Will this American century be dry? The evidence of the observational record

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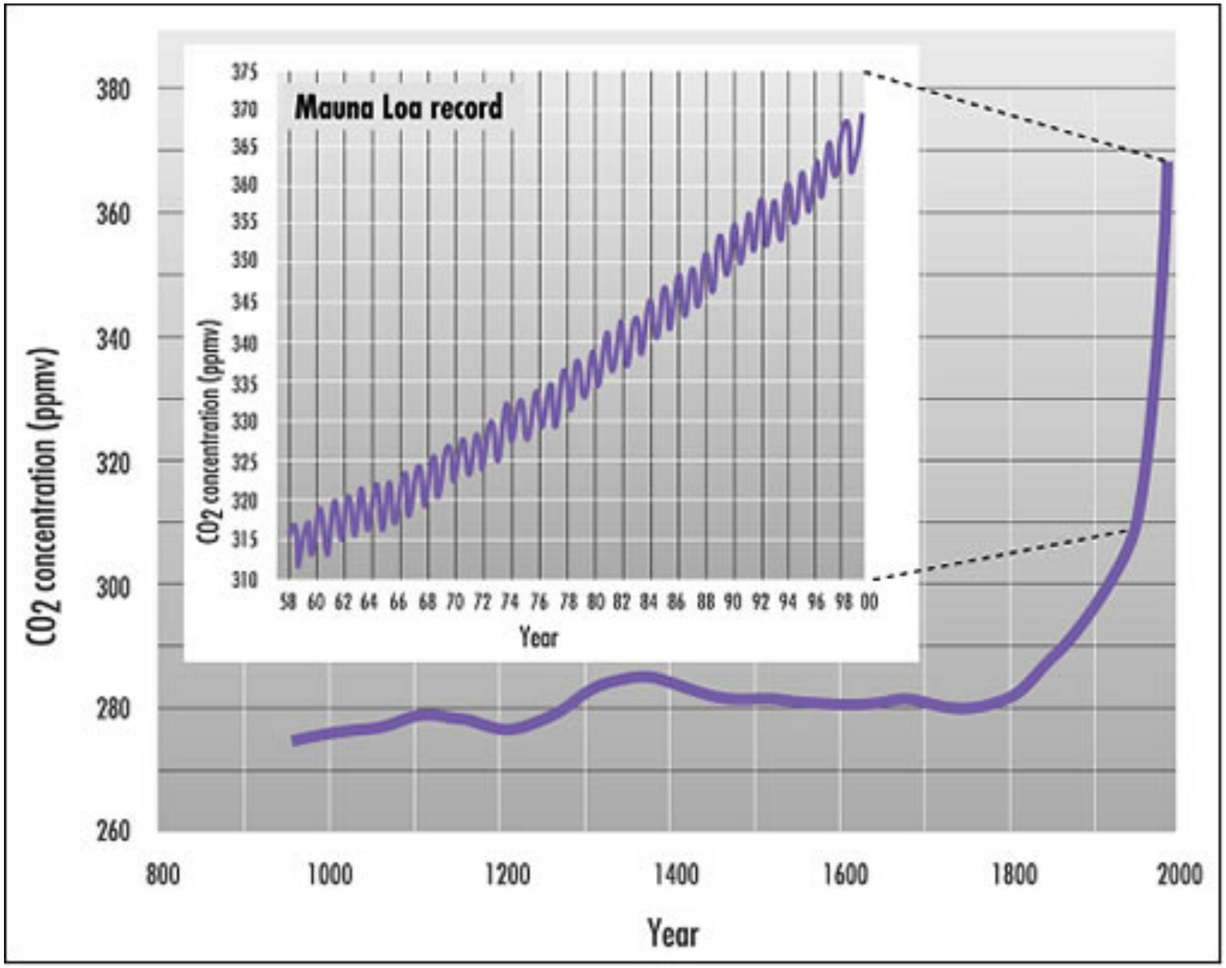
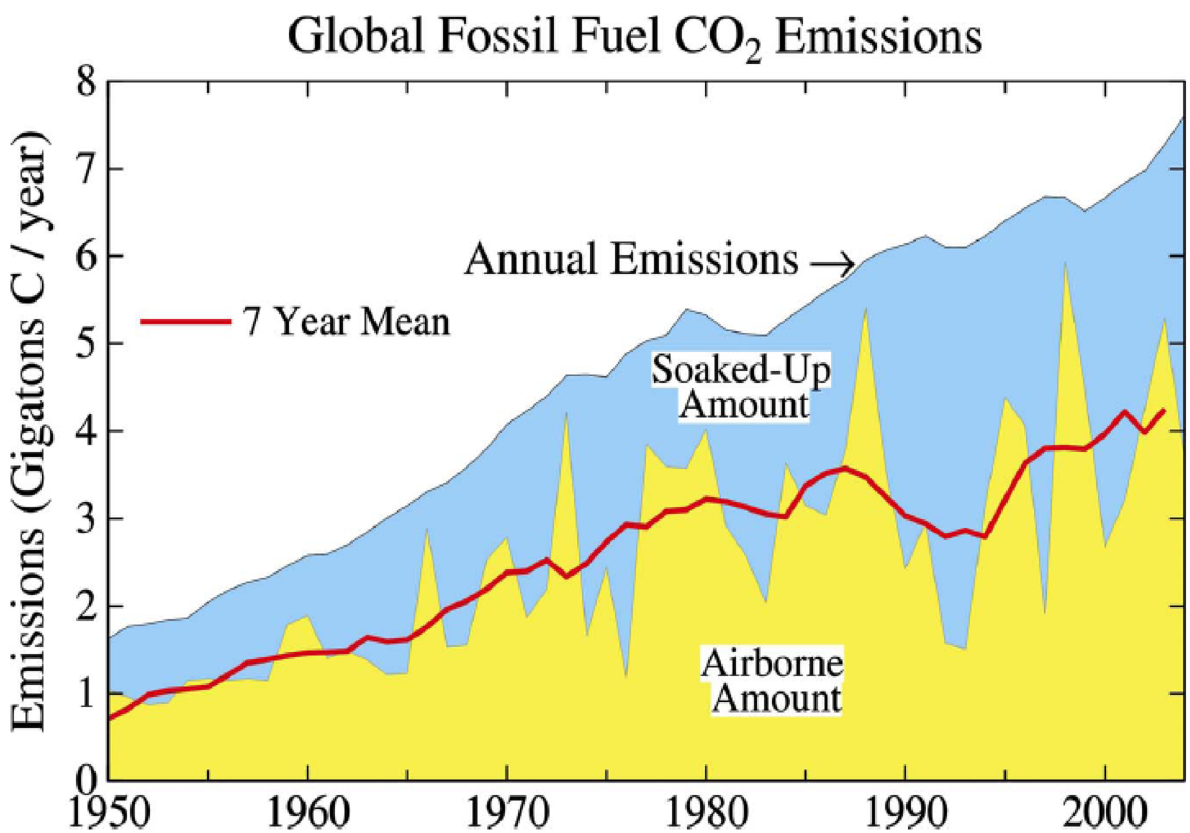
The atmospheric CO_2 mixing ratio



Australian Bureau of Meteorology

Will carbon sinks continue?

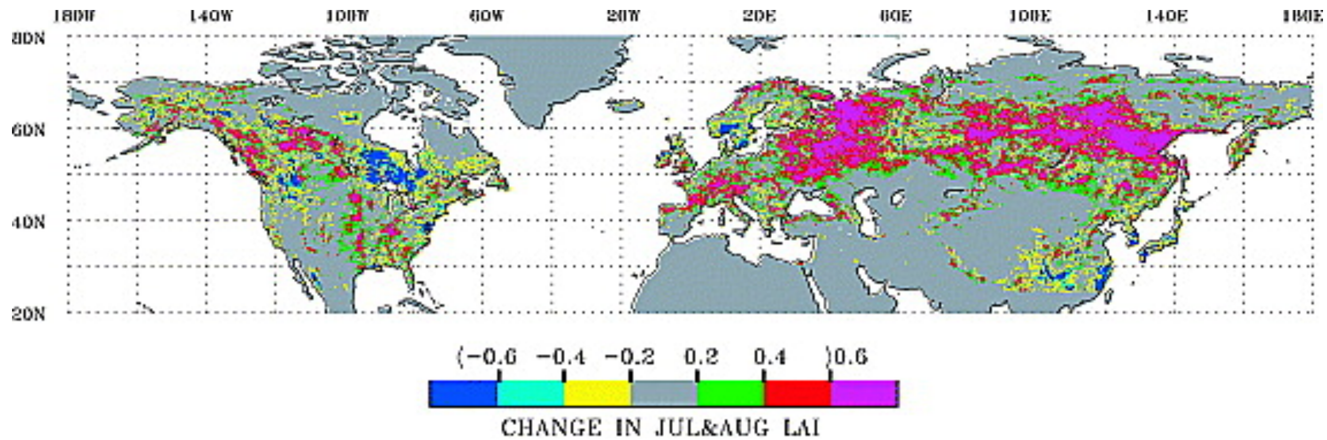
- **Consistently, the atmospheric CO_2 increase amounts to 55-60% of emissions from fossil-fuel burning**
- **What are the *sinks* that absorb over 40% of the CO_2 that we emit?**
  - **Land or ocean? Where? What processes?**
  - **Why the interannual variability?**
- **How will CO_2 sinks change?**



Global fossil fuel CO_2 emissions with division into portions that remain airborne or are soaked up by the ocean and land.

Source: Hansen and Sato, *PNAS*, **101**, 16109, 2004.

CO_2 uptake on land

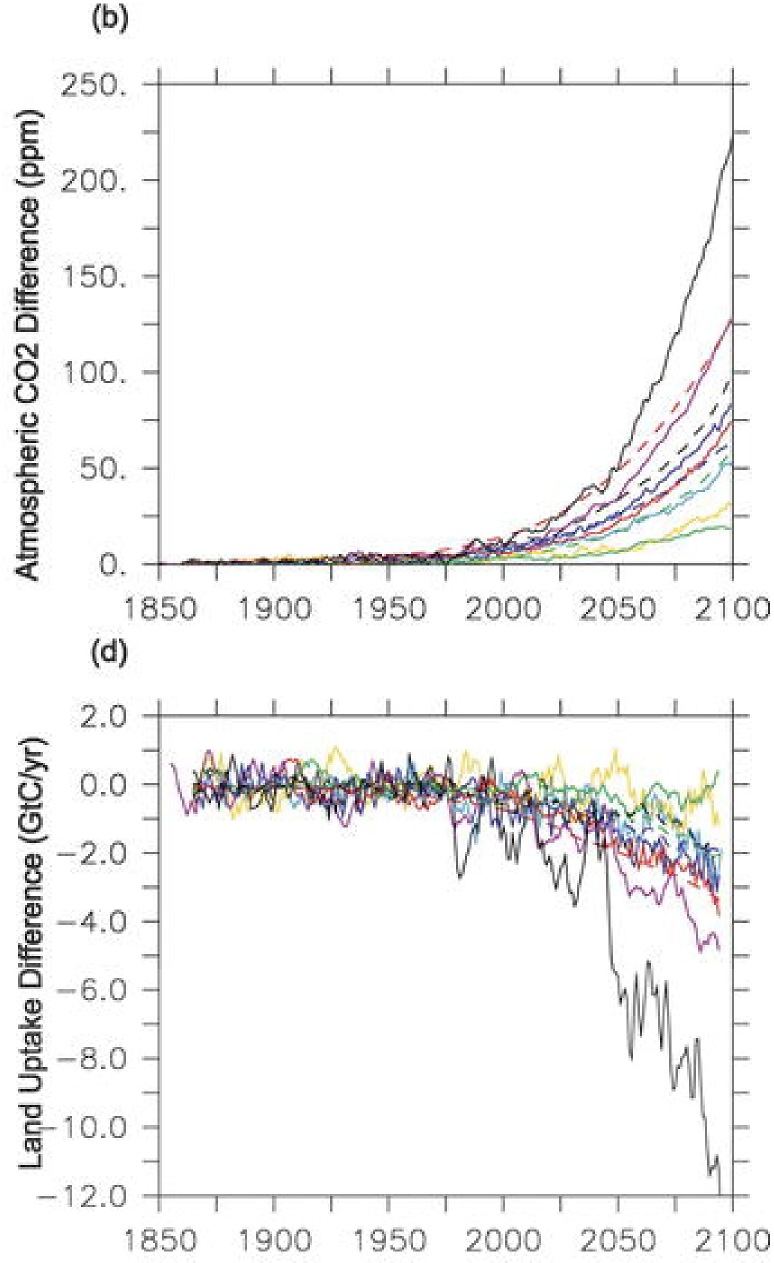


Trend for 1981-1994; Buermann et al 2002

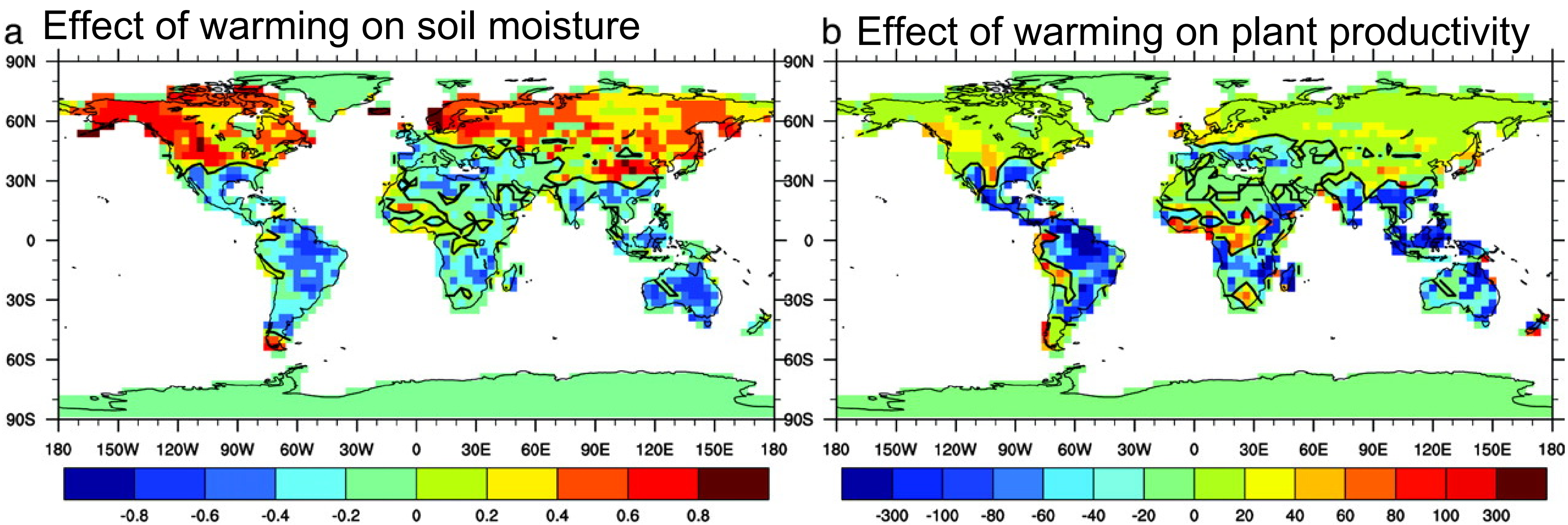
- Can separate ocean, land uptake from observations: for the 1990s, ocean uptake of 2.2±0.4, net land uptake of 1.0±0.6 Pg C / y (IPCC)
- Uptake must make up for ~1.5 Pg C / year deforestation
- Where is carbon being taken up? Biomass can be directly measured only in small-scale surveys; net uptake is small compared with gross plant growth of ~100 Pg C / y
- Plants might be growing more because of longer growing seasons, CO_2 fertilization, N fertilization, fire suppression, forest regrowth…

Will land carbon uptake continue?

- Friedlingstein et al. (2006): C^4MIP, an intercomparison of 11 climate-vegetation models with given 21st century human emissions
- In all models, land vegetation initially grows faster because of CO_2 fertilization
- In some models, the land changes from a carbon sink to a source with projected 21st century warming
- In all models, warming results in at least a smaller land carbon sink than would be the case if climate stayed the same



The negative impact of warming on plant growth is largely due to water shortage

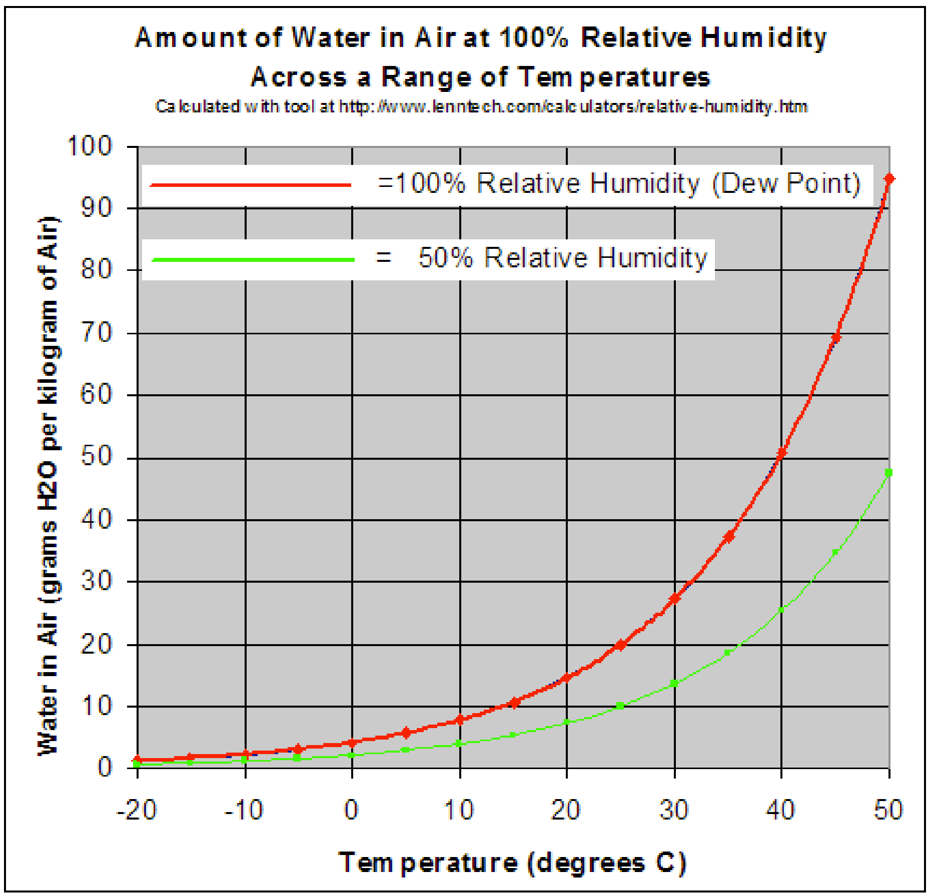


- Fung et al. (2005): response of plants to warming in a climate model
- In this model, warming decreases *global* plant productivity only slightly
- But large offsetting regional impacts: in tropics/subtropics, warming dries out the soil, and plants suffer; in cold places, warming increases precipitation more than evaporation, and plants thrive
- Evidently, small differences (like those between current models) in water availability and plant response could have a large effect on global plant carbon uptake

In (the rest of) this talk…

- What climate factors are expected to affect water availability over this century?
- What do observations suggest about the effect of greenhouse warming so far on the water cycle?
  - An analysis of USA streamflow trends
- Is the impact of drought on land carbon uptake already detectable?

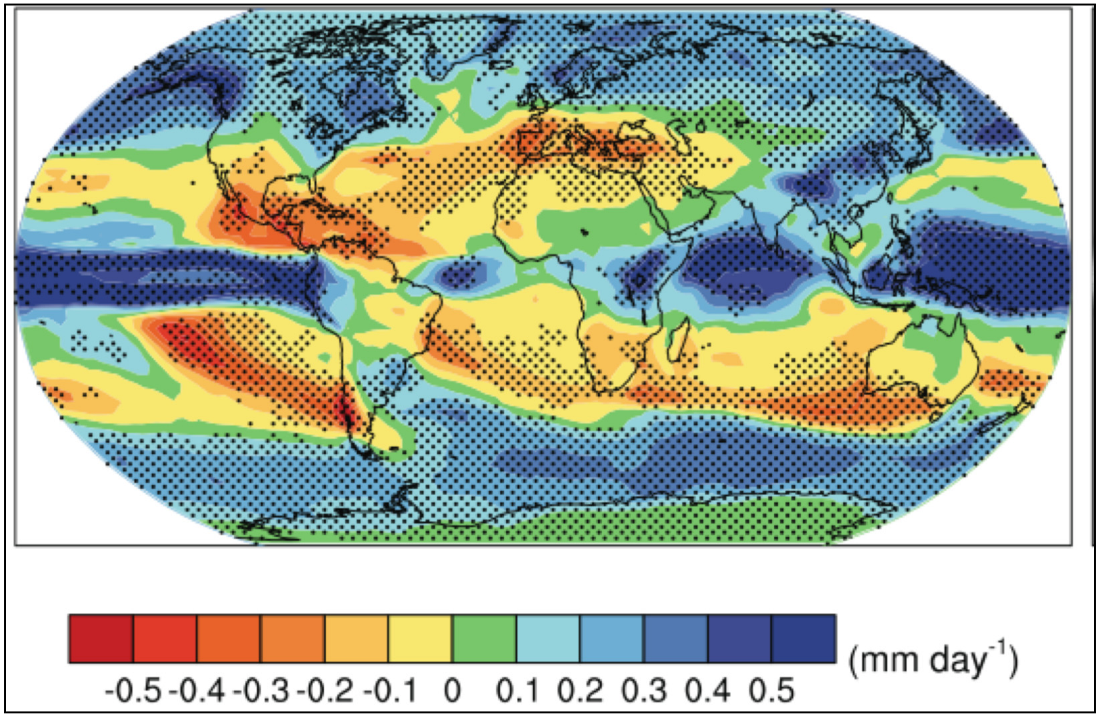
What might we expect for water availability under global warming?



Gregg Benson (Wikipedia)

- A naïve view: warmer → steamier → wetter
- For given relative humidity, the amount of water vapor in air increases exponentially with warming (~7%/K)
- Therefore more 'tropical' conditions – more evaporation and precipitation, stronger storms?

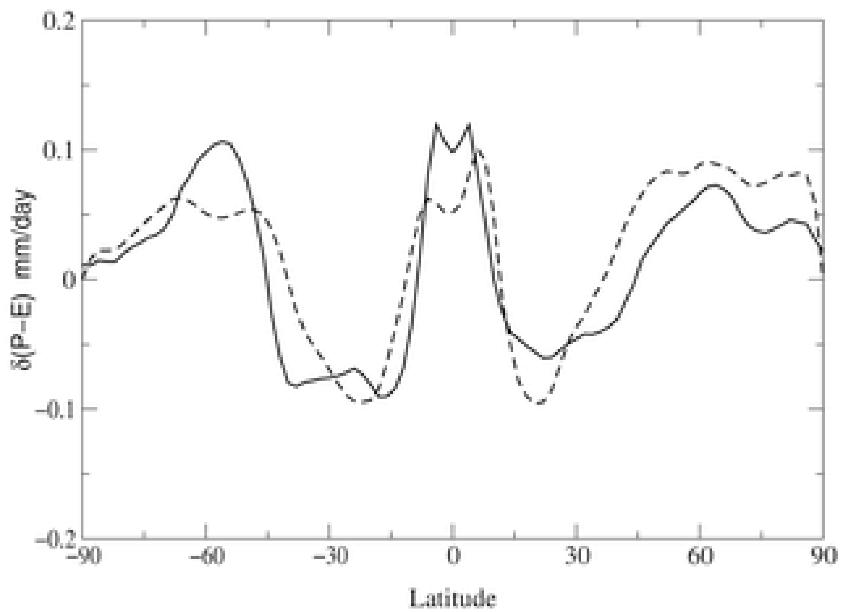
But climate models predict otherwise



IPCC AR4
Model mean precip.
A1B emissions
2080-2099 minus
1980-1999
Stippling: 80% of
models agree on
sign of change

- *Slight* increase in average precip. (~2%/K warming)
- Not uniform
- “Wet get wetter, dry get drier”
- Combined with changes in evaporation, should have a large impact on plants

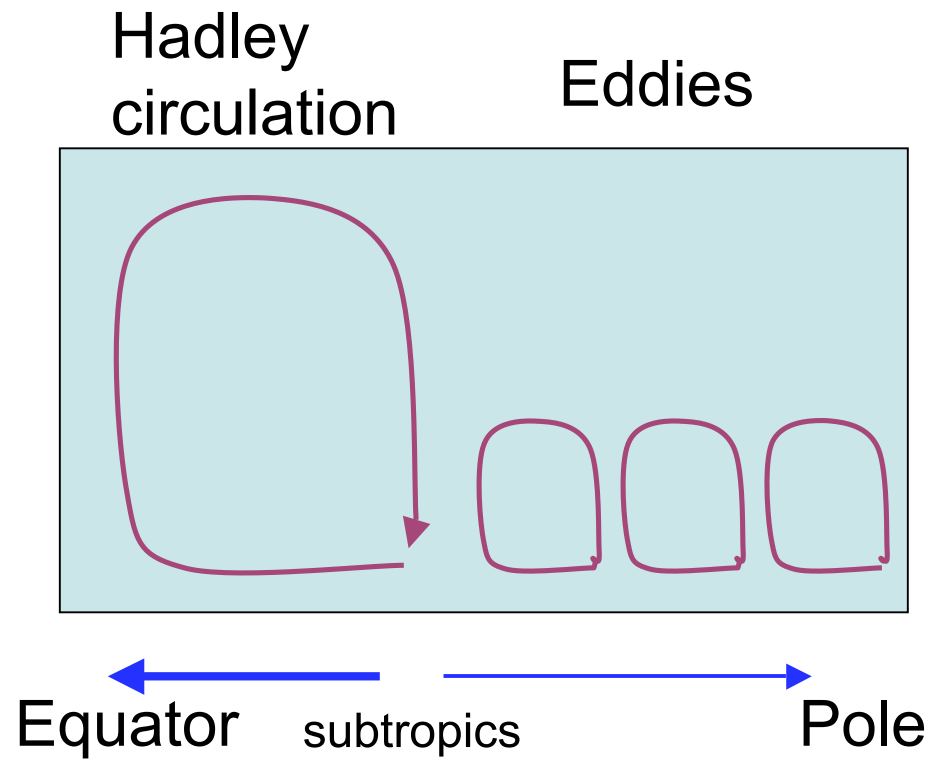
Parts of the world get drier *because* the air holds more water vapor



Solid lines: climate model responses

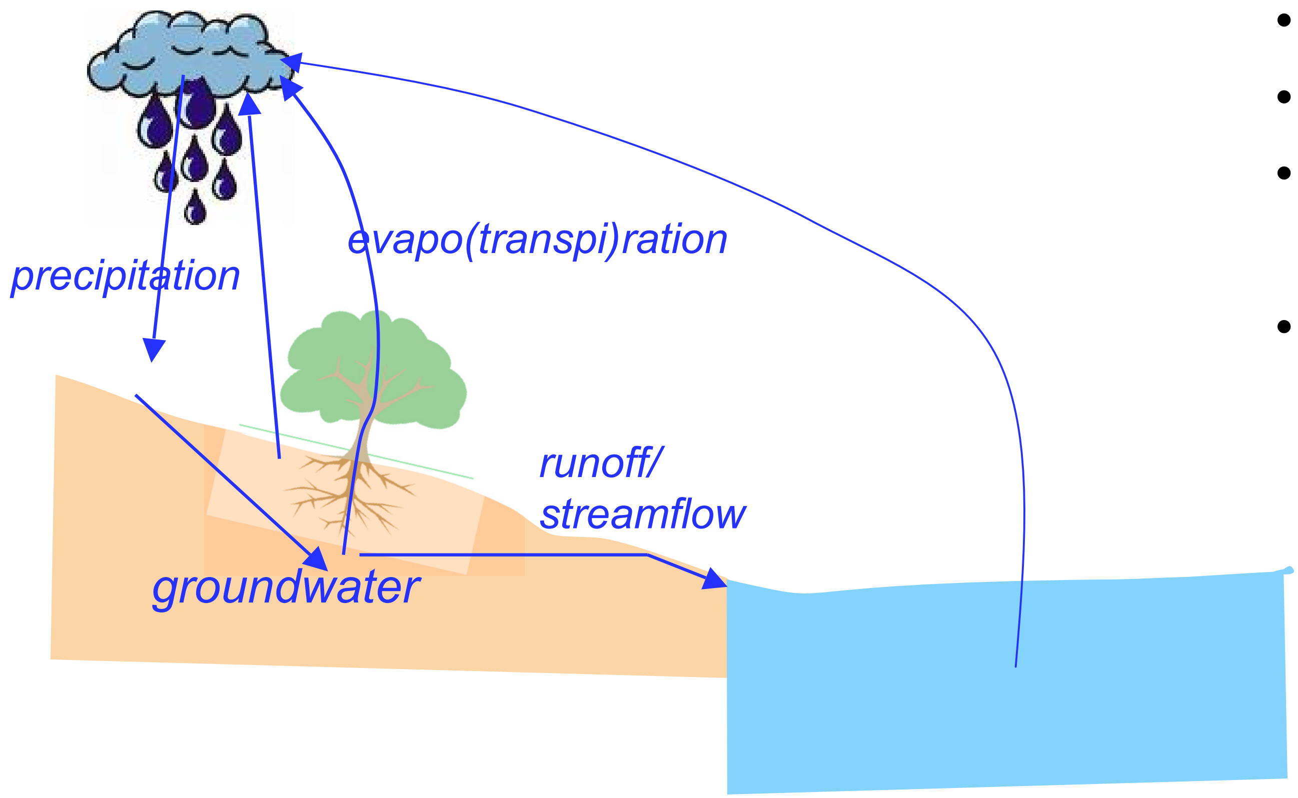
Dashed lines: Effect of greater water vapor transport

Held and Soden, J. Climate, 2006



Same transport + more water vapor → more extreme convergence and divergence

On land, the water cycle is even more complicated…



- Topography
- Drought
- Plants

- Evaporation depends on soil moisture, plant cover, plant health, root depth…

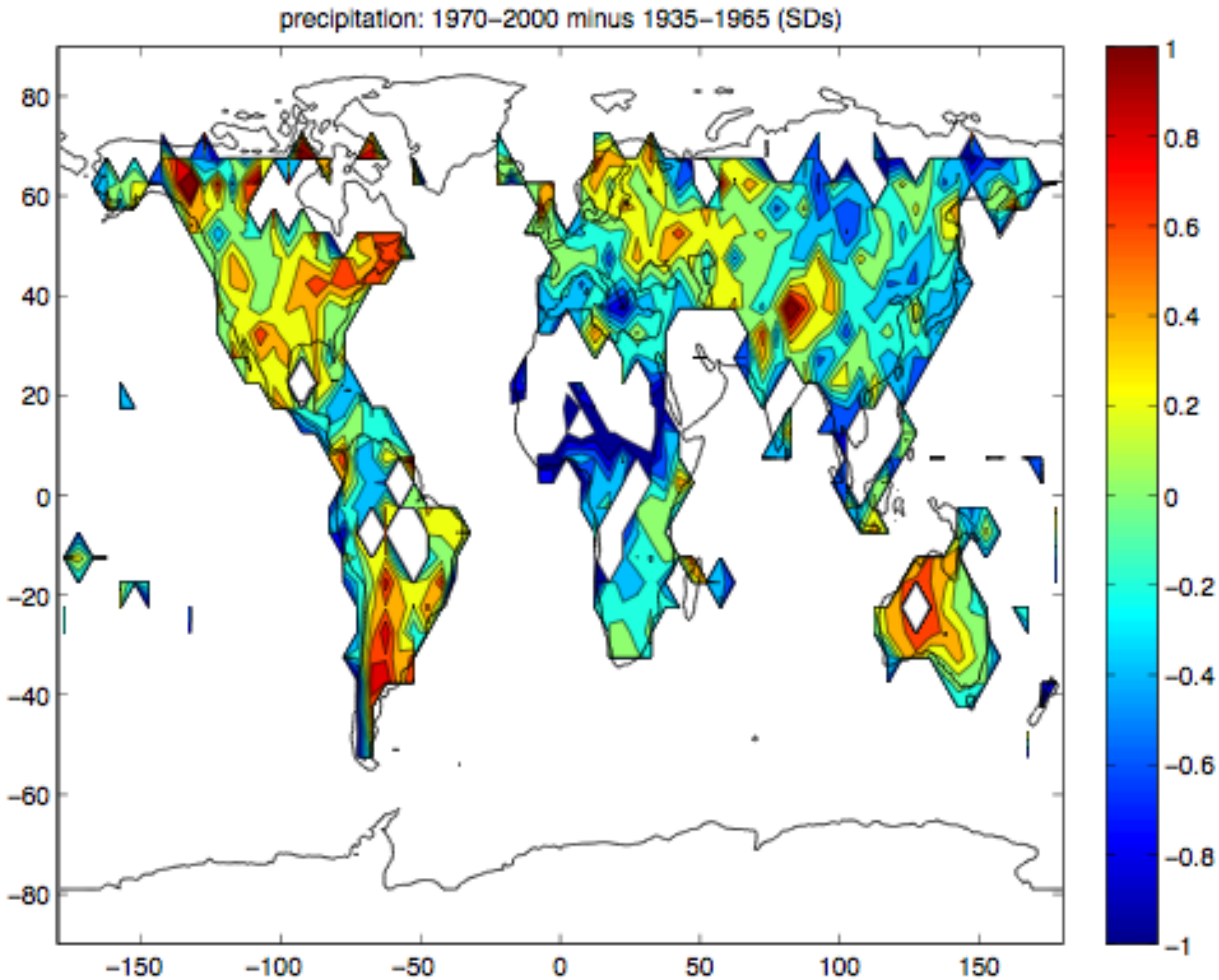
Water budget:

Storage = precipitation - evaporation - runoff|streamflow

small when integrated over a long period

WPclipart; NOAA

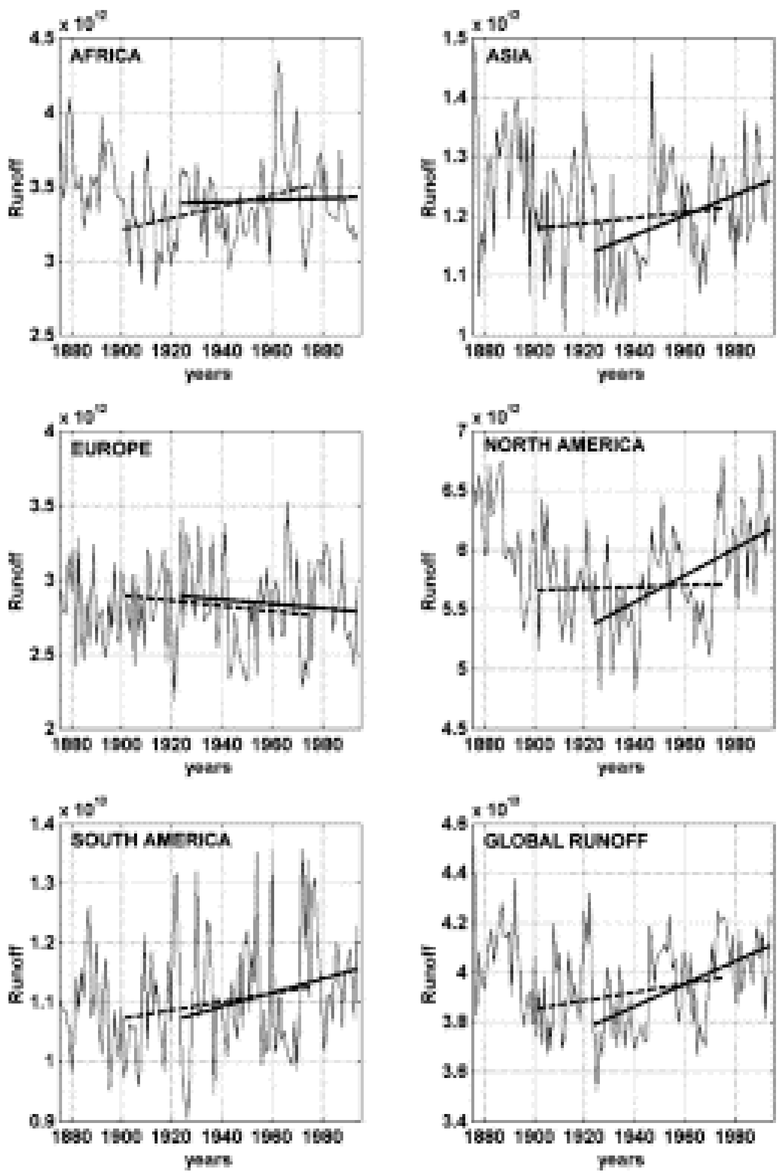
What's happening to land precip.?



Data: GHCN

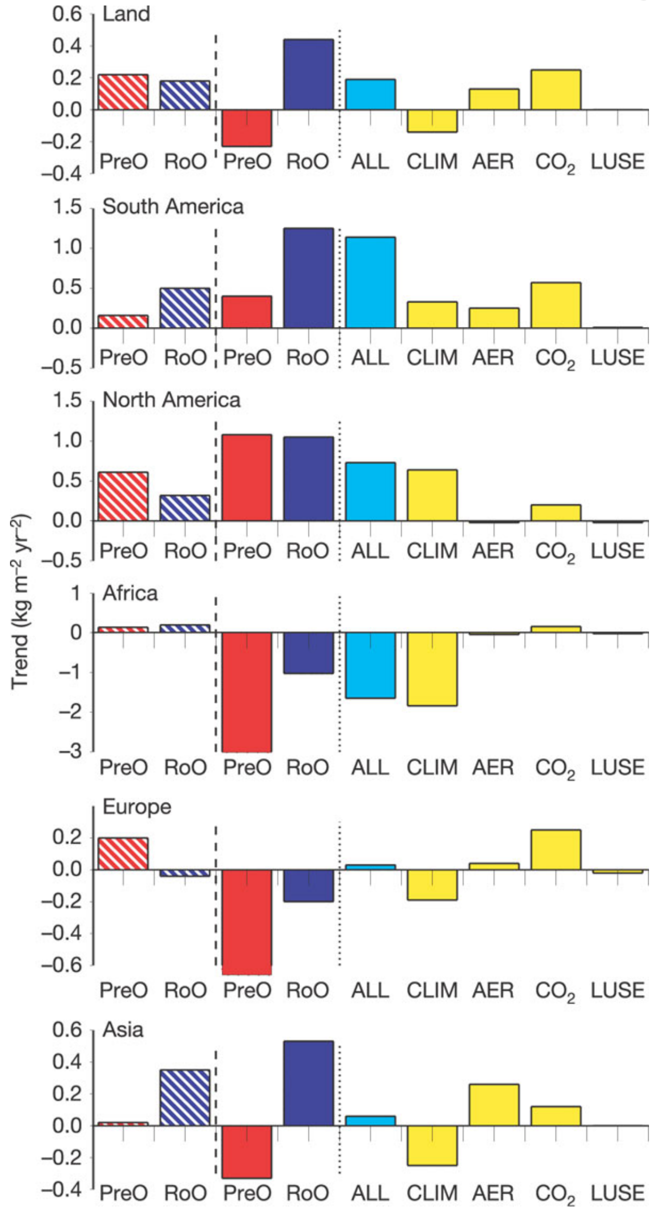
- More in midlatitudes, less in Mediterranean and Sahel
- Latitudinal pattern is broadly consistent with modeled effects of greenhouse gas radiative forcing (Zhang et al, 2007)

What about evaporation?



- No measurements of long-term trends
- Can infer from streamflow and precip. by difference
- Labat et al. (2004)
  - Reconstruct patterns in continental runoff from streamflow records using a wavelet transform
  - Over 1926-1994, global runoff increased 4%/K warming
  - Positive response was largest in North America
  - Is this because precip. Is increasing or evaporation is decreasing?

Is high CO_2 reducing plant transpiration?



1901-1994|1960-1994

- Gedney et al. (2006) compared the changes in continental streamflow estimated by Labat et al. with Hadley Center climate model predictions
  - Much of the runoff increase is due to plants transpiring less water because CO_2 enters leaves more easily
  - Land use changes do not affect global runoff
- Betts et al. (2007): therefore plants and streams will do relatively better under high CO_2 levels

Or not?

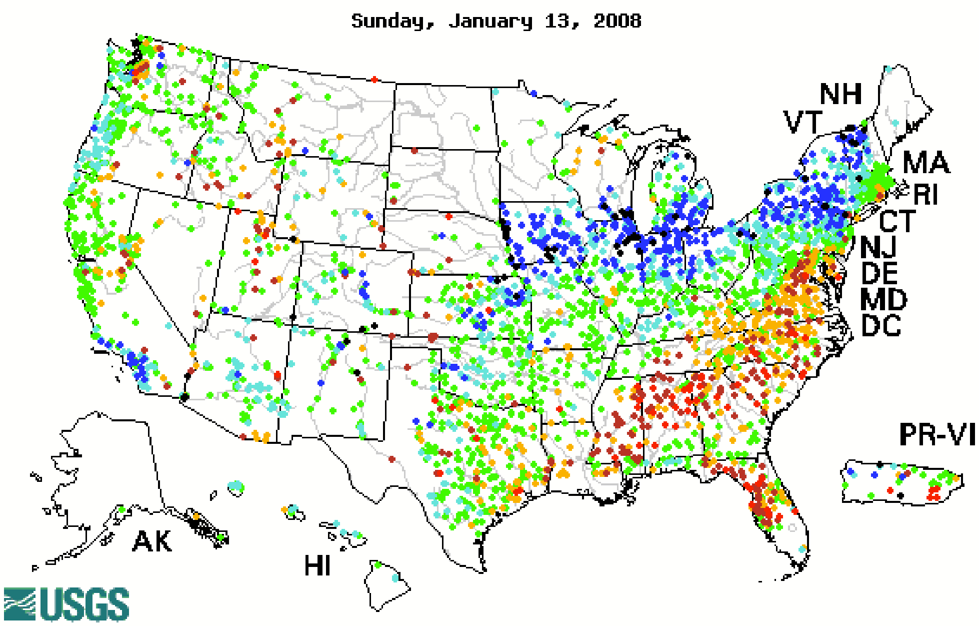
- Piao et al. (2007), using a different land surface model (ORCHIDEE) that permits plant cover to change: If plants can use water more efficiently because of higher CO_2 levels, they will just grow more leaves until they're using as much water as before
- Land use change (deforestation) explains much of the observed runoff trend

Table 1. Observed and ORCHIDEE-modeled global runoff trends (mm/year^2) over the 20th century

Trends	CO_2 (simulation E1)	CO_2 + climate (simulation E2)	CO_2 + climate + land use (simulation E3)	Labat *et al.* (2)	Gedney *et al.* (1)
Global trends	−0.04	0.09	0.17	0.18	0.19

The Gedney *et al.* (1) study trend (simulation ALL) also is given for comparison.

My approach

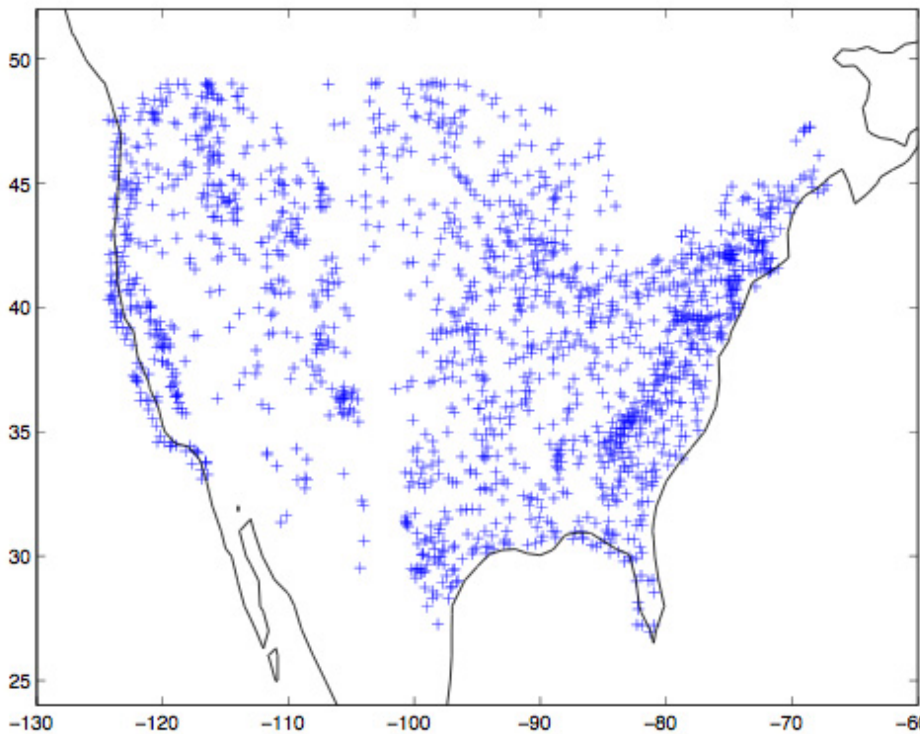


Explanation - Percentile classes						
Low	<10	10-24	25-75	76-90	>90	High
	Much below normal	Below normal	Normal	Above normal	Much above normal	

USGS Waterwatch

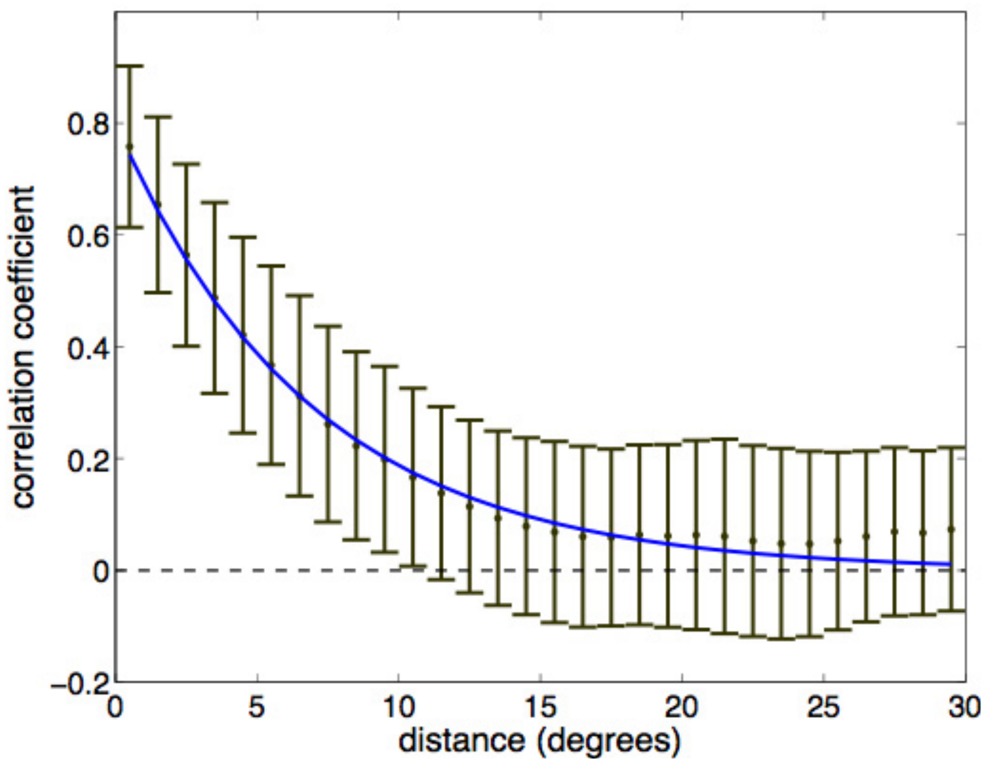
- The USA is interesting because in the transition zone between the subtropics (supposed to get drier) and the temperate zone (supposed to get wetter), and also has good measurements
- Use an undistrurbed-watershed subset of the US Geological Survey gauge network
- Map changes in USA annual streamflow; compare with precip. measurements to estimate change in evaporation
- A trend of evaporation decrease (streamflow increase) that remains after regression on precip. and temperature might plausibly be attributed to reduced plant transpiration caused by higher CO_2

Streamflow data

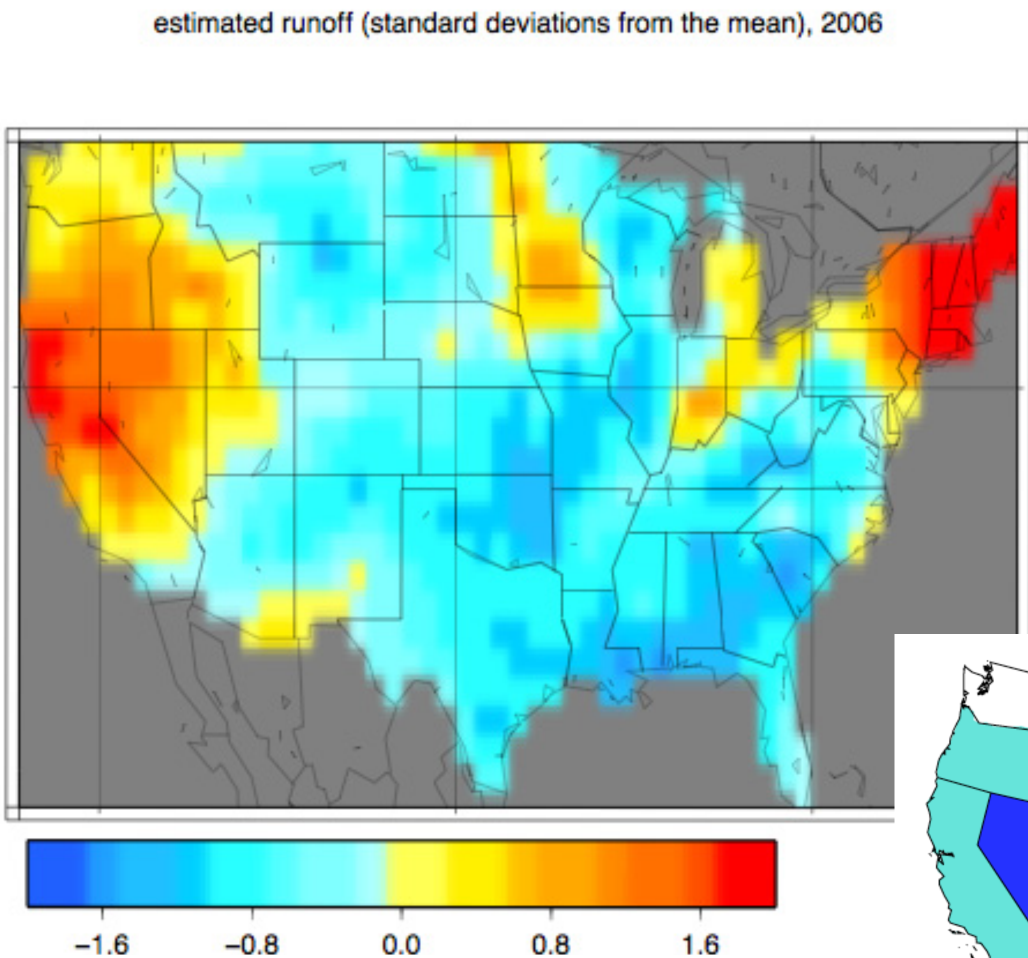


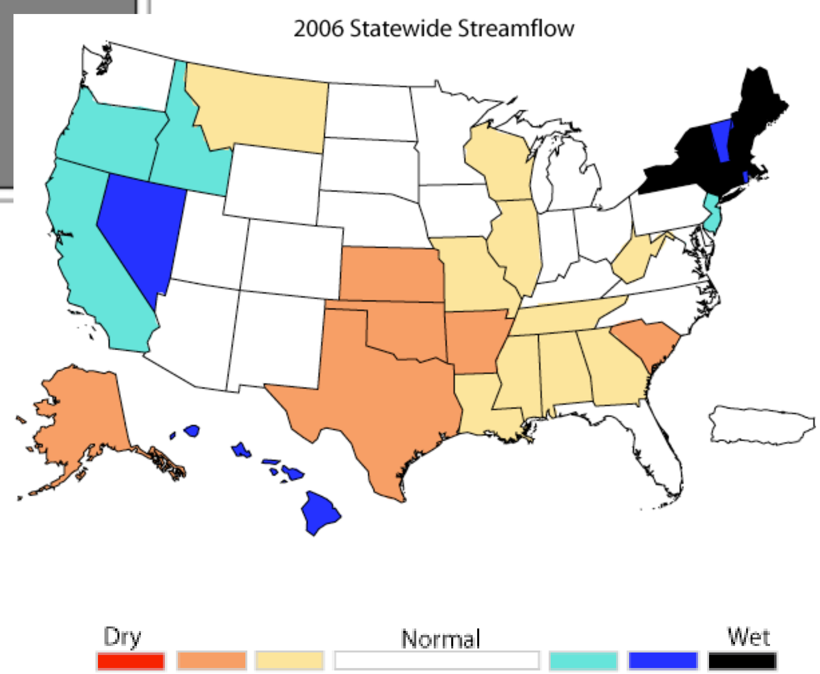
- Hydro-Climatic Data Network (HCDN; Slack and Landwehr 1992): 1659 sites with long records, with streamflow believed "unaffected by artificial diversions, storage, or other works of man"
- Mostly small watersheds (median area: 740 km^2, 10th-90th percentiles: 73-6700 km^2)
- Acceptable records for various intervals in 1874-1988, with good coverage starting from ~1920

Streamflow processing



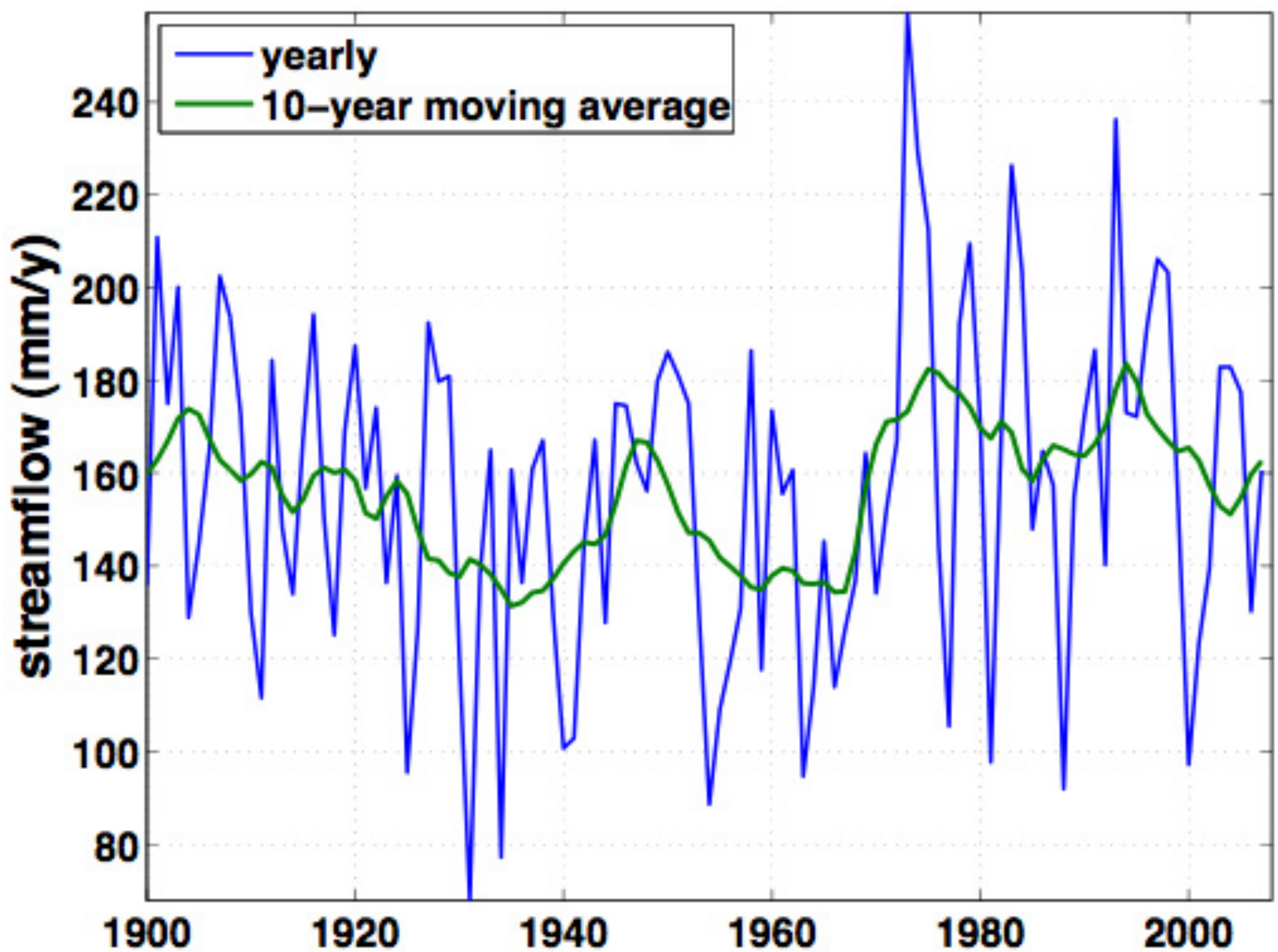
- Subtract mean, divide by standard deviation
- Fill in missing site-years using regularized multiple linear regression (obtain uncertainty estimates and the covariance matrix of streamflow between sites)
- Fit a spatial correlation model to the between-stream covariances
- Optimally interpolate annual streamflow anomalies to a 1º grid
- Scale by runoff mean and SD to get absolute numbers



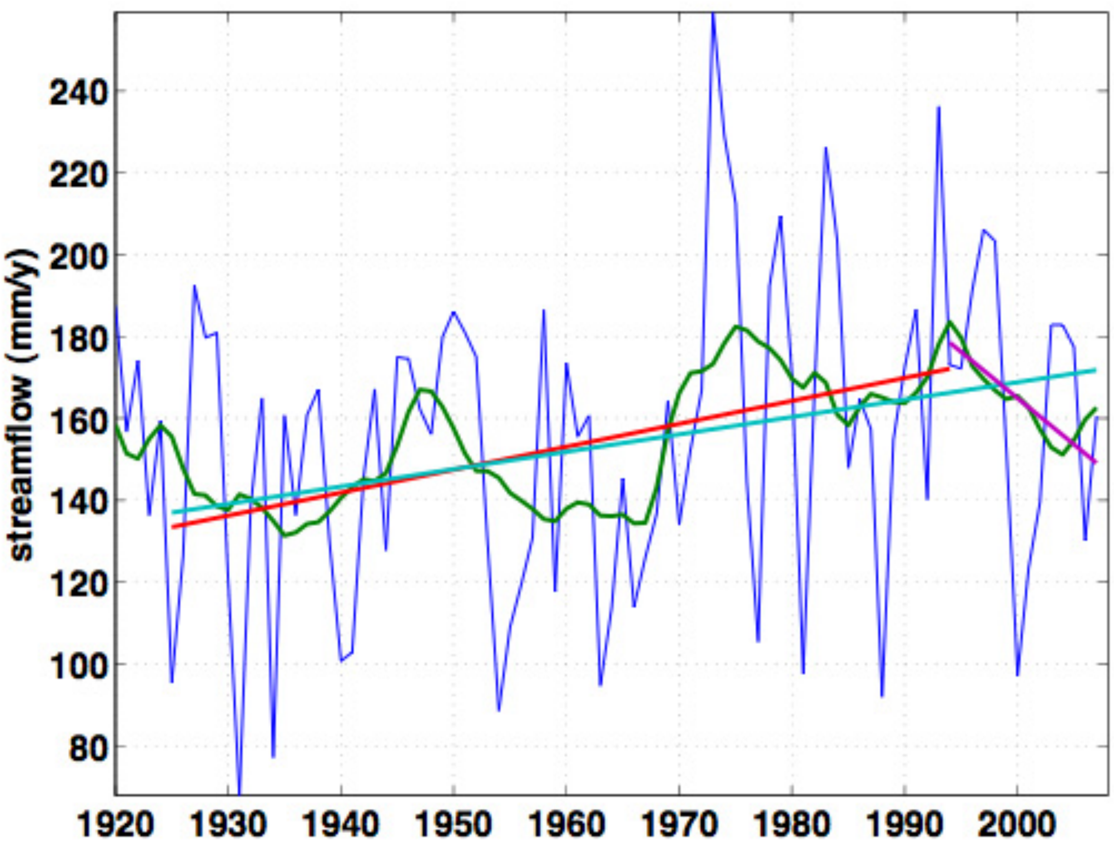


USGS 2006 Streamfow Report

Reconstructed USA streamflow



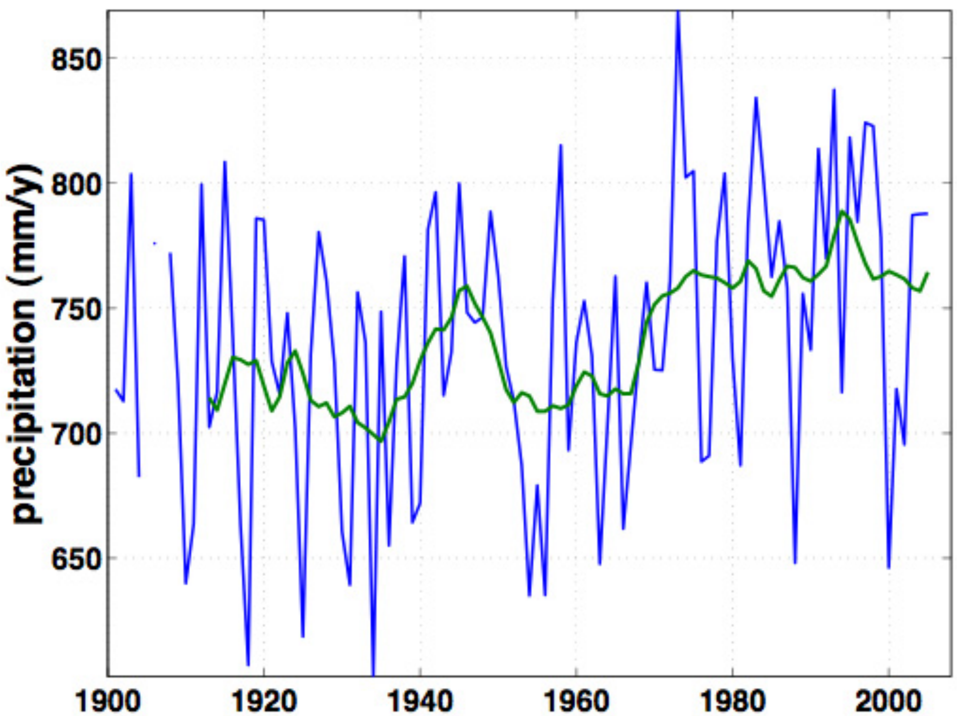
What's the trend? Depends on what period you use…



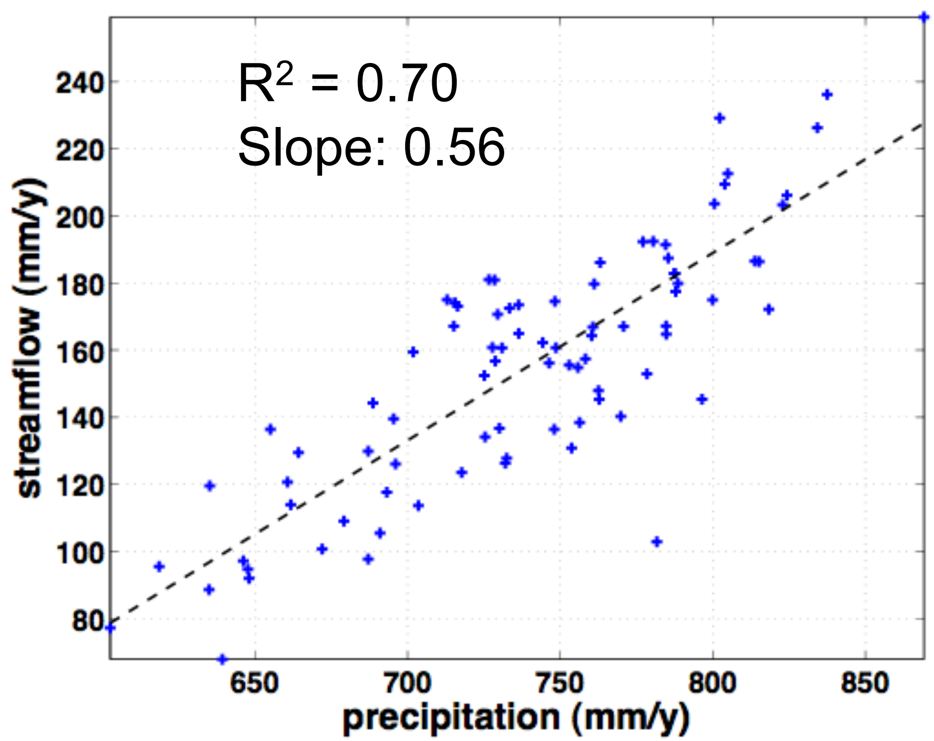
1925-1994: +0.56±0.22 mm/yr per yr
1925-2007: +0.43±0.17
1994-2007: –2.3±2.2

No clear relationship to temperature or CO_2 level

Most of the trend and variability of streamflow is attributable to change in precip.

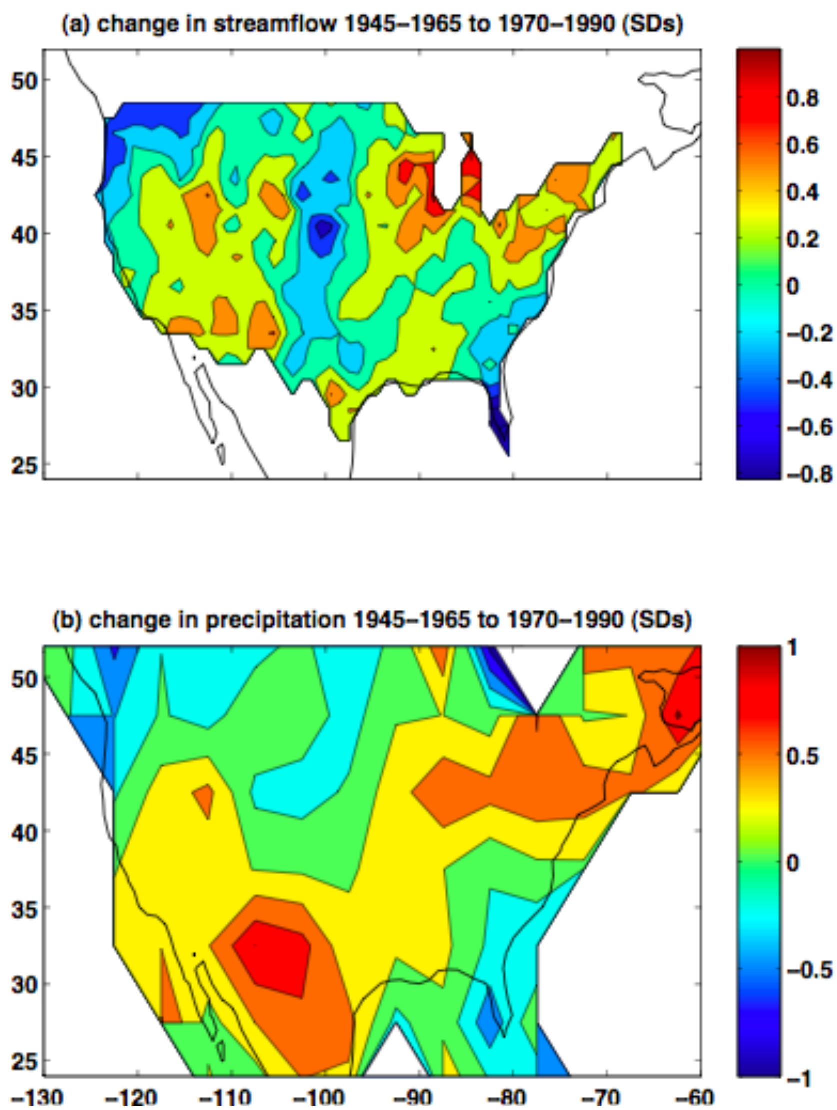


1920-2005



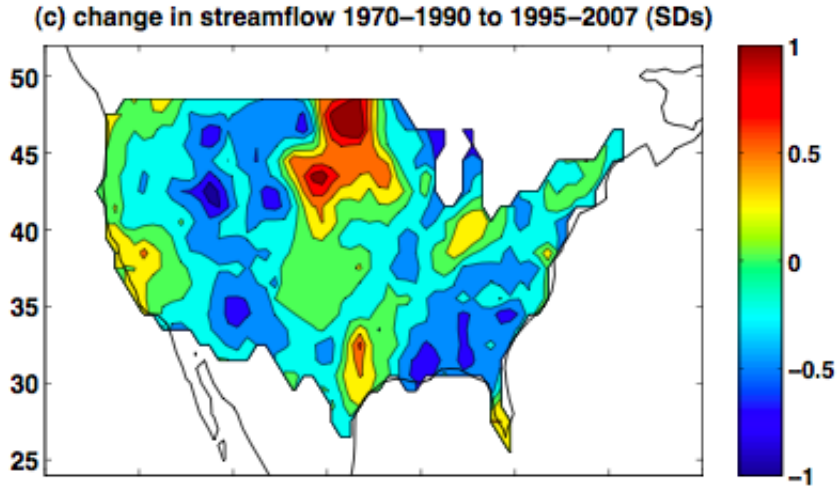
Precip. data: GHCN

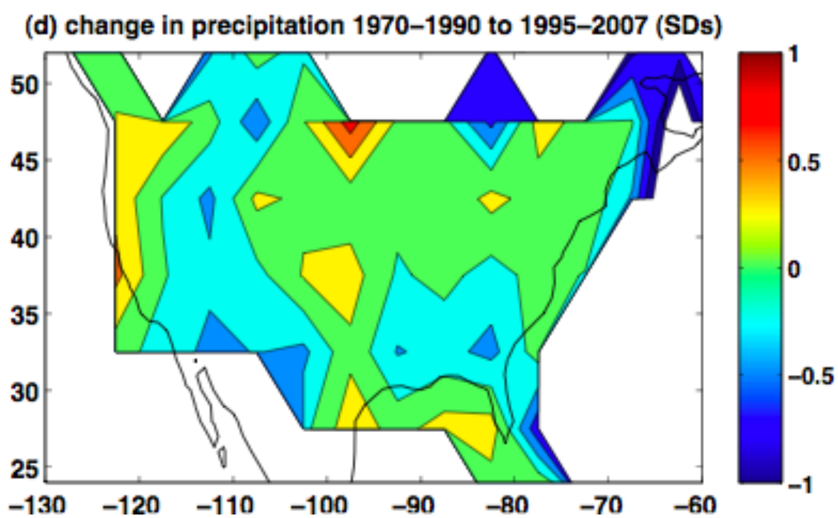
Precipitation and streamflow changes: 1945-1965 to 1970-1990



- Precipitation increased in most of the country around 1970, as did streamflow, but especially in the Northeast
- Regions with lower precip. also saw lower streamflow: Florida, Northwest, central Great Plains

Precipitation and streamflow changes: 1970-1990 to 1995-2007

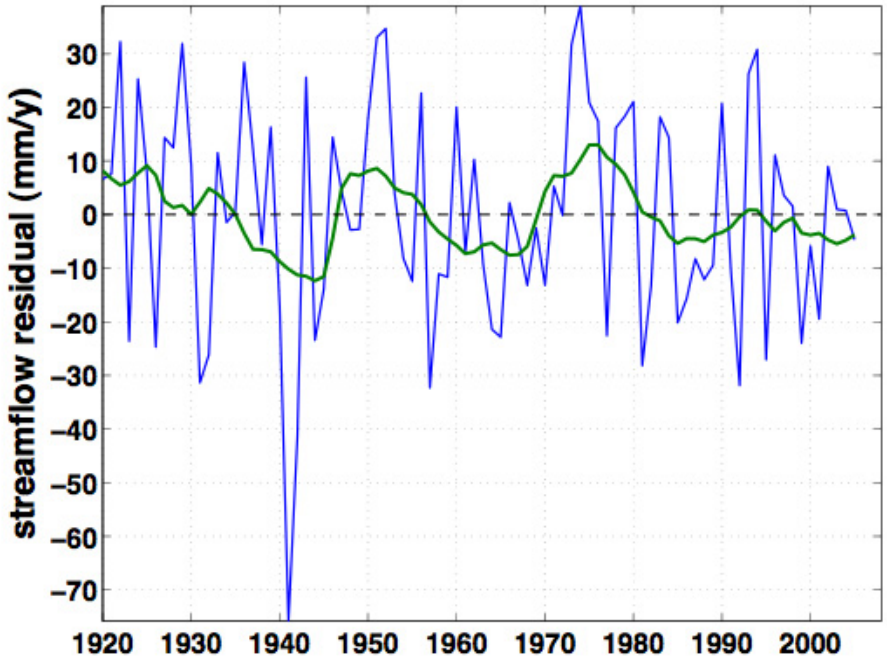




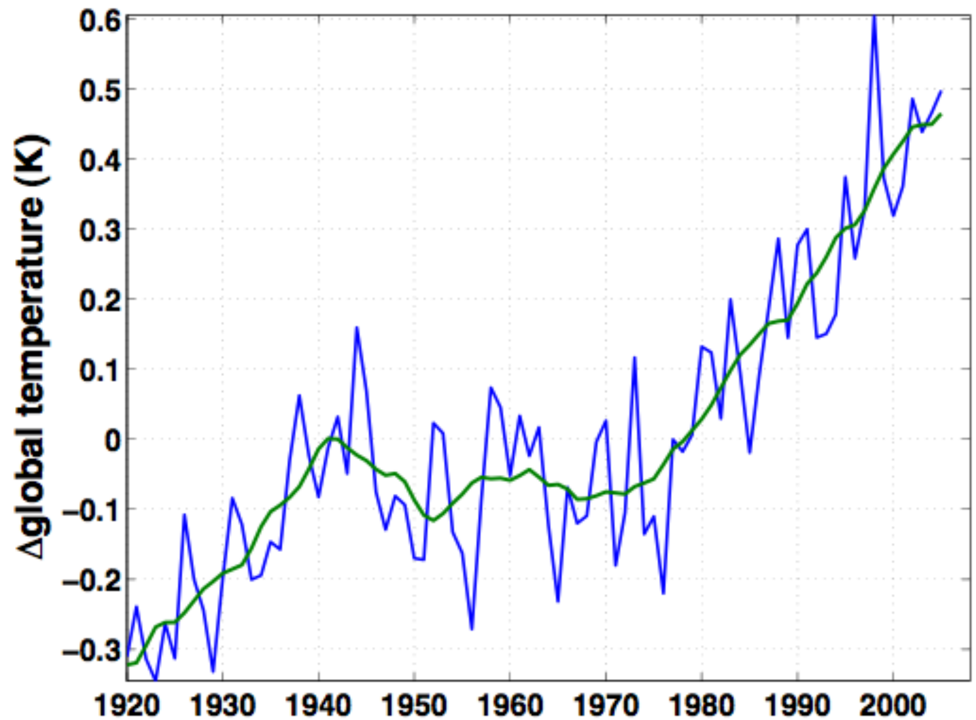
- Not much increase in precip. over most of the country
- Lower precip. (and much lower streamflow) over the Southeast and Mountain West, which have, indeed. been experiencing persistent drought

What's left? Let's add in temperature

Residual US streamflow after regression with precip.



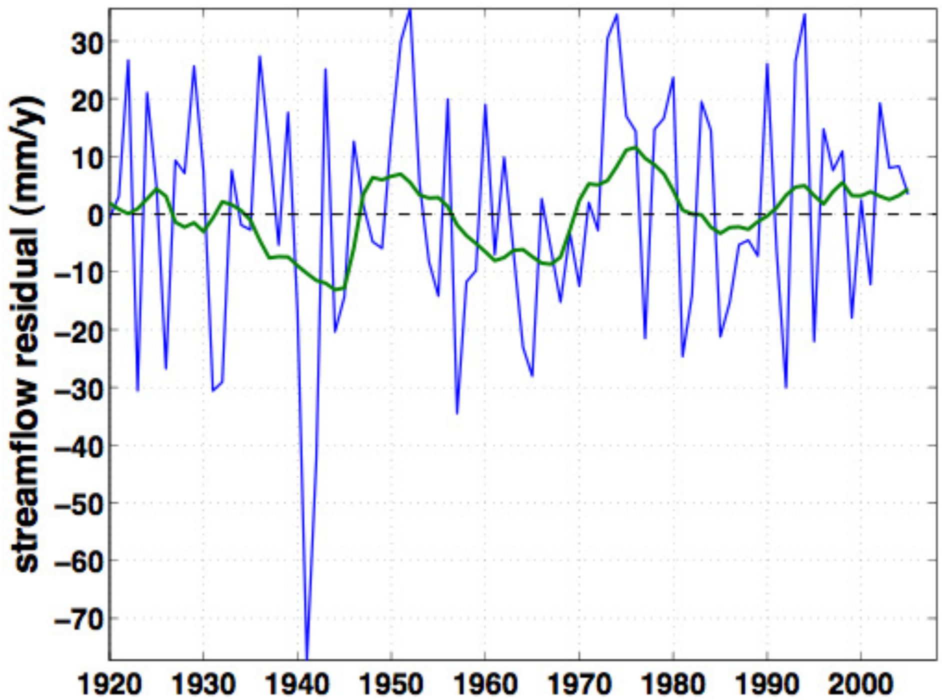
Global temperature (CRU)



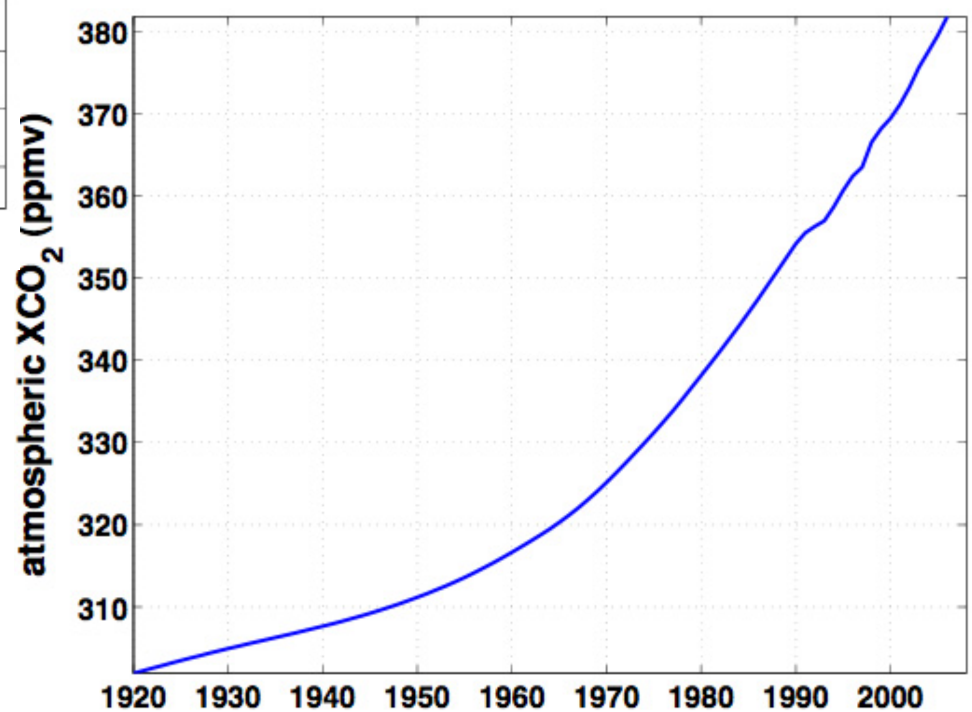
Δrunoff = $(0.58\pm0.04)\Delta P$ + $(-19\pm11\ \mathrm{mm\cdot y^{-1}\cdot K^{-1}})\Delta T$

A direct CO_2 effect on streamflow?

Residual after regression with precip. and temp.



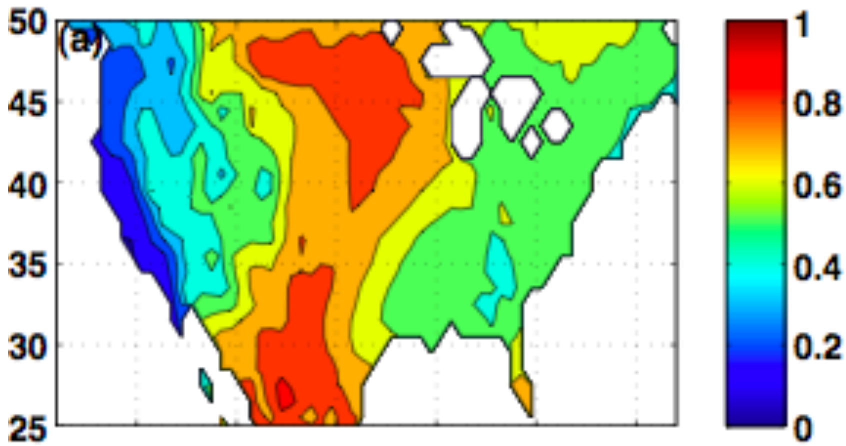
Atmospheric CO_2



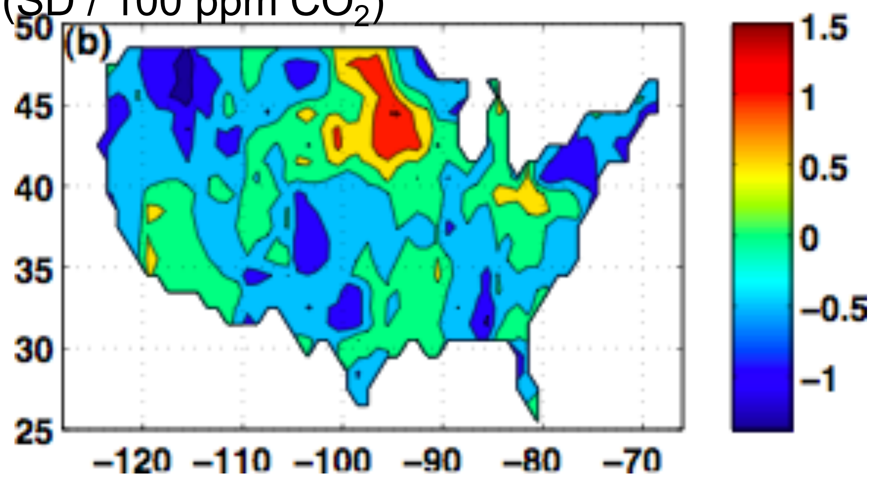
$$\Delta\text{runoff} = (0.58 \pm 0.04)\Delta P + (-50 \pm 20\ \text{mm}\cdot\text{y}^{-1}\cdot\text{K}^{-1})\Delta T + (0.34 \pm 0.19\ \text{mm}\cdot\text{y}^{-1}\cdot(\text{ppm})^{-1})\ \Delta pCO_2$$

Mapping the effect of warming

Fraction of precip. that falls in warm season

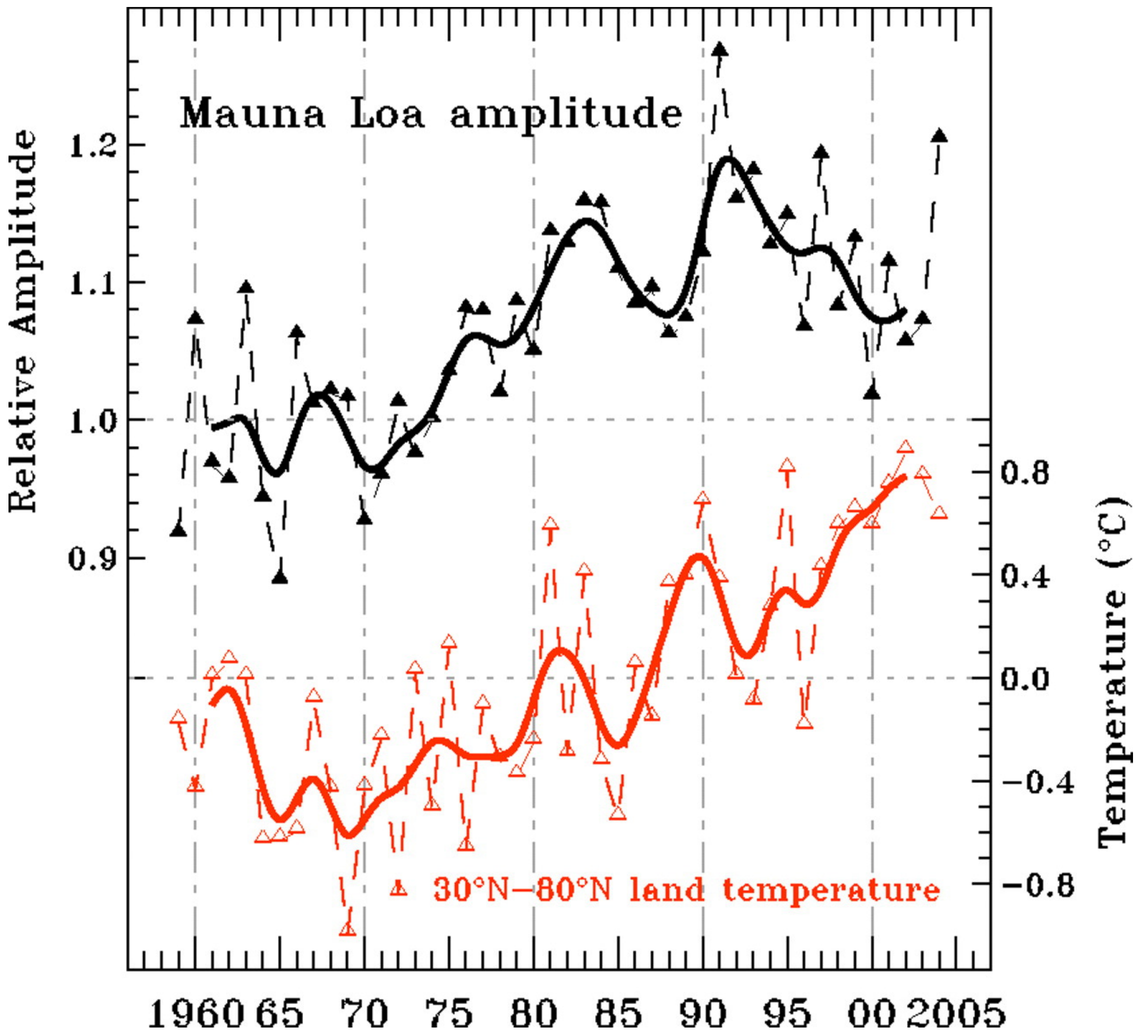


Apparent response of streamflow to greenhouse warming (SD / 100 ppm CO_2)



- The net impact of rising CO_2 combined with warming apparently is to reduce streamflow (increase evaporation)
- An exception seems to be the upper Great Plains, where streamflow is increasing - suppression of plant transpiration by higher CO_2 might be relatively more important there because most precip. falls during the growing season

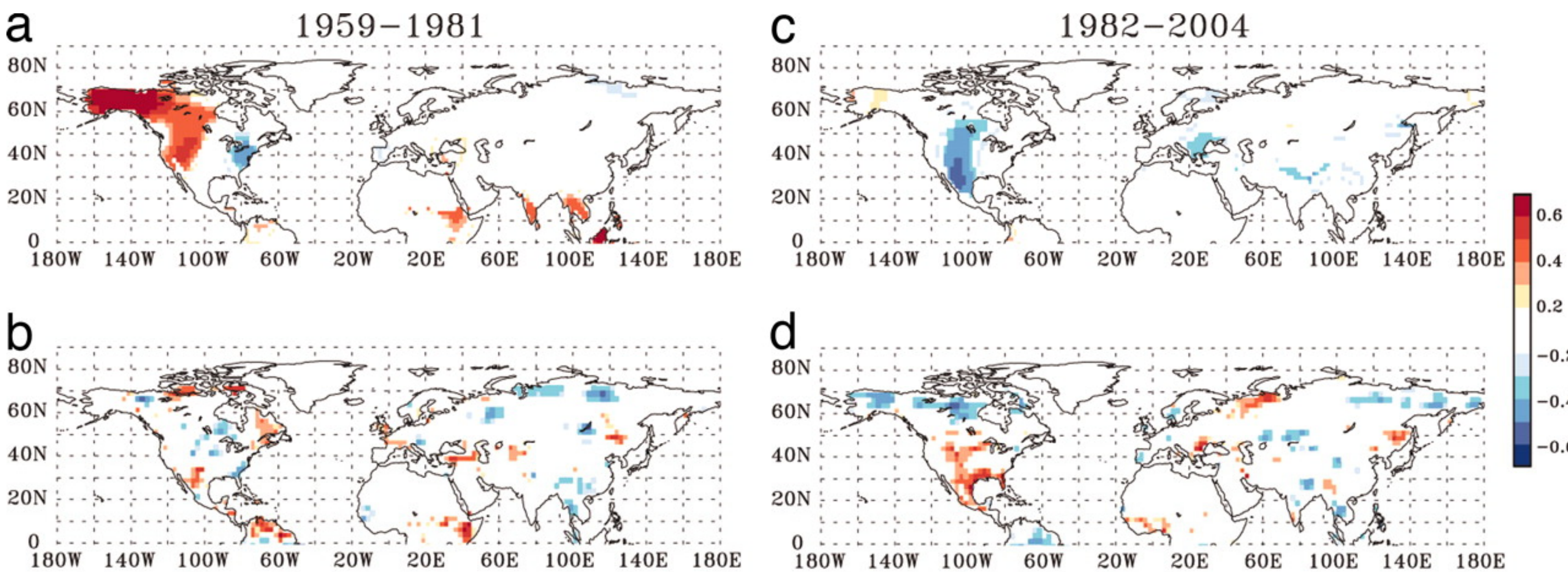
Can we see the effect of drought on land C uptake?



Buermann et al. 2007

- The size of the seasonal cycle in CO_2 concentration in Mauna Loa, Hawai'i, reflects how much northern plants grow in the summer
- 1959-~1991: warmer summers → more C uptake; since ~1991: warmer summers → less C uptake

The Mauna Loa seasonal cycle vs. local temperature and moisture



- The Mauna Loa seasonal cycle size increases with N American summer warming (red) for the first half of the record (a) but decreases with warming (blue) for the second half (c)
- The positive response (red) of the seasonal cycle size to N American growing-season precip. (b,d) is more pronounced for the second half of the record (d)

Buermann et al. 2007

Conclusions

- Interannual variation in USA streamflow is mostly due to variation in precipitation
- The net combined effect of global warming and rising CO_2 has been to increase evaporation (precip. minus streamflow)
- USA precip. increased abruptly in the late 1960s but has not increased with greenhouse warming since then
- USA streamflow has shown a decreasing trend since the early 1990s, driven by slightly lower precip. plus higher evaporation (linked with global warming), but with regional variability
- The effect of increasing drought in, e.g., the USA on CO_2 concentration patterns and on plant carbon uptake may already be detectable
- Predicting changes in water availability and plant response requires region-specific understanding of plant behavior (CO_2 response, root distribution, effect of water stress) as well as atmospheric water transport; analysis of observed change can help test this understanding as it is incorporated in land-process models
- Given the response to warming so far of increasing evaporation but not precipitation, an increase in drought seems likely over the coming decades for the USA

Acknowledgements

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- NOAA for a Climate and Global Change Postdoctoral Fellowship