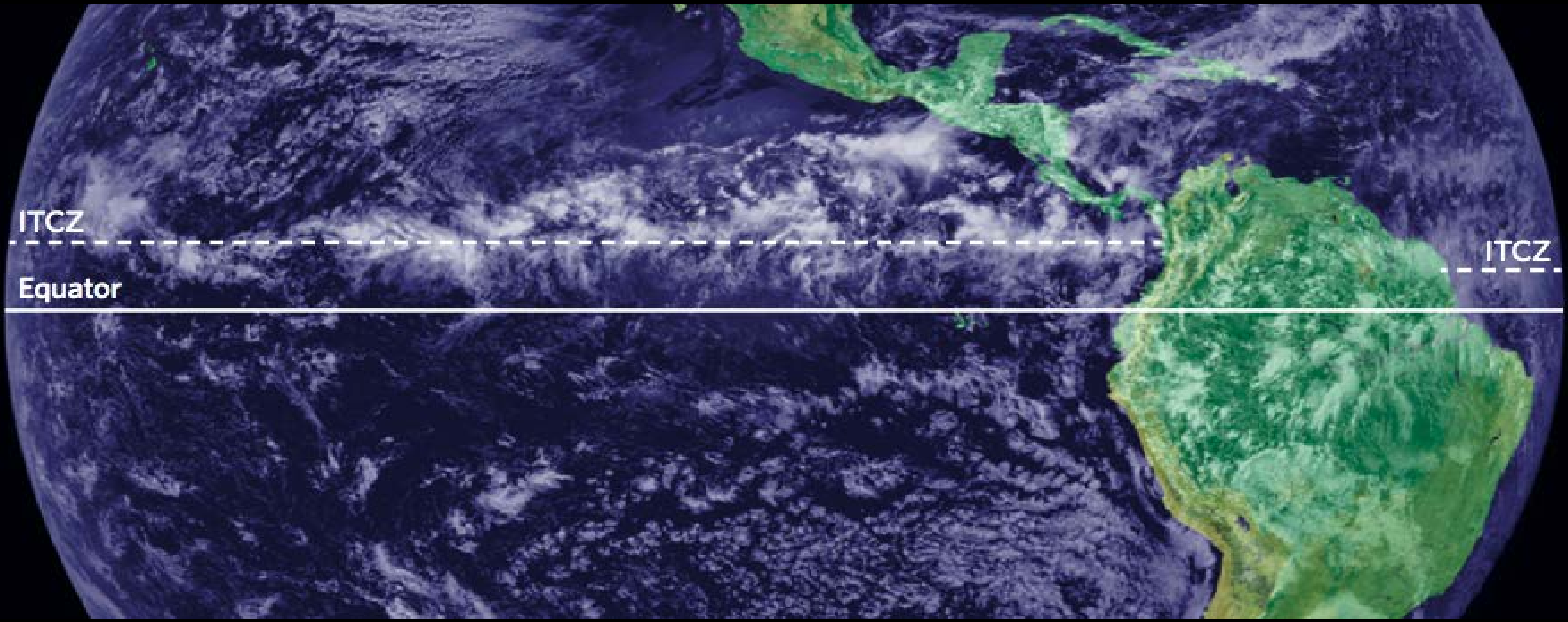
An Interconnected Planet

How Clouds, Aerosols, and the Ocean Cause Distant Rainfall Anomalies



Dargan M. W. Frierson

University of Washington

CESM Workshop, 6-15-15

New Connections

Recent research has uncovered some remarkable new links

- The **ozone hole** caused a large shift in the Southern Hemisphere storm tracks
- **Air pollution** affects 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

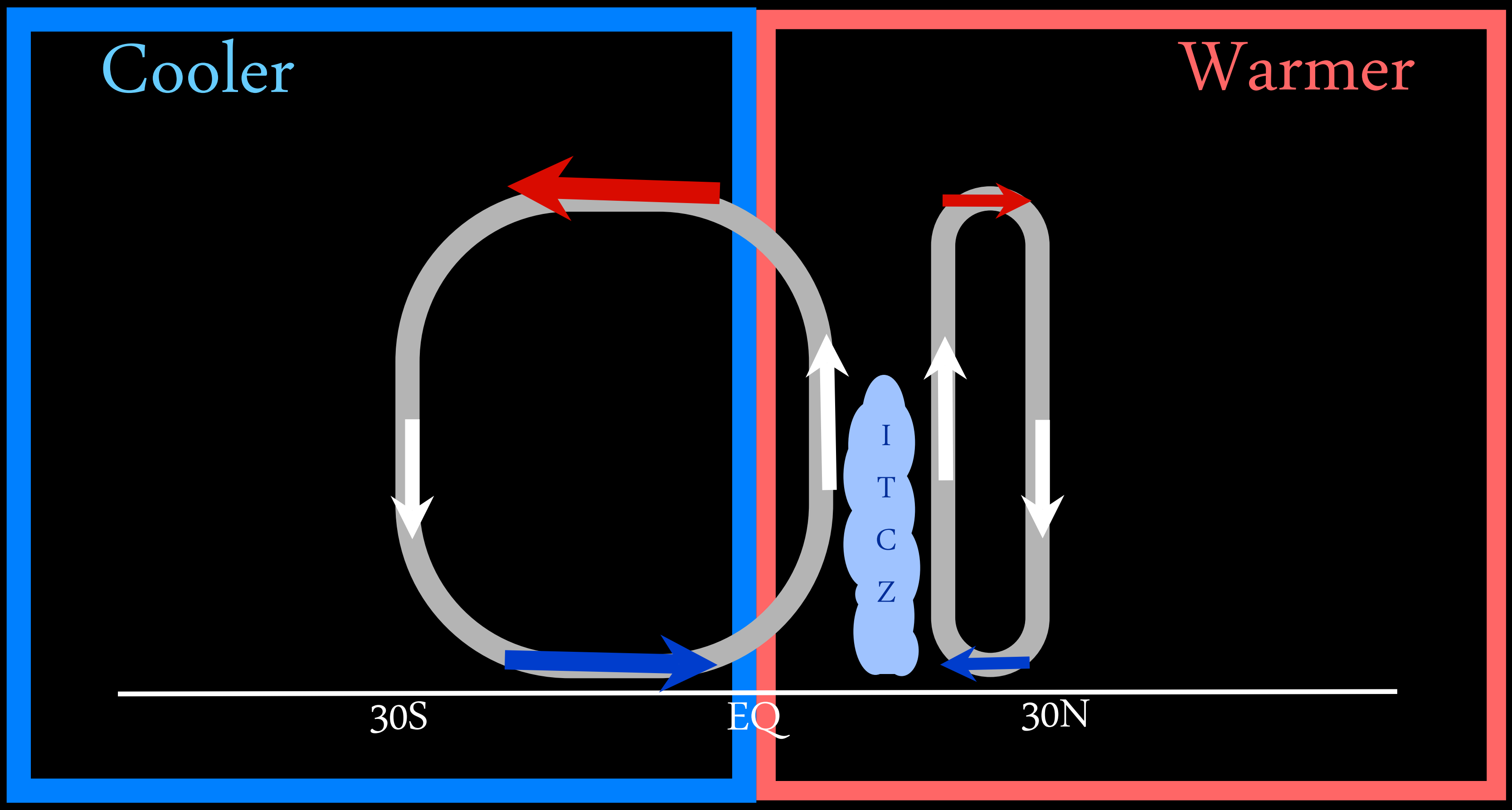
1. What role does convection play in **cloud feedbacks**?
2. What role does **convective aggregation** play in climate?
3. What controls the position, strength and variability of **extratropical storm tracks**?
4. What controls the position, strength, and variability of the **tropical rain belts**?

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

Long-distance connections

- This talk is about remote rainfall teleconnections
- Tropical origins are well-known
  - **El Niño** causes disruptions around the planet
- Extratropical influences have only more recently been discovered

Hadley cells respond to heating



Southern Hemisphere (SH)

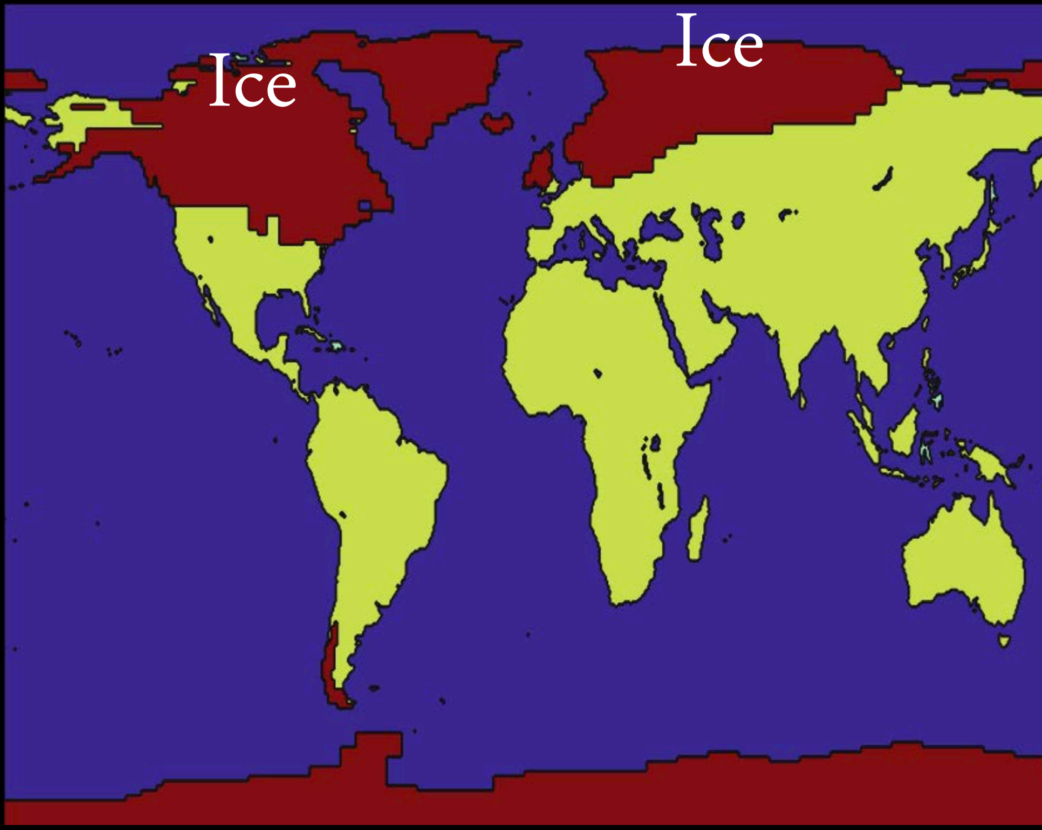
Northern Hemisphere (NH)

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

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

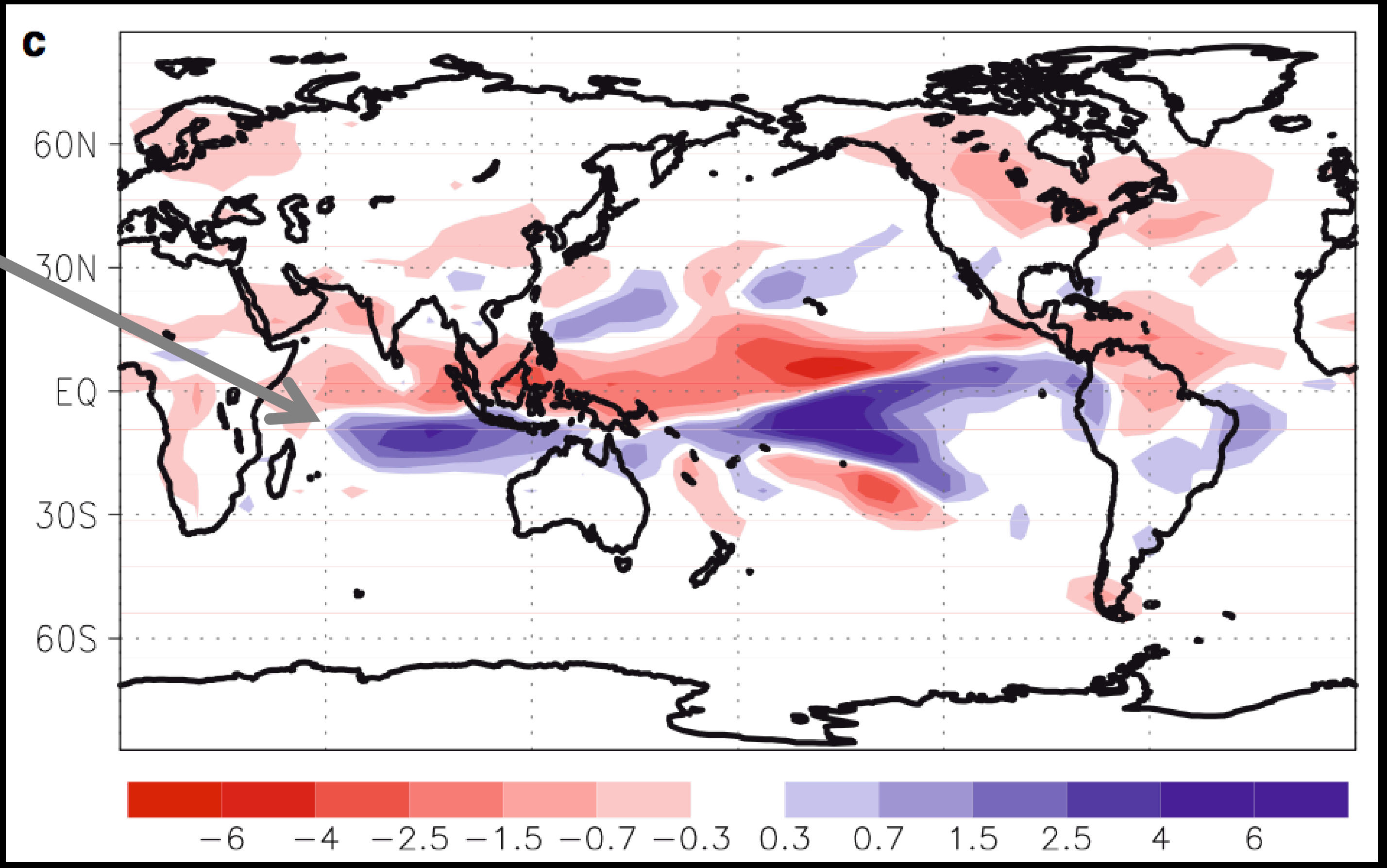
ITCZ Shifts Away from Cooling

The tropics even responds to heating/cooling far away...



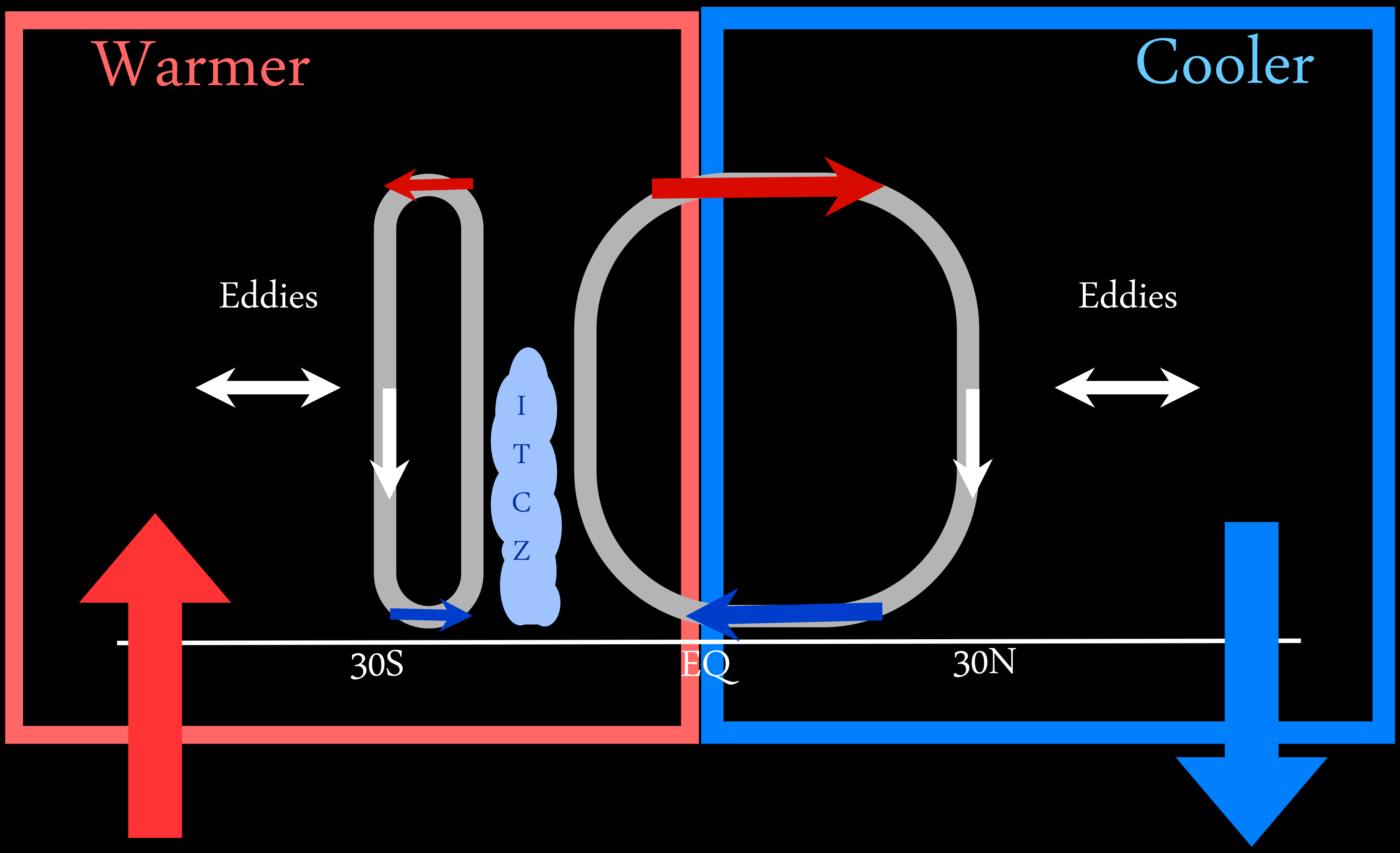
Last Glacial Maximum simulation of Chiang and Bitz 2005

NH cooling results in big southward shift of the ITCZ! (change in precip is plotted)

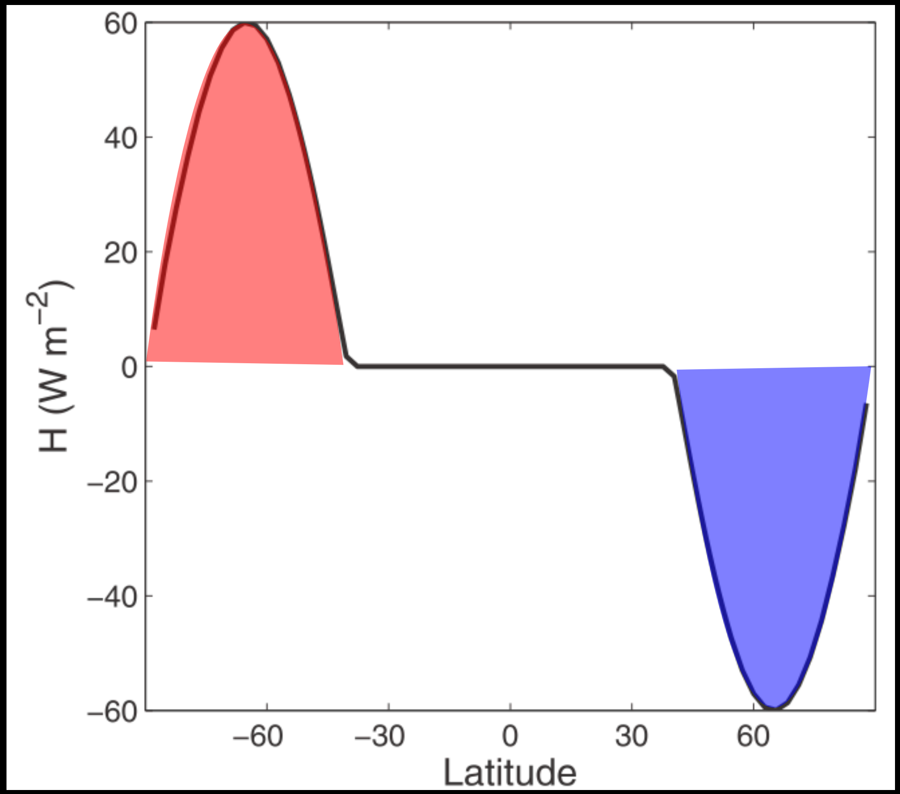


See also Broccoli et al. 2006 Zhang and Delworth 2005

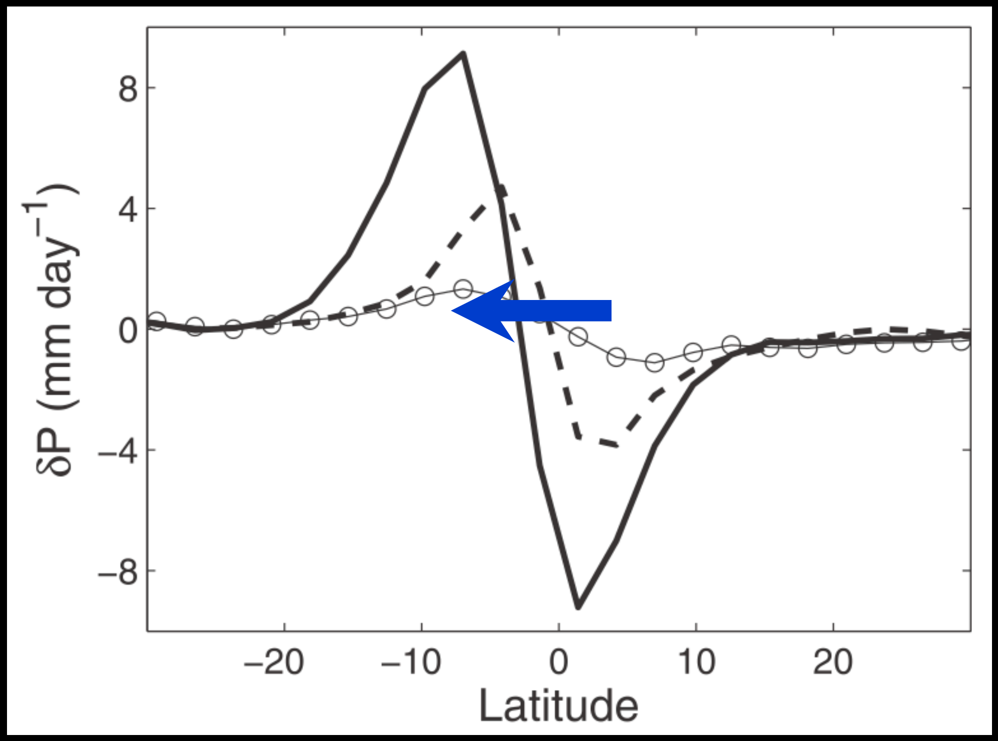
ITCZ Shifts Towards the Heating



imposed q-flux



Changes in Precipitation



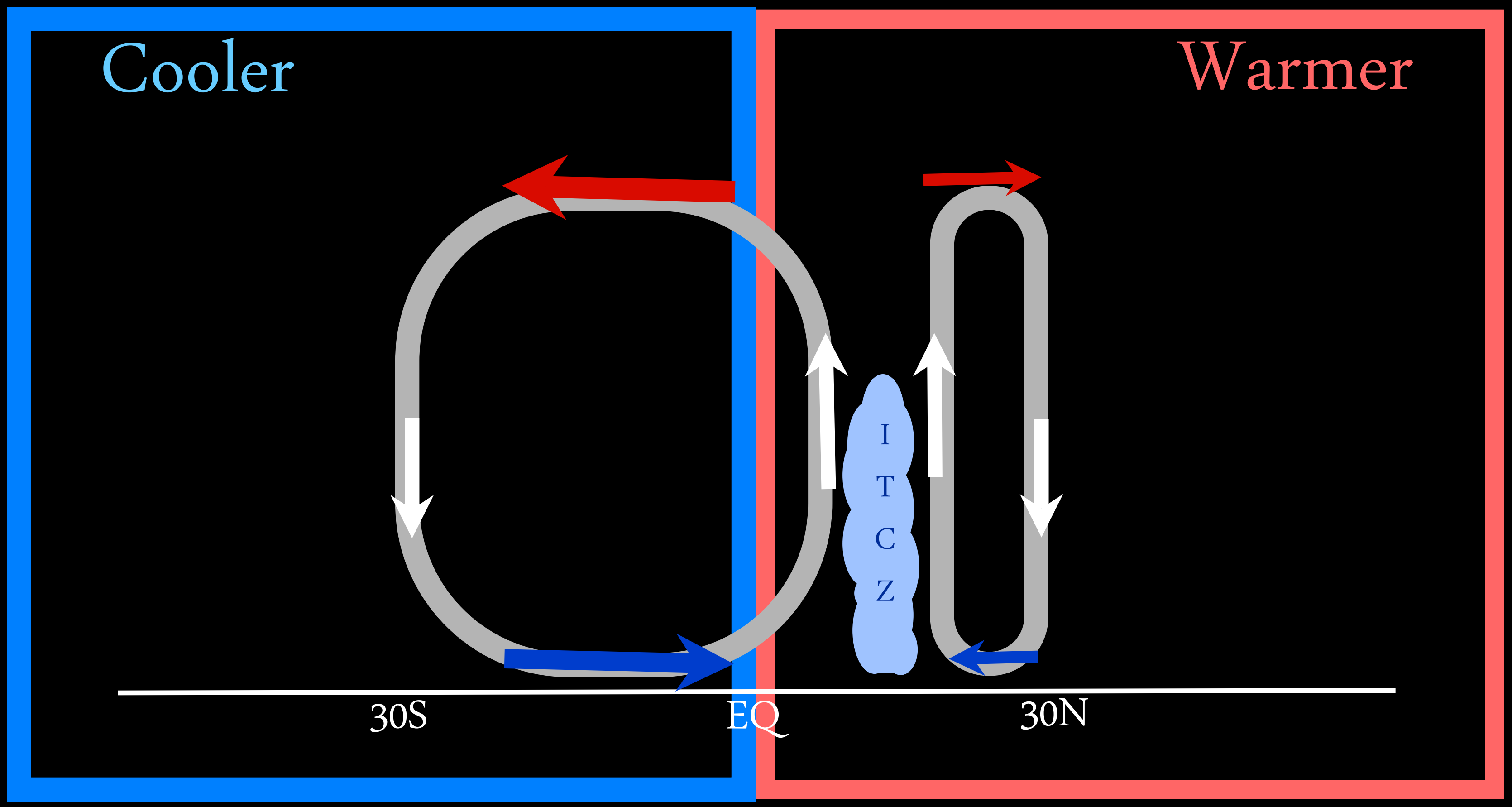
Eddies spread warmth to the tropics, affecting the Hadley cell

Kang, Held, Frierson and Zhao 2008

Kang, Frierson, and Held 2009

Claim: Whatever **heats** the NH atmosphere **more** than the SH

also causes the ITCZ to be in the NH

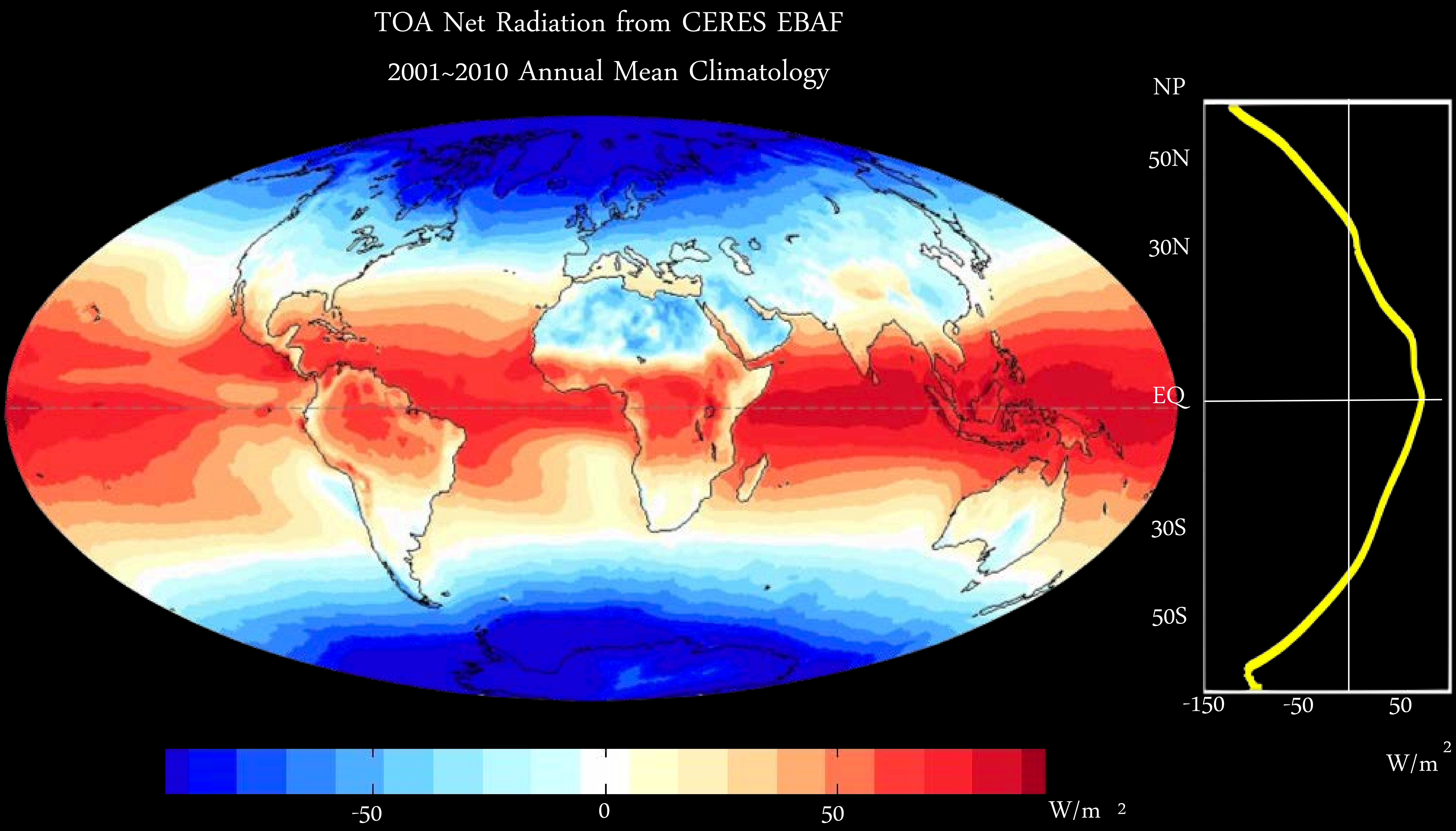


The Sun? Albedo?

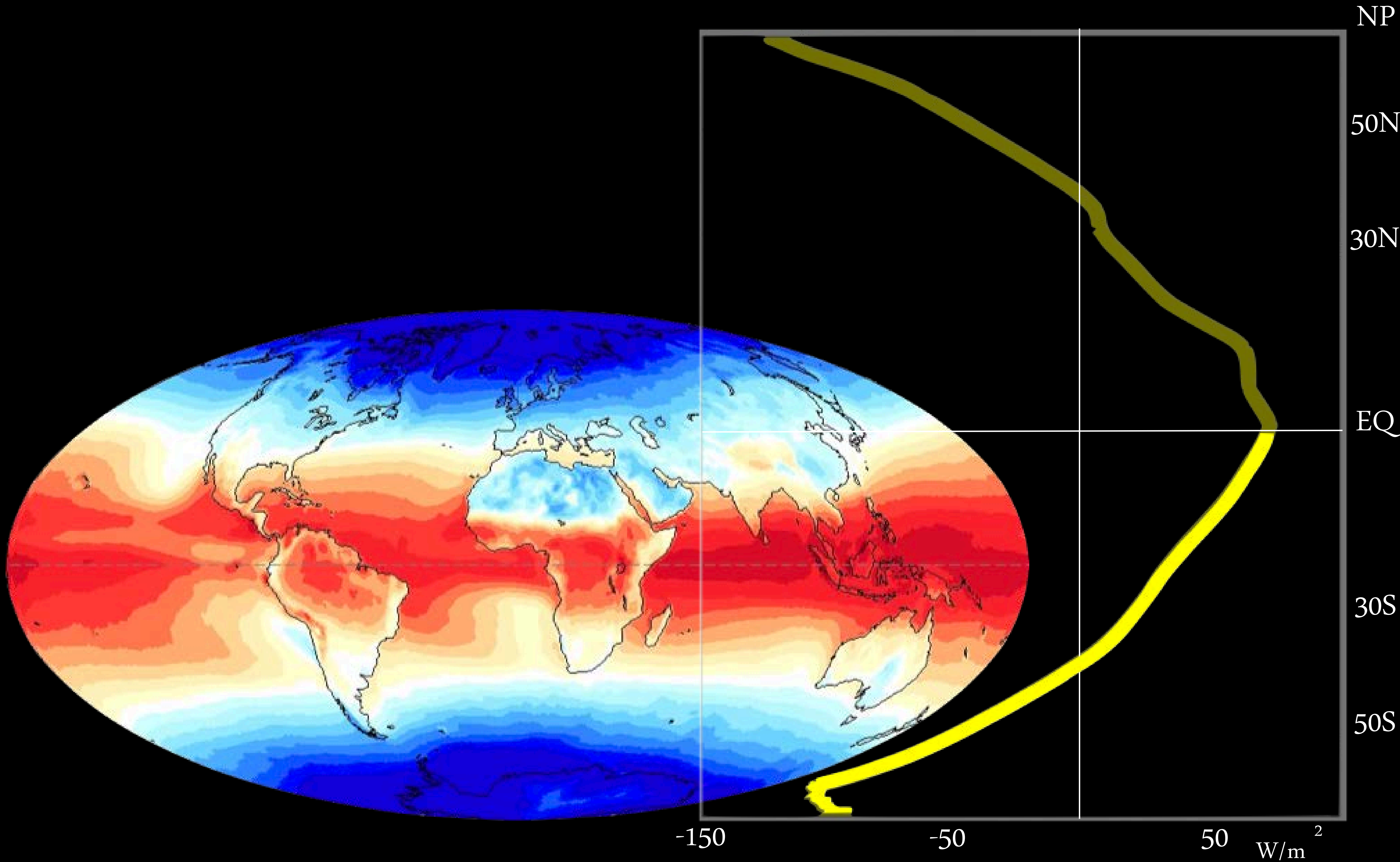
Greenhouse effect? The ocean?

Frierson et al 2013, Nature Geosci

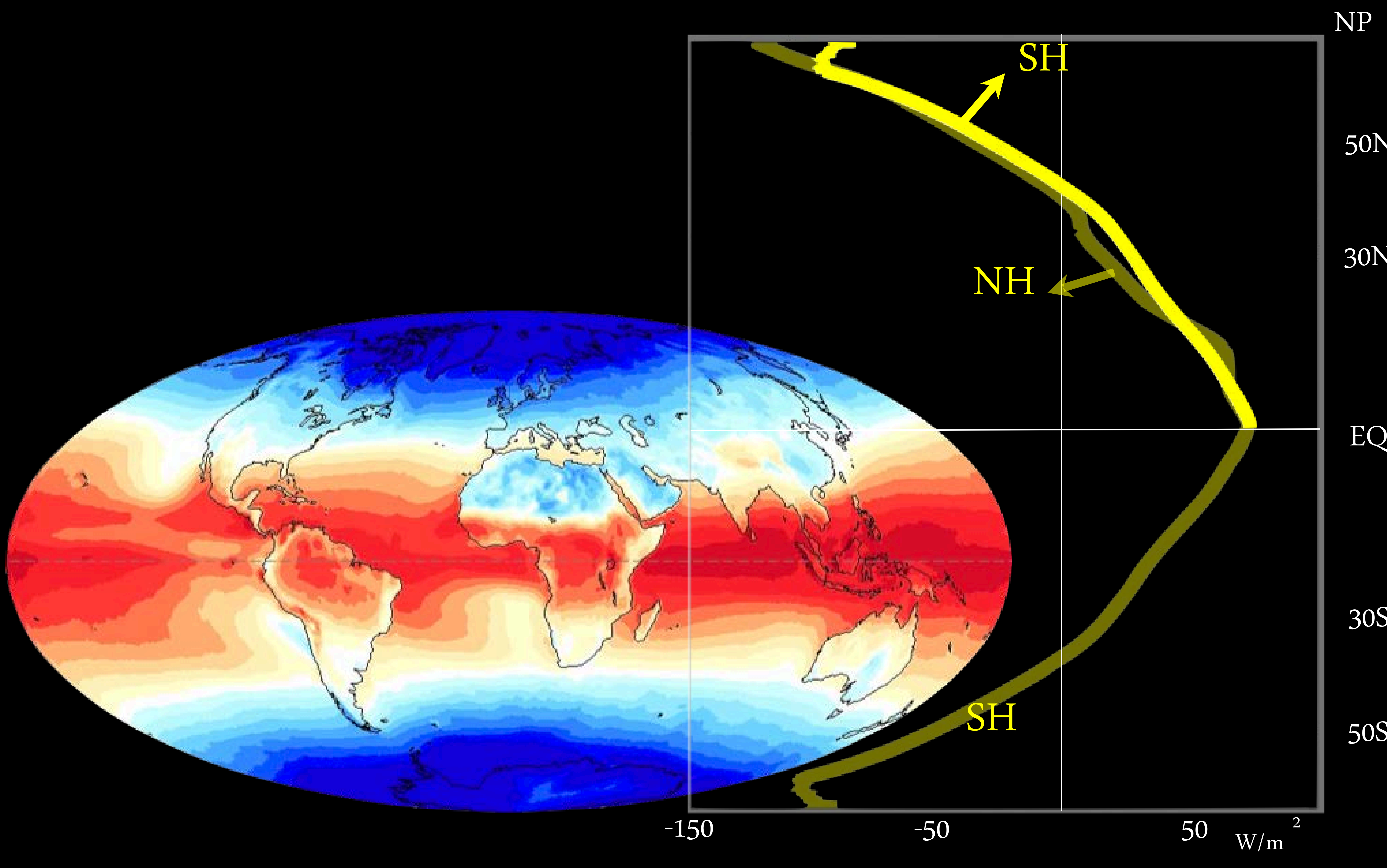
Top of Atmosphere Radiation



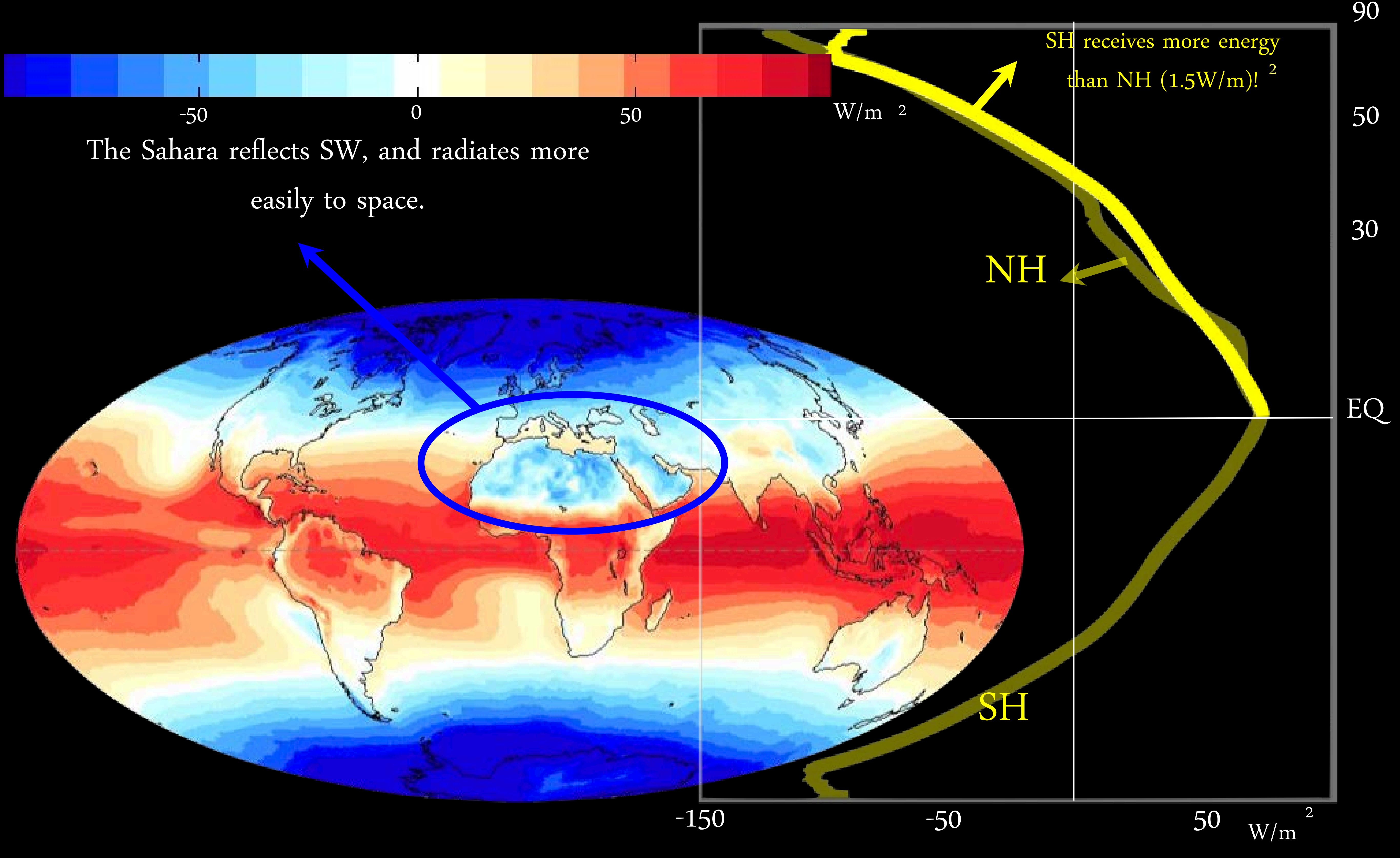
Top of Atmosphere Radiation

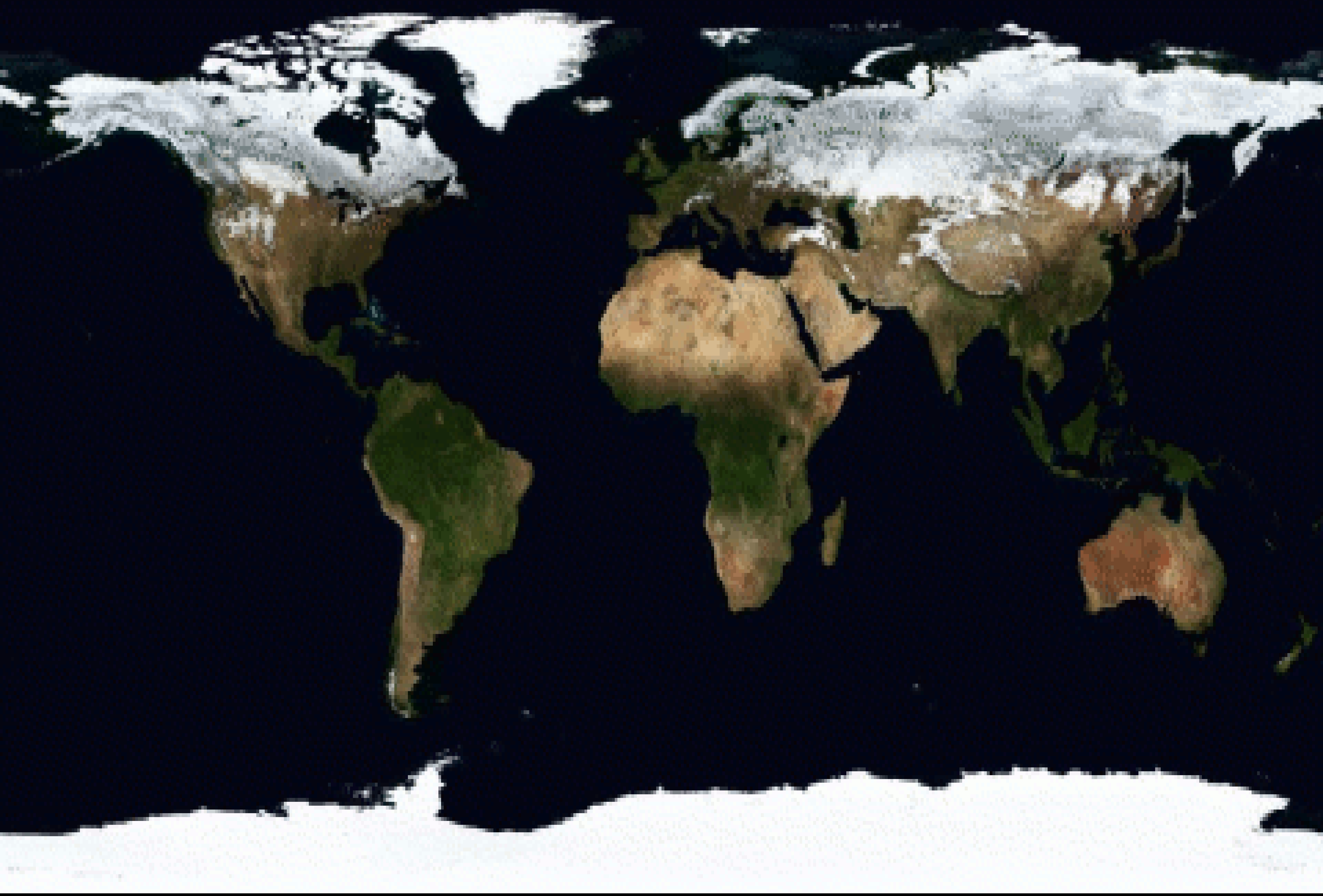


Top of Atmosphere Radiation



Top of Atmosphere Radiation





NASA Terra “Blue Marble Next Generation” (cloud-free conditions in 2004)

Recognized by Nimbus III Team

First observation that the Sahara is a net radiation sink, even in summer (1-15 July 1969)

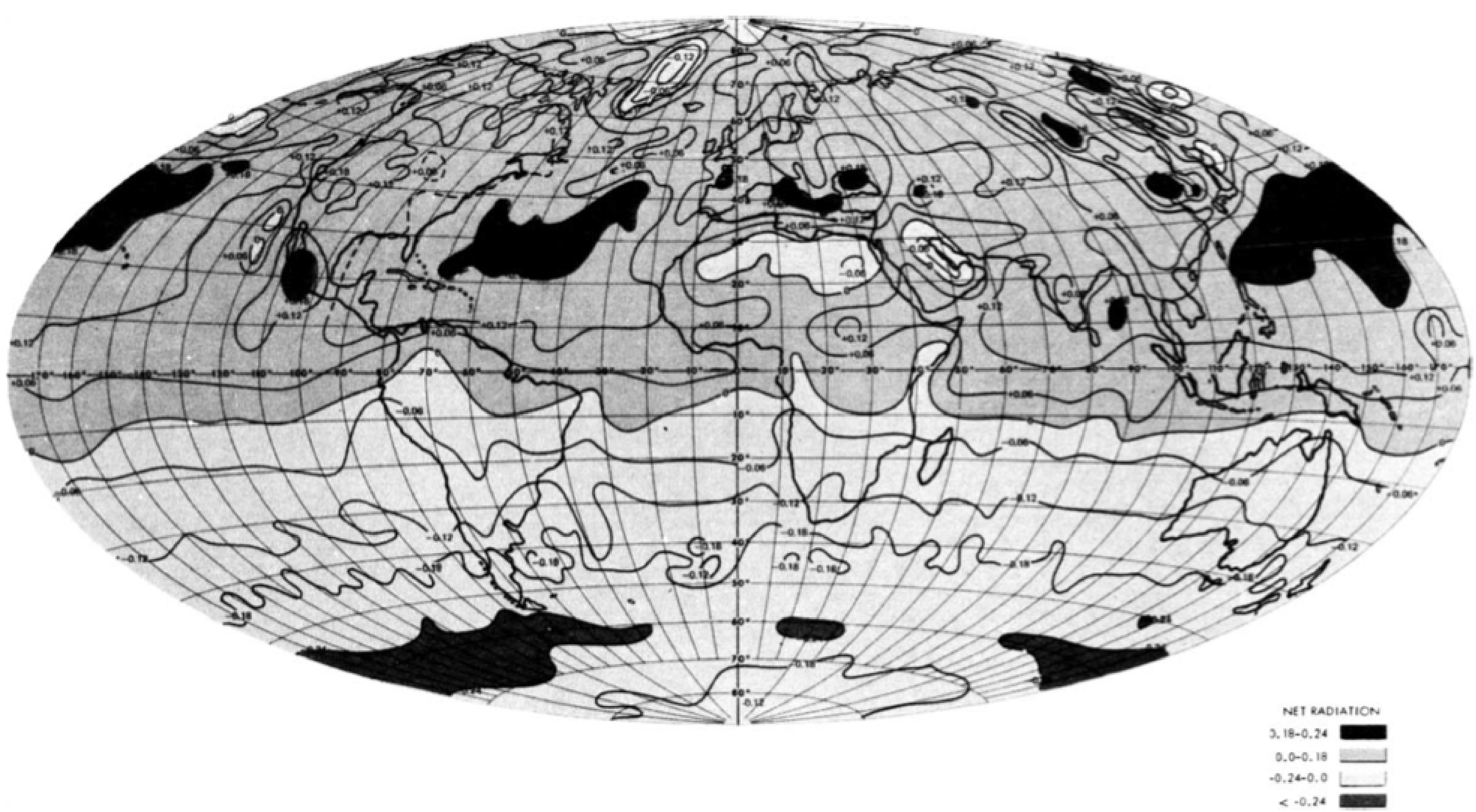
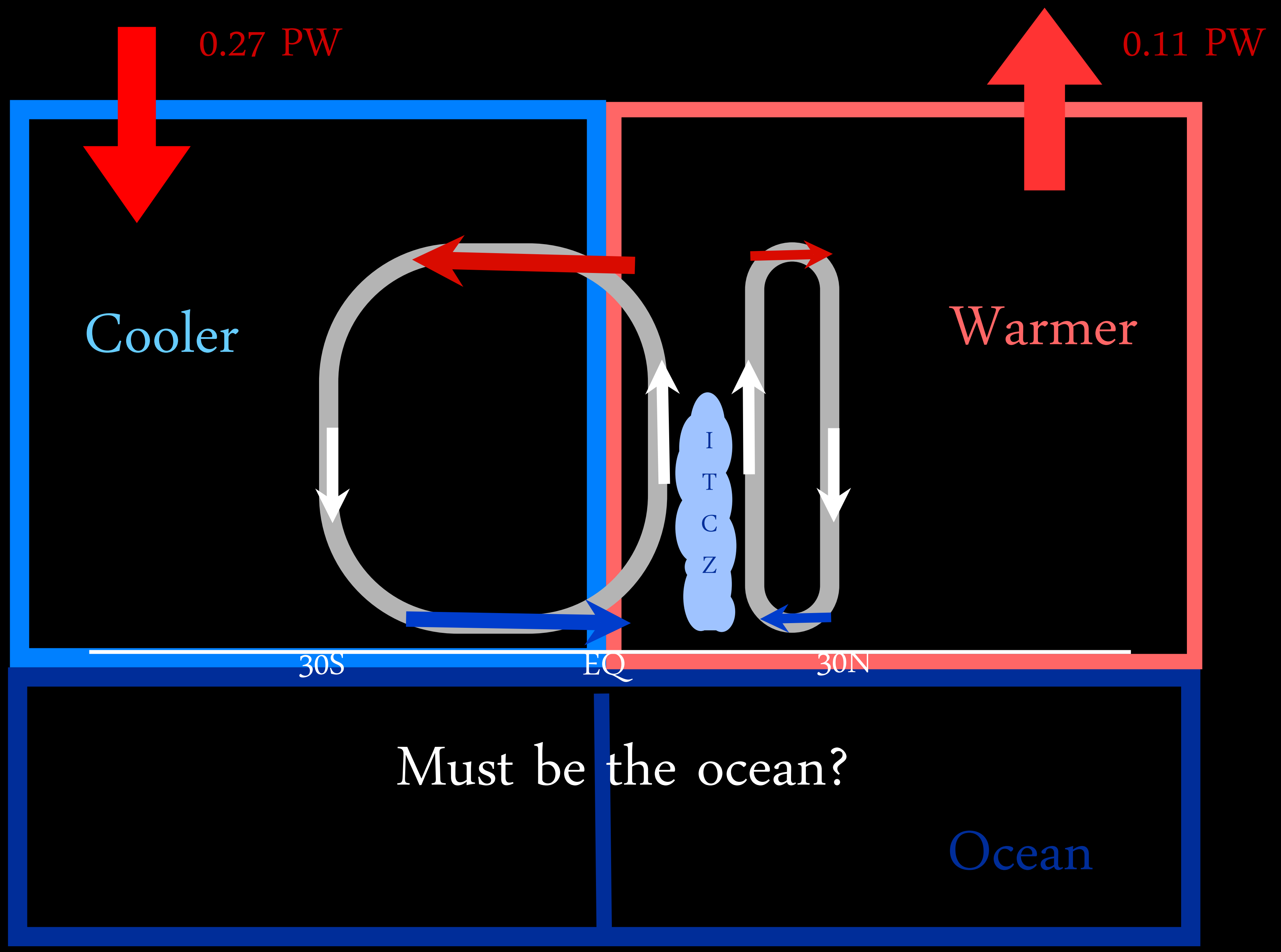


Figure 1. Net radiation at the top of the atmosphere ($cal/cm^2/min$) measured from Nimbus III, 1-15 July 1969.

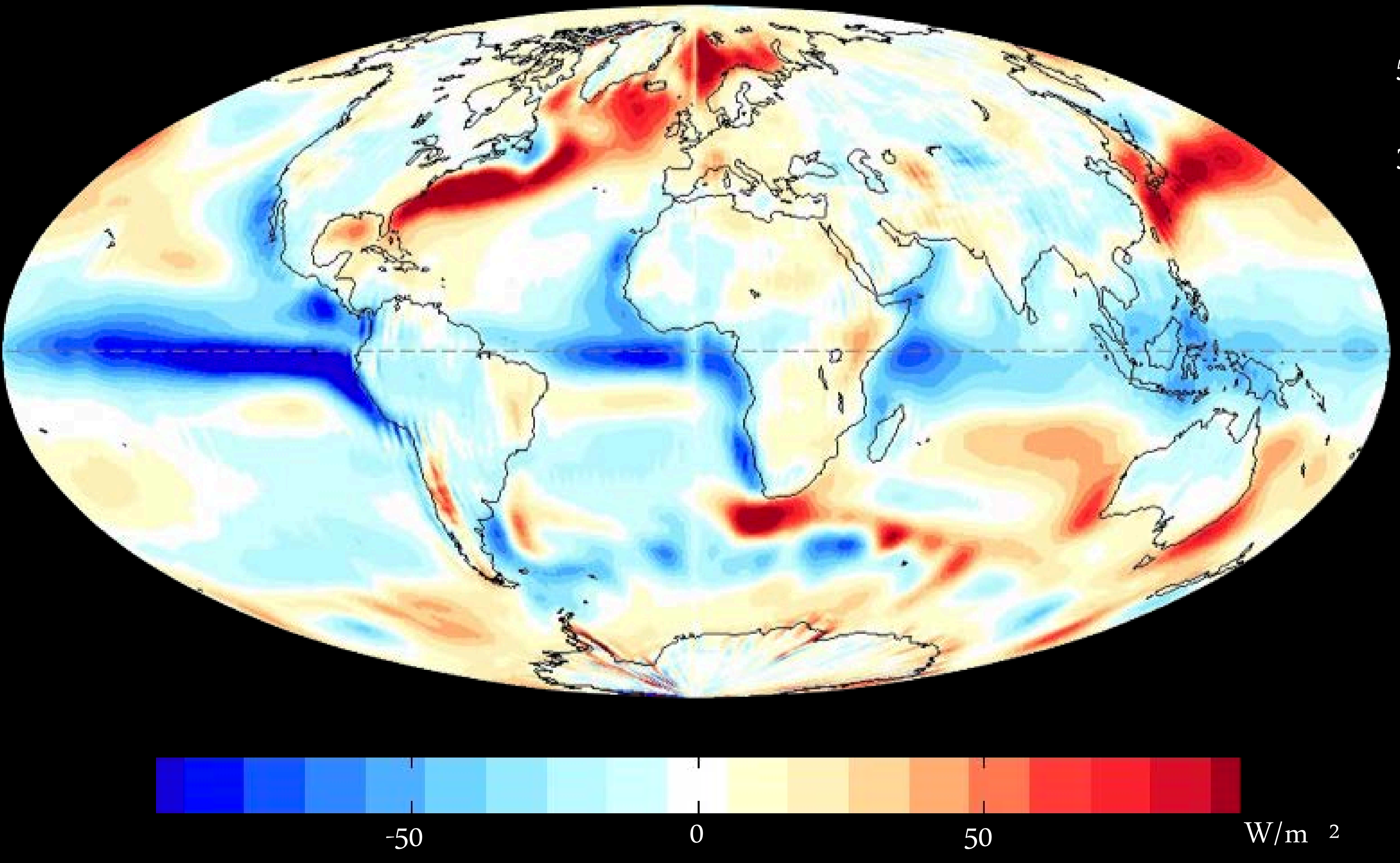
What makes the NH warm?

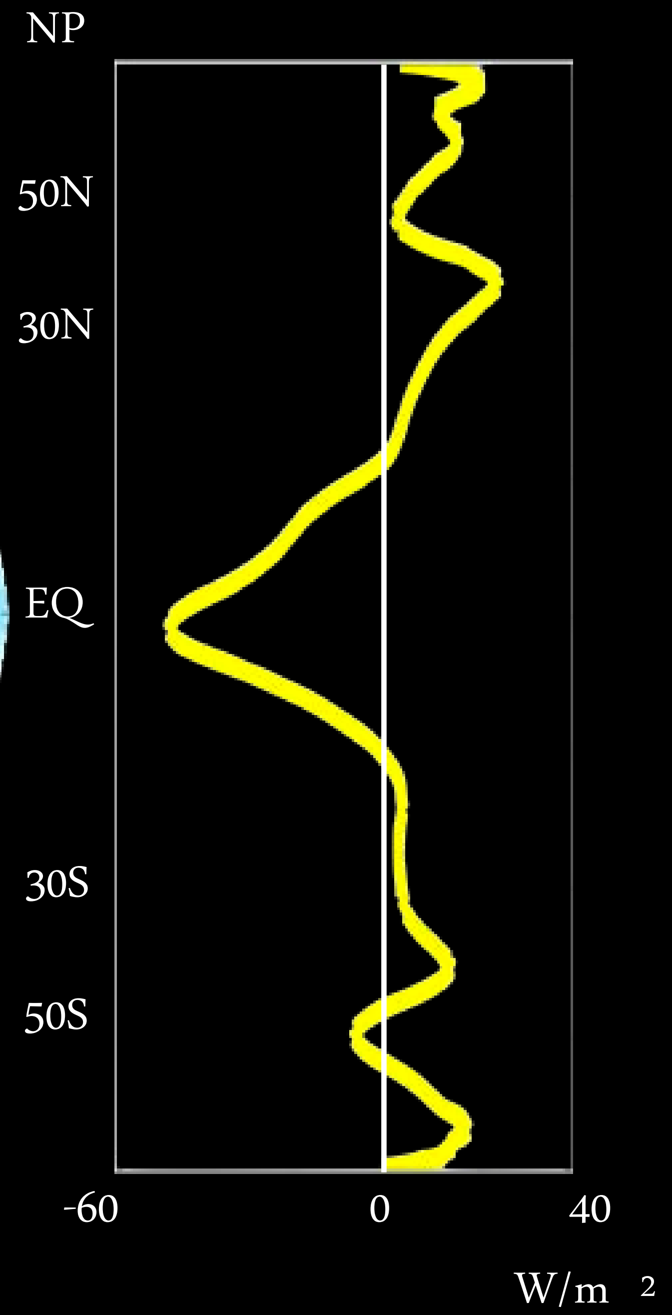


Kang, Seager, Frierson and Liu (2015)

Heat flux from ocean to atmosphere

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

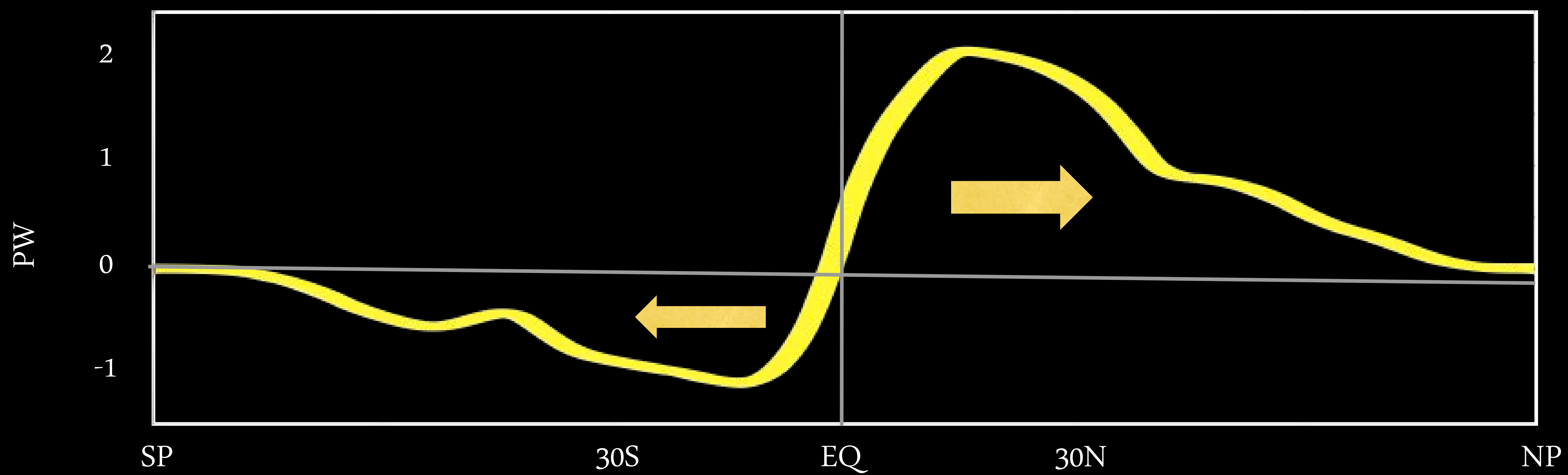




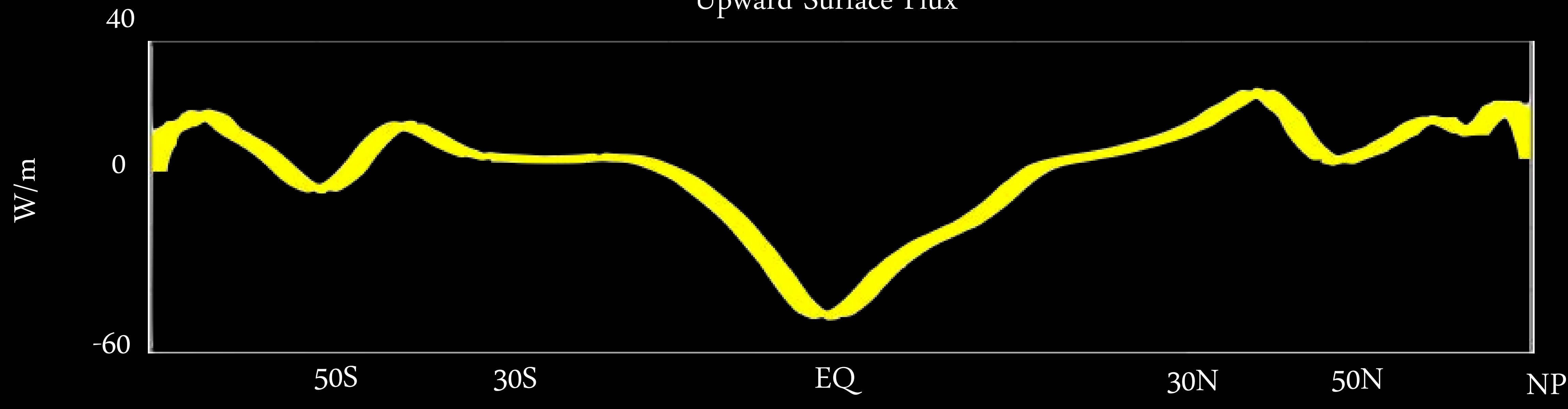
The Ocean Transports Energy Northward Across the Equator

(due to the Meridional Overturning Circulation, **MOC**)

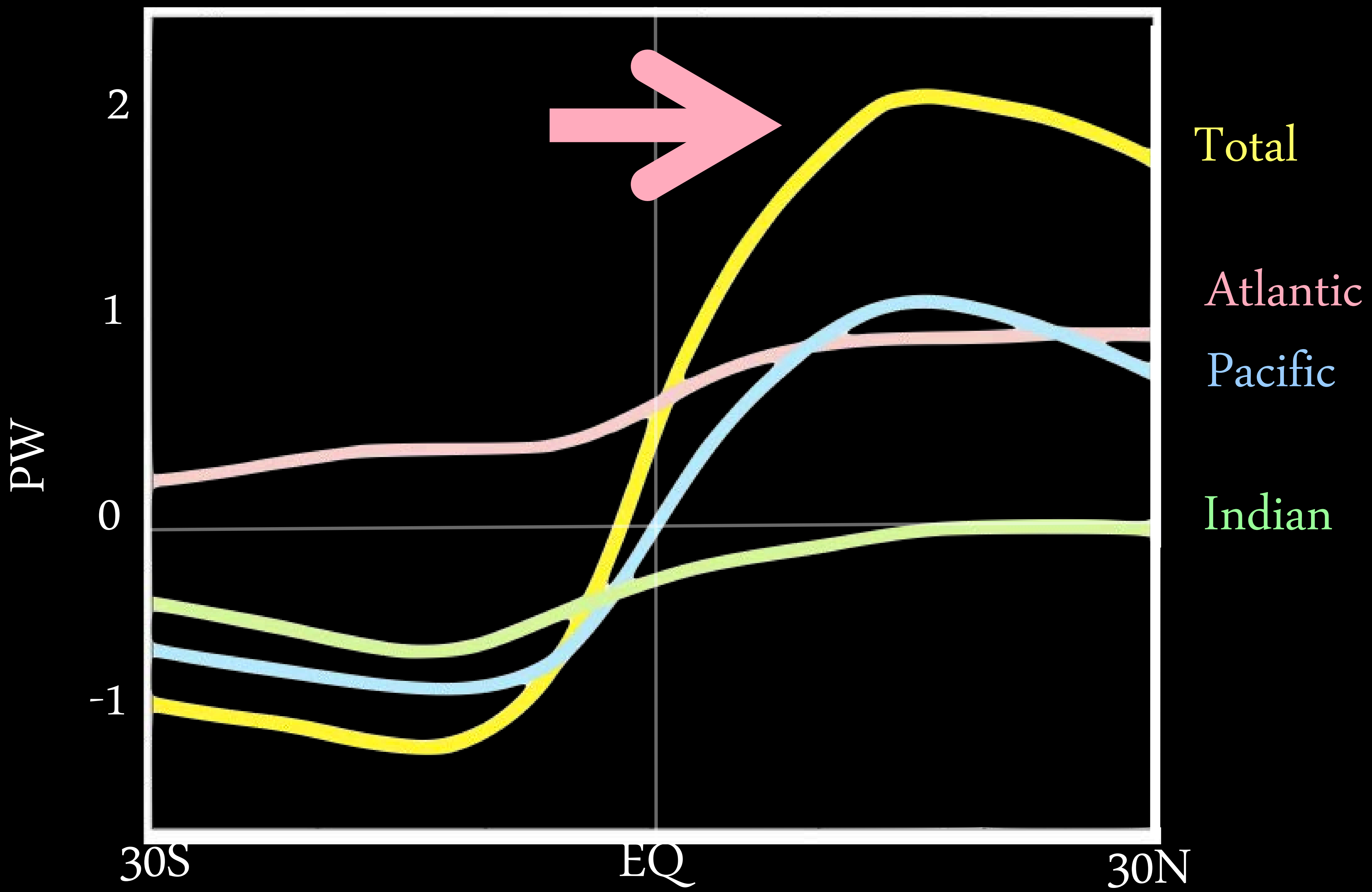
Northward Oceanic Energy Transport



Upward Surface Flux

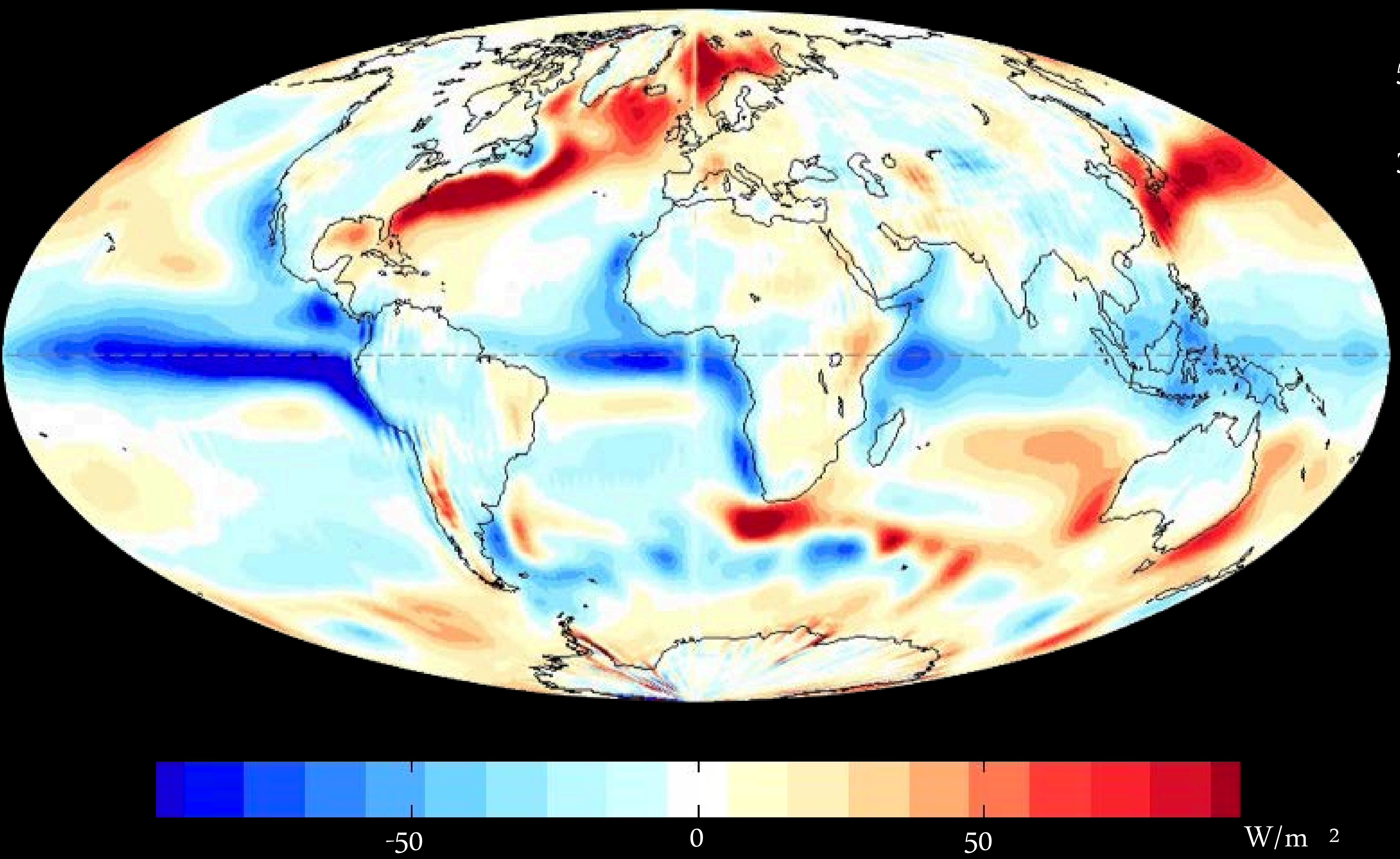


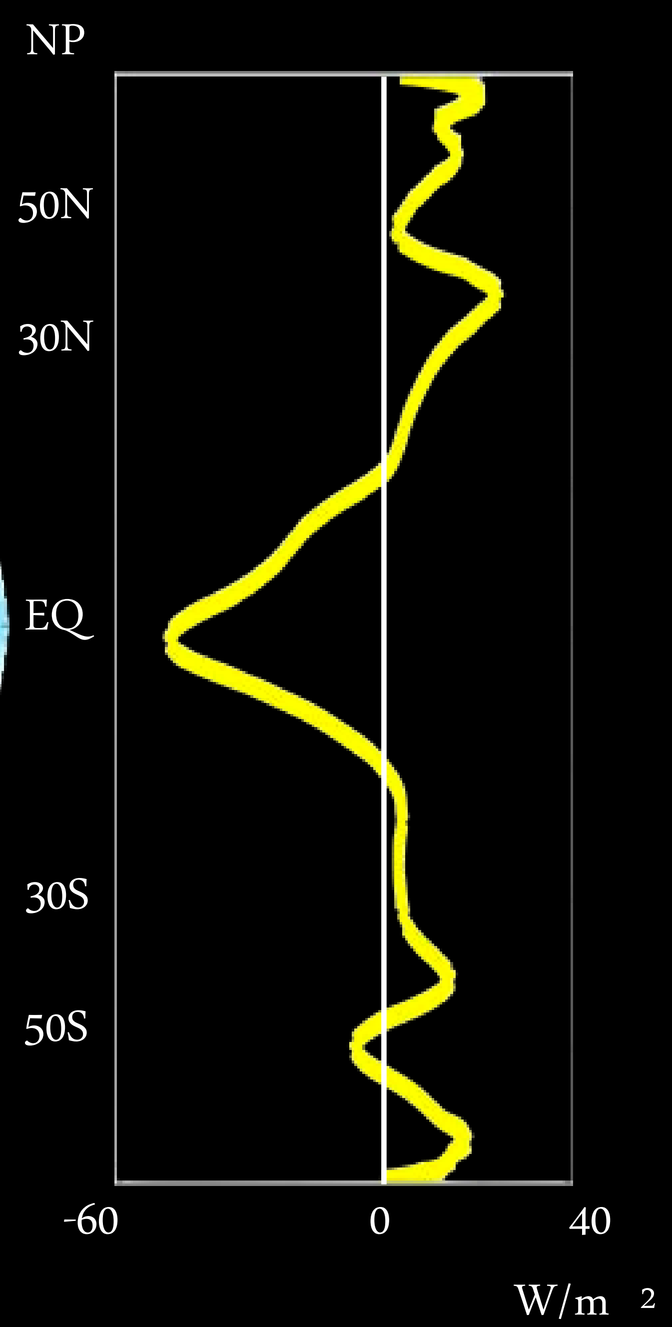
Northward Cross-equatorial Transport Happens Entirely in Atlantic



Let's put this surface heat flux into an aquaplanet GCM

Will it be enough to shift the ITCZ into the NH?

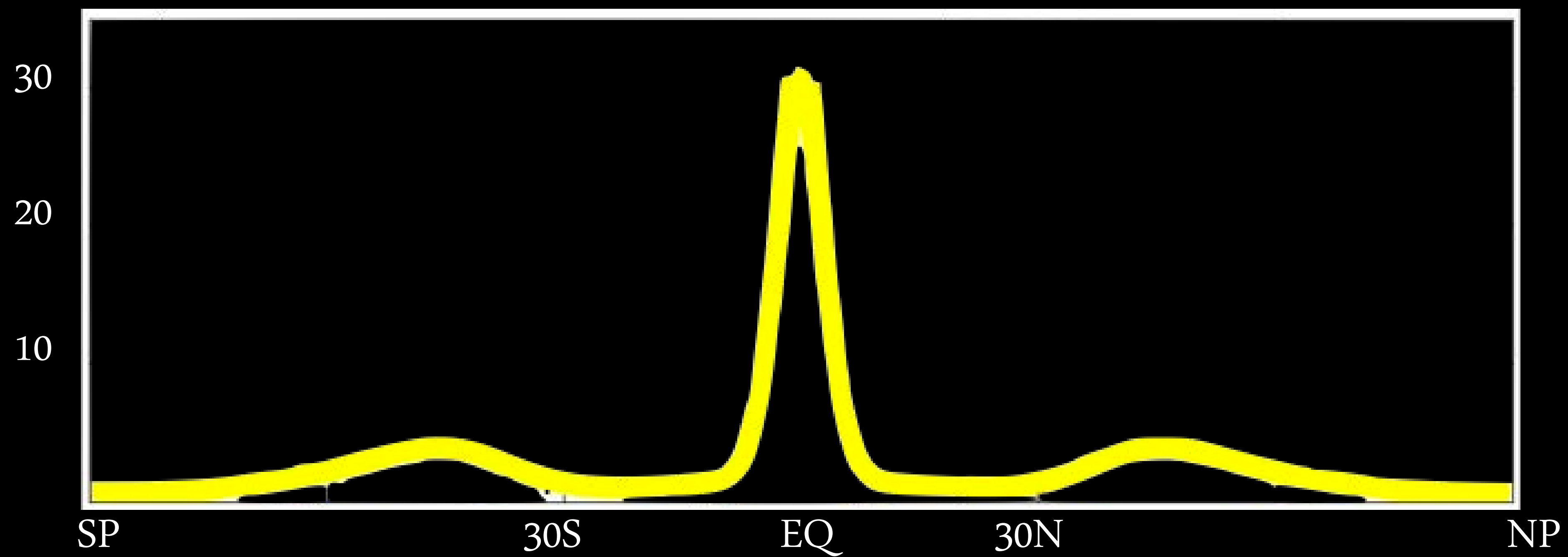




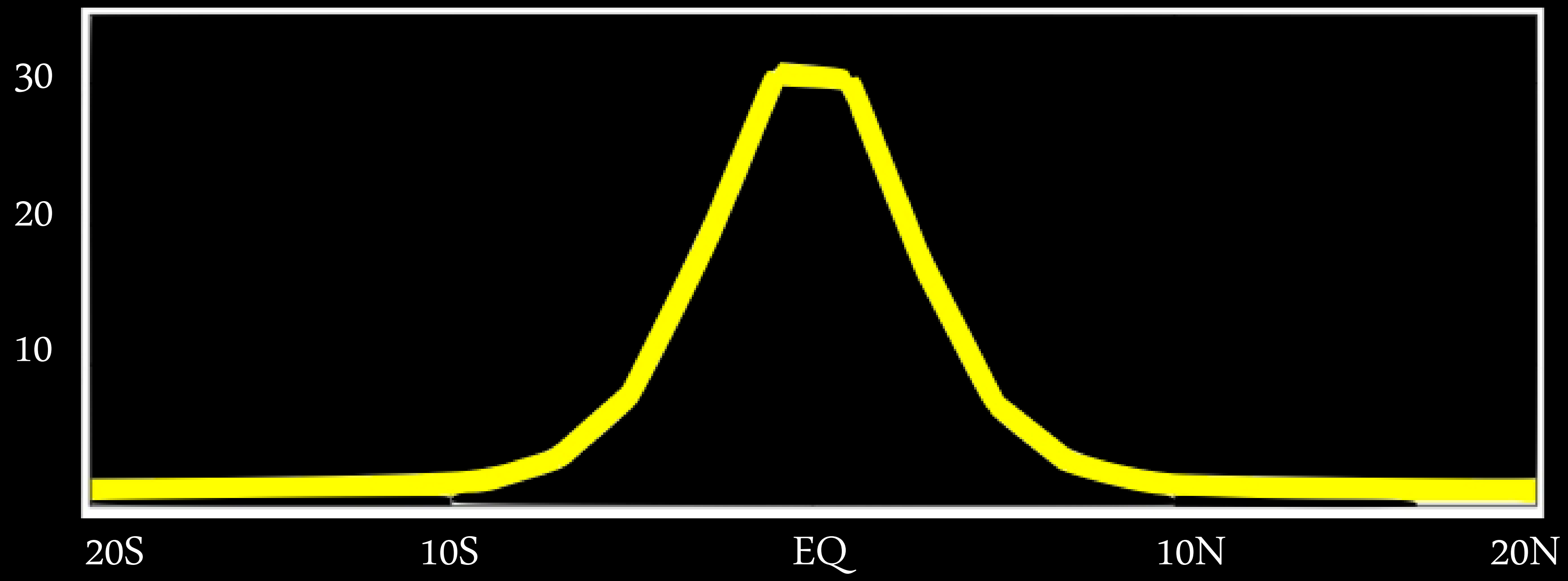
Aqua-planet Experiments

no land!!

Precipitation in the Control Simulation (mm/day)



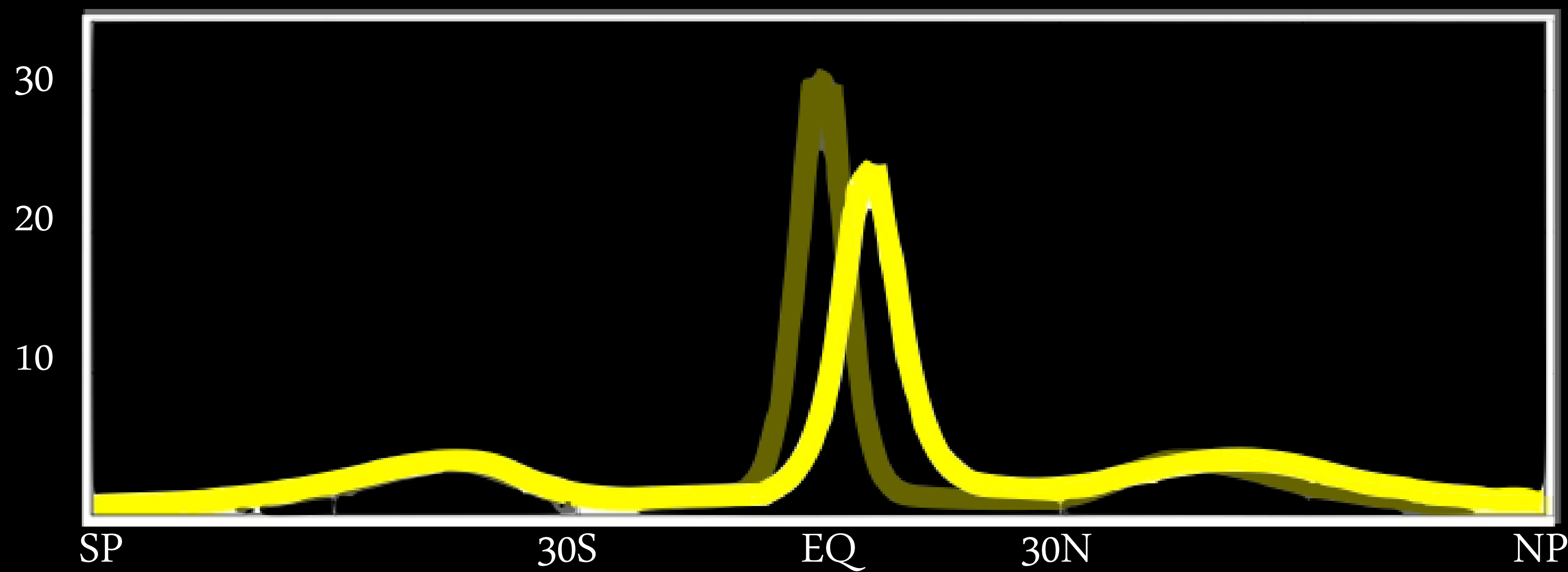
Zoom in to the Tropics



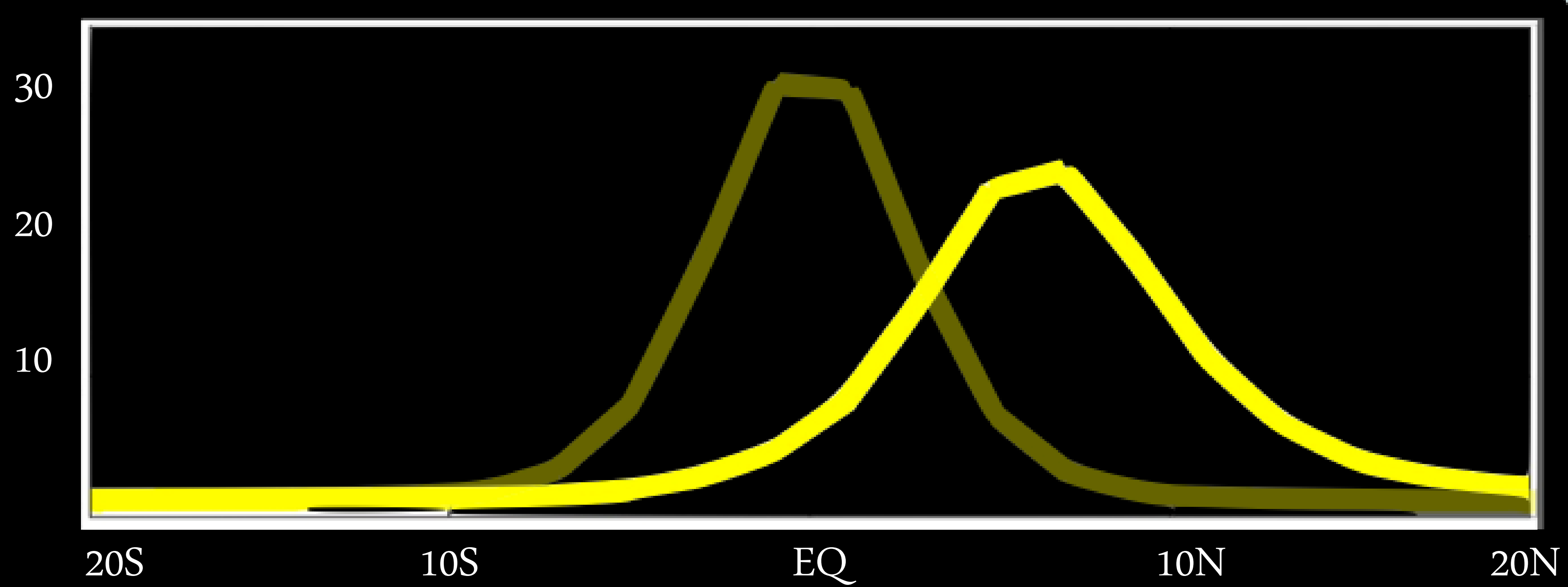
Precipitation in an aquaplanet atmospheric GCM (GFDL's AM2 model)

Aqua-planet Experiments

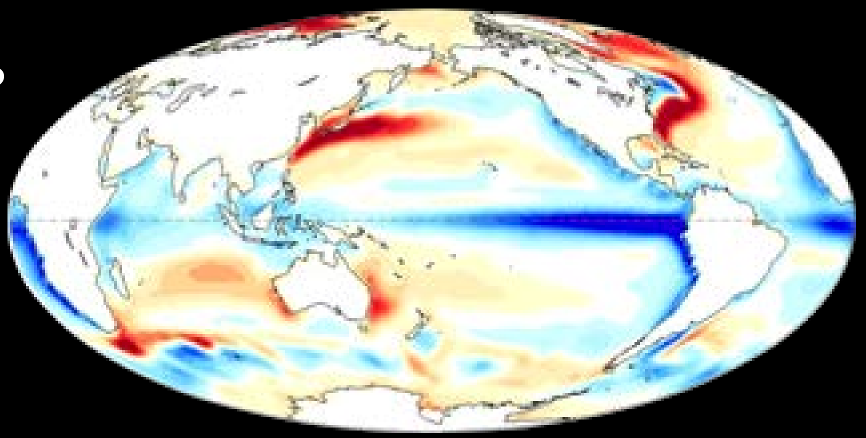
Precipitation in the Control Simulation (mm/day)

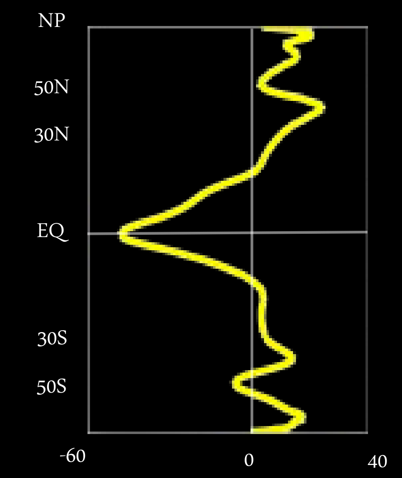


Zoom in to the Tropics



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

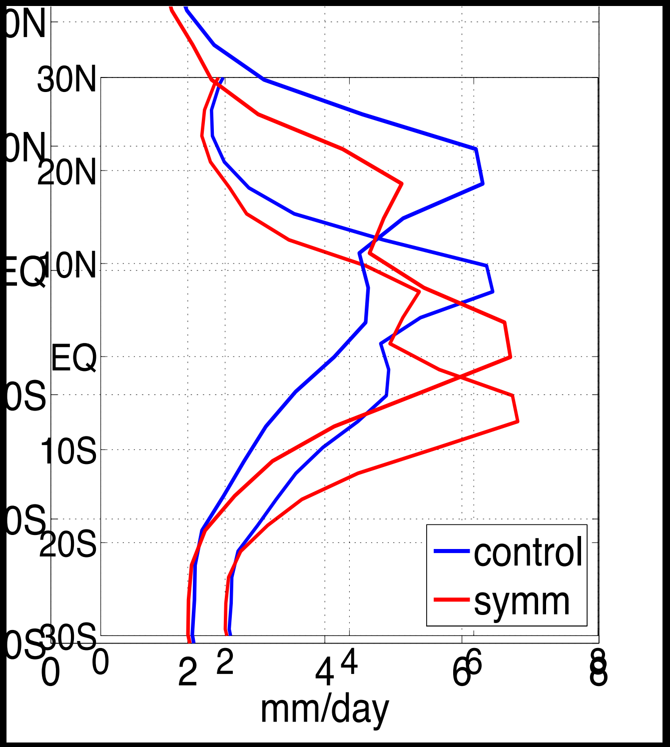




How about *removing* the ocean heat divergence asymmetry from a full GCM?

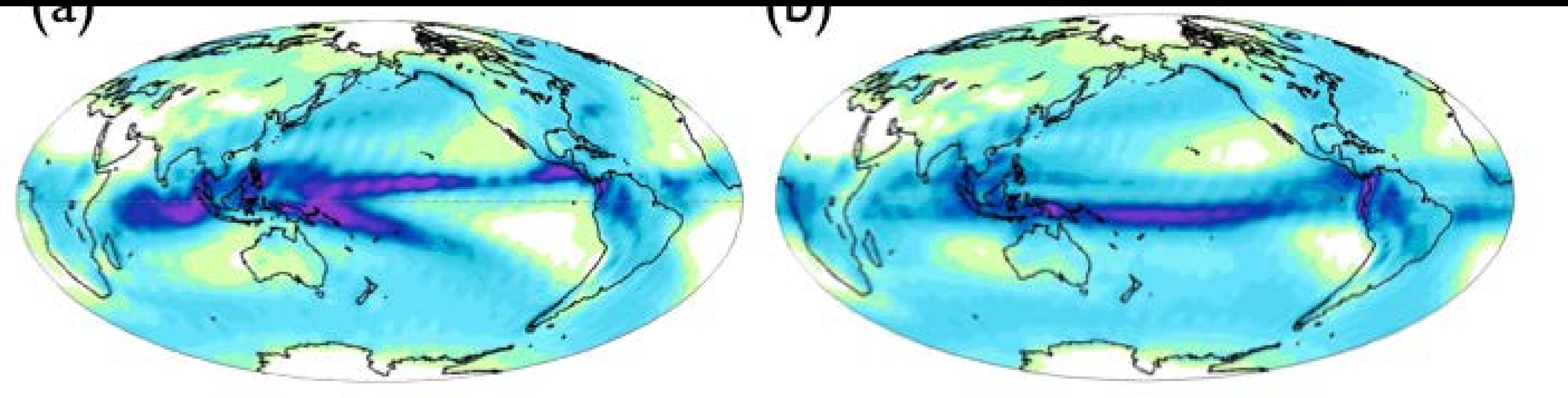
- Experiments with full and symmetrized surface heat flux

Frierson et al 2013, Nature Geoscience



Control

Symmetrized

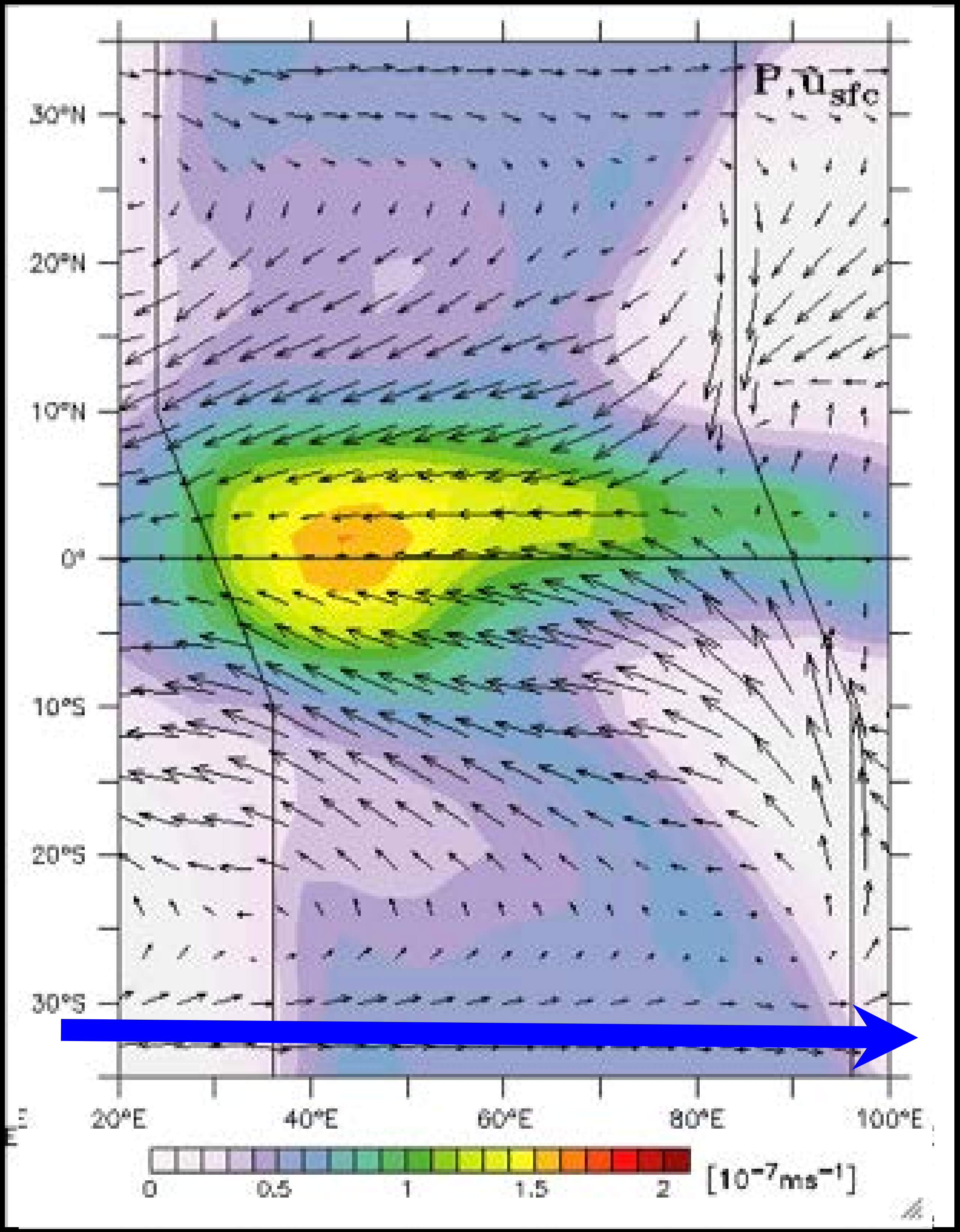


Experiments with a **Dynamical Ocean**

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)



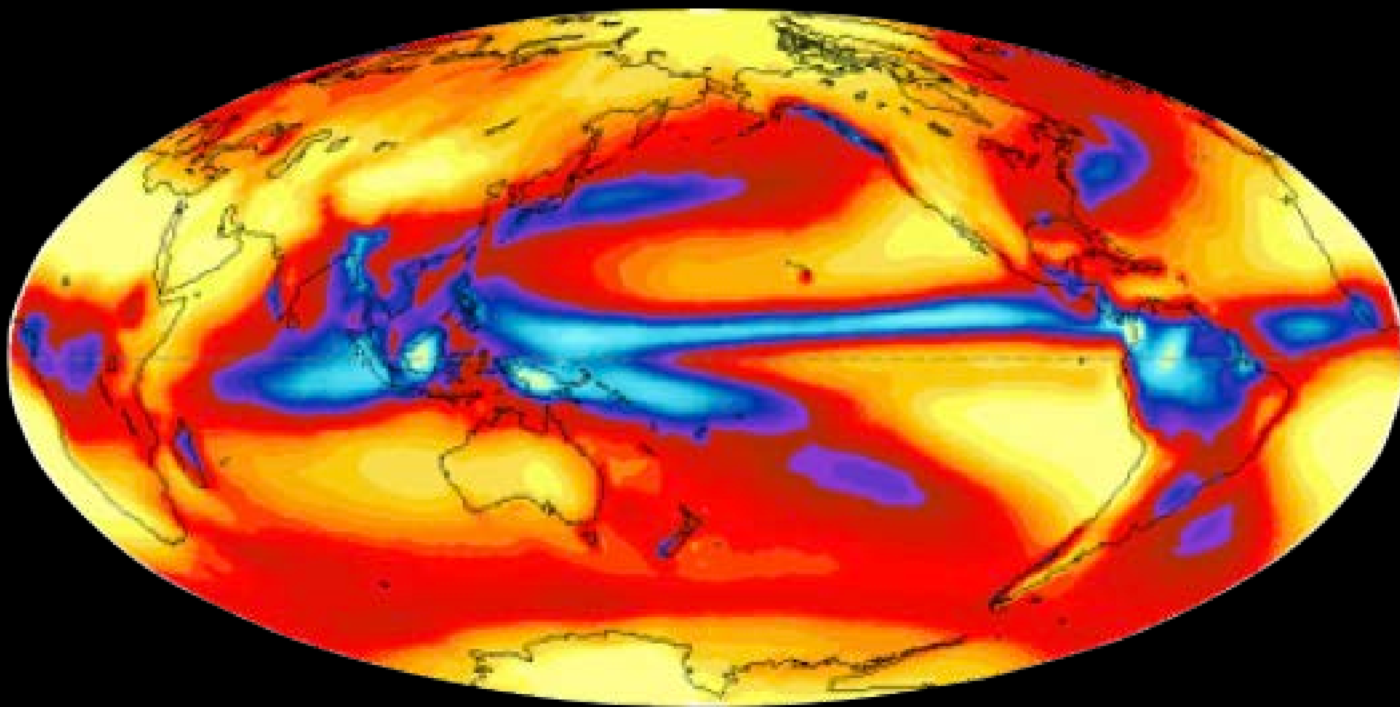
How about the **Double ITCZ** problem?

Can some of this be explained by our energetic framework?

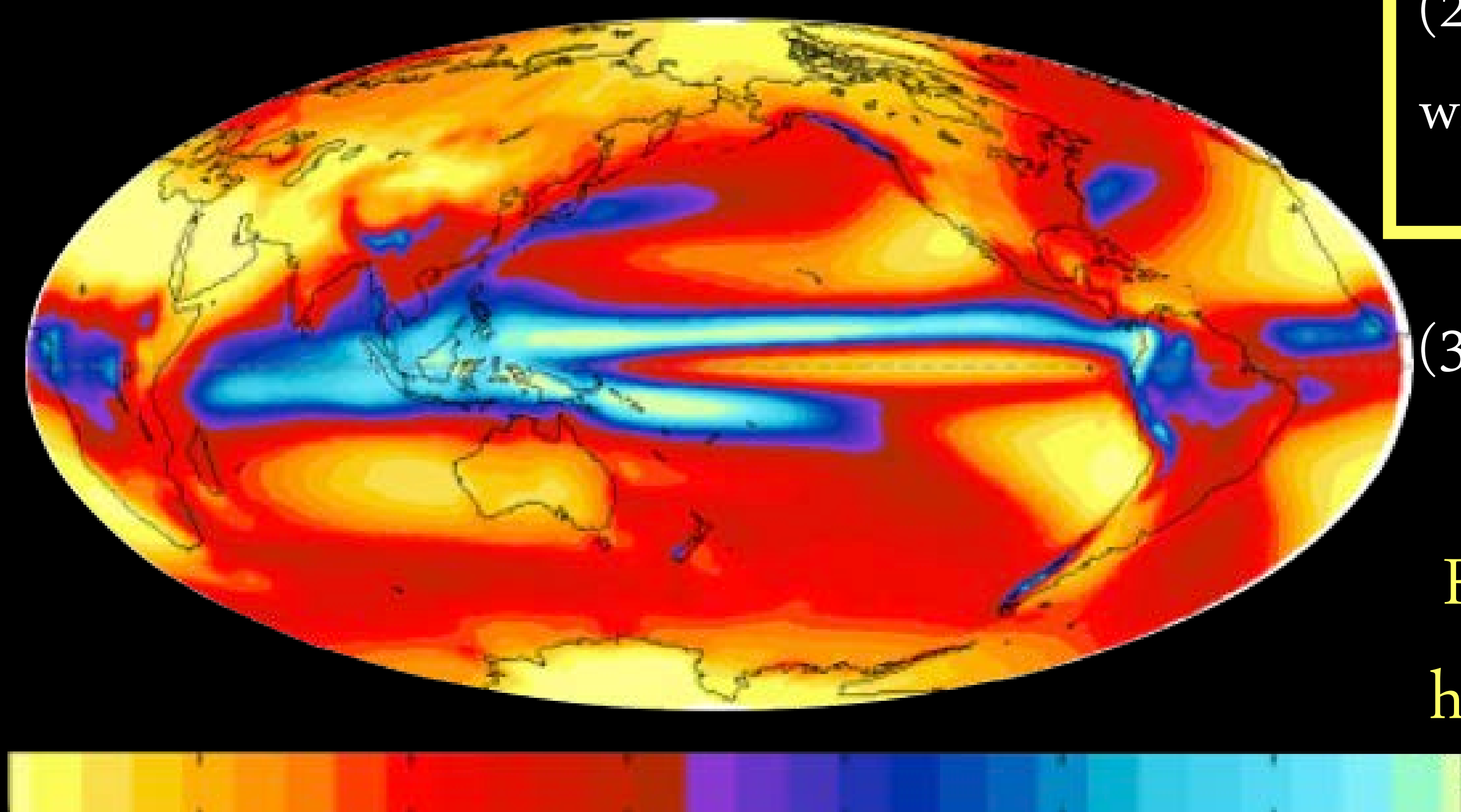
Next few slides from Hwang and Frierson, 2013 (PNAS)

Observed Annual Mean Precipitation

1985~2004



20 CMIP5 models



The Double ITCZ Problem has long plagued climate models (Mechoso et al 1995)

(1) Precip minimizes too much at the EQ

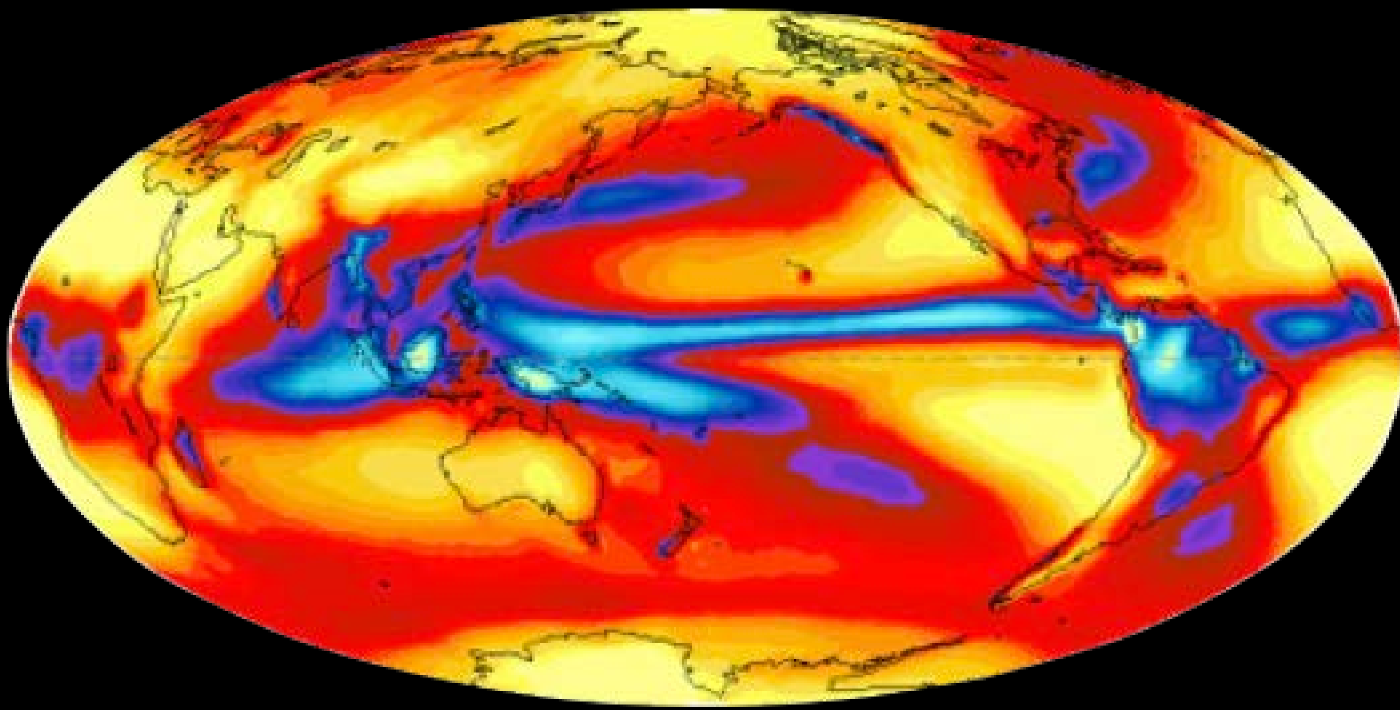
(2) Too much tropical precip in the SH compared with the NH

(3) SPCZ too horizontal (not tilted)

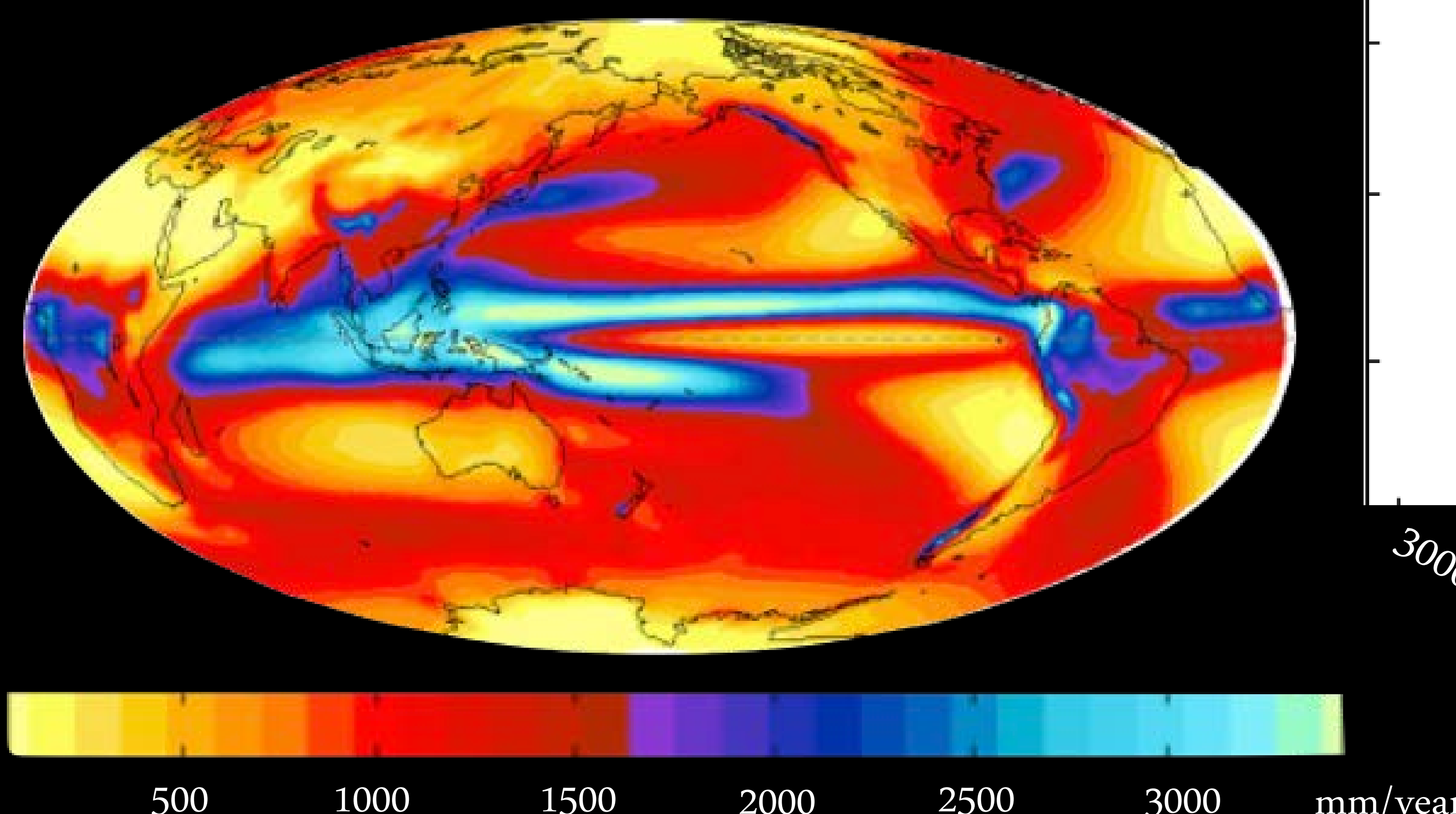
Focus: Models don't simulate the proper hemispheric asymmetry in tropical precip

Observed Annual Mean Precipitation

1985~2004

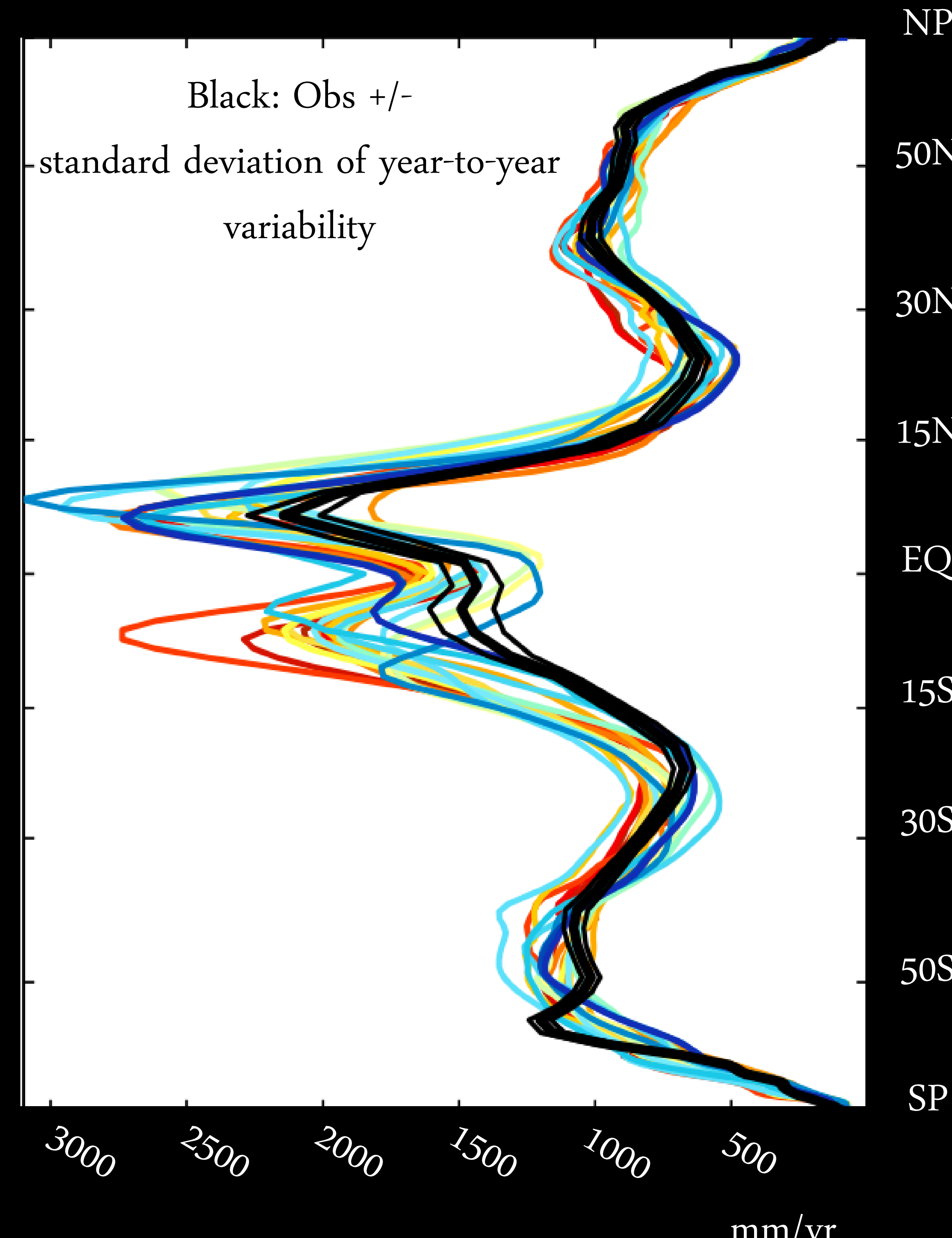


20 CMIP5 Models



Zonal Mean

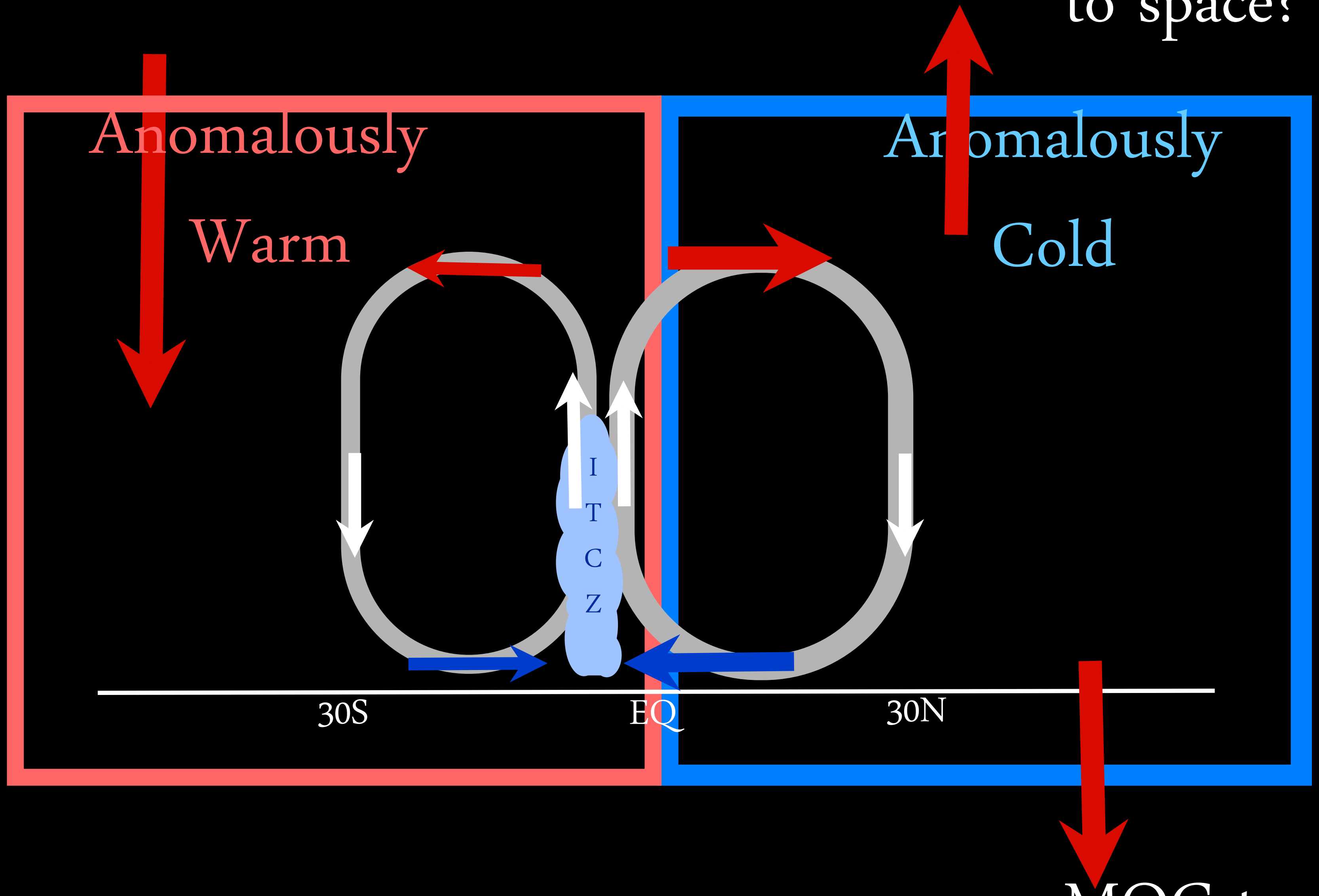
(each line is one GCM)



Why is the SH atmosphere heated more than the NH in models?

Too much radiation into the SH?

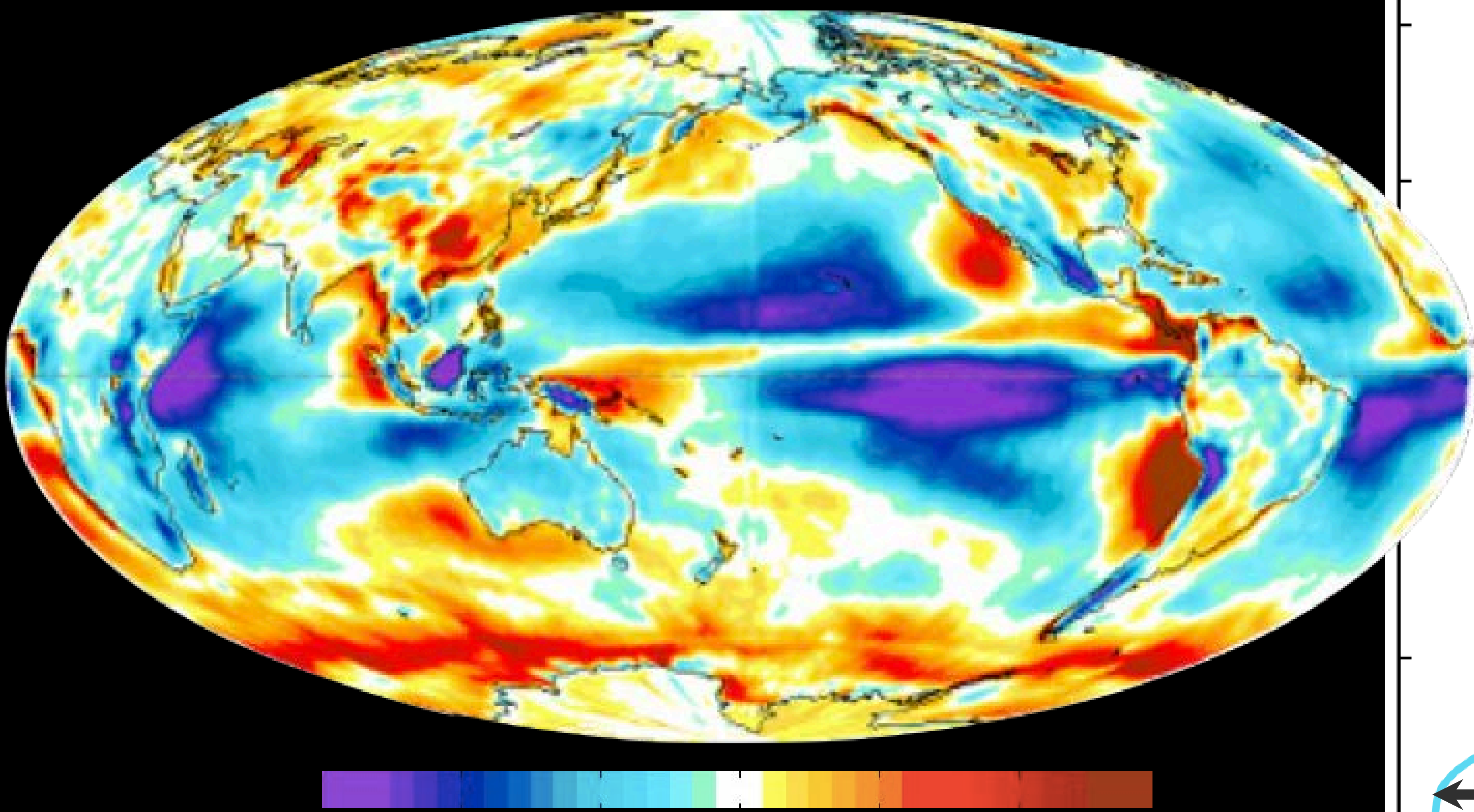
Radiate/reflect too much to space?



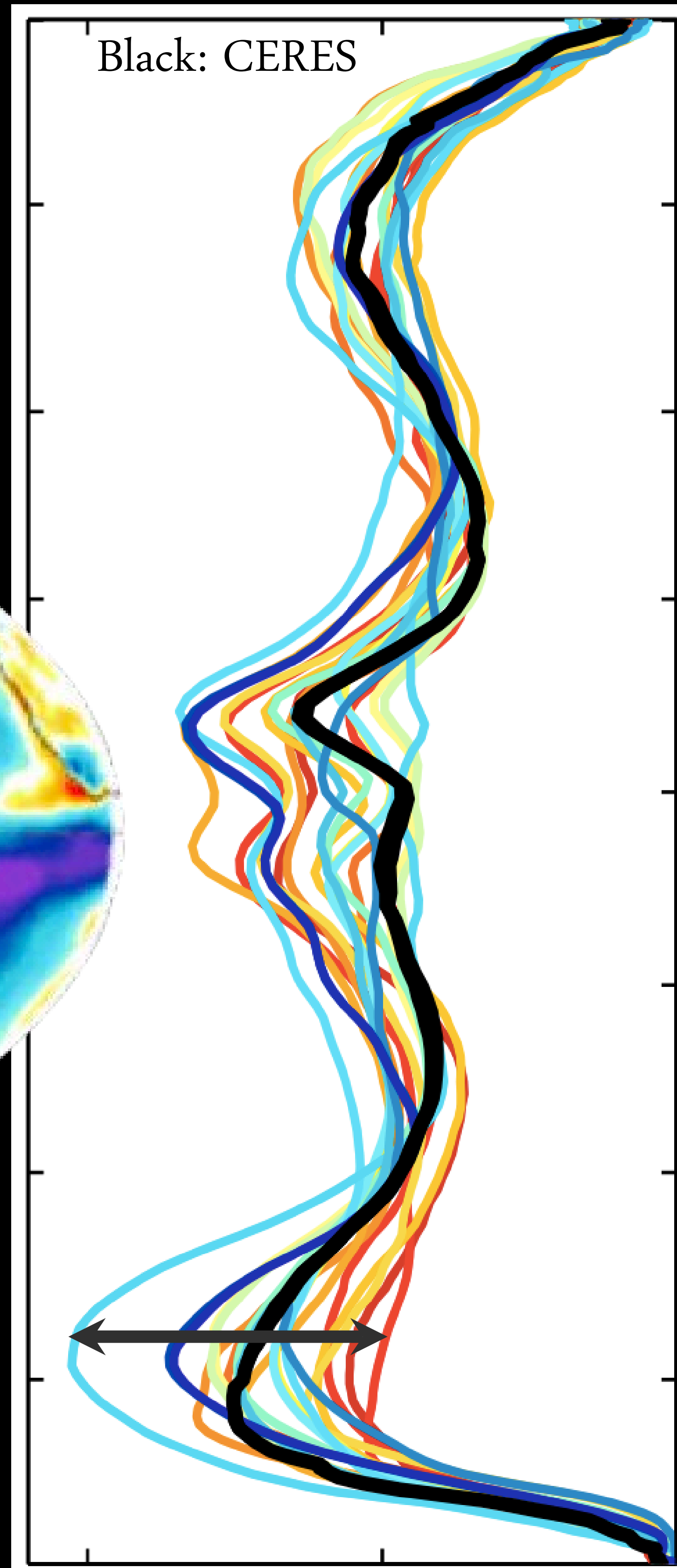
MOC too weak?

Biases in SW Cloud Radiative Effect

Ensemble Mean Biases in SW CRE
(compared with CERES)

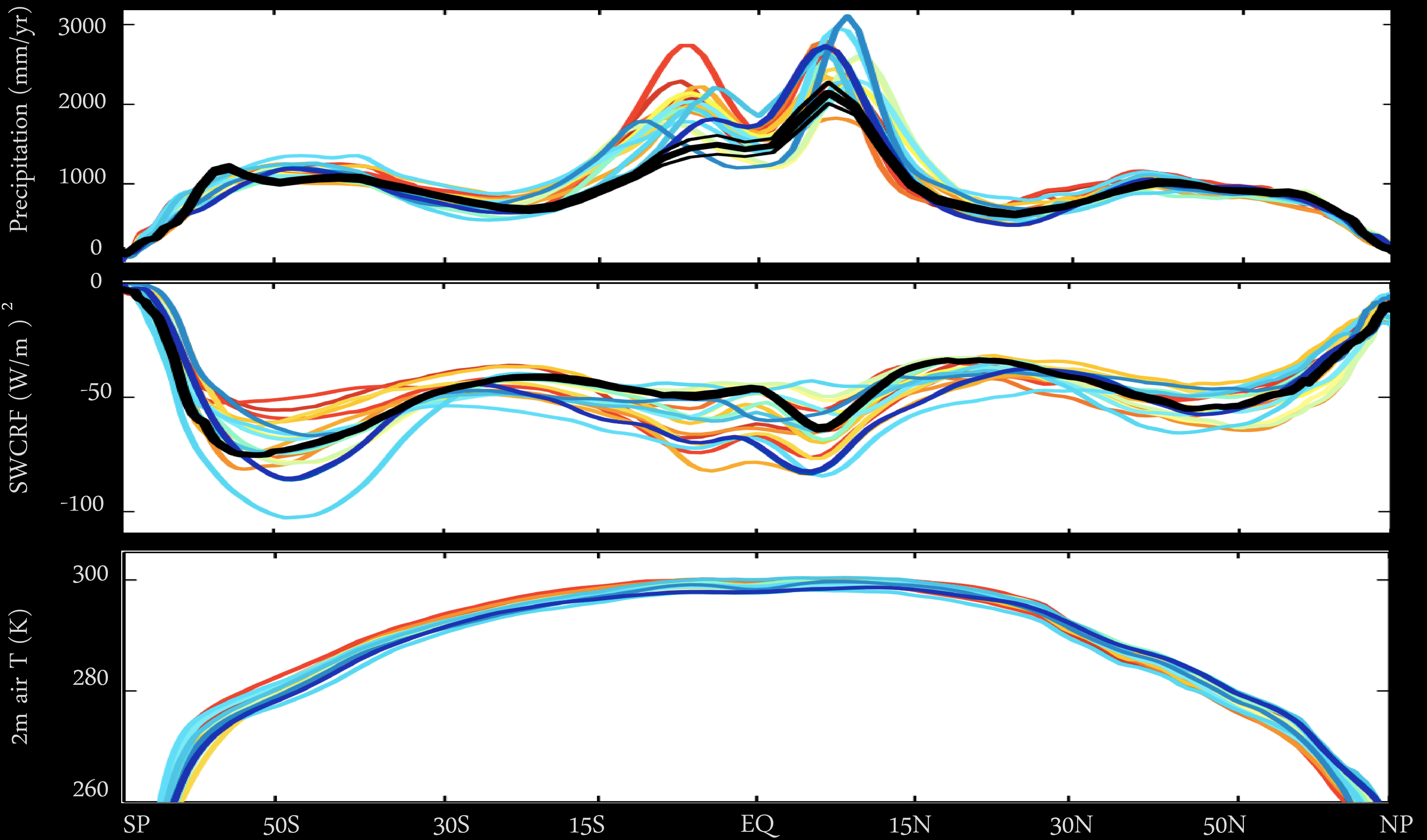


Annual Mean Zonal Mean



See also Trenberth and Fasullo 2010 for CMIP3

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



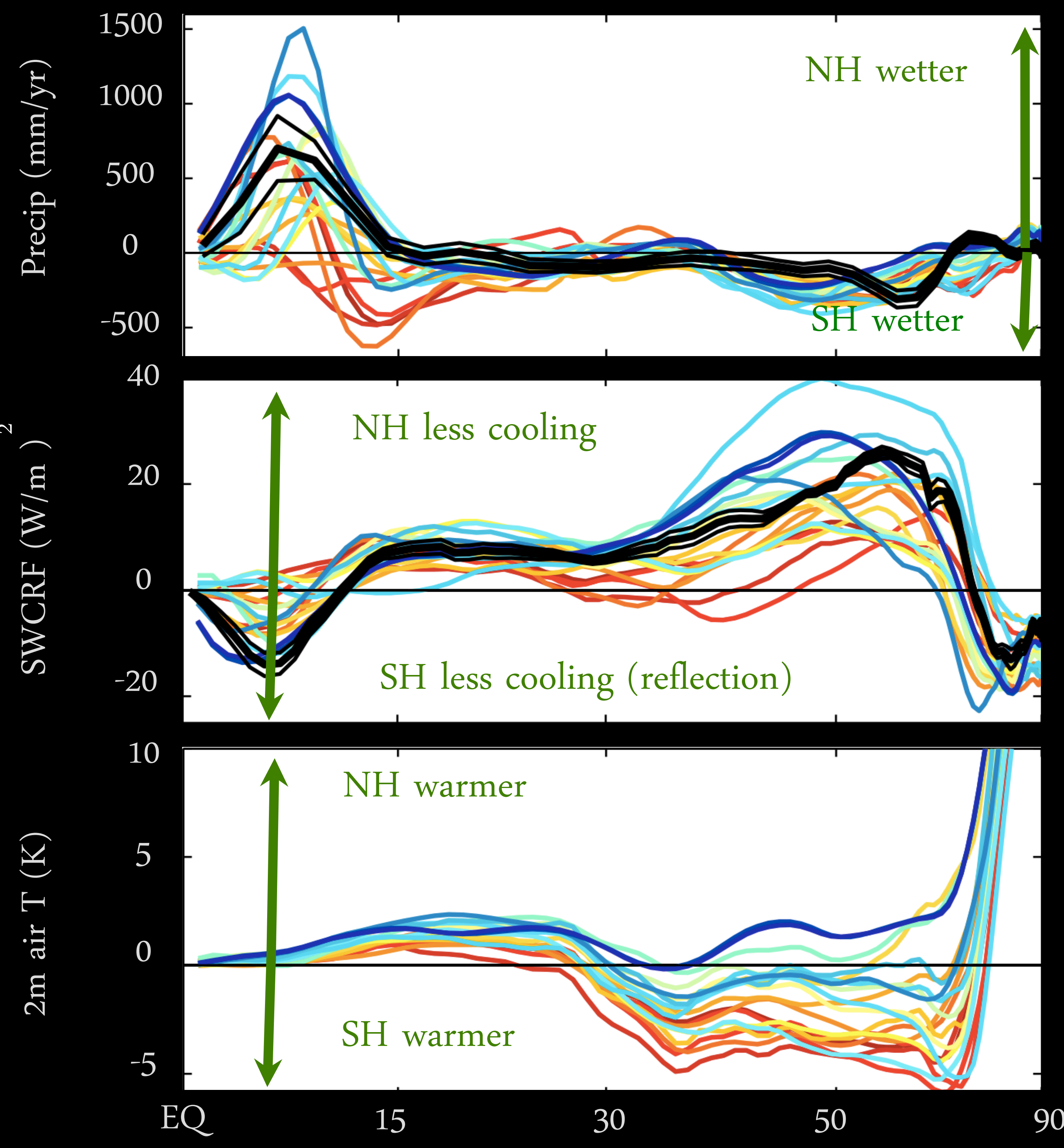
NH minus SH

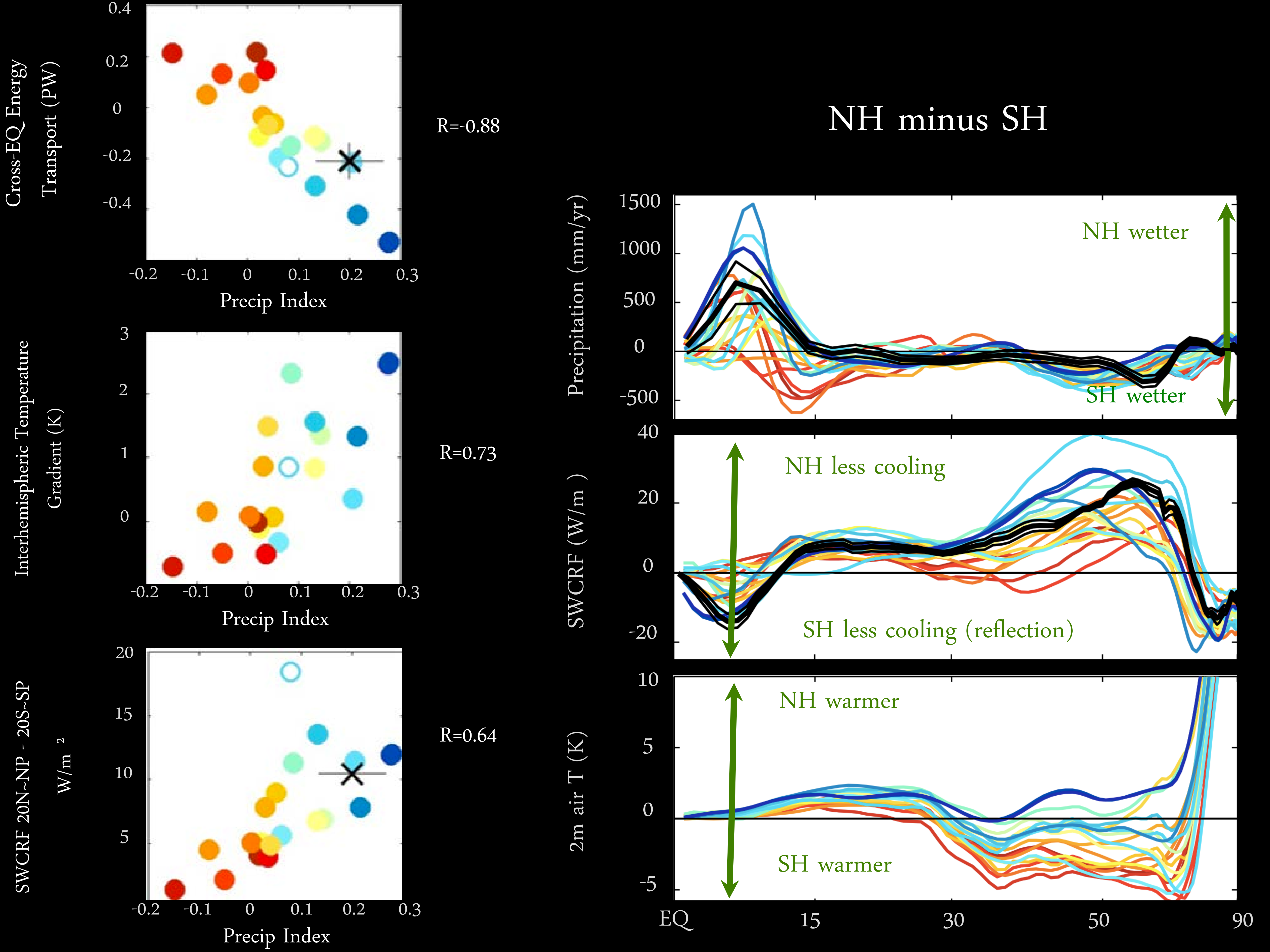
Red Models:

More precipitation in the SH tropics

Less cooling from clouds in SH mid-to-high latitudes

Too warm in SH mid-to-high latitudes





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
Precip Index
R=0.73
SWCRF 20N~NP - 20S~SP
W/m 2
20
15
10
5
Precip Index
R=0.64
NH minus SH
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

How Much Bias Does this Effect Cause?

Multi-model mean bias

Correlation coeff b/w asymm index and precip bias

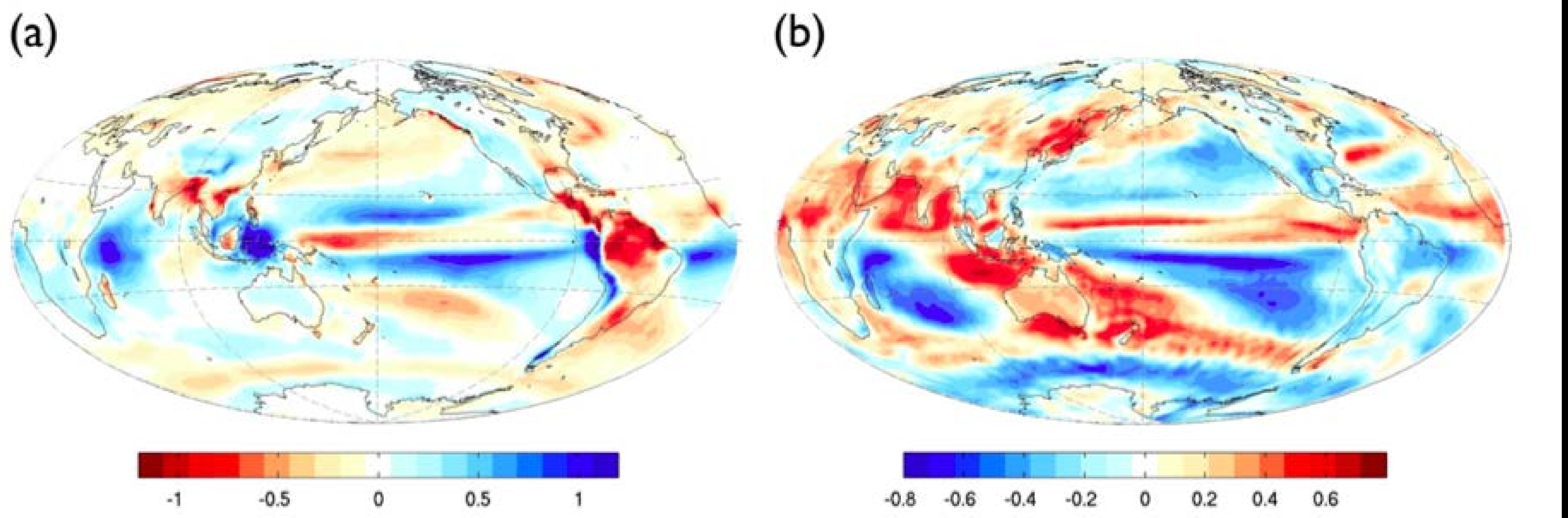
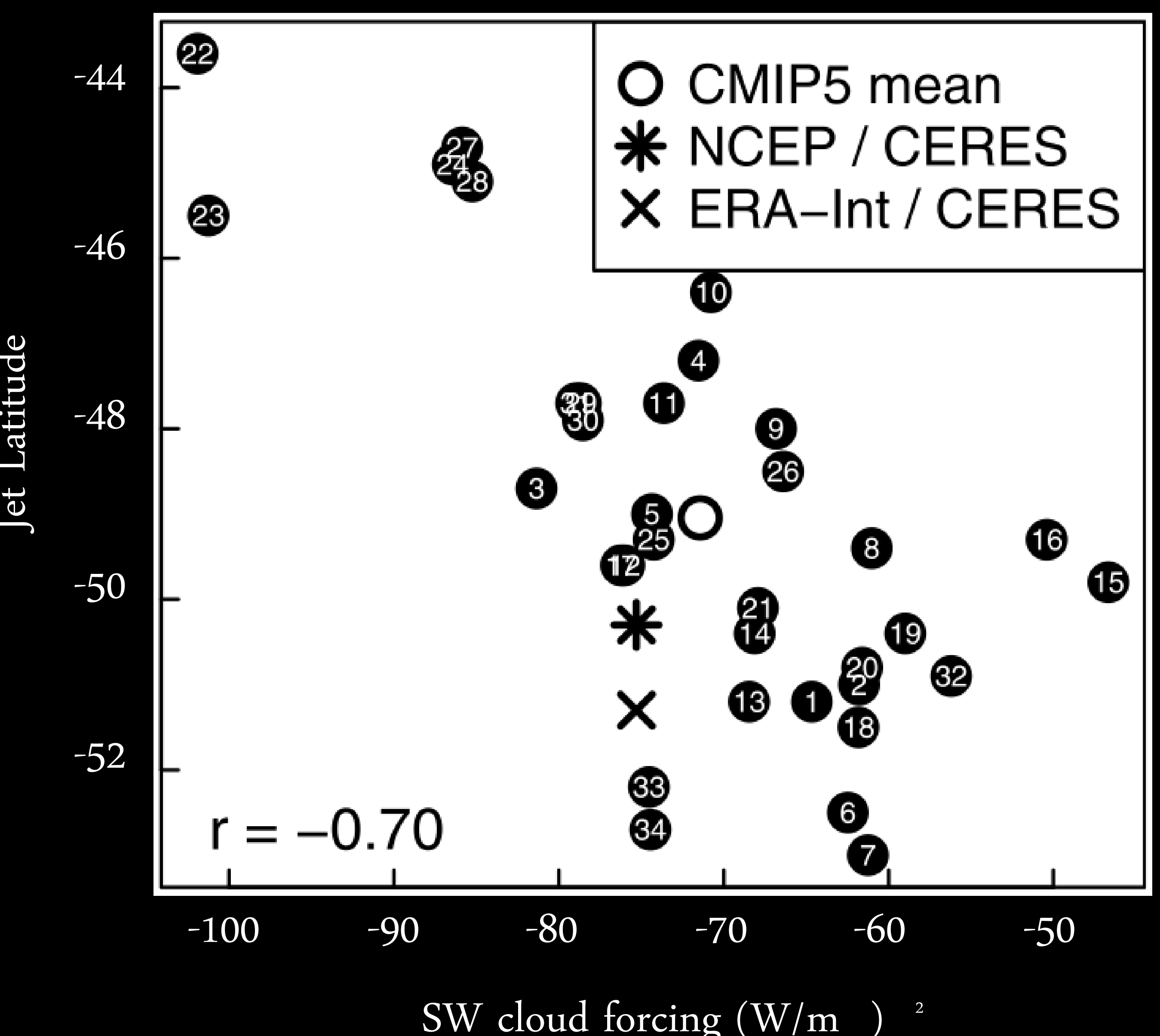


Fig. S1. (*A*) Biases in CMIP5 multimodel mean precipitation relative to GPCP data, normalized by global mean precipitation from each model and GPCP data, respectively. (*B*) Correlation coefficient between the precipitation asymmetry index and the precipitation biases in each model.

Equatorial minimum, ITCZs too far off-equator will not be fixed

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

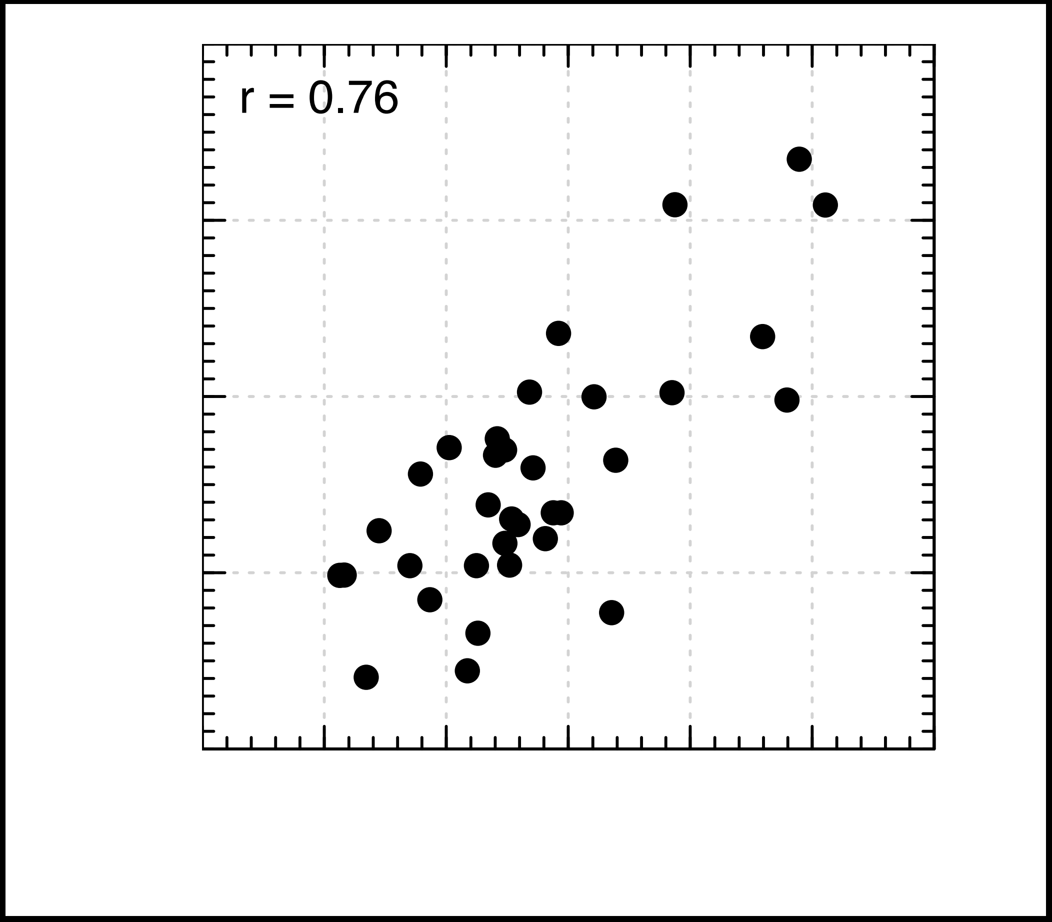
Cloud feedbacks help determine poleward shift w/ global warming

Bigger temperature gradient

(from cloud feedbacks)

→ more jet shift

jet shift vs δ ASR gradient

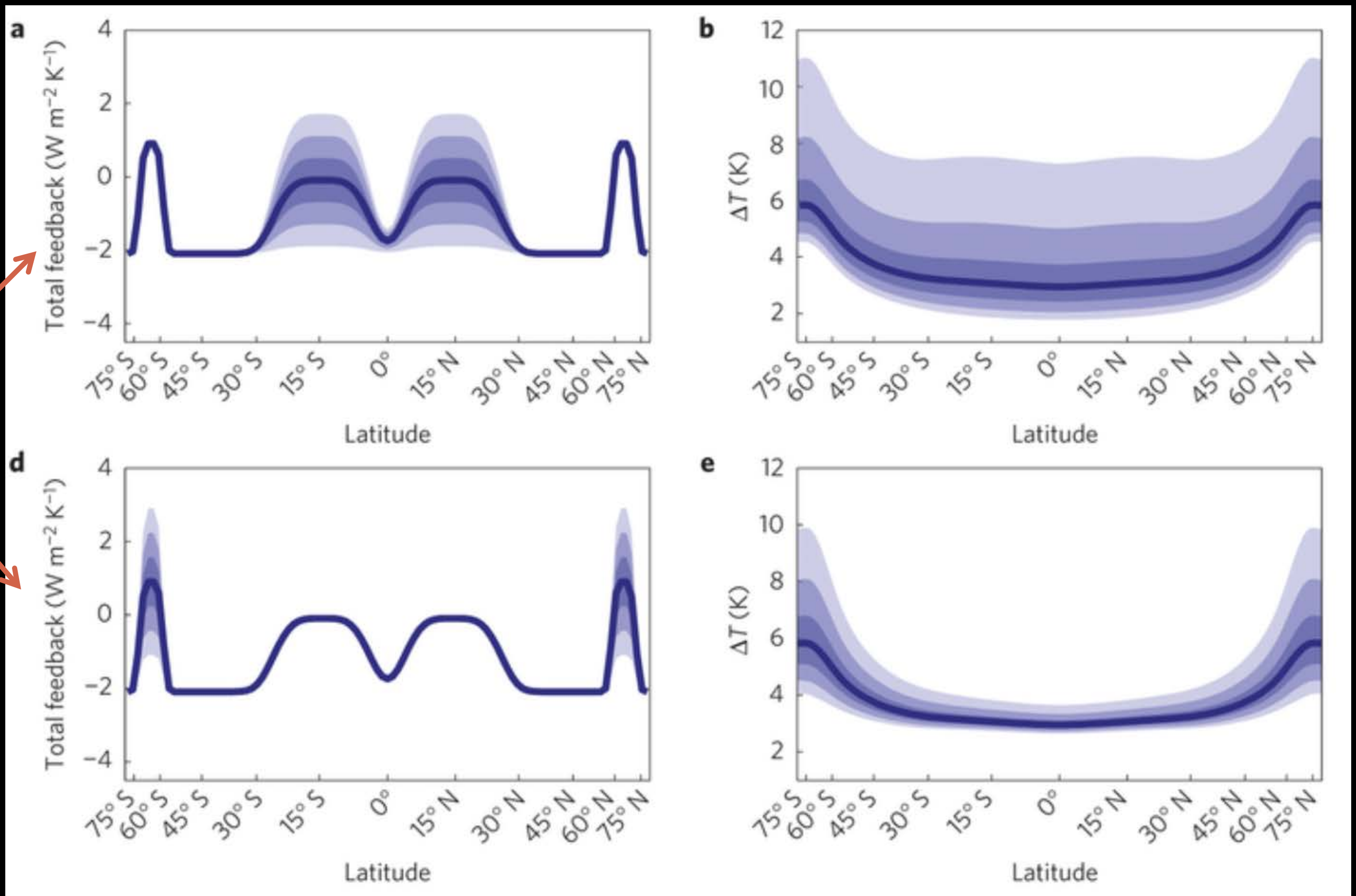


Ceppi et al 2014, see also Ceppi et al (submitted), Voigt and Shaw (2015)

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

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

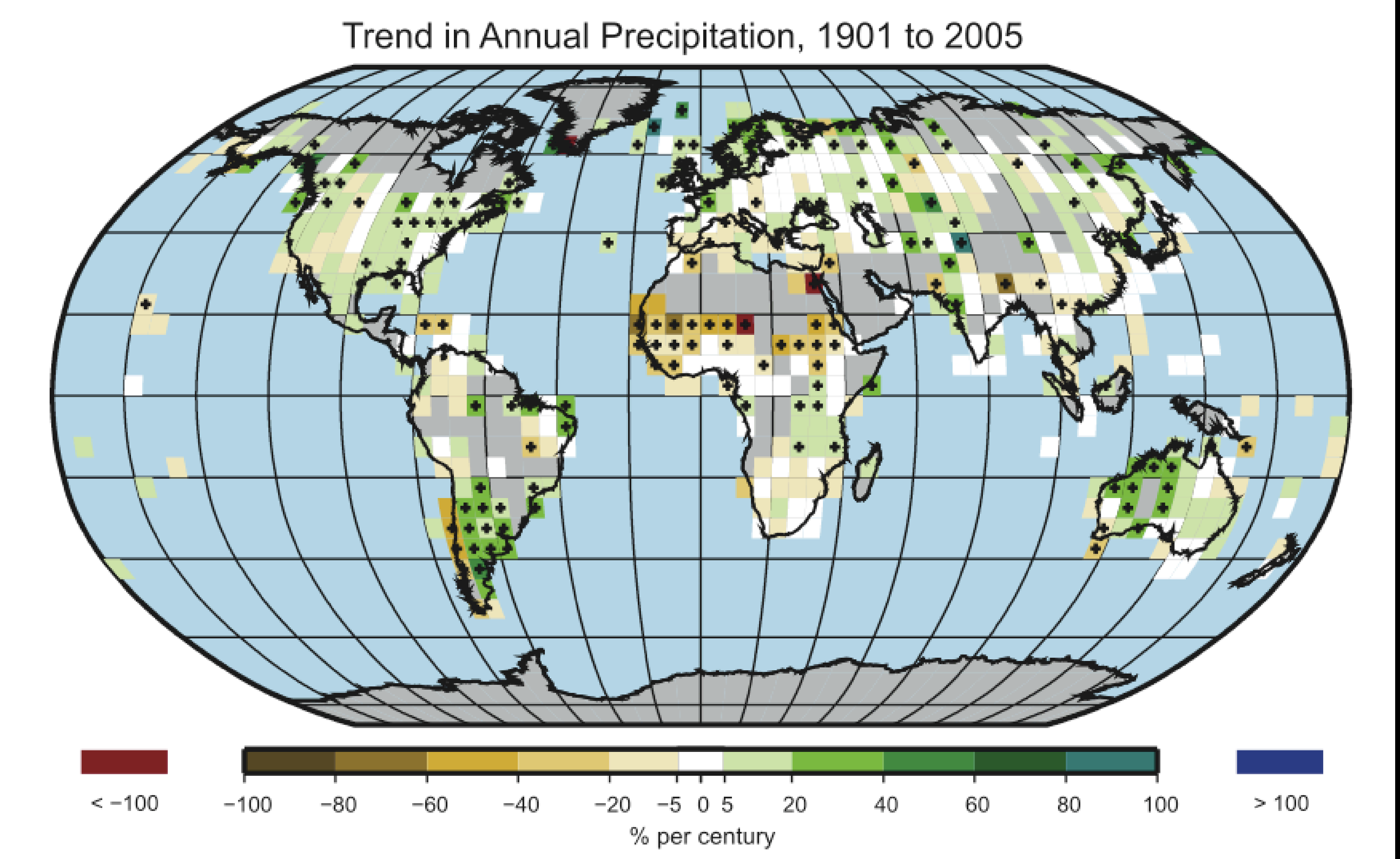
Feedback



Temperature change

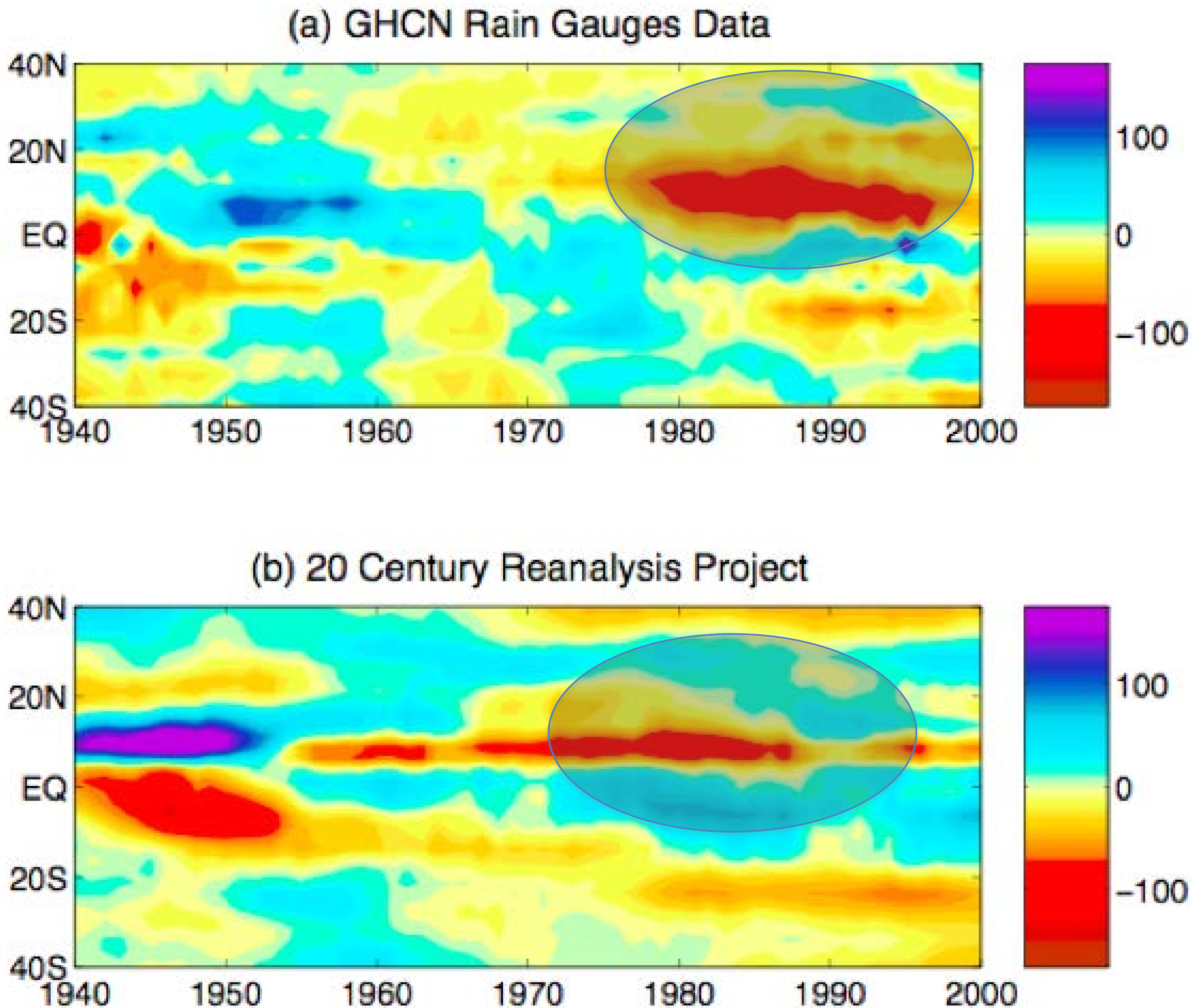
20th Century Precipitation Changes

Drying in NH tropics, especially in Sahel region of Africa



IPCC AR4

Observed Zonally Averaged Land Precip Changes

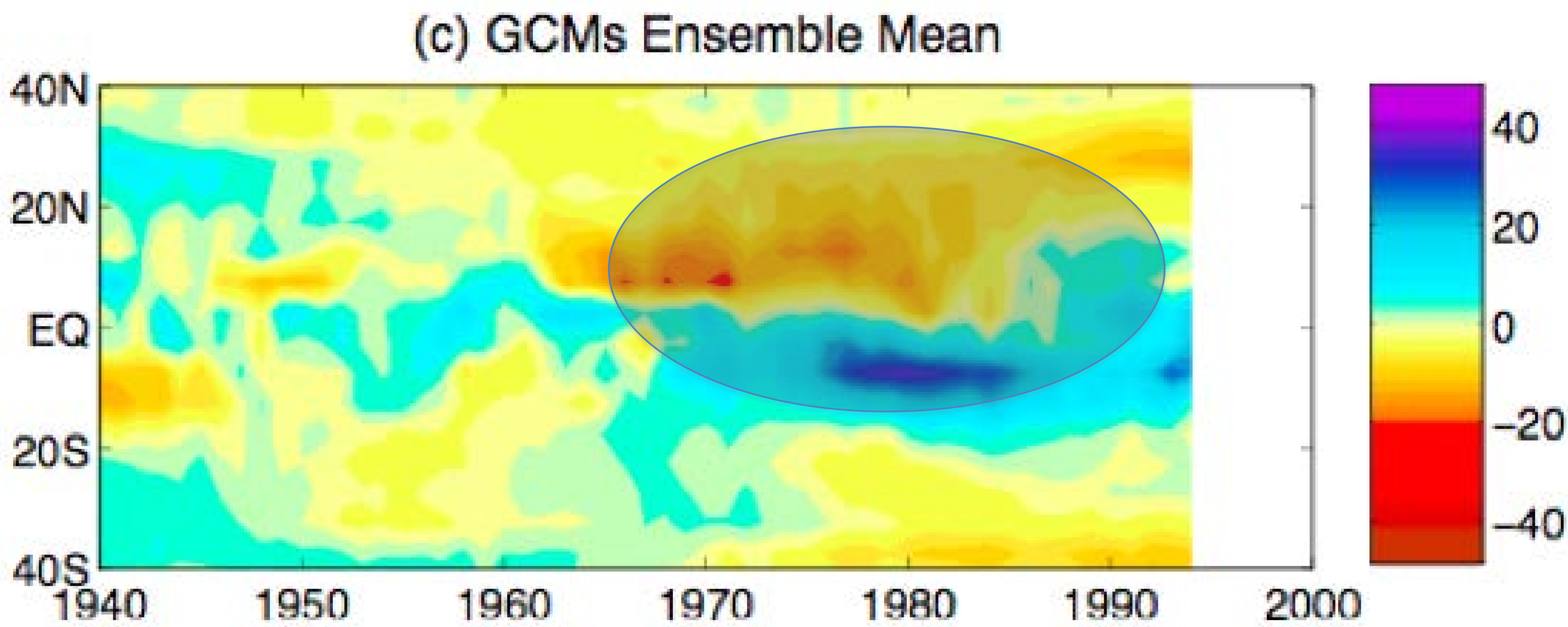


Precip change relative to 20th century mean

Southward shift of precipitation peaking around 1980…

Hwang, Frierson & Kang, 2013

Modeled Zonally Averaged Land Precip Changes

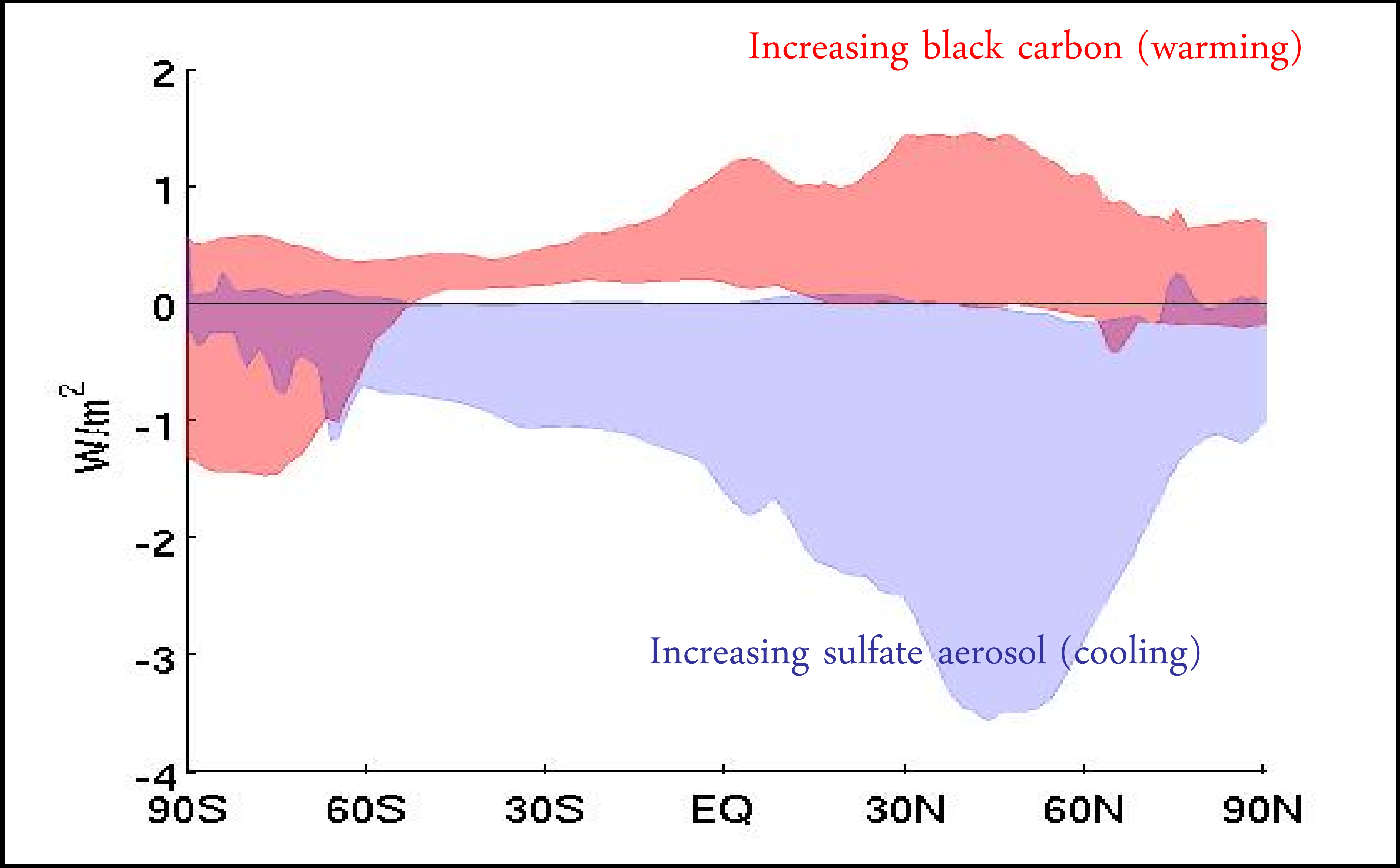


Southward shift in models too! Weaker though

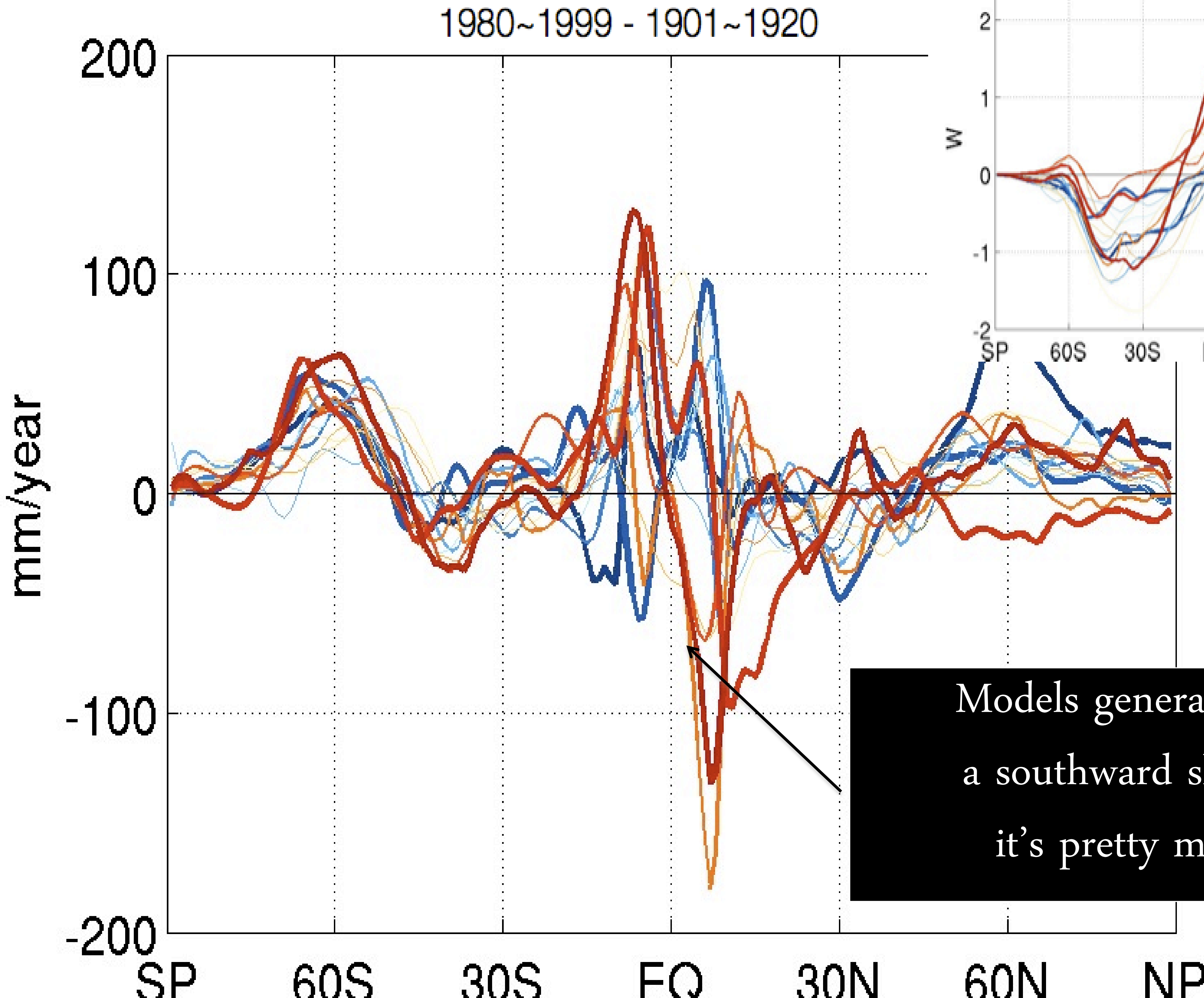
Aerosol Forcings in 20th Century Simulations

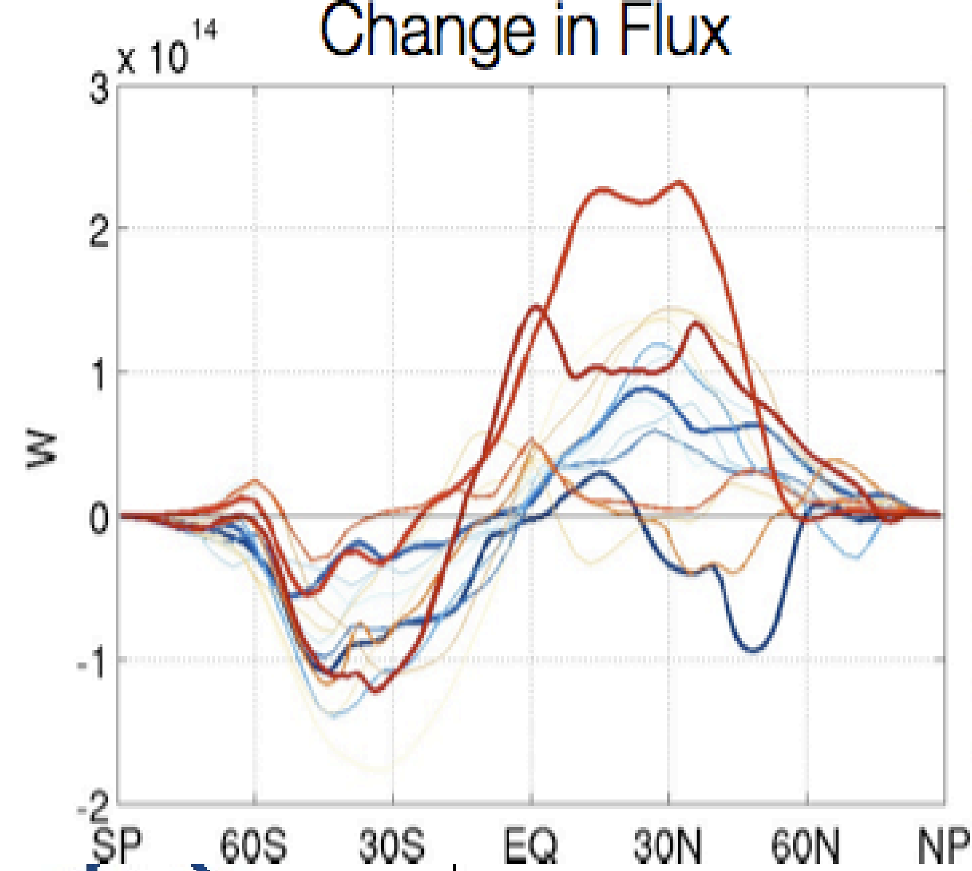
Structure of aerosol forcing in 20C3M:

(envelope shows the range in forcings used, i.e., model with most forcing & model with least forcing at each latitude)



20th Century Precip Change

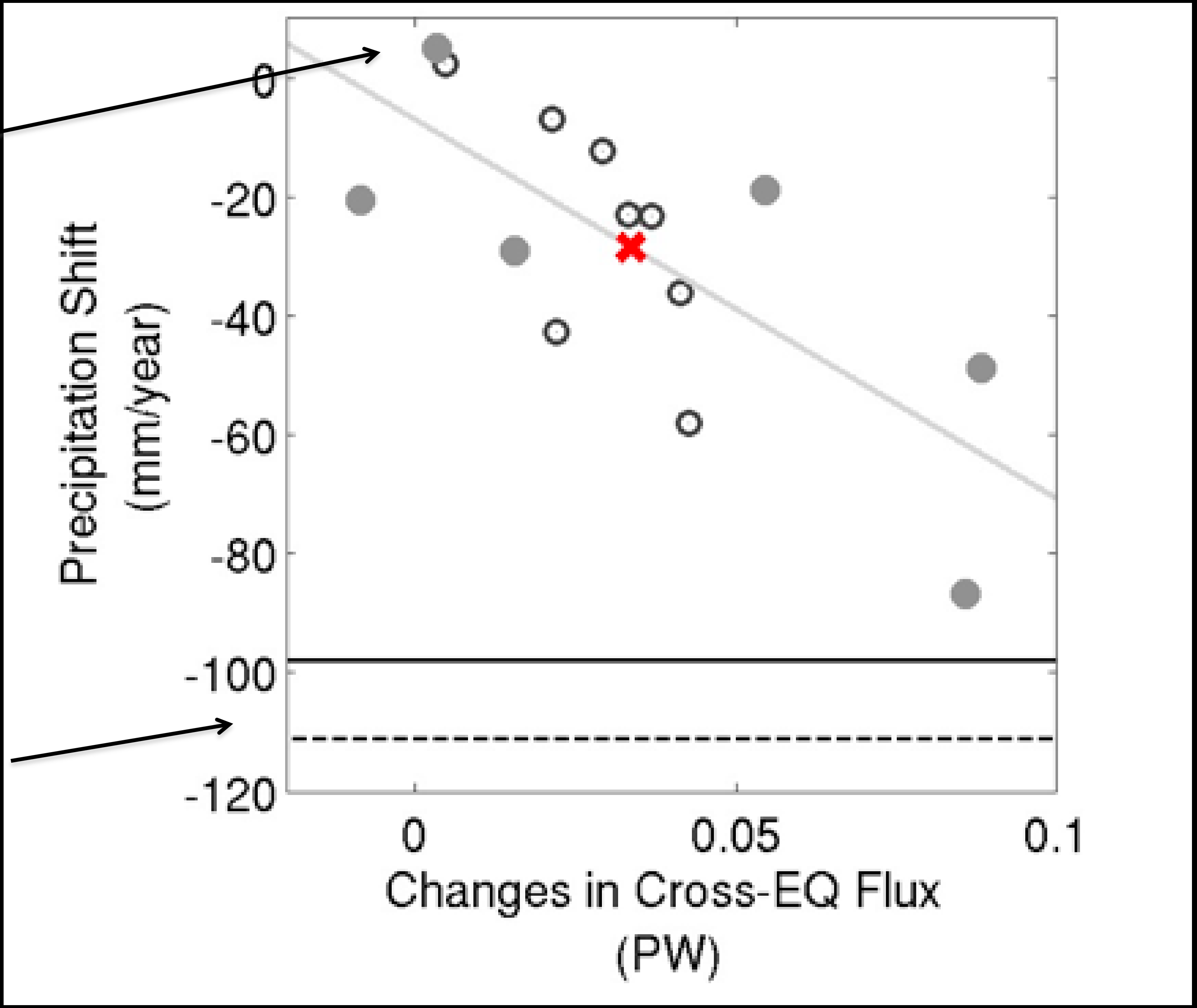




Models generally show a southward shift, but it's pretty messy…

Correlation of precip shift w/ energy flux

Only two models show northward shift…



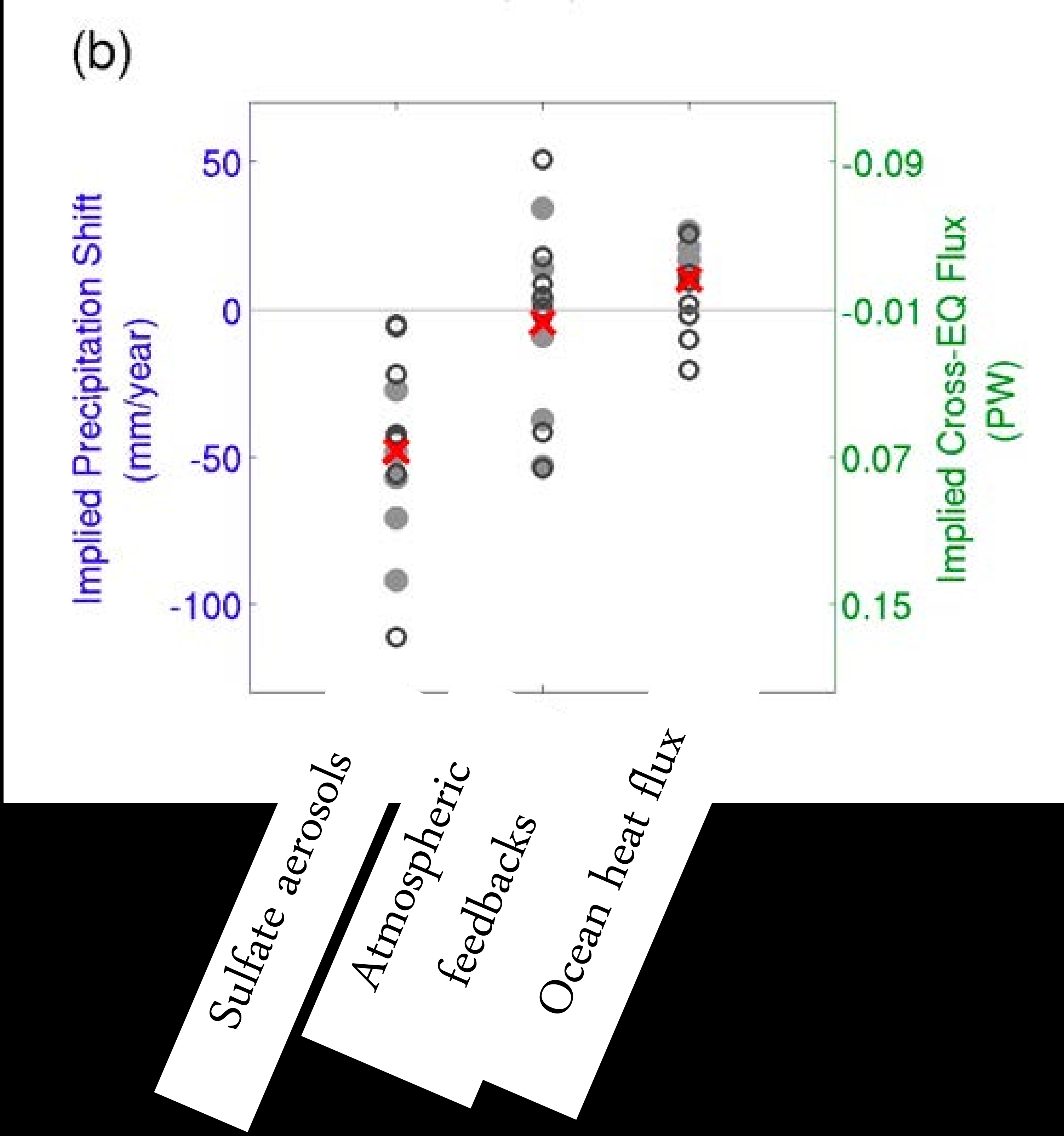
All models underestimate the observed shift…

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 of 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?? Air pollution??
- ITCZ may shift northward, but models don't agree

Recap

- The **global ocean circulation** warms the NH and puts the ITCZ north of the equator.
- Poor **cloud** simulation over **Southern Ocean** in models warms the SH & 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.

- Importance of idealized modeling/hierarchies
  - Please help support this!