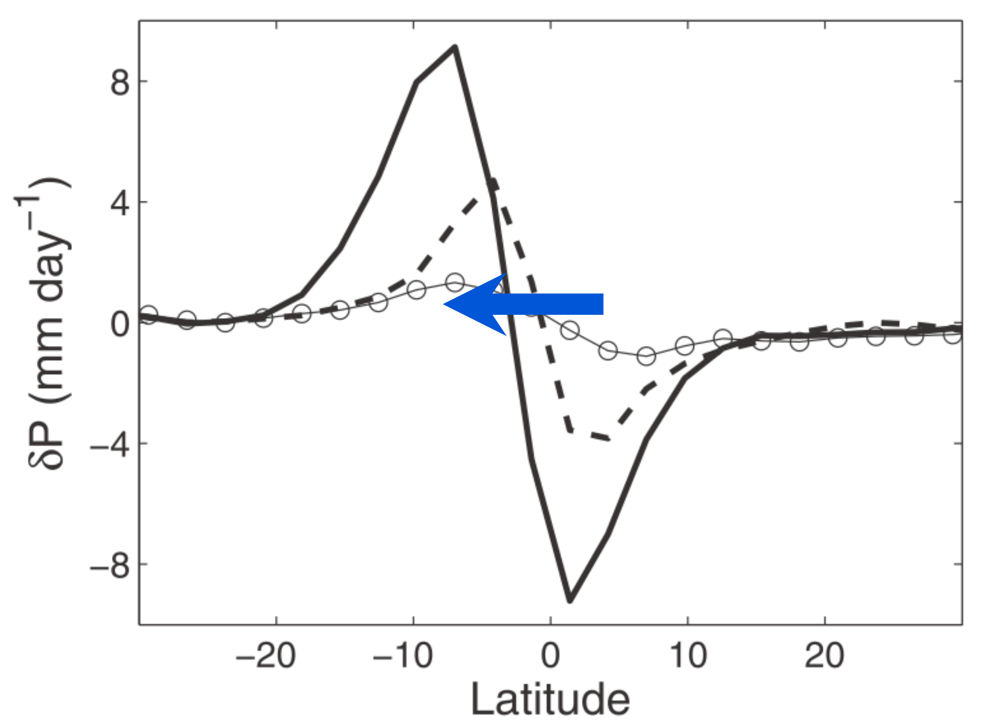
ITCZ Shifts Towards the Heating



imposed q-flux



Changes in Precipitation

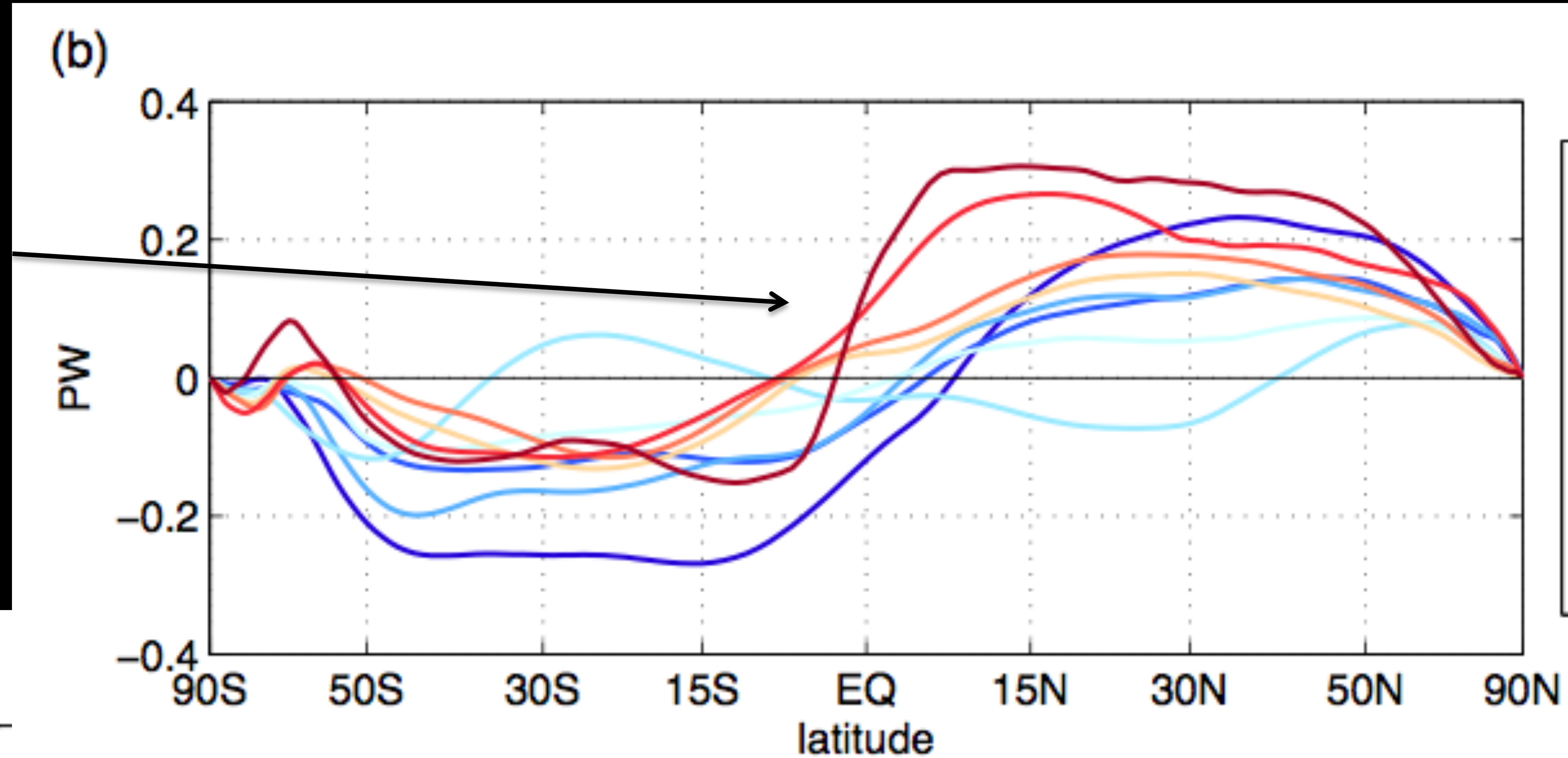


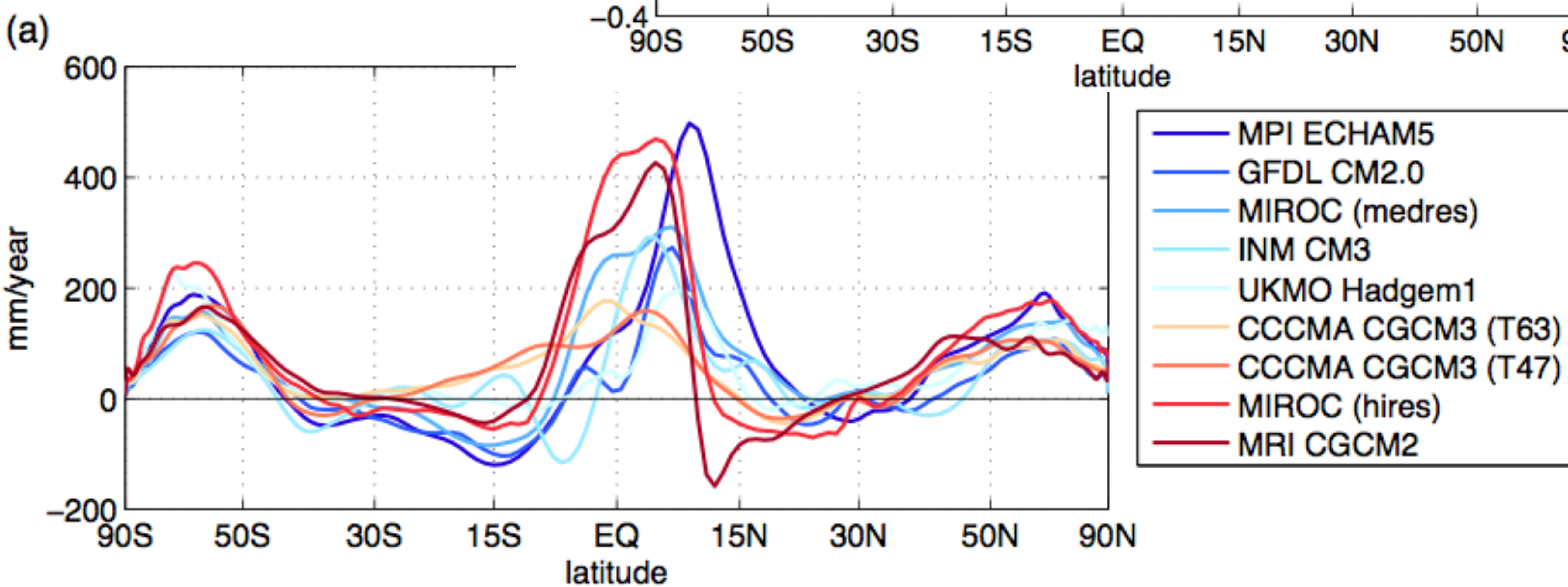
Eddies spread warmth to the tropics, affecting the Hadley cell

Kang, Held, Frierson and Zhao 2008
Kang, Frierson, and Held 2009

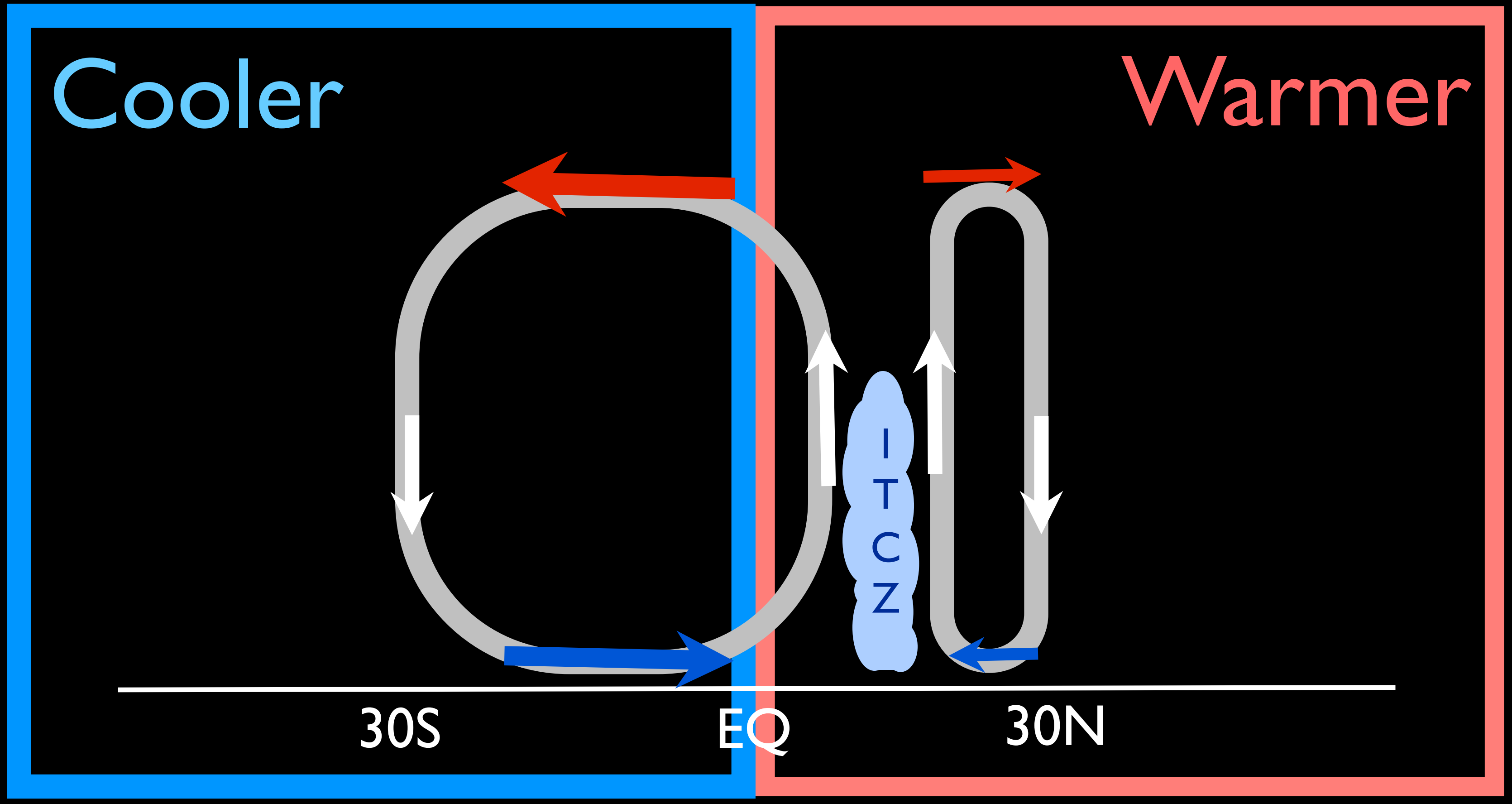
Change in Energy Transport with Doubled CO_2

Coloring by cross-equatorial
energy transport change



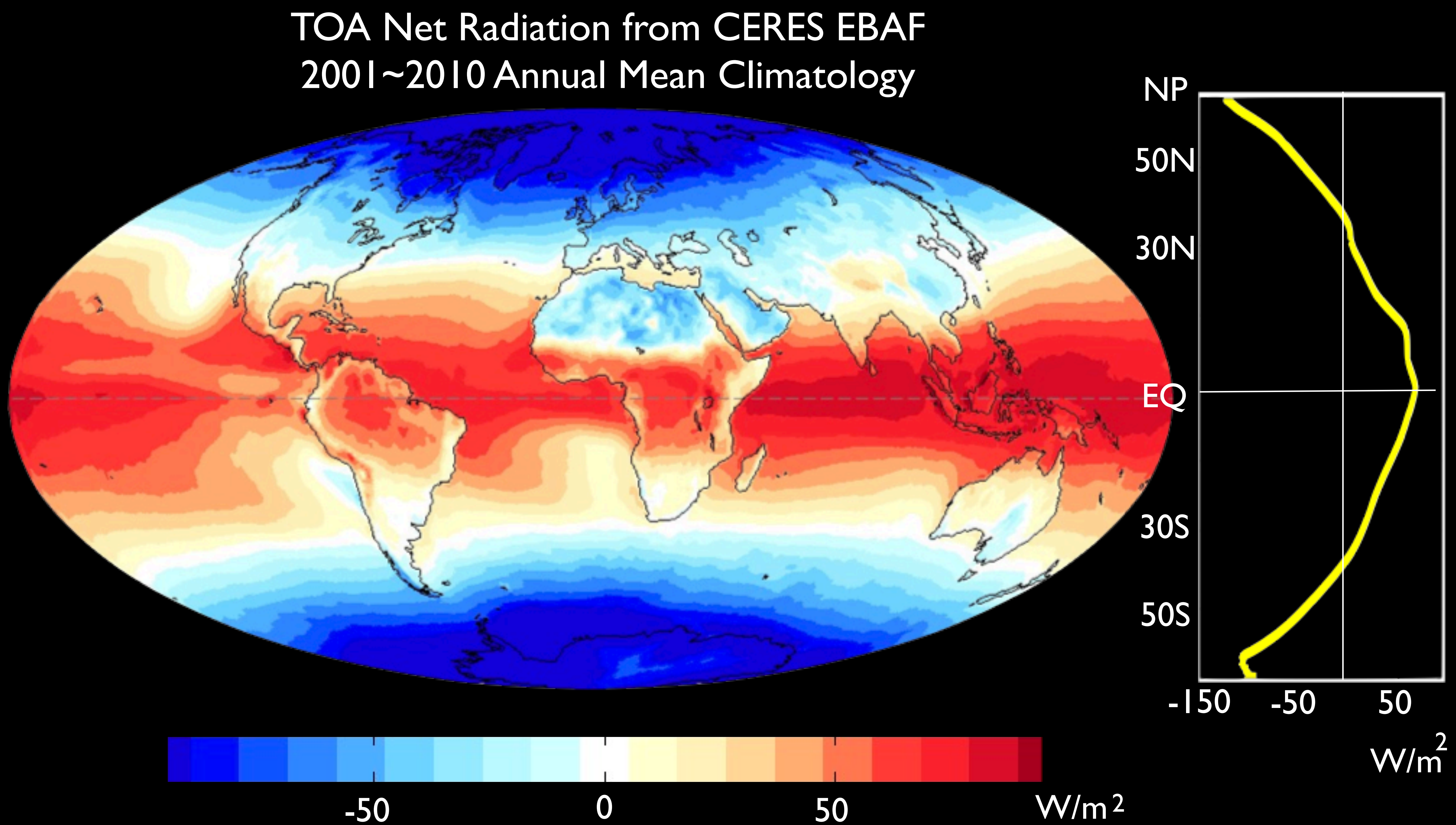


Worked for global warming in slab ocean models. Applicable to other problems??

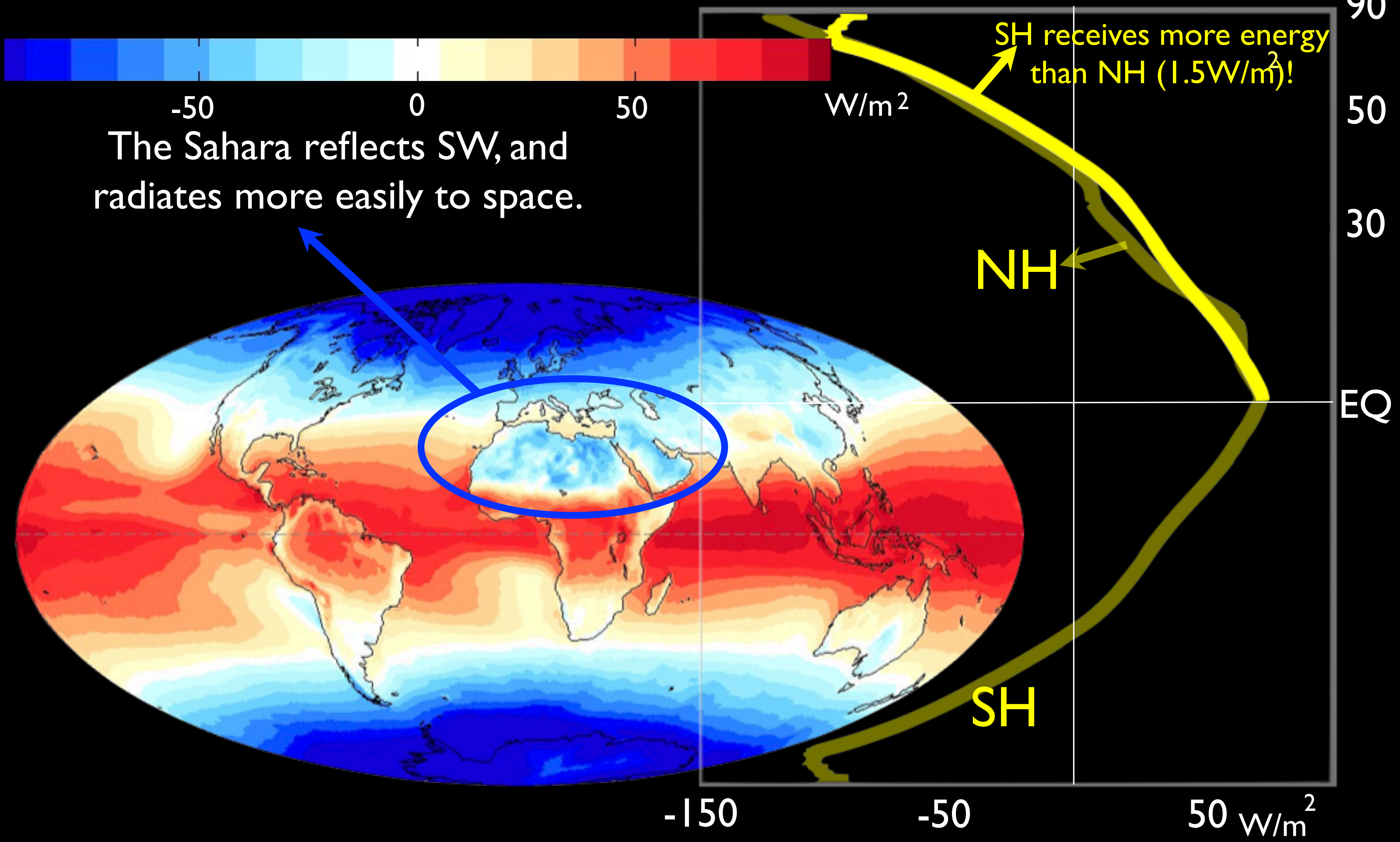


Let's examine why there's southward cross-equatorial transport in obs

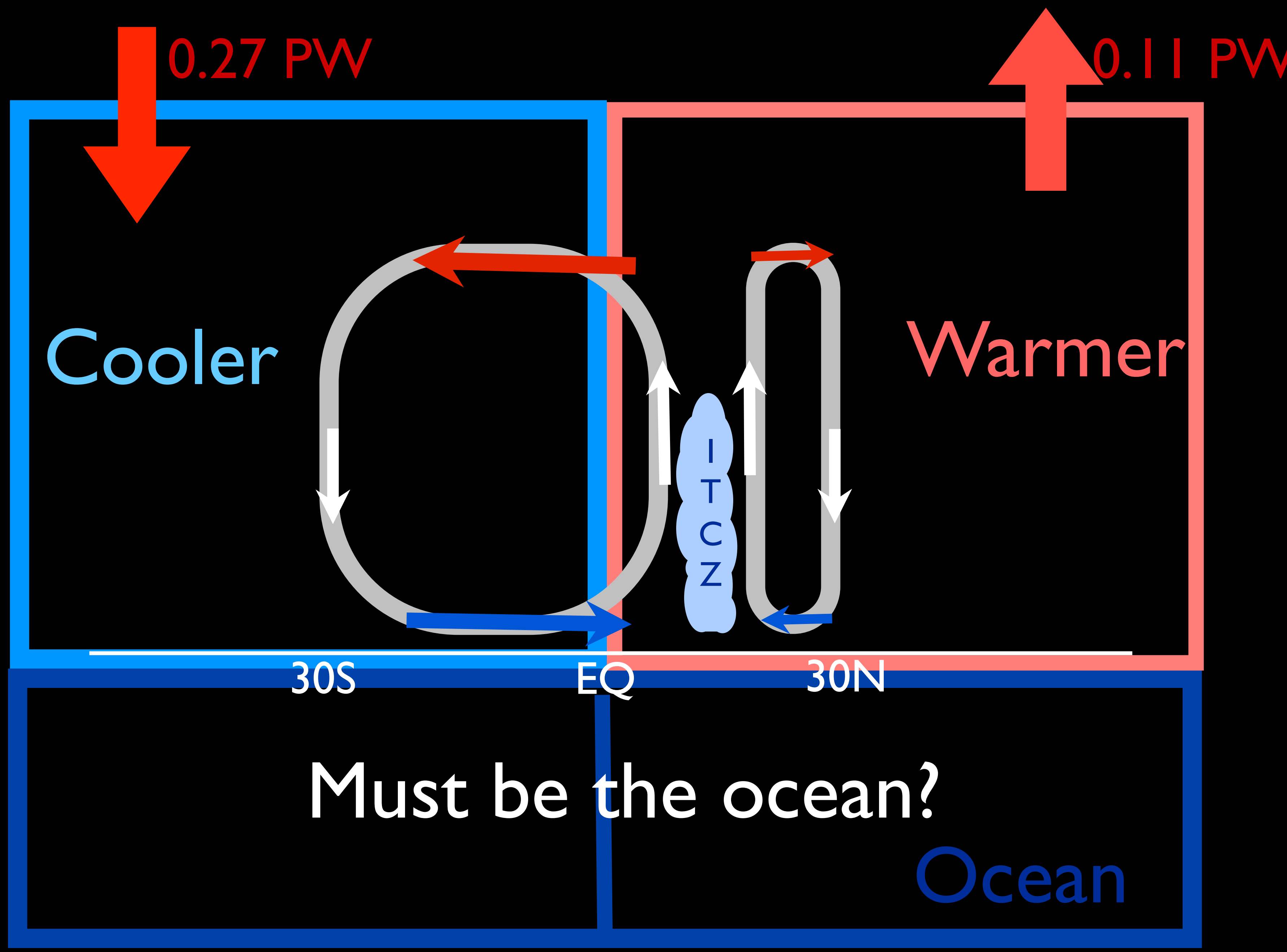
Top of Atmosphere Radiation



Top of Atmosphere Radiation



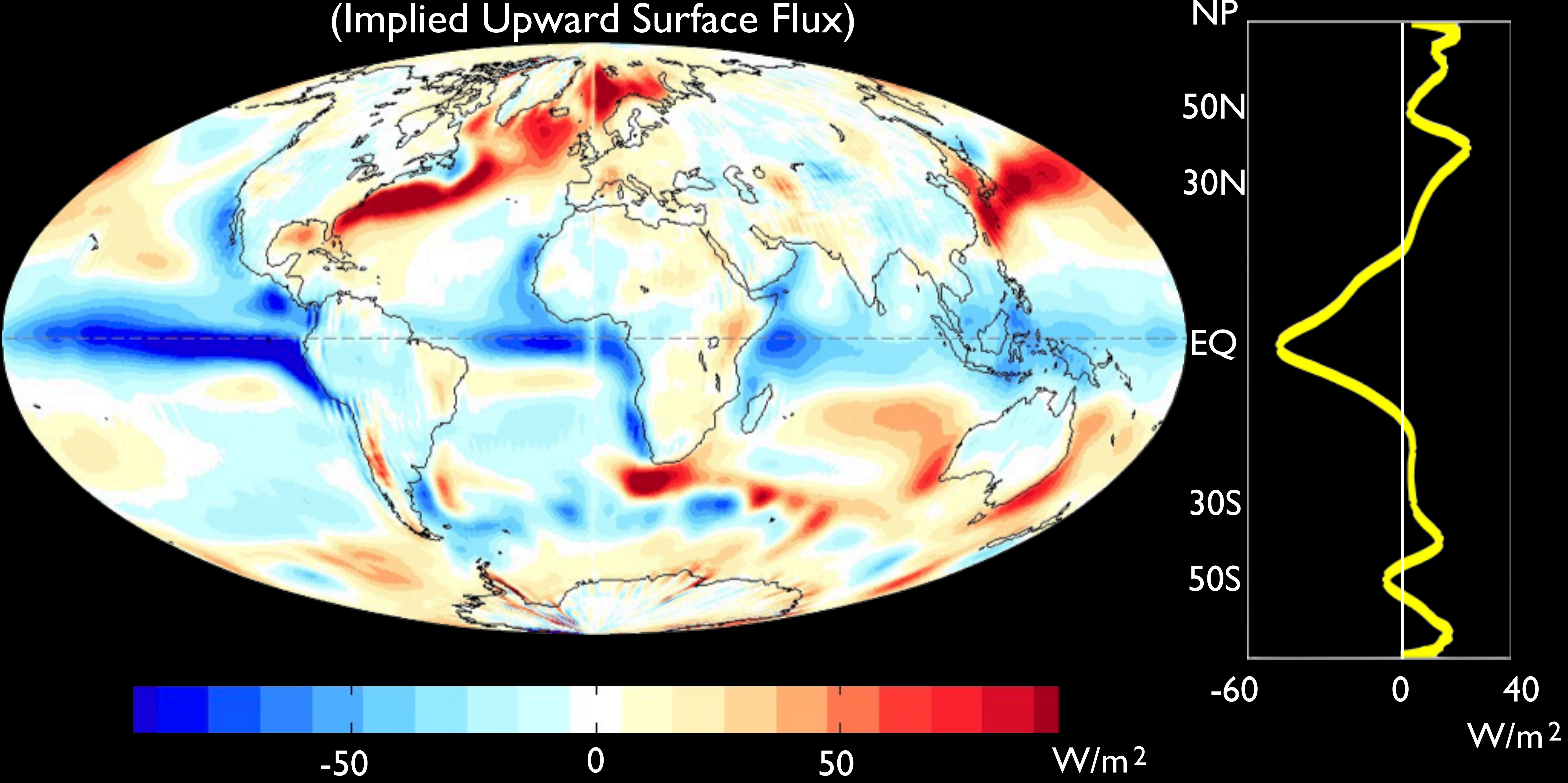
What makes the NH warm?



Kang, Seager, Frierson and Liu (2015)

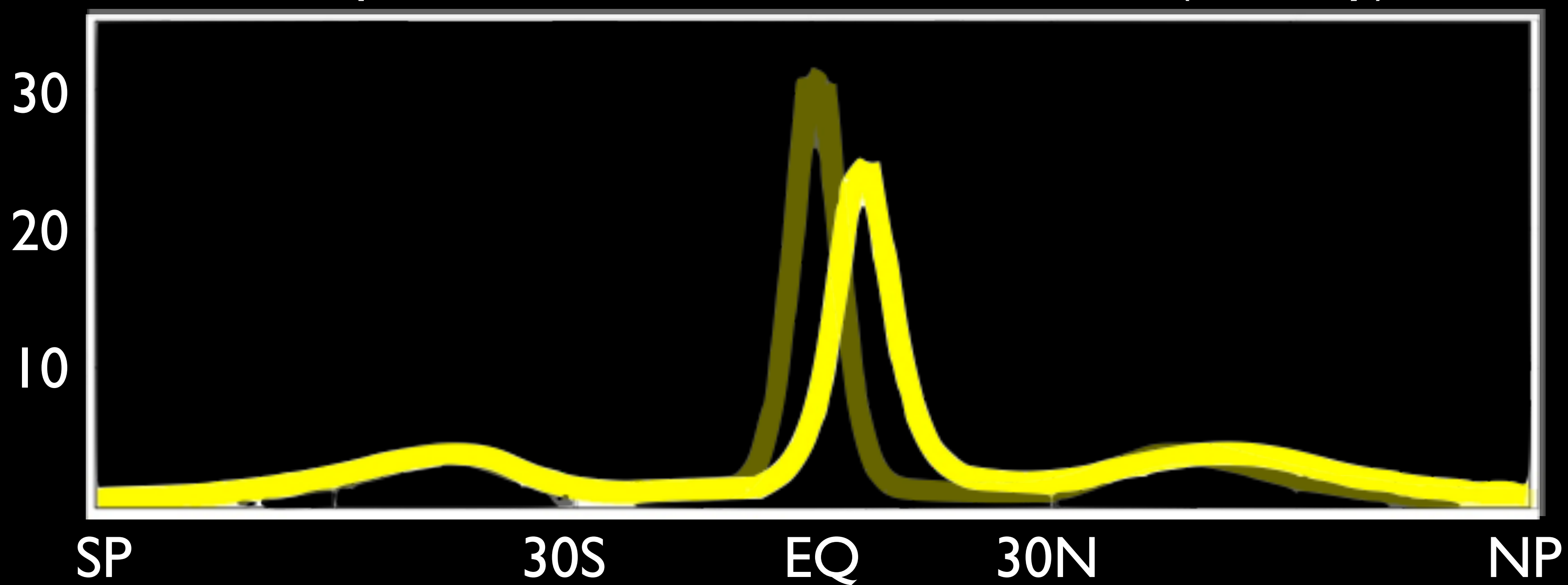
Heat flux from ocean to atmosphere

2001~2010 ERA-I MSE Divergence minus
CERES TOA Budget
(Implied Upward Surface Flux)

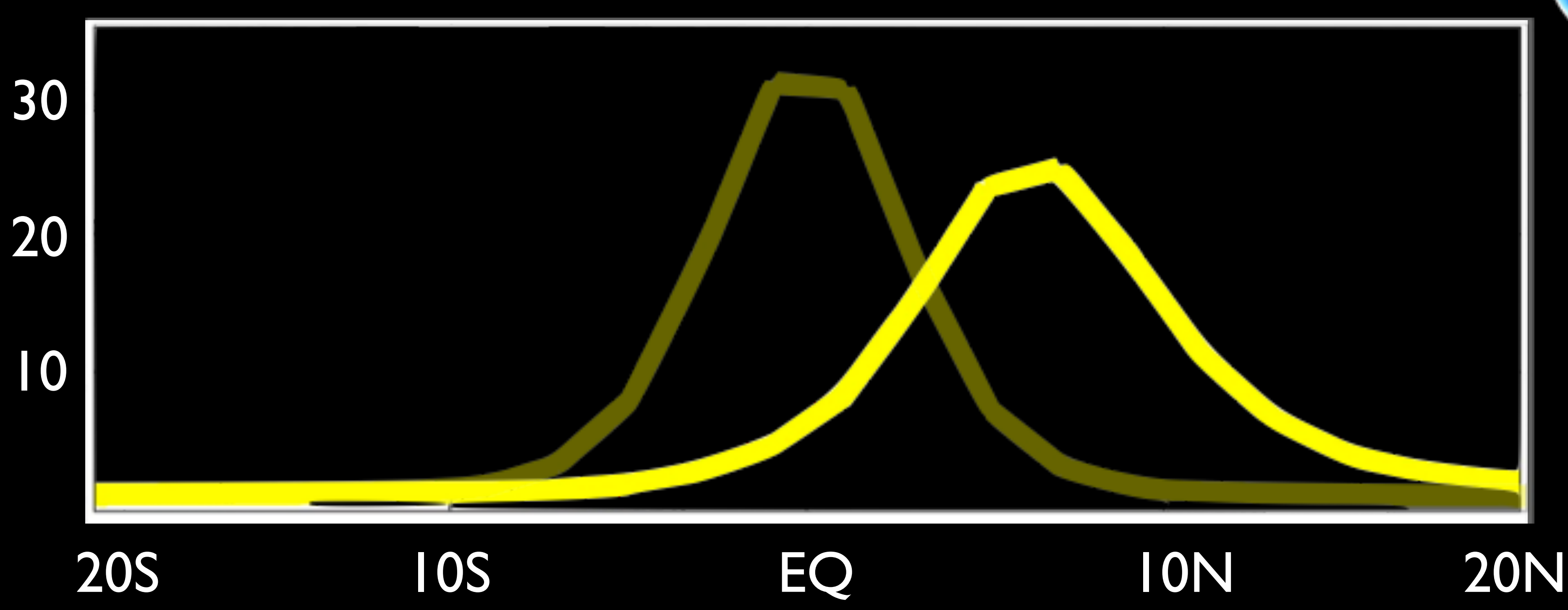


Aqua-planet Experiments

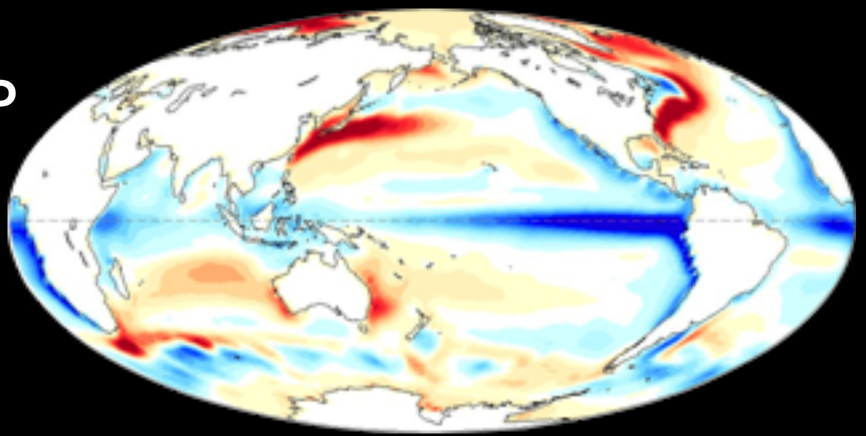
Precipitation in the Control Simulation (mm/day)

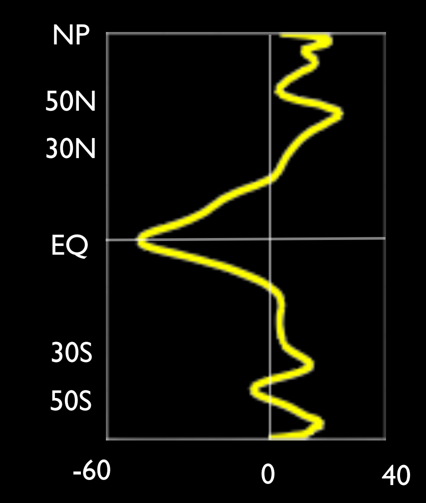


Zoom in to the Tropics



Surface flux is quite sufficient to move the ITCZ into the NH

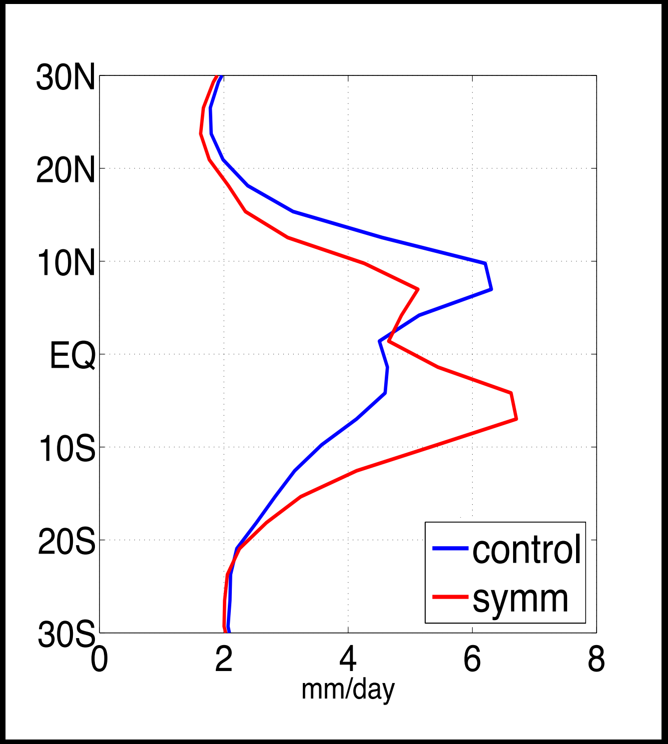




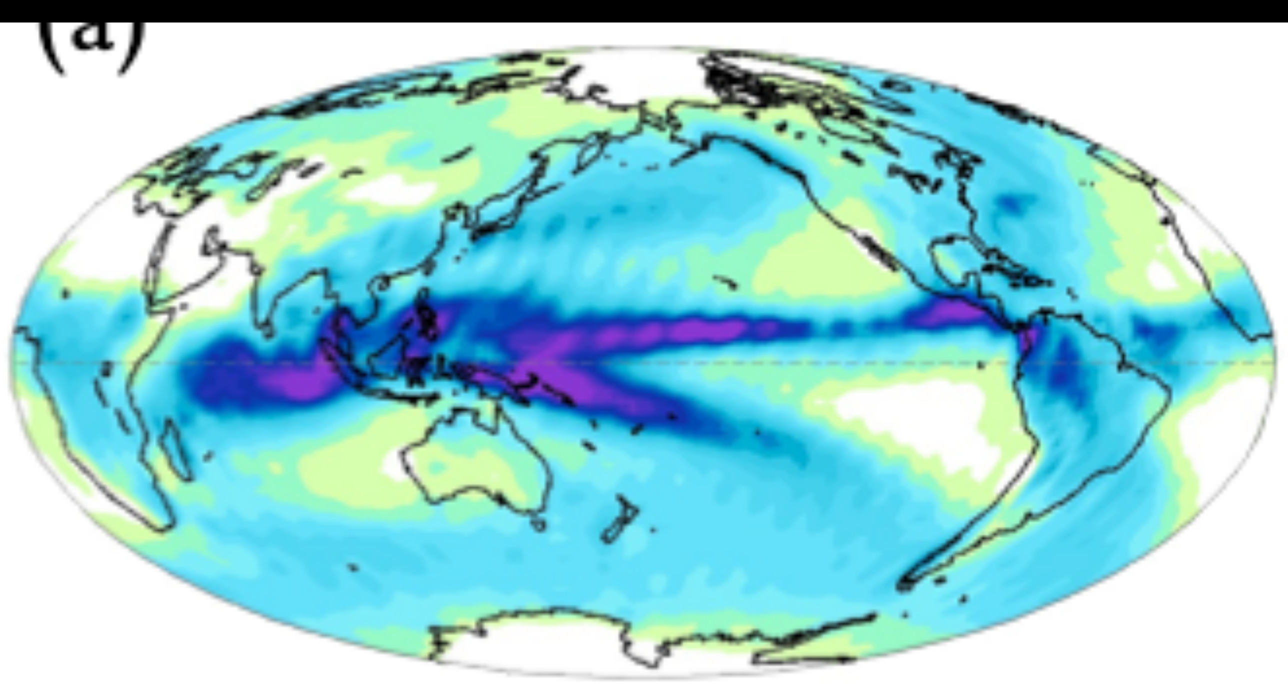
How about *removing* the ocean heat divergence asymmetry from a full GCM?

- Experiments with **full** and **symmetrized** surface heat flux

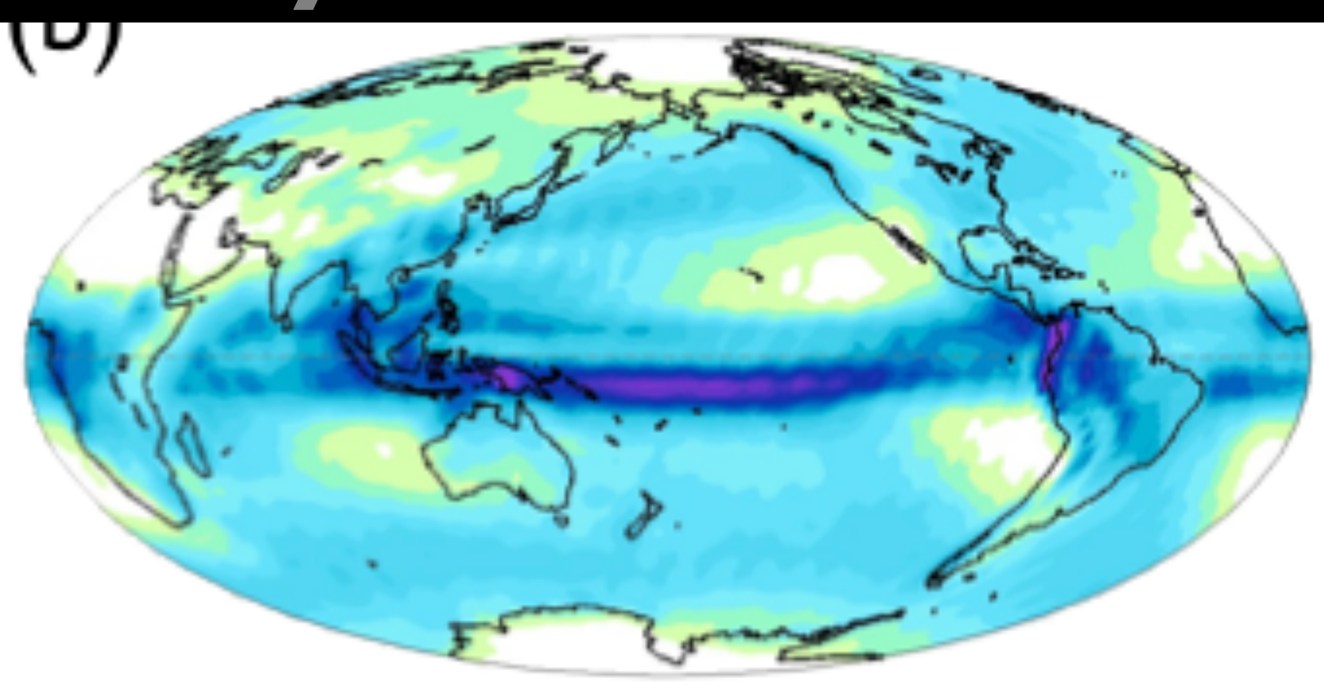
Frierson et al 2013, Nature Geoscience



Control



Symmetrized

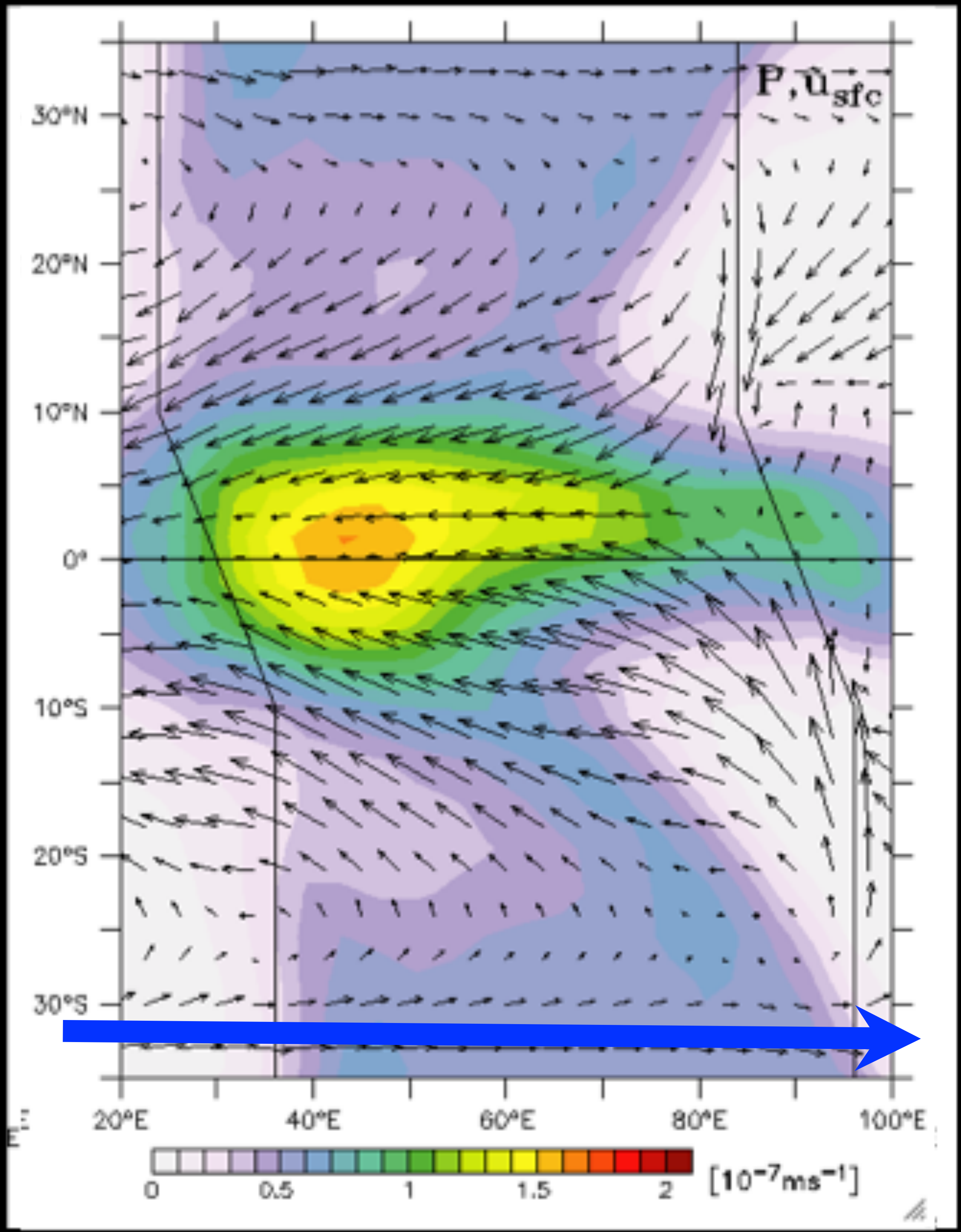


Experiments with a **Dynamical Ocean**

Coupled, idealized physics model "GRaM-MOM"

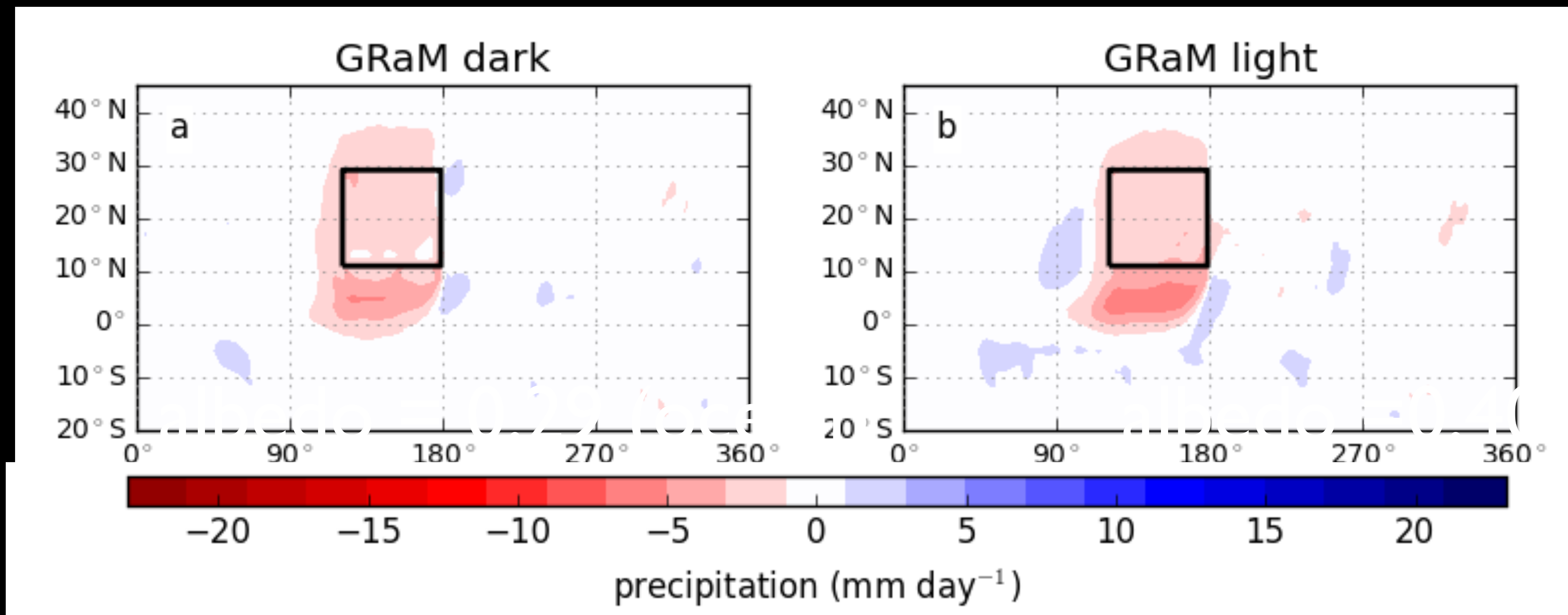
Adding a **Drake passage** sets up the MOC & northward ocean heat transport
And the ITCZ shifts northward!

(from Fučkar, Xie, Farneti, Maroon & Frierson, J. Climate 2013, & Fučkar et al in prep)



Effect of a continent?

First in a simple GCM…

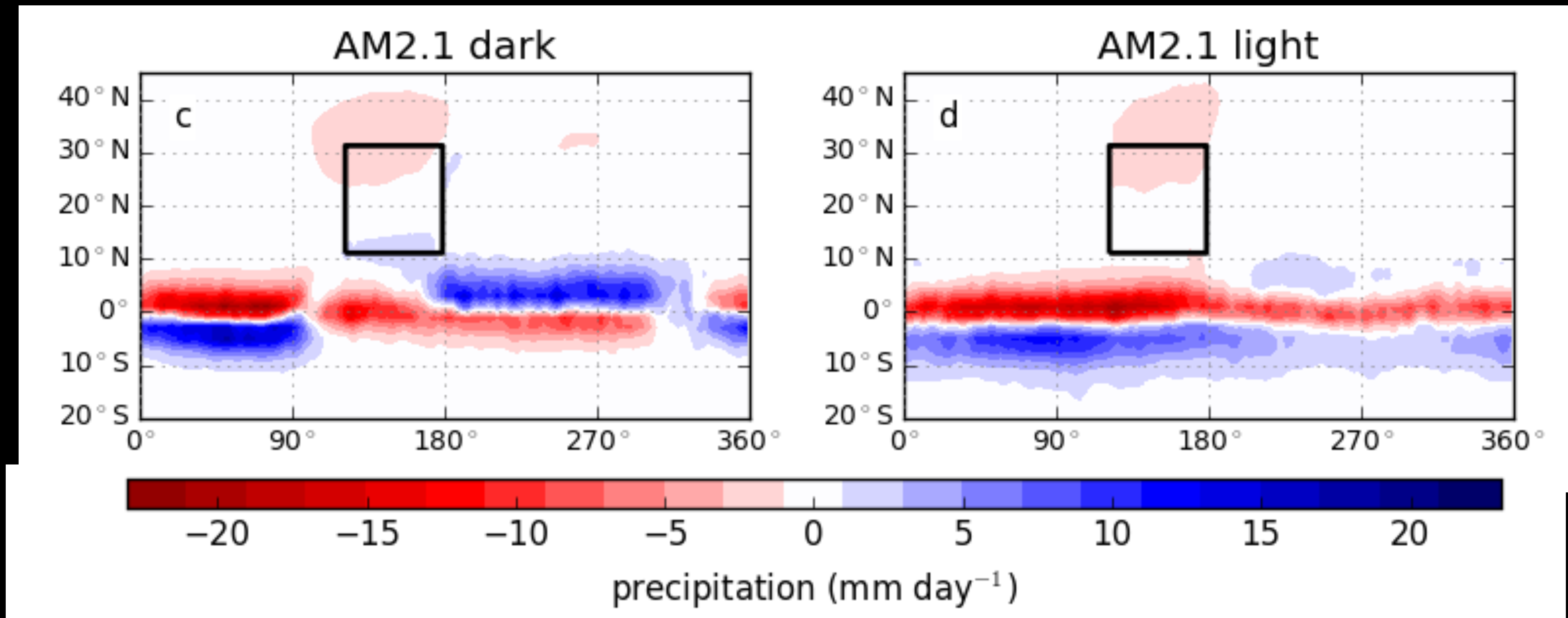


Decreased evaporation responsible for decreased precipitation when continent is dark.

With a light continent, rainfall shifts even more, due to an anomalous circulation.

Maroon et al (submitted)

Comprehensive GCM



In a comprehensive GCM (GFDL AM2), there is a rich, zonally asymmetric response of precipitation to the addition of the continent.

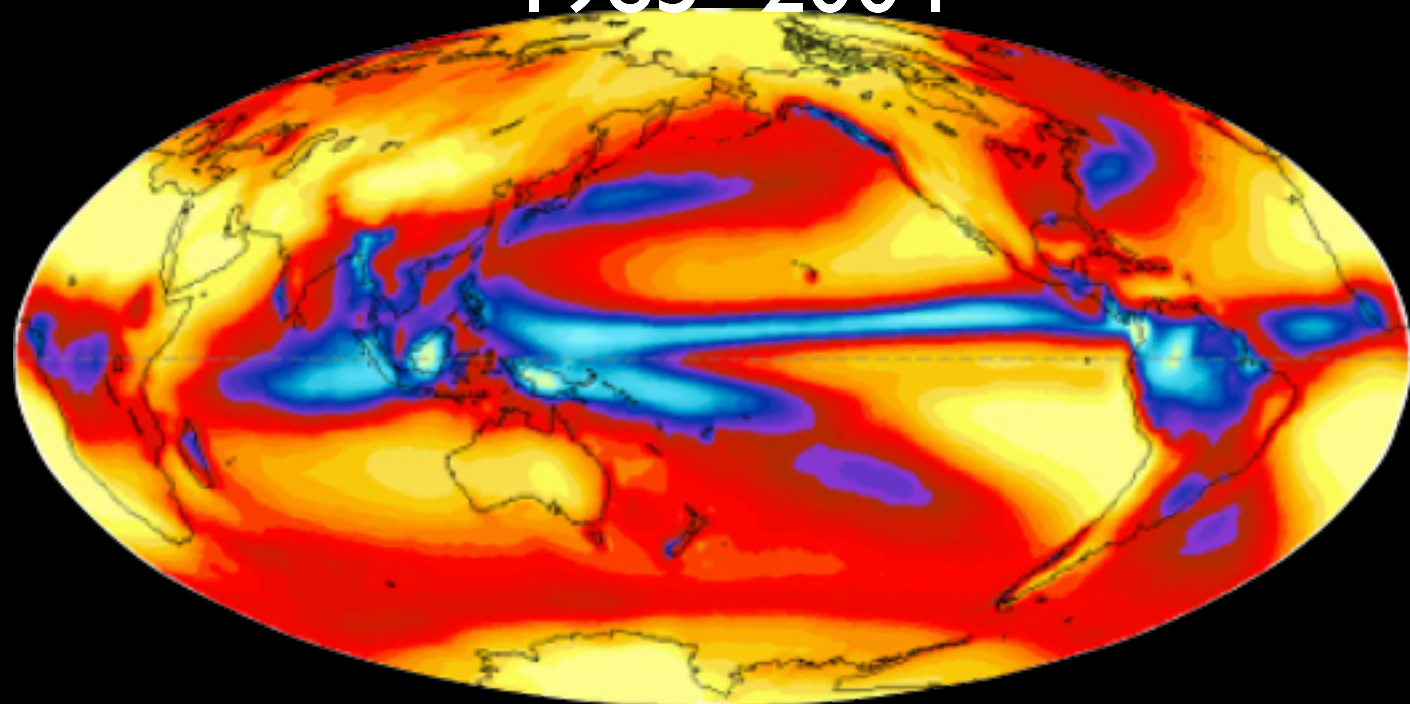
Maroon et al (submitted)

How about the **Double ITCZ** problem?

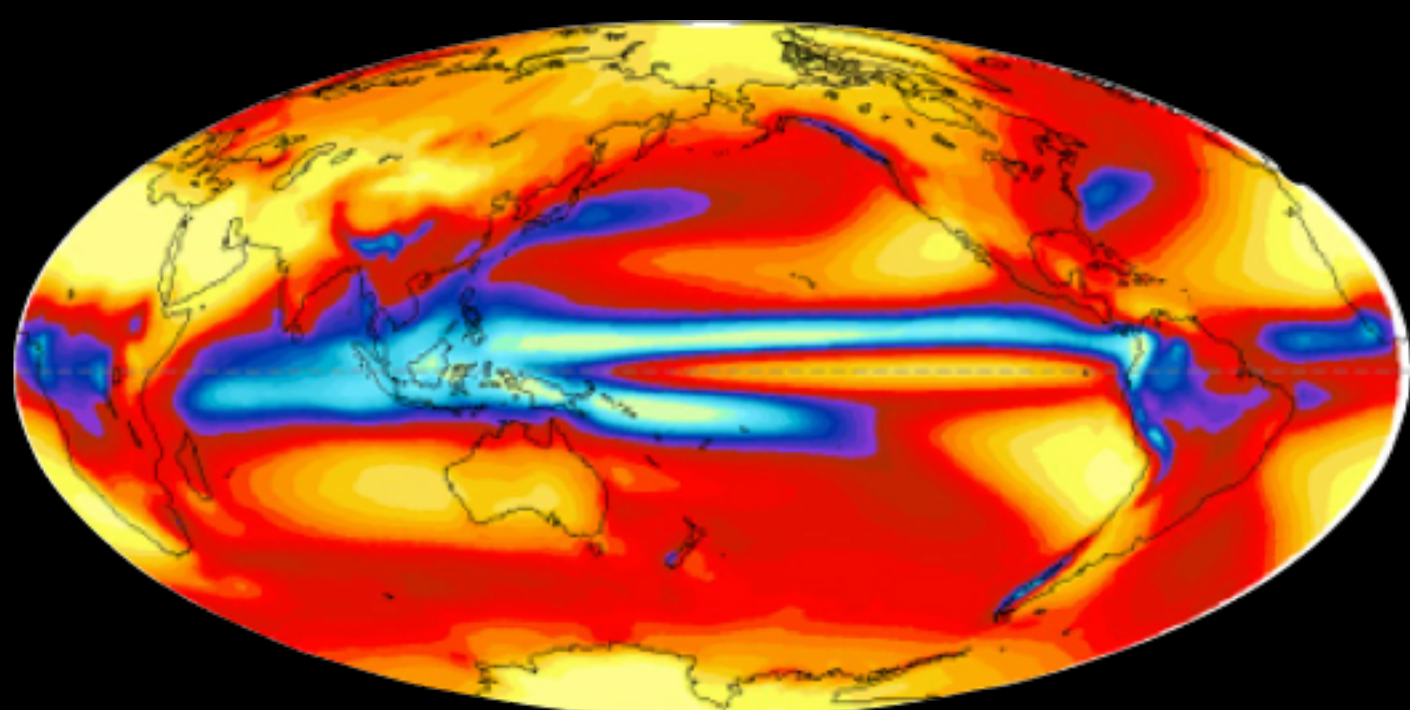
Can some of this be explained by our energetic framework?

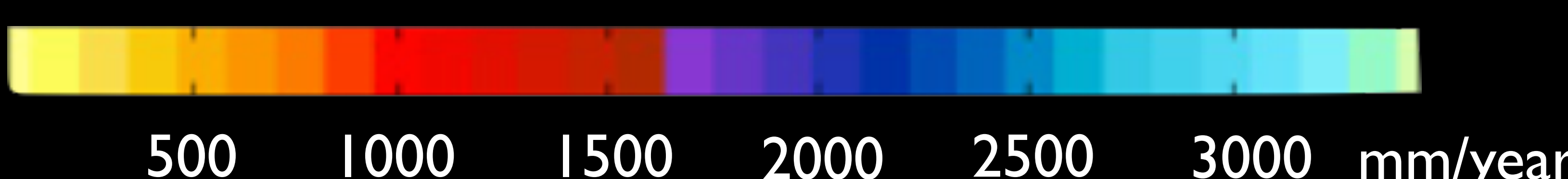
Hwang and Frierson, 2013 (PNAS)

Observed Annual Mean Precipitation 1985~2004

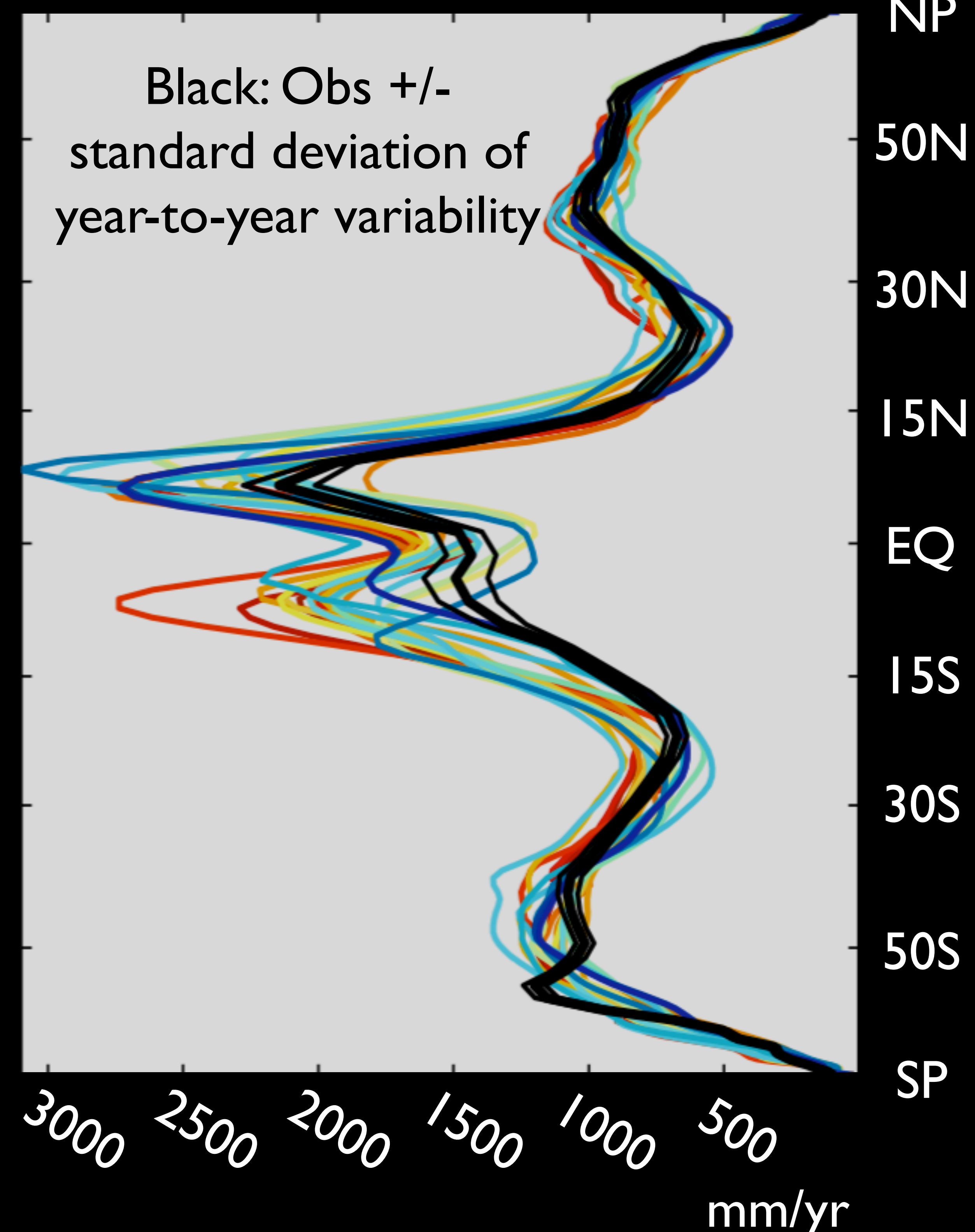


20 CMIP5 models



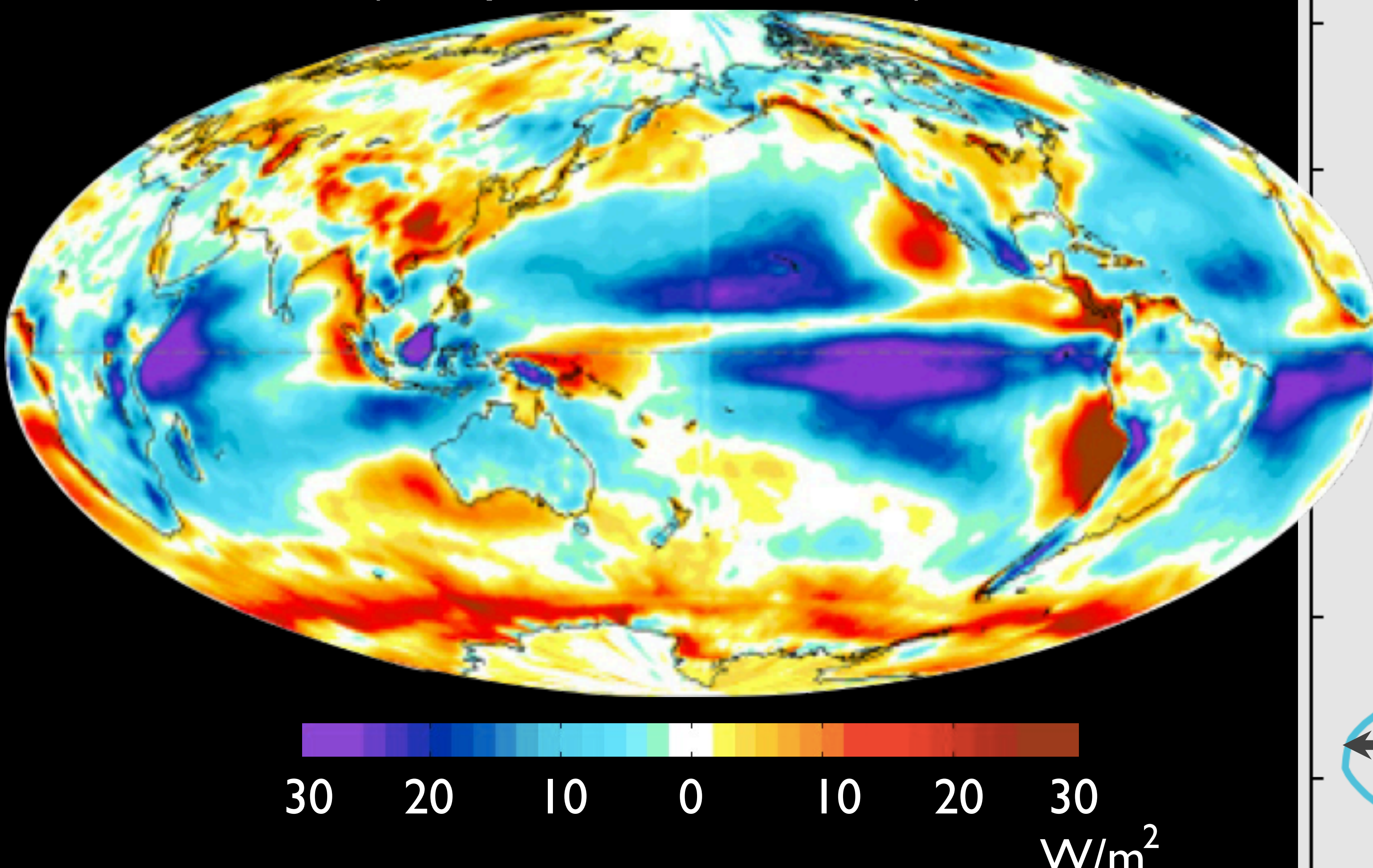


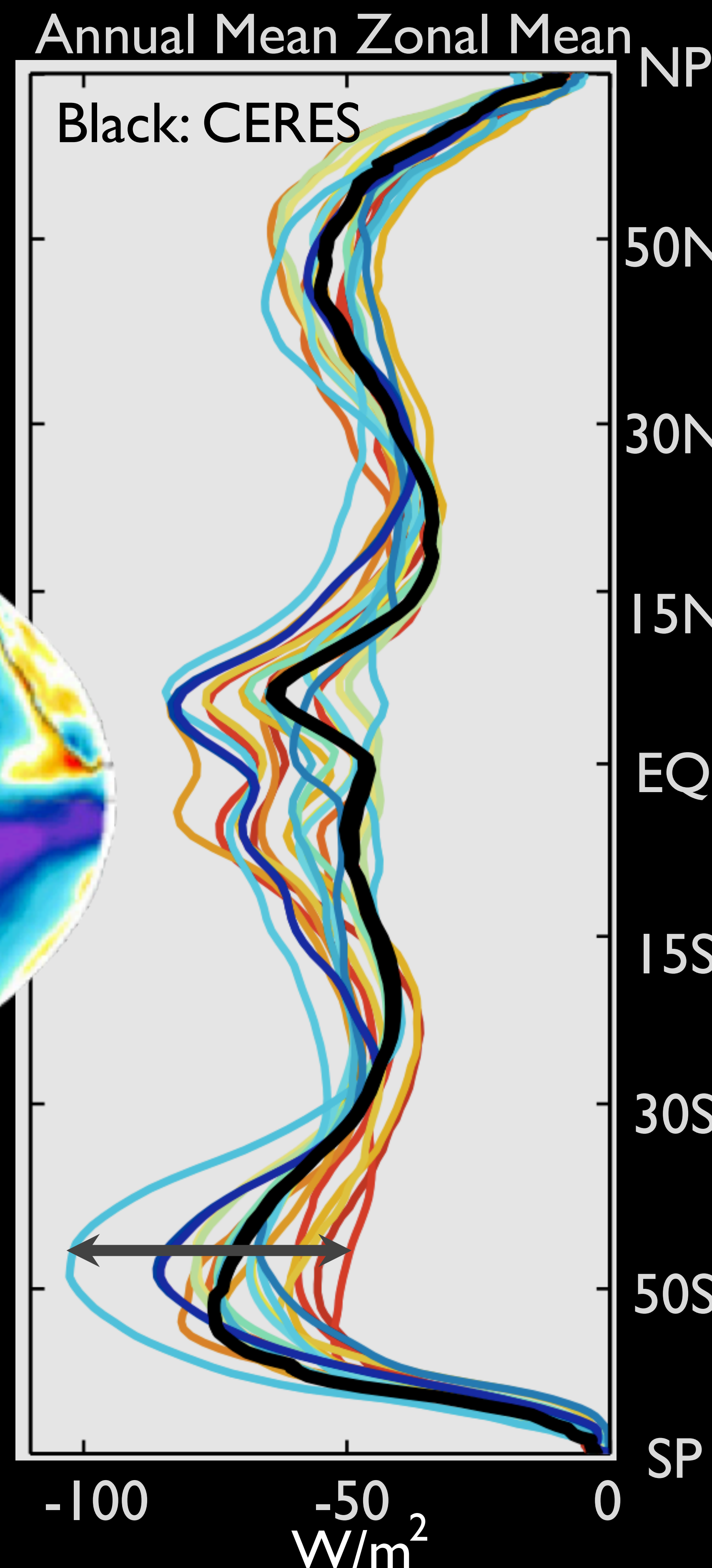
Zonal Mean (each line is one GCM)



Biases in SW Cloud Radiative Effect

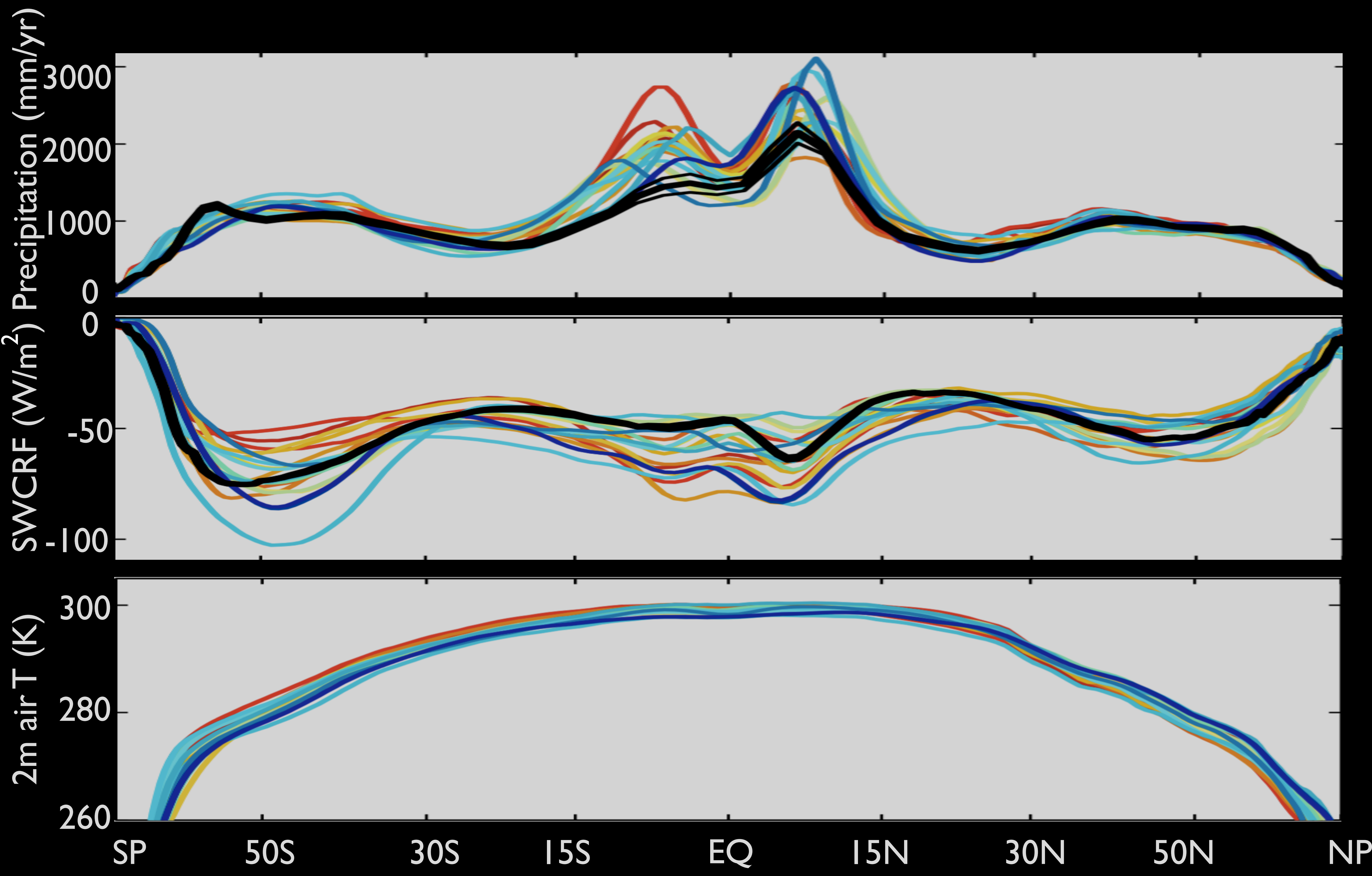
Ensemble Mean Biases in SW CRE
(compared with CERES)

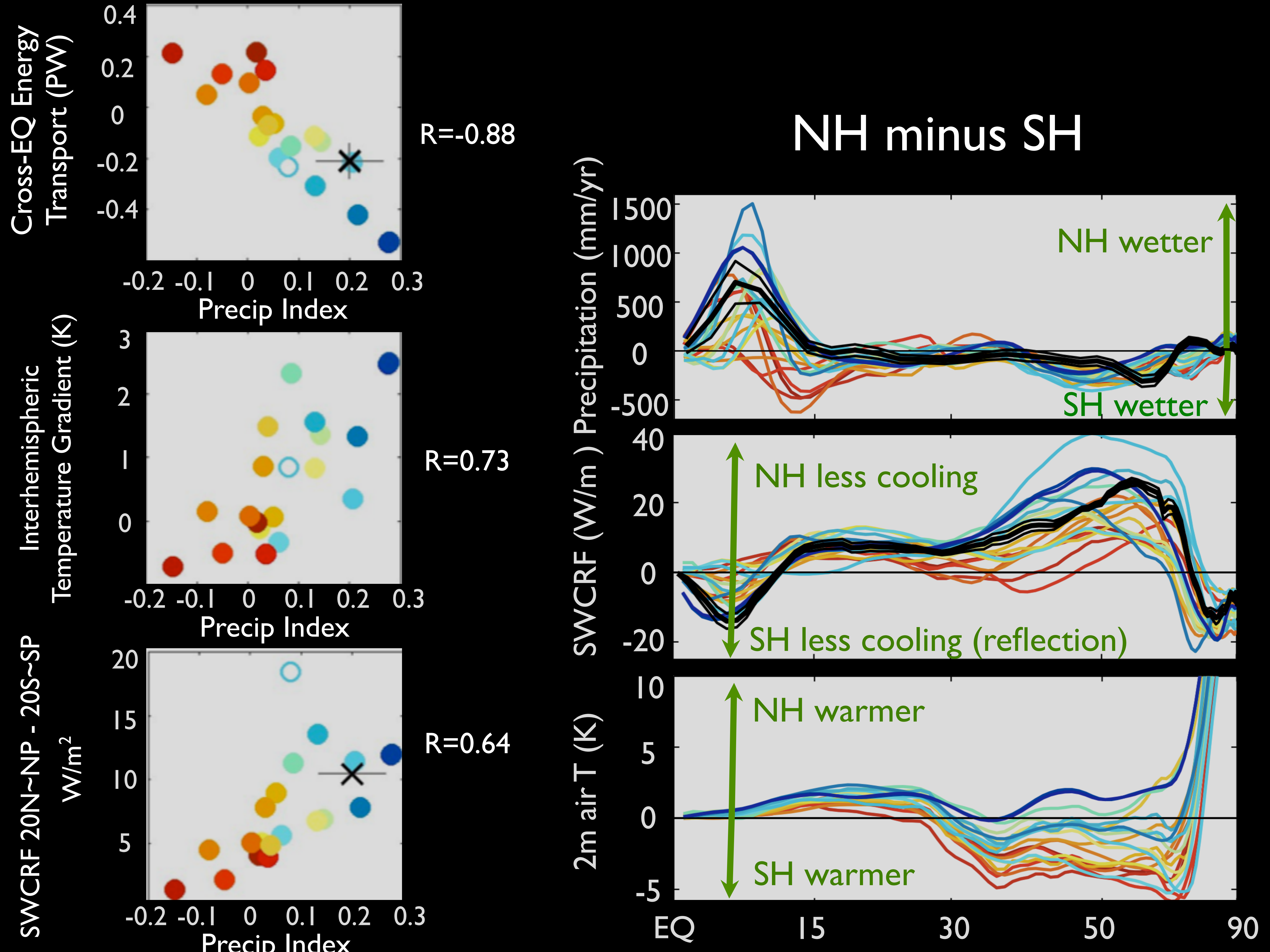




See also Trenberth and Fasullo 2010 for CMIP3

Surface temperature in SH is affected all the way to the tropics

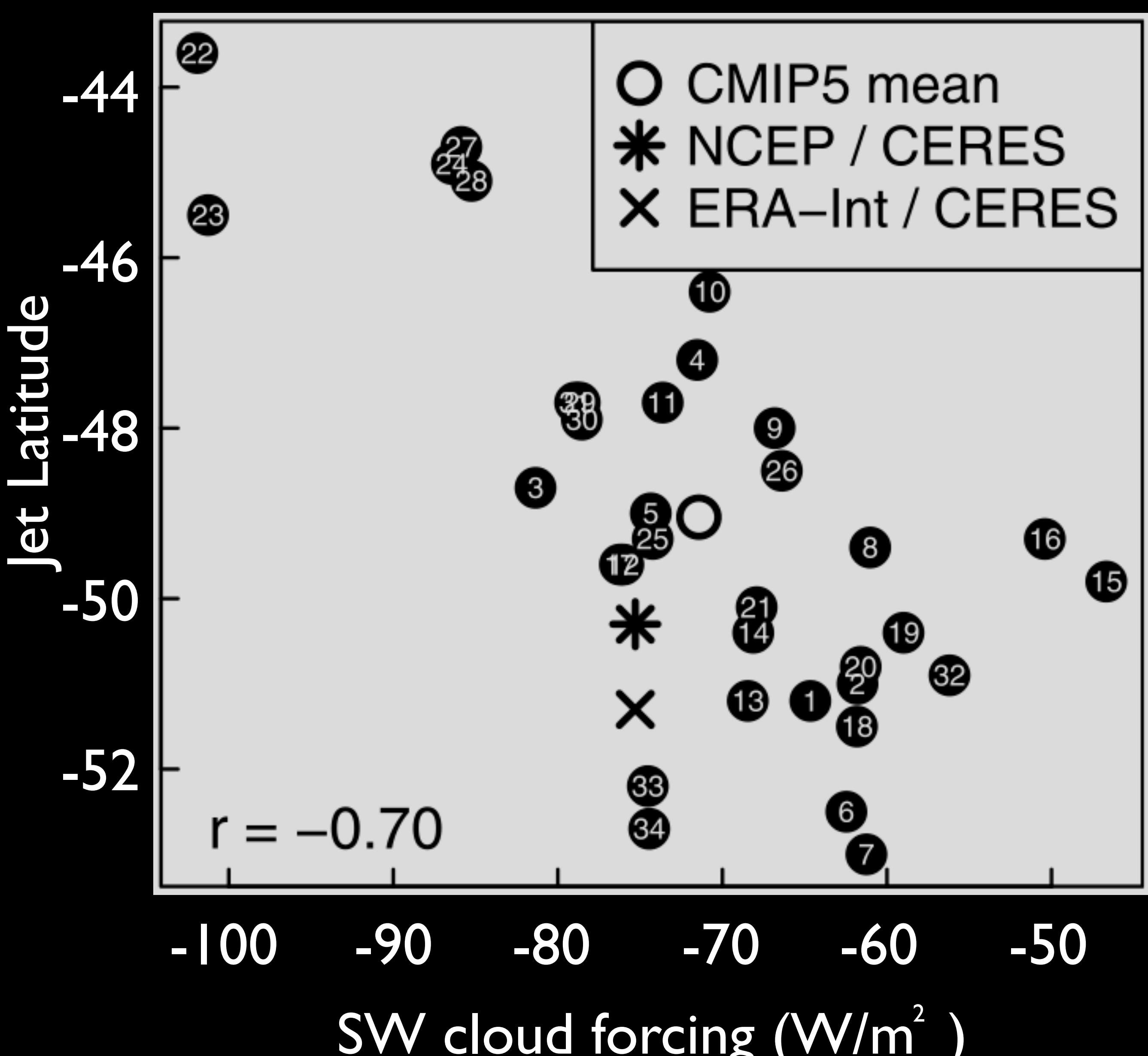




NH minus SH
Cross-EQ Energy Transport (PW)
0.4
0.2
0
-0.2
-0.4
-0.2 -0.1 0 0.1 0.2 0.3
Precip Index
R=-0.88
Interhemispheric Temperature Gradient (K)
3
2
1
0
-0.2 -0.1 0 0.1 0.2 0.3
Precip Index
R=0.73
SWCRF 20N~NP - 20S~SP W/m2
20
15
10
5
-0.2 -0.1 0 0.1 0.2 0.3
Precip Index
R=0.64
Precipitation (mm/yr)
1500
1000
500
0
-500
NH wetter
SH wetter
SWCRF (W/m)
40
20
0
-20
NH less cooling
SH less cooling (reflection)
2m air T (K)
10
5
0
-5
NH warmer
SH warmer
EQ 15 30 50 90

Same cloud biases are correlated with **jet latitude**

SH Jet Latitude vs.
SW Cloud Radiative Forcing



Too much solar → poleward shifted storm track

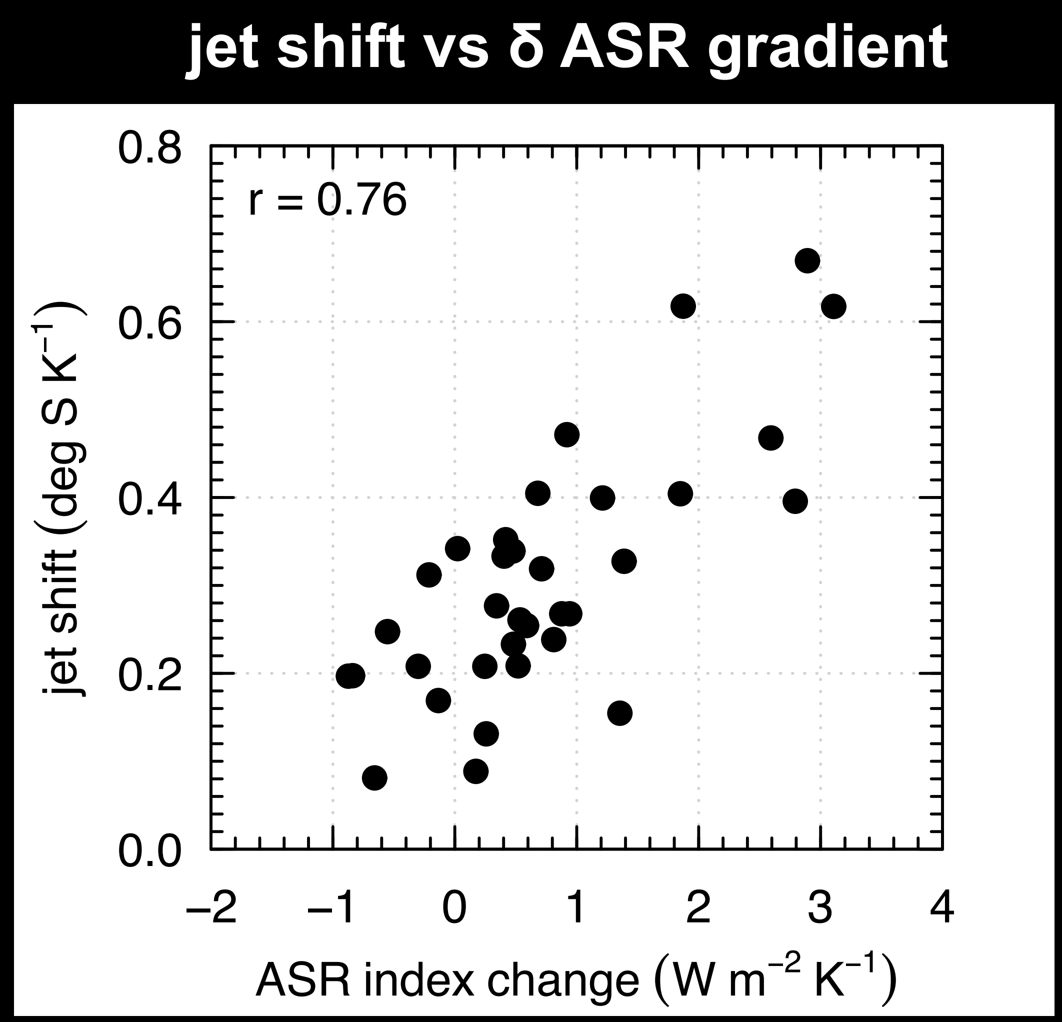
Anomalous warming in midlats shifts **baroclinicity** poleward, results in poleward shifted jet

Obs are not on the best fit line though – there must be additional problems

Ceppi, Hwang, Frierson, and Hartmann 2012, GRL

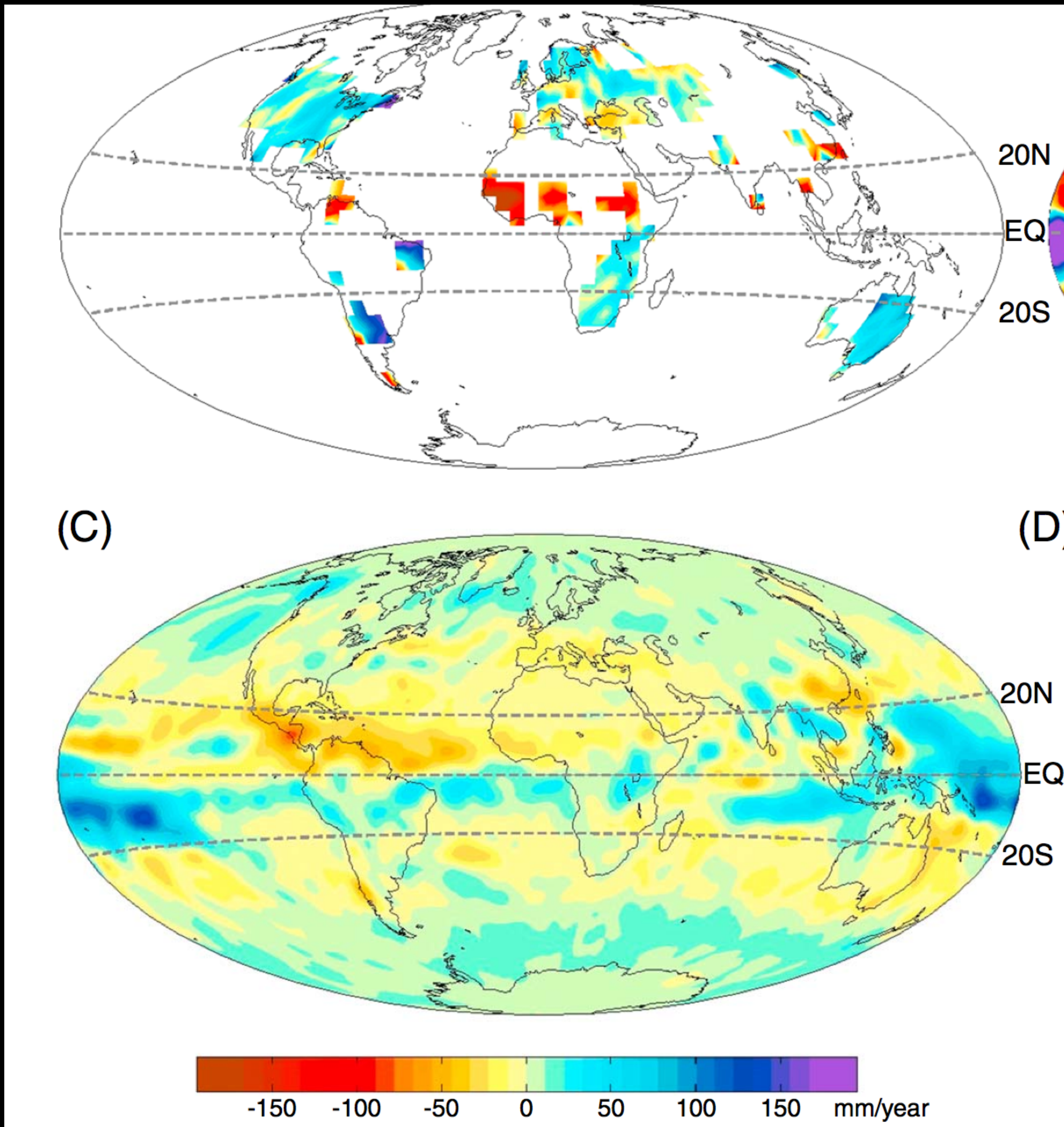
Cloud feedbacks help determine poleward shift w/ global warming

Bigger temperature gradient (from cloud feedbacks)
→ more jet shift



Ceppi et al 2014, see also Ceppi et al (submitted), Voigt and Shaw (2015)

Late 20th Century Precipitation Changes



← Obs

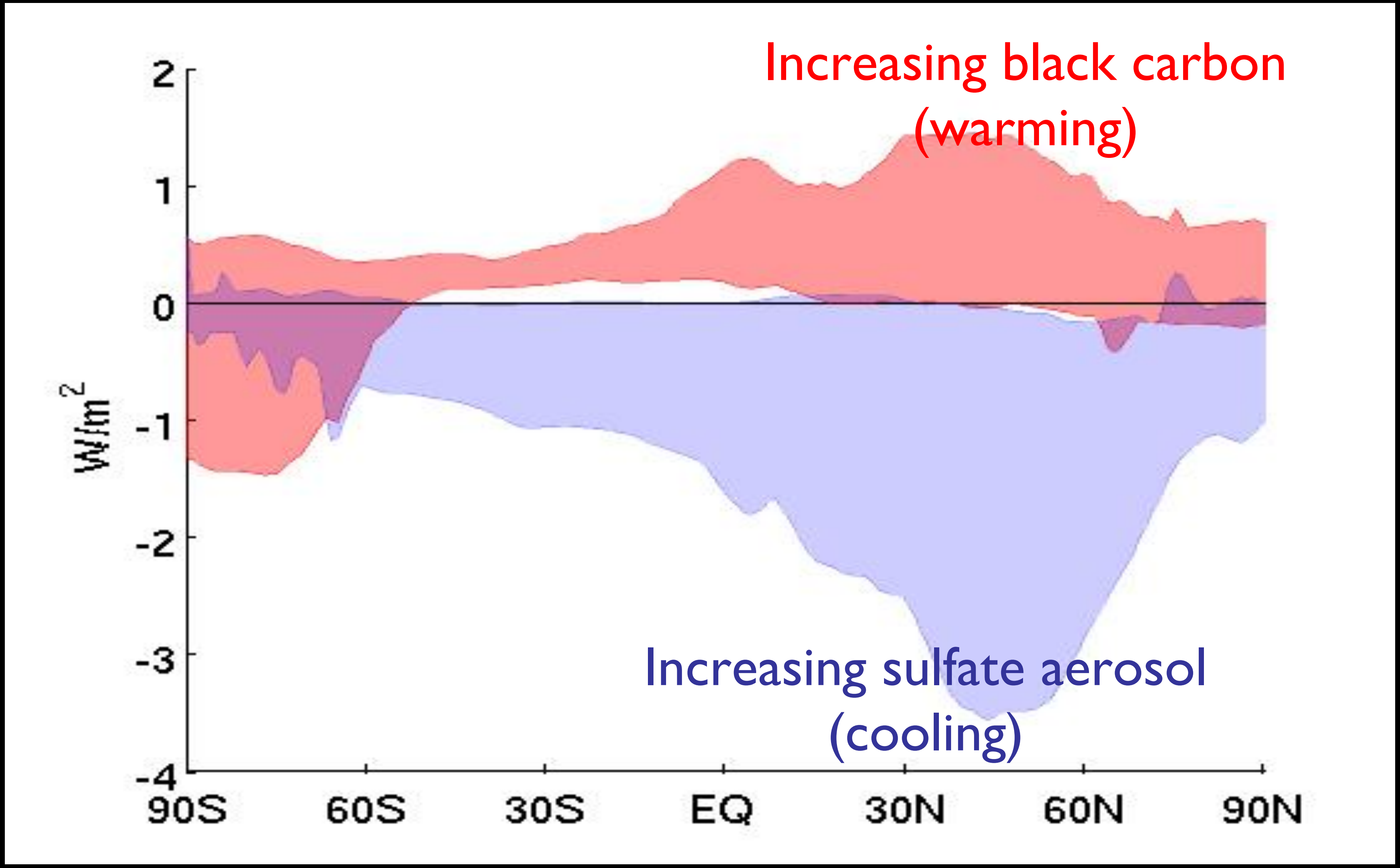
1970-80s minus 1930-40s

← Models

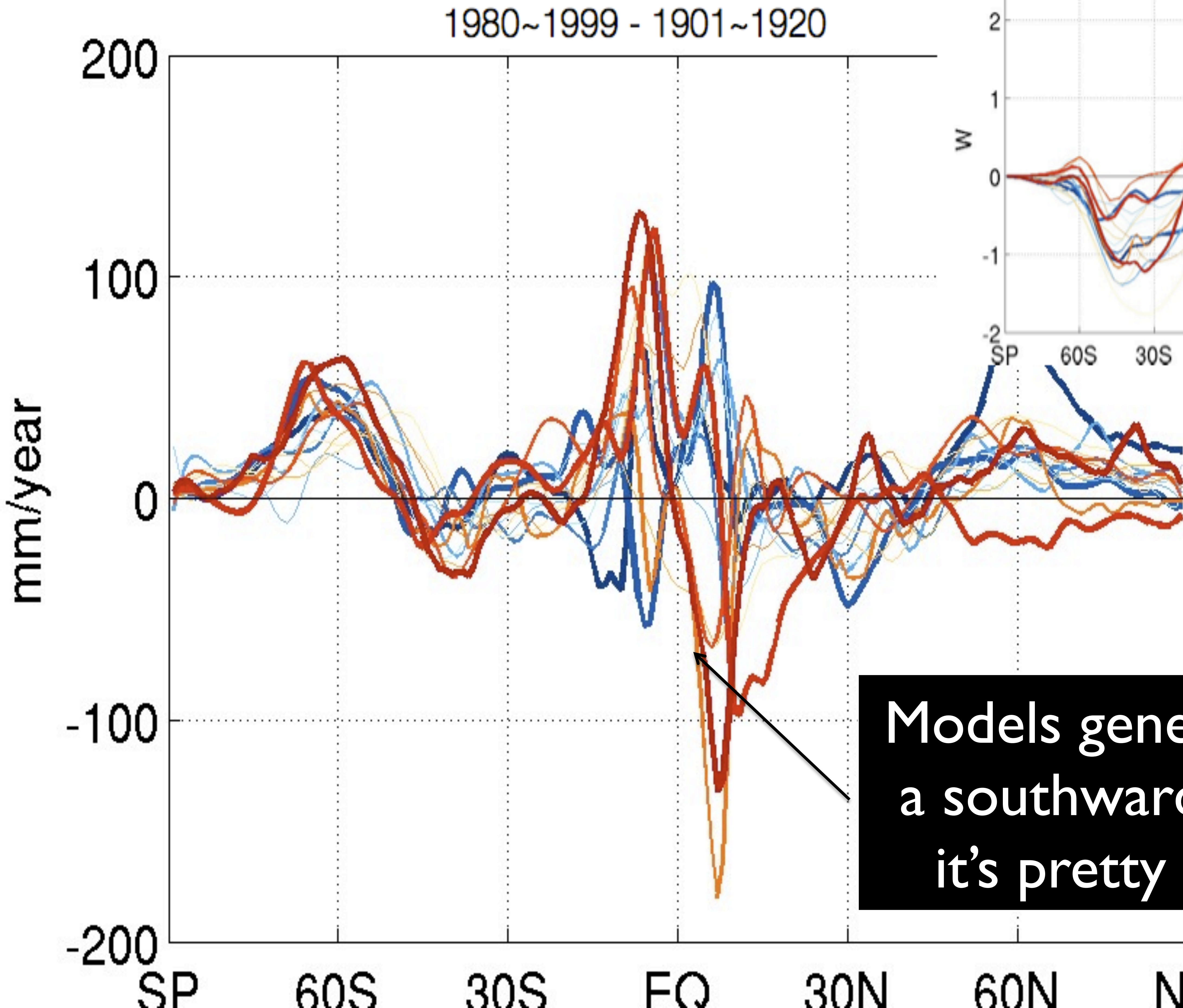
Hwang, Frierson and Kang 2013

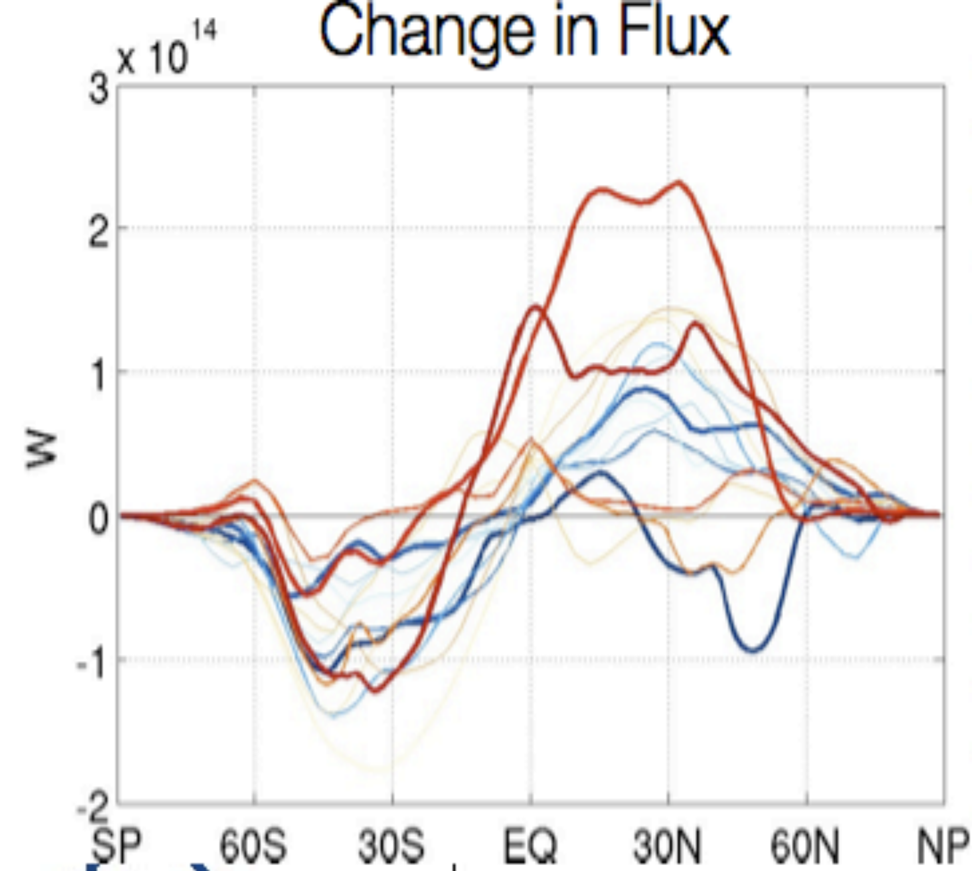
Aerosol Forcings in 20th Century Simulations

Structure of aerosol forcing in 20C3M:
(envelope shows the range in forcings used, i.e., model with most forcing & model with least forcing at each latitude)



20th Century Precip Change



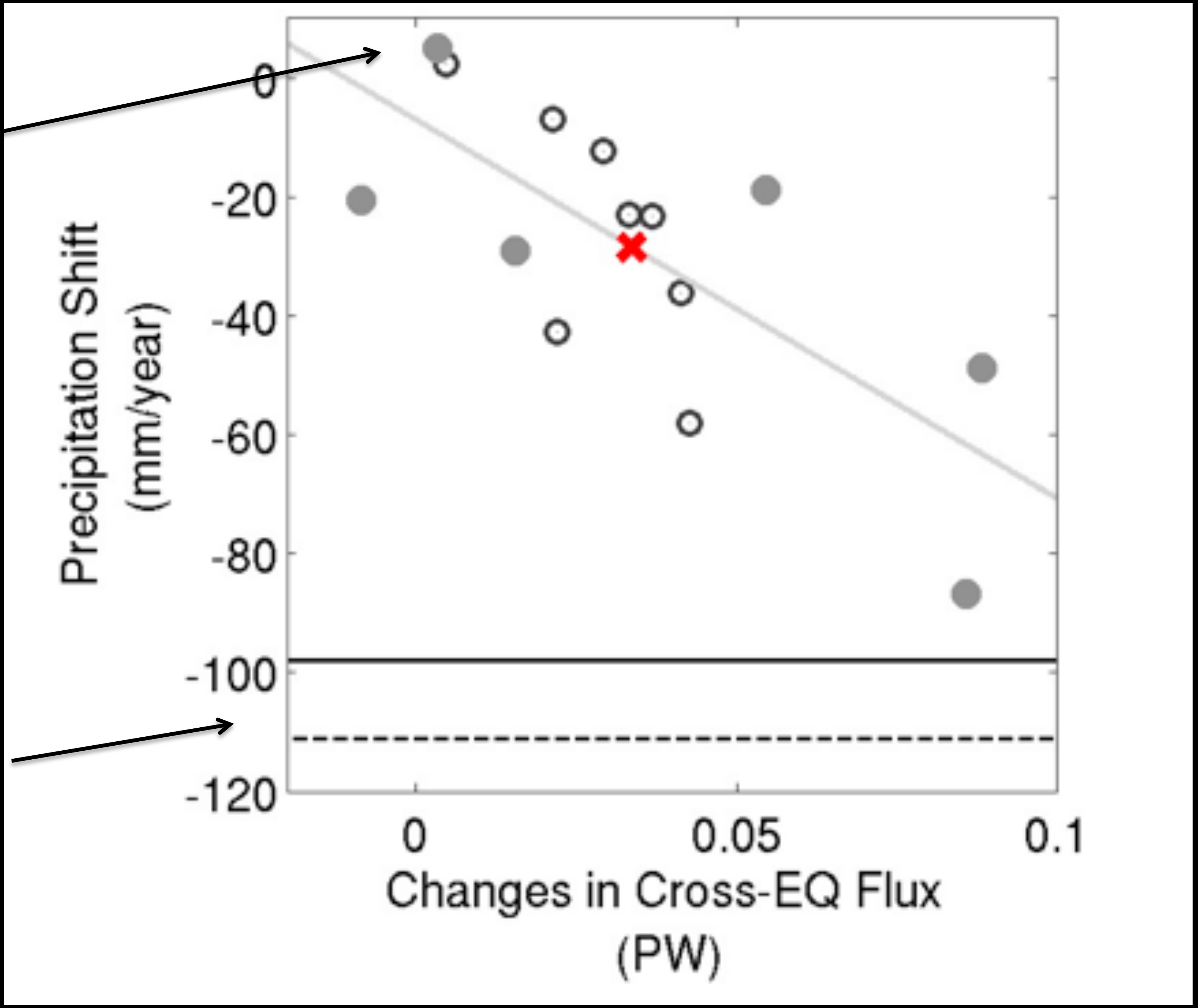


Models generally show a southward shift, but it's pretty messy…

Correlation of precip shift w/ energy flux

Only two models show northward shift…

All models underestimate the observed shift…

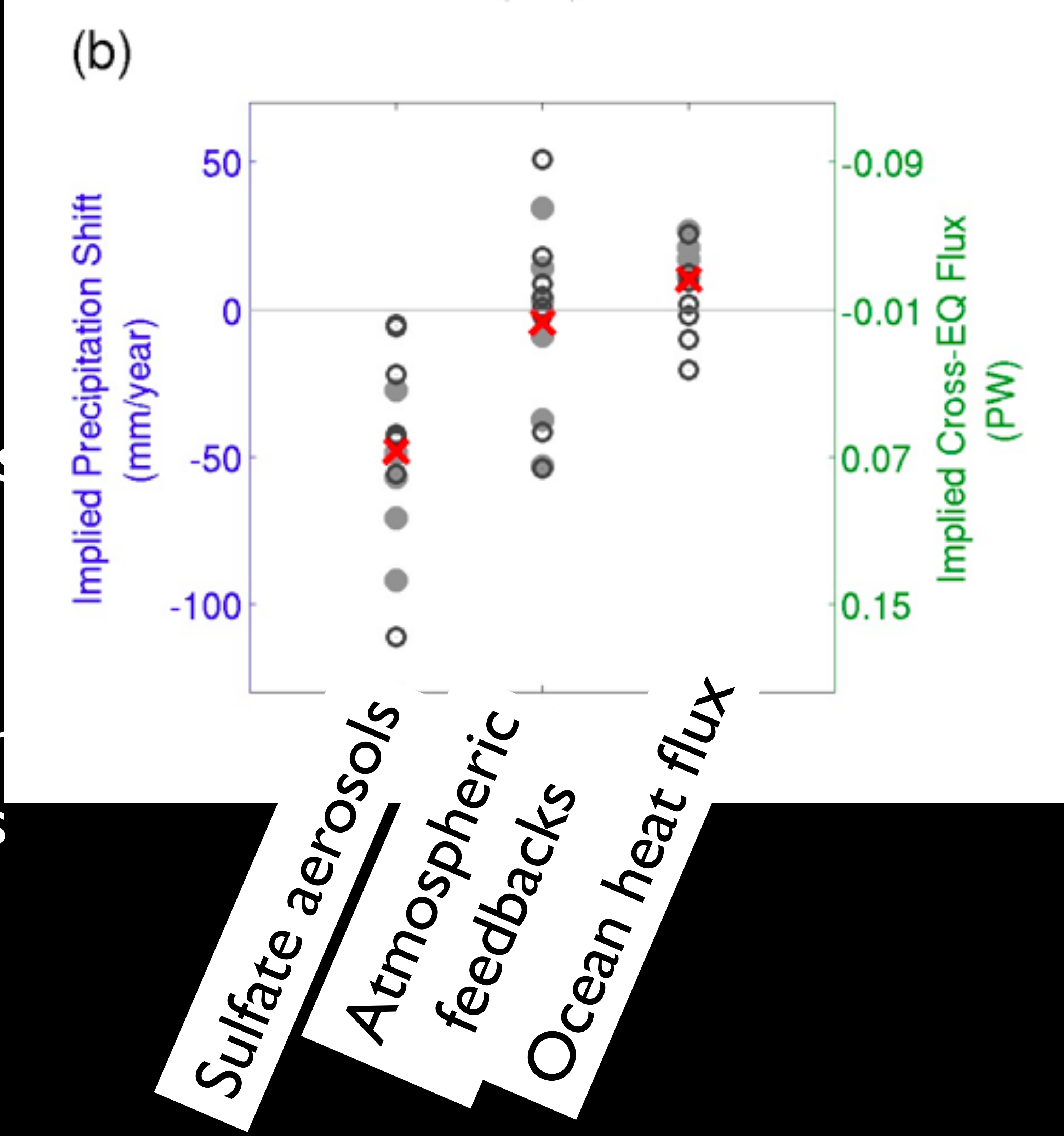


Attribution of Multi-Model Mean Shift

- **Sulfate aerosols** are most important for S'ward ITCZ shift

- Atmospheric feedbacks cause a lot of spread though…

  Hard to say how much the observed shift was aerosols



The Future??

- Global warming will lead to:
  - Warming in high northern latitudes
  - Slowdown in the oceanic MOC
  - Changes in clouds??
  - Cleanup of aerosols is important??
- ITCZ may shift northward, but models don’t agree

recap

- Heating affects climate nonlocally
    - First order effect: heating spreads diffusively
- Tropical precip affected too:
    - Ocean causes rainfall to peak in the NH
    - Poor **cloud** simulation over **SH extratropics** causes part of the double ITCZ bias.
    - Sulfate **aerosol pollution** caused some of the observed southward shift of tropical rainfall in the late 20th century.