Energy and Thermodynamic Constraints on the Global Water Cycle

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Climate model projections (IPCC 2007)

- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??
Physical basis: energy balance

Trenberth et al. (2009) BAMS
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$^{-1}$)

\[
\frac{dP}{dT_s} \sim \frac{1}{\rho_w L} \frac{dQ}{dT_s}
\]
The energy constraint on global precipitation

Andrews et al. (2009) J Climate
Evaporation

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

Muted Evaporation changes in models are explained by small changes in Boundary Layer:
1) declining wind stress
2) reduced surface temperature lapse rate \((T_s - T_o)\)
3) increased surface relative humidity \((R_{Ho})\)
Current tropical ocean variation in water vapour and precipitation

Allan and Soden (2008) Science
Current changes in tropical ocean column water vapour

\[ \frac{\delta e^*}{e^*} \approx \frac{L}{R_v T^2} \delta T, \]

...despite inaccurate mean state, Pierce et al.; John and Soden (both GRL, 2006)
Thermodynamic constraint

- Clausius-Clapeyron
  - Low-level water vapour (~7%/K)

- Changes in intense rainfall also constrained by moist adiabat
  - O’Gorman and Schneider (2009) PNAS

\[ c = -\omega \left. \frac{dq_s}{dp} \right|_{\theta^*} \]

- Could extra latent heat release within storms enhance rainfall intensity above Clausius Clapeyron?
  - e.g. Lenderink and van Meijgaard (2008) Nature Geoscience
Increases in the frequency of the heaviest rainfall with warming: daily data from models and microwave satellite data (SSM/I)

• Increase in intense rainfall with tropical ocean warming (close to Clausius Clapeyron)
• SSM/I satellite observations at upper limit of model range

Model intense precipitation dependent upon conservation of moist adiabatic lapse rate but responses are highly sensitive to model-specific changes in upward velocities (see O’Gorman and Schneider, 2009, PNAS; Gastineau & Soden 2009).
Large-scale water cycle response

• Clausius-Clapeyron
  – Low-level water vapour (~7%/K)
  – Enhanced moisture transport (F)
  – Enhanced P-E patterns (below)


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

Updated from Allan and Soden (2007) GRL
Avoid reanalyses in defining wet/dry regions

- Sample grid boxes:
  - 30% wettest
  - 70% driest
- Do wet/dry trends remain?
Current trends in wet/dry regions of tropical oceans

- Wet/dry trends remain
  - 1979-1987 GPCP record may be suspect for dry region
  - SSM/I dry region record: inhomogeneity 2000/01?

- GPCP trends 1988-2008
  - Wet: 1.8%/decade
  - Dry: -2.6%/decade
  - Upper range of model trend magnitudes
Conclusions

• **Robust Responses**
  – Low level moisture; clear-sky radiation
  – Mean and Intense rainfall
  – Observed precipitation response at upper end of model range?
  – Contrasting wet/dry region responses

• **Less Robust/Discrepancies**
  – Moisture at upper levels/over land and mean state
  – Inaccurate precipitation frequency 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?
  – Precipitation and radiation balance datasets: forward modelling
  – Surface feedbacks: ocean salinity, soil moisture (SMOS?)
  – Boundary layer changes and surface fluxes