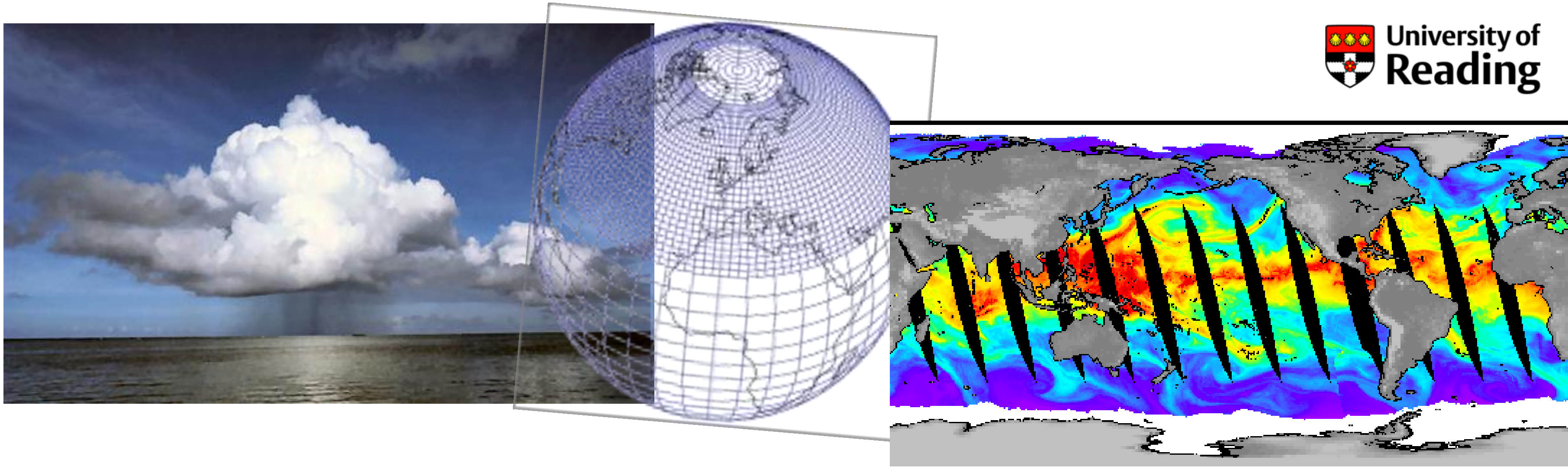

Physically consistent responses in the atmospheric hydrological cycle in models and observations

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Collaborators: Chunlei Liu, Matthias Zahn, David Lavers, Brian Soden
http://www.met.reading.ac.uk/~sgs02rpa
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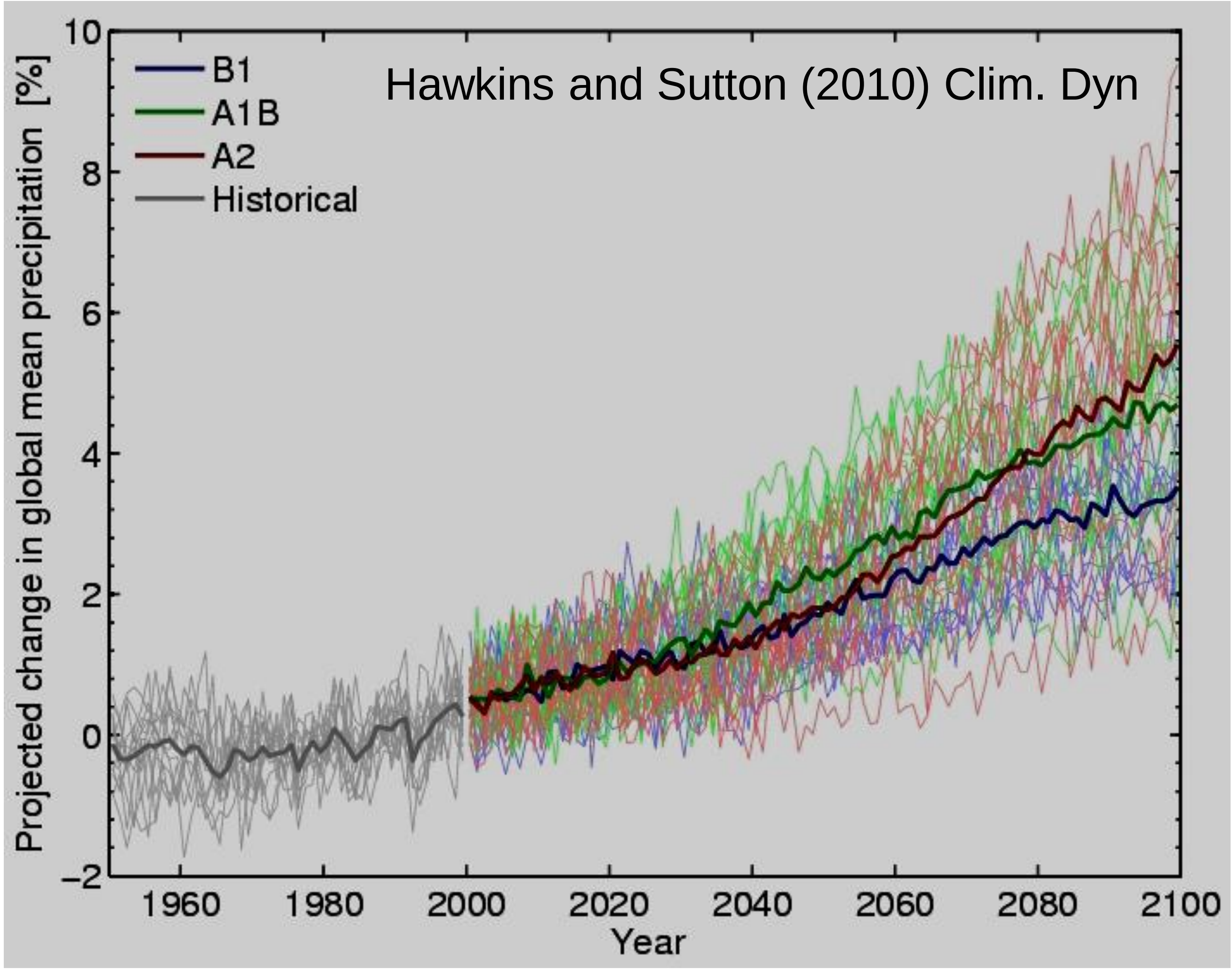
How should global precipitation respond to climate change?



see also Allen and Ingram (2002) Nature; Trenberth (2011) Climate Research

Climate model projections (IPCC 2007)

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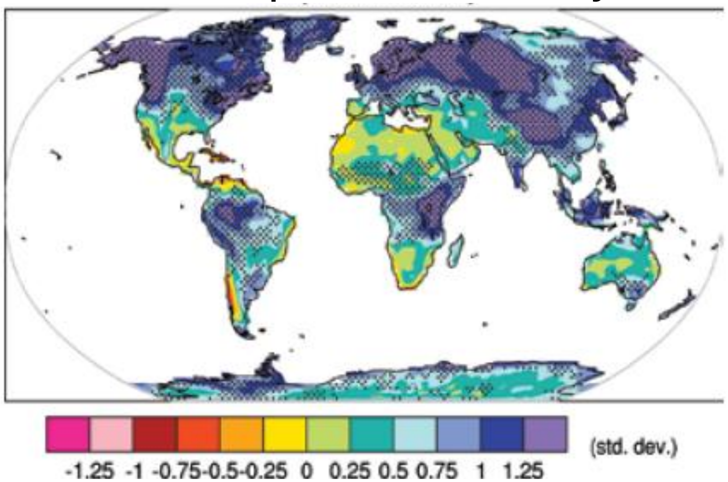
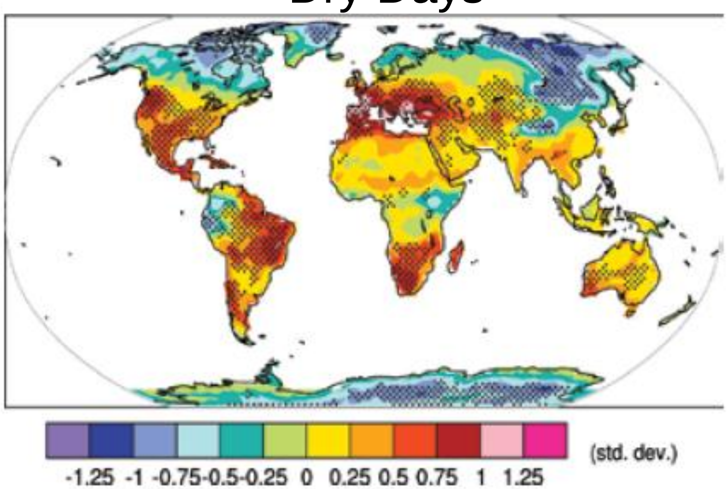
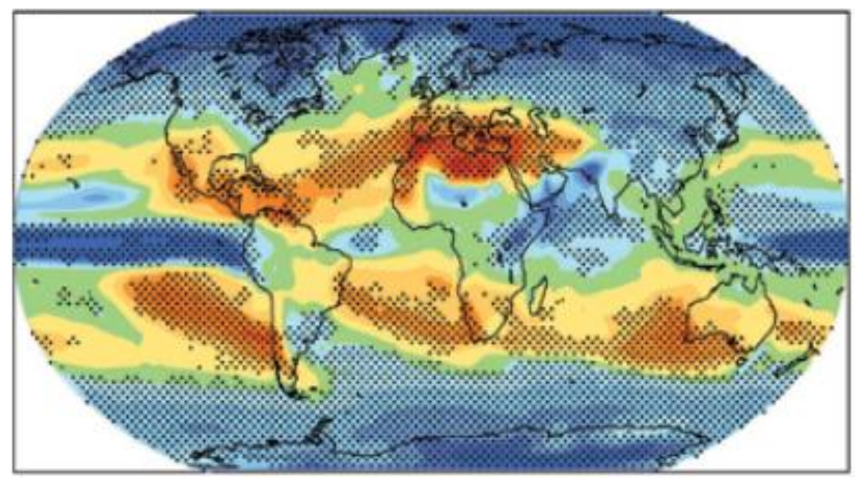
Precipitation Intensity



Dry Days

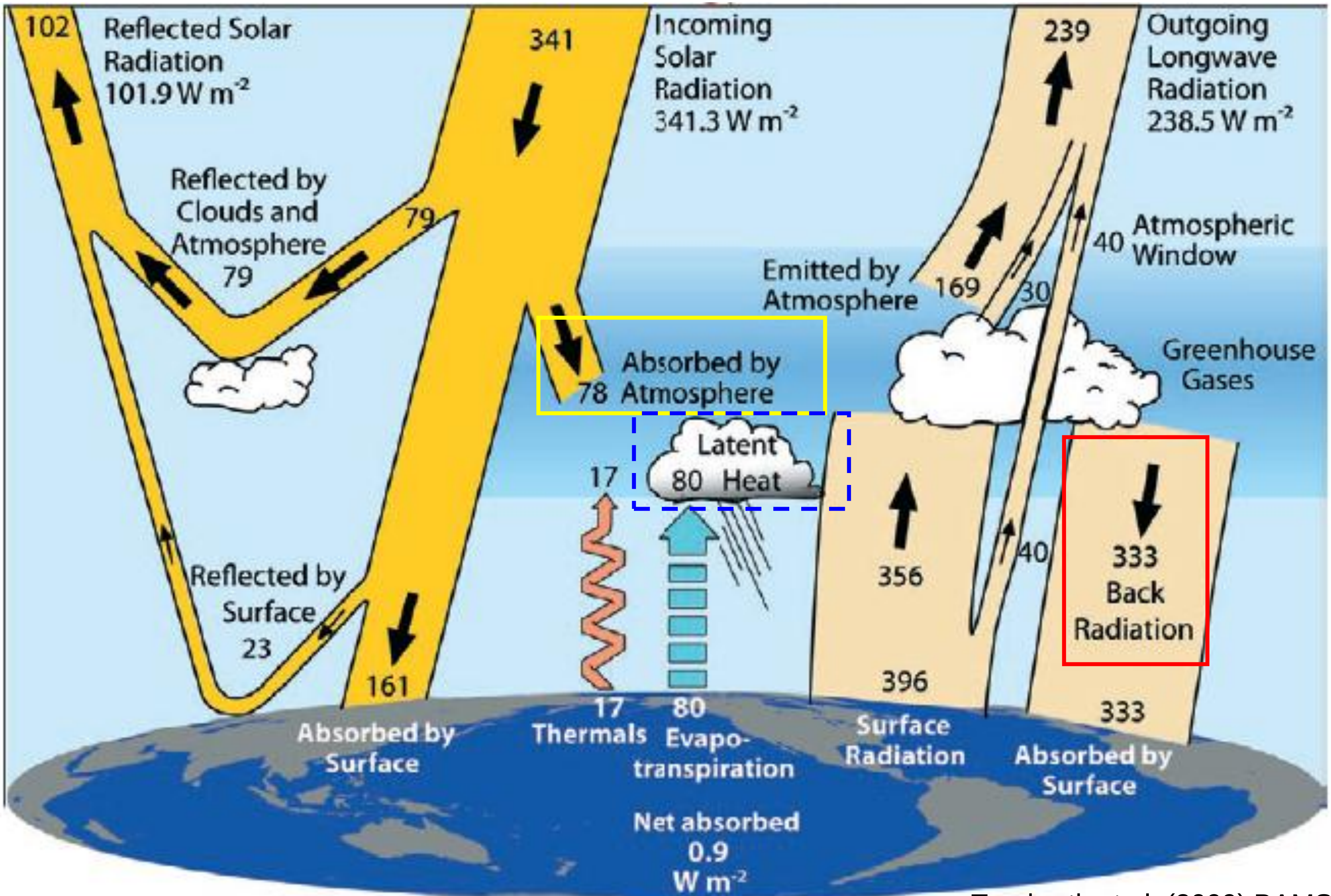


- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??



Precipitation Change (%)

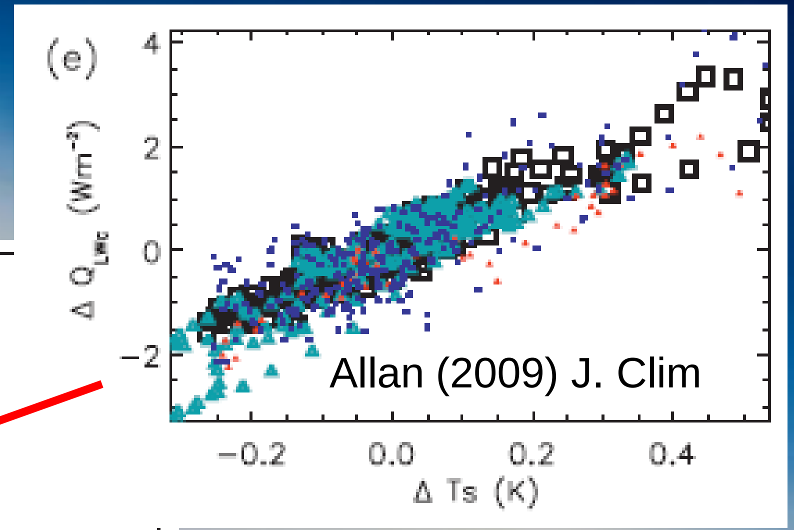
Physical basis: energy balance

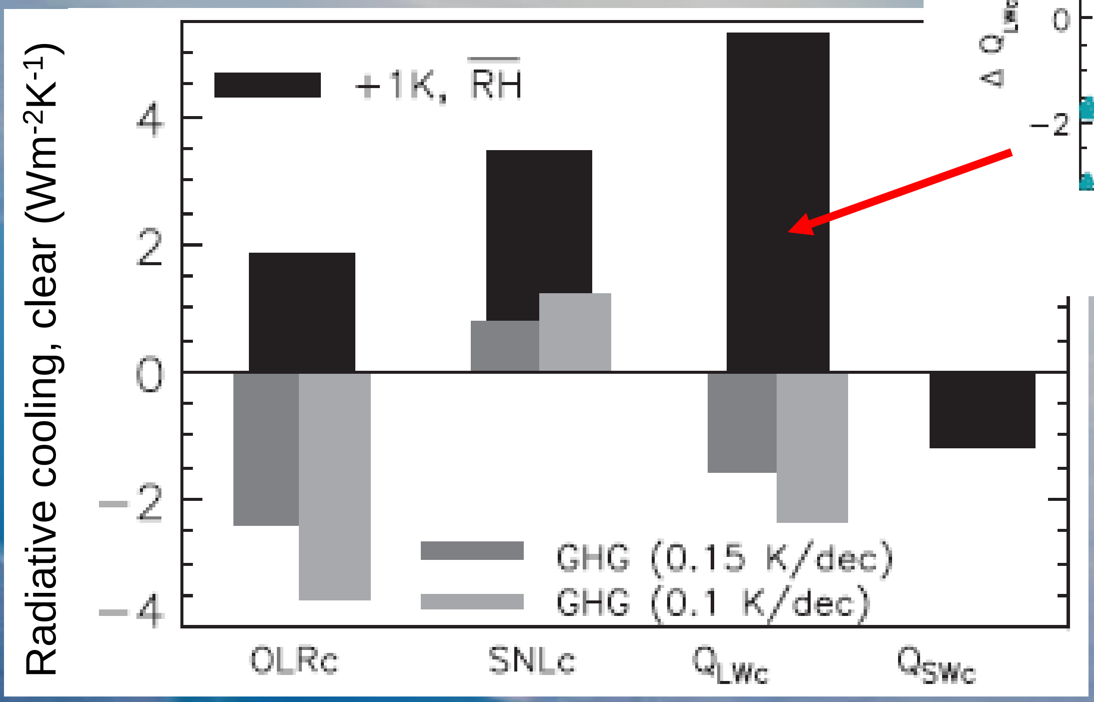


Trenberth et al. (2009) BAMS

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. Stephens & Ellis (2008) J Clim, Lambert and Webb (2008) GRL

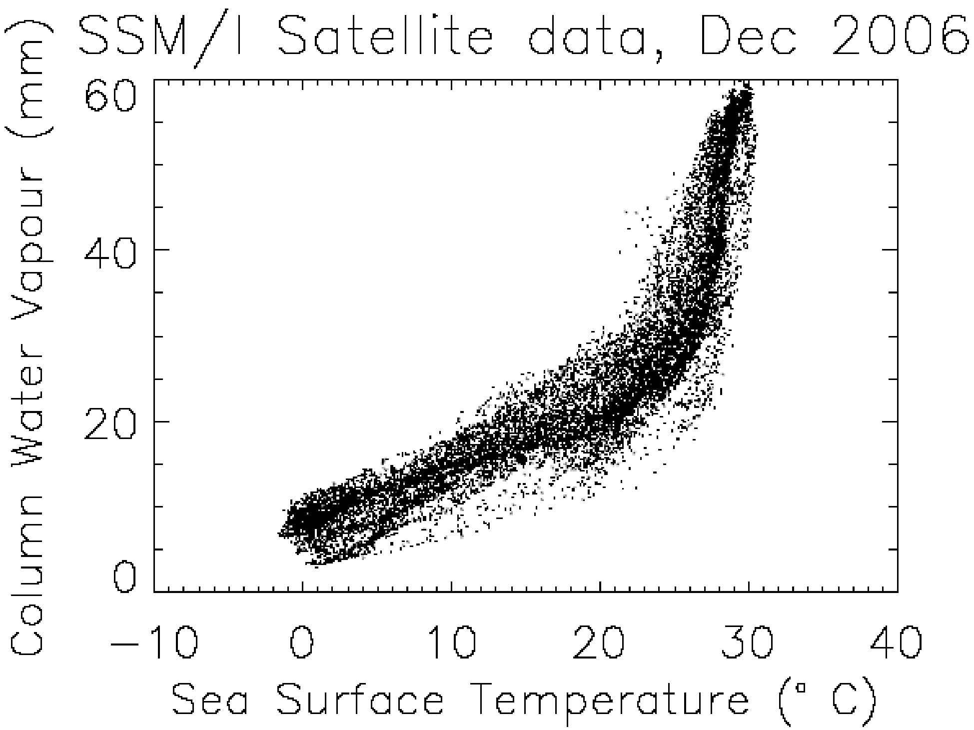




$$\frac{dP}{dTs} \sim \frac{1}{\rho_w L}\frac{dQ}{dTs}$$

Physical basis: Clausius Clapeyron

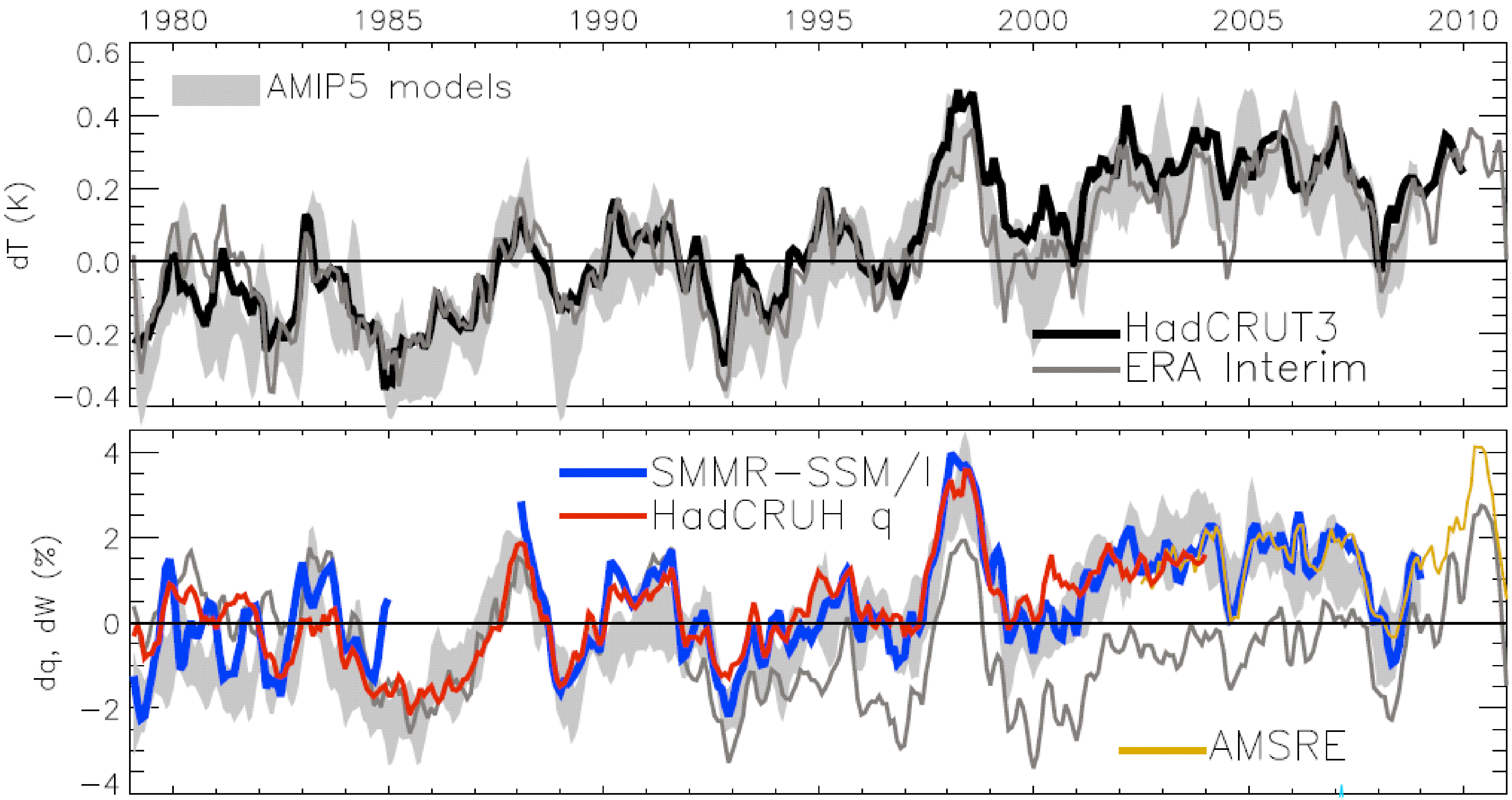
$$\frac{1}{q_s}\frac{dq_s}{dT} \approx \frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2} = \begin{cases} 0.14K^{-1} & T = 200K \\ 0.07K^{-1} & T = 273K \\ 0.06K^{-1} & T = 300K \end{cases}$$



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

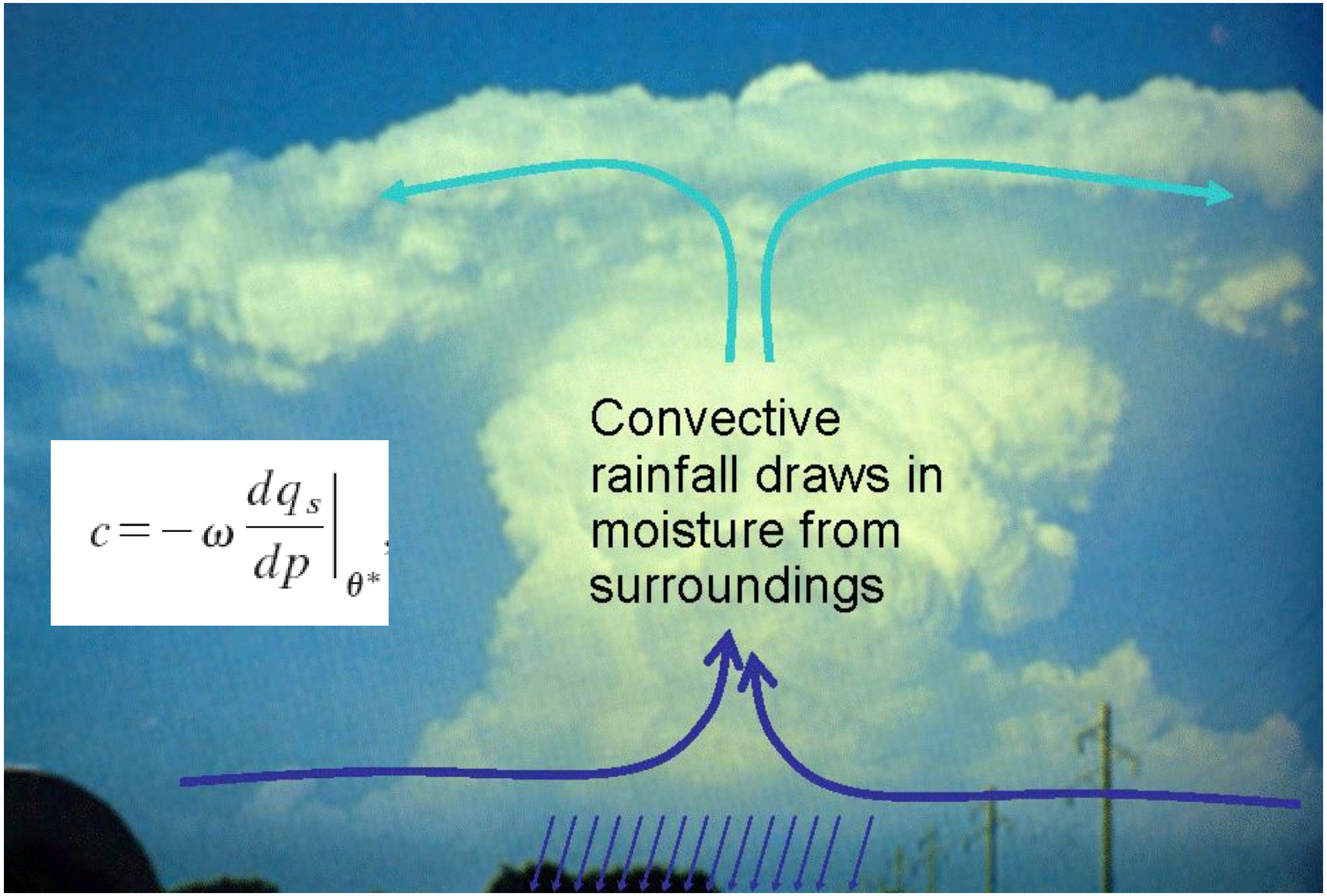
e.g. Allan (2012) *Surv. Geophys. in press*

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?)

O'Gorman and Schneider (2009) PNAS; Gastineau and Soden (2009) GRL

Observed and Simulated responses in extreme Precipitation

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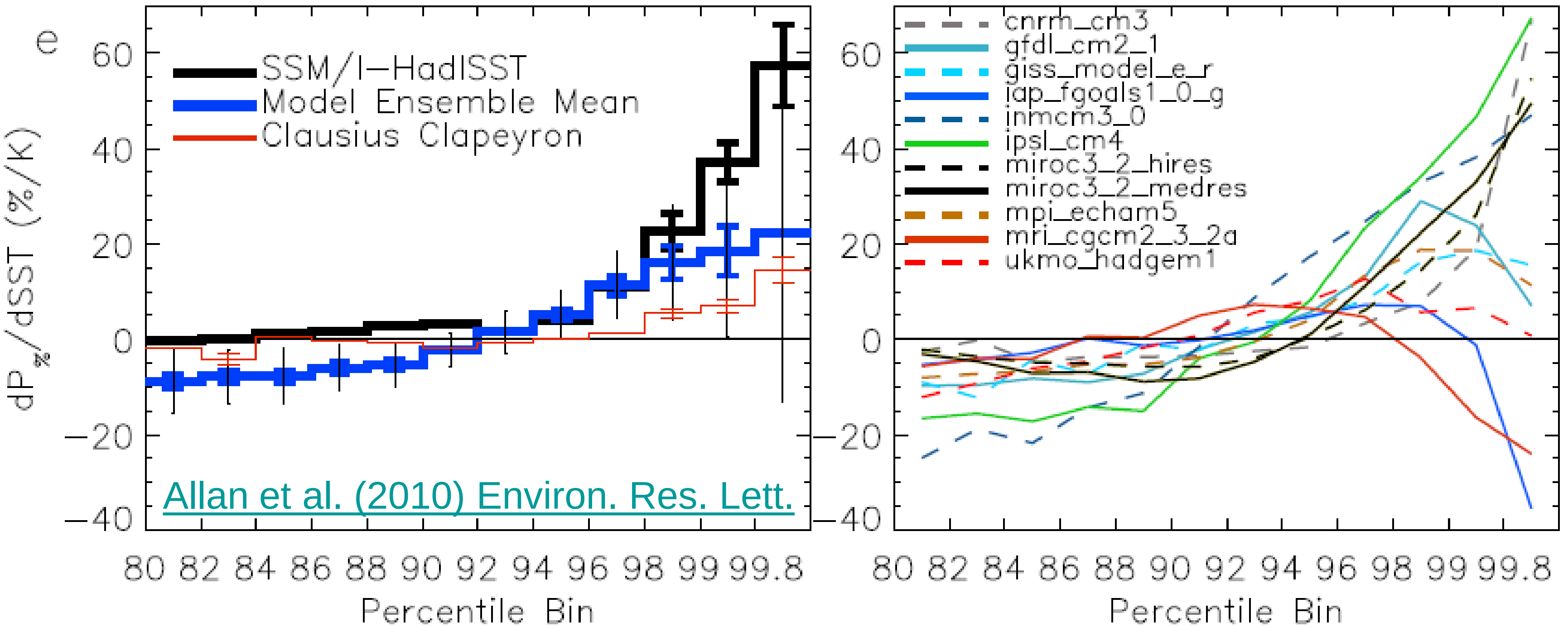
- Increase in intense rainfall with tropical ocean warming
- SSM/I satellite observations at upper range of models

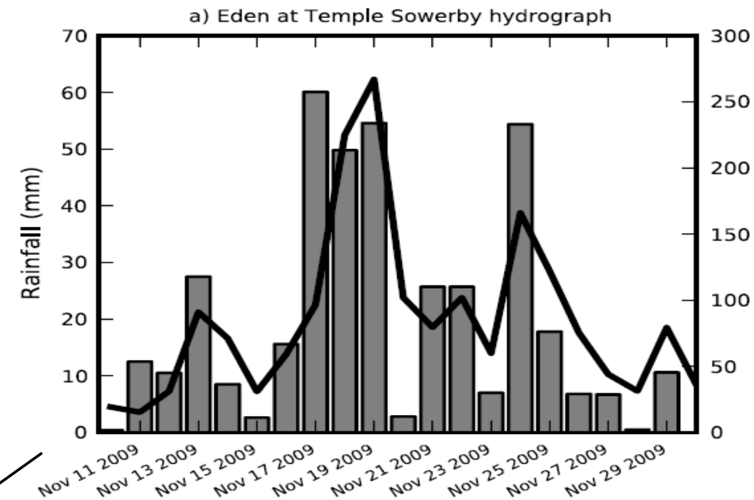


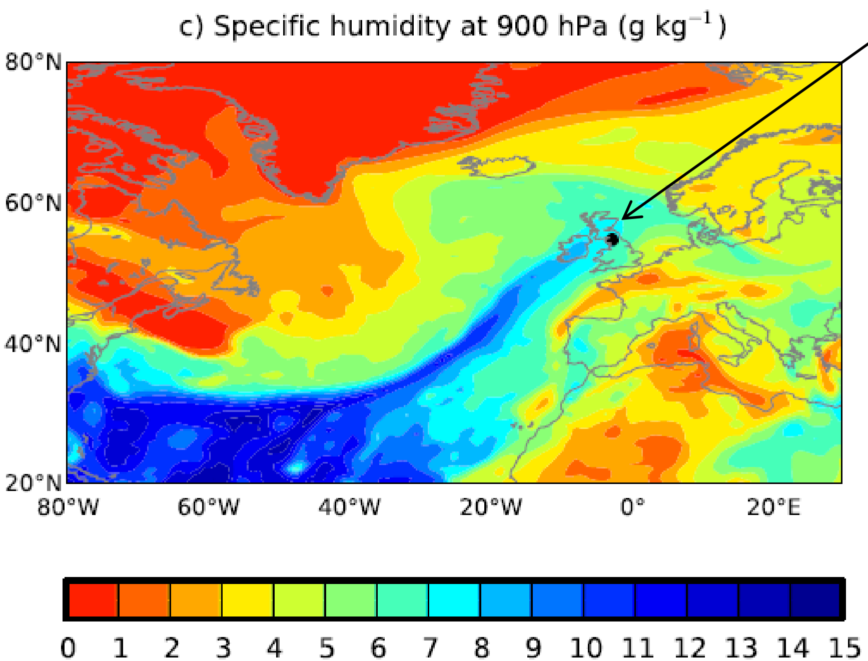
Tropical response uncertain: O'Gorman and Schneider (2009) PNAS….
but see also: Lenderink and Van Meijgaard (2010) ERL; Haerter et al. (2010) GRL

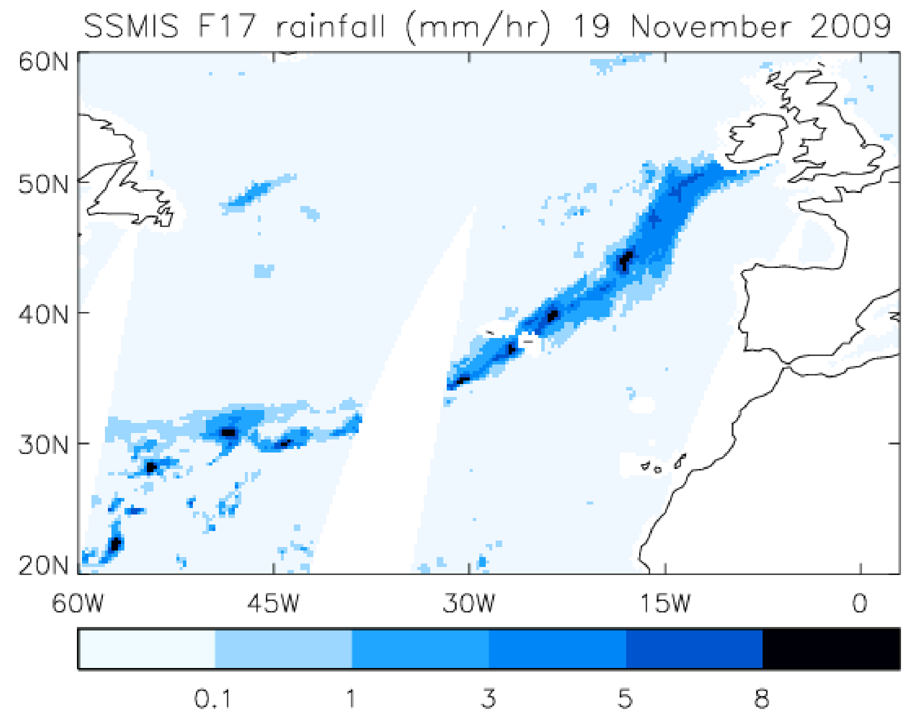
HydEF project:

Extreme precipitation & mid-latitude Flooding

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

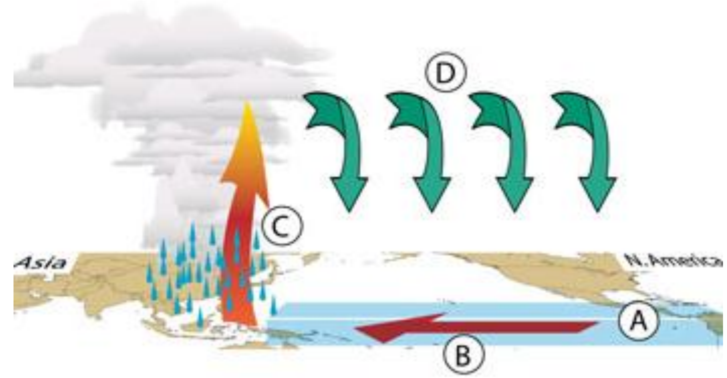




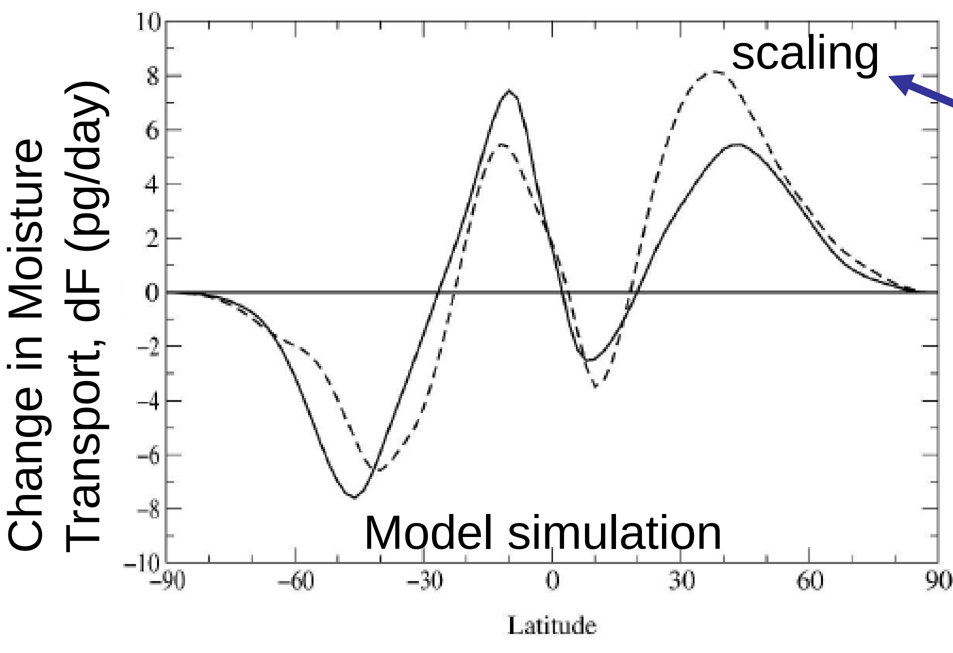


Lavers et al. (2011) Geophys. Res. Lett.

Physical Basis: Moisture Balance



P-E ~ (∇ . (u q)) (units of s^{-1}; scale by $(p/g\rho_w)$ for units of mm/day)



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

$$\alpha \approx 0.07\ \mathrm{K}^{-1}$$

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

Held and Soden (2006) J Climate

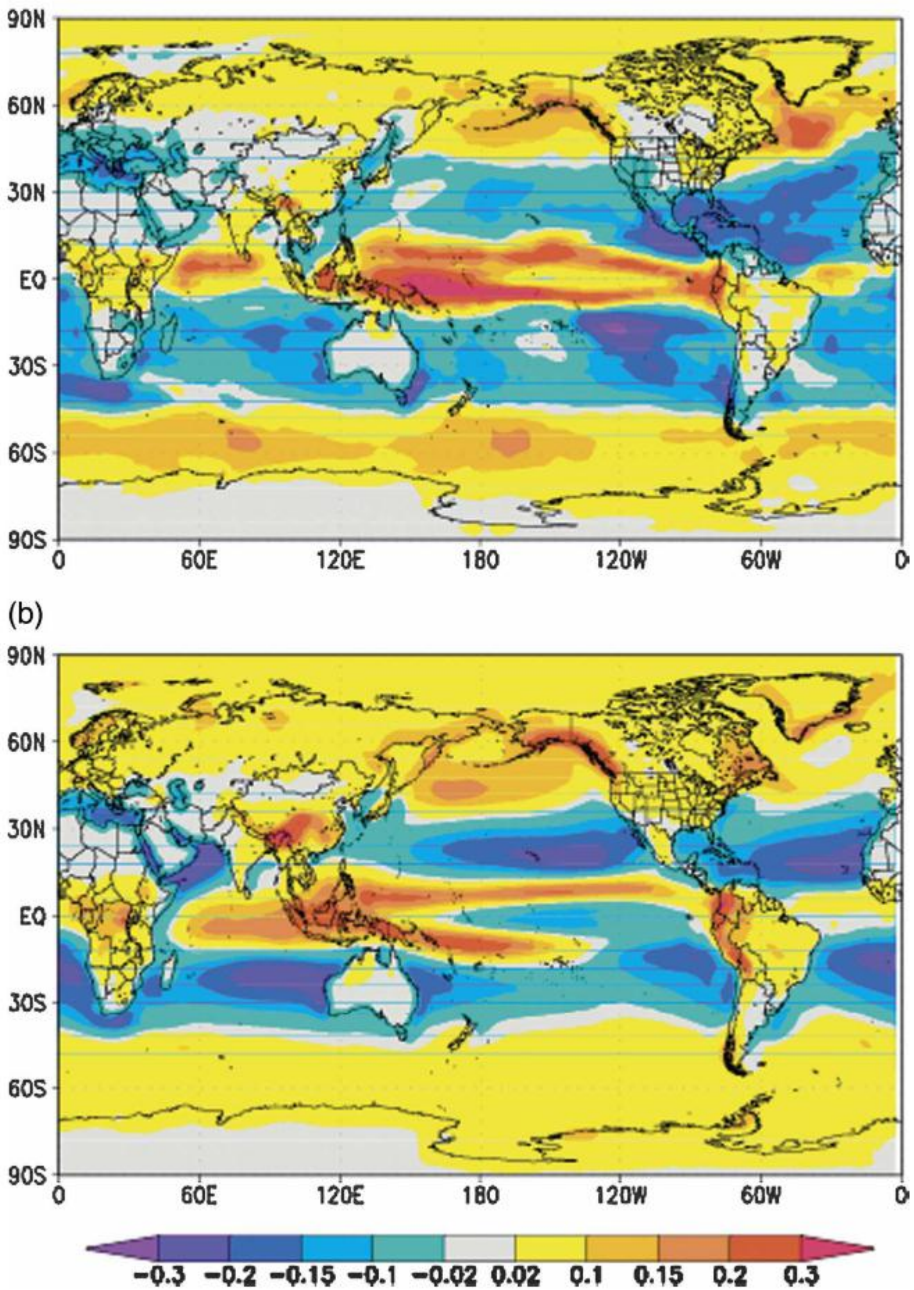


FIG. 7. The annual-mean distribution of $\delta(P - E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

Projected (top) and estimated (bottom) changes in P-E

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

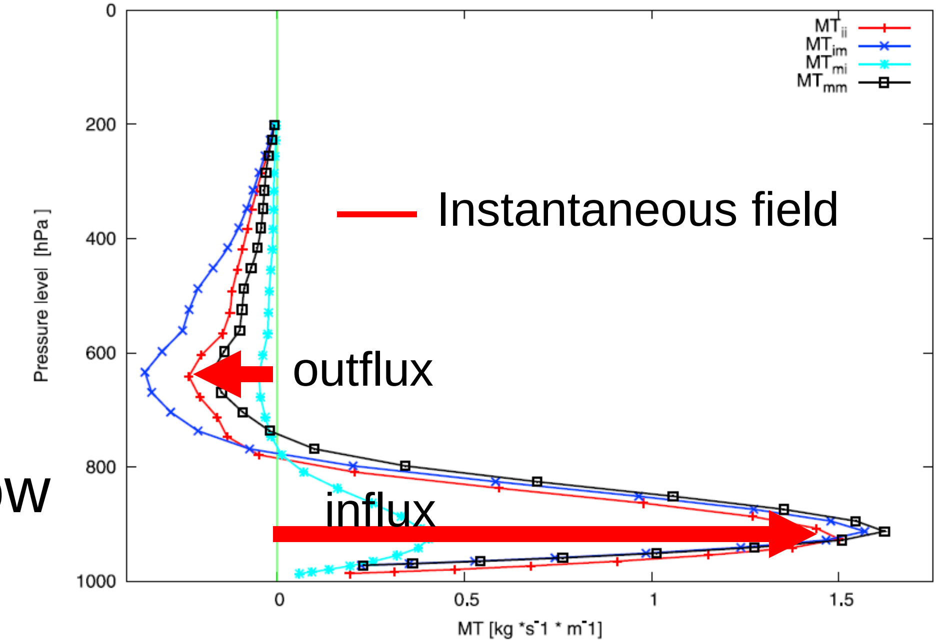
$$\delta(P - E) = -\nabla \cdot (\alpha \delta T F). \sim \alpha \delta T (P - E).$$

$$\alpha \approx 0.07\ \mathrm{K}^{-1}$$

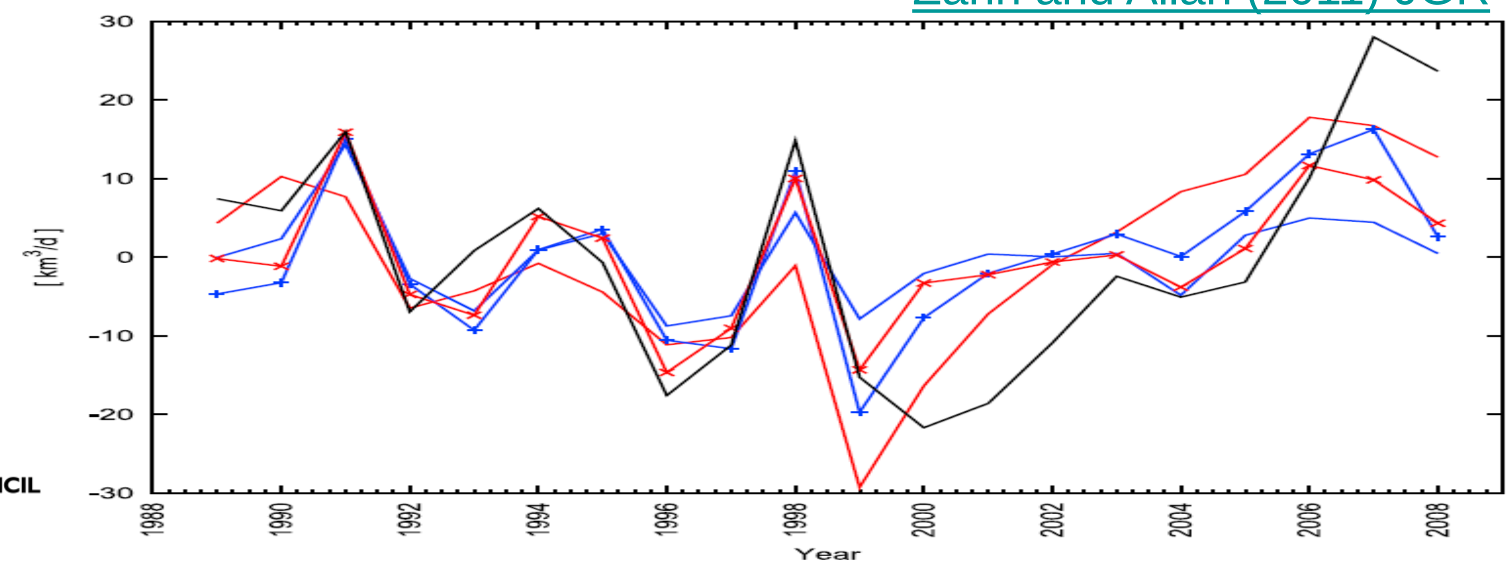
Held and Soden (2006) J Climate

Moisture transports from ERA Interim

- Moisture transport into tropical ascent region
- Significant mid-level outflow
- 2000s: increases in inflow or drift in ERA Interim?



Zahn and Allan (2011) JGR

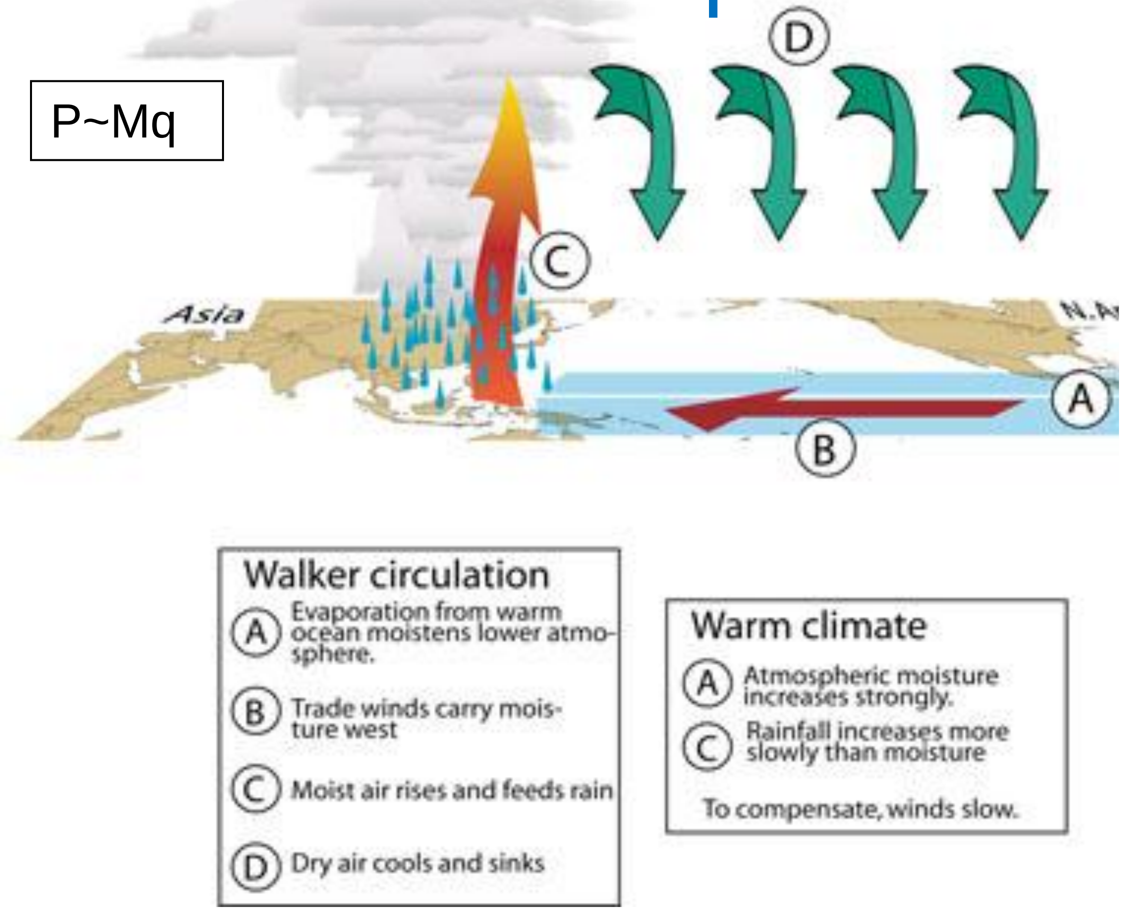


(a) yearly MT anomaly

NATURAL ENVIRONMENT RESEARCH COUNCIL

PREPARE project

Physical Basis: Circulation response



First argument:

P ~ Mq.

So if P constrained to rise more slowly than q, this implies reduced M

Second argument:

ω=Q/σ.

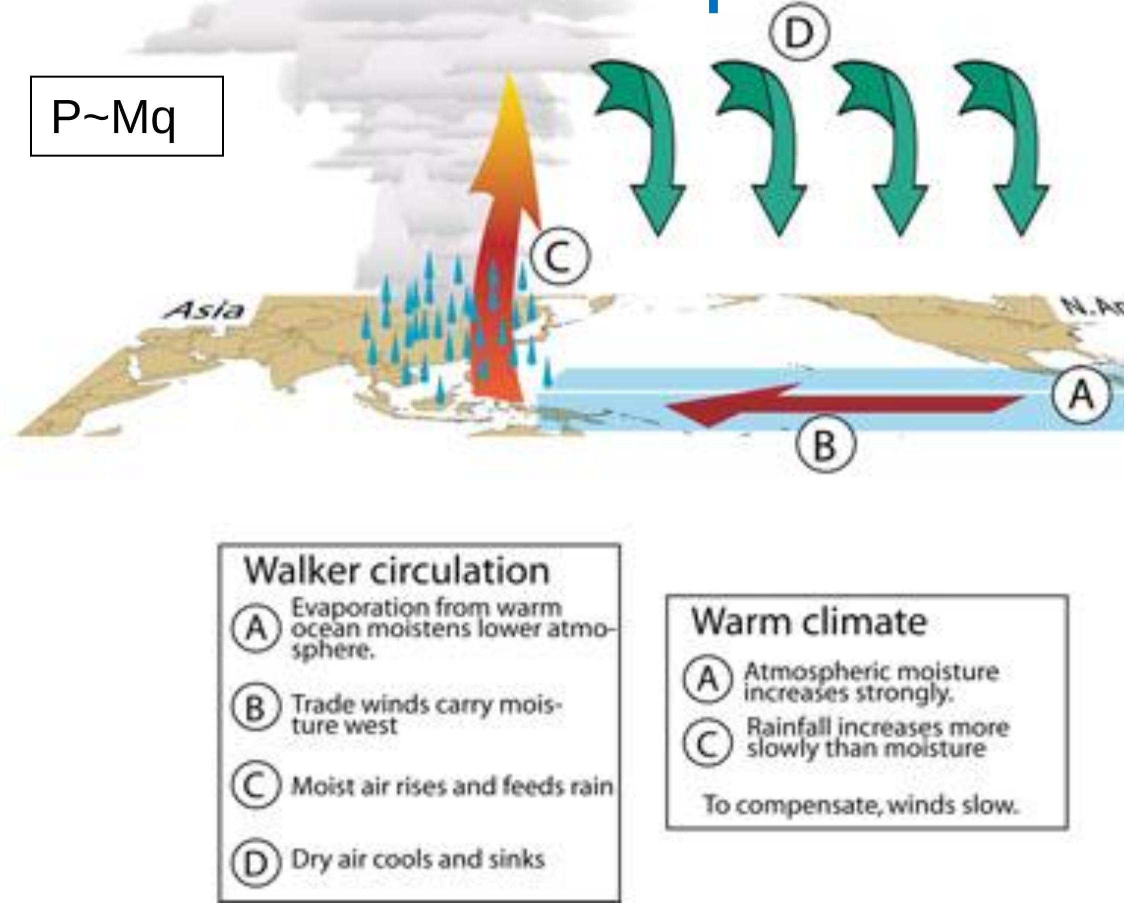
Subsidence (ω) induced by radiative cooling (Q) but the magnitude of ω depends on $(\Gamma_d - \Gamma)$ or static stability (σ).

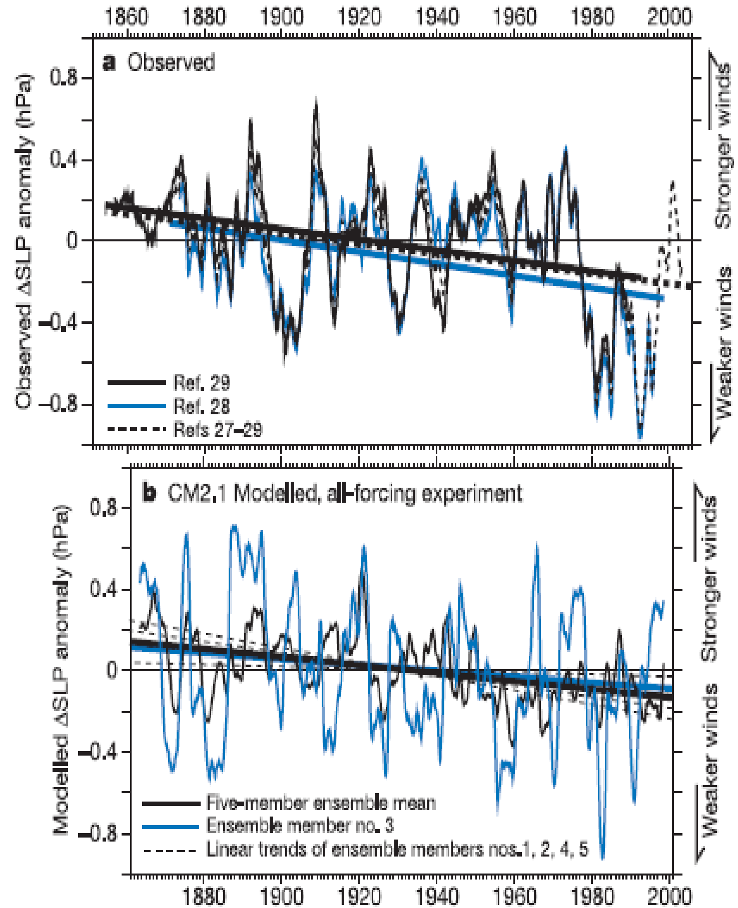
If Γ follows MALR → increased σ. This offsets Q effect on ω.

See Held & Soden (2006) and Zelinka & Hartmann (2010) JGR

Physical Basis: Circulation response

P~Mq



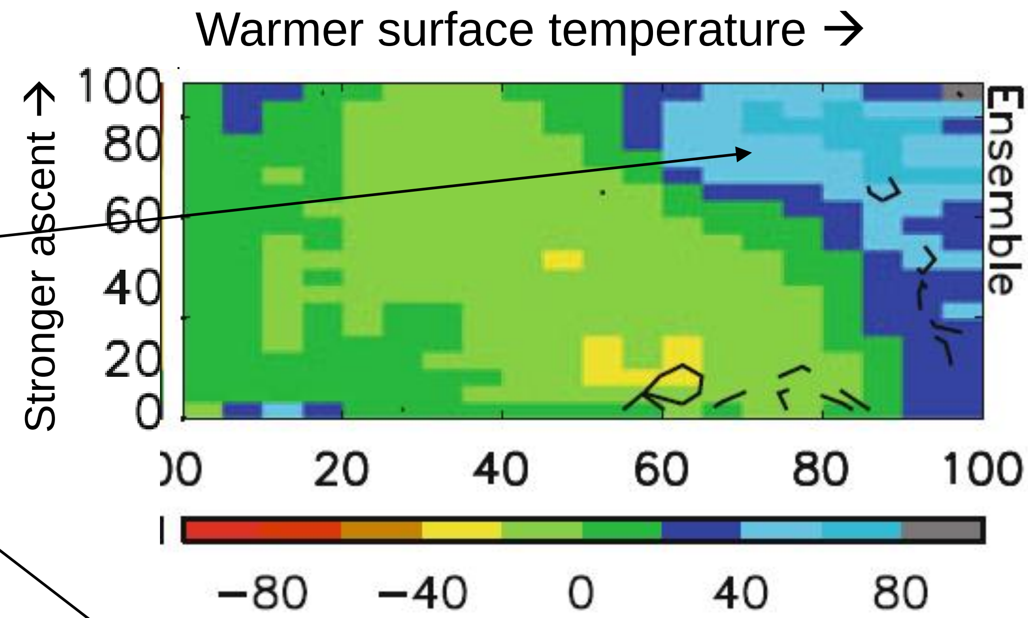


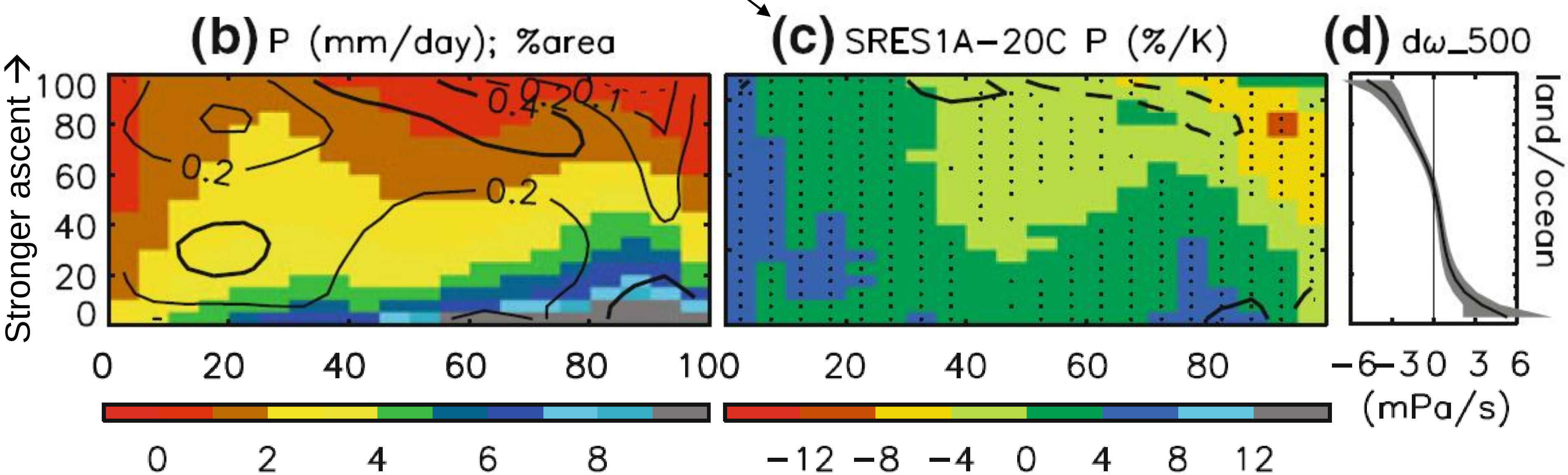
Models/observations achieve muted precipitation response by reducing strength of Walker circulation. Vecchi and Soden (2006) Nature

Precipitation bias and response binned by dynamical regime

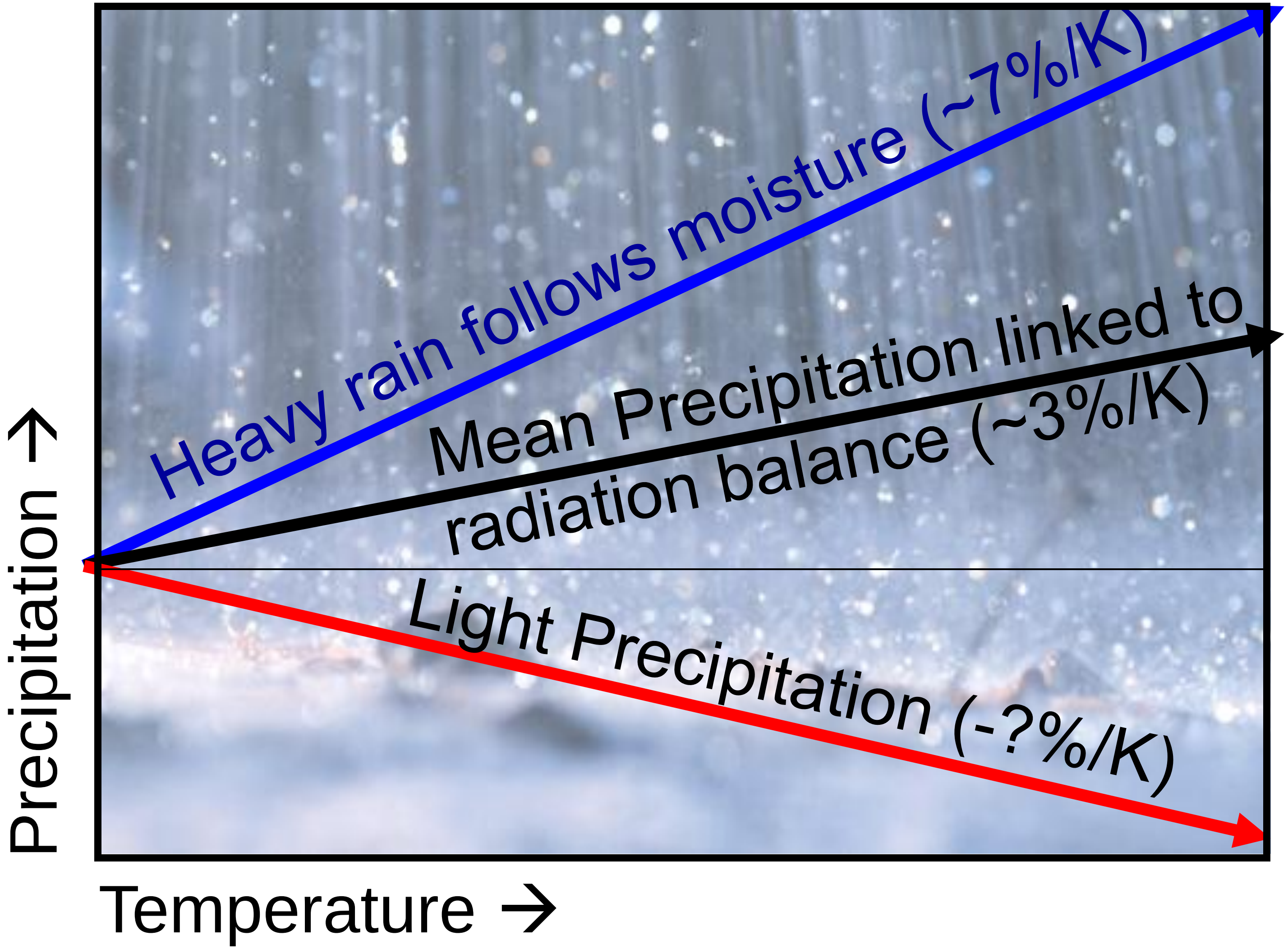
- Model biases in warm, dry regime
- Strong wet/dry fingerprint in model projections (below)

Allan (2012) Clim. Dyn.

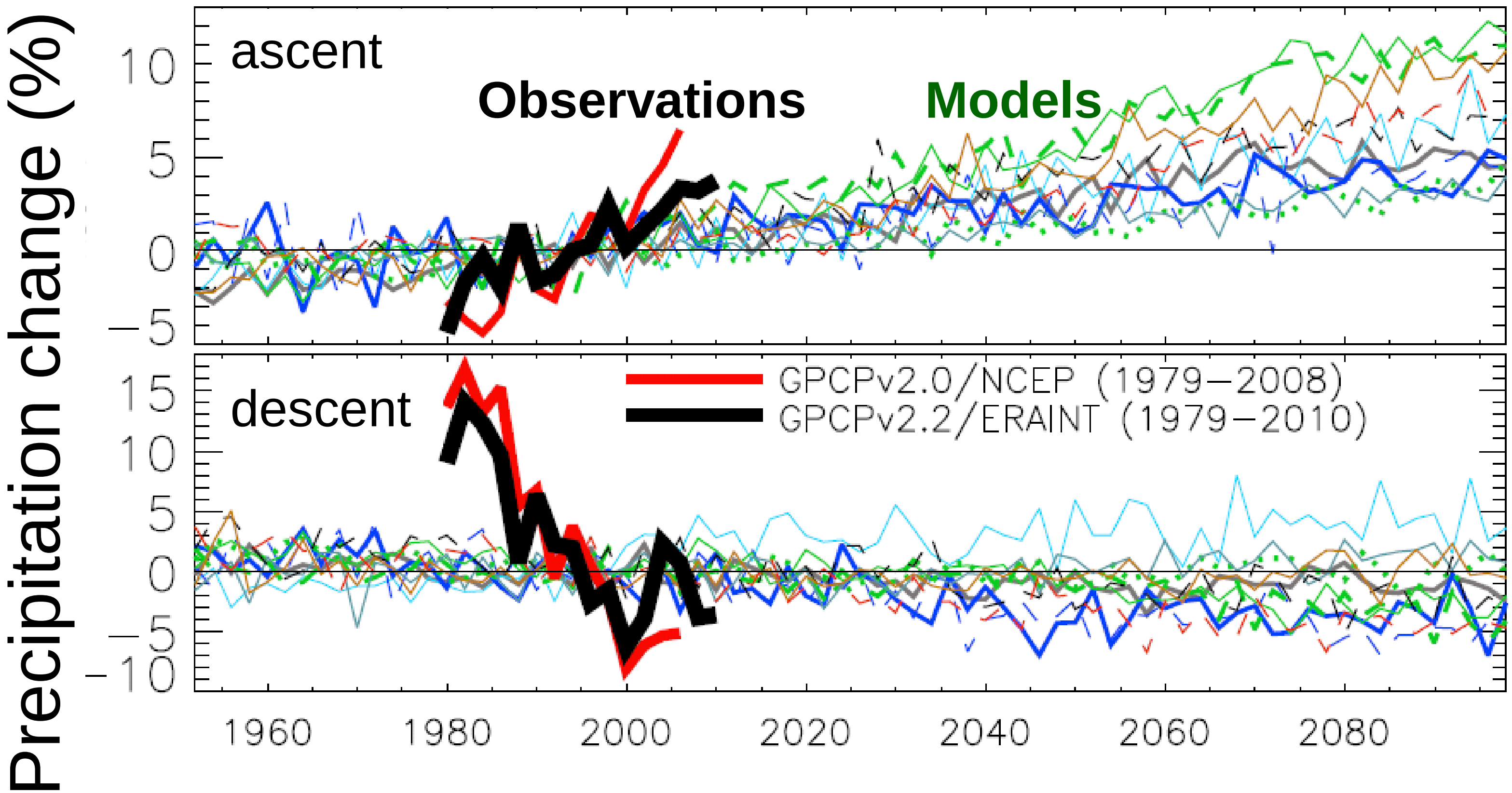




Contrasting precipitation response expected



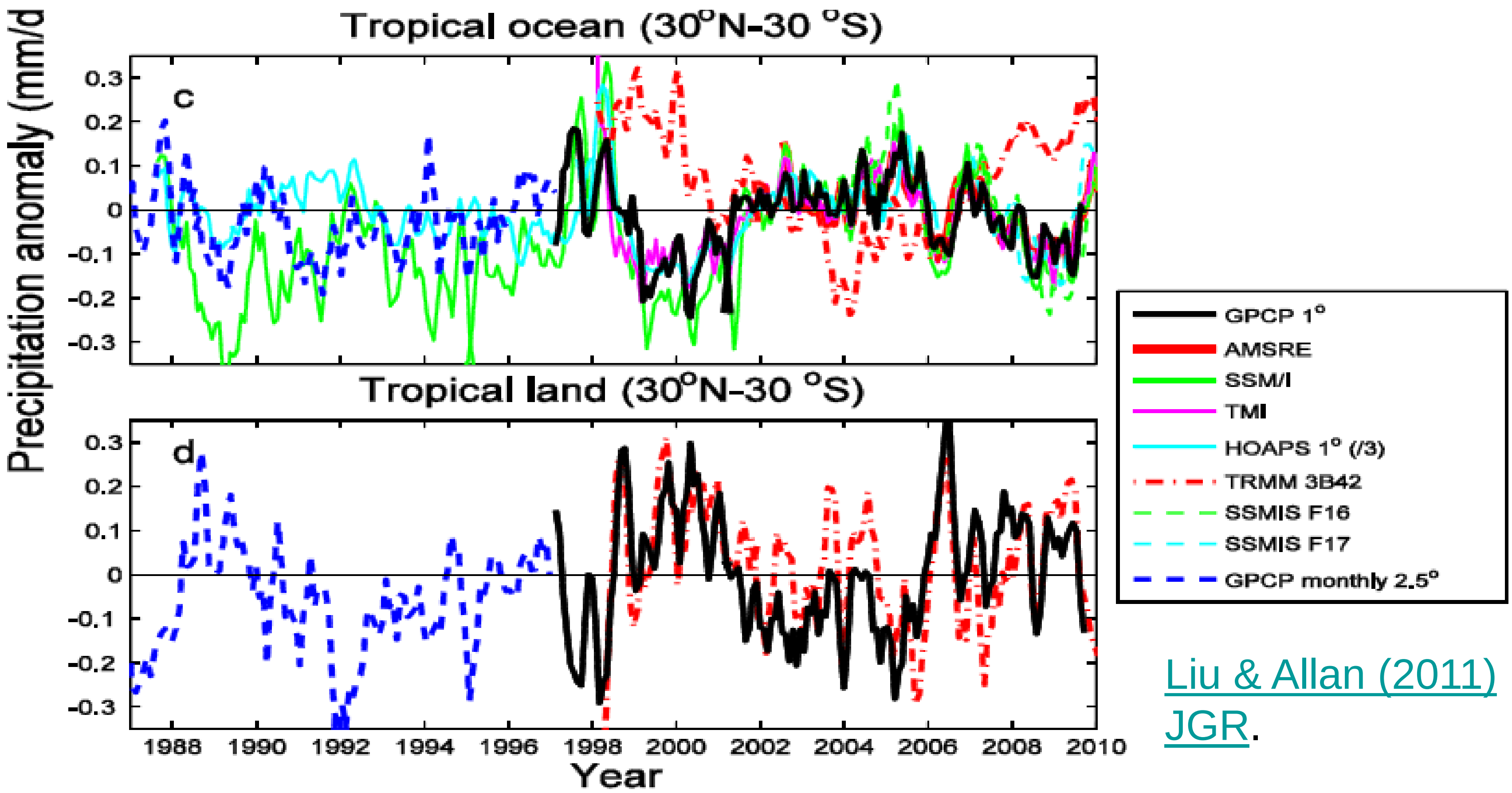
Contrasting precipitation response in wet and dry regions of the tropical circulation



Sensitivity to reanalysis dataset used to define wet/dry regions

Updated from Allan and Soden (2007) GRL; [Allan *et al.* (2010) Environ. Res. Lett.]

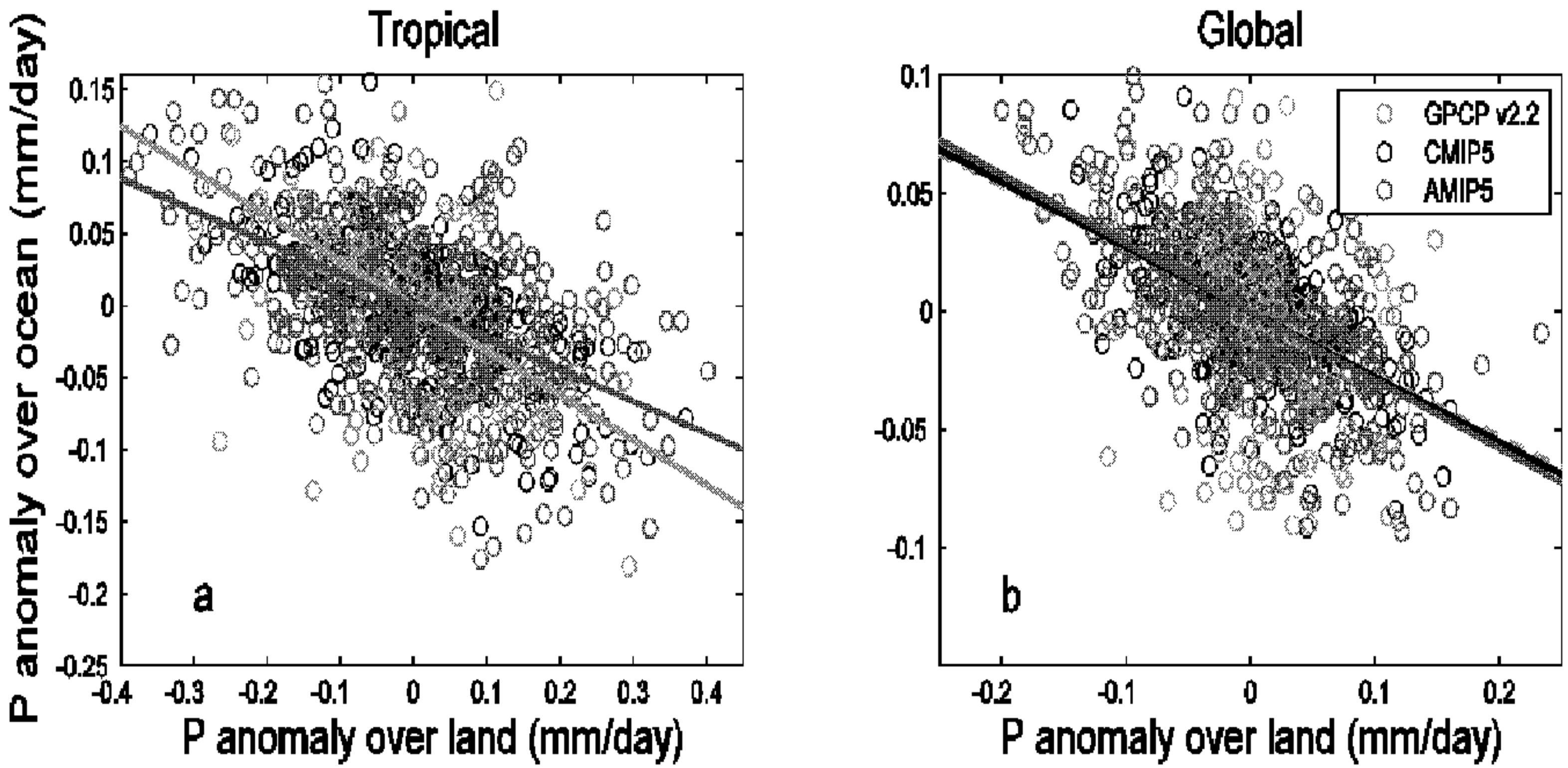
Exploiting satellite estimates of precipitation



Liu & Allan (2011) JGR.

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

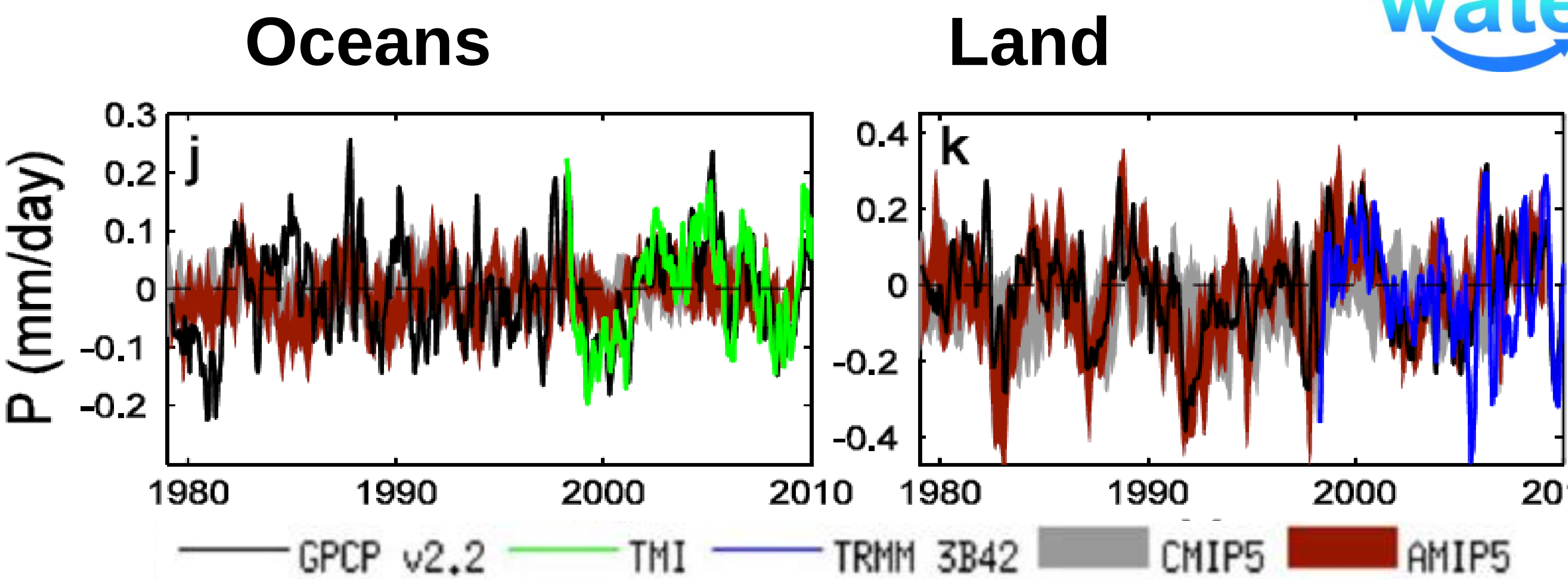
Contrasting land/ocean changes relate to ENSO



Liu and Allan (2012) in preparation

See also Gu et al. (2007) J Clim

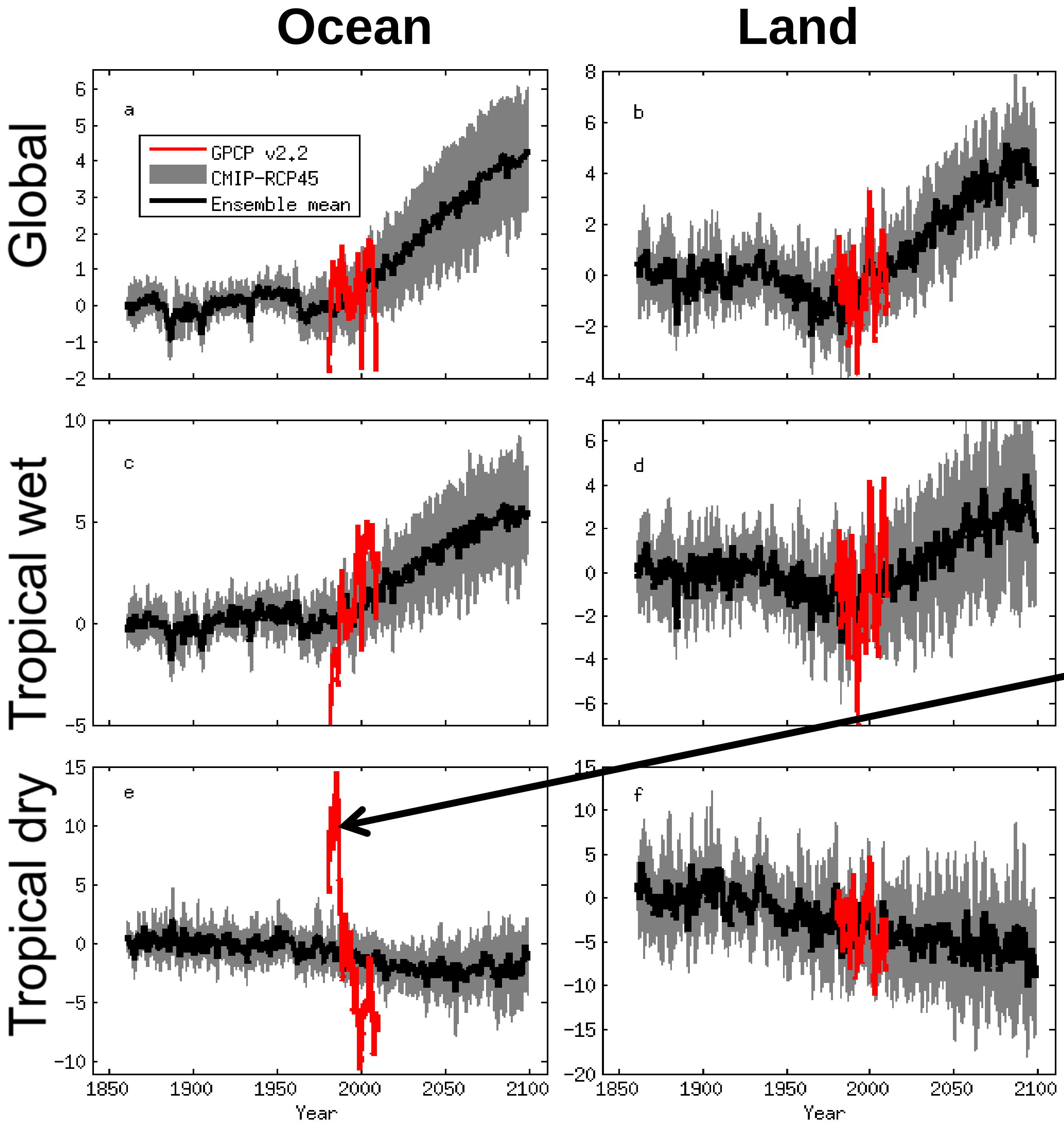
PAGODA: Understanding global changes in the water cycle



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

Note realism of atmosphere-only AMIP model simulations

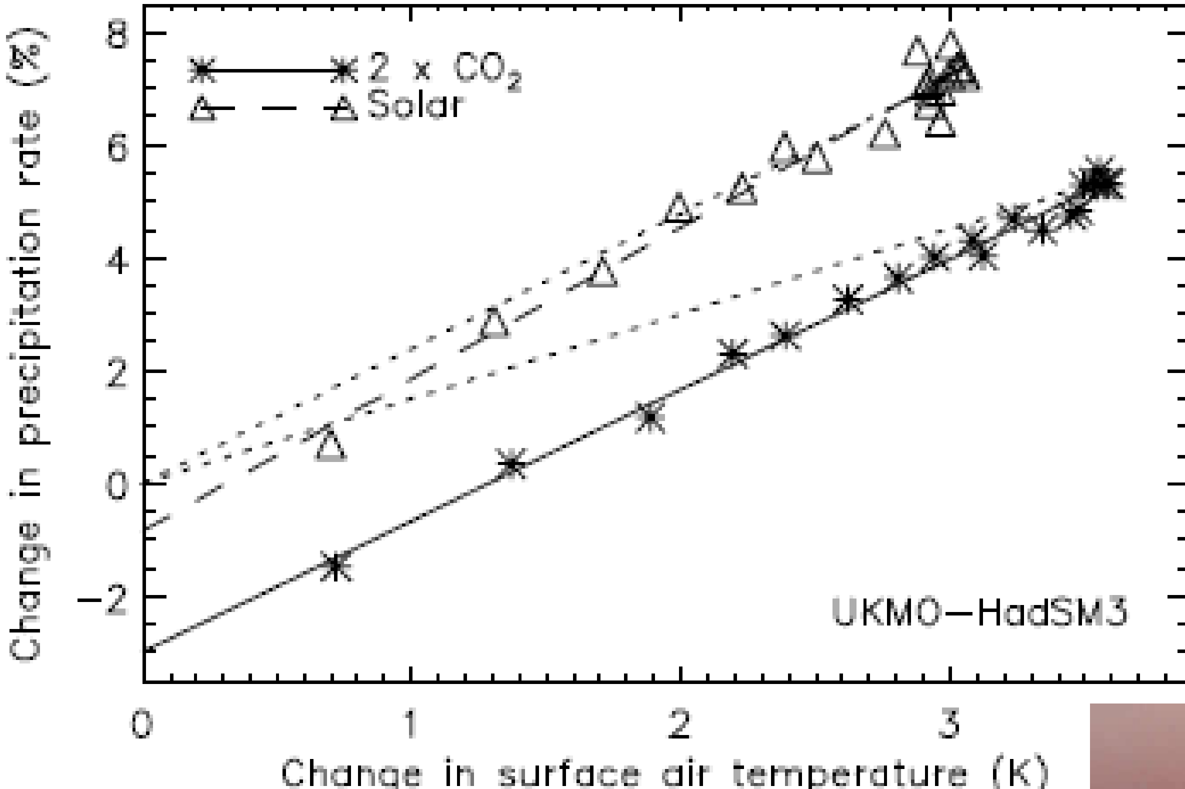
Liu and Allan in prep…



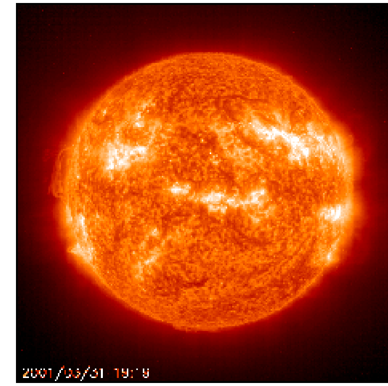
CMIP5 simulated & projected % changes in precipitation

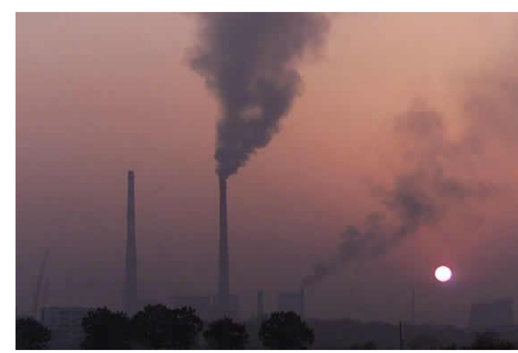
Pre-1988 GPCP ocean data does not contain microwave observations

Transient responses

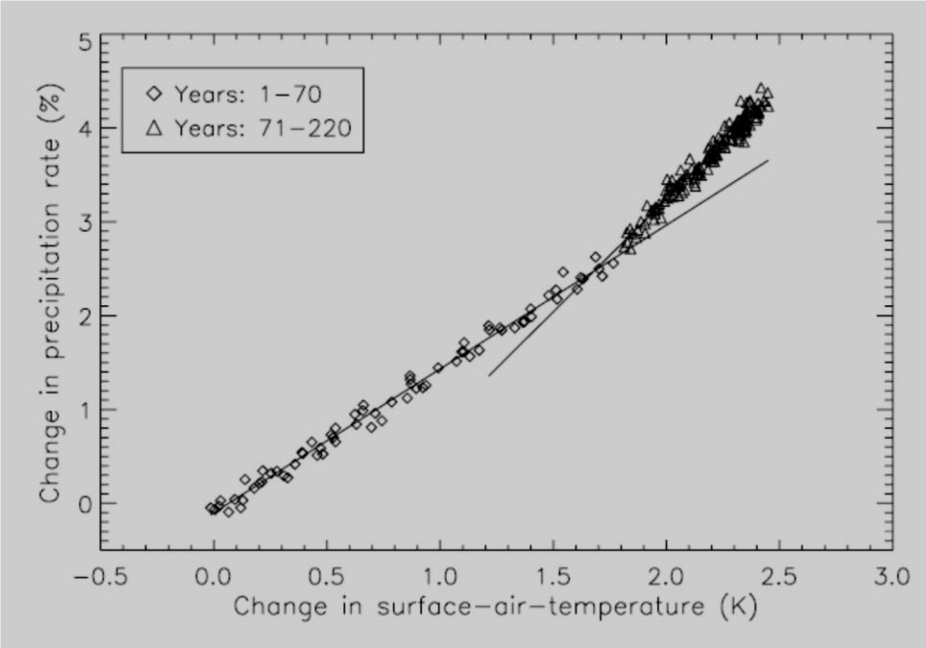


Andrews et al. (2009) J Climate



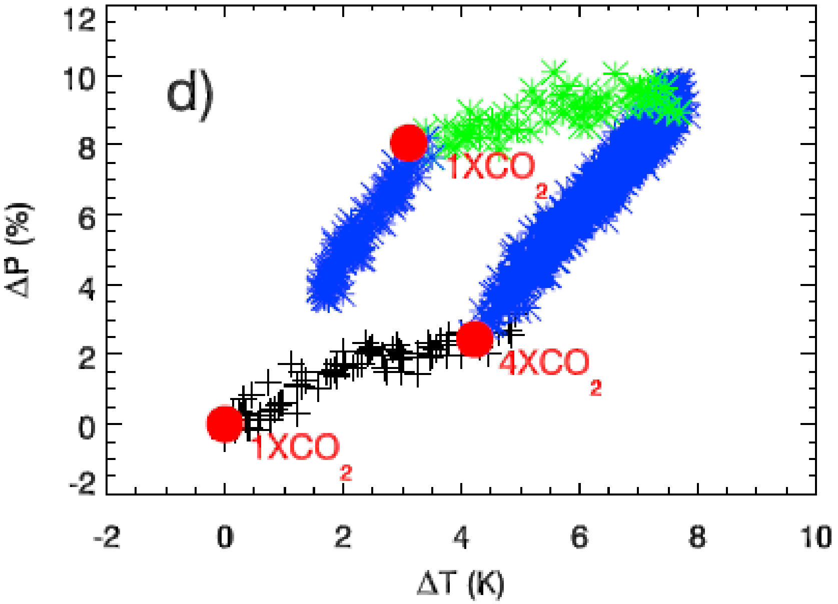


Transient responses



CMIP3 coupled model ensemble mean: Andrews et al. (2010) Environ. Res. Lett.

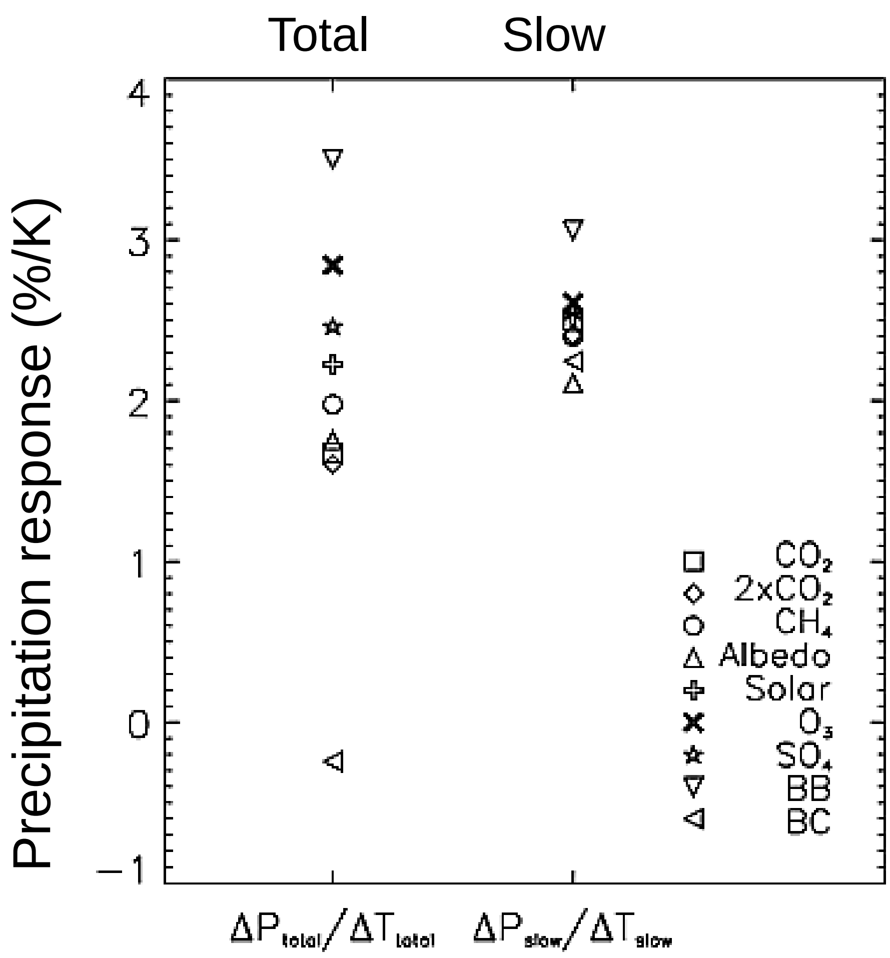
- CO_2 forcing experiments
- Initial precip response supressed by CO_2 forcing
- Stronger response after CO_2 rampdown



HadCM3: Wu et al. (2010) GRL

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

Forcing related fast responses



Andrews et al. (2010) GRL

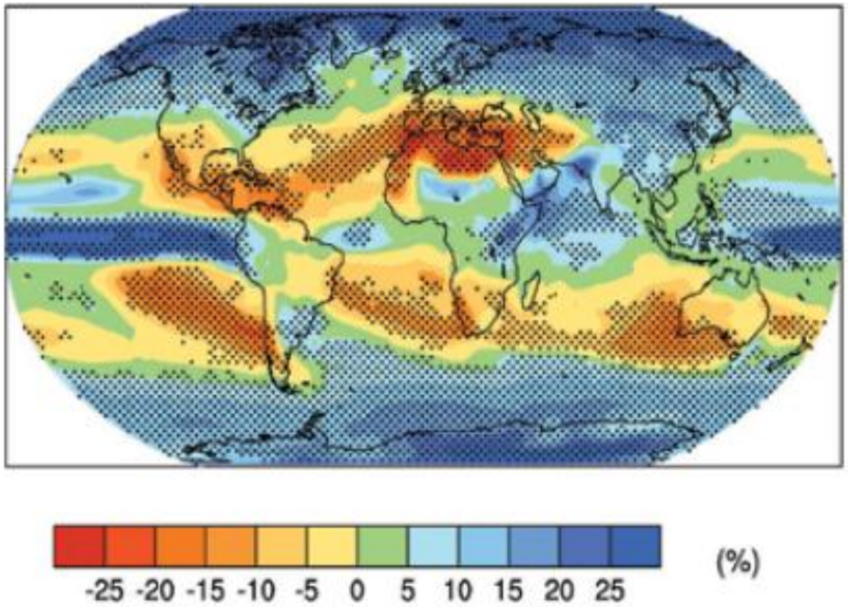
- Surface/Atmospheric forcing determines "fast" precipitation response
- Robust slow response to T
- Mechanisms described in Dong et al. (2009) J. Clim
- CO_2 physiological effect potentially substantial (Andrews et al. 2010 Clim. Dyn.; Dong et al. 2009 J. Clim)
- Hydrological Forcing:

  HF=kdT-dAA-dSH

  (Ming et al. 2010 GRL; also Andrews et al. 2010 GRL)

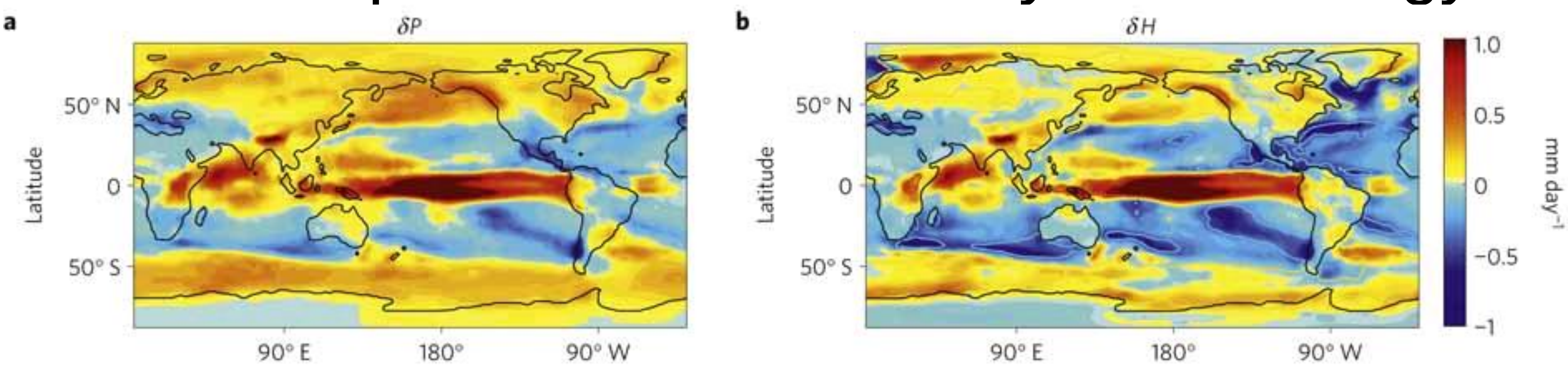
Regional responses in precipitation

Energetic contraints?



- ΔPrecipitation

ΔDry 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?**