The water cycle and its response to climate change

Climate and the Global Circulation of the Atmosphere

Wednesday, December 9th 2015
• Final homework to be posted online later this week - Prof. Schneider will email you all when it is available
Outline for today’s class

• Why is water cycle important?

• Earth’s water cycle: atmospheric water vapour, precipitation, evaporation, runoff, vapour transport in the atmosphere

• How and why will the water cycle change in the future?
Why is the water cycle important? Society

- Societal and economic importance (agriculture, drinking water, etc)
- Natural hazards (flooding, hail, severe snow)
Why is the water cycle important? Climate

- Water (and the water cycle) extremely important for maintaining and changing the Earth’s climate:
  - Strongly absorbs SW and LW radiation & feedbacks
  - Clouds
  - Ice
Earth’s water cycle

Figure 9.1: Hydrologic cycle.

Physics of Earth’s Climate
(Tapio Schneider)
Residence times

Days

$O$(thousand years)

$O$(hundred years)

Figure 9.1: Hydrologic cycle.
Atmospheric water vapour

$\frac{\delta q^*}{q^*} \approx \frac{L}{RT^2} \delta T$

7%/K
Water vapour transport

Physics of Earth’s Climate
(Tapio Schneider)
Water vapour transport

[Graph showing water vapour transport with various curves labeled as Transient eddies, Stationary eddies, Mean meridional circulations, and Total.]

Physics of Earth’s Climate  
(Tapio Schneider)
Precipitation climatology
(1998-2010)
Average precipitation

1957-2002

ERA-40 Atlas
Average evaporation

Mean annual evaporation, 1958 - 2005

OAFlux Dataset

1958-2005
Evaporation minus precipitation

1957-2002
Evaporation minus precipitation

(from a simulation)
Ocean salinity
Runoff

Water Systems Analysis Group, UNH
Water vapour transport, $P-E$, runoff

-> classic equation of hydrology & the balance equation for atmospheric water vapour
Water vapour transport and $P-E$

Red (dry): $P-E < 0$
Blue (wet): $P-E > 0$

Physics of Earth’s Climate
(Tapio Schneider)
The water cycle & climate change
Response of water vapour

- **Quiz:** Does column-integrated water vapor increase, decrease, or stay the same as climate warms? By how much?
Response of water vapour

- **Quiz:** Does column-integrated water vapor increase, decrease, or stay the same as climate warms? By how much?

\[
\frac{\delta q}{q} = \frac{\delta q^*}{q^*} + \frac{\delta RH}{RH} \approx 7\%/K
\]
Response of water vapour

- Simulations of global warming
- All models show $dq/q \sim 7 \%/K$
- Small relative humidity changes

Held & Soden (2006)
Response of water vapour

Why are relative humidity changes small? Will discuss shortly

• Simulations of global warming
• All models show $dq/q \sim 7 \% / K$
• Small relative humidity changes

Held & Soden (2006)
Response of precipitation

- **Quiz**: How will precipitation change as the climate warms?
Response of precipitation

- $\delta P/P \sim 2\%/K$ - much weaker than water vapor response
- Why?

Held & Soden (2006)
Response of precipitation

• Free troposphere: approx. balance between latent heating and radiative cooling (in global mean)

O’Gorman et al. (2012)
Response of precipitation

- Free troposphere: approx. balance between latent heating and radiative cooling (in global mean)
- Changes in latent heating/precip and evaporation constrained by changes in radiative cooling

\[ L \delta P \approx \delta R_{TOA} - \delta R_{LCL} \]

\( \sim 2\%/K \rightarrow \text{smaller than Clausius-Clapeyron} \)

O’Gorman et al. (2012)
$P-E$: “Rich get richer, poor get poorer”

Precipitation minus evaporation: $P-E$

CMIP5: Historical simulations (1975-2004)
$P-E$: “Rich get richer, poor get poorer”

Change in $P-E$

CMIP5: RCP8.5 (2070-2099) - historical (1975-2004)
$P-E$: “Rich get richer, poor get poorer”

Precipitation minus evaporation: $P-E$

CMIP5: Historical simulations (1975-2004)
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Change in $P-E$

CMIP5: RCP8.5
(2070-2099) -
historical
(1975-2004)
$P-E$: “Rich get richer, poor get poorer”

Change in $P-E$

Why does the water cycle intensify with warming?

CMIP5: RCP8.5 (2070-2099) - historical (1975-2004)
P-E: “Rich get richer, poor get poorer”

\[ P - E > 0 \]

Held & Soden (2006)
$P - E$: “Rich get richer, poor get poorer”

“Wet get wetter”

\[ \delta(P - E) > 0 \]

Warm the climate

Held & Soden (2006)
$P-E$: “Rich get richer, poor get poorer”

\[ F_1 \quad | \quad P - E < 0 \quad | \quad F_2 \]

\[ Held & Soden (2006) \]
$P-E$: “Rich get richer, poor get poorer”

“Dry get drier”

Warm the climate

\[ \delta(P - E) < 0 \]

Held & Soden (2006)
Derivation: “Rich get richer, poor get poorer”

\[ P - E = -\nabla \cdot F = -\nabla \cdot [uq] \]

\[ \Rightarrow \delta(P - E) = -\nabla \cdot \delta F \]
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Assume: \( \frac{\delta F}{F} \approx \frac{\delta q^*}{q^*} = \alpha \delta T \) (neglecting changes in relative humidity and winds under warming)
Derivation: “Rich get richer, poor get poorer”

\[ P - E = -\nabla \cdot F = -\nabla \cdot [uq] \]

\[ \Rightarrow \delta(P - E) = -\nabla \cdot \delta F \]

Assume: \( \frac{\delta F}{F} \approx \frac{\delta q^*}{q^*} = \alpha \delta T \)

(neglecting changes in relative humidity and winds under warming)

\[ \Rightarrow \delta(P - E) \approx -\nabla \cdot (\alpha \delta TF) \]

(assume small spatial gradients of temperature change)

\[ \Rightarrow \delta(P - E) \approx -\alpha \delta T \nabla \cdot F \]

Held & Soden (2006)
Derivation: “Rich get richer, poor get poorer”

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\[ \Rightarrow \delta(P - E) \approx -\alpha \delta T \nabla \cdot F \]

“Wet get wetter, dry get drier”: \[ \delta(P - E) \approx \alpha \delta T_S (P - E) \]

Held & Soden (2006)
Application of scaling to global warming simulations

$\delta(P-E)$

Simulated

CMIP5: RCP8.5 (2070-2099) - historical (1975-2004)

Held & Soden (2006)
Application of scaling to global warming simulations

“Wet get wetter, dry get drier”: \( \delta(P - E) \approx \alpha \delta T_S (P - E) \)

\( \delta(P - E) \) [mm day\(^{-1}\)]

Latitude (degrees)

CMIP5: RCP8.5 (2070-2099) - historical (1975-2004)

Held & Soden (2006)
Application of scaling to global warming simulations

Simulations

Prediction from scaling

Held & Soden (2006)
Response of relative humidity to warming

$\delta RH (\text{sfc-air})$

CMIP5: RCP8.5 (2070-2099) - historical (1975-2004)

Byrne & O’Gorman (2016)
Response of relative humidity to warming

Why are the changes over ocean so small?

Byrne & O’Gorman (2016)