Climate Dynamics (PCC 587): Hydrologic Cycle and Global Warming

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DAY 4: 10-7-13

Changes in Precip in 21st Century Simulations

- Multi-model mean precip change
  - With stippling based on a weak significance criteria

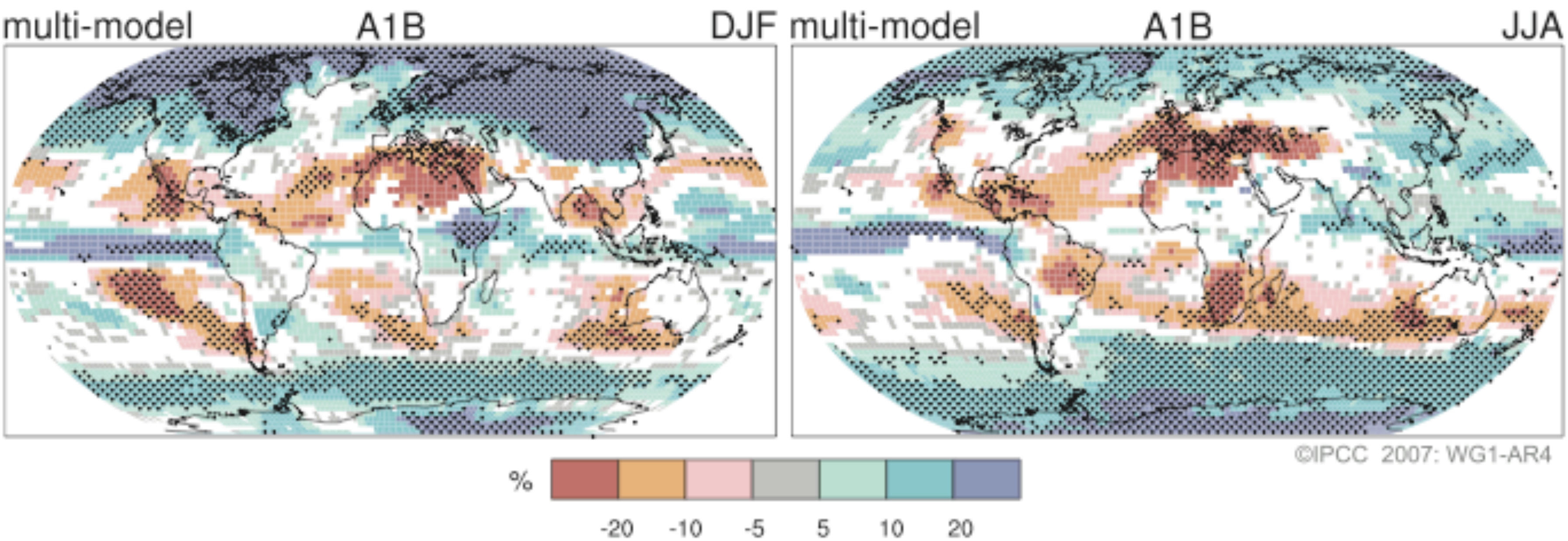


Figure SPM.7. *Relative changes in precipitation (in percent) for the period 2090–2099, relative to 1980–1999. Values are multi-model averages based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. {Figure 10.9}*

How Can Precipitation Change?

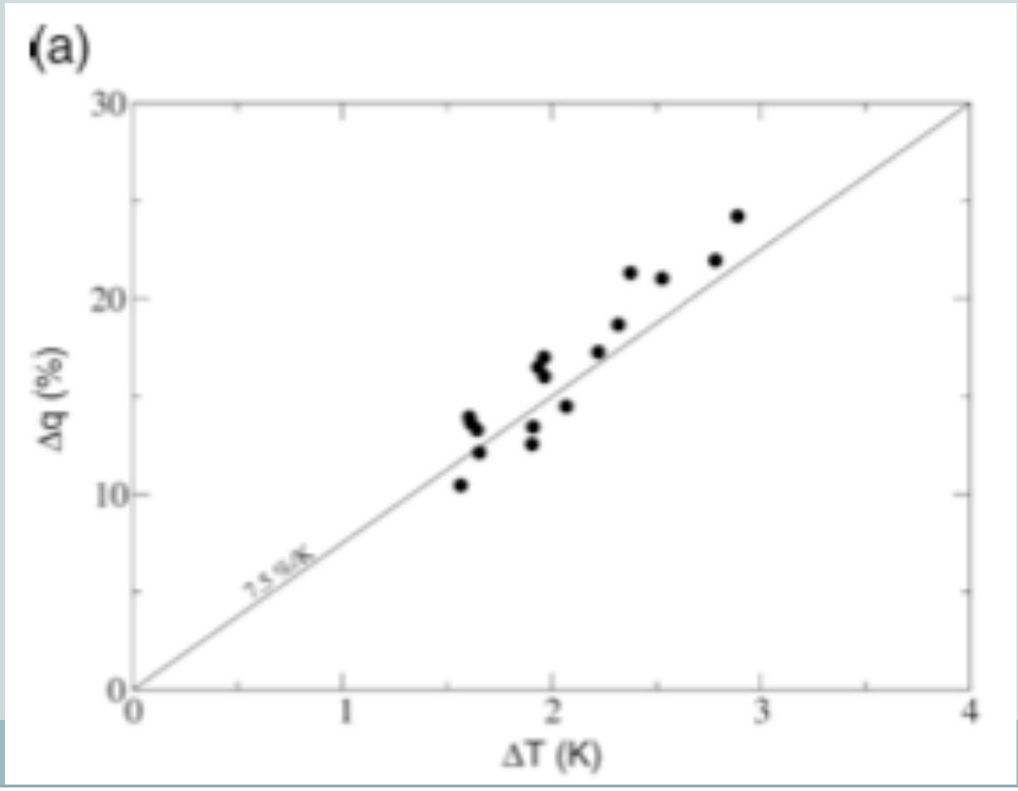
- I’ll argue that precipitation changes can be usefully separated into two components
  - Changes in **intensity** of features
    - “Wet gets wetter” with warmth
    - Also “dry gets drier”
  - Changes in **position** of features
    - **Poleward shifts** of **midlatitude** storms with warmth
    - **Tropical** precipitation shifts towards the **warmer hemisphere**

Increases in Water Vapor

- Most important fact: **water vapor content increases rapidly in a warmer climate**
  - Increase will be around 7.5%/degree warming
- For a given amount of upward motion, there will be more rainfall in a warmer climate

Changes in Water Vapor in AR4 Simulations

- Changes in water vapor content (% increase) versus temperature change (K) for change over 21st century (A1B scenario):



Water vapor increases by 10-25% with warming.

Spread among models is mostly due to spread in amount of warming.

Why Wet Get Wetter

- More moisture in the atmosphere
  → more moisture convergence
  → wet get wetter

- This explains tendency for **high latitudes** and **tropics** to moisten

Global Average Precipitation Changes

- As it turns out, global mean precip can't rise very fast (only 1-2%/K or so)

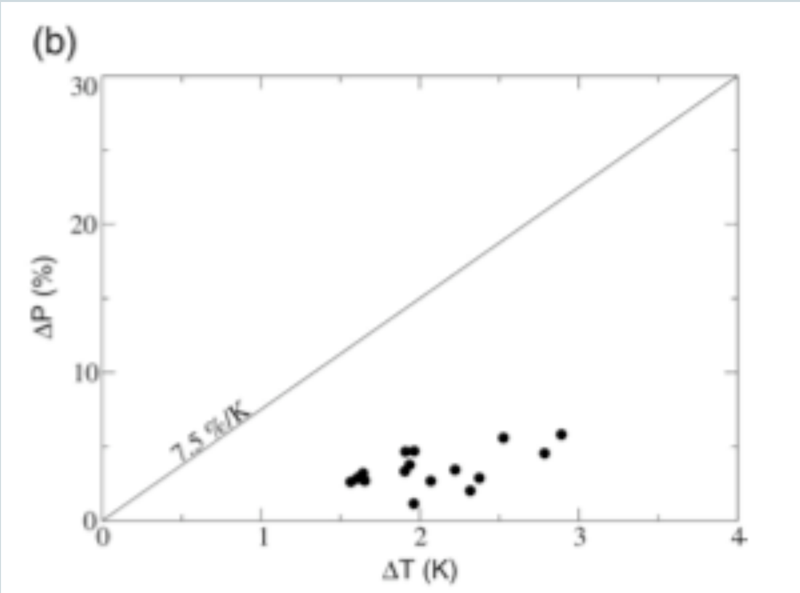
- Why?
- Evaporation **cools the surface** so requires energy
- Condensation **releases heat** into the atmosphere, so requires the atmosphere to be able to shed that heat

Precip vs Water Vapor

- Doesn't a higher water vapor concentration require more evaporation/precipitation?
  - Nope.
  - Only takes a few weeks for the atmosphere to humidify
    - Increased evaporation doesn't cause the water vapor to increase…
  - A longer residence time for vapor is an easy way to achieve increased water vapor with no increase in precip

Precipitation Changes with Warming

- Models show approximately 2% increase in global precipitation per degree warming
  - Significantly less than water vapor content increase

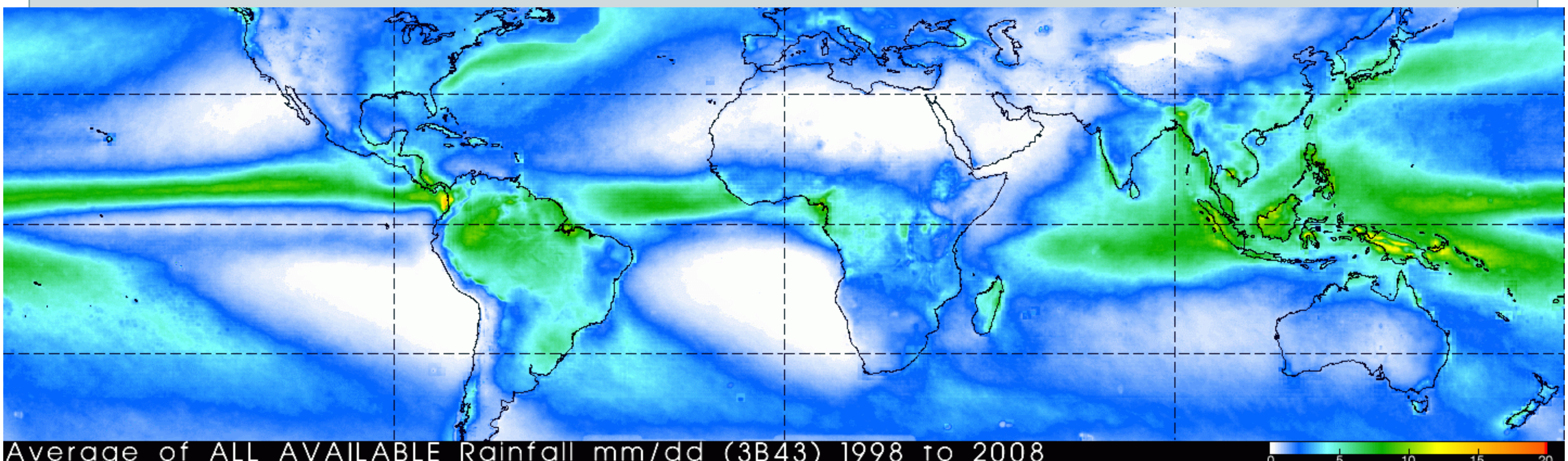


Why Dry Regions Persist/Expand

- Anyway, some regions will raining much more while the global mean precip only increases a little
- So some regions **have to dry** as well…
  - **Subtropics** are a place where this happens
  - Part of this is because **more moisture is fluxed away** from there

Annual Mean Precipitation

- For reference, the precip climatology from TRMM (1998-2008)



Wet Gets Wetter, Dry Gets Drier

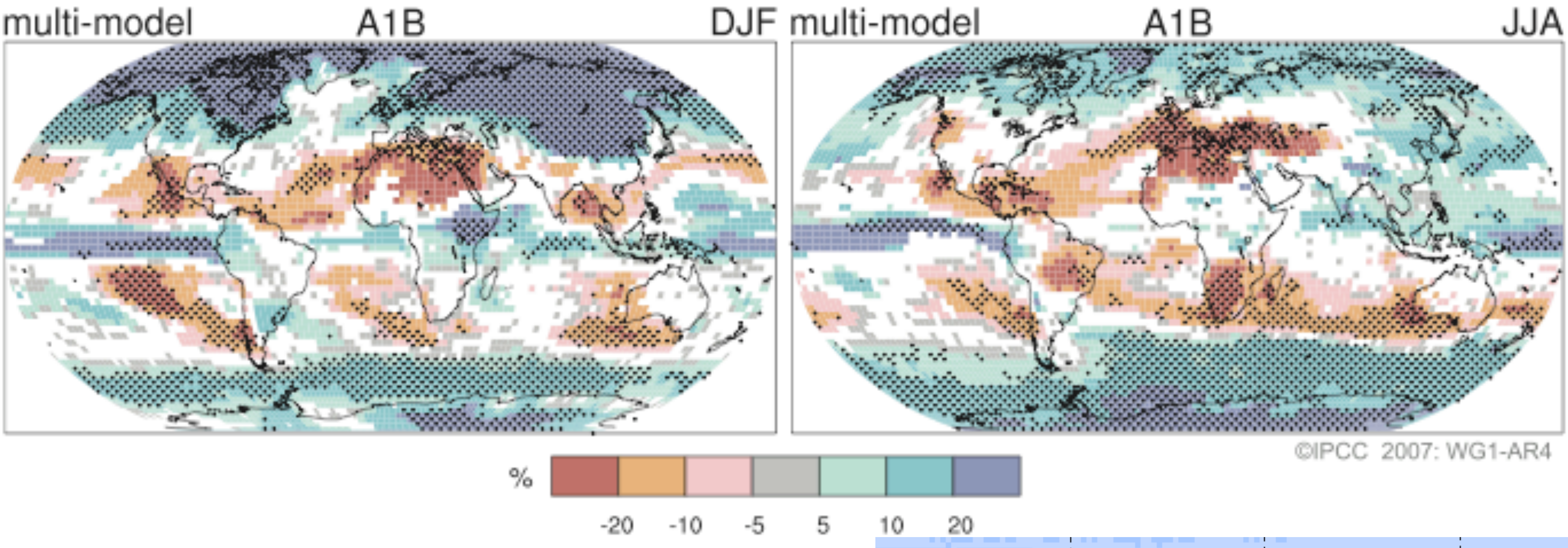
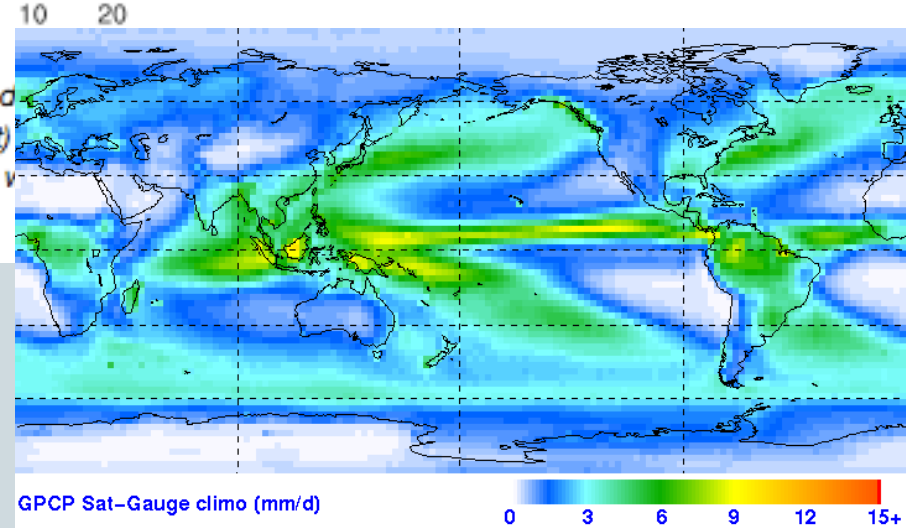


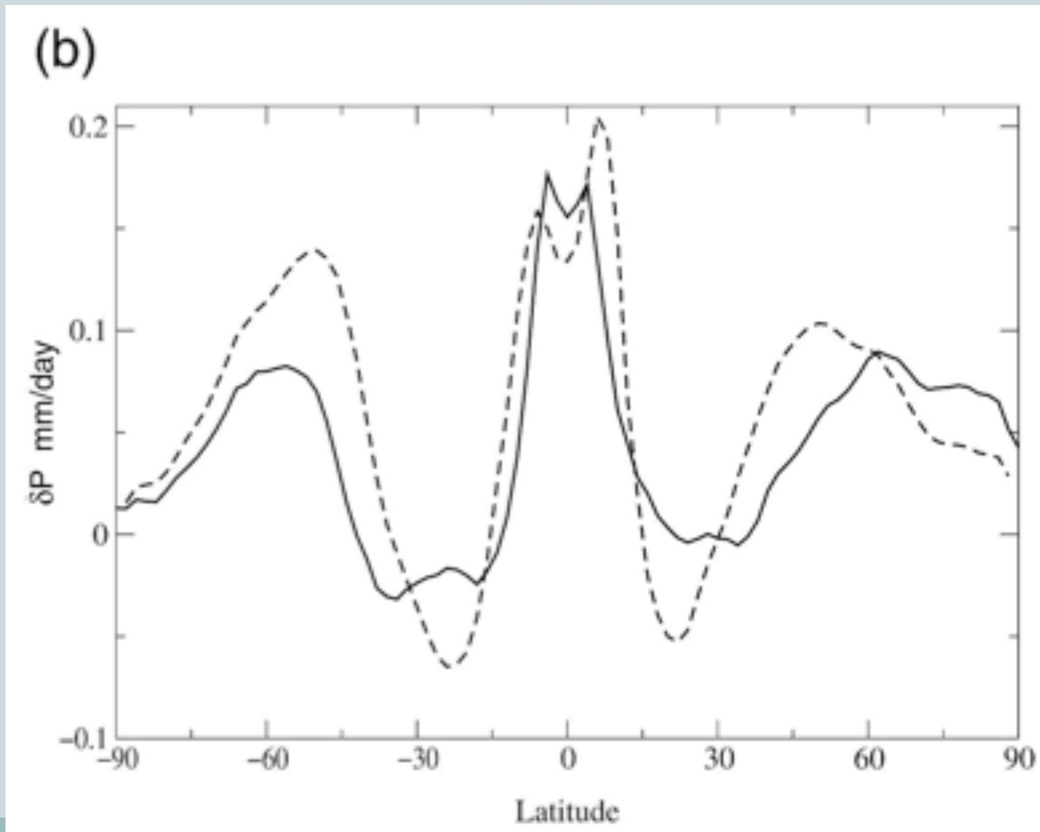
Figure SPM.7. *Relative changes in precipitation (in percent) for the period*
averages based on the SRES A1B scenario for December to February (left)
66% of the models agree in the sign of the change and stippled areas are v
change. {Figure 10.9}



Note lots of confidence in high latitudes. Little confidence in tropics.

Change in Precipitation

- Change in precipitation in global warming simulations (solid) vs prediction based on more moisture (dashed)

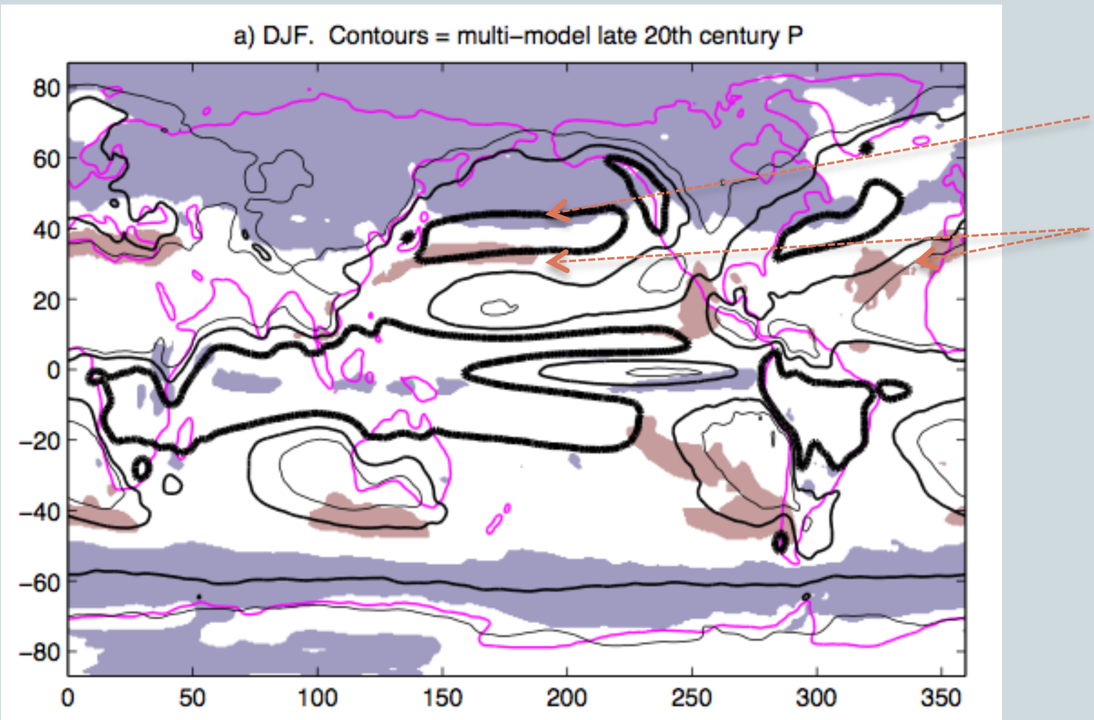


Wet gets much wetter,
dry gets a bit drier
(although this can be a large percentage change relative to the current value in arid regions)

Note also poleward shifts relative to simple prediction

Poleward Shifts of Midlatitude Storm Tracks

- Midlatitude precipitation shifts with the storm tracks:
  - Moistens high latitudes
  - Dries on the equatorward side of the storm track



From Scheff and Frierson (J. Climate 2012, GRL 2012): Storm track shifts are the primary cause of significant drying

Global Warming Rain Responses

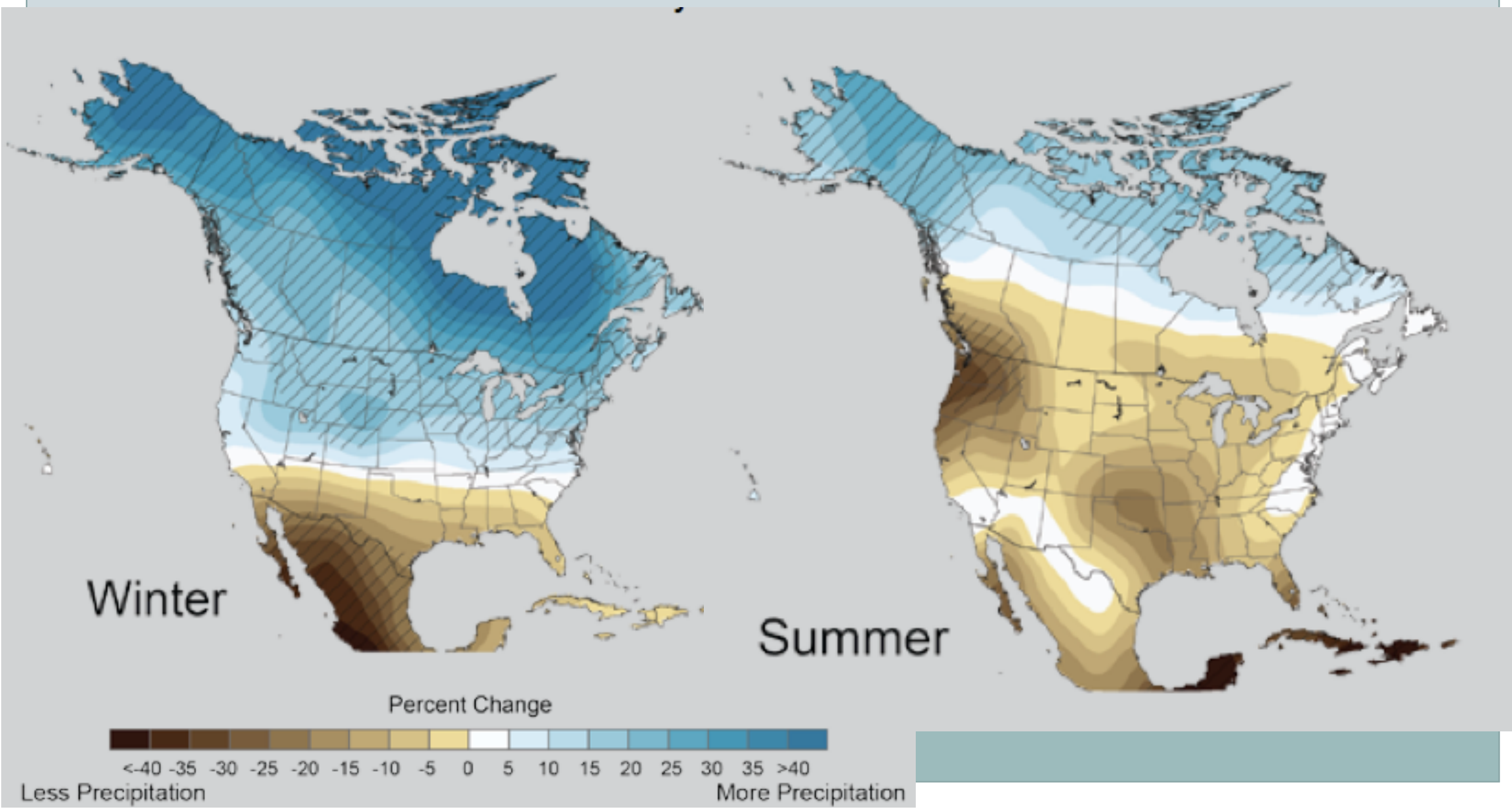
- Wet get wetter
  - More water vapor is brought into the regions that are already rainy
  - Specifically, **tropical** regions, **monsoons**, **storm tracks**, and **high latitudes** are expected to **get rainier**
- Dry regions dry/expand
  - Many **subtropical** regions (in between tropics & midlatitudes) are expected to **dry**
    - More vapor taken out of dry regions
    - More evaporation from dry land surfaces at higher temperatures
    - Tendency for midlatitude weather to shift poleward

Global Warming Rain Responses: Caveat

- There's a lot of uncertainty about specific precipitation responses though
  - Regional responses could change significantly due to **shifts in rising motion**
    - Small shifts can make a big difference for rainfall!
  - Precipitation is much harder to predict than temperature

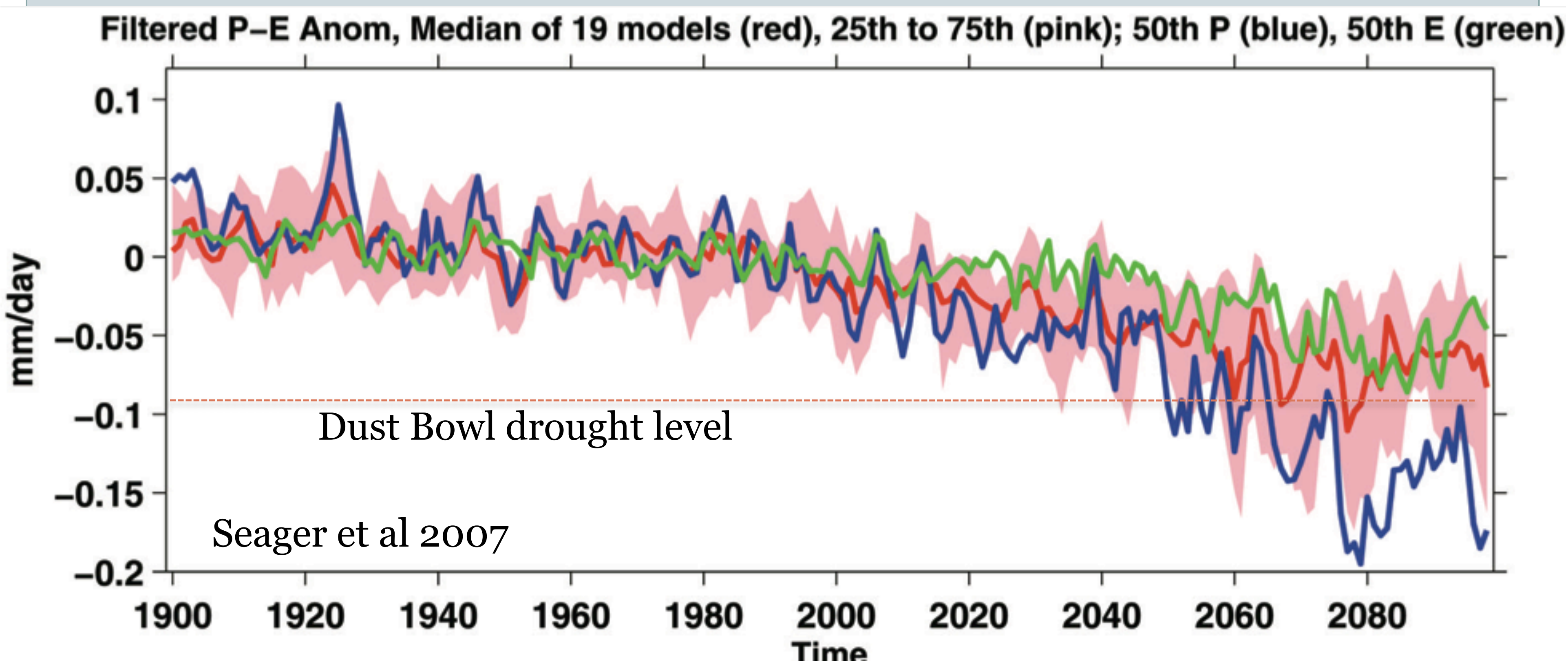
US Predictions

- US predictions



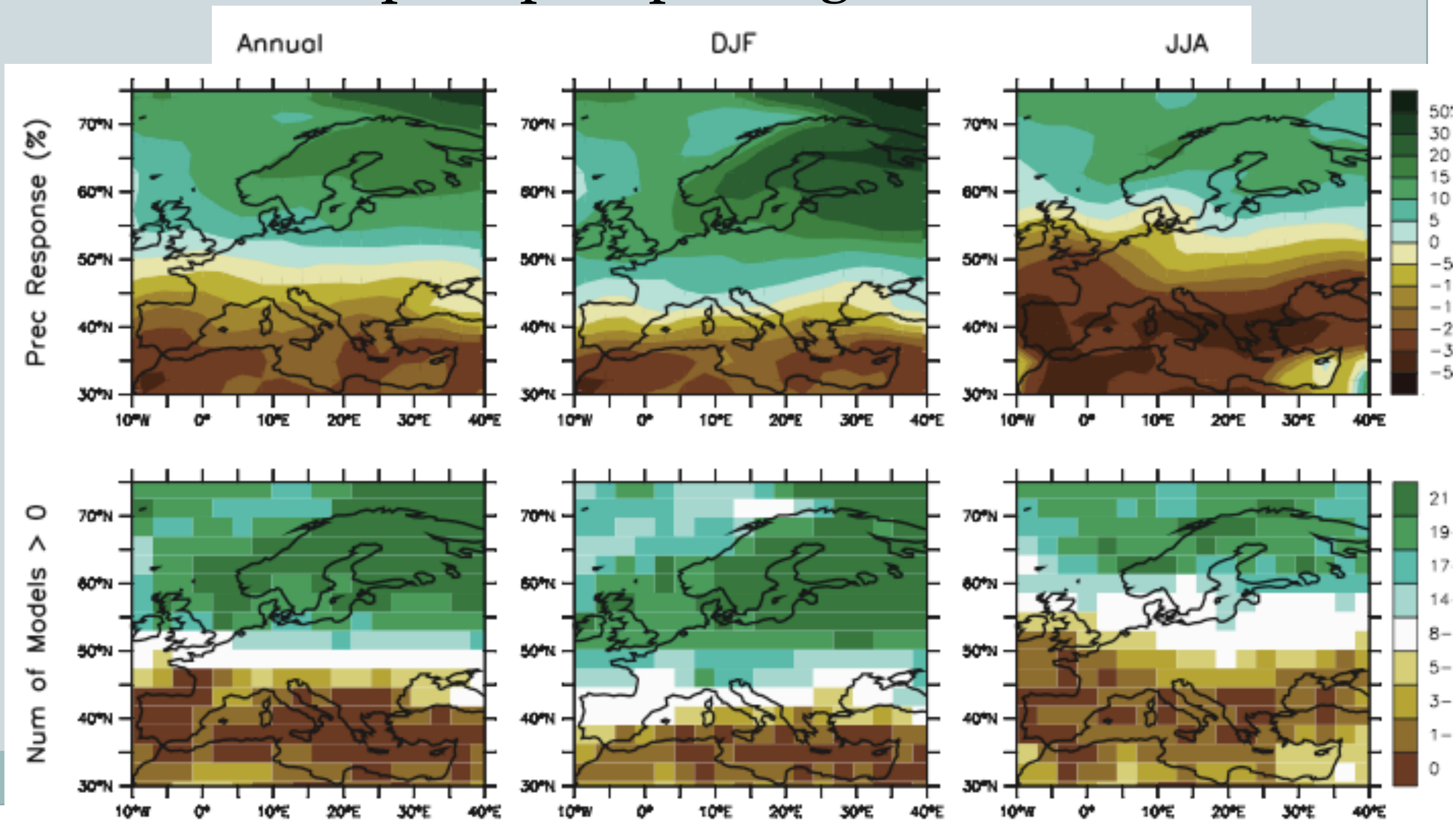
Some Additional Predictions

- Southwestern North America predicted to dry dramatically
  - As bad as the Dust Bowl by 2060 in some models



Europe

- Modeled European precip changes



Extra-tropical summary

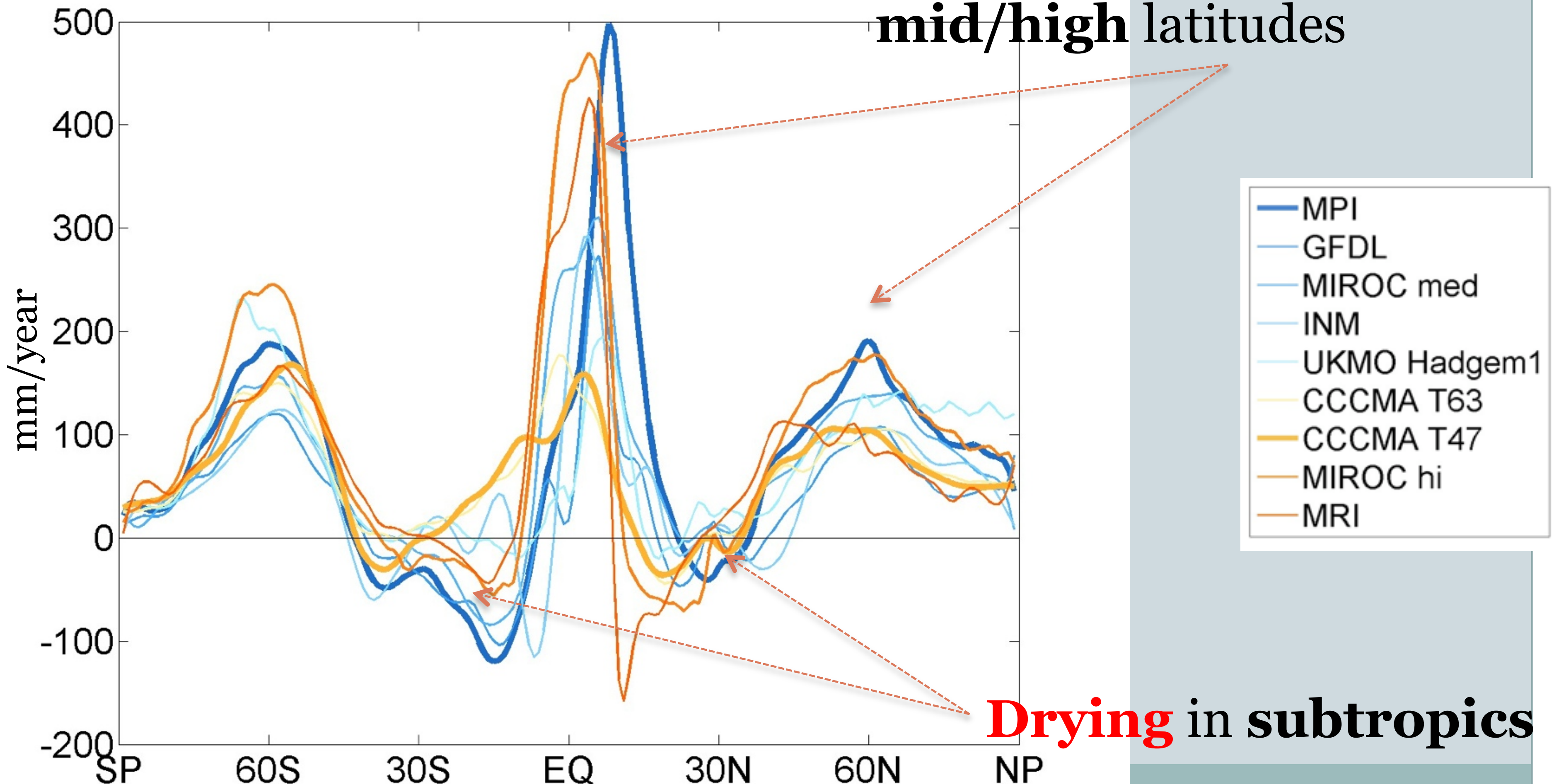
- Wet regions get wetter (high latitudes)
- Dry regions persist/expand poleward
  - And land surfaces get **more arid** unless precip goes up b/c **potential evaporation** increases
- What about the tropics?
  - We generally expect moistening but we don't have much confidence there
  - I'll explain the reasons for lack of confidence & show some situations where we are sure what will happen

Tropical Precip Shifts Towards Warmth

- Generally speaking, it’s the **warmest** ocean air that rises
- But tropical precipitation shifts in response to warming **even very far away**
  - Recent studies have shown even **high latitude heating** draws the tropical rain belt towards it
- Let’s use this concept to interpret changes with global warming

Change in Precip, IPCC AR4 **Slab** Ocean Models

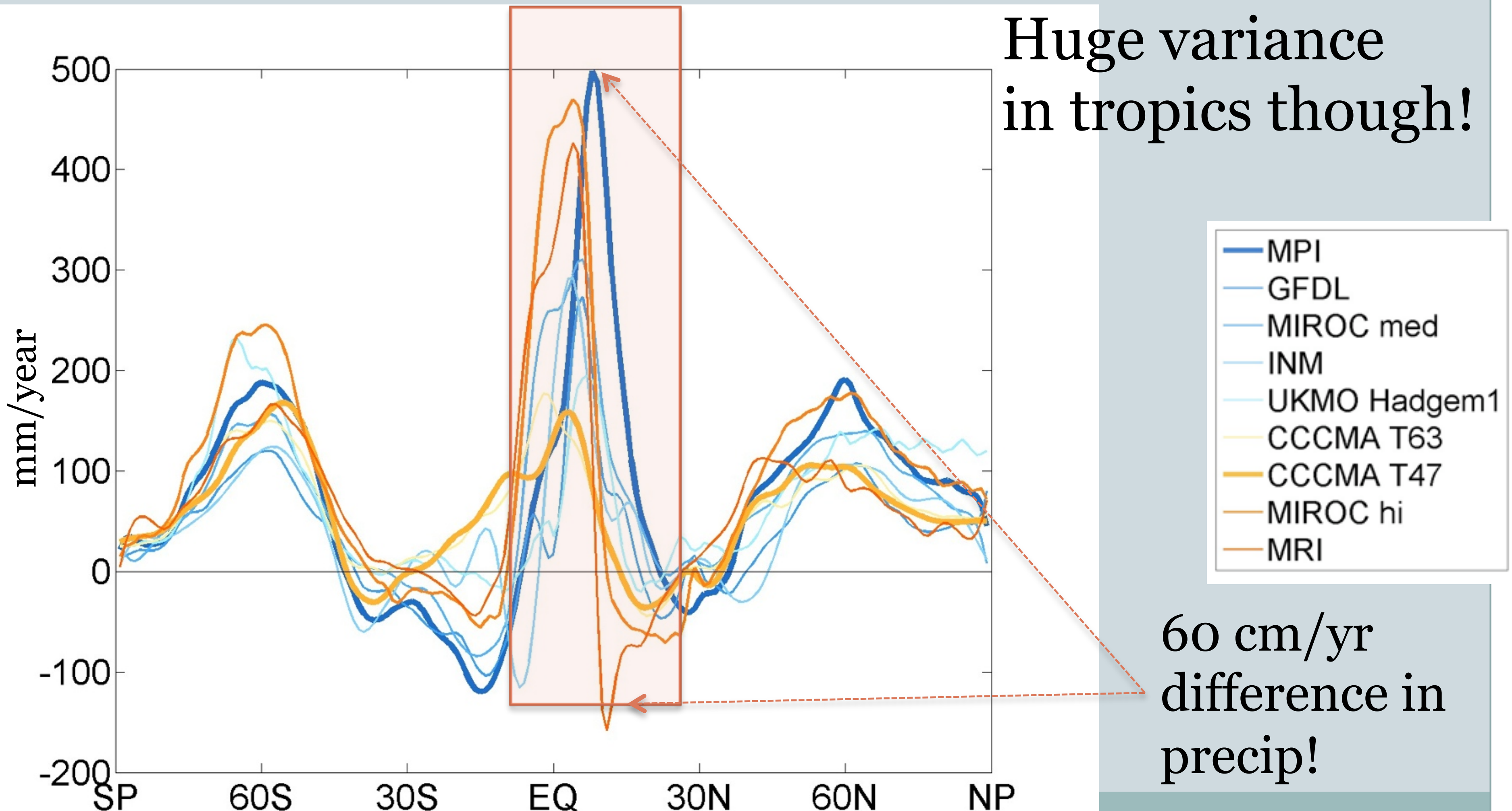
Moistening in **tropics** and **mid/high** latitudes



Drying in **subtropics**

Plot by Yen-Ting Hwang

Change in Precip, IPCC AR4 **Slab** Ocean Models

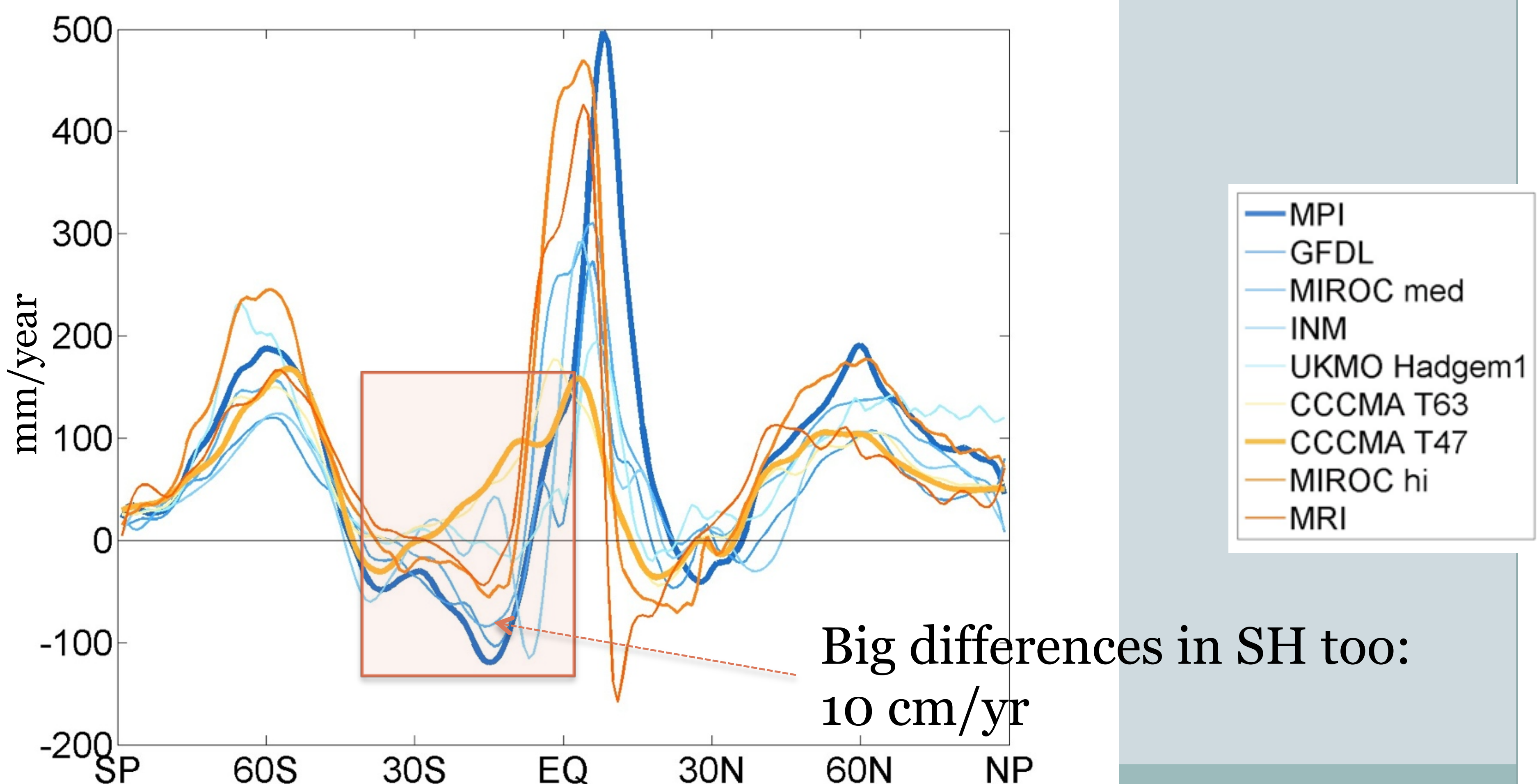


Huge variance in tropics though!

60 cm/yr difference in precip!

Plot by Yen-Ting Hwang

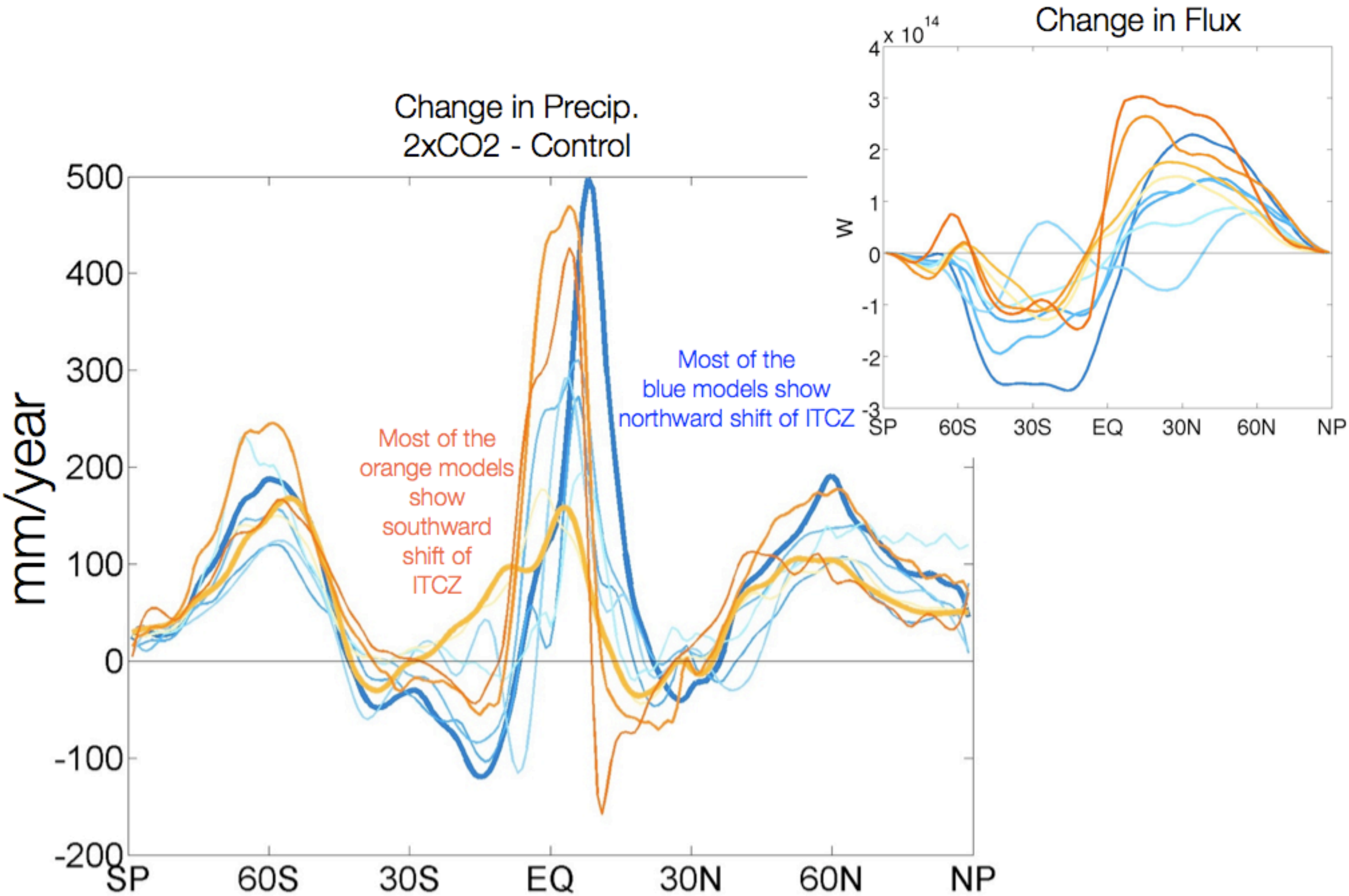
Change in Precip, IPCC AR4 **Slab** Ocean Models



Big differences in SH too:
10 cm/yr

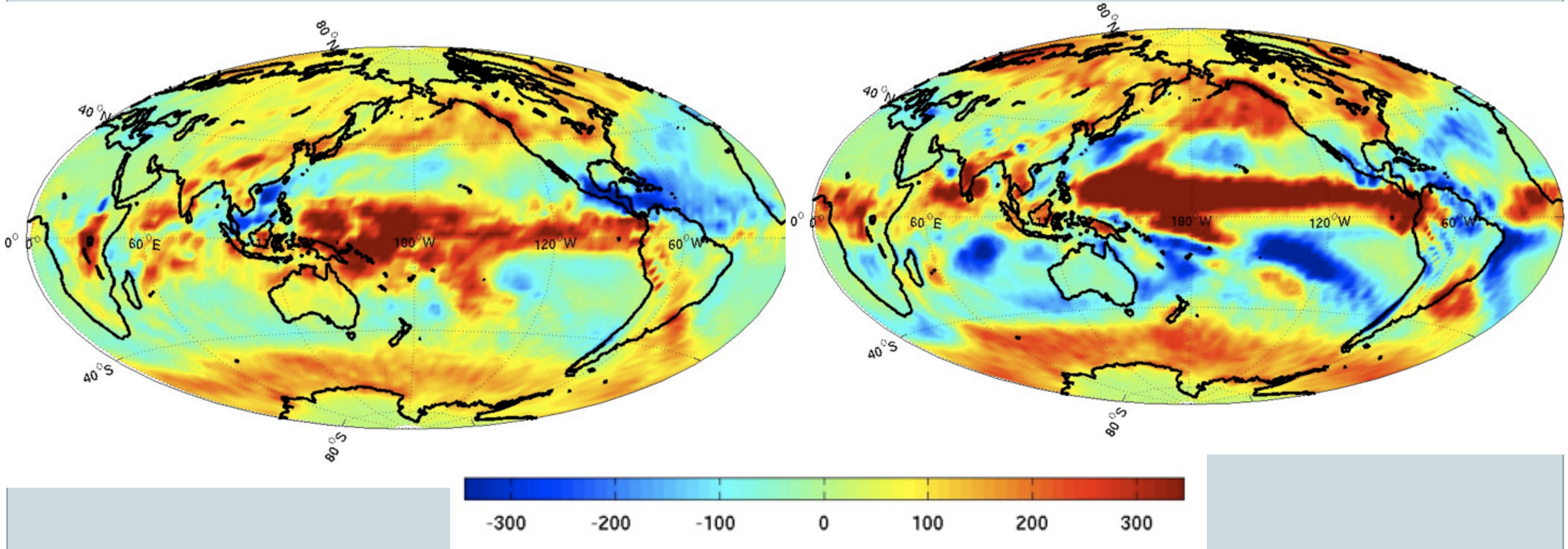
Plot by Yen-Ting Hwang

Precip vs. Cross EQ flux: Slab Models



Change in Precipitation in Extreme Cases

CCCMA (most S-ward) **MPI (most N-ward)**

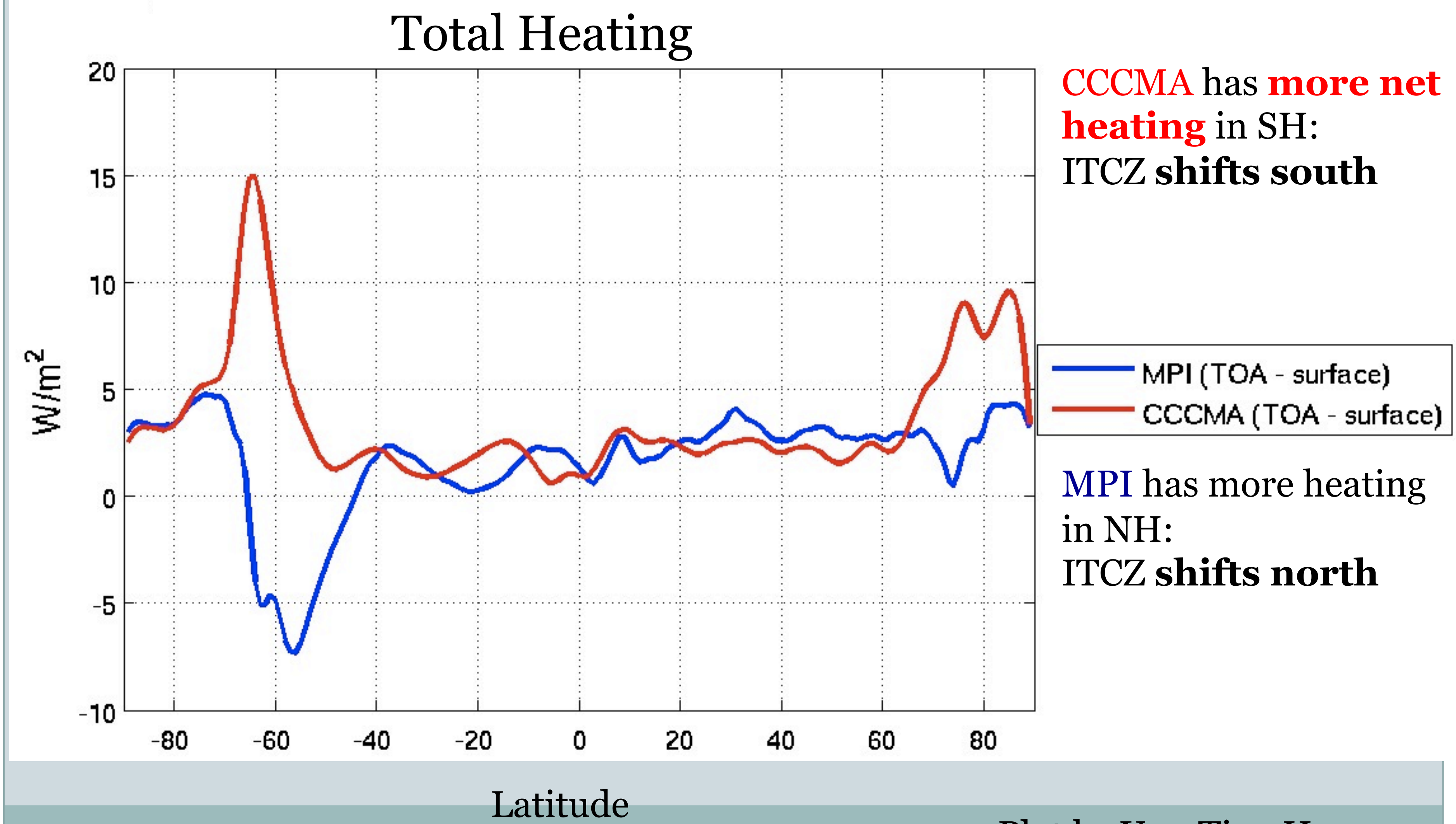


mm/year

Seen across all longitudes, and over continents as well

Plot by Yen-Ting Hwang

Total Heating in the Two Extreme Models



CCCMA has **more net heating** in SH:
ITCZ **shifts south**

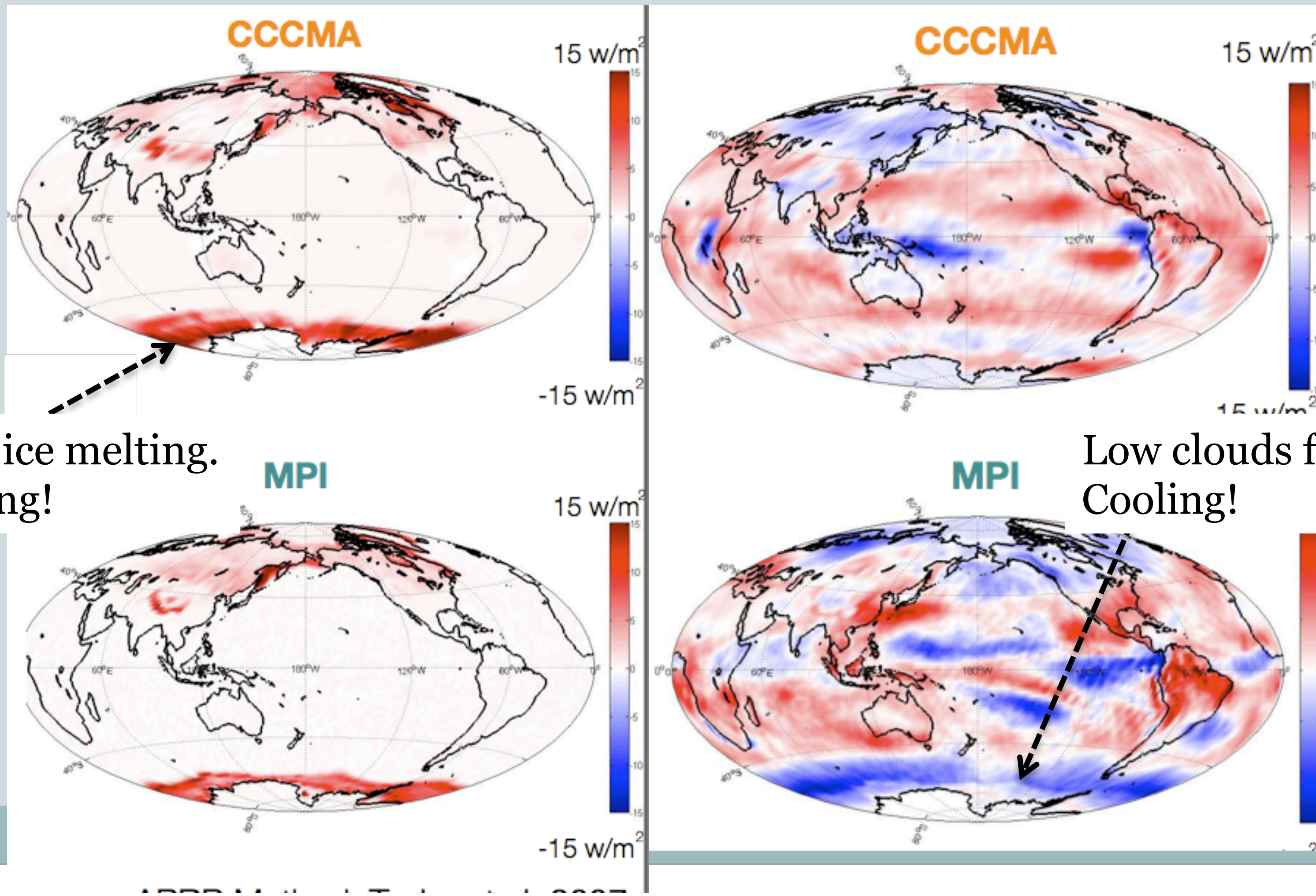
MPI has more heating in NH:
ITCZ **shifts north**

Plot by Yen-Ting Hwang

Feedbacks

Ice-albedo feedback

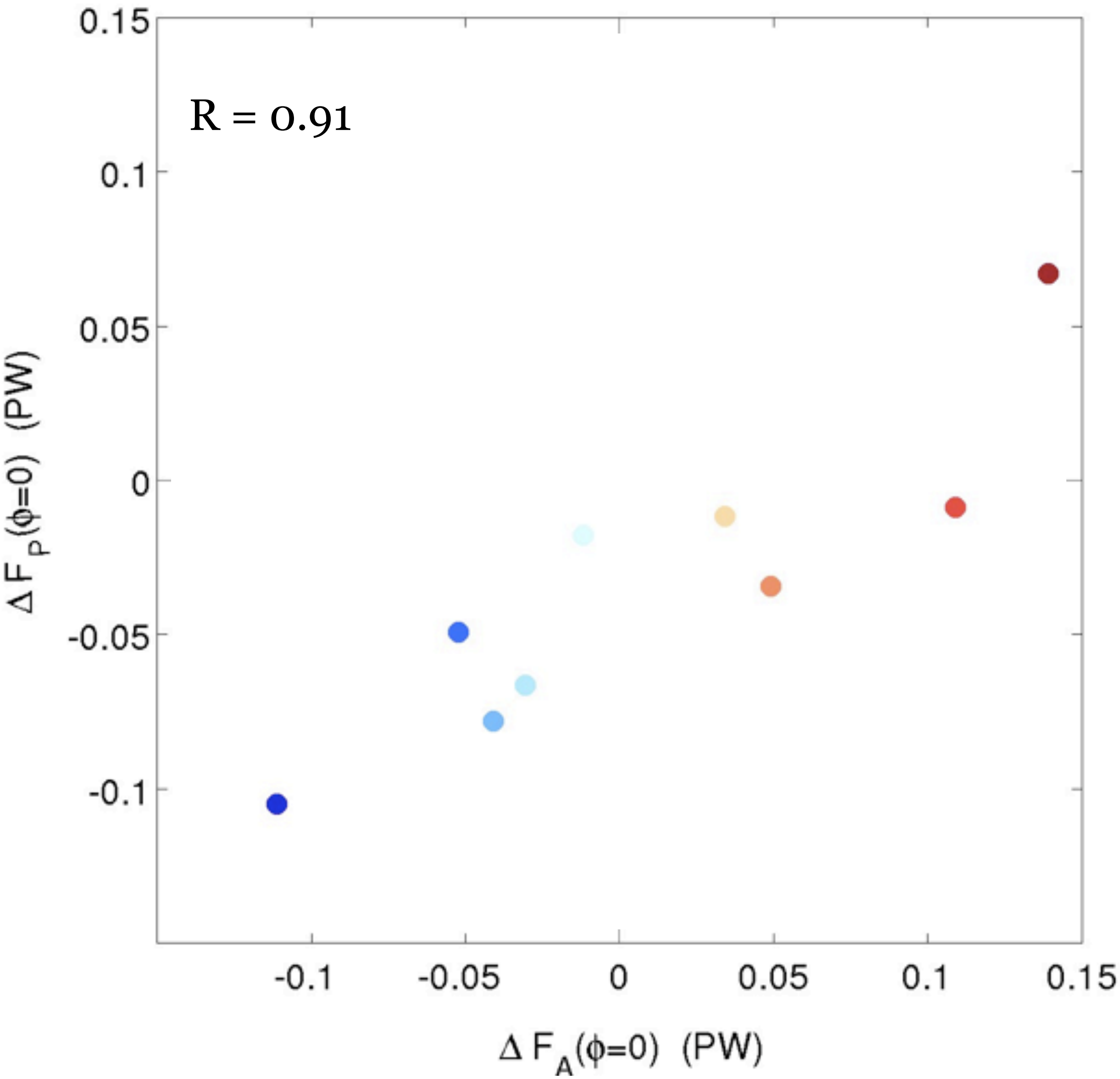
Cloud-albedo feedback



Lots of ice melting.
Warming!

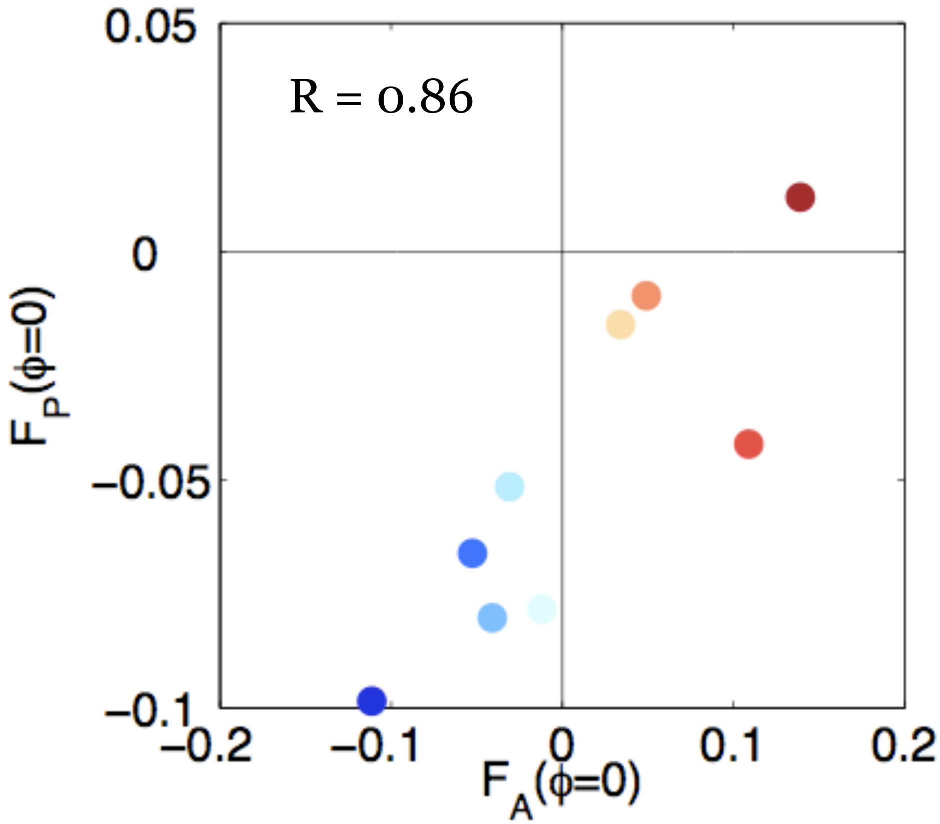
Low clouds form.
Cooling!

Energetic Prediction for Slab Models



Importance of Extratropical Forcing

- EBM forced by terms **outside of the tropics only** (poleward of 20º N/S)

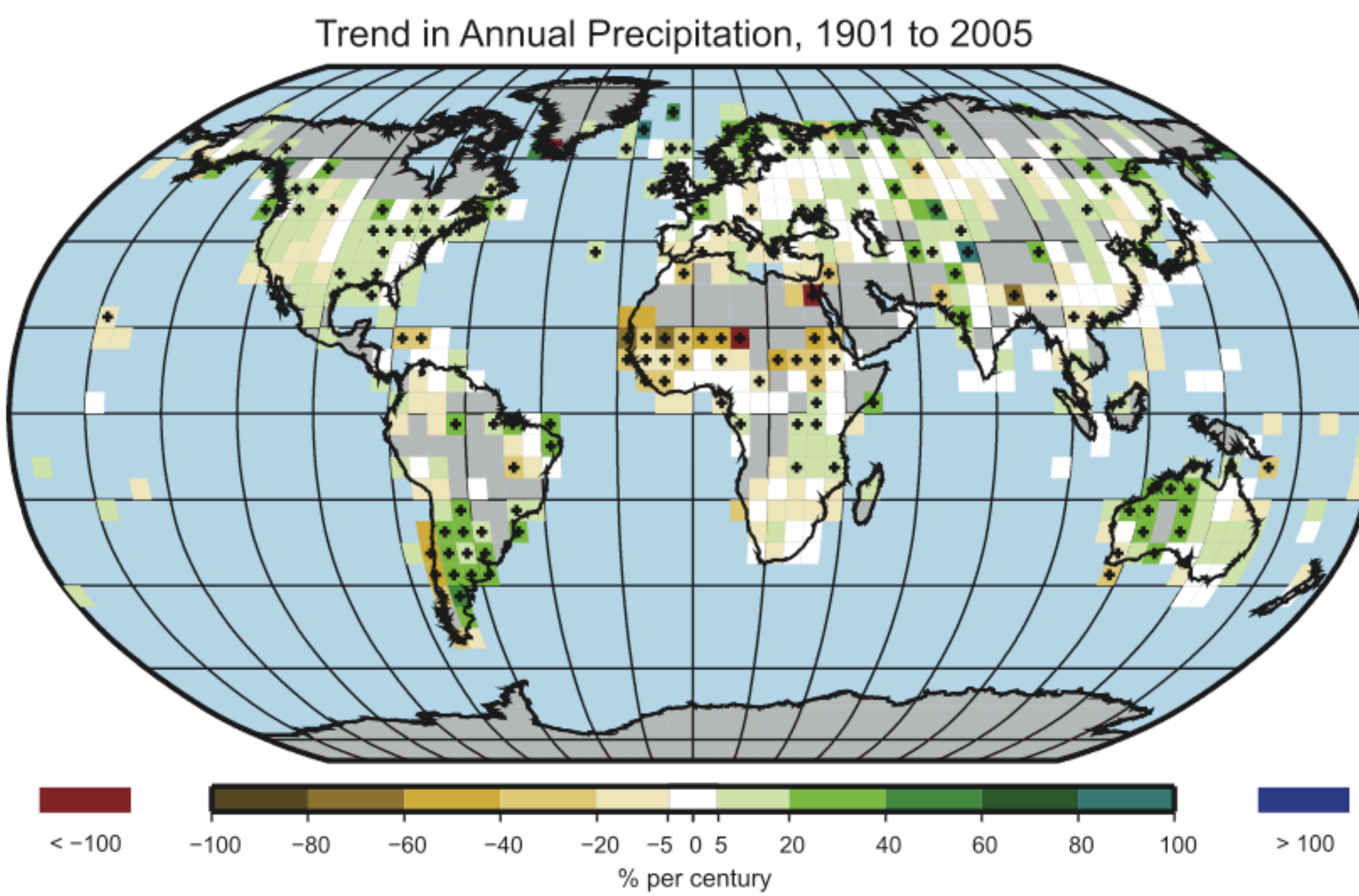


Extratropical forcing explains the range in ITCZ shifts in this set of models…

From Frierson and Hwang, in J. Climate, 2012

20th Century Precipitation Changes

- Drying in NH tropics, especially in Sahel region of Africa



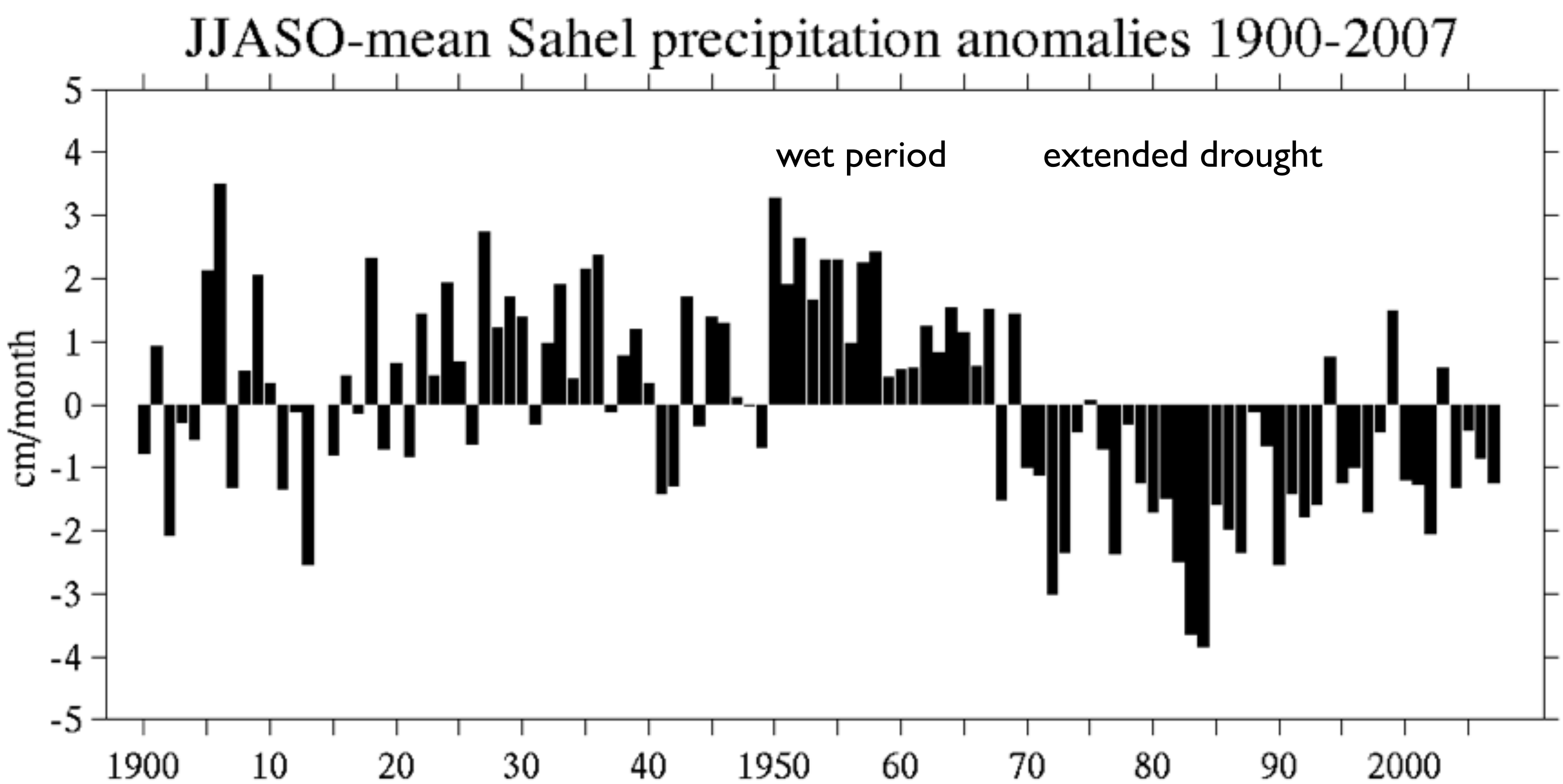
IPCC AR4

The Sahel region of Africa

The Sahel is in between desert and the region drenched by the African monsoon

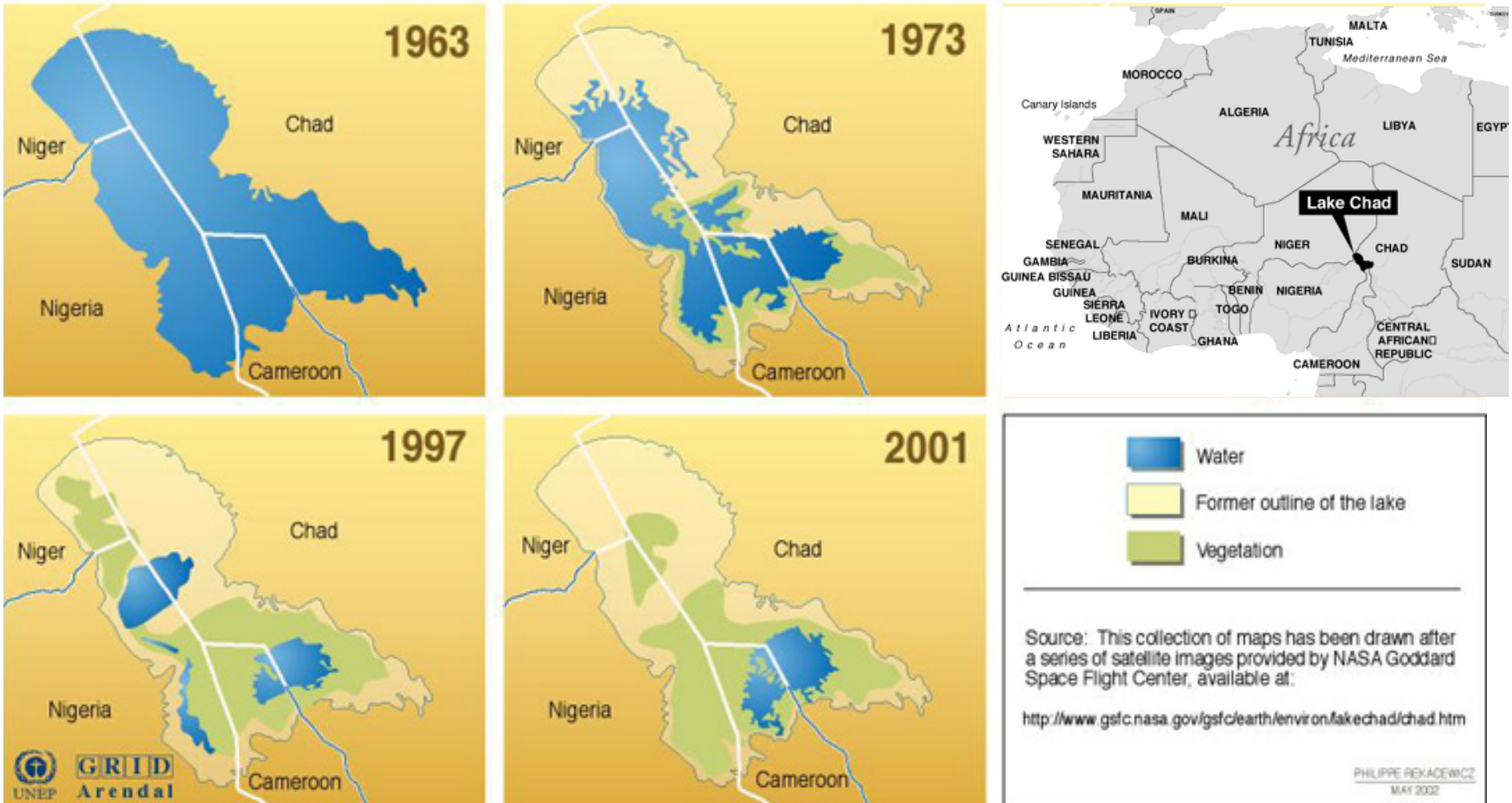
The African Monsoon in full swing

Sahel drought

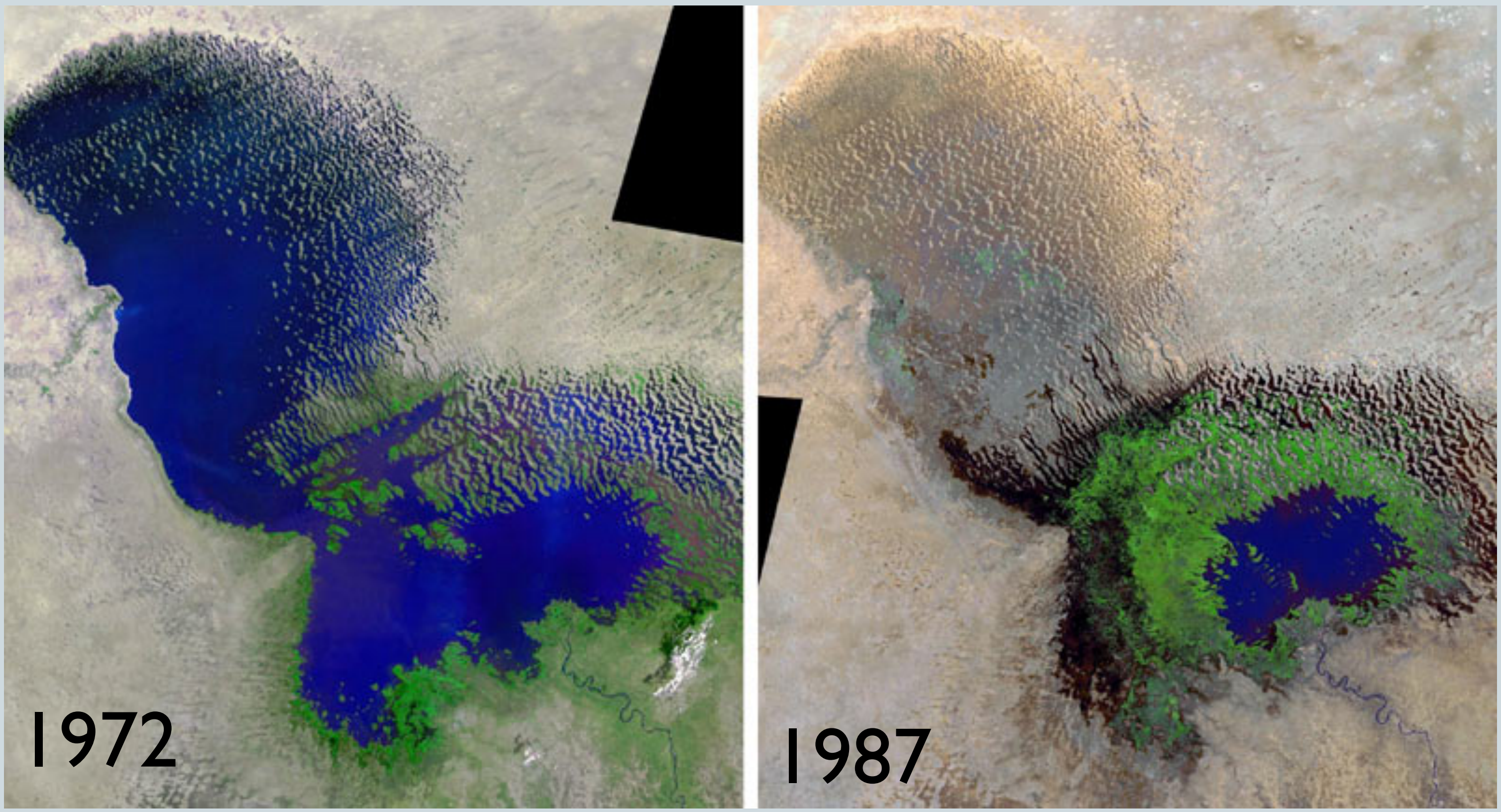


The shift around 1970 is believed to be due to changing sea surface temperature patterns in the tropical Atlantic (quite possibly driven by aerosol forcing).

The disappearance of Lake Chad



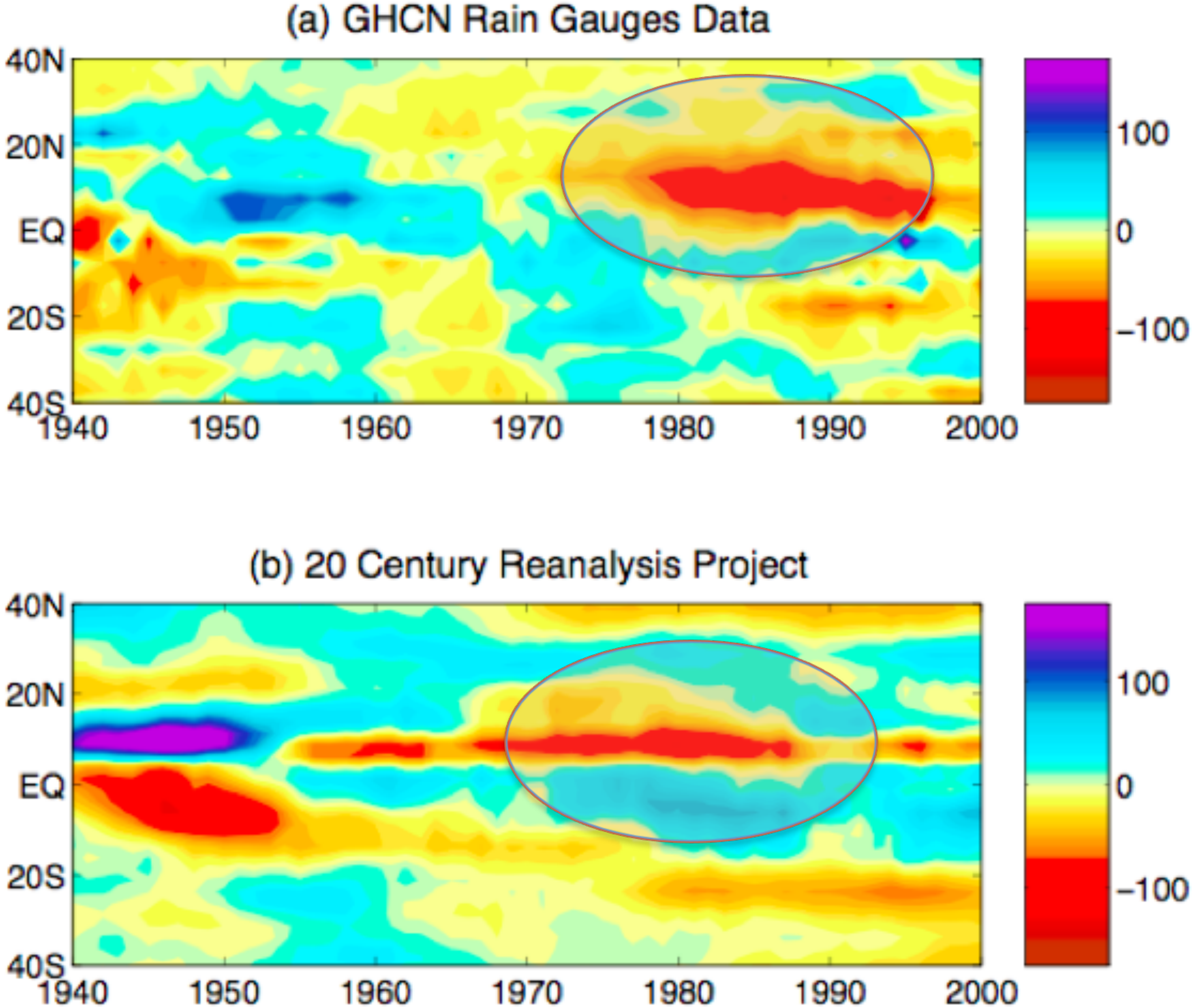
Lake Chad



Some of My Group's Research…

- Ph.D. student Ting Hwang
- Studying shifts in tropical precipitation in simulations of 20th century climate

Observed Zonally Averaged Land Precip Changes



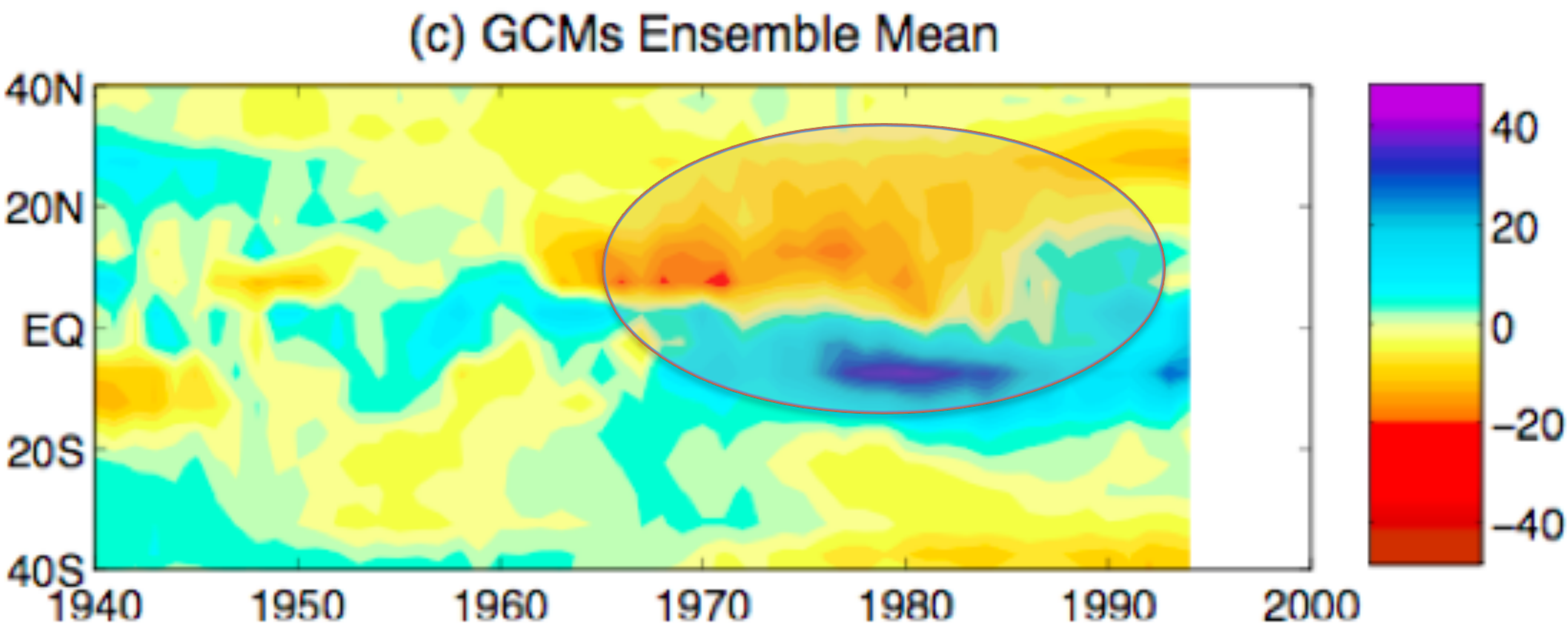
Precip change relative to 20th century mean in two datasets

Southward shift of precipitation peaking around 1980…

All these plots are from Hwang, Frierson & Kang, in prep

Modeled Zonally Averaged Land Precip Changes

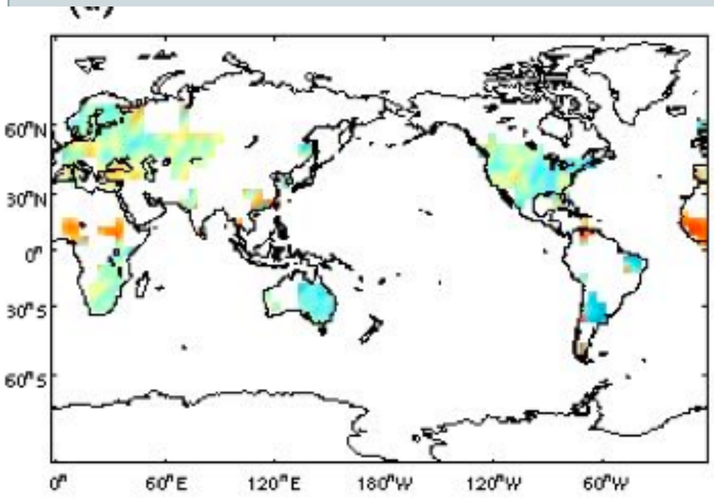
- Modeled 20th Century changes:

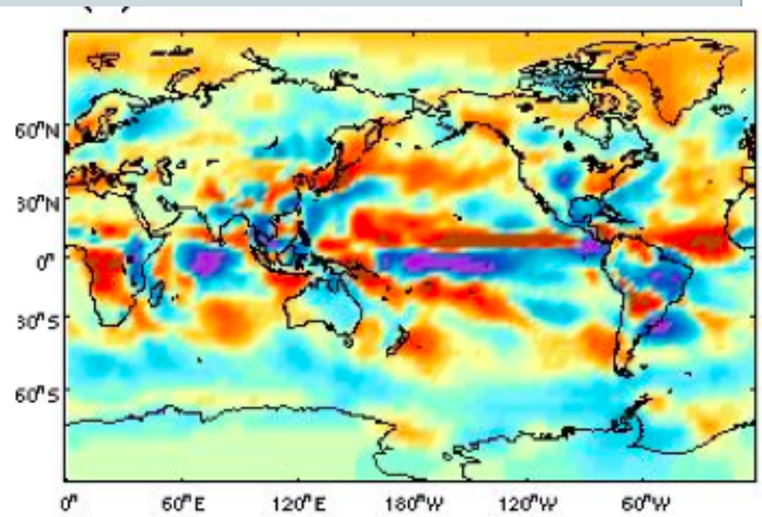


Southward shift in models too!

Aerosols: An Asymmetric Forcing

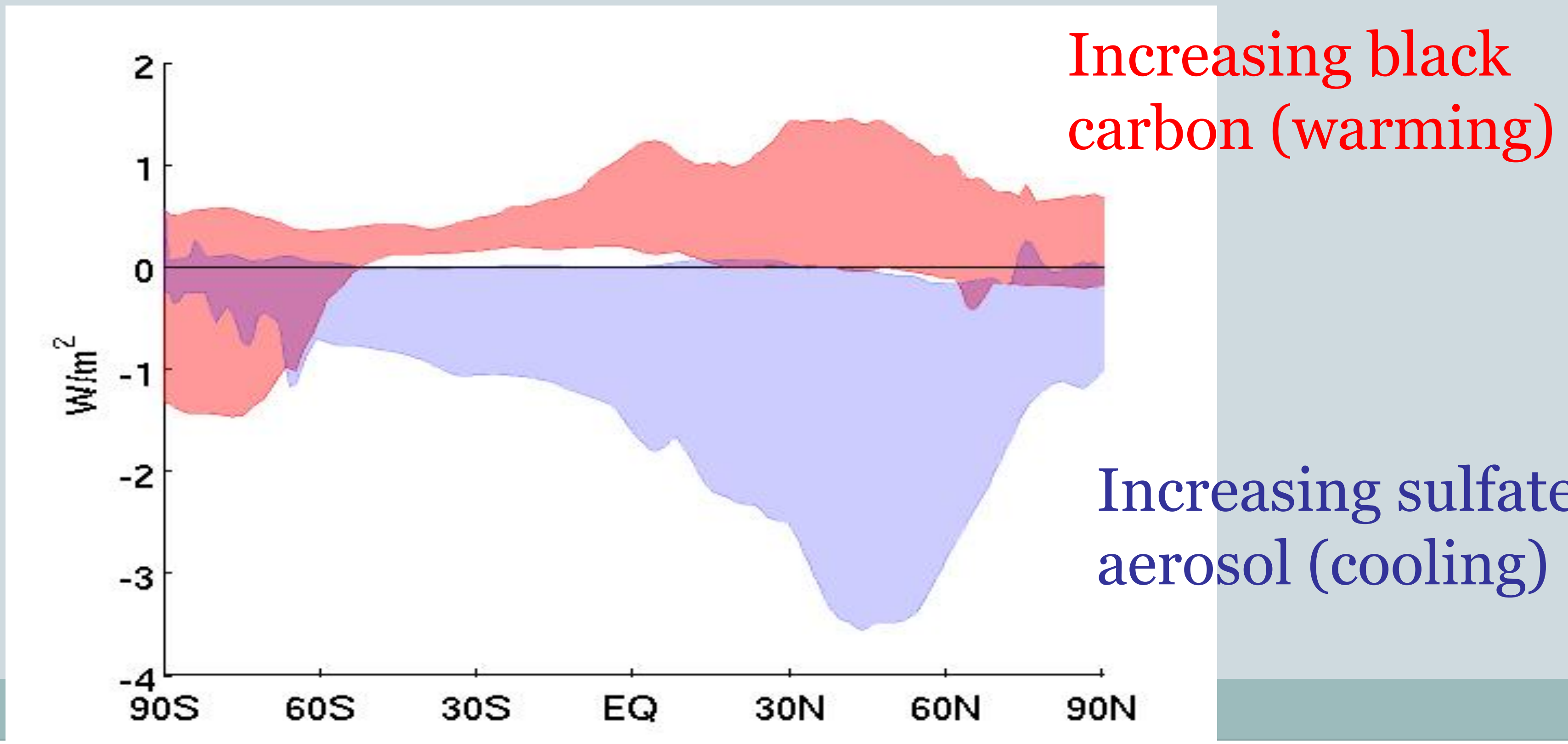
- **Sulfate aerosols** increased significantly in 20th century, especially in the NH
  - Mostly from dirty **coal burning**
  - We controlled emissions of this with Clean Air Acts to solve acid rain & other public health problems
  - Cools the NH – could this have caused the southward shifts?



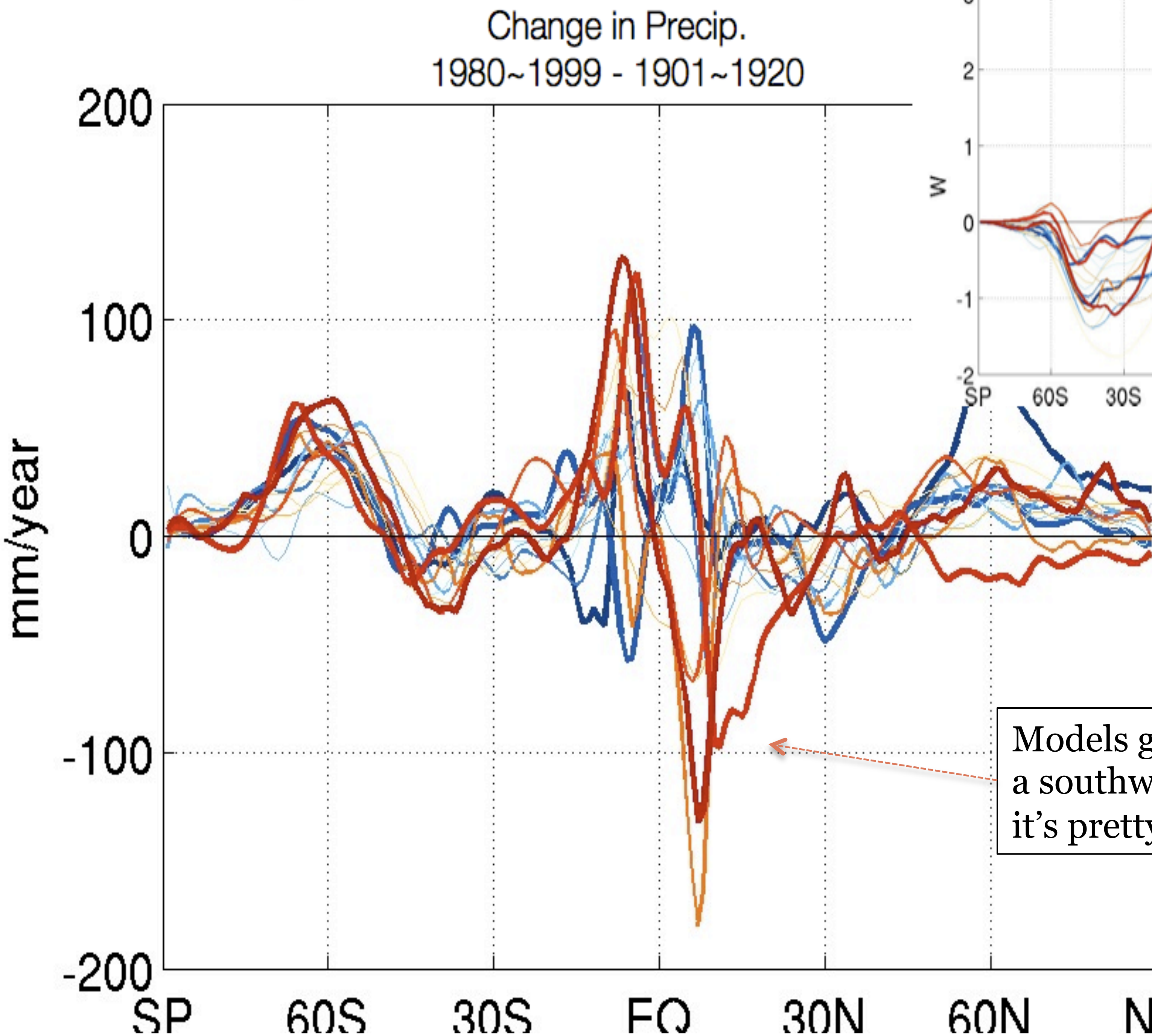


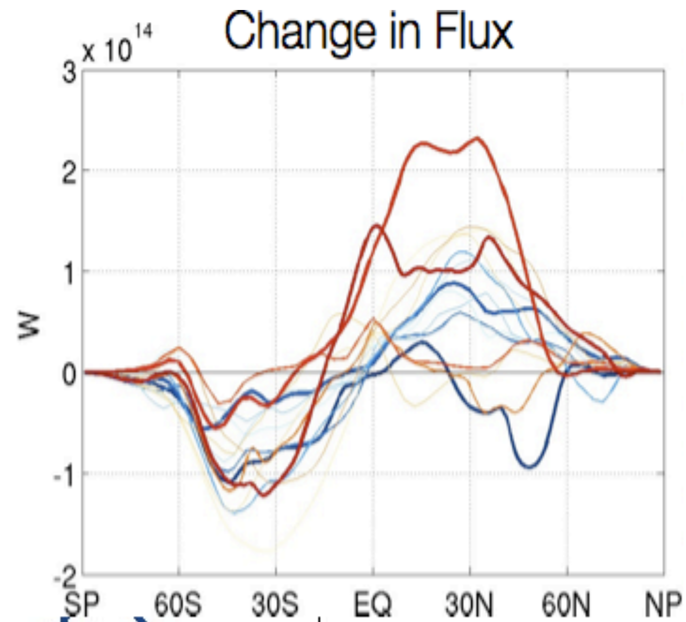
Aerosol Forcings in 20th Century Simulations

- Structure of aerosol forcing in 20C3M:
  - Envelope shows the range in forcings used (model with most forcing & model with least forcing at each latitude)



Change in Precip over 20th Century



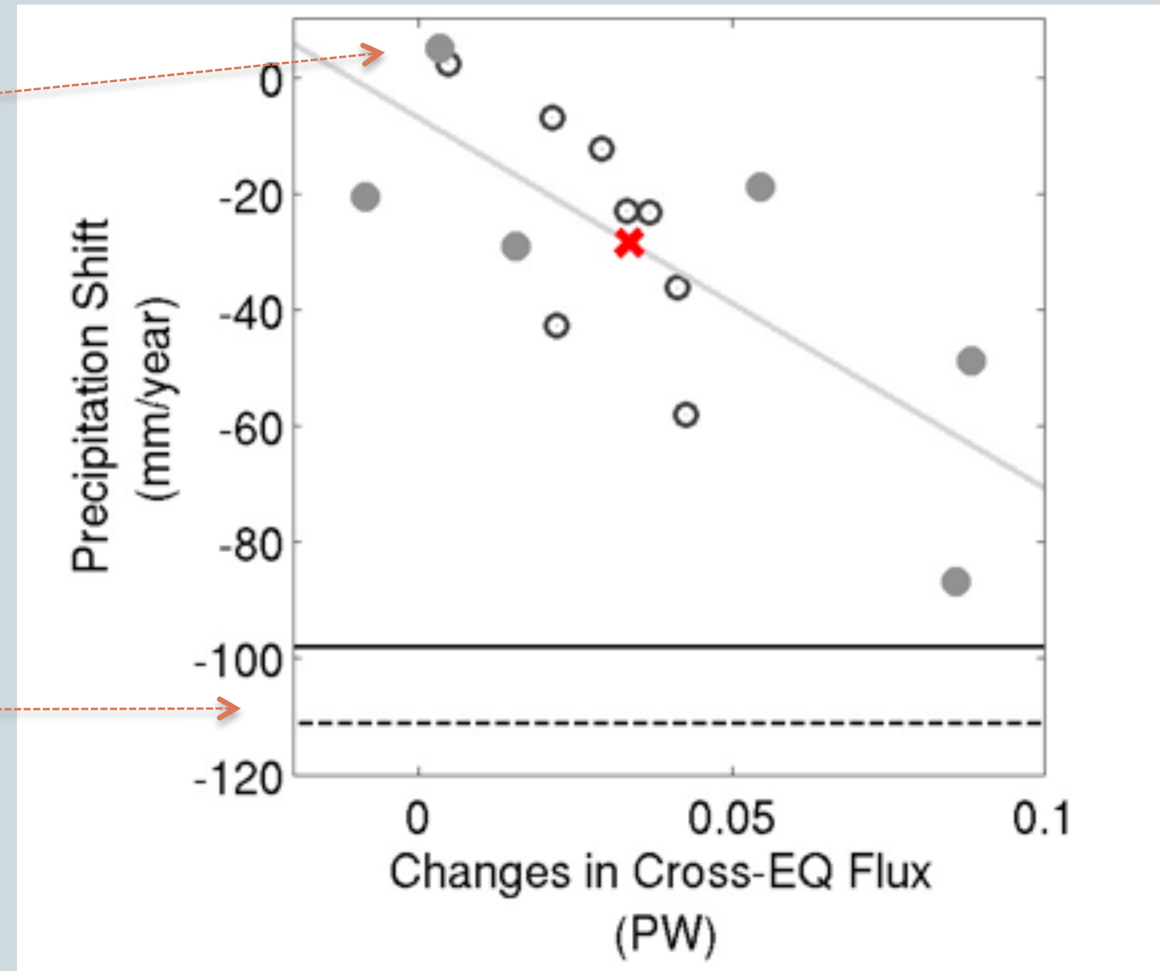


Models generally show a southward shift, but it's pretty messy…

Correlation of precip shift w/ energy flux

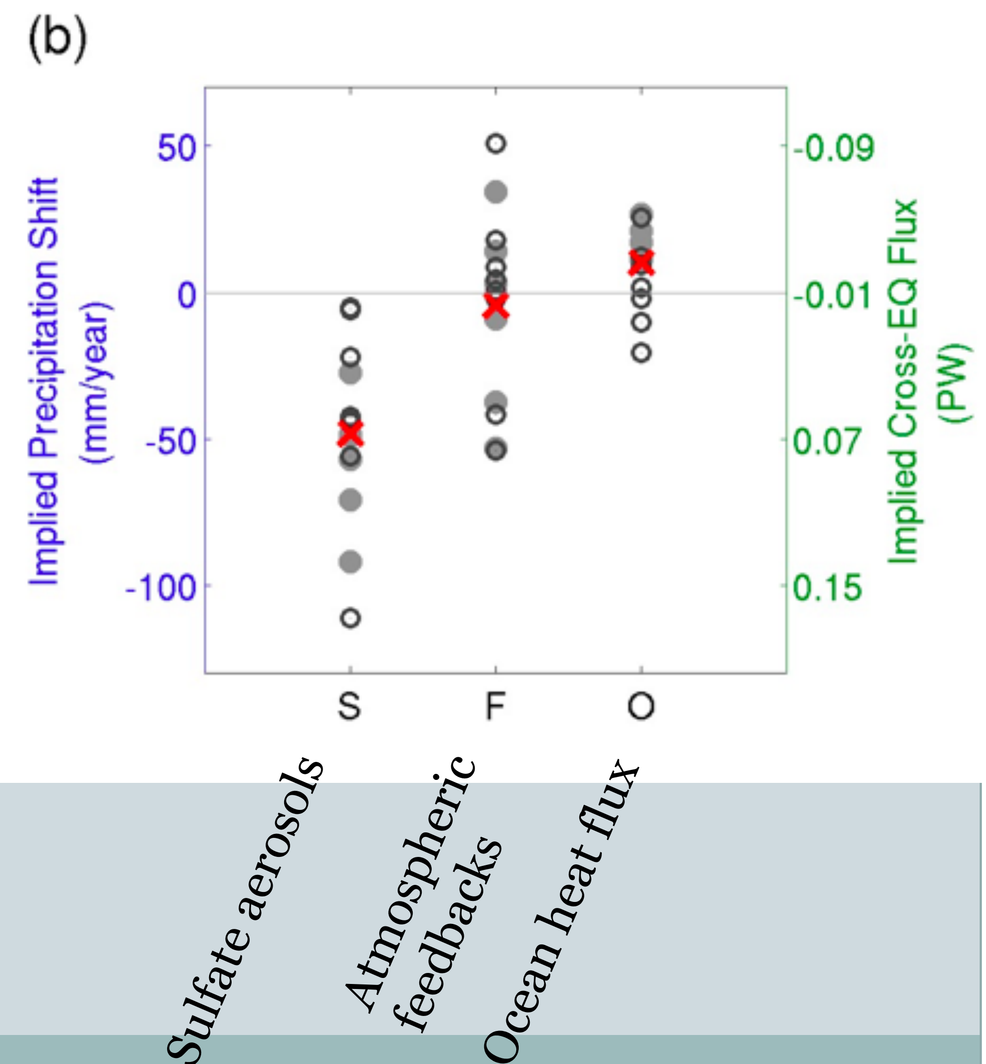
Only two models show northward shift…

All models underestimate the observed shift…



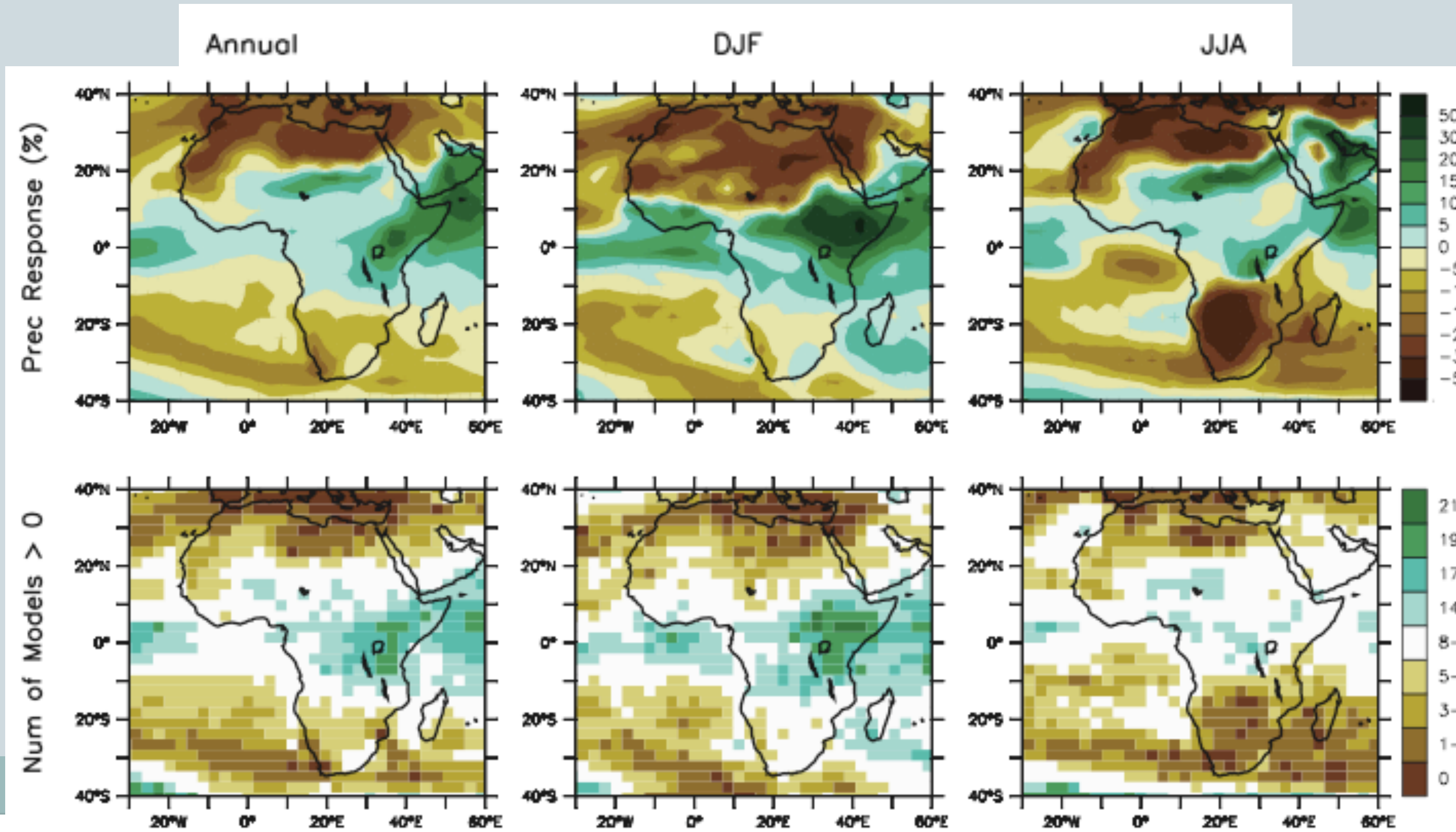
Attribution of Multi-Model Mean Shift

- **Sulfate aerosols** are most important for S'ward ITCZ shift
  - Preferentially cooled the NH
- Atmospheric feedbacks cause a lot of spread though…
  - Hard to say how much of the observed shift was aerosols



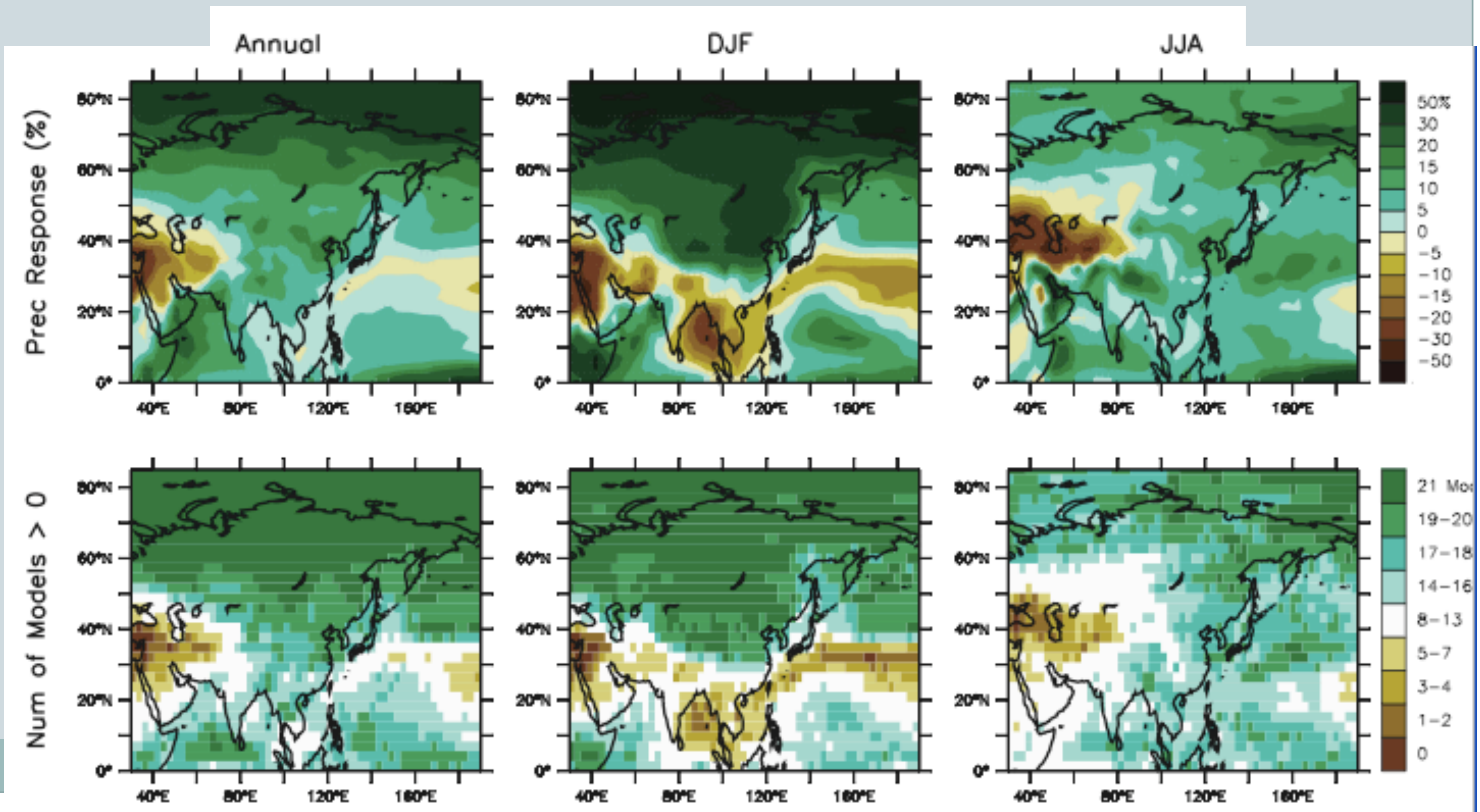
Africa

- Modeled African precip changes



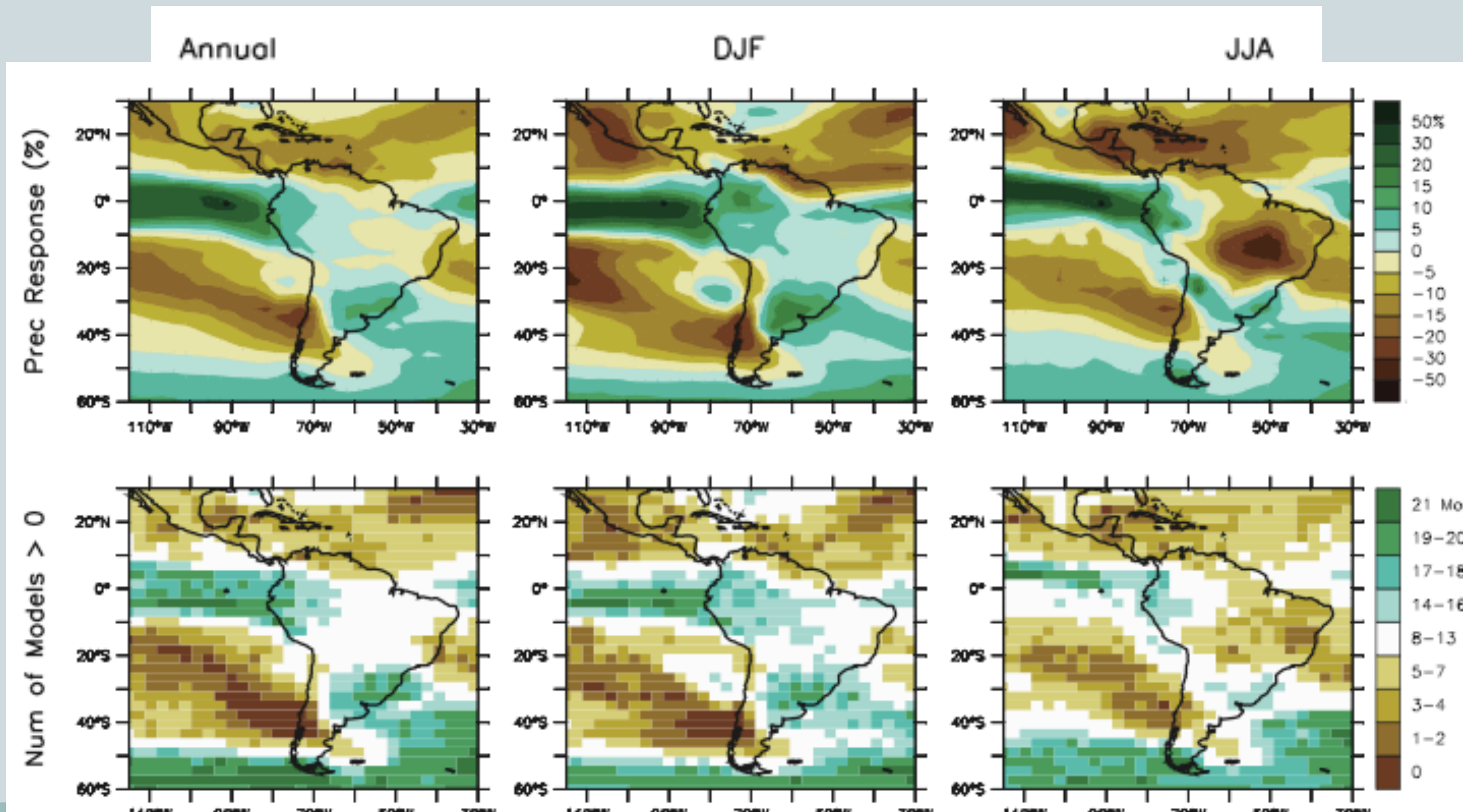
Asia

- Modeled Asian precipitation changes



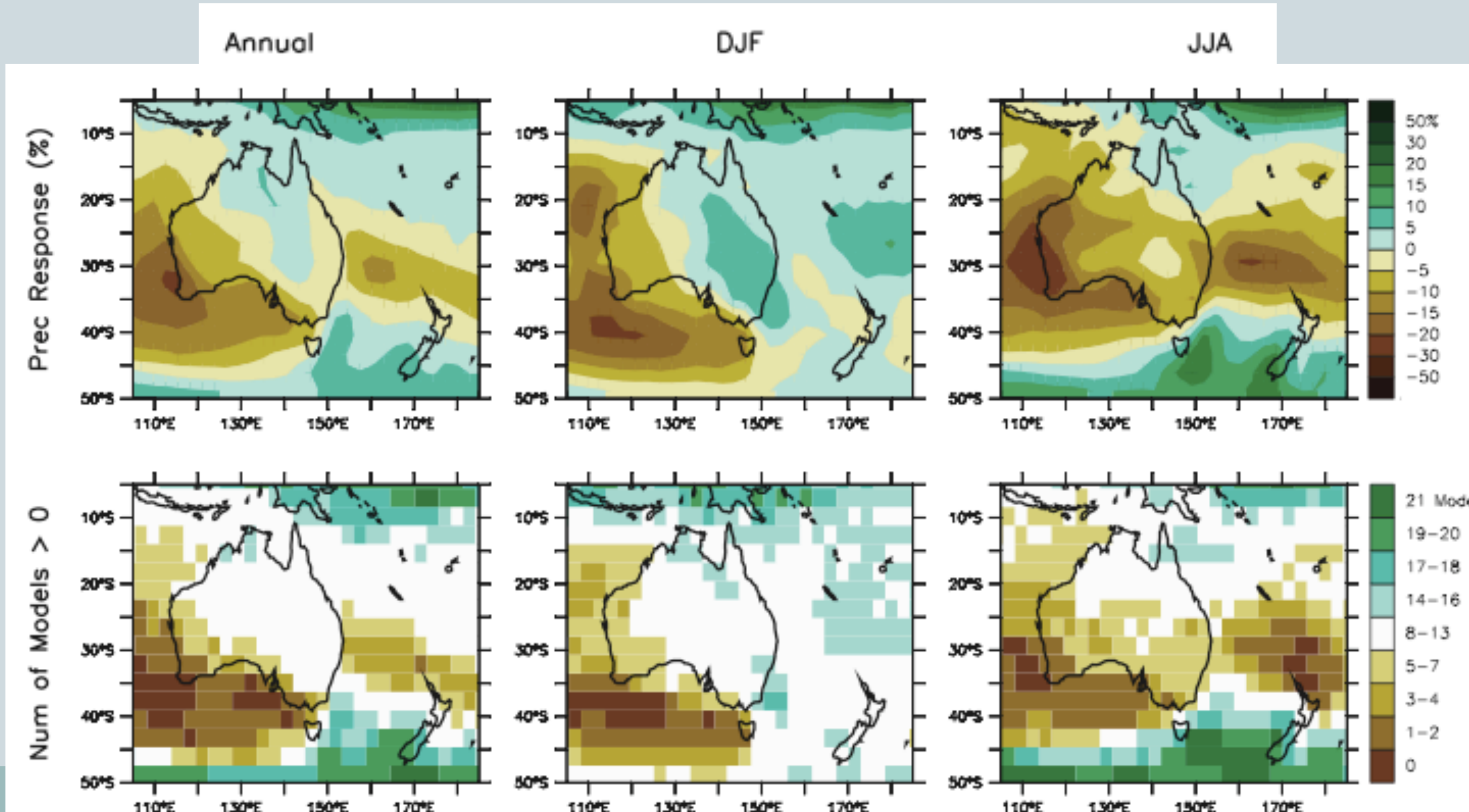
South America

- Modeled South American precip changes



Australia

- Modeled Australian precipitation changes



How about the **most intense storms**?

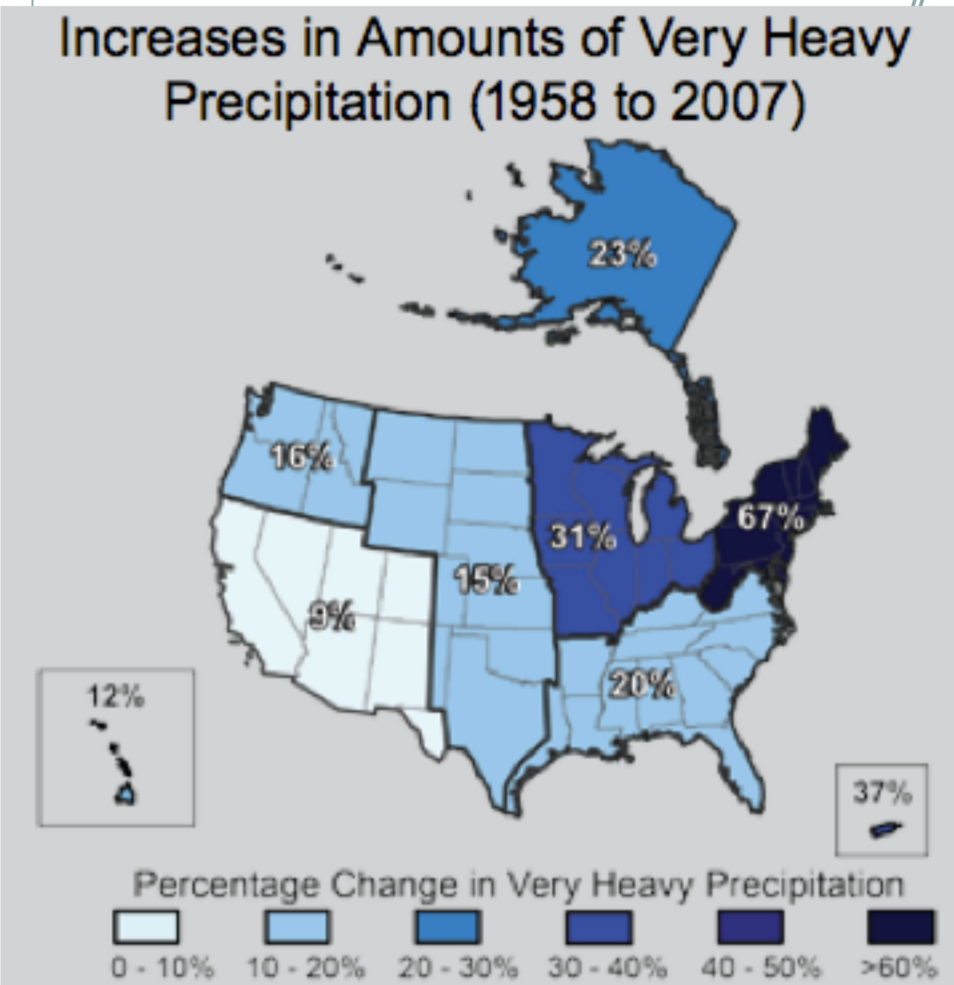
The strongest downpours require a lot of water vapor in the atmosphere

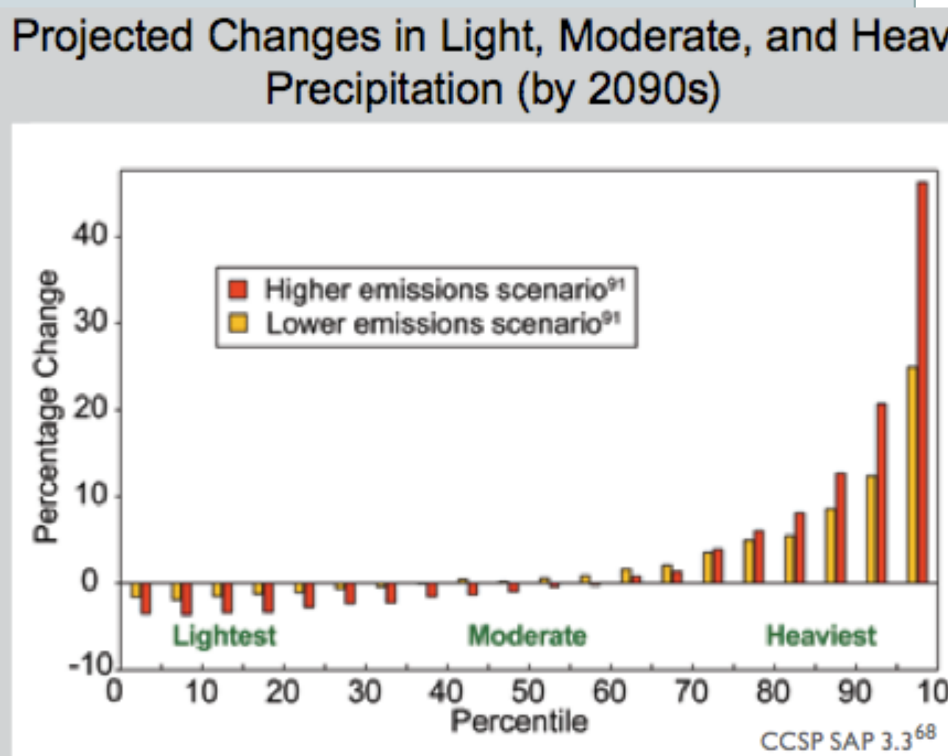
Warmer temperatures → more water vapor

Thus, heavy rainfall events should become more extreme

Also heavy snowfall events!

Are heavy rain events increasing?





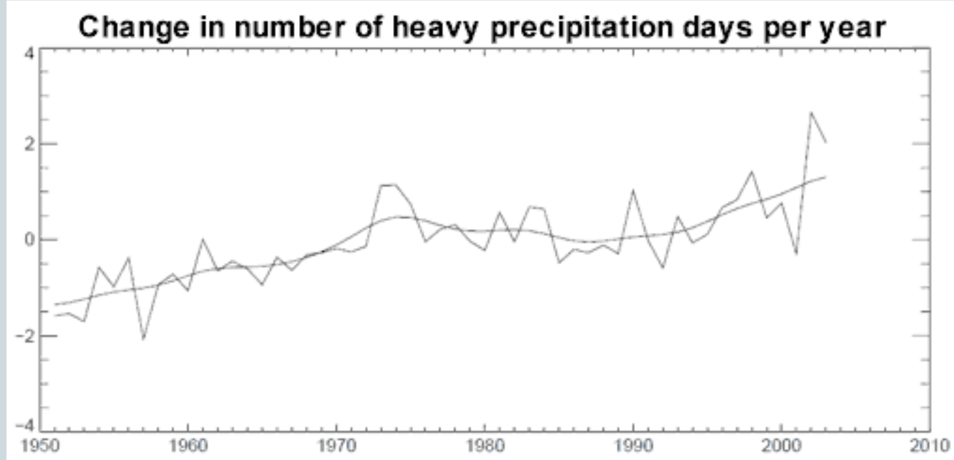
Very heavy events have been **increasing**

And heavy precipitation events in the US are **projected** to get worse

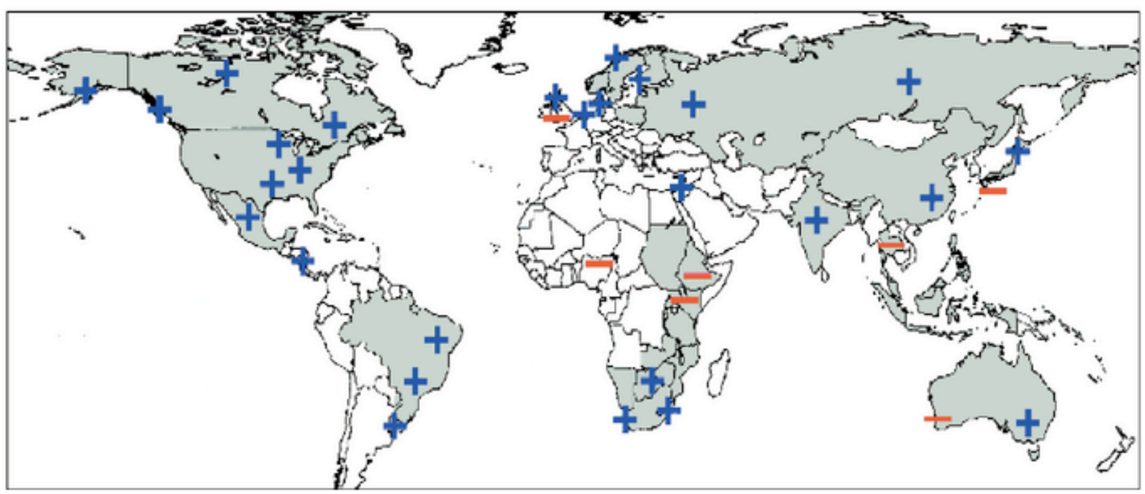
Are heavy rain events increasing?

The global picture on how much heavy rain is increasing

Global increase in **heavy rain days**



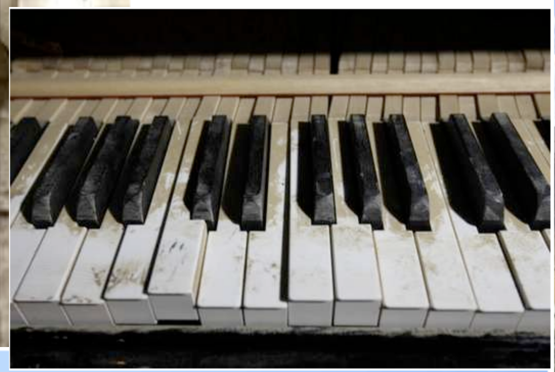
Locations where heavy rain is changing **disproportionally** (i.e., not just due to changes in average precipitation)



Let's look at some recent flood events…

Nashville, TN, May 2010

A 1000 year flood event (should happen once every 1000 yrs)
2 day rainfall: 13.57” at Nashville airport




Country Music Hall of Fame


LP Field (home of Titans)

Are floods increasing?

Extreme flood events should increase with increased heavy rain

Trends in the frequency of flood events are difficult to quantify because

Rare events, especially when considered season-by-season.
    it's difficult to establish statistical significance when dealing with rare events.

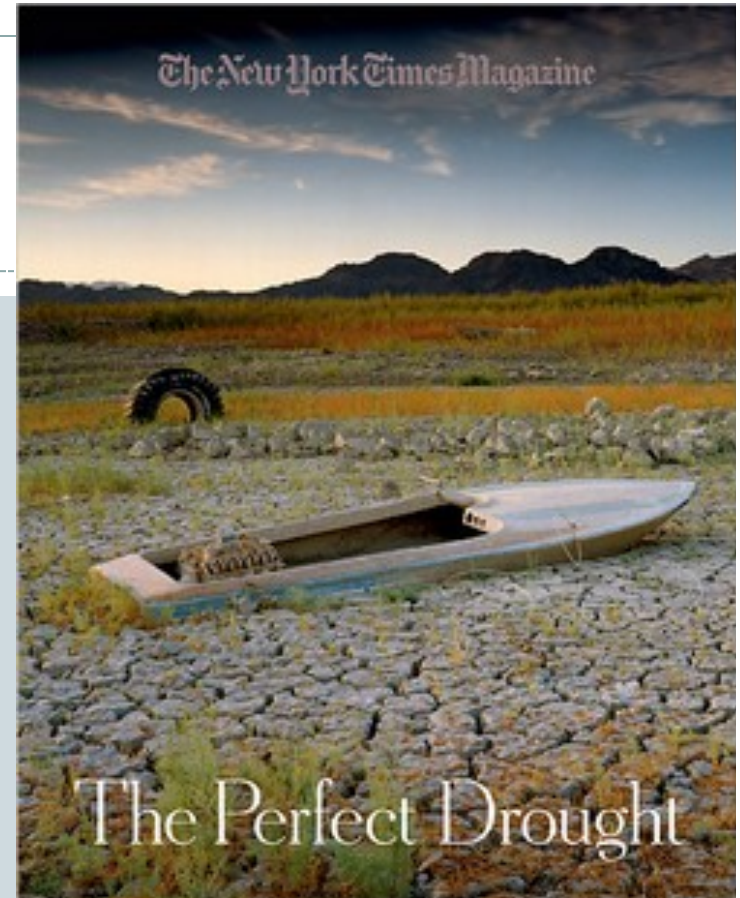
Hourly rainfall data are available only over limited regions of the globe

River configurations and land use are continually changing

The first two are true for heat waves too

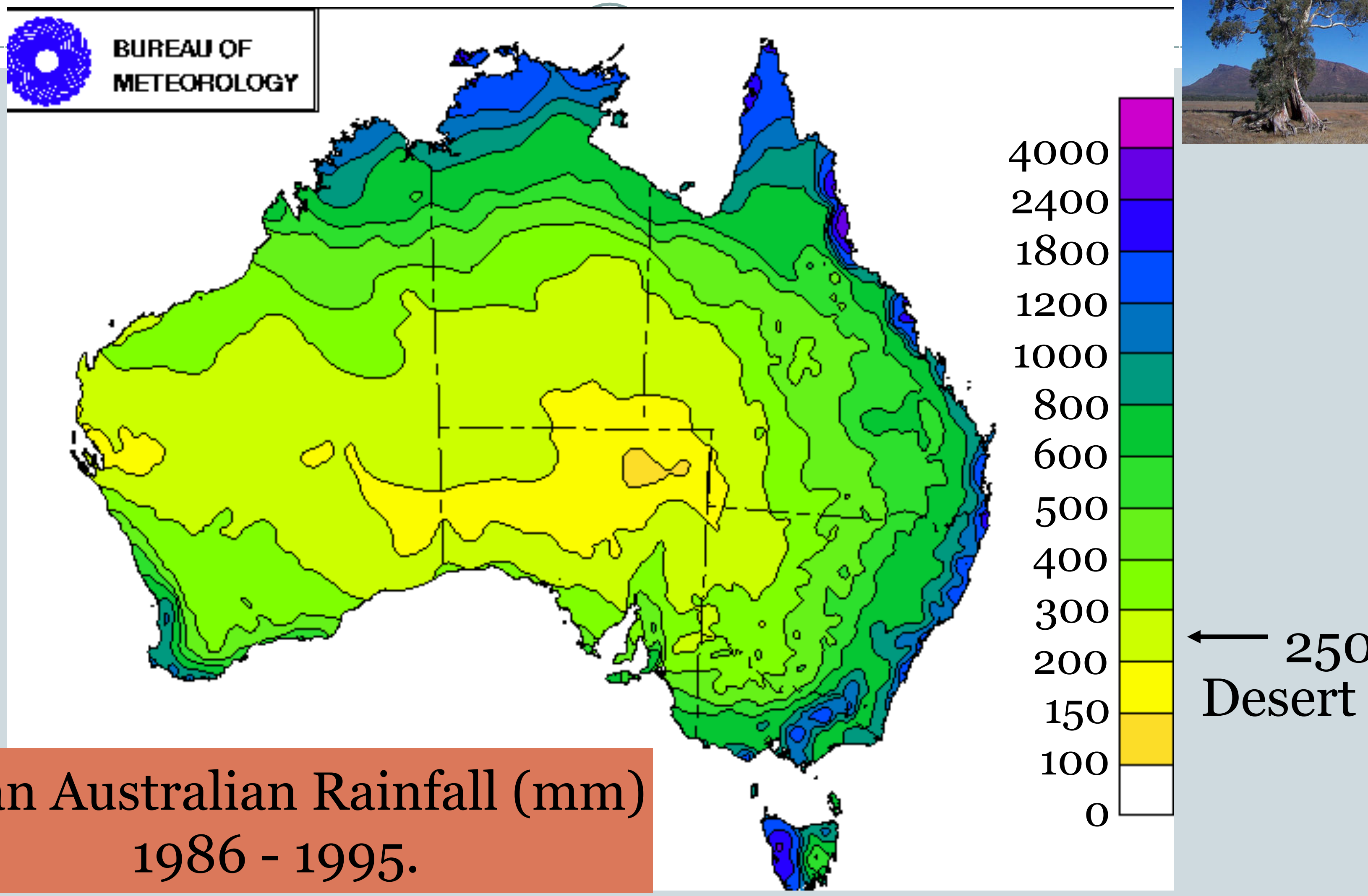
Defining drought

Months or years with below normal water supply.
Usually from below average precipitation.

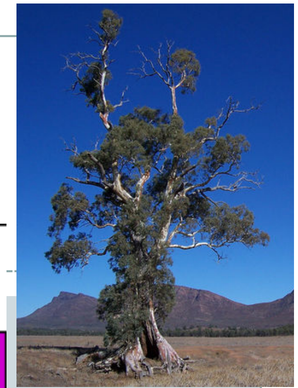


The definition is not quantitative.
Specific criteria (e.g., how long, how severe...) need to be specified.
Other factors such as population growth can create deficiencies in water supply (ie Lake Chad)

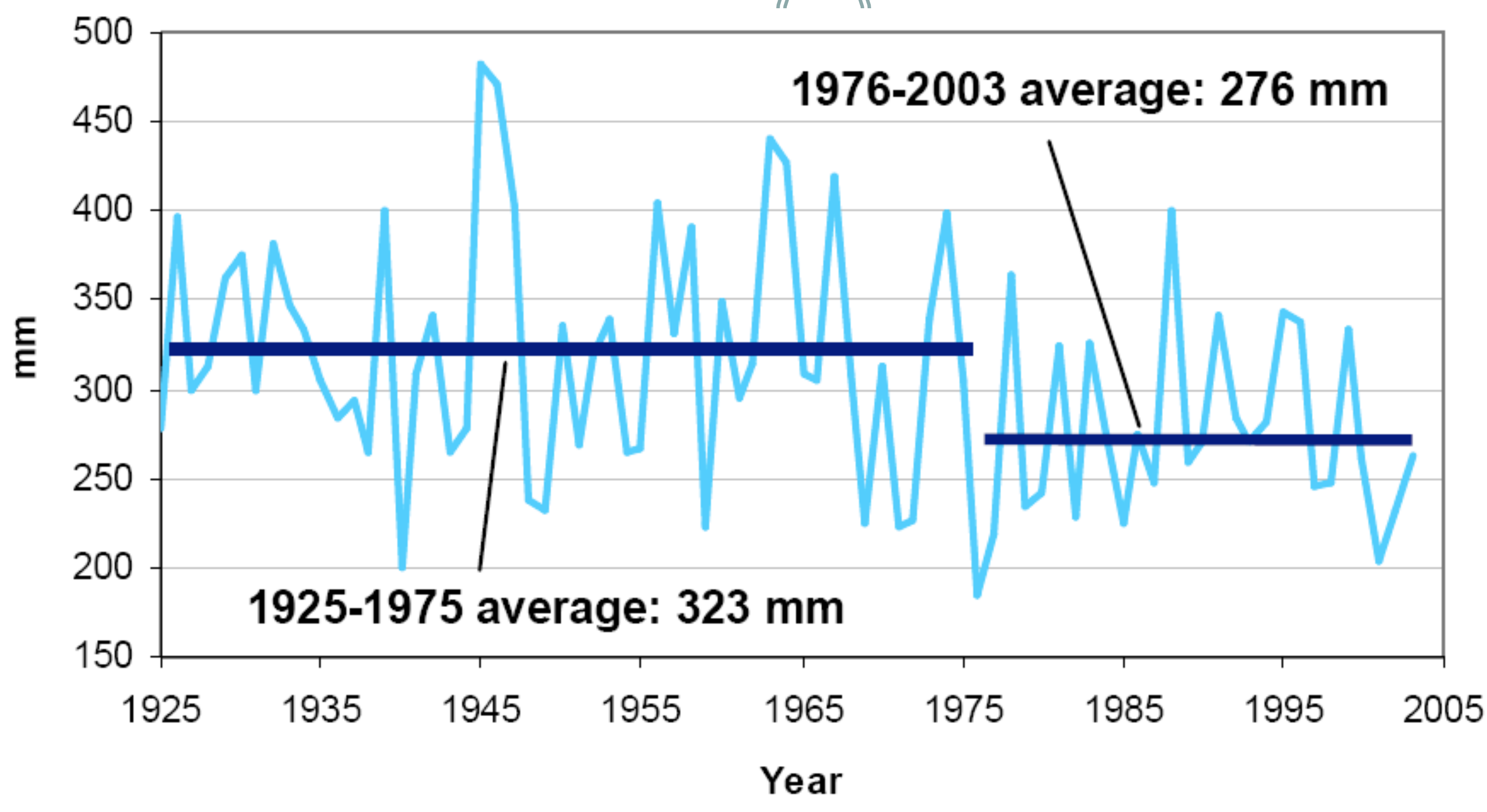
The drying of southern Australia



Mean Australian Rainfall (mm)
1986 - 1995.

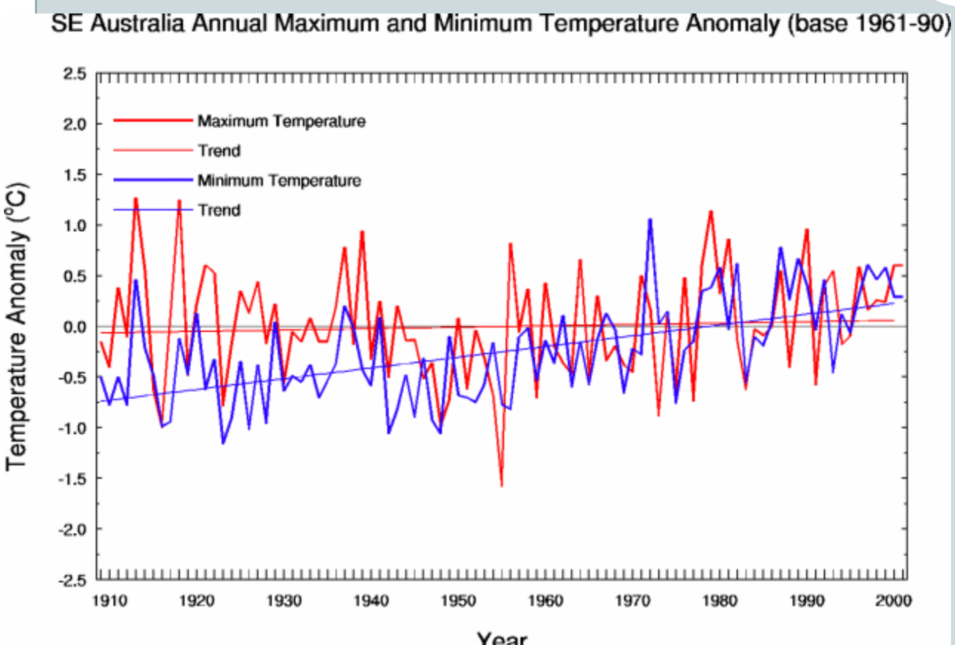


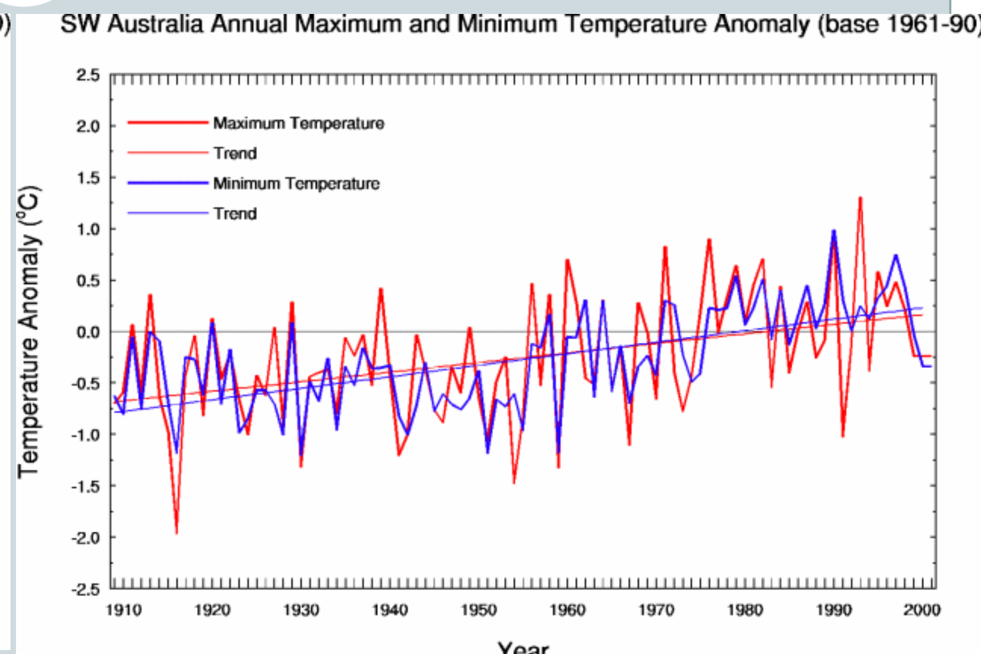
The drying of southern Australia



Shift in midlatitude storm track southward is important for drying
The decline in rainfall in south-western Australia since the 1960s.
Source:http://www.ioci.org.au/publications/pdf/IOCI_Notes_Series2.pdf.

Drying effects on temperature





In most places (as in SE Australia, shown here) **minimum** temperatures are rising faster than the maximum (greenhouse effect).

Note that in SW Australia, the **drying** causes very high **maximum** temperature rise too.

The drying of southern Australia

Other factors that may be playing a role

- southward shift in the storm track due to the ozone hole
- increased water demand due to rising temperatures:
  - "Potential evaporation"
- increased water demand due to population growth

What is potential evaporation???

- We've brought this up for being important for **drying land surfaces** a couple of times…
- aka PE aka potential evapotranspiration aka PET aka reference evapotranspiration aka ET_o aka ET_r aka E_o aka pan evaporation aka E_p aka evaporative demand aka …………………………

Thanks to Jack Scheff for these slides…

OK, pop quiz

- Climatological annual evaporation in a very hot, very dry desert is…

  Potential evapotranspiration (PET) is this sense of the word!

- a) much higher than in Seattle
- b) about the same as in Seattle
- c) much lower than in Seattle

So…

- In other words, PET is what would evaporate under given atmospheric and radiative conditions if water were available.
- The climate's "demand" for water.
- ~ Rate of water loss when stomata are open.
- Used in ecology, drought monitoring, …

What determines PET?

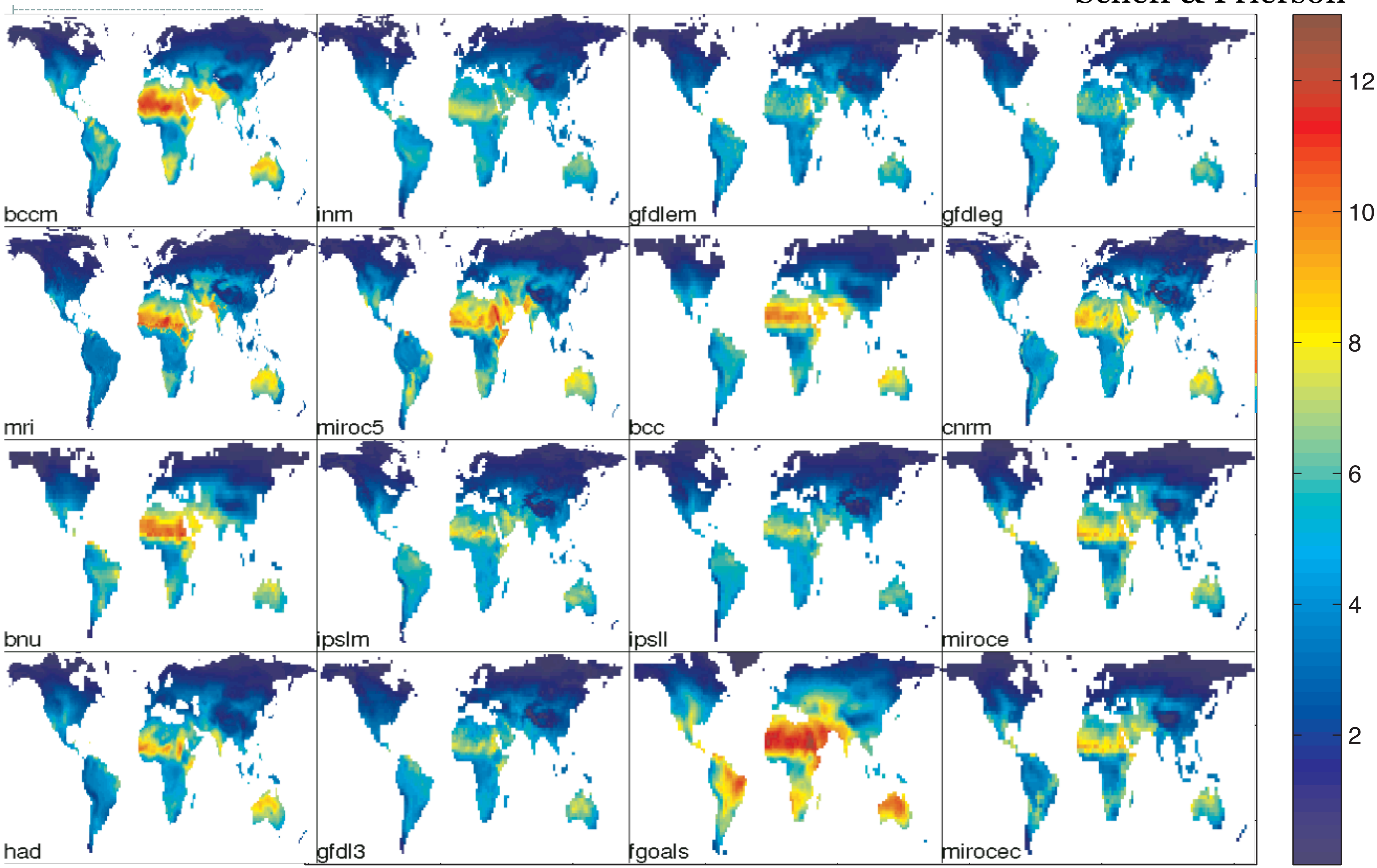
- Radiative energy input

- Drying capacity of the air itself
  - Vapor deficit: e_s*(1-RH)
    - (saturation vapor pressure times 1 minus relative humidity)
  - Windspeed

- Let's take a look at climatologies of PET in models…

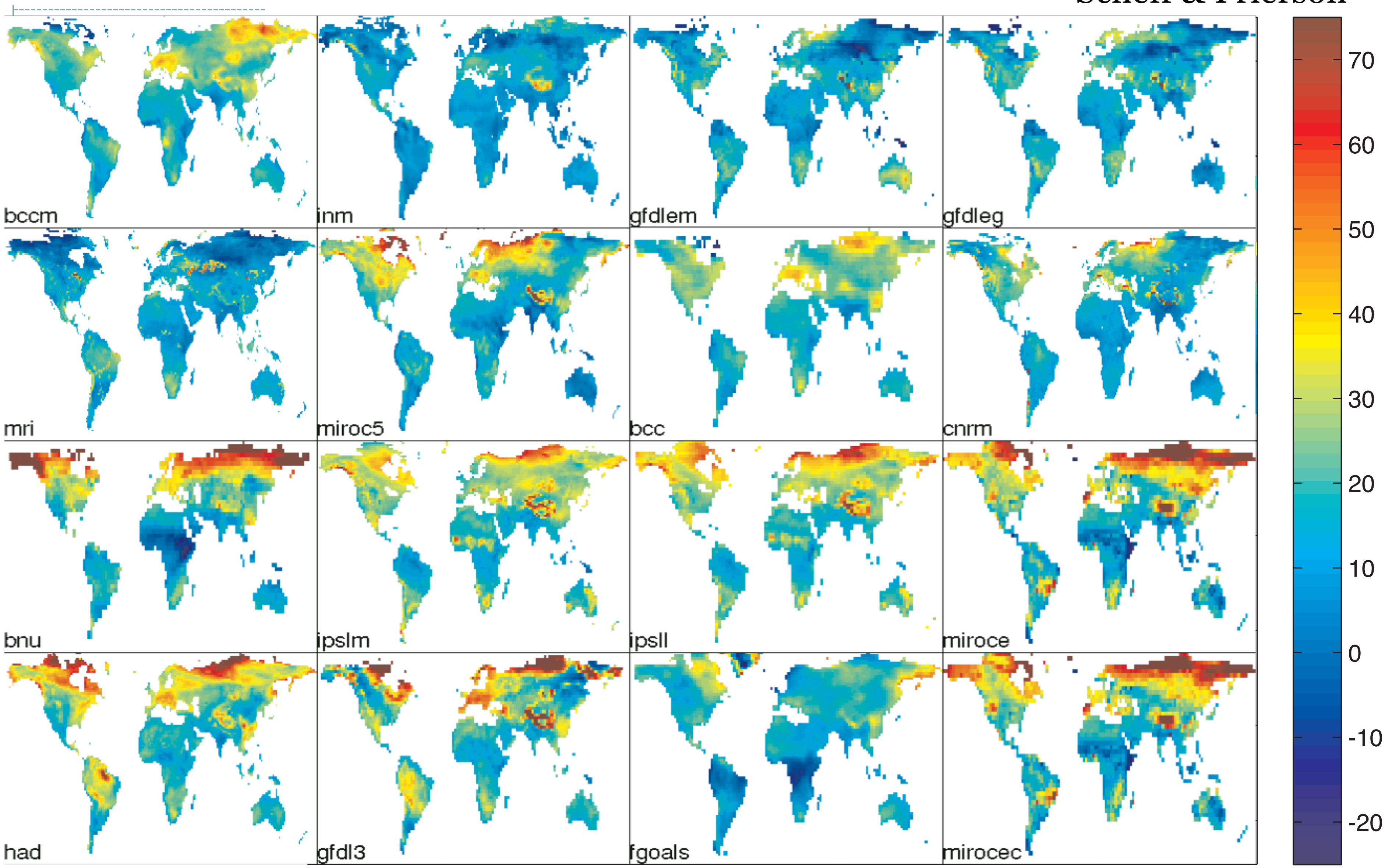
CMIP5 1981-99 PET climatologies (mm/day)

Scheff & Frierson



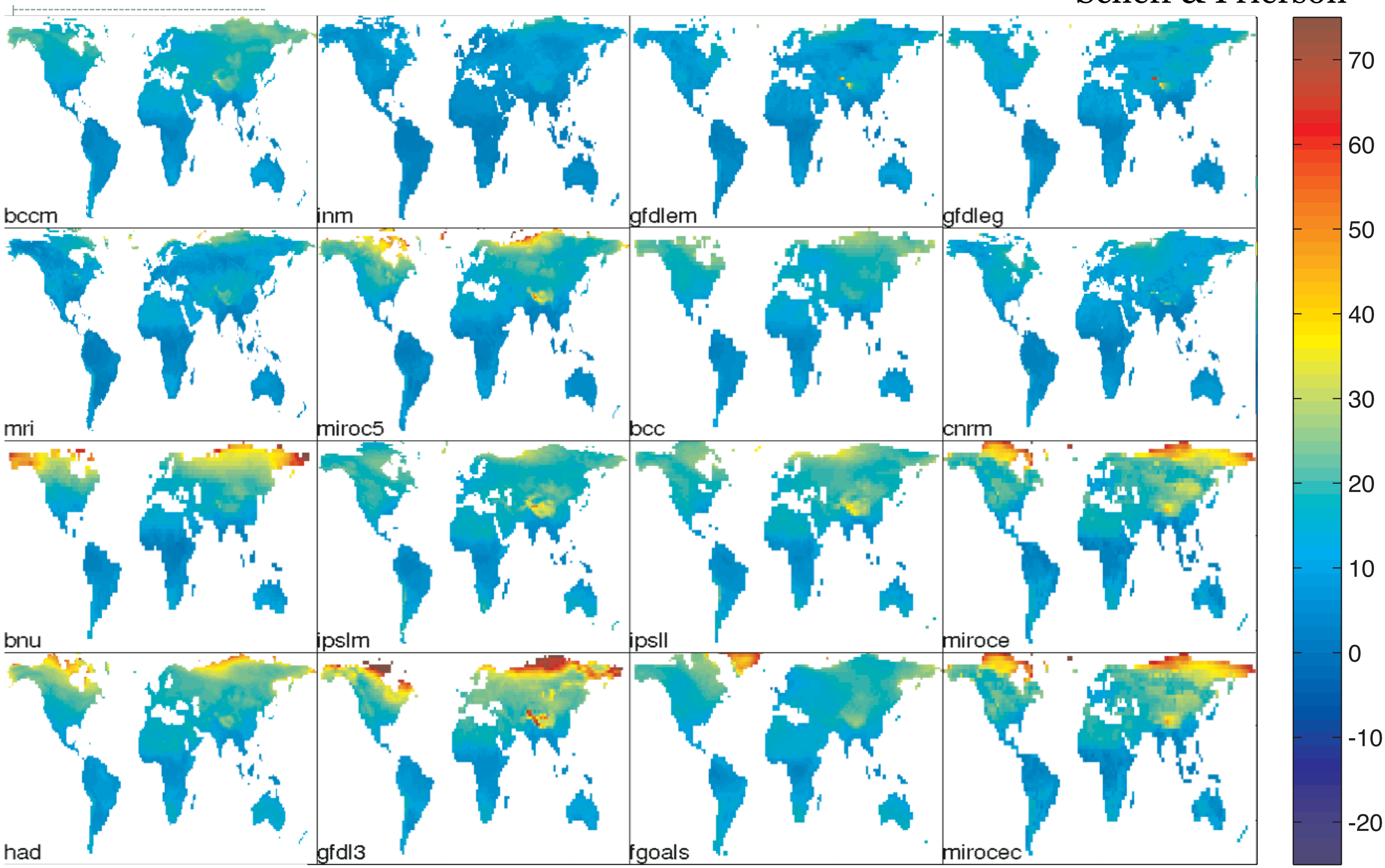
% Change in PET: rcp8.5 2081-99 vs. 1981-99

Scheff & Frierson

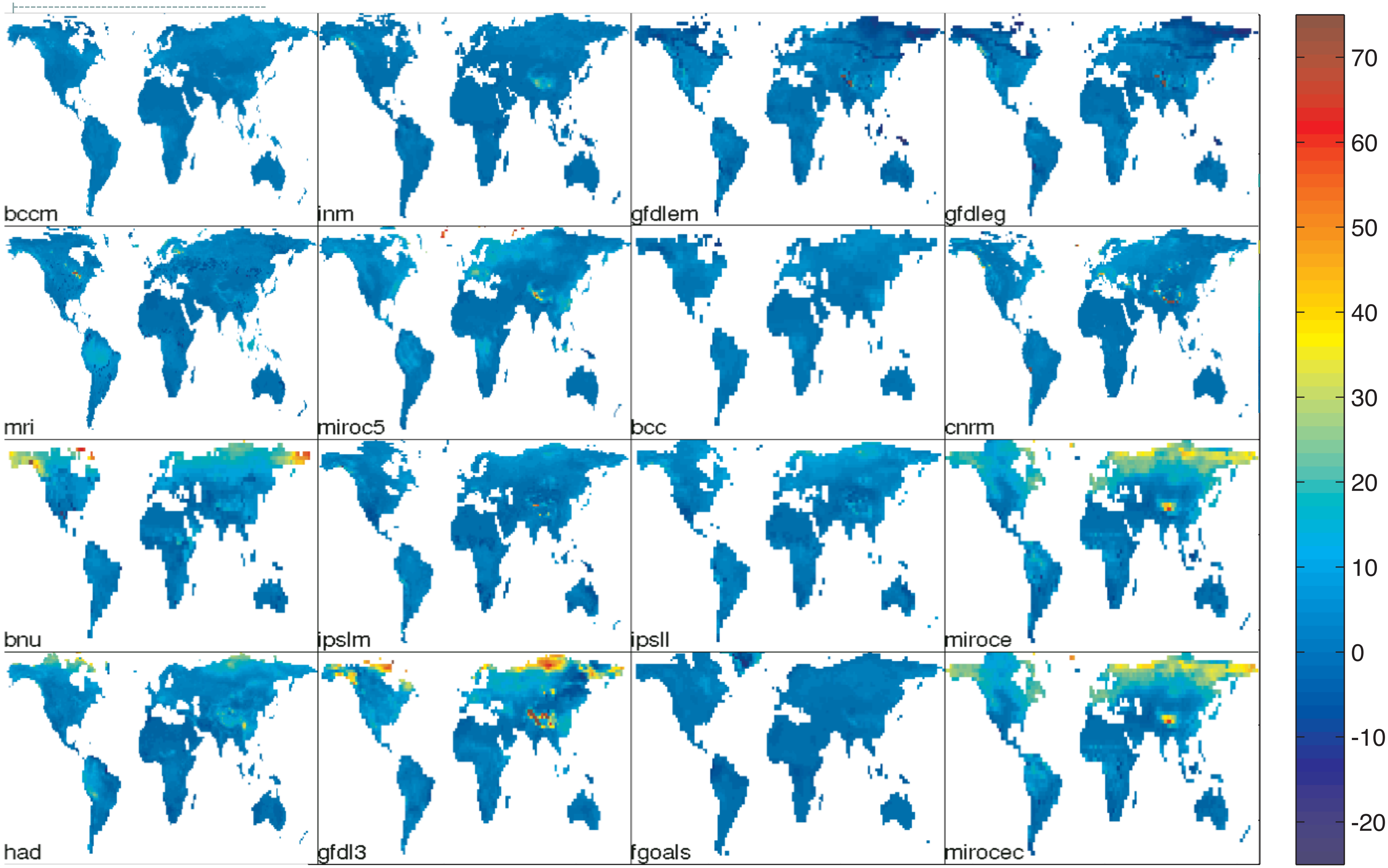


Due to temperature only, constant RH

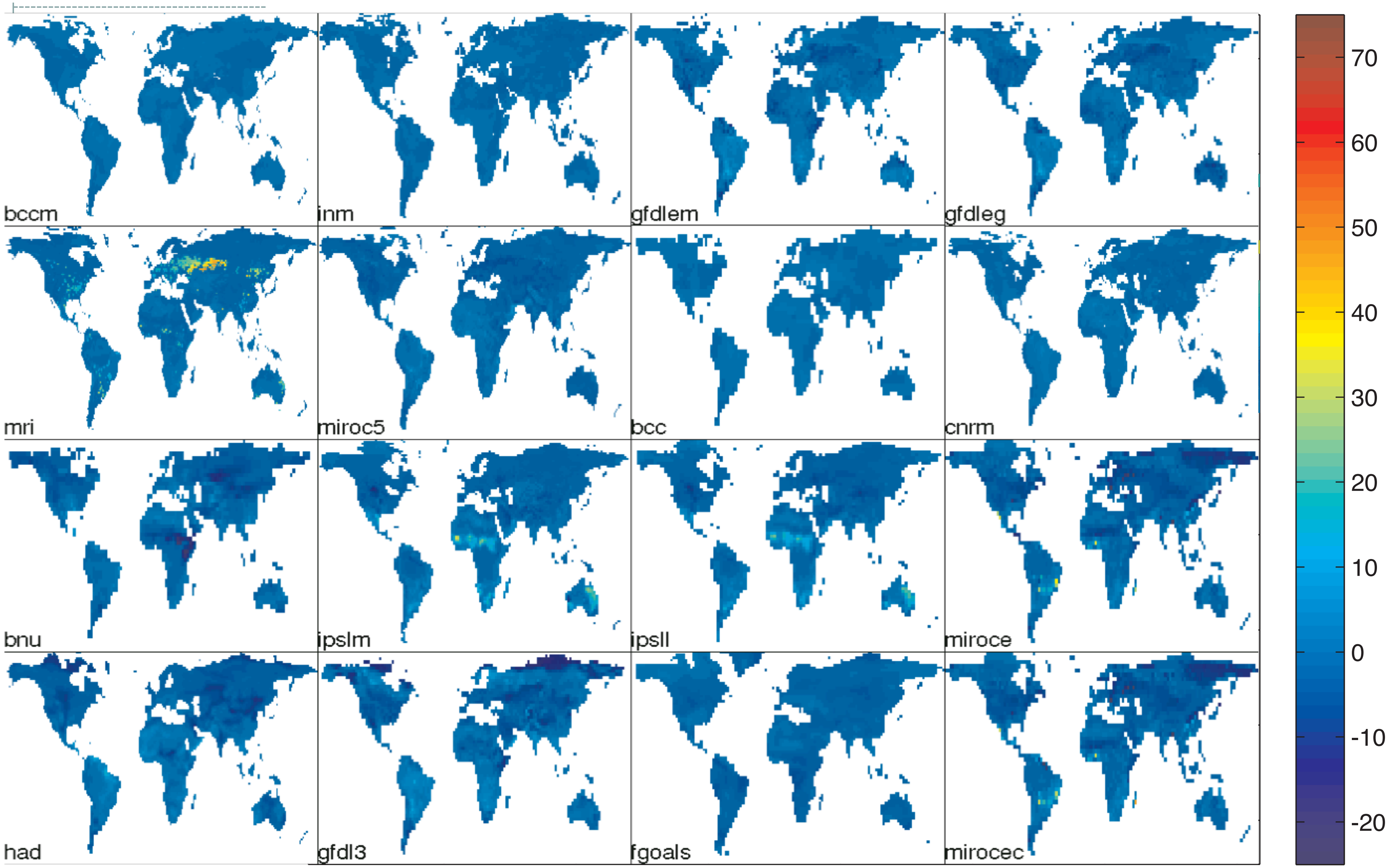
Scheff & Frierson



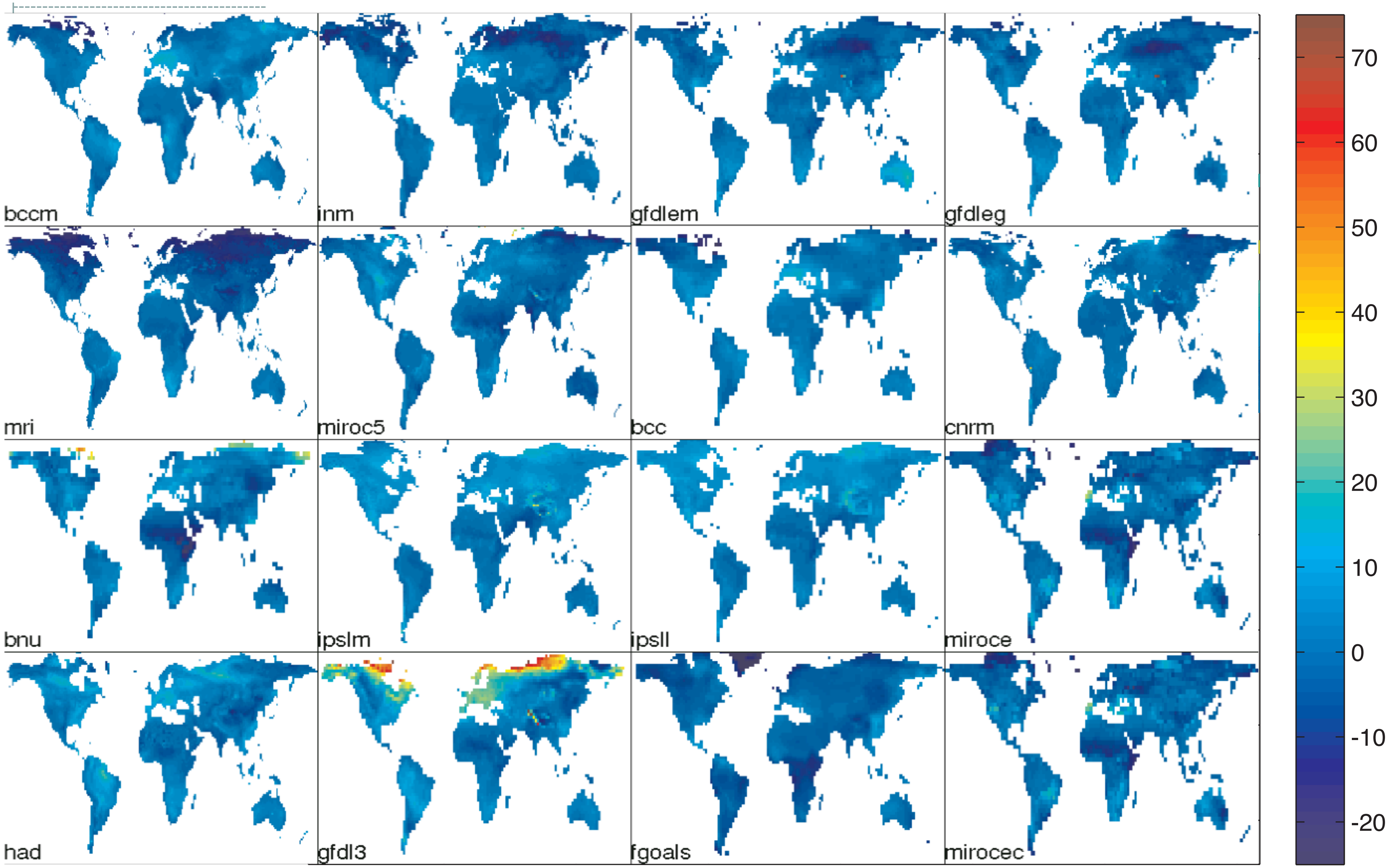
Due to surface net radiation only



Due to windspeed only



Due to relative humidity only, constant T



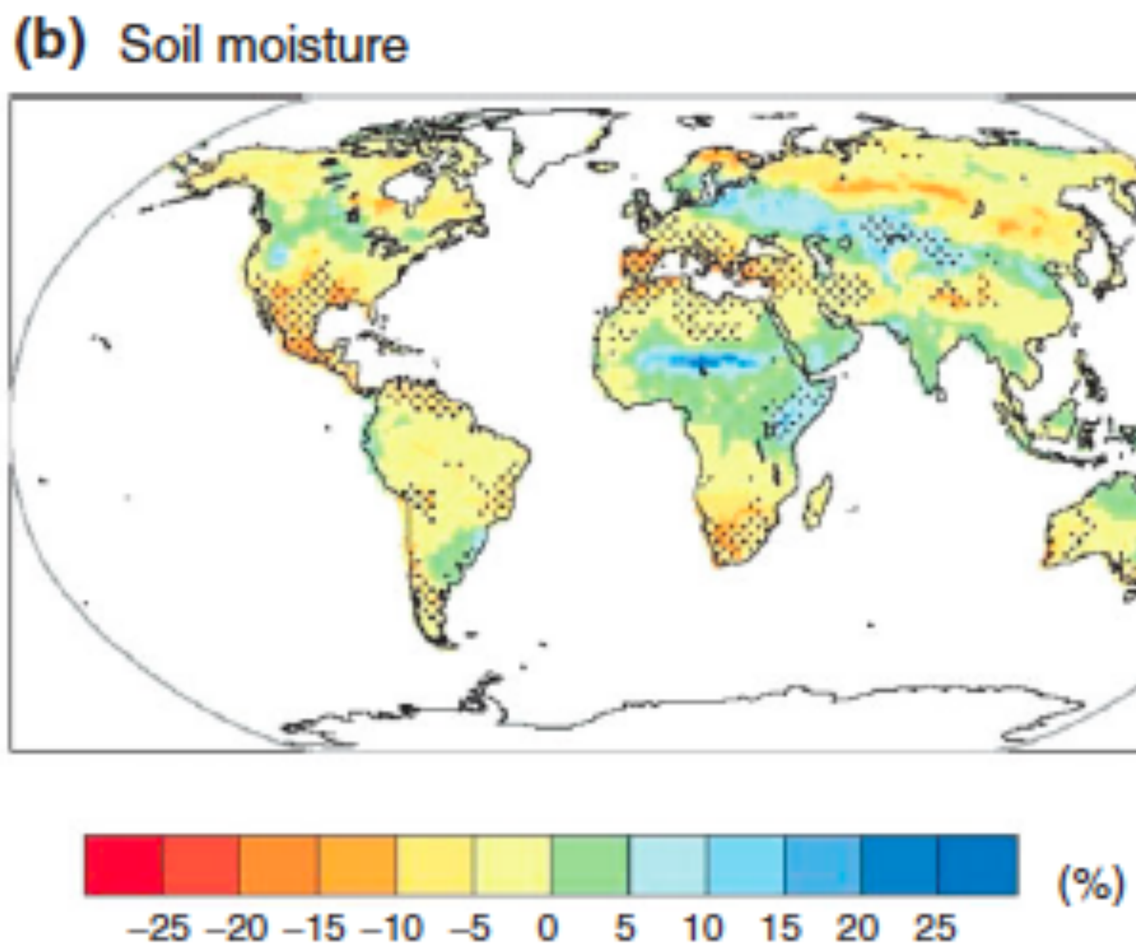
Summary of PET

- Models simulate rather different climatologies of PET
  - (so be a little careful with use for predictions)
- PET increases in a warmer world
  - Mostly due to **temperature** but a little due to **radiation** (more greenhouse effect)
- **More moisture will be sucked out of the land due to global warming**

Thanks to Jack Scheff for these slides…

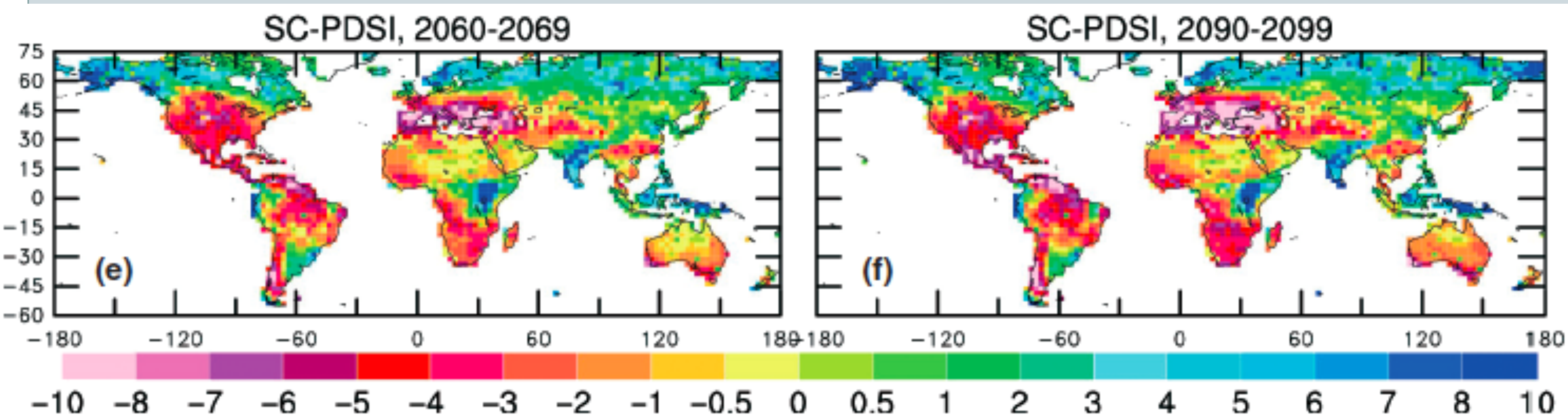
Impacts of PET + Precip Change

- Soil moisture (from IPCC AR4)



Palmer Drought Severity Index

- From Dai 2011



Summary of **Floods and Droughts**

- With global warming we will have **more water vapor** in the atmosphere
  - Warmer air can hold more moisture
  - Precipitation is limited by the energy budget though
  - Hence **rainy places get rainier**
  - **Big downpours** will be more intense
- Many land areas will dry out
  - More potential evaporation out of the land surfaces

Final Summary: Precip Shifts are Hard to Predict

- **Shifts** in rising motion or midlatitude storms could happen **due to**:
  - Differences in **forcings**
    - E.g., aerosols cooling the oceans in places
  - Differences in **feedbacks**
    - E.g., cloud responses
  - Changes in **ocean currents**
    - A natural example that messes with rain patterns is **El Niño**

Summary of **Floods and Droughts**

- Floods and droughts will doubtlessly be some of the most important impacts of global warming
  - **Hard to predict** exactly though
  - Small shifts in location of rising motion can make a big difference
  - Affected by many things
    - Forcings like aerosols
    - Feedbacks like ice or cloud changes
    - Natural variability like ocean current changes