How confident are we in the response of the global water cycle to climate change?

Richard P. Allan    r.p.allan@reading.ac.uk    @rpallanuk

Department of Meteorology, University of Reading, UK

Thanks to: Chunlei Liu, Matthias Zahn, David Lavers, Brian Soden, Viju John
Climate model projections

- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??

**Precipitation intensity**

**Soil moisture**

IPCC WGI (2013)
How will global precipitation respond to climate change?

**Observations**

**Simulations:**
- RCP 8.5
- Historical
- RCP 4.5

See also [Allan et al. (2013) Surv. Geophys](#)

See also [Hawkins & Sutton (2010) Clim. Dyn](#)
Confident global precipitation increases with warming

• Enhanced atmospheric radiative cooling with warming
  – Clear-sky dominates
  – Model agreement
  – Radiative transfer and thermodynamics

• Energy balance constrains increase in precipitation
Improved understanding: radiative forcing & precipitation response

Andrews et al. (2009) J Climate

A simple model of precipitation change

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

- Direct radiative heating of troposphere

Allan et al. (2013) Surv. Geophys, using \( f \) calculated by Andrews et al. (2010) GRL; see also Kvalevåg et al. (2010) GRL
Implications for transient responses

CMIP3 coupled model ensemble mean: 

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

• Above: GHG-aerosol influence on precipitation
• Left: precipitation ramp-up on CO₂ ramp-down

Wu et al. (2013) Nature-Climate
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 SMMR-SSM/I, AMSRE and ERA Interim over land and high latitudes)

Allan et al. (2013) Surv. Geophys

dW/dT ≈ 7%/K

≈ 1%/decade
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
Linking flooding impacts to atmospheric precursors

- UK winter flooding linked to strong moisture transport events
  - Cumbria November 2009 (Lavers et al. 2011 GRL)
  - “Atmospheric Rivers” (ARs) in warm conveyor

- Future increase in moisture explains most (but not all) of intensification of AR events
  - Confident in the mechanisms and physics involved
Contrasting precipitation response expected

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

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*
CMIP5 simulations: Wettest tropical grid-points get wetter, driest drier


Ocean

Land

GPCC GPCP

Wet land: strong ENSO influence

Pre 1988 GPCP observations over ocean don’t use microwave data

Robust drying of dry tropical land

30% wettest gridpoints vs 70% driest each month
Circulation response

First argument:

\[ P \sim Mq \]

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 CO\textsubscript{2}**

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 Horn of Africa drought? Williams et al. (2011) Clim Dyn

Enhanced energy transport

Hwang et al. (2013) GRL
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
• Are regional responses predictable?
• Will extreme precipitation outpace Clausius Clapeyron constraint?
• What are changes in radiative forcings and their associated fast adjustments?
• Implications for climate geoengineering
• 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 (~2-3%/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
- How SST patterns and the land surface respond to rising CO₂ is crucial for improving regional predictions
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

after Takahashi (2009) JAS.
See also Manabe & Wetherald (1975) JAS
Simple model of precipitation change

Thanks to Keith Shine and Evgenios Koukouvagias

![Graphs showing radiative forcings and surface temperature trends over time.]

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Prescribed values of atmospheric forcing scaling parameter $f = \Delta F_{\text{zm}}/\Delta F$</th>
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</thead>
<tbody>
<tr>
<td>Forcing</td>
<td>CO$_2$</td>
</tr>
<tr>
<td>$f$</td>
<td>0.8</td>
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</tbody>
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Well-Mixed Greenhouse Gases (WMGHG) includes CH$_4$, N$_2$O and CFCs; SO$_4$ includes all sulfate aerosol forcings (direct, indirect and volcanic). BB biomass burning aerosol, BC black carbon aerosol
Altitude dependence of response (kernels)

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