Physically consistent responses in the atmospheric hydrological cycle in models and observations

Richard P. Allan
Department of Meteorology/NCAS, University of Reading
Collaborators: Chunlei Liu, Matthias Zahn, David Lavers, Brian Soden
http://www.met.reading.ac.uk/~sgs02rpa
r.p.allan@reading.ac.uk
How should global precipitation respond to climate change?

Climate model projections (IPCC 2007)

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

![Precipitation Intensity](chart)

![Dry Days](chart)

![Precipitation Change (%)](chart)
Physical basis: energy balance
Models simulate robust response of clear-sky radiation to warming (~2 Wm\(^{-2}\)K\(^{-1}\)) and a resulting increase in precipitation to balance (~2 %K\(^{-1}\))

Physical basis: Clausius Clapeyron

\[
\frac{1}{q_s} \frac{dq_s}{dT} \approx \frac{1}{e_s} \frac{de_s}{dT} = \frac{L}{R_v T^2} = \begin{cases} 
0.14 K^{-1} & T = 200 K \\
0.07 K^{-1} & T = 273 K \\
0.06 K^{-1} & T = 300 K 
\end{cases}
\]

- Strong constraint upon low-altitude water vapour over the oceans
- Land regions?

SSM/I Satellite data, Dec 2006

e.g. Allan (2012) Surv. Geophys. in press
Global changes in water vapour

Updated from O’Gorman et al. (2012) Surv. Geophys; see also John et al. (2009) GRL
Extreme Precipitation

- Large-scale rainfall events fuelled by moisture convergence
  - e.g. Trenberth et al. (2003) *BAMS*. But see Wilson and Toumi (2005) *GRL*
  - Intensification of rainfall (~7%/K?)
Observed and Simulated responses in extreme Precipitation

- Increase in intense rainfall with tropical ocean warming
- SSM/I satellite observations at upper range of models

Tropical response uncertain: O’Gorman and Schneider (2009) PNAS....
but see also: Lenderink and Van Meijgaard (2010) ERL; Haerter et al. (2010) GRL
HydEF project:
Extreme precipitation & mid-latitude Flooding

• Links UK winter flooding to moisture conveyor events
e.g. Nov 2009 Cumbria floods

Physical Basis: Moisture Balance

\[ P - E \sim (\nabla \cdot (u q)) \] (units of \(s^{-1}\); scale by \((p/g \rho_w)\) for units of mm/day)

If the flow field remains relatively constant, the moisture transport scales with low-level moisture.

Held and Soden (2006) J Climate
Projected (top) and estimated (bottom) changes in P-E

\[
\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T.
\]

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

\[
\alpha \approx 0.07 \text{ K}^{-1}.
\]

Fig. 7. The annual-mean distribution of \(\delta(P - E)\) from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.
Moisture transports from ERA Interim

- Moisture transport into tropical ascent region
- Significant mid-level outflow
- 2000s: increases in inflow or drift in ERA Interim?
First argument:
\[ P \sim Mq. \]
So if \( P \) constrained to rise more slowly than \( q \), this implies reduced \( M \).

Second argument:
\[ \omega = \frac{Q}{\sigma}. \]
Subsidence (\( \omega \)) induced by radiative cooling (\( Q \)) but the magnitude of \( \omega \) depends on (\( \Gamma_d - \Gamma \)) or static stability (\( \sigma \)). If \( \Gamma \) follows MALR \( \rightarrow \) increased \( \sigma \). This offsets \( Q \) effect on \( \omega \).
Precipitation bias and response binned by dynamical regime

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

Contrasting precipitation response expected

- Heavy rain follows moisture (~7%/K)
- Mean Precipitation linked to radiation balance (~3%/K)
- Light Precipitation (~?%/K)
Contrasting precipitation response in wet and dry regions of the tropical circulation

Sensitivity to reanalysis dataset used to define wet/dry regions

Exploiting satellite estimates of precipitation

- HOAPS and TRMM 3B42 are outliers
- Strong sensitivity to ENSO

Liu & Allan (2011) JGR.
Contrasting land/ocean changes relate to ENSO

See also Gu et al. (2007) J Clim

PAGODA: Understanding global changes in the water cycle

Oceans

Land

Above: Current changes in tropical precipitation in CMIP5 models & satellite-based observations

*Note realism of atmosphere-only AMIP model simulations*

*Liu and Allan in prep…*
CMIP5 simulated & projected % changes in precipitation

Pre-1988 GPCP ocean data does not contain microwave observations
Transient responses

Andrews et al. (2009) J Climate
Transient responses

• CO$_2$ forcing experiments
• Initial precip response suppressed by CO$_2$ forcing
• Stronger response after CO$_2$ rampdown


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

HadCM3: Wu et al. (2010) GRL
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
- Hydrological Forcing: $\text{HF}=kdT-d\text{AA}-d\text{SH}$ (Ming et al. 2010 GRL; also Andrews et al. 2010 GRL)
Regional responses in precipitation

Energetic constraints?

• $\Delta$Precipitation

• $\Delta$Dry static energy

Muller and O’Gorman (2011) Nature Climate Change
Implications for monsoon? Levermann et al. (2009) PNAS
Conclusions

- **Robust Responses**
  - Low level moisture; clear-sky radiation
  - Mean and Intense rainfall (roughly)
  - Contrasting wet/dry region responses

- **Less Robust/Discrepancies**
  - Observed precipitation response at upper end of model range?
  - Moisture at upper levels/over land and mean state
  - Inaccurate precipitation frequency/intensity distributions
  - Magnitude of change in precipitation from satellite datasets/models

- **Further work**
  - Decadal changes in global energy budget, aerosol forcing effects and cloud feedbacks: links to water cycle?
  - Separating forcing-related fast responses from slow SST response
  - Are regional changes in the water cycle, down to catchment scale, predictable?