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

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

Seager et al 2007

Dust Bowl drought level
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 Precip.  
2xCO2 - Control

Most of the blue models show northward shift of ITCZ

Most of the orange models show southward shift of ITCZ

Change in Flux

W

mm/year

SP  60S  30S  EQ  30N  60N  NP
Change in Precipitation in Extreme Cases

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

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**

Lots of ice melting. Warming!

**Cloud-albedo feedback**

Low clouds form. Cooling!
Energetic Prediction for Slab Models

$R = 0.91$

![Graph showing a scatter plot with points and a correlation coefficient of R = 0.91.](image)
Importance of Extratropical Forcing

- EBM forced by terms outside of the tropics only (poleward of 20° 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
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

Source: This collection of maps has been drawn after a series of satellite images provided by NASA Goddard Space Flight Center, available at:
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)

Graph:
- Increasing black carbon (warming)
- Increasing sulfate aerosol (cooling)
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
• Modeled Asian precipitation changes
South America

- Modeled South American precip changes
Modeled Australian precipitation changes
The strongest downpours require a lot of water vapor in the atmosphere.

Warmer temperatures $\rightarrow$ more water vapor

Thus, heavy rainfall events should become more extreme.

Also heavy snowfall events!

How about the **most intense storms**?
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.
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.
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 $ET_0$ 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 \textit{would} evaporate under given atmospheric and radiative conditions \textit{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: \( e_s \times (1 - RH) \)
    - (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)
% 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