Radiative constraints on current and future changes in the global water cycle

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Thanks to: Chunlei Liu, Matthias Zahn, Norman Loeb, Brian Soden, Viju John
“Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems.”

IPCC (2008) Climate Change and Water
How will global precipitation respond to climate change?

Observations

Simulations:
- RCP 8.5
- Historical
- RCP 4.5


Allan et al. (2013) Surv. Geophys
• Increased Precipitation
• More Intense Rainfall
• More droughts
• Wet regions get wetter, dry regions get drier?
• Regional projections??

IPCC WGI (2007)
Earth’s Energy Budget & the Global Water Cycle

Wild et al. (2012) Clim. Dynamics (see talk Tuesday!). Also: Trenberth et al. (2009) BAMS
Radiative energy budget of the atmosphere and hydrological response

- Adjustments in latent heating LP (precipitation) for change in radiative energy budget $\Delta R$ above LCL (lifting condensation level)
- $\Delta R$ below LCL $\rightarrow$ adjustments in SH (sensible heat flux) important

Models simulate robust clear-sky radiation response to warming (∼2-3 Wm\(^{-2}\)K\(^{-1}\)) and resulting increase in latent heating (precipitation) to balance (∼2 %K\(^{-1}\)) e.g. Lambert & Webb (2008) GRL; Stephens & Ellis (2008) J. Clim;

\[
\frac{dP}{dT_s} \sim \frac{1}{\rho_w L} \frac{dQ}{dT_s}
\]

Also: Previdi (2010) ERL
Evaporation

"Muted" Evaporation changes in models are explained by small adjustments in Boundary Layer:
1) declining wind stress
2) reduced surface temperature lapse rate ($T_s - T_o$)
3) increased surface relative humidity ($RH_o$)

\[ Q_E = L_v C_E \rho_a W (q_s - q_a) \]

Richter and Xie (2008) JGR

"Clausius Clapeyron"

Wind $T_s - T_o$ $RH_o$
Direct influence of radiative forcing and climate response on precipitation changes

Andrews et al. (2009) J Climate
Energetic constraint upon global precipitation

\[ \Delta P \sim k \Delta T - f \Delta F. \]

(i) \( k \sim 2 \text{ Wm}^{-2}\text{K}^{-1} \) depends on spatial pattern of warming

(ii) \( f \) dependent upon nature of radiative forcing \( \Delta F \)

Precipitation change \( \Delta P \) determined by:

(i) “slow” response to warming \( \Delta T \) (enhanced radiative cooling of warmer troposphere)

(ii) “fast” direct influence of radiative forcing on surface/tropospheric energy budget (rapid adjustment)

Simple model of precipitation change

Thanks to Keith Shine and Evgenios Koukouvagias

Table 1 Prescribed values of atmospheric forcing scaling parameter $f = \frac{\Delta F_{atm}}{\Delta F}$

<table>
<thead>
<tr>
<th>Forcing</th>
<th>CO₂</th>
<th>Other WMGHG</th>
<th>O₃ trop.</th>
<th>O₃ strat.</th>
<th>SO₄ (all)</th>
<th>BB</th>
<th>BC</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>0.8</td>
<td>0.5</td>
<td>-0.3</td>
<td>0.0</td>
<td>0.0</td>
<td>-0.9</td>
<td>2.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Well-Mixed Greenhouse Gases (WMGHG) includes CH₄, N₂O and CFCs; SO₄ includes all sulfate aerosol forcings (direct, indirect and volcanic). BB biomass burning aerosol, BC black carbon aerosol.
A simple model of precipitation change

\[ L\Delta P \sim k\Delta T - f\Delta F. \]

(b) Atmospheric Heating

(d) Precipitation

\[ f\Delta F. \]

direct radiative heating of troposphere


see also Kvalevåg et al. (2010) GRL
It matters where you put your radiative forcing

Surface sensible heat flux adjustment (rather than latent heat adjustment) increasingly important for absorbing aerosol within boundary layer e.g. Black Carbon (BC) Ming et al. (2010) GRL →

- Hydrological Forcing:
  \[ HF = kdT - dAA - dSH \]

Geographical location also important for regional response


See also Pendergrass & Hartmann (2012) GRL; Previdi (2010) ERL
Implications for transient responses

CMIP3 coupled model ensemble mean: 

HadCM3: Wu et al. (2010) GRL
- CO₂ forcing experiments
- Initial precipitation response suppressed by CO₂ forcing
- Stronger response after CO₂ rampdown

Degree of hysteresis determined by forcing related fast responses and linked to ocean heat uptake

Work also by: McInerney & Moyer; Schaller et al. (2013) ESDD
How is global precipitation and radiative cooling currently changing?

1988-2008: Precipitation trends not significant

Global mean estimates (use ERA Interim over land and high latitudes for SSM/I & AMSRE)
The role of water vapour

- Physics: Clausius-Clapeyron
- Low-level water vapour concentrations increase with atmospheric warming at about 6-7%/K
Global changes in water vapour

Global mean estimates (use ERA Interim over land and high latitudes, SMMR-SSM/I & AMSRE)

Allan et al. (2013) Surv. Geophys

\[ \frac{dW}{dT} \approx 7\%/K \]
Extreme Precipitation

- Moisture convergence fuels large-scale rainfall events
  e.g. *Trenberth et al. (2003) BAMS*
- Intensification of rainfall with warming
  e.g. *Allan & Soden (2008) Science*
- Amplifying latent heat feedbacks?
  e.g. *Berg et al. (2013) Nature Geo*
- Time/space scale important
- Observational constraints? →
  e.g. *O’Gorman (2012) Nature Geosci; Liu & Allan (2012) JGR*
Contrasting precipitation response expected

- Heavy rain follows moisture ($\sim 7\%/{K}$)
- Mean Precipitation linked to energy balance ($\sim 2-3\%/{K}$)
- Light Precipitation ($\sim ?\%/{K}$)

Moisture Balance

\[
\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T. \quad \alpha \approx 0.07 \text{ K}^{-1}
\]

\[
\delta(P - E) = -\nabla \cdot (\alpha \delta TF) \approx \alpha \delta T(P - E).
\]

Enhanced moisture transport \( F \) leads to amplification of
(1) \( P-E \) patterns (left)
Held & Soden (2006) *J Climate*
(2) ocean salinity patterns
Durack et al. (2012) *Science*

See also Mitchell et al. (1987) *QJRMS*

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Enhanced moisture transports into the “wet” tropics, high latitudes and continents

\[
\frac{\partial w}{\partial t} + \nabla \cdot \frac{1}{g} \int_0^P \mathbf{v} q \, dp = E - P,
\]

PREPARE project
Zahn & Allan, submitted to WRR

Allan et al. (2013) Surv. Geophys
see also: Zahn and Allan (2013) J Clim
CMIP5 simulations: Wettest tropical grid-points get wetter, driest drier

First argument:

\[ P \sim M q \]

So if \( P \) constrained to rise more slowly than \( q \), this implies reduced \( M \):

- Bony et al. (2013) Nat Geosci
- Chadwick et al. (2012) J Clim

Second argument:

\[ \omega = Q/\sigma \]

Subsidence (\( \omega \)) induced by radiative cooling (\( Q \)) but the magnitude of \( \omega \) depends on static stability (\( \sigma = \Gamma_d - \Gamma \)).

If \( \Gamma \) follows MALR \( \rightarrow \) increased \( \sigma \). This offsets \( Q \) effect on \( \omega \).


Schematic from Gabriel Vecchi
Walker circulation response to fast and slow precipitation effects

Thermodynamic response to warming

Fast response to $4 \times \text{CO}_2$

Fast response to warming

Fast response to $4 \times \text{CO}_2$

Bony et al. (2013) *Nature Geosciences* (see talk on Tuesday!)

Both fast and slow responses to CO$_2$ forcings induce reduced Walker circulation in response to $P = Mq$ constraint

Aerosol & regional circulation response

- N Hemisphere Aerosol cooling 1950-1980s
- Induces southward movement of ITCZ
- Reduced Sahel rainfall →
- Recovery after 1980s e.g. Wild 2012 BAMS
- +Asymmetric volcanic forcing e.g. Haywood et al. (2013) Nature Climate

- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science
- Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn
Shifts in circulation systems are crucial to regional changes in water resources and risk yet predictability is often poor (but see Power et al. (2012) J Clim).

How will jet stream positions and monsoons respond to warming? e.g. Levermann et al. (2009) PNAS

How will primary land-surface and ocean-atmosphere feedbacks affect the local response to global warming?
Outstanding Issues

• Observing systems can’t monitor changes in precipitation & radiation adequately
• Regional responses are unpredictable
• Extreme precipitation is outpacing Clausius Clapeyron constraint
• What are changes in radiative forcings and their associated fast adjustments?
• Implications for geoengineering of climate
• What is the effect of the global surface temperature hiatus on the water cycle?
Conclusions

• Radiative energy balance is fundamental to climate response
  Energy and moisture balance powerful constraints on global water cycle
• Global precipitation rises with surface warming (~2%/K)
• Direct effects of radiative forcing from greenhouse gases/absorbing aerosol cause rapid adjustments in E and P (+cloud)
• Current & future increases in wet and dry extremes
  – Linked to rises in low-level moisture of about 7%/K
  – Combined energy and moisture balance constraints via circulation
• Aerosol radiative forcing appears key in determining global and circulation-driven precipitation responses
• Heating of Earth continues at rate of ≈ 0.6 Wm$^{-2}$ over the last decade despite stable Surface Temperature
Extra slides
Altitude dependence of response (kernels)

See also O’Gorman et al. (2012) Surv. Geophys

Previdi (2010) ERL
Quantifying Hydrological Feedbacks

Fig. 4 Feedbacks (blue dashes) on the atmospheric energy budget in coupled simulations with nine climate models. Positive values indicate a gain in energy for the atmospheric column and a negative feedback on precipitation. Feedbacks shown are water vapor (WV), lapse rate (LR), the sum of water vapor and lapse rate (WV + LR), Planck (Pl), cloud (C), surface sensible heat flux (SH), and the sum ALL = WV + LR + Pl + C + SH. Albedo feedback is negligible and is not shown. Black dashes show the water vapor feedback for invariant relative humidity (RH).

O’Gorman et al. (2012) Surv. Geophys; see also Previdi (2010) ERL

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Forcing related fast responses

- Surface/Atmospheric forcing determines “fast” precipitation response
- Robust slow response to T
- Mechanisms described in Dong et al. (2009) J. Clim; Cao et al. 2012 ERL
- Hydrological Forcing: $\text{HF}=kdT-dAA-dSH$

Andrews et al. (2010) GRL; see also Kvalevåg et al. (2010) GRL

Ming et al. (2010) GRL

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Fingerprints of precipitation response by dynamical regime

- Model biases in warm, dry regime
- Strong wet/dry fingerprint in model projections (below)

Precipitation intensity (mm/day)

Uncertainty in observed P intensity & response (tropical oceans)

Precipitation intensity percentile (%)

Liu & Allan (2012) JGR

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Response of Precipitation intensity distribution to warming: Observations and CMIP5, 5-day mean

Is present day variability a good proxy for climate response?

Allan et al. (2013) Surv. Geophys