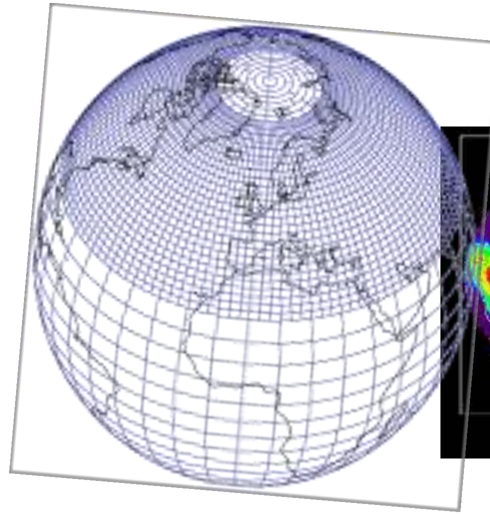

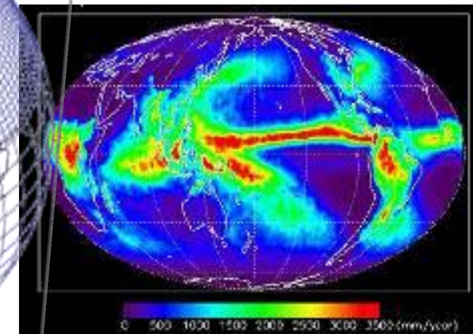

Energy and Thermodynamic Constraints on the Global Water Cycle

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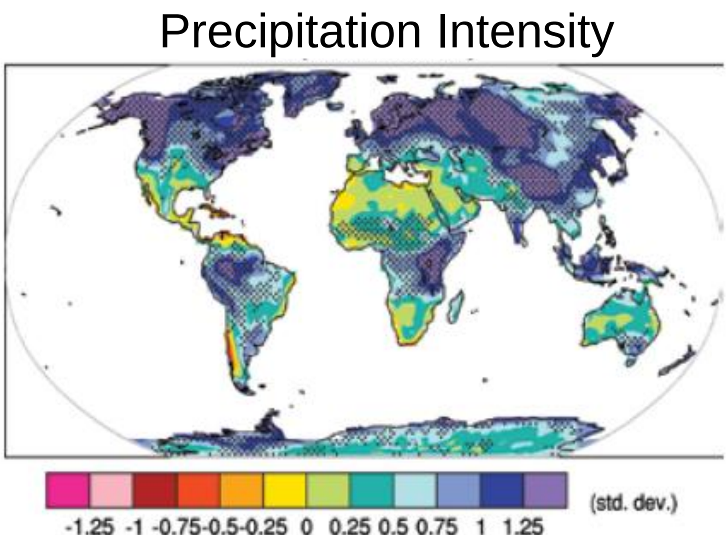
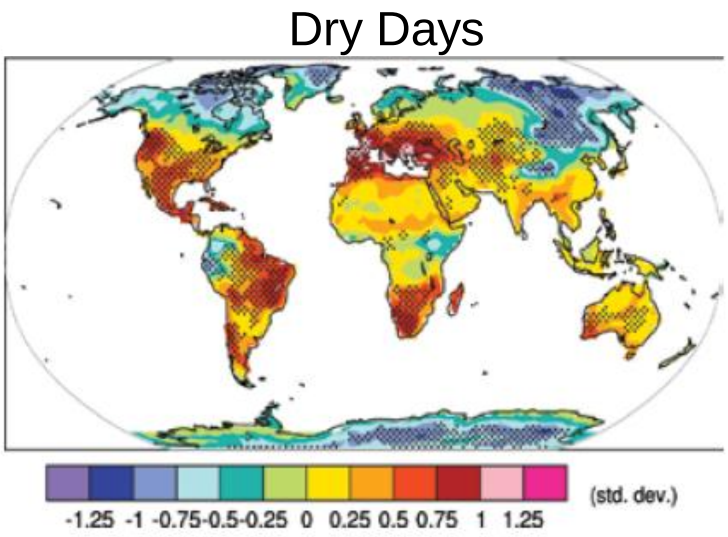
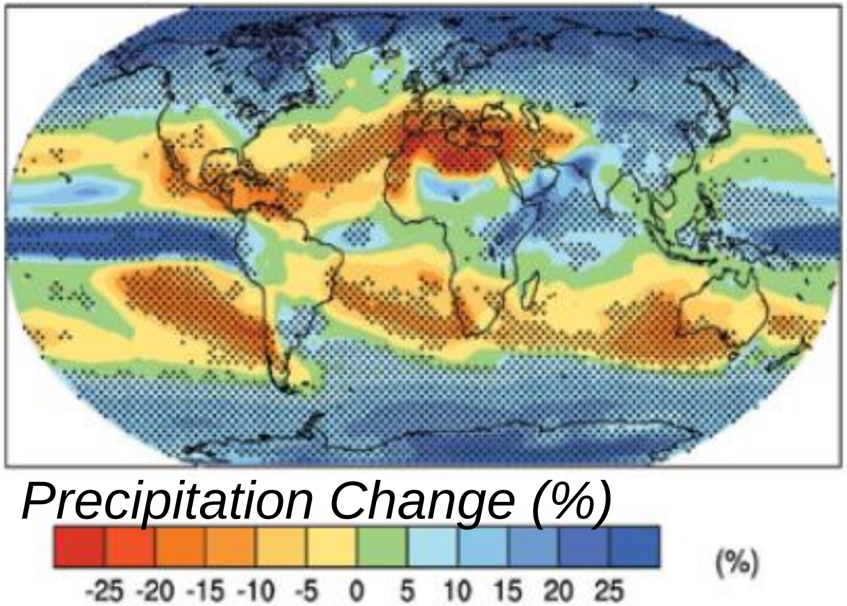
Climate model projections (IPCC 2007)

University of Reading

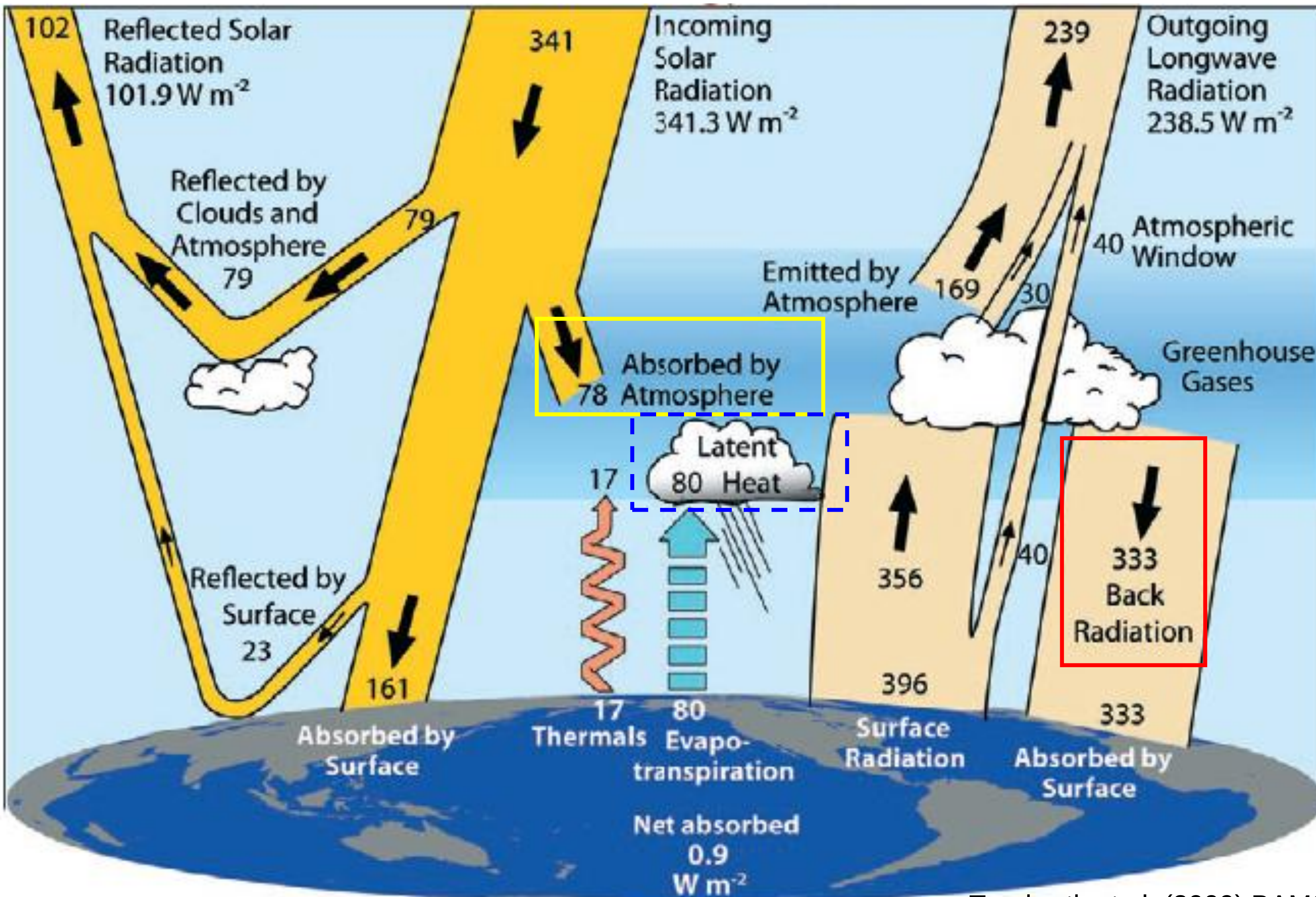




- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??



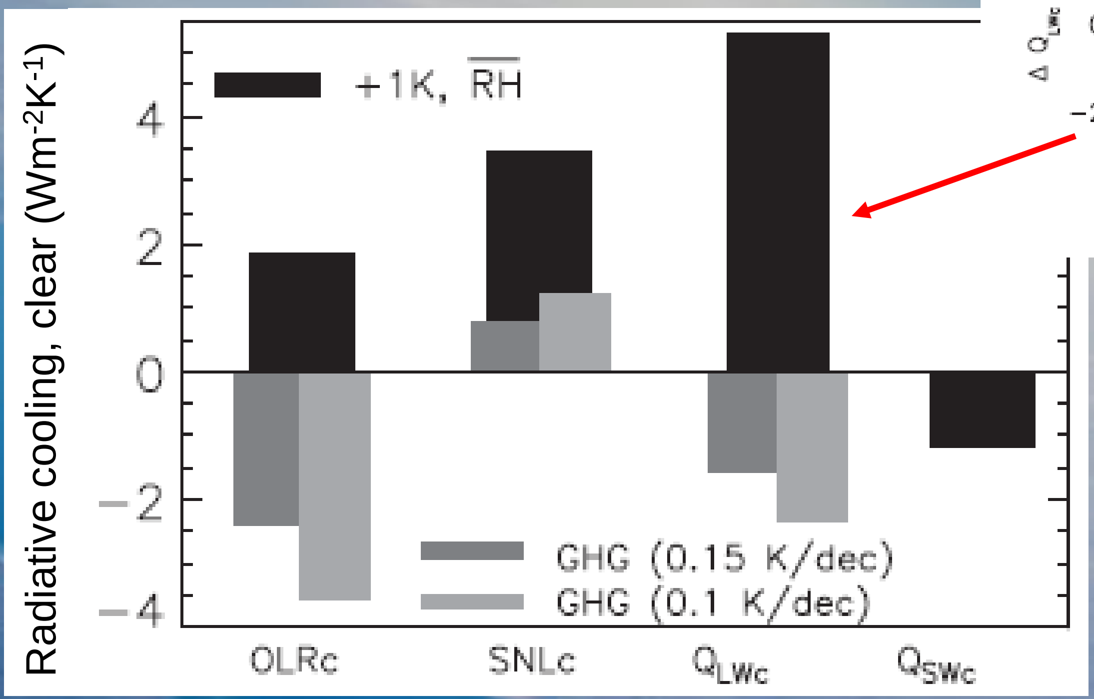
Physical basis: energy balance

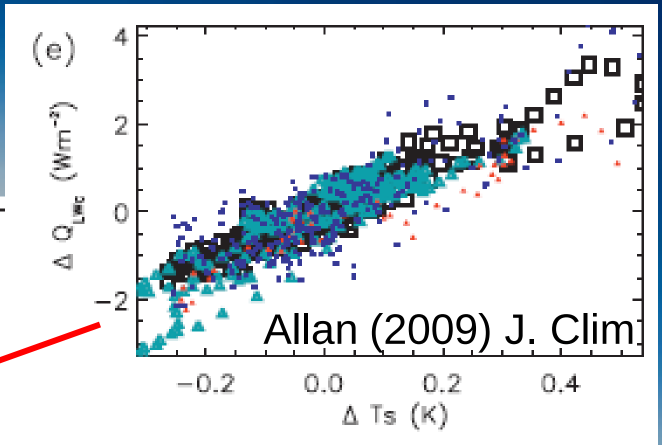


Trenberth et al. (2009) BAMS

Models simulate robust response of clear-sky radiation to warming (~2 $Wm^{-2}K^{-1}$) and a resulting increase in precipitation to balance (~2 $\%K^{-1}$)

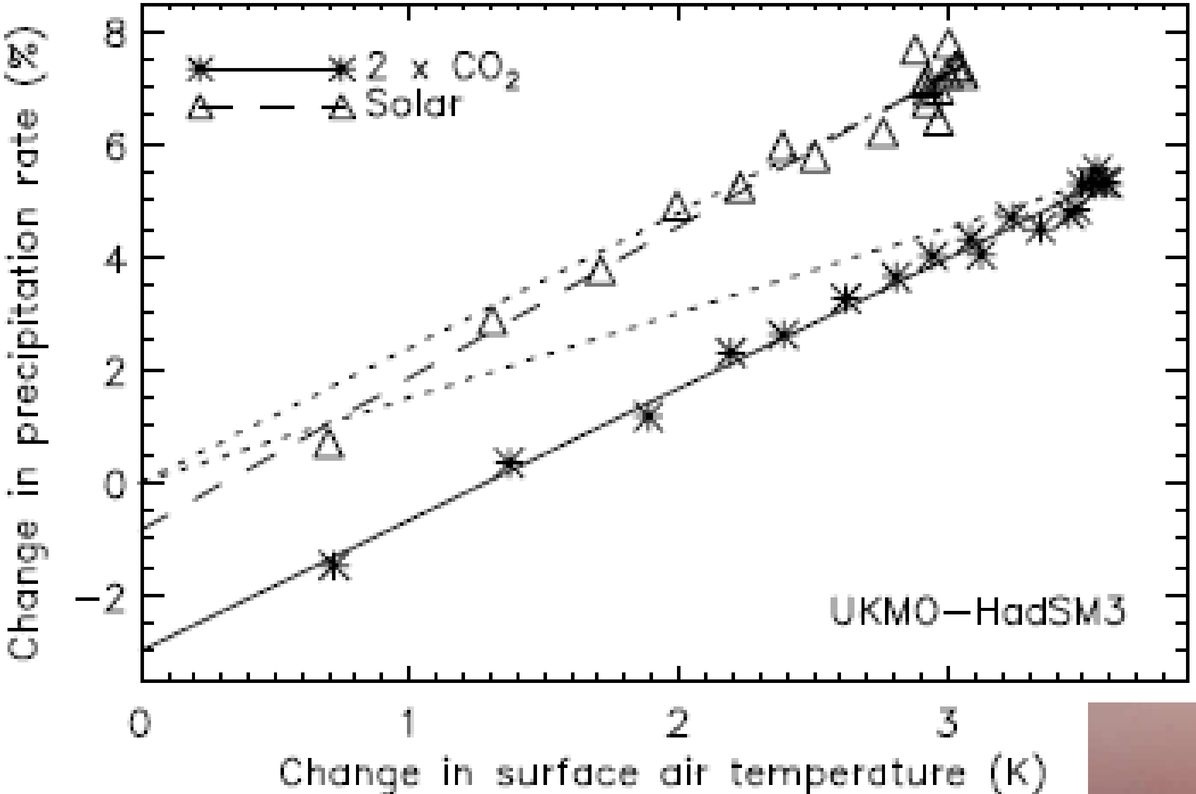
e.g. Allen and Ingram (2002) Nature, Stephens & Ellis (2008) J. Clim



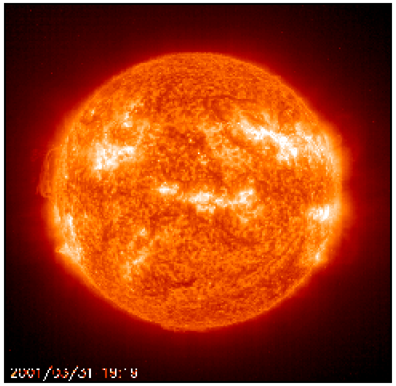


$$\frac{dP}{dTs} \sim \frac{1}{\rho_w L}\frac{dQ}{dTs}$$

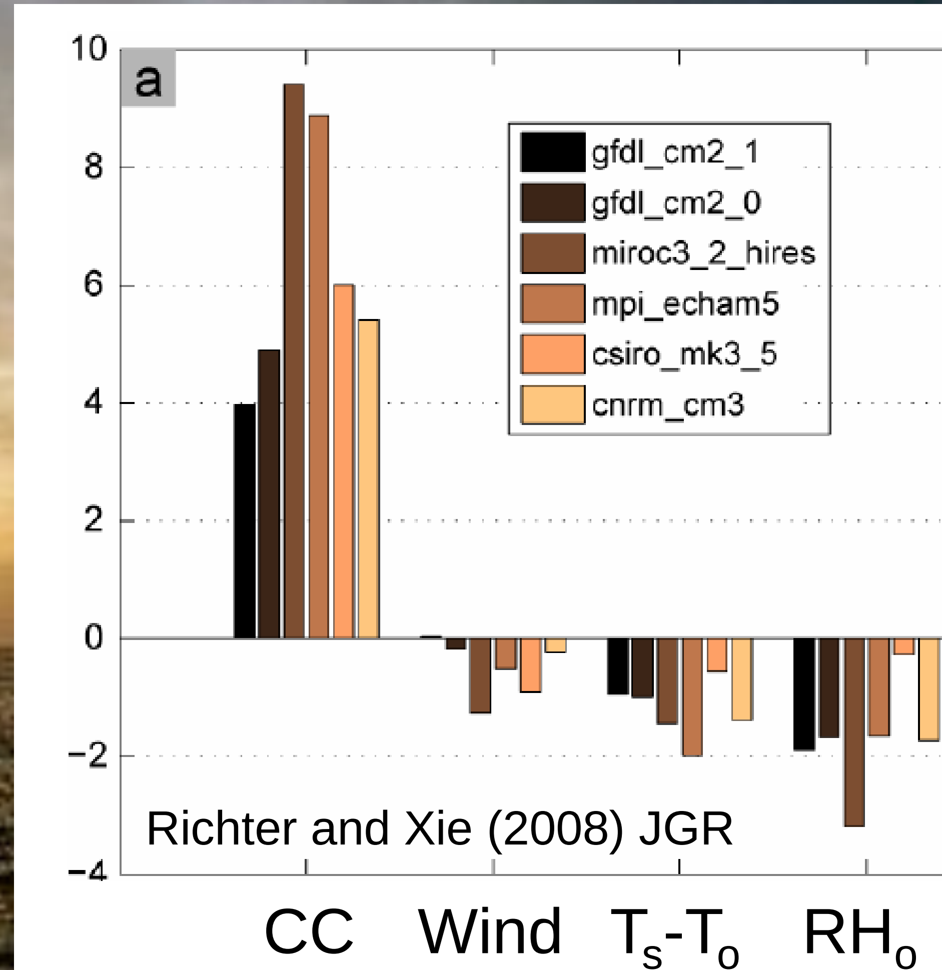
The energy constraint on global precipitation



Andrews et al. (2009) J Climate



Evaporation

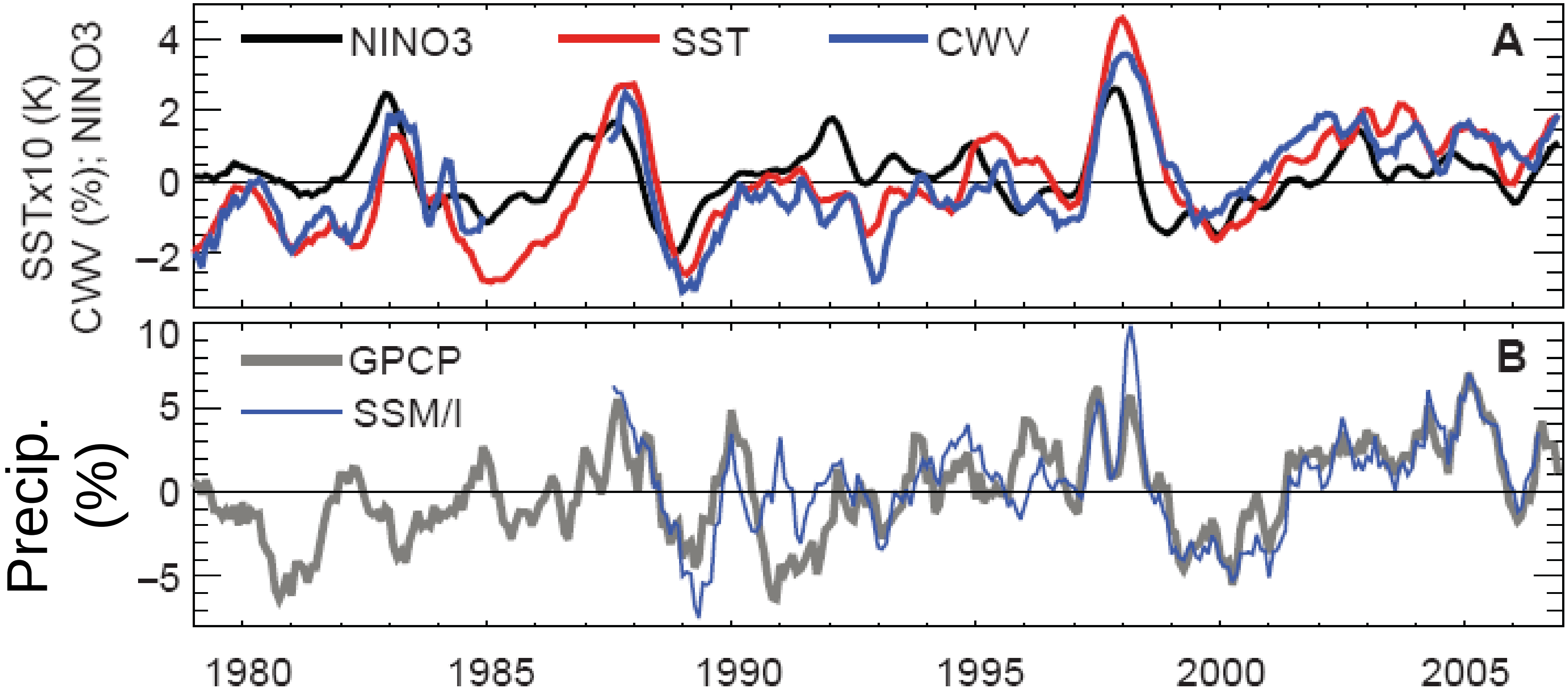


$$Q_E = L_v C_E \rho_a W (q_s - q_a)$$

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 (RH_o)

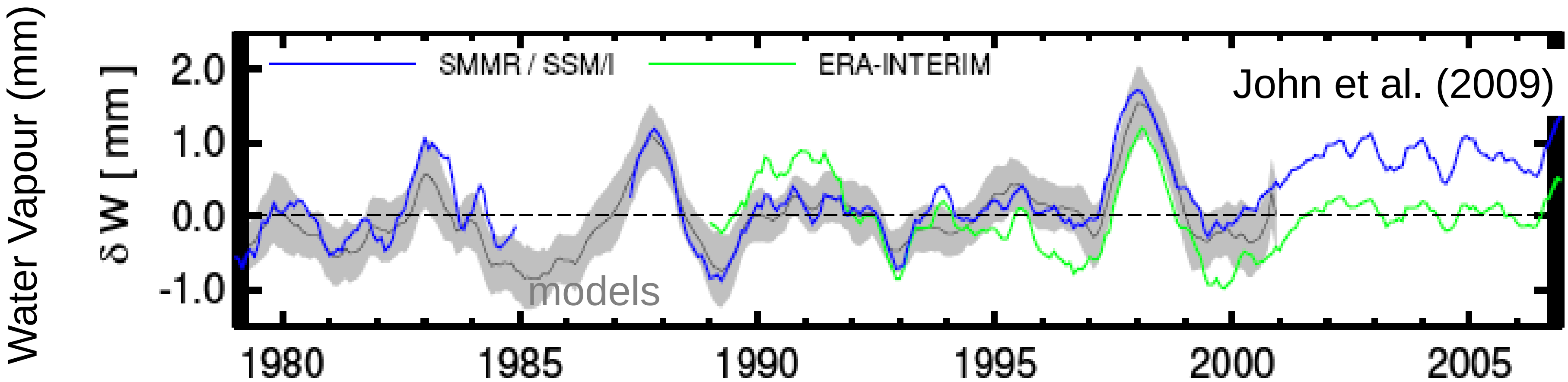
Current tropical ocean variation in water vapour and precipitation



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)

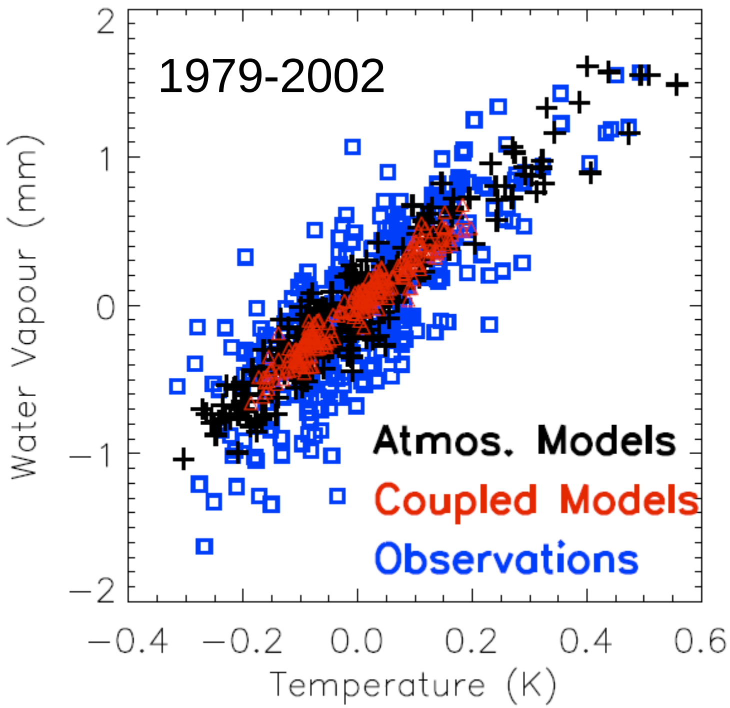
- see also Trenberth et al. (2005) Clim. Dyn., Soden et al. (2005) Science

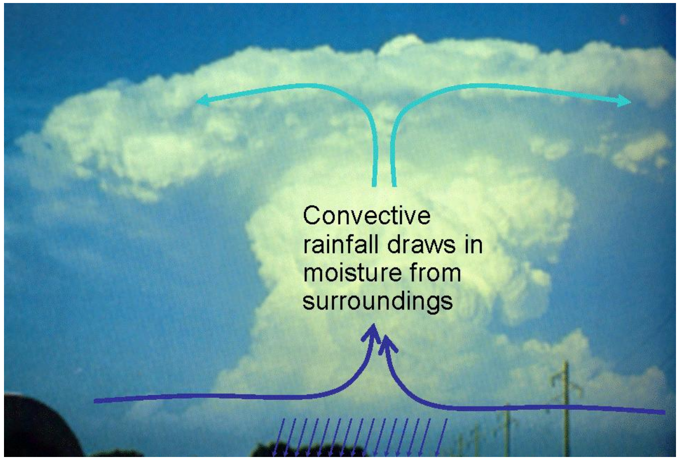
Thermodynamic constraint

- Clausius-Clapeyron
  - Low-level water vapour (~7%/K)
  - Intensification of rainfall: Trenberth et al. (2003) BAMS; Pall et al. (2007) Clim Dyn
- Changes in intense rainfall also constrained by moist adiabat
  - -O'Gorman and Schneider (2009) PNAS

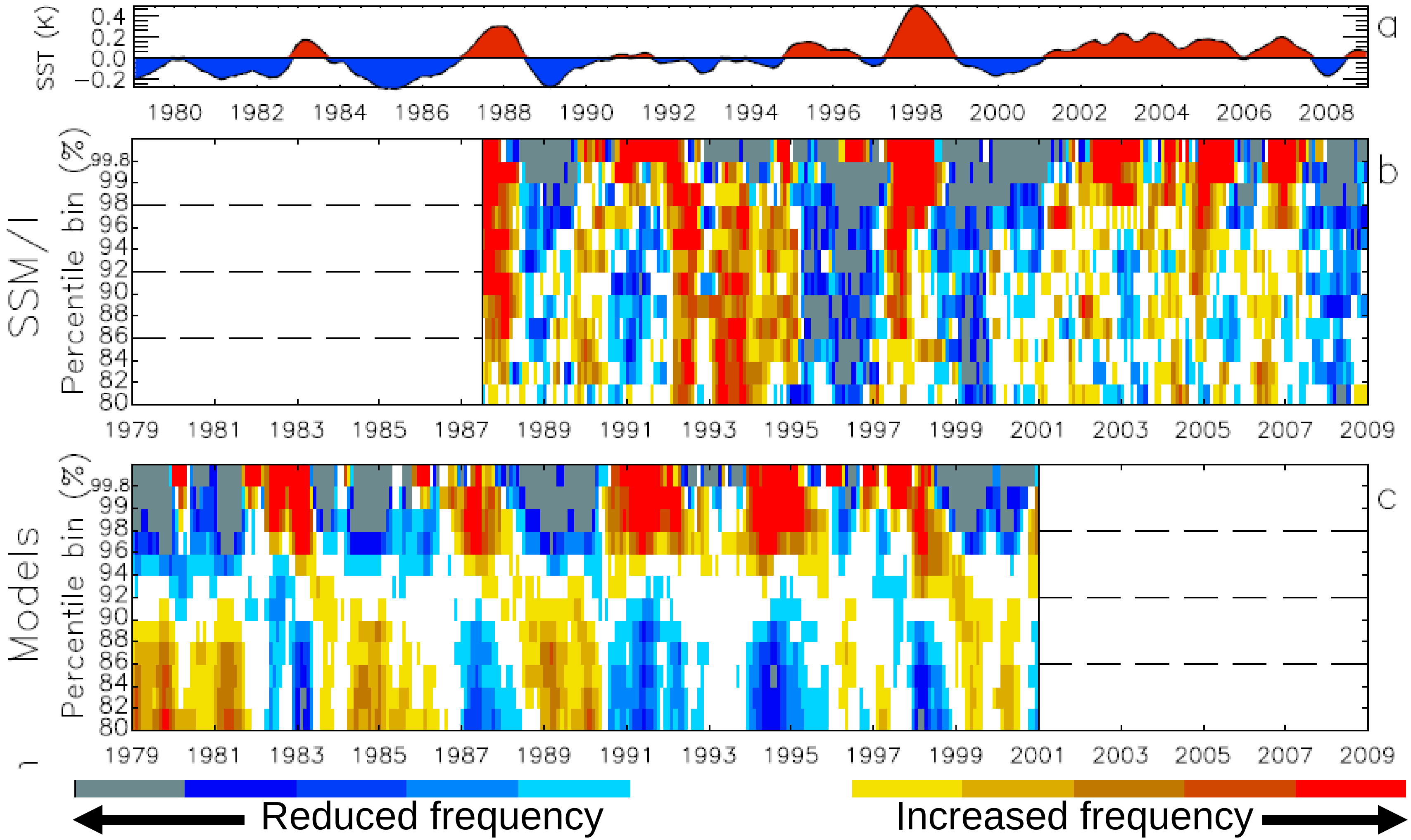
$$c = -\omega \frac{dq_s}{dp}\bigg|_{\theta^*}$$

- Could extra latent heat release within storms enhance rainfall intensity above Clausius Clapeyron?
  - e.g. Lenderink and van Meijgaard (2008) Nature Geoscience



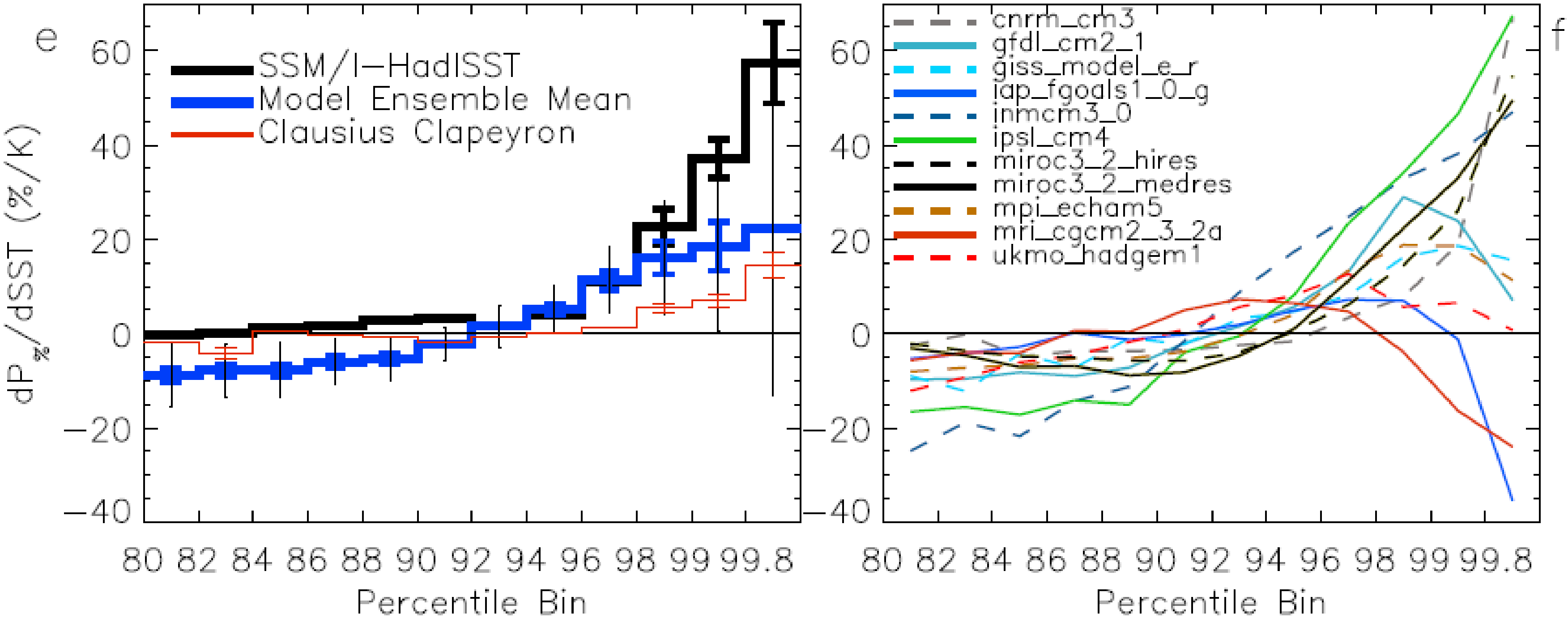


Increases in the frequency of the heaviest rainfall with warming: daily data from models and microwave satellite data (SSM/I)



Allan et al. (2010) Environ. Res. Lett.

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



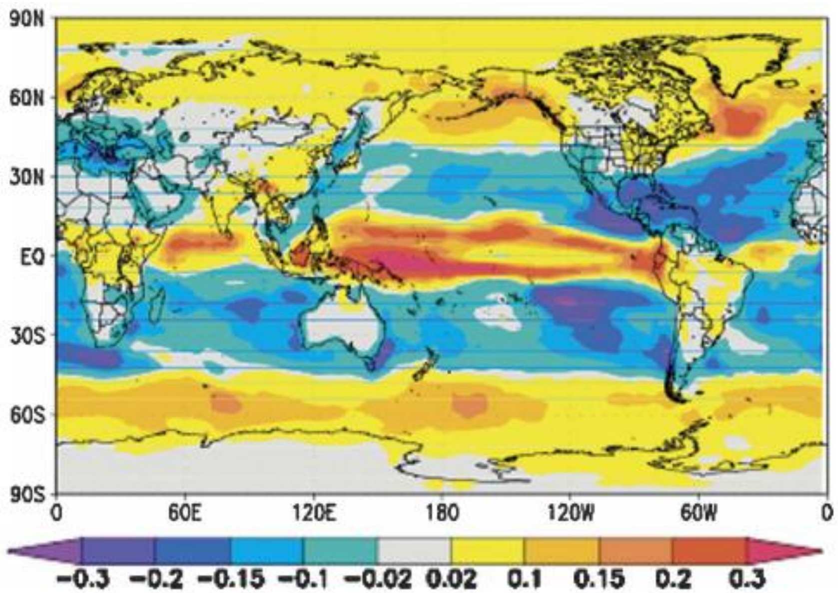
Model intense precipitation dependent upon conservation of moist adiabatic lapse rate but responses are highly sensitive to model-specific changes in upward velocities (see O'Gorman and Schneider, 2009, PNAS; Gastineau & Soden 2009).

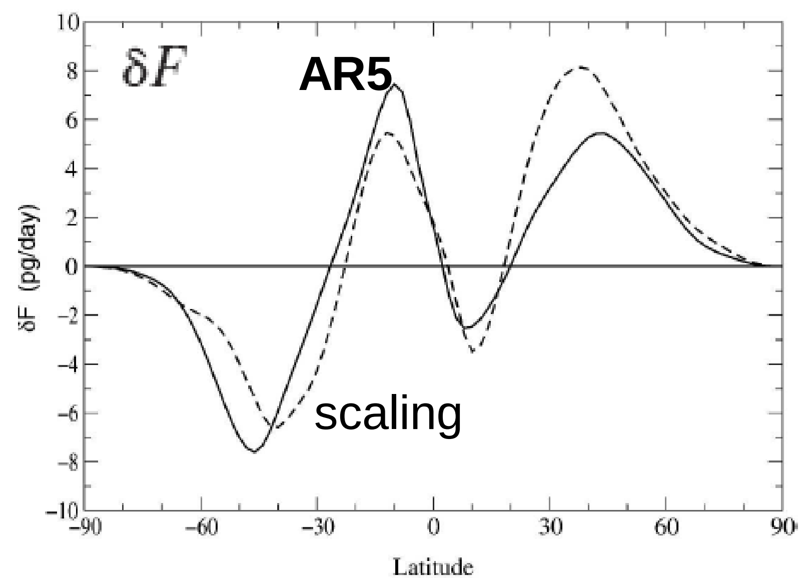
Large-scale water cycle response

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

    See Held and Soden (2006) J Clim

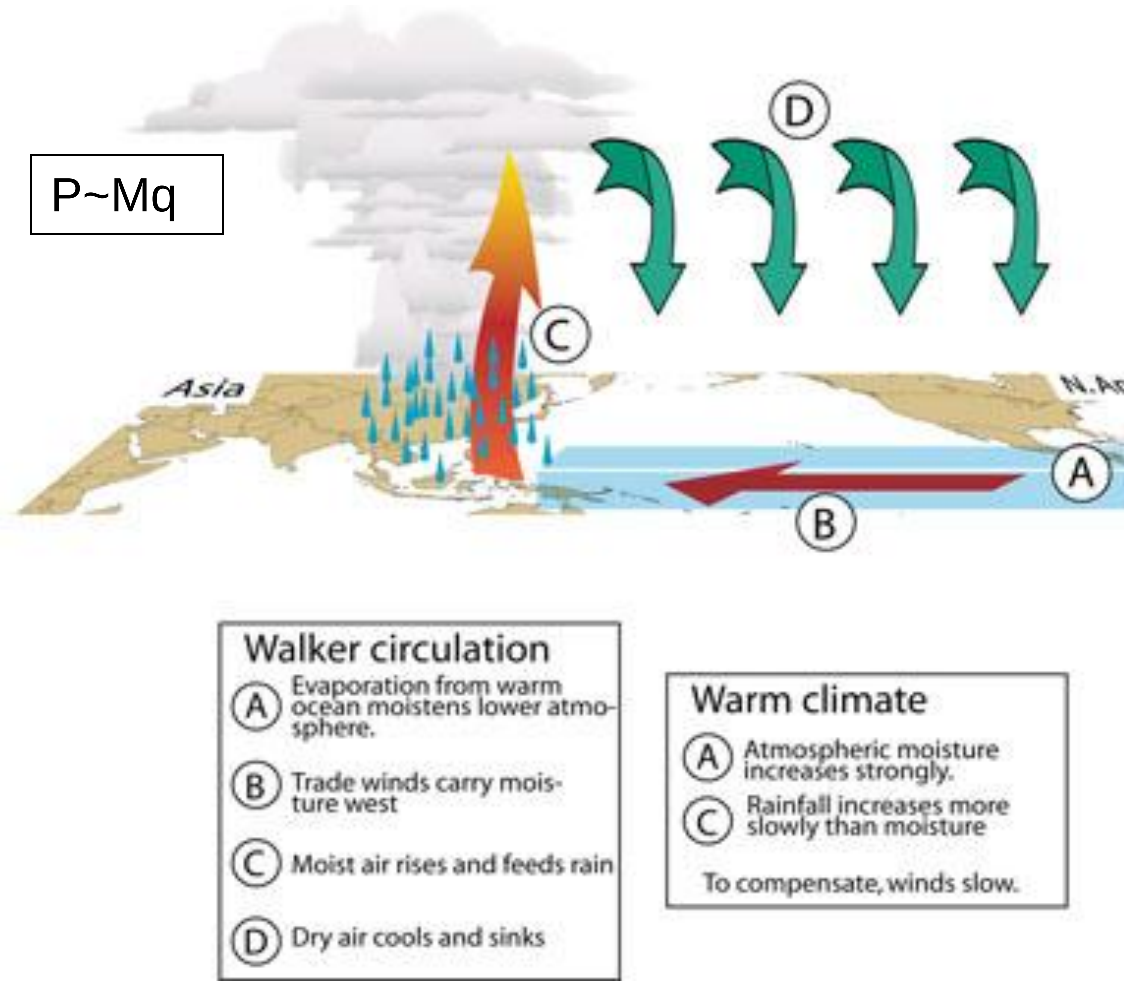
$$\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T.$$

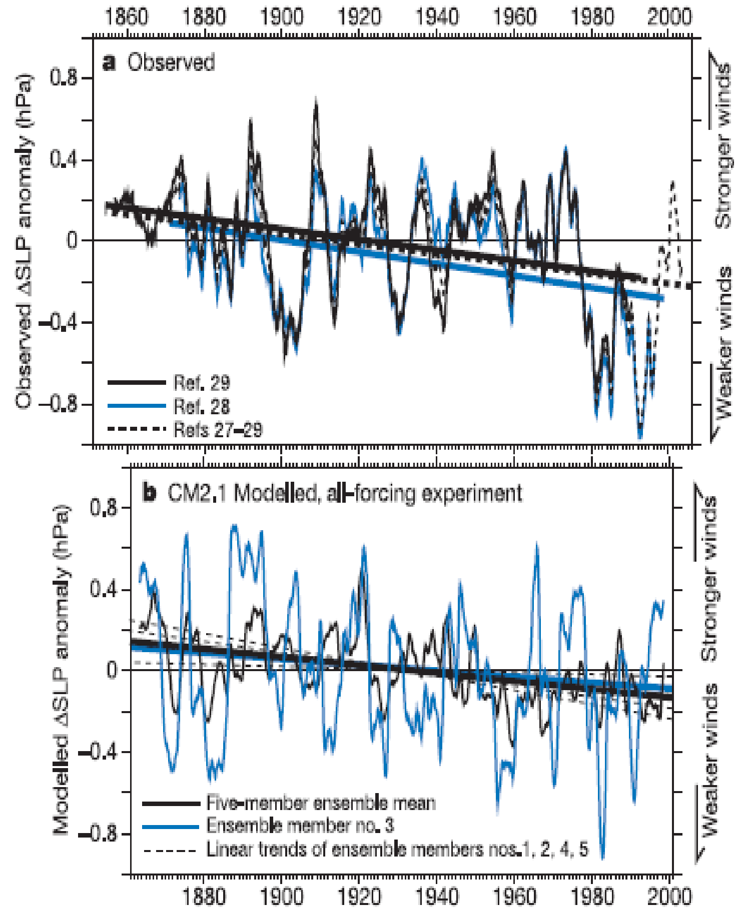




Circulation response

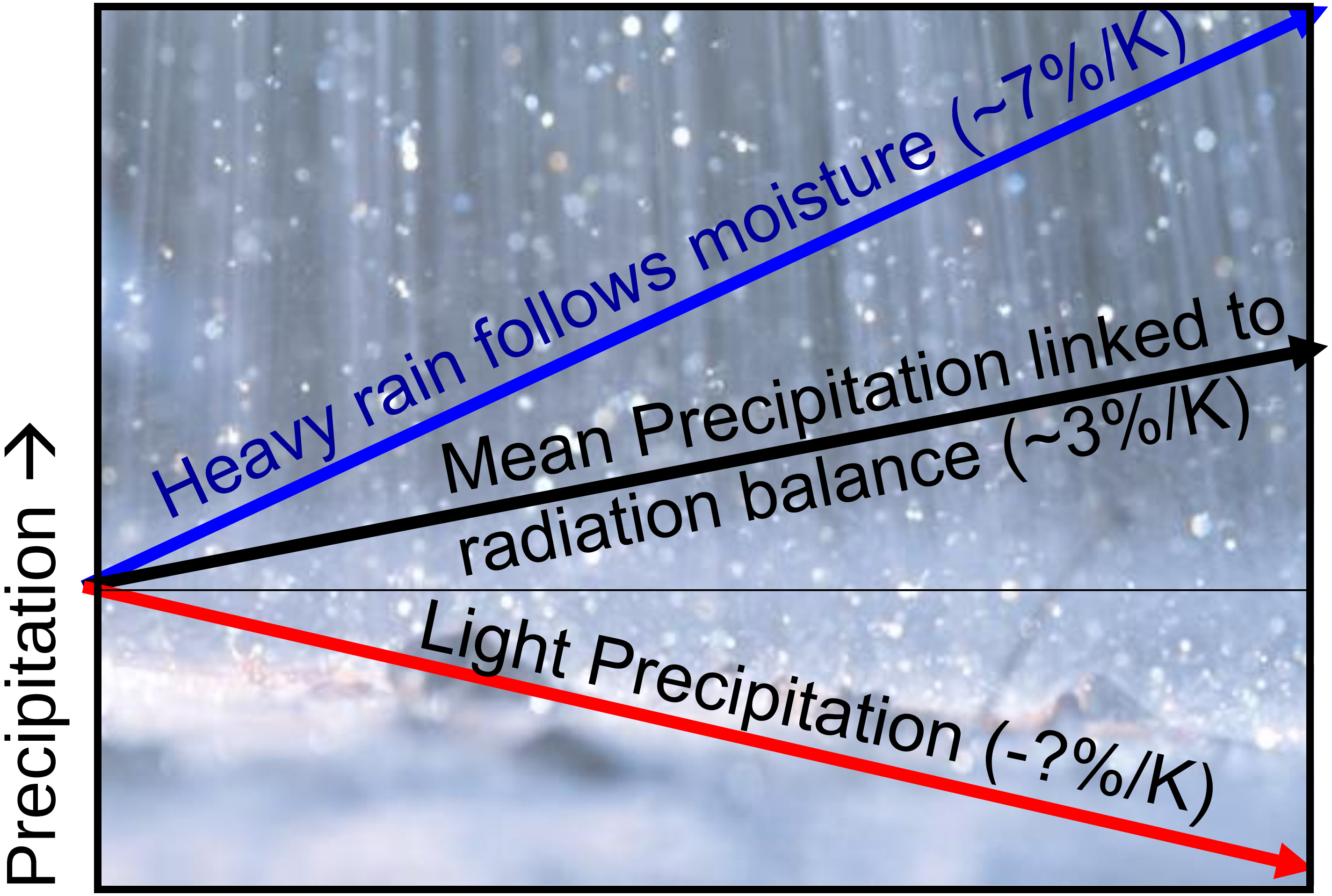
P~Mq





Models/observations achieve muted precipitation response by reducing strength of Walker circulation. Vecchi and Soden (2006) Nature

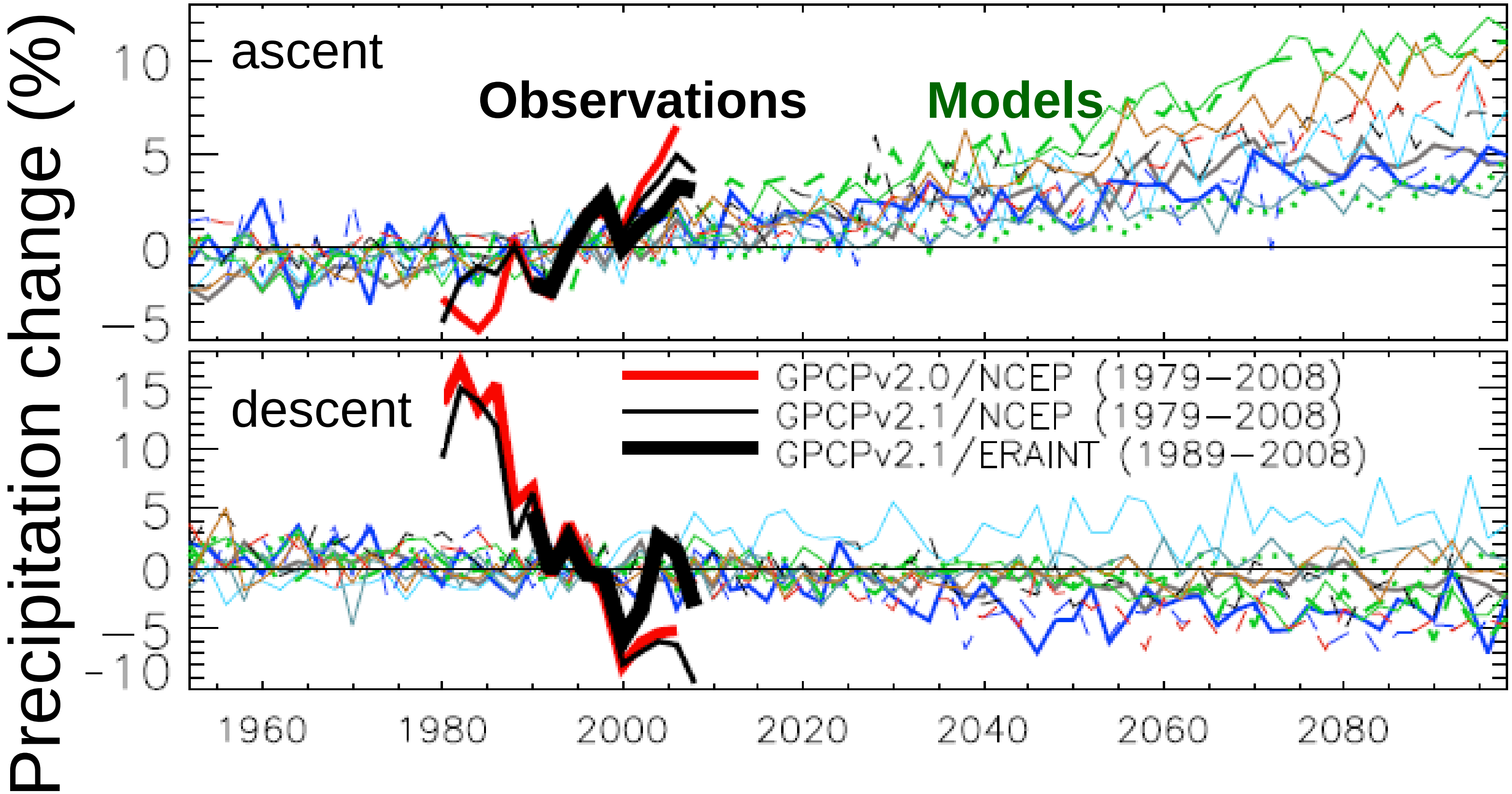
Contrasting precipitation response expected



Temperature →

e.g.Held & Soden (2006) J. Clim; Trenberth et al. (2003) BAMS; Allen & Ingram (2002) Nature

Contrasting precipitation response in wet and dry regions of the tropical circulation

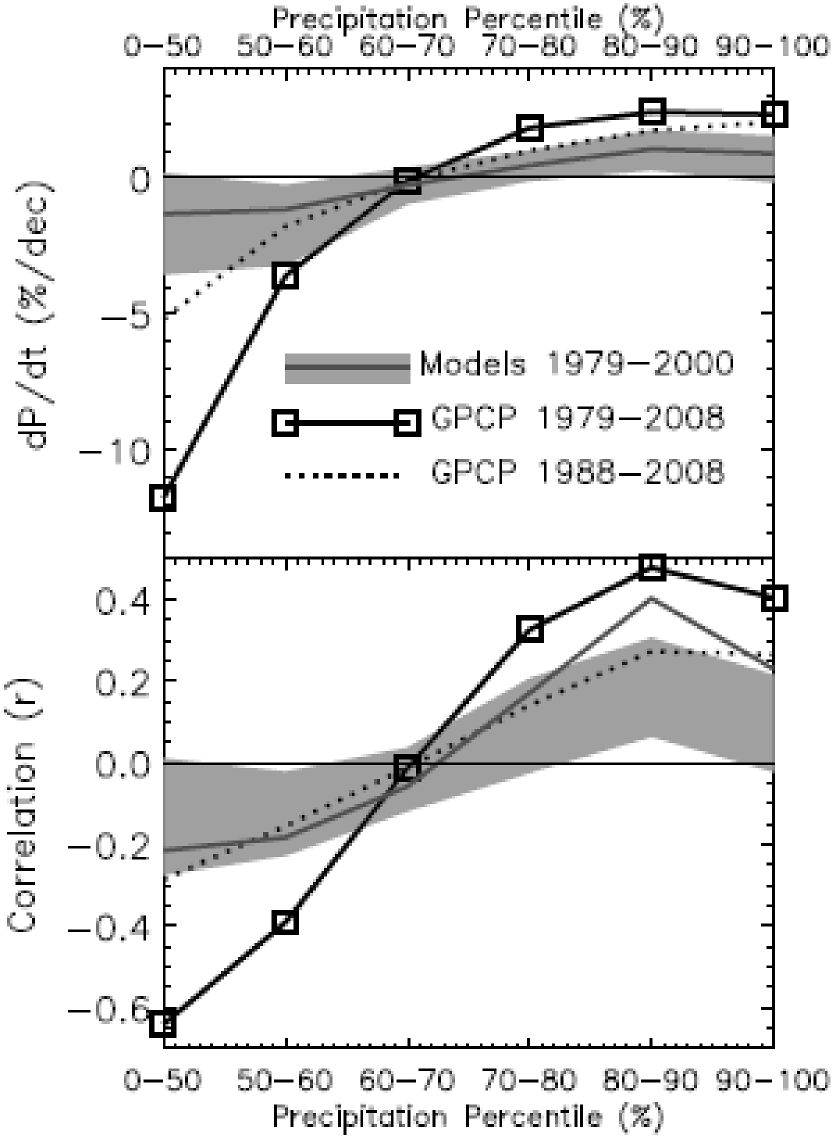


Sensitivity to reanalysis dataset used to define wet/dry regions

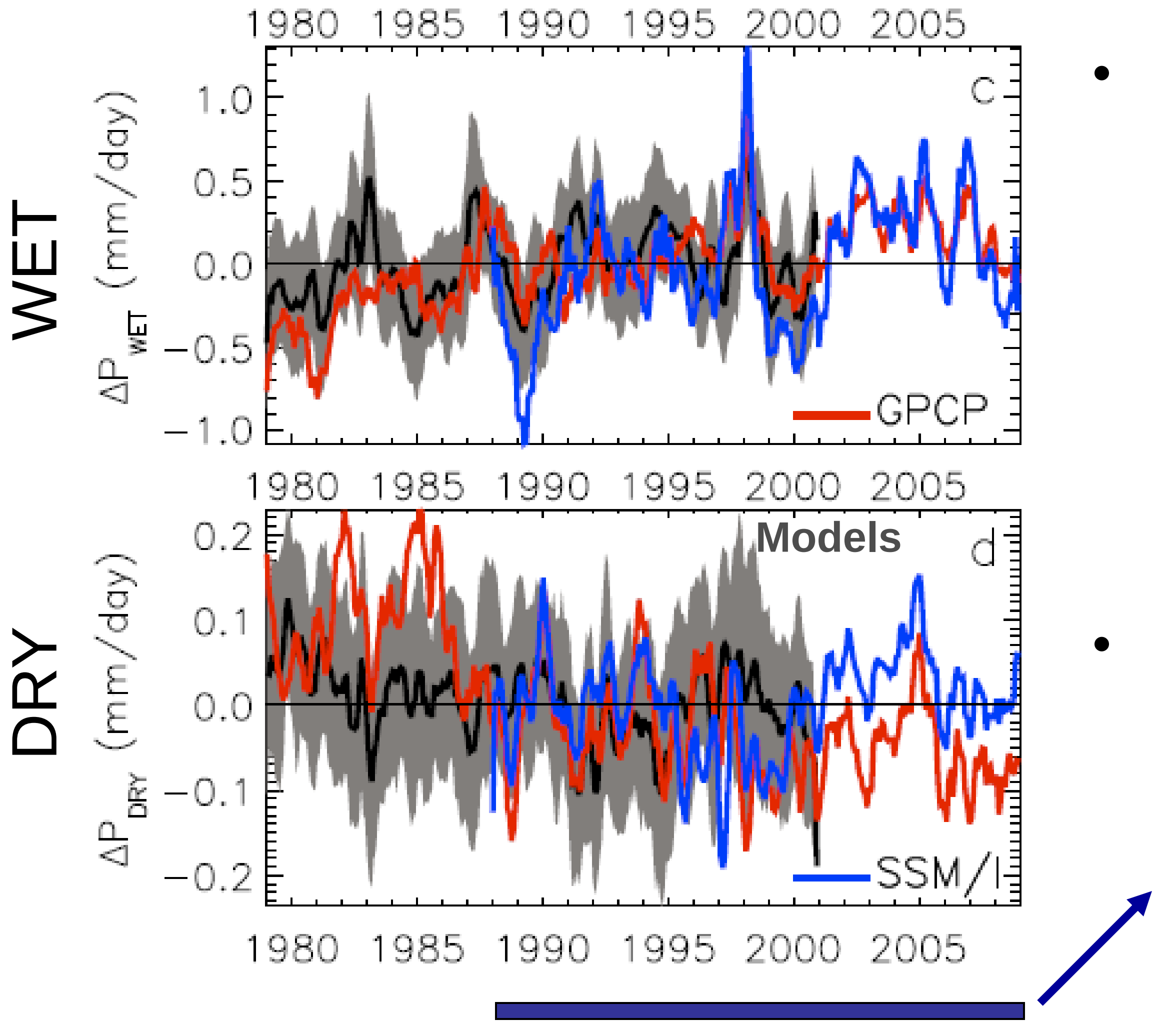
Updated from Allan and Soden (2007) GRL

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