Large-scale changes in the atmospheric water cycle in models and observations

Richard Allan

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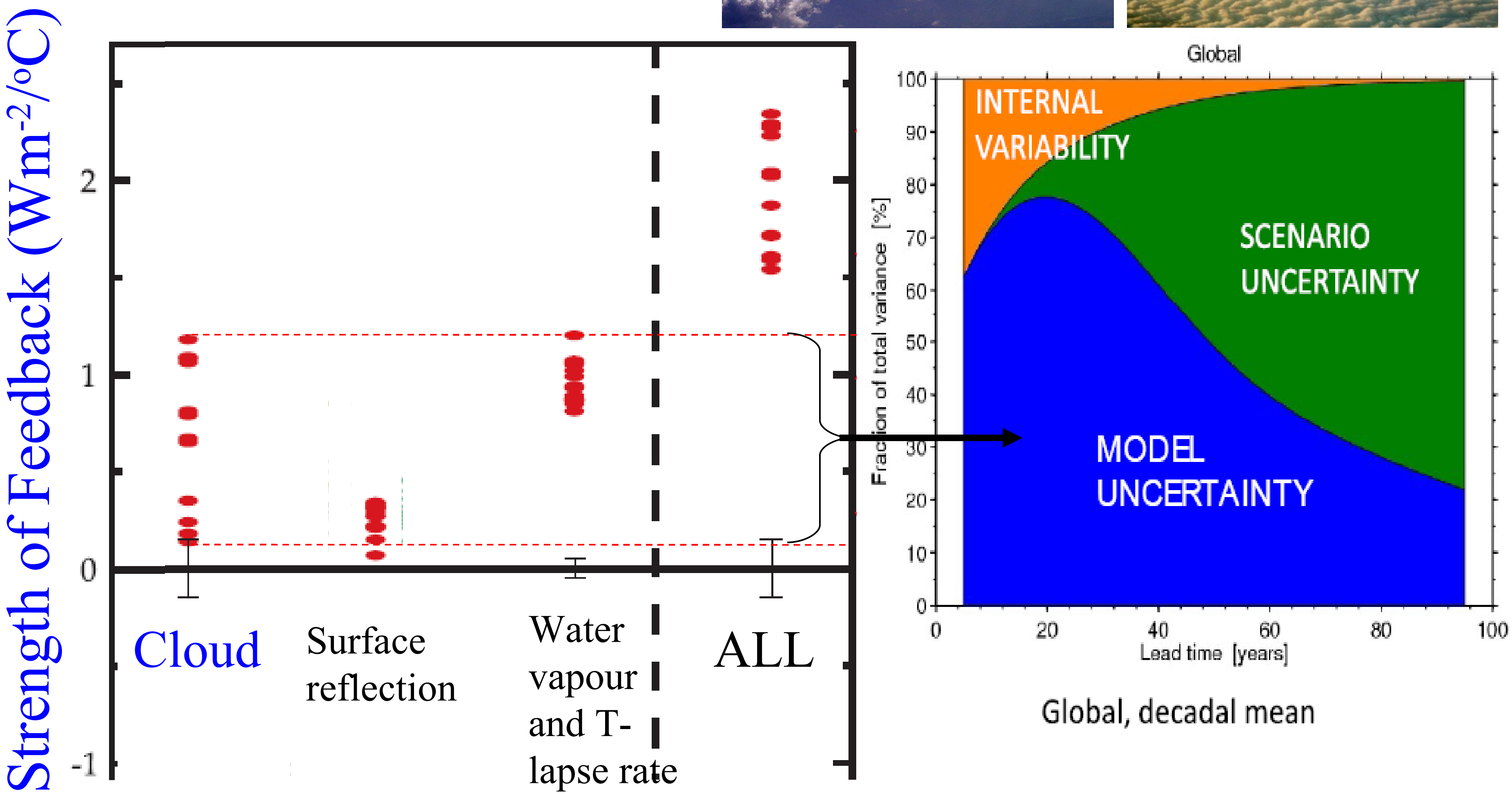
Uncertainty in strength of cloud feedback



Global, decadal mean

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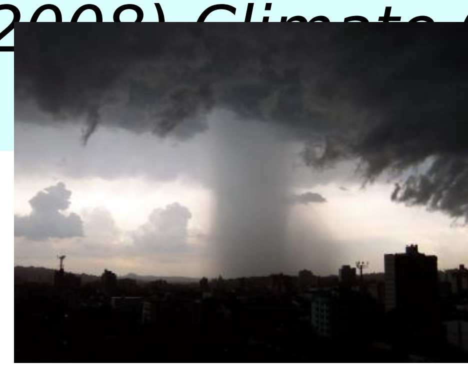
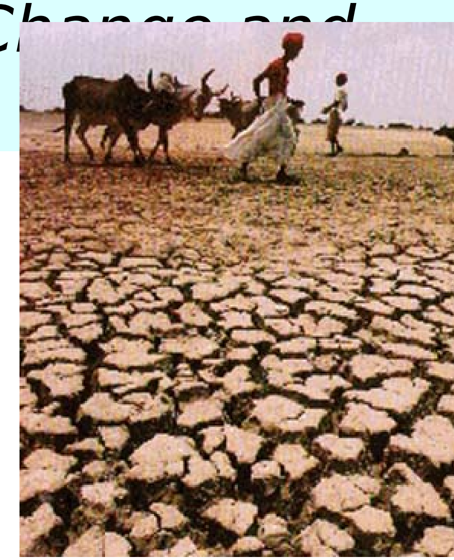
Introduction

“Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems.” *IPCC (2008) Climate Change and*





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CLIMATE MODEL PROJECTIONS IPCC WGI

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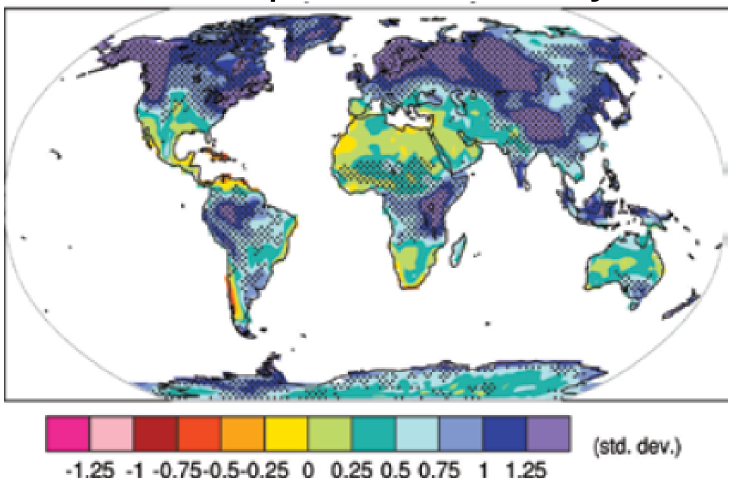
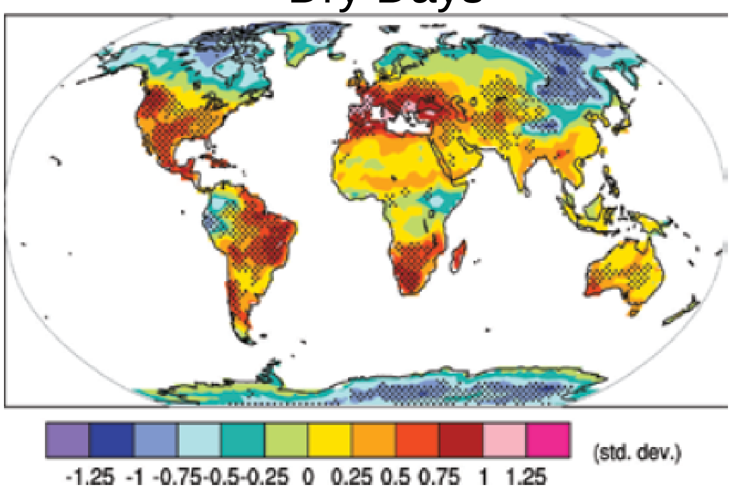
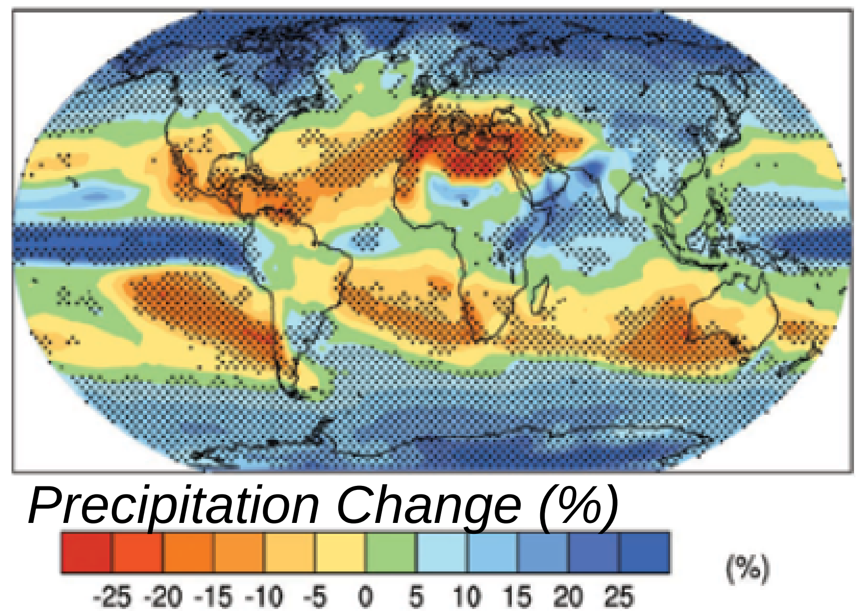
Precipitation Intensity



Dry Days



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



Precipitation Change (%)

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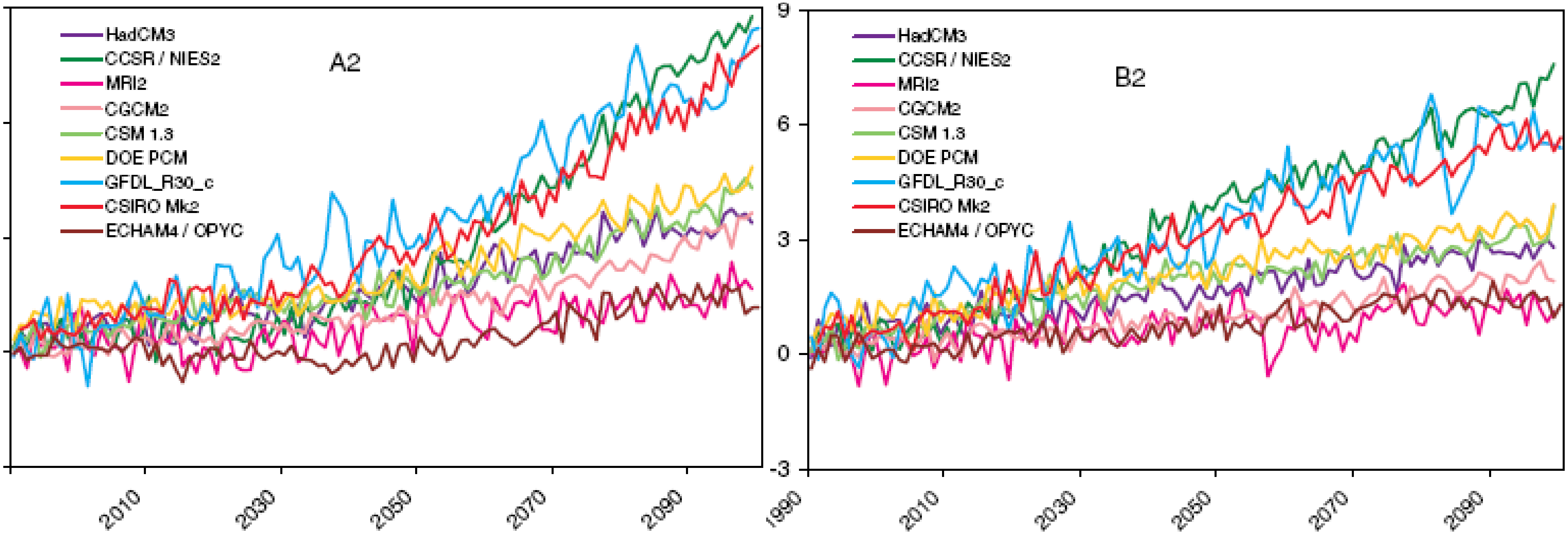
How should the water cycle respond to climate change?

Precipitation Change (%) relative to 1961-1990: 2 scenarios, multi model (IPCC, 2001)



See discussion in: Allen & Ingram (2002) Nature; Trenberth et al. (2003) BAMS

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How should mean precipitation respond to warming?

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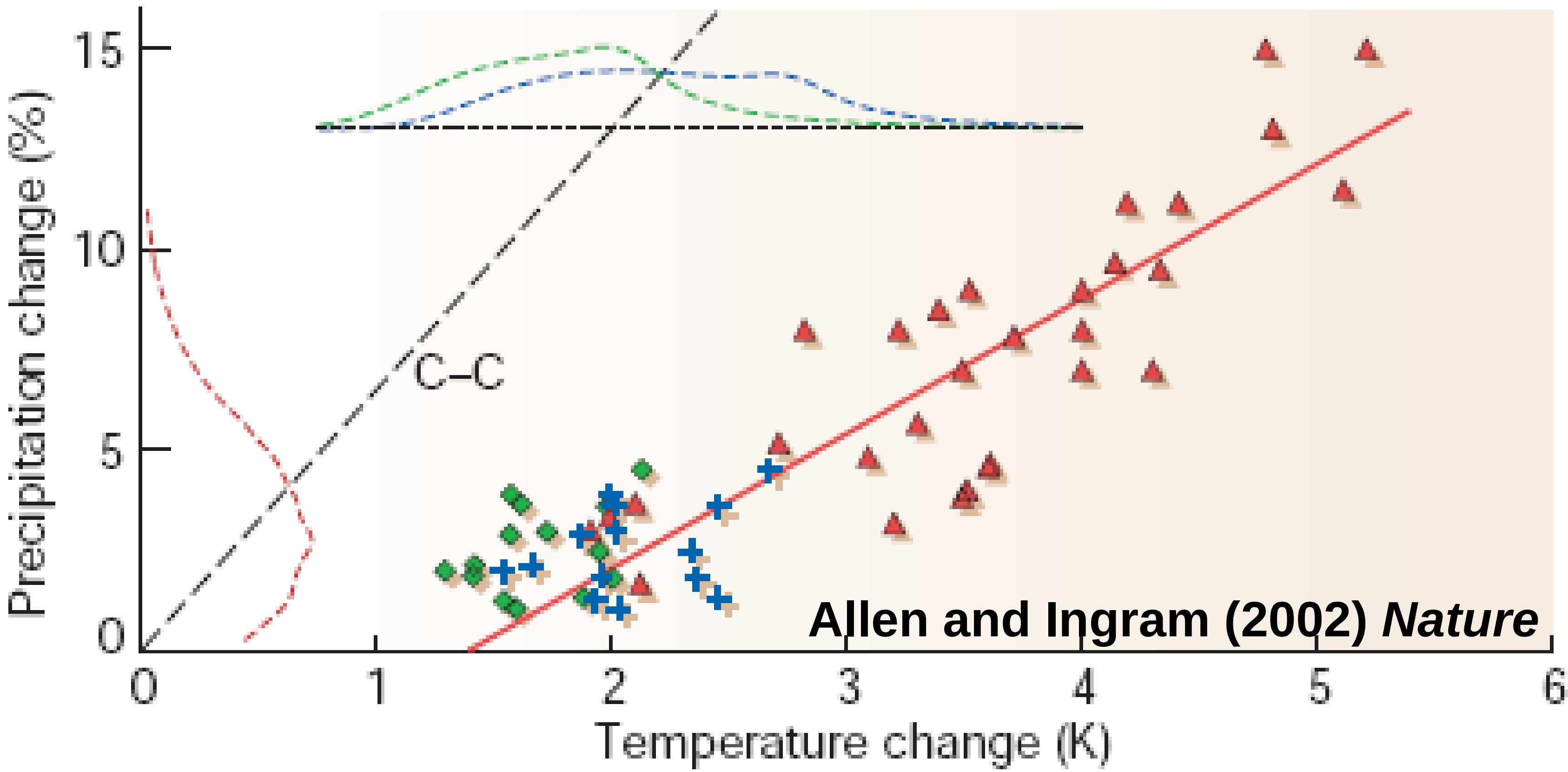

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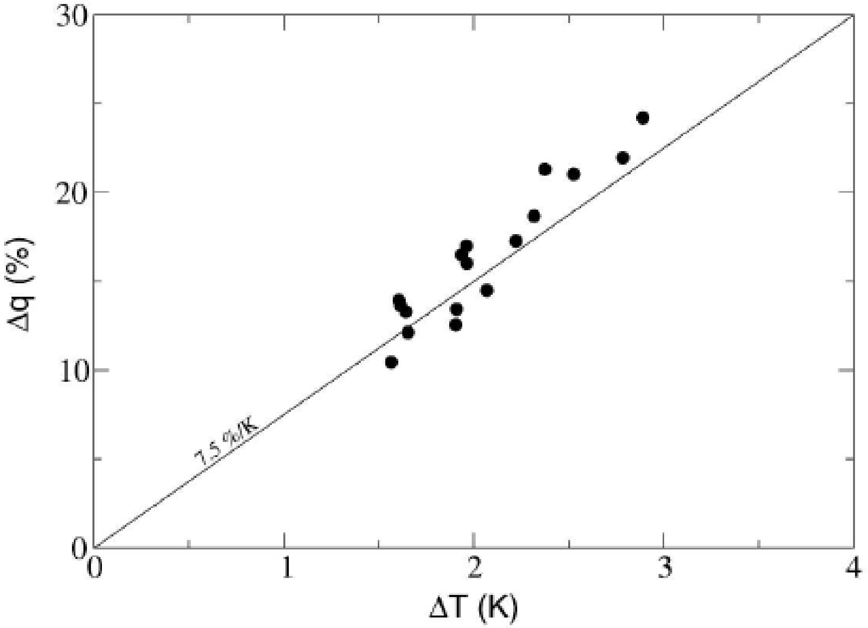
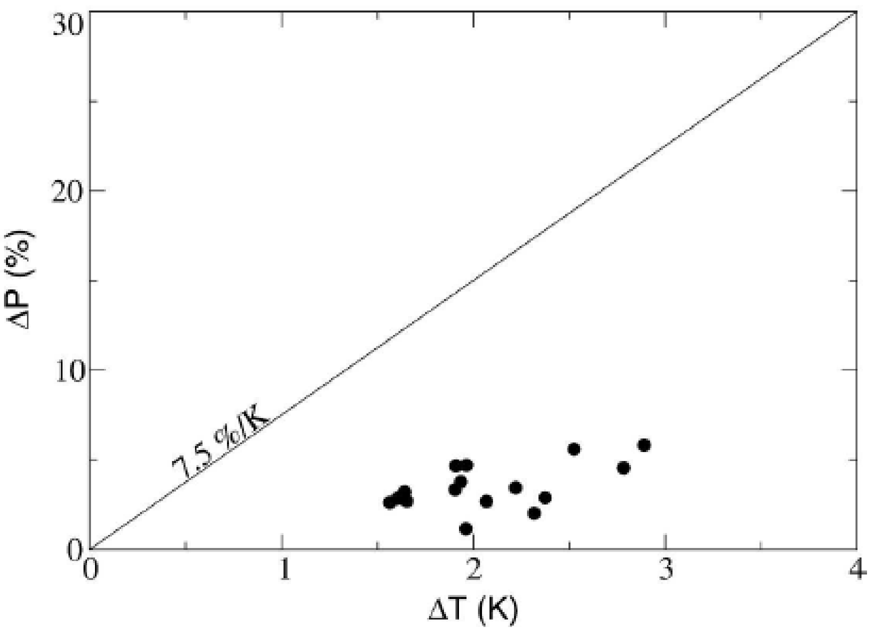
Projected changes in specific humidity and precipitation (A1B)





Held and Soden (2006) J Climate

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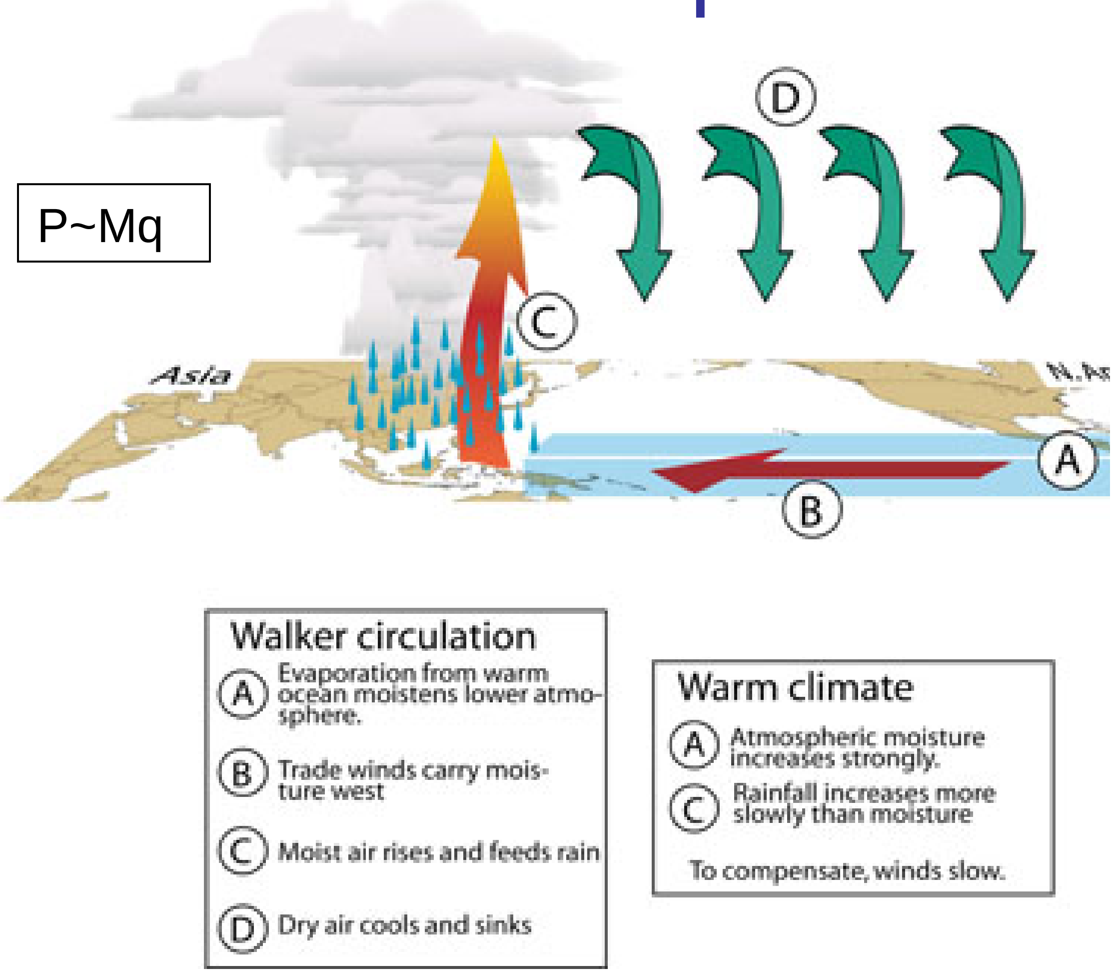
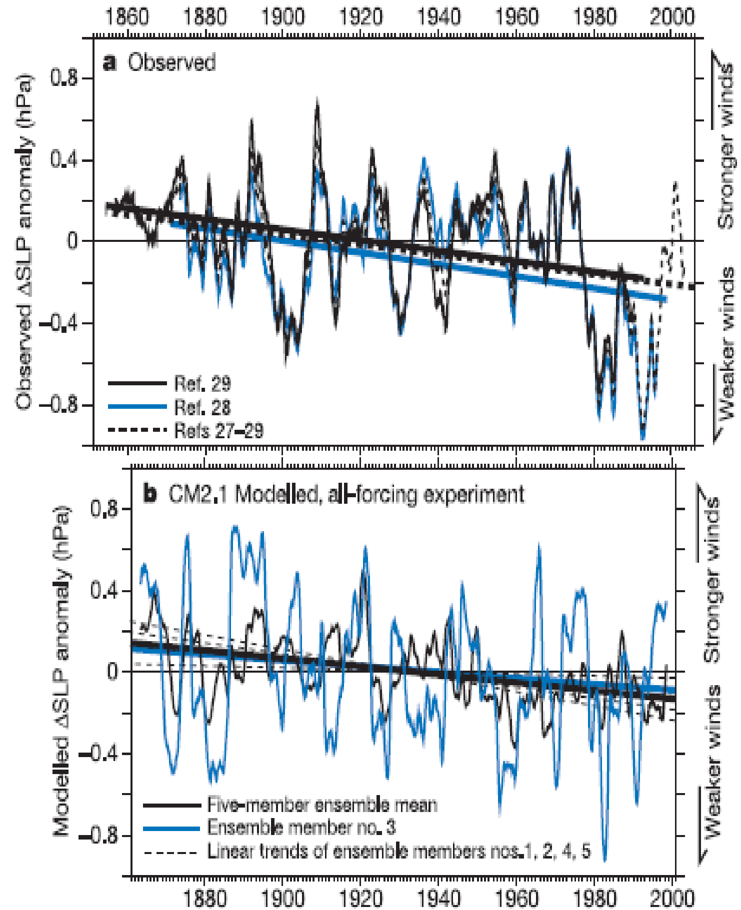
Circulation response

P~Mq

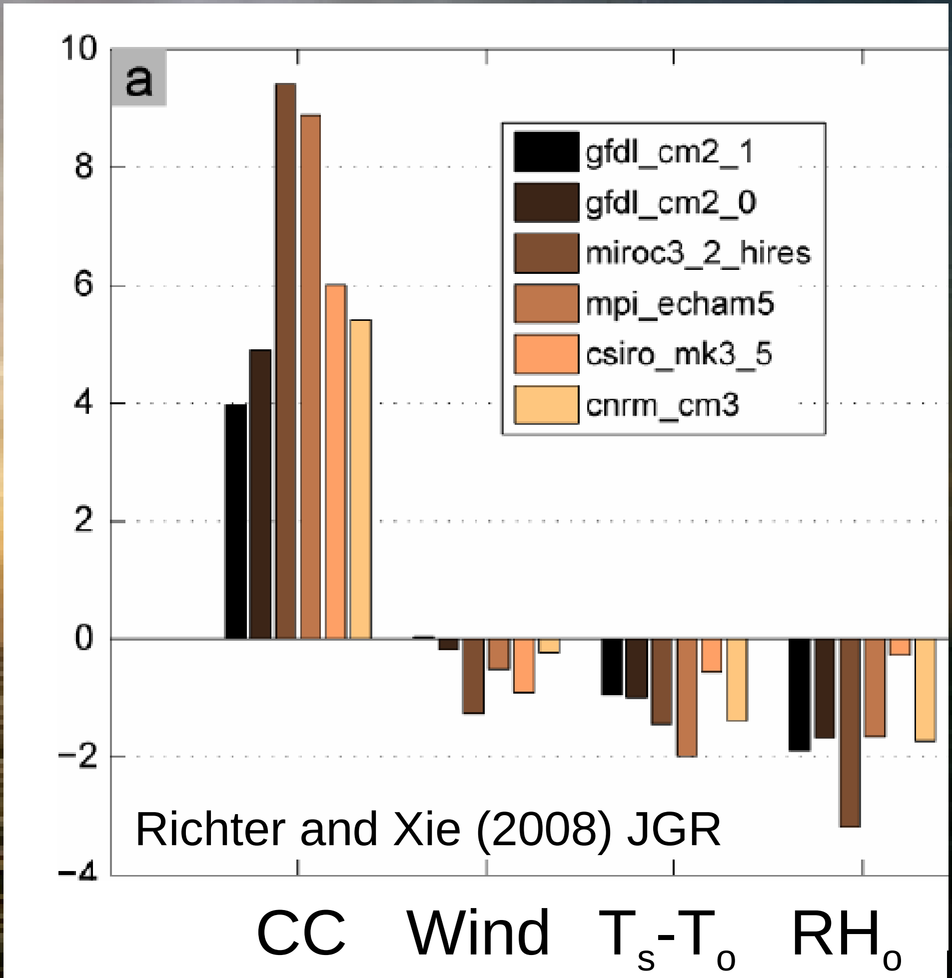




Models achieve muted precipitation response by reducing strength of Walker circulation.

Some observational evidence of this (Vecchi and Soden 2006 Nature)

Evaporation

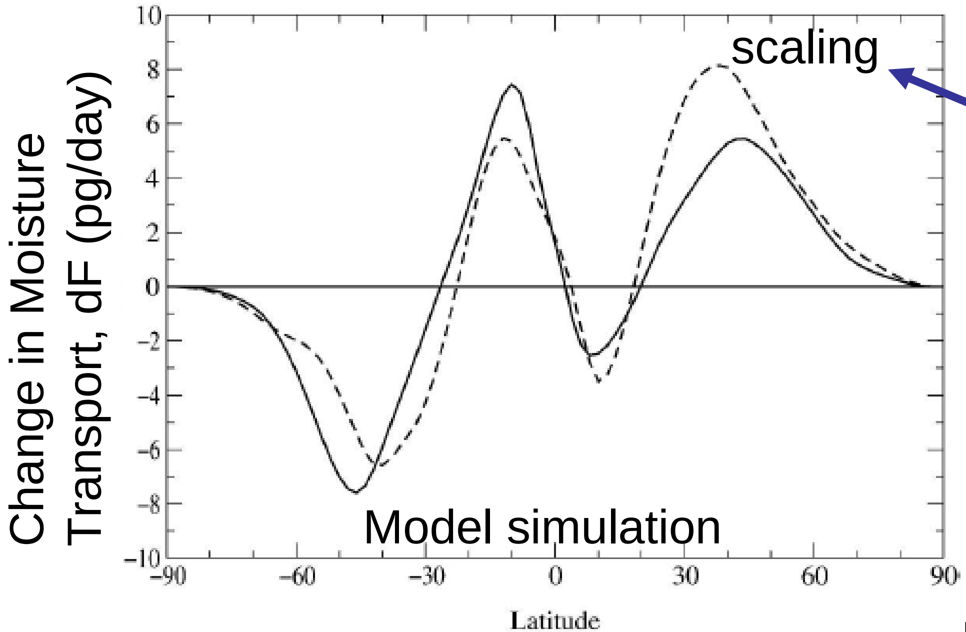


$$Q_E = L_v C_E \rho_a W (q_s - q_a)$$

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)

Moisture Transport



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

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

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

Held and Soden (2006) J Climate

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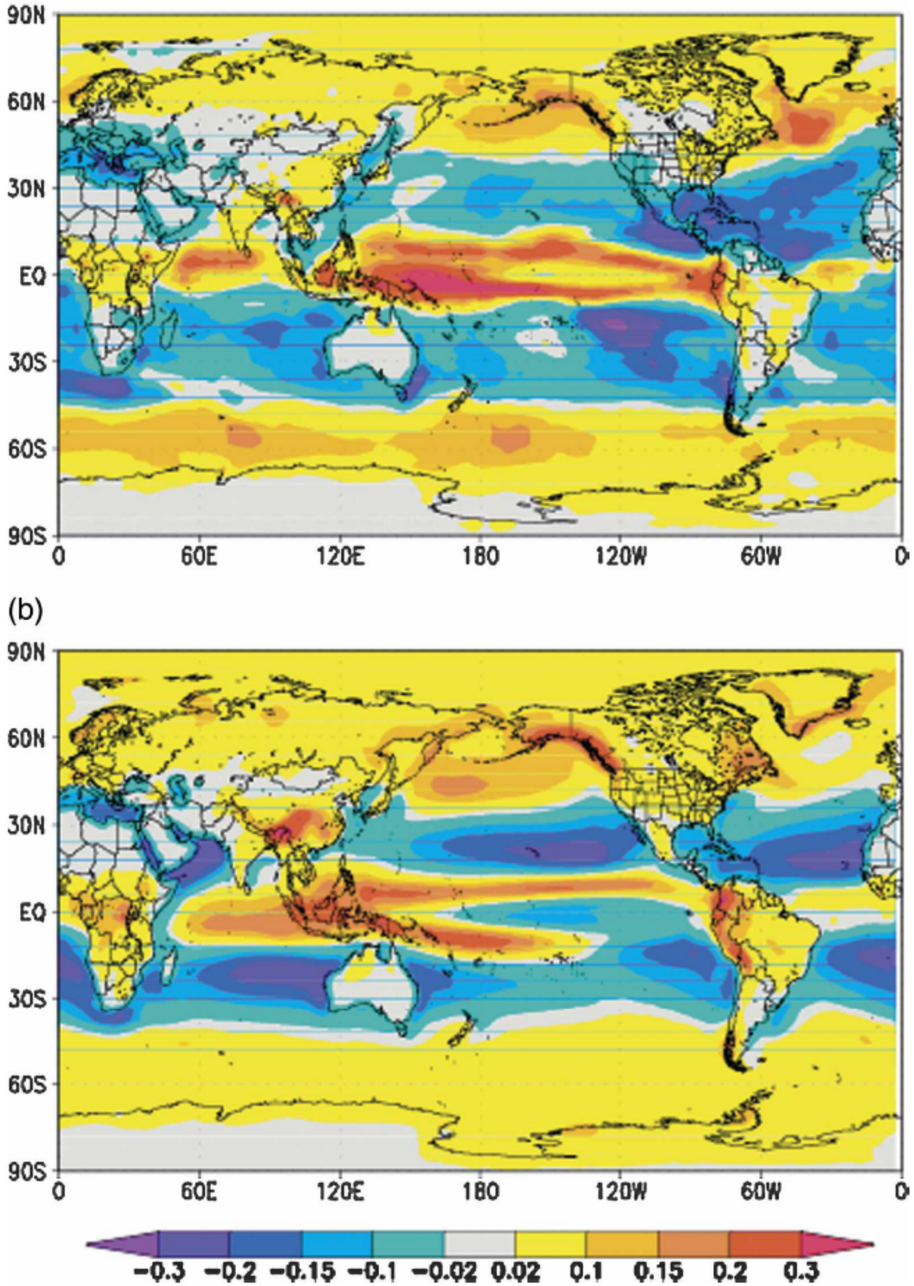

FIG. 7. The annual-mean distribution of $\delta(P - E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

Projected (top) and estimated (bottom) changes in Precipitation minus Evaporation d(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

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Using observations and a physical basis to inform projections in future changes in the water cycle

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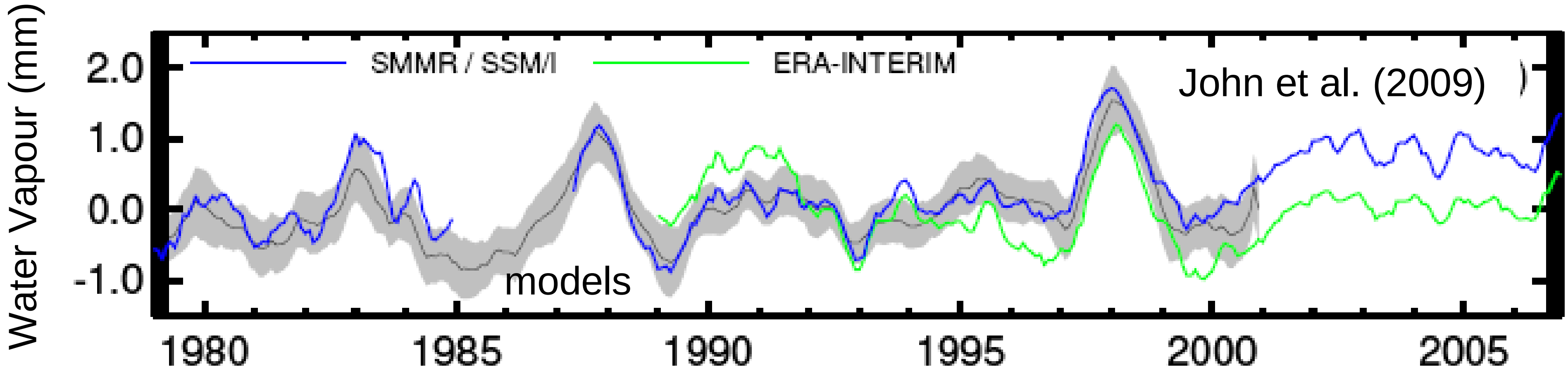
Low-level water vapour rises with temperature in models & observations in accordance with Clausius Clapeyron equation

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



…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

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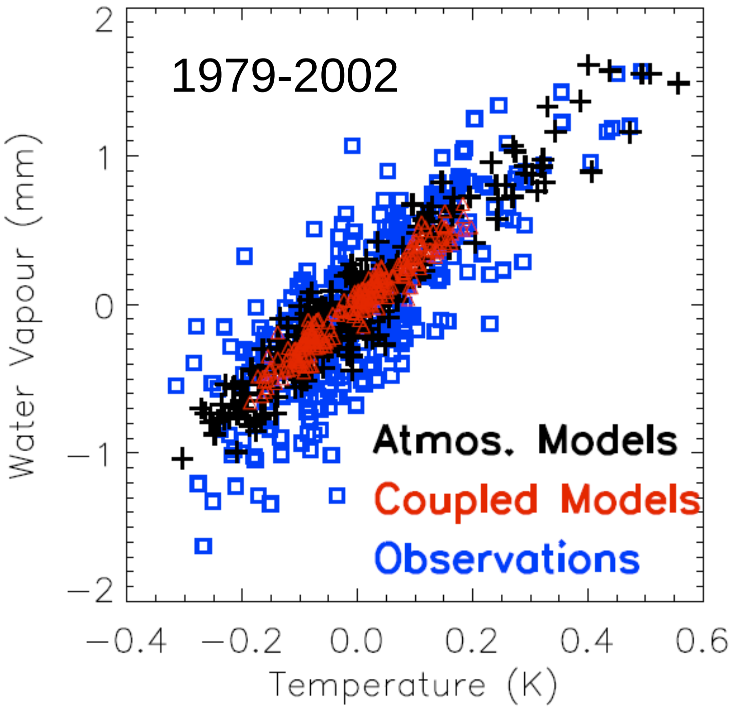
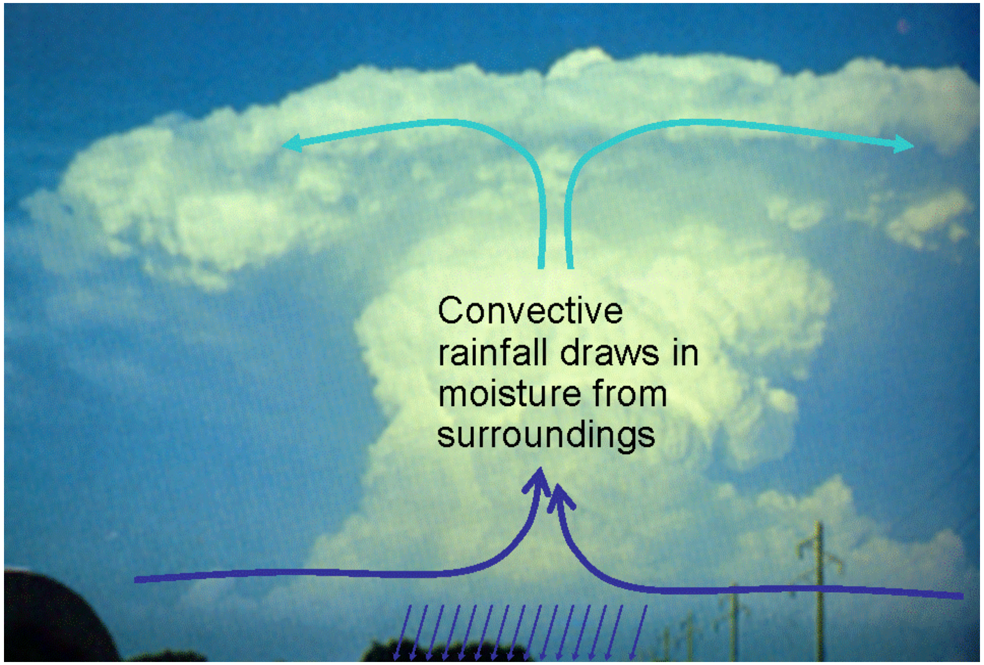
For a given precipitation event, more moisture would suggest more intense rainfall





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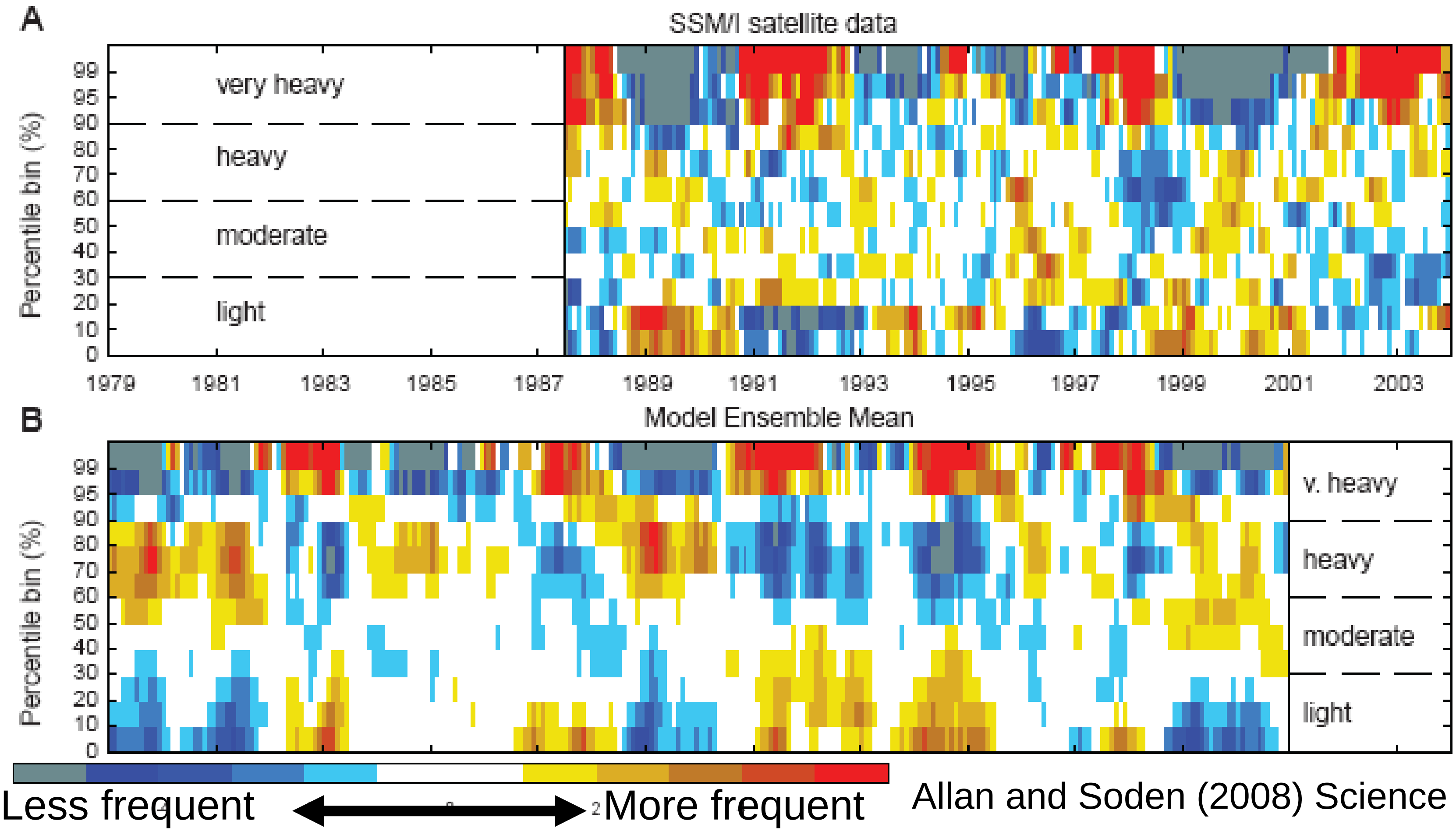
Daily Satellite Microwave Observations over tropical ocean appear to confirm warmer months are associated with more frequent intense rainfall



Allan and Soden (2008) Science

Water vapour in the climate system

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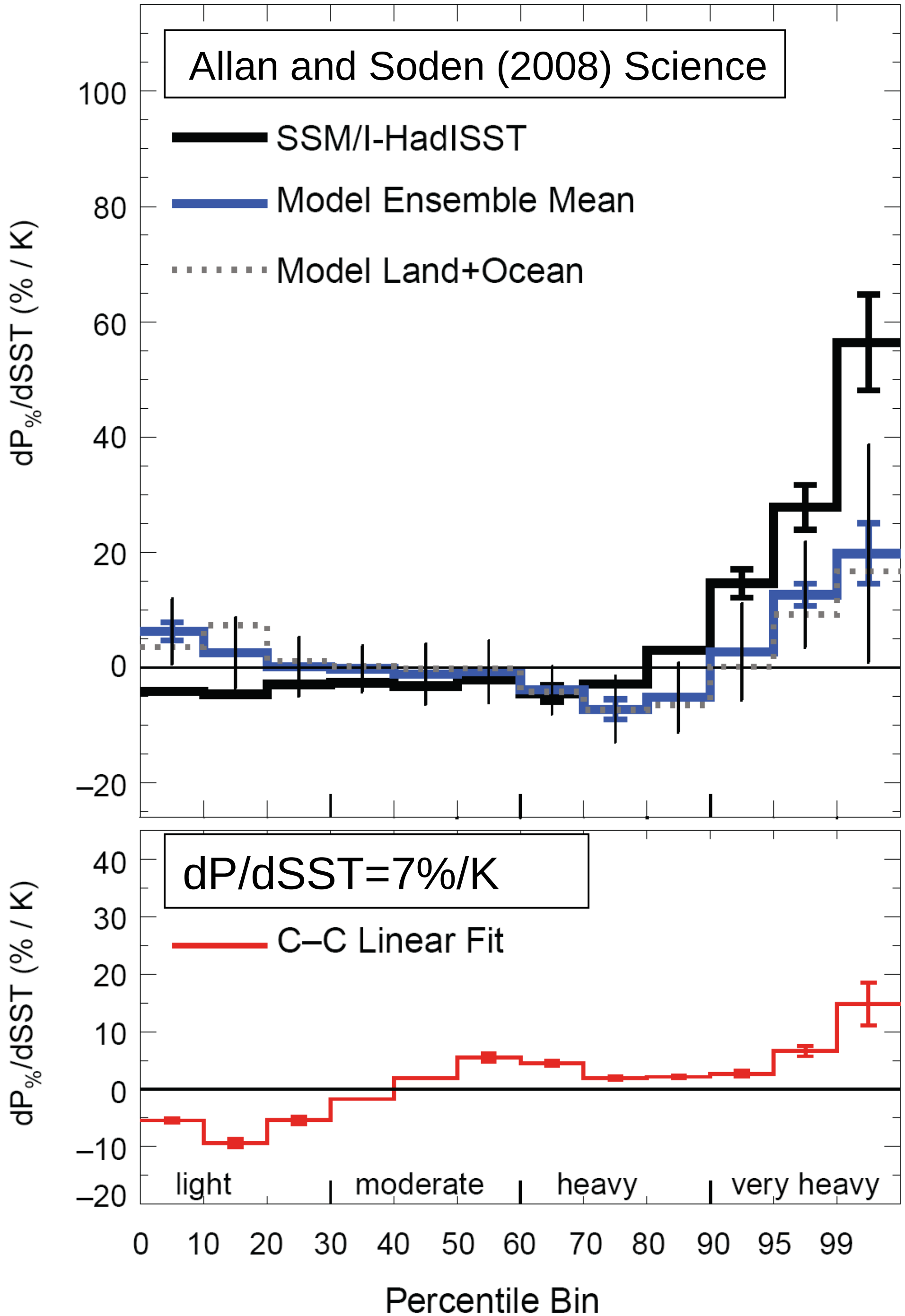
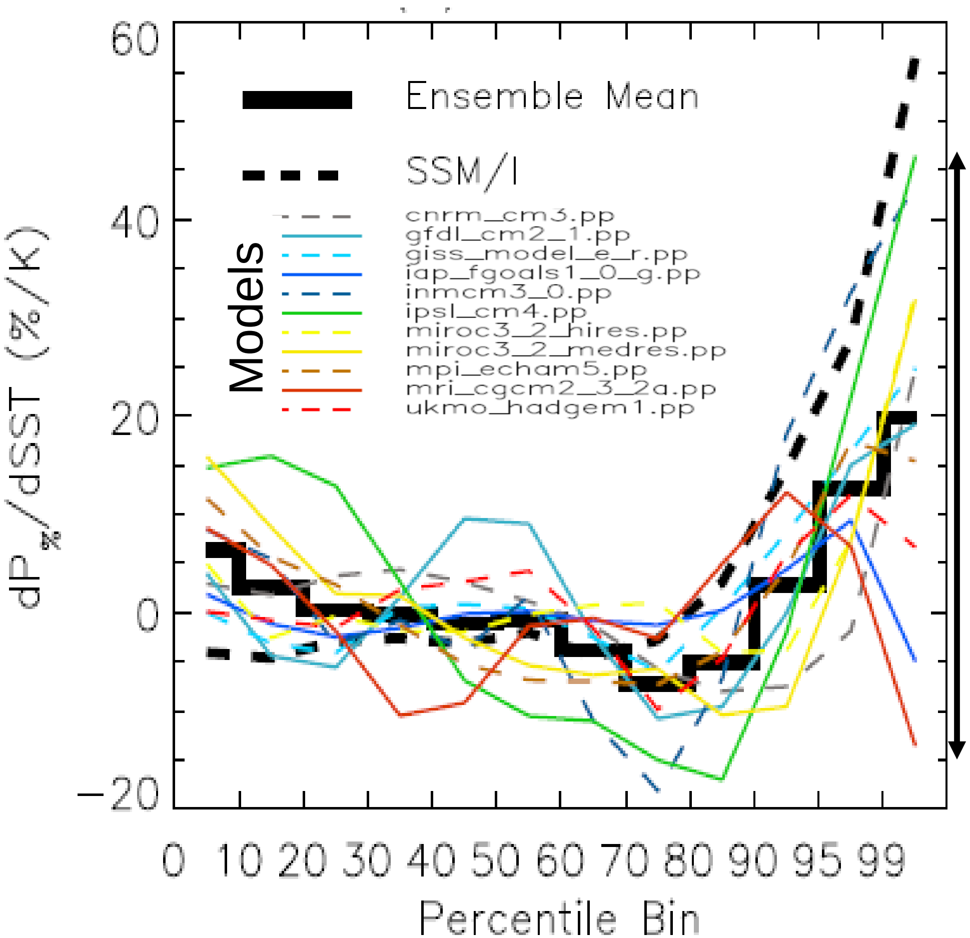


Frequency of rainfall intensities vary with SST in models and obs

- Frequency of intense rainfall increases with warming in models and satellite data
- Model scaling close to 7%/K expected from Clausius Clapeyron
- SSM/I satellite data suggest a greater response of intense rainfall to warming

Change in Frequency of Precipitation (% per K warming) in Bins of Intensity



← Light Rain Heavy Rain →

- Large spread in the response of the heaviest precipitation to warming between models and compared with satellite data.
- But intense vertical motion and PDF of precipitation events in models are unrealistic:
  Wilcox and Donner (2007) J Clim;
  Field and Shutts (2009) QJ
- Changes in extreme vertical motion may be important:
  Gastineau & Soden (2009) GRL;
  O'Gorman & Schneider (2009) PNAS;
  Lenderink & van Meijgaard (2008) Nature Geoscience

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Changes in Extreme Precipitation Determined by changes in low-level water vapour and updraft velocity

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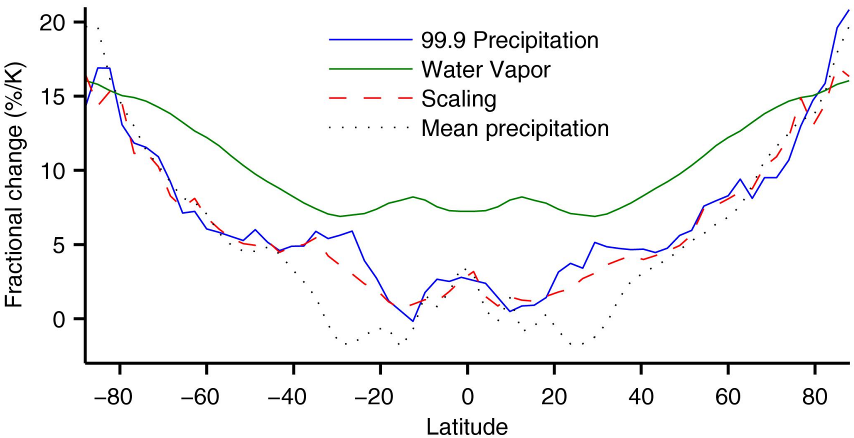
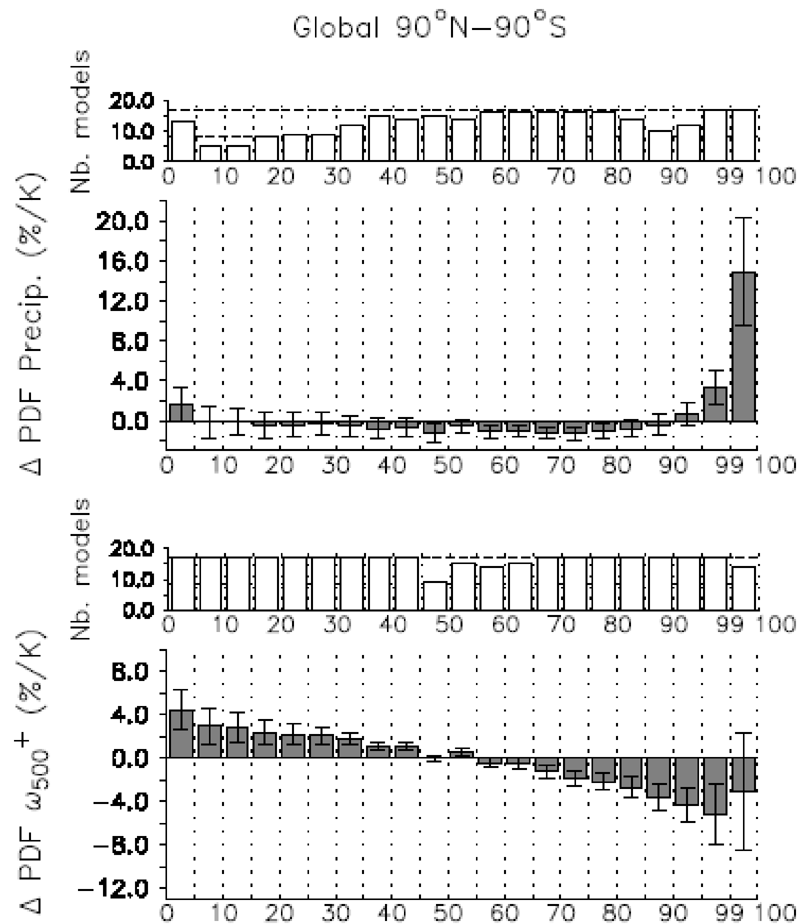


Above: O'Gorman & Schneider (2008) J Clim

Aqua planet experiment shows extreme precipitation rises with surface q, a lower rate than column water vapour



Right: Gastineau and Soden (2009) GRL
Reduced frequency of upward motion offsets extreme precipitation increases.

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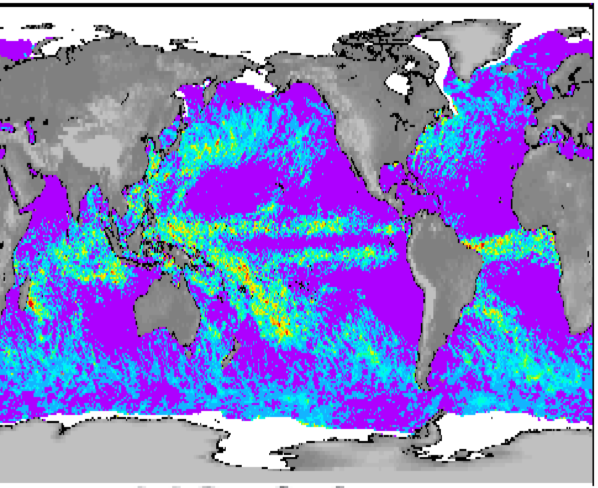
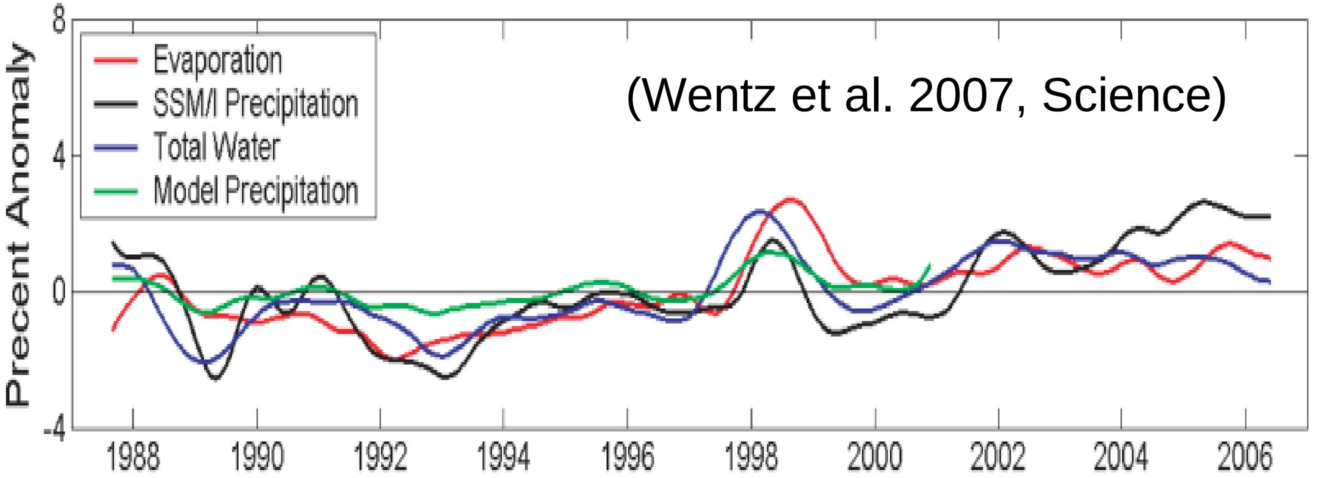
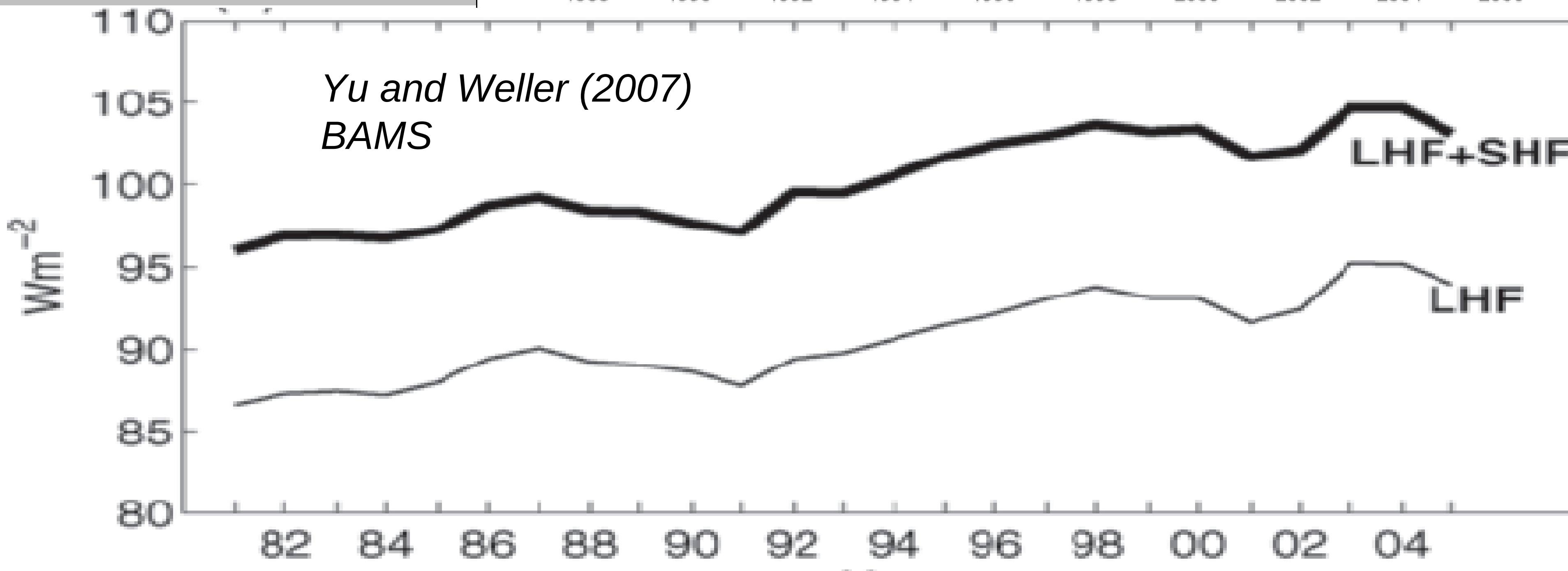
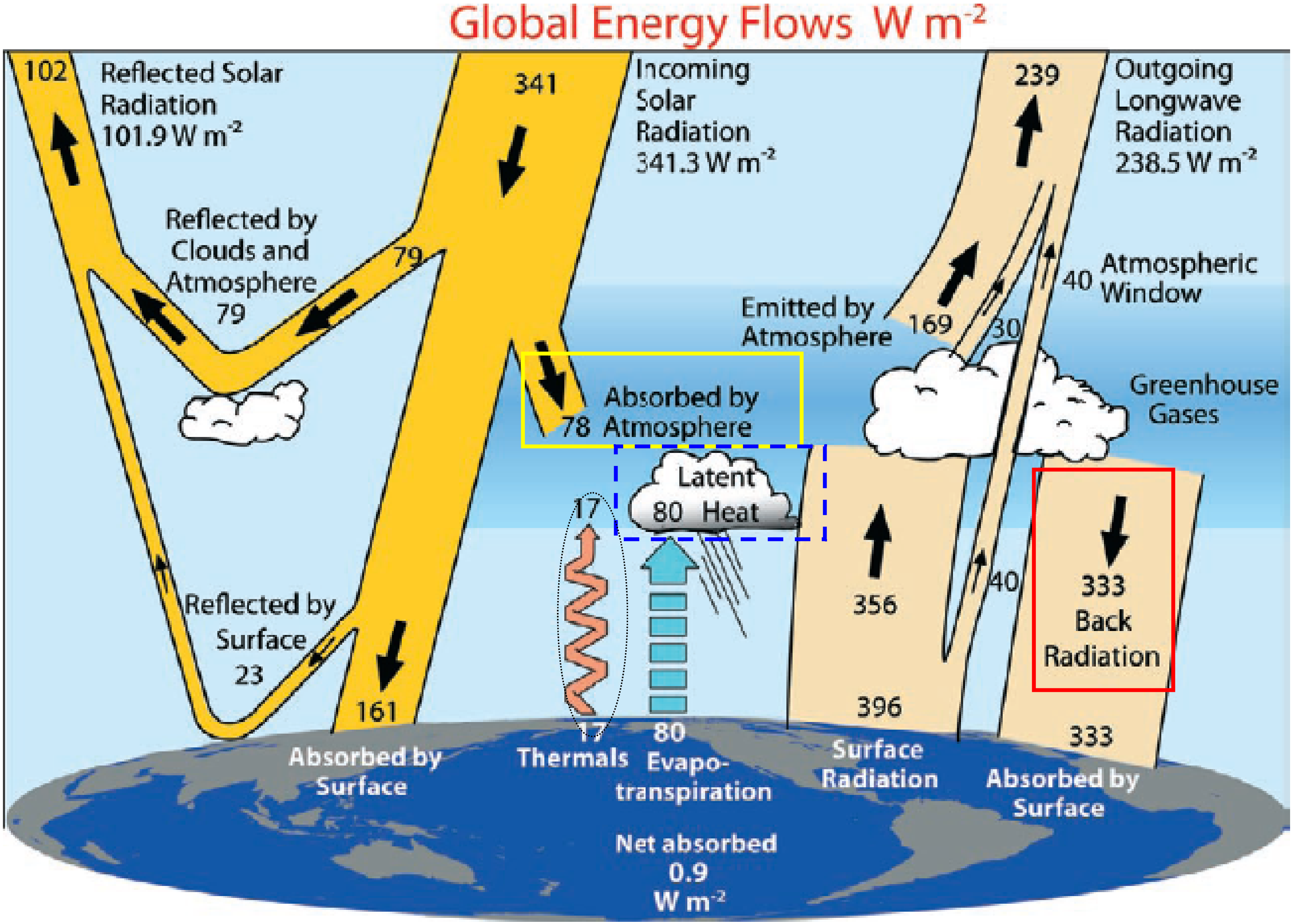
Does Observed Mean Precipitation and Evaporation Follow Clausius Clapeyron?









Water vapour in the climate system

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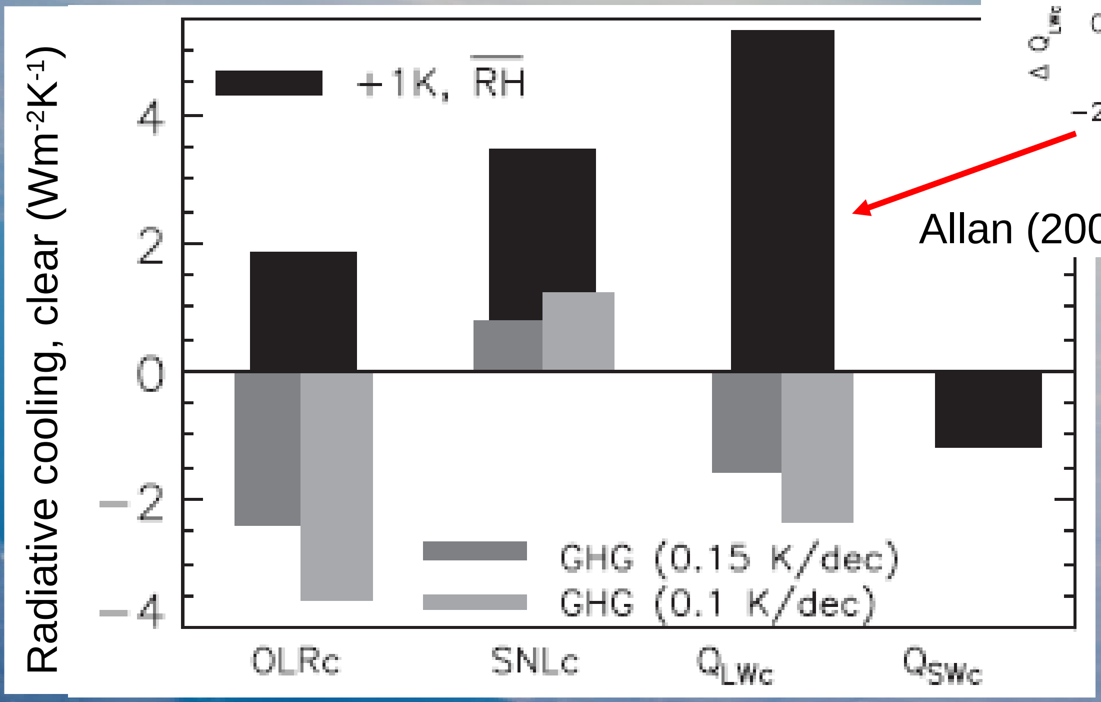
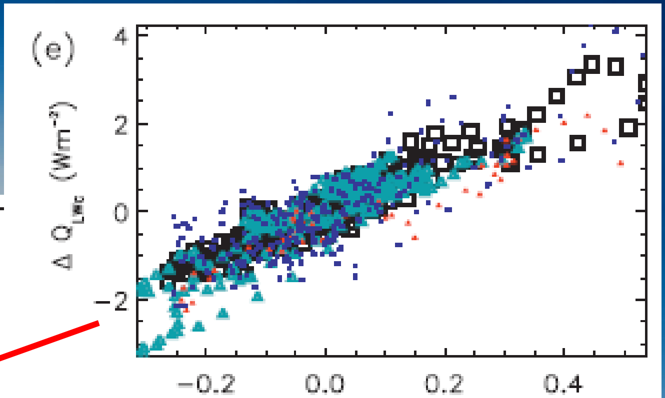
Trenberth et al. (2009) BAMS

Models simulate robust response of clear-sky radiation to warming (~2-3 $Wm^{-2}K^{-1}$) and a resulting increase in precipitation to balance **(~2-3 %K^{-1})**

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





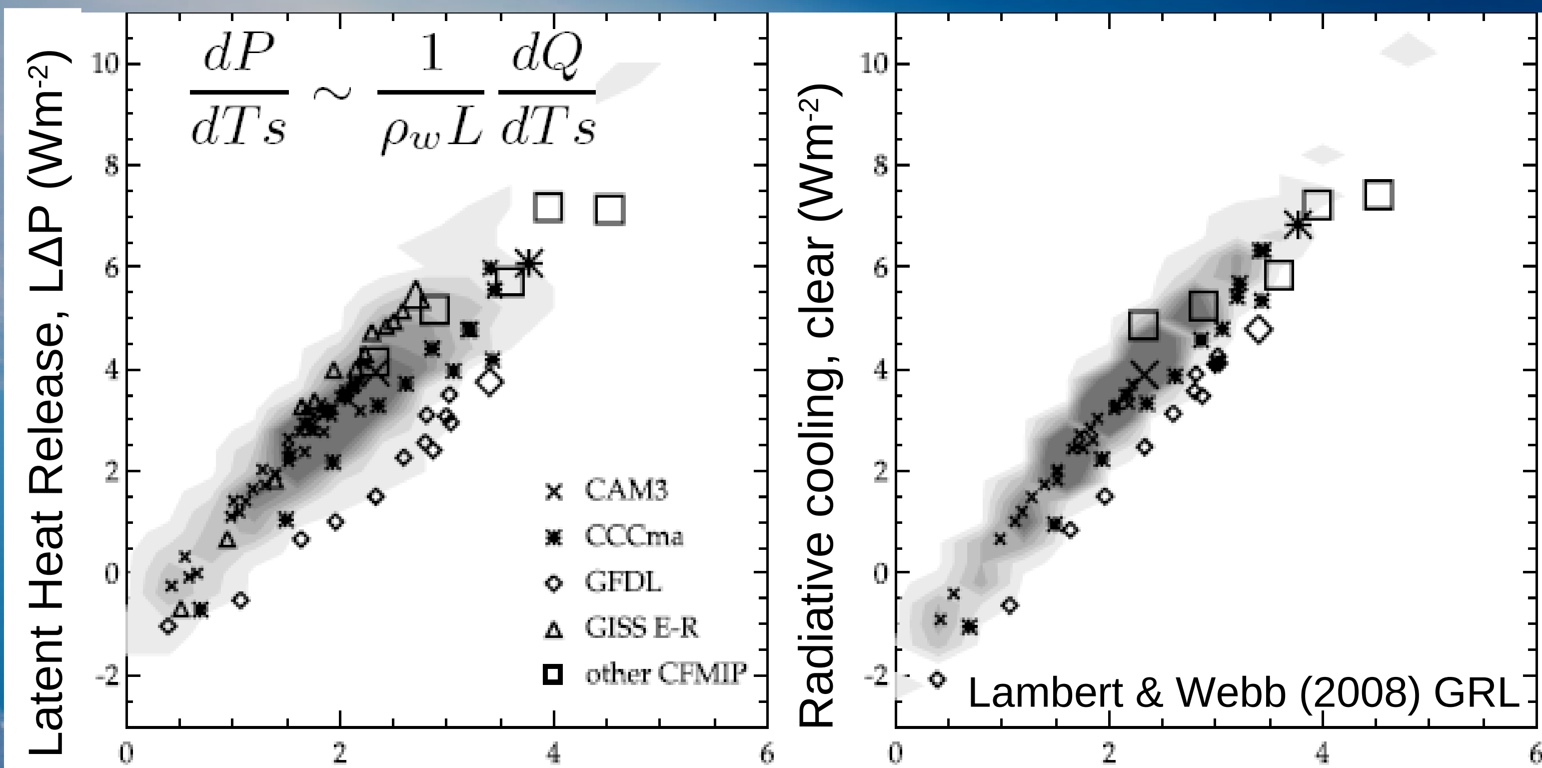
Allan (2009) J Clim

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

dP/dQ~[1000 mm/m 86400 s day^{-1}/(1000 kgm^{-3} x 2.5x10^6 J/kg)]~0.035 mm/day per Wm^{-2}, P~3mm/day

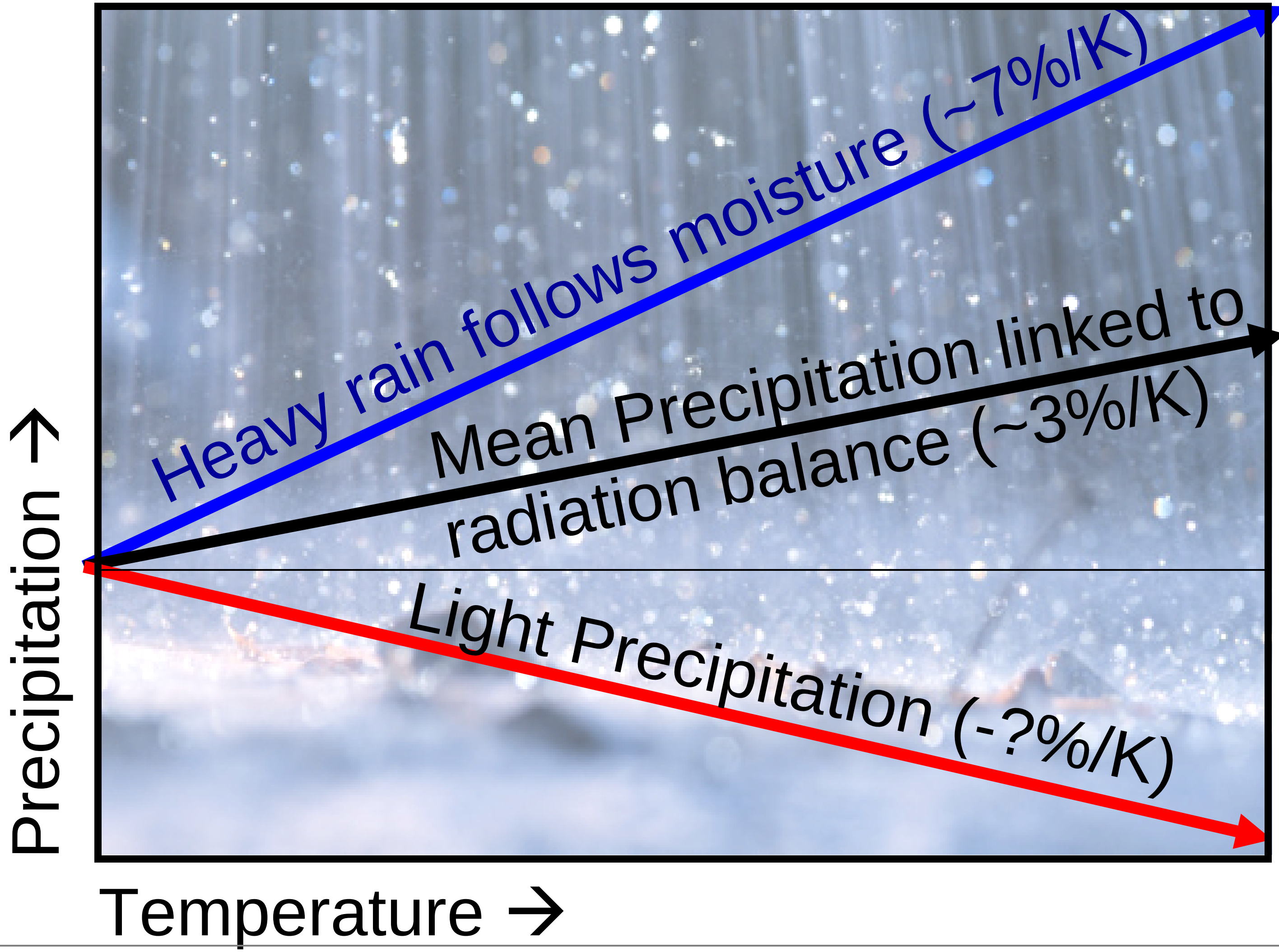
Models simulate robust response of clear-sky radiation to warming (~2-3 $Wm^{-2}K^{-1}$) and a resulting increase in precipitation to balance (~2-3 $\%K^{-1}$)

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



Surface Temperature (K)

Contrasting precipitation response expected



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

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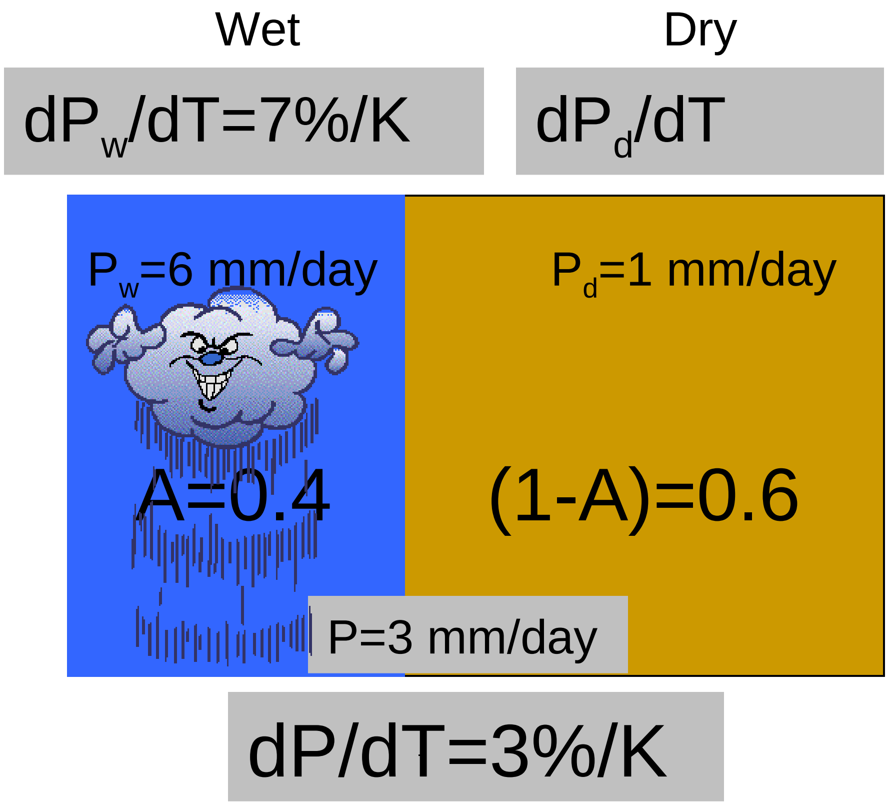

Assume wet region follows Clausius Clapeyron (7%/K) and mean precip follows radiation constraint (~3%/K)

A is the wet region fractional area

P is precipitation

T is temperature

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Wet

$dP_w/dT = 7\%/K$

Dry

dP_d/dT

$P_w = 6$ mm/day

$P_d = 1$ mm/day

$A = 0.4$

$(1-A) = 0.6$

$P = 3$ mm/day

$dP/dT = 3\%/K$

Assume wet region follows Clausius Clapeyron (7%/K) and mean precip follows radiation constraint (~3%/K)

$$\frac{dP}{dT} = A\left(\frac{dP_w}{dT}\right) + (1-A)\left(\frac{dP_d}{dT}\right)$$

$$\rightarrow \mathbf{dP_d = (dP - A\,dP_w)/(1-A)}$$

A is the wet region fractional area

P is precipitation

T is temperature

A	P_w	P_d	dP_d/dTs (mm/day/K)	“ (%/K)
0.4	6	1	-0.1	-10
0.2	9	1.5	-0.05	-4.5
0.1	10.5	2.2	+0.02	+0.9

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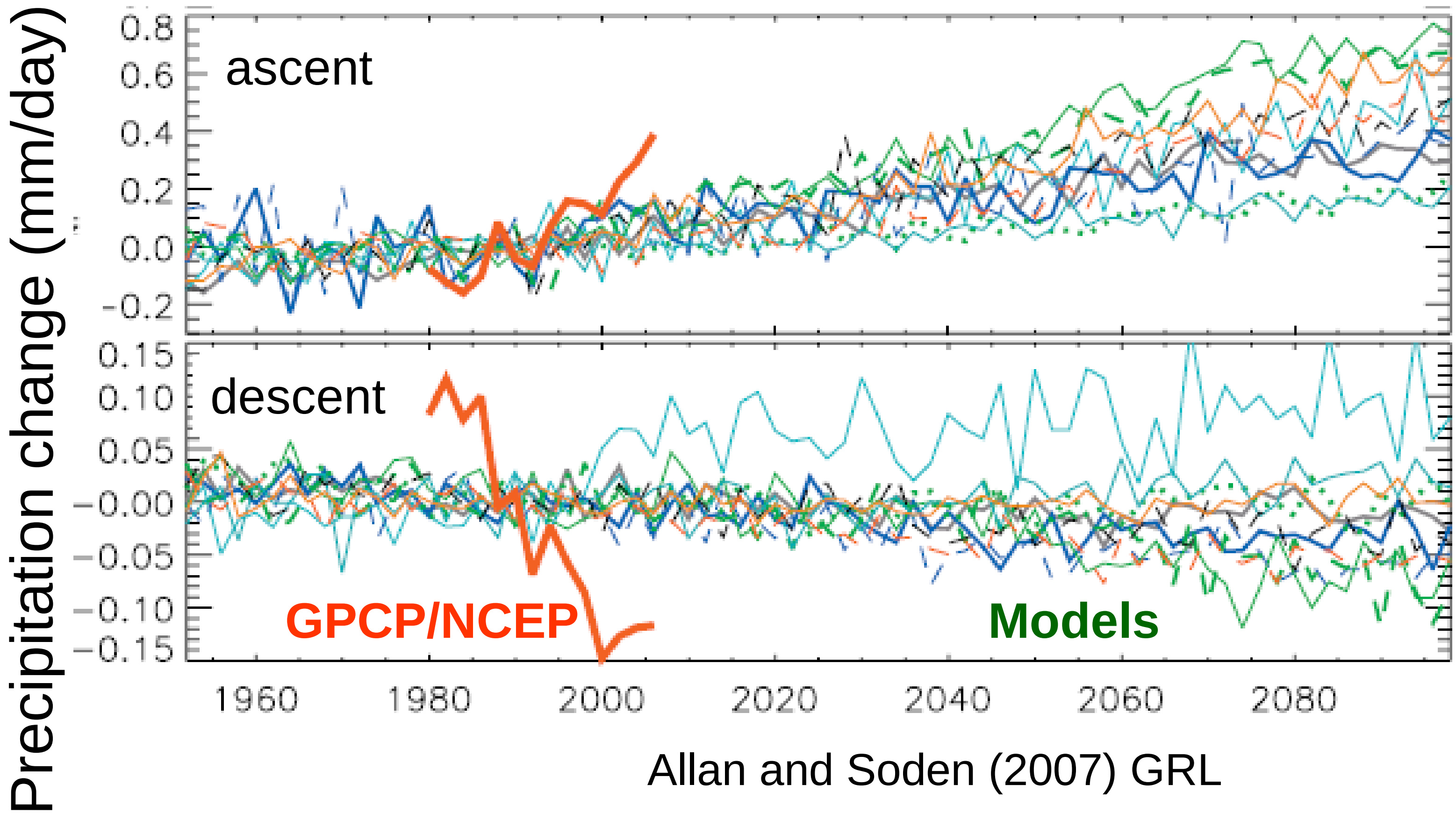
Contrasting precipitation response in ascending and descending portions of the tropical circulation



Allan and Soden (2007) GRL

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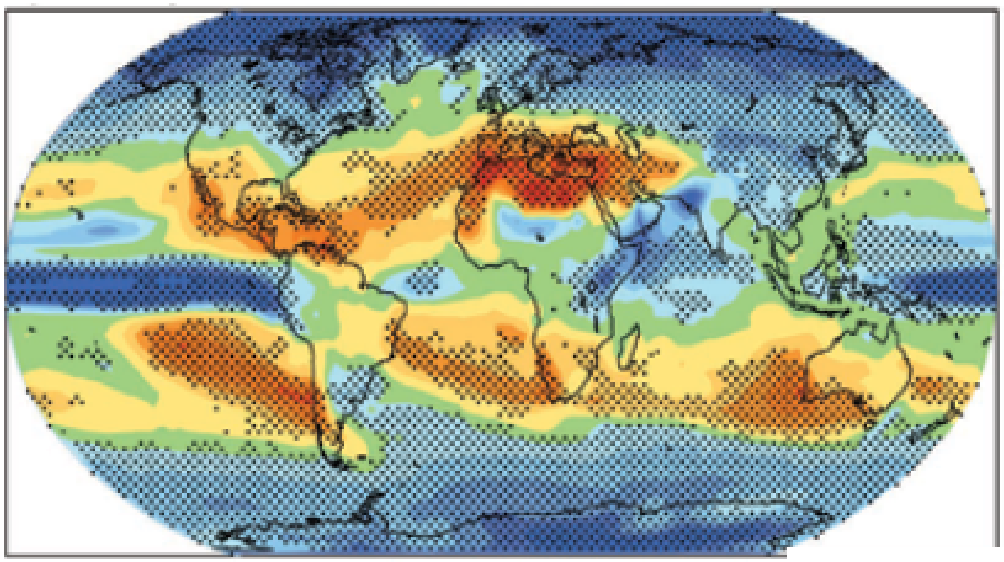
The Rich Get Richer?



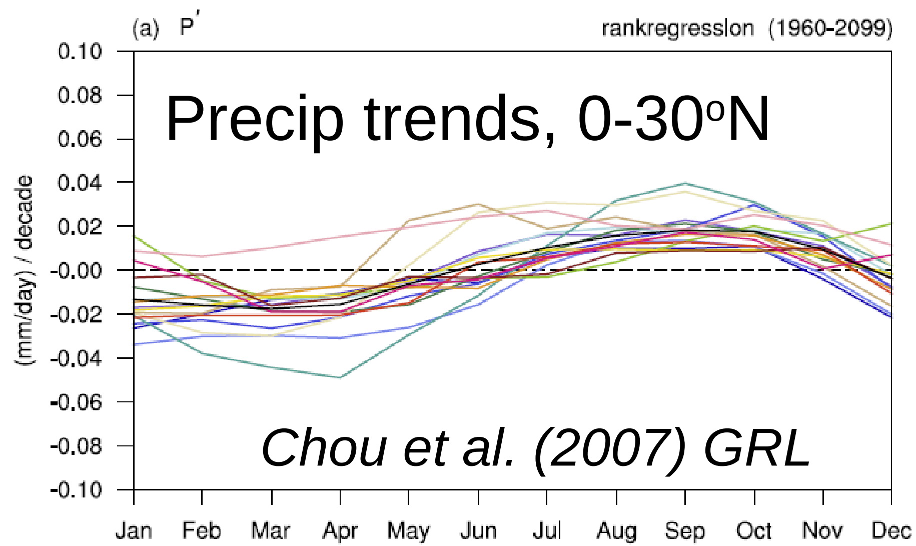
Models ΔP [IPCC 2007 WGI]

There is limited observational evidence of a contrasting precipitation responses in wet and dry regions over land (Zhang et al. 2007 Nature)

A further consequence:

Rainy season: wetter

Dry season: drier



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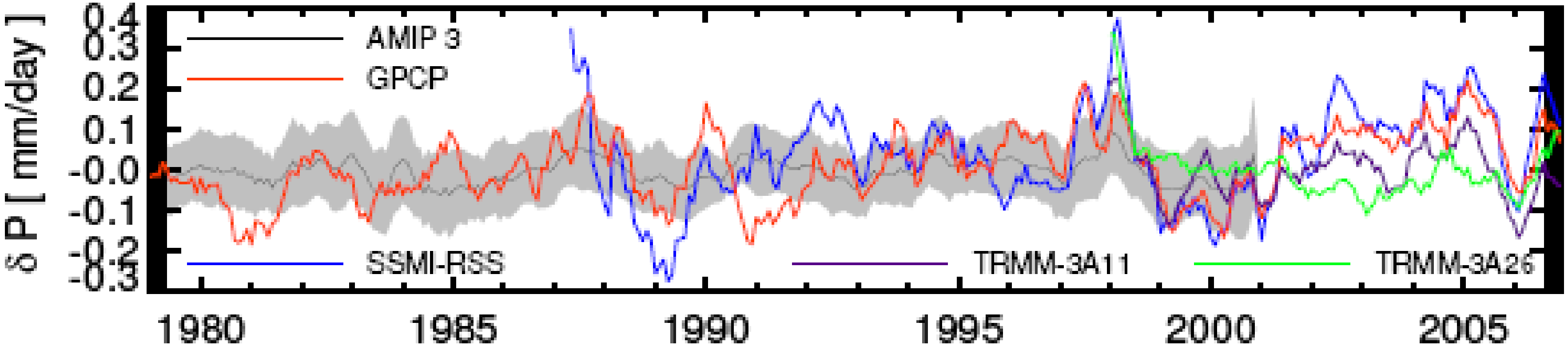
Are observing systems adequate?

- It is notoriously difficult to measure changes in precipitation from space



John et al. (2009) GRL

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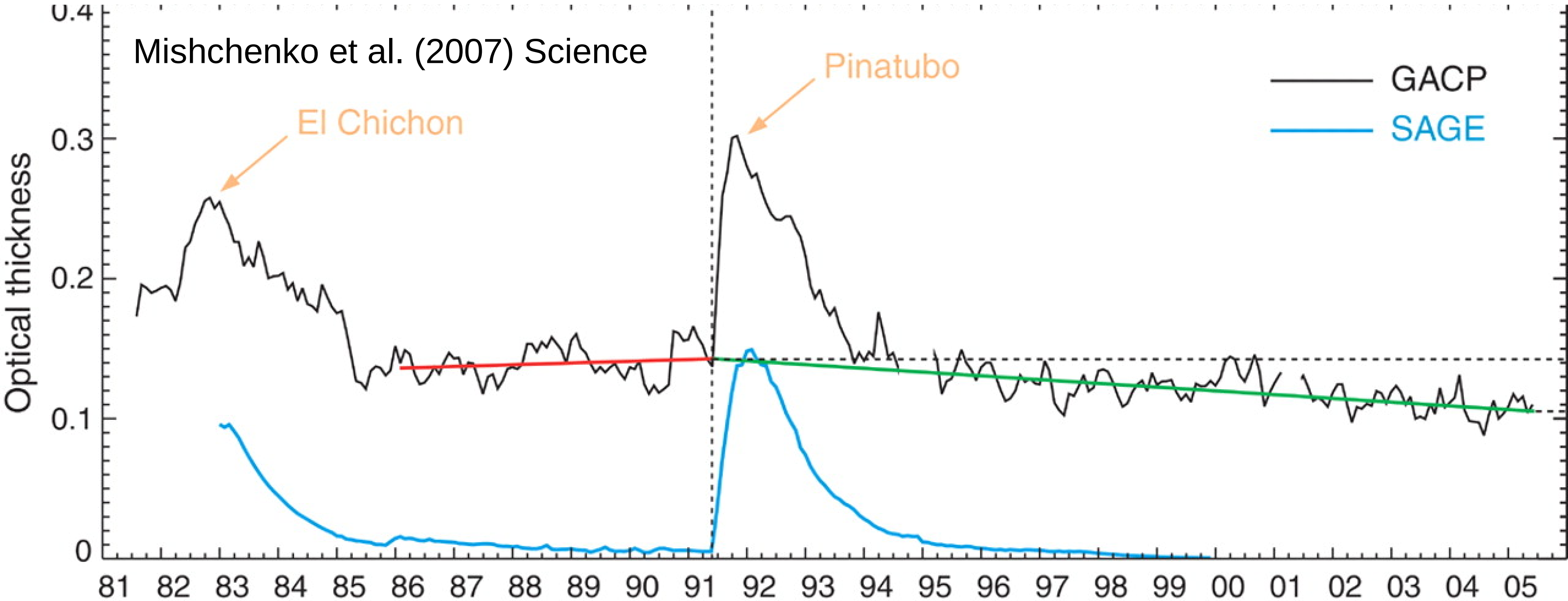
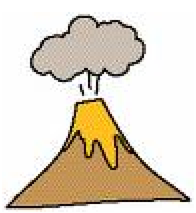
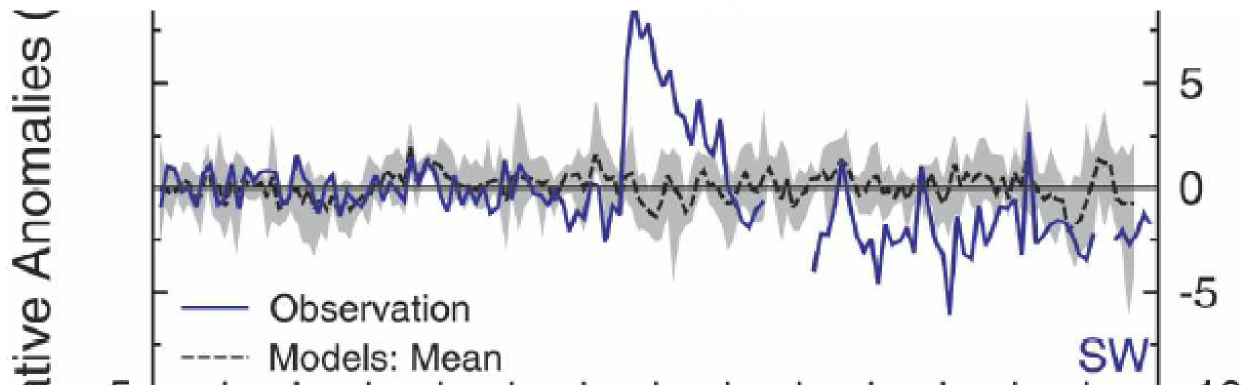
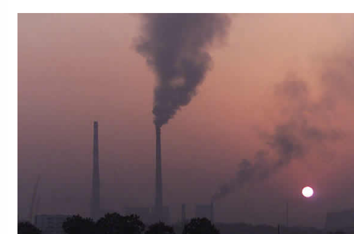
Could changes in aerosol be imposing direct and indirect changes in the hydrological cycle? e.g. Wild et al. (2008) GRL



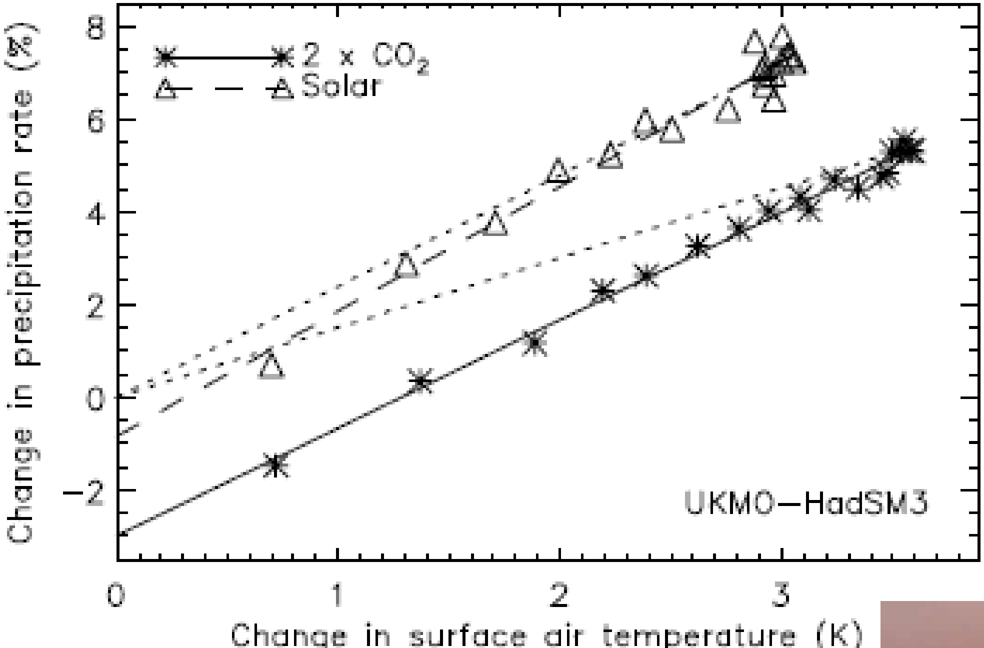




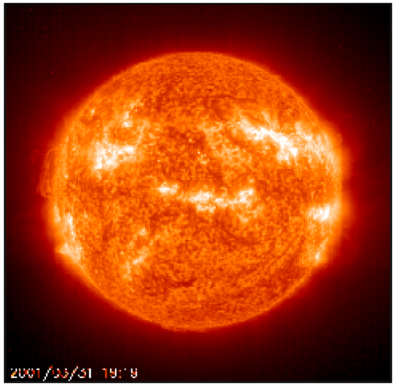


Wielicki et al. (2002) Science; Wong et al. (2006) J. Clim; Loeb et al. (2007) J. Clim

Precipitation response depends upon the forcing and the feedback



Andrews et al. (2009) J Climate



Partitioning of energy between atmosphere and surface is crucial to the hydrological response

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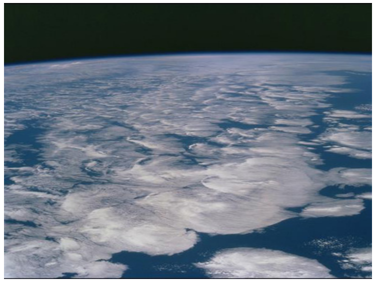
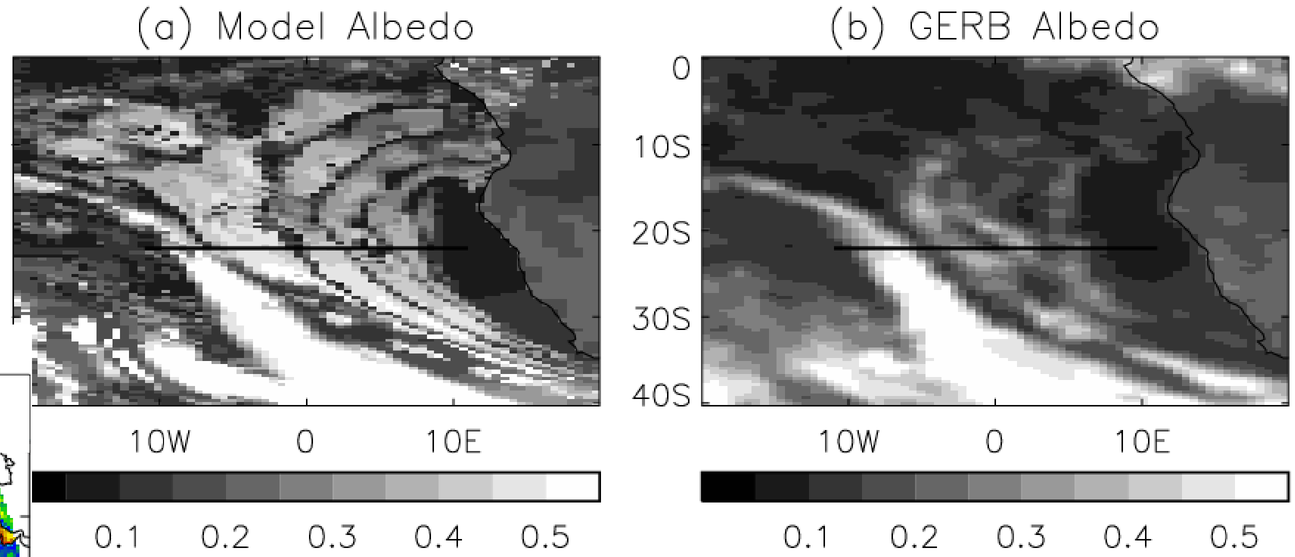
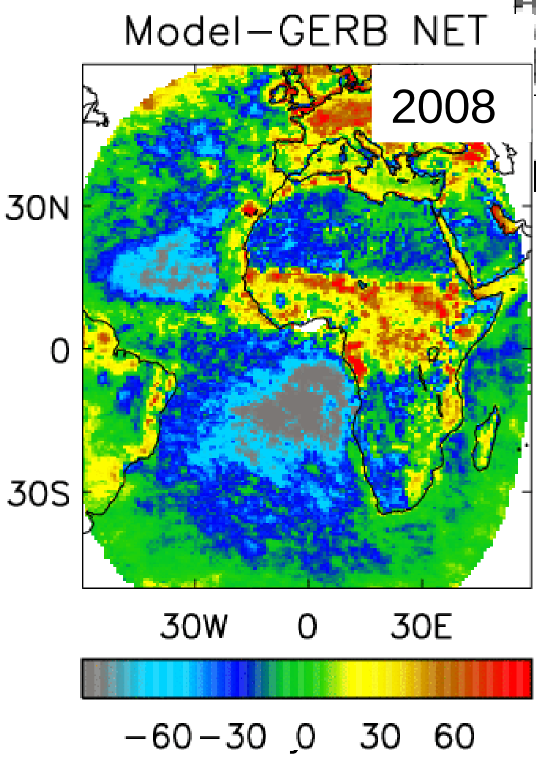
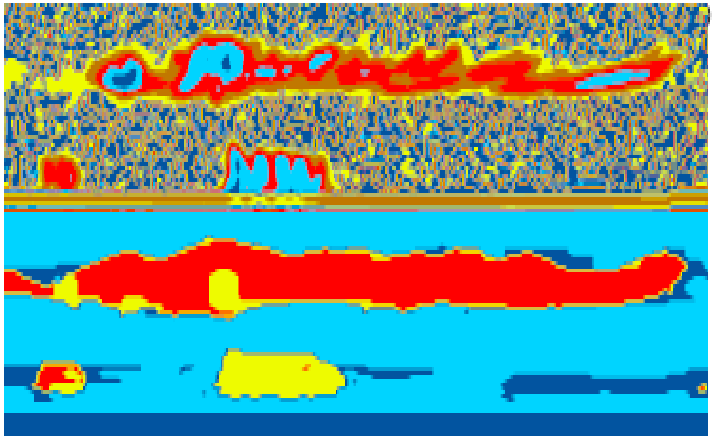
Are the issues of cloud feedback and the water cycle linked?

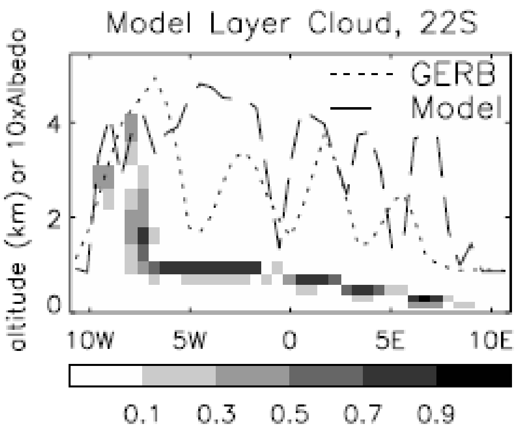




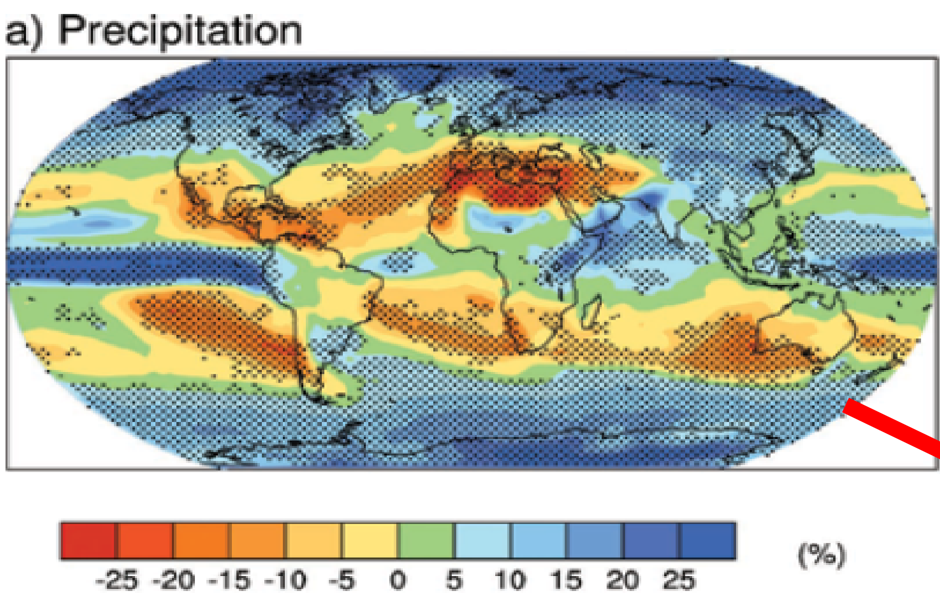


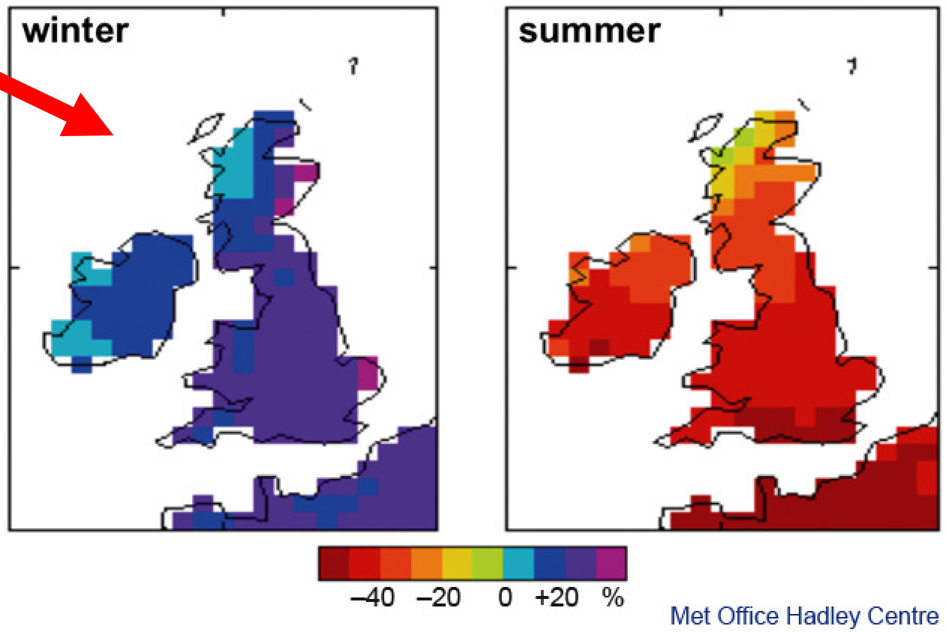
Allan et al. (2007) QJRMS





Towards regional prediction of the water cycle…





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Conclusions

- **Low level moisture responses robust**
  - Less clear over land and at higher levels.
  - Inaccurate model mean state?
- **Precipitation extremes linked to moisture**
  - Moisture response at lowest level?
  - Changes in updraft velocity?
  - Differences between individual models/obs

- **Mean and regional precipitation response: a tug of war**
  - Slow rises in radiative cooling (~3 $Wm^{-2}K^{-1}$)
  - Rises in low-level moisture (~7%/K) faster than precipitation (~3%/K)
  - Reduced frequency? Wet get wetter and dry get drier
  - Who cares about drought/flooding over the ocean?
- **Recent Precipitation Responses appear larger in observations than models.**
  - Could aerosol be influencing decadal variability in the hydrological cycle?
  - Are observing systems up to monitoring changes in the water cycle?
- **Understanding changes in near surface conditions may be important**

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Unanswered questions

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- How does UTH really respond to warming?
- Do we understand the upper tropospheric moistening processes?
- Is moisture really constrained by Clausius Clapeyron over land?
- What time-scales do feedbacks operate on?
- Apparent discrepancy between observed and simulated changes in precipitation
  - Is the satellite data at fault?
  - Are aerosol changes short-circuiting the hydrological cycle?
  - Could model physics/resolution be inadequate?
- Could subtle changes in the boundary layer be coupled with decadal swings in the hydrological cycle?
- How do clouds respond to forcing and feedback including changes in water vapour?
- Are the cloud feedback and water cycle issues linked?

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