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?
CO$_2$ uptake on land

- 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…

Trend for 1981-1994; Buermann et al 2002
Will land carbon uptake continue?

- Friedlingstein et al. (2006): C4MIP, 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?

- 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?

Gregg Benson (Wikipedia)
But climate models predict otherwise

- *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

IPCC AR4
Stippling: 80% of models agree on sign of change
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
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
What’s happening to land precip.?

- 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)

Data: GHCN
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 CO₂ reducing plant transpiration?

- 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 CO₂ 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 CO₂ 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.
**My approach**

- 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 undisturbed-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 km², 10th-90th percentiles: 73-6700 km²)
- 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 1° grid
- Scale by runoff mean and SD to get absolute numbers
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.

$R^2 = 0.70$
Slope: 0.56

Precip. data: GHCN

- 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.

- 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.

\[ \Delta \text{runoff} = (0.58 \pm 0.04) \Delta P + (-19 \pm 11 \text{ mm} \cdot \text{y}^{-1} \cdot \text{K}^{-1}) \Delta T \]
A direct CO$_2$ effect on streamflow?

\[ \Delta \text{runoff} = (0.58 \pm 0.04) \Delta P + (-50 \pm 20 \text{ mm yr}^{-1} \cdot \text{K}^{-1}) \Delta T + (0.34 \pm 0.19 \text{ mm yr}^{-1} \cdot \text{ppm}^{-1}) \Delta p\text{CO}_2 \]
Mapping the effect of warming

- The net impact of rising CO₂ 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 CO₂ 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?

- The size of the seasonal cycle in CO$_2$ concentration in Mauna Loa, Hawai’i, reflects how much northern plants grow in the summer.

Buermann et al. 2007
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 CO₂ 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 CO₂ 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 (CO₂ 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

• Inez Fung, Jim Hunt (UCB), Tom Pagano (USGS)
• NOAA for a Climate and Global Change Postdoctoral Fellowship