How confident are we in the response of the global water cycle to climate change?

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Thanks to: Chunlei Liu, Matthias Zahn, David Lavers, Brian Soden, Viju John

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Climate model projections

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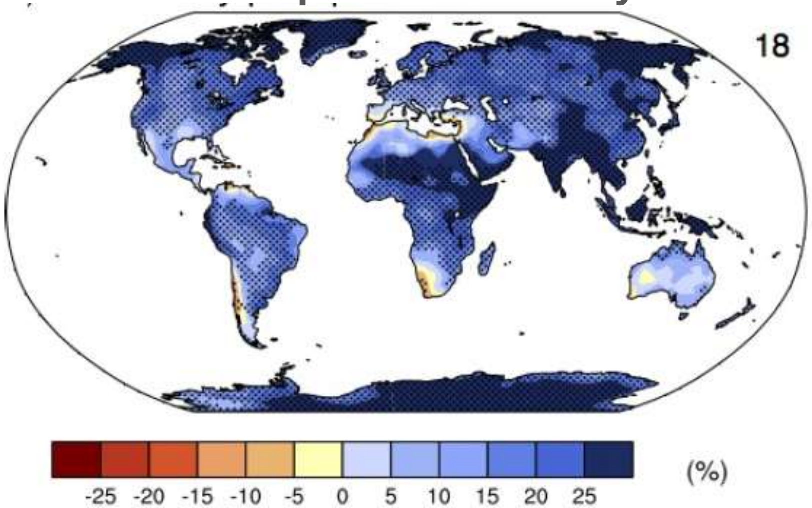
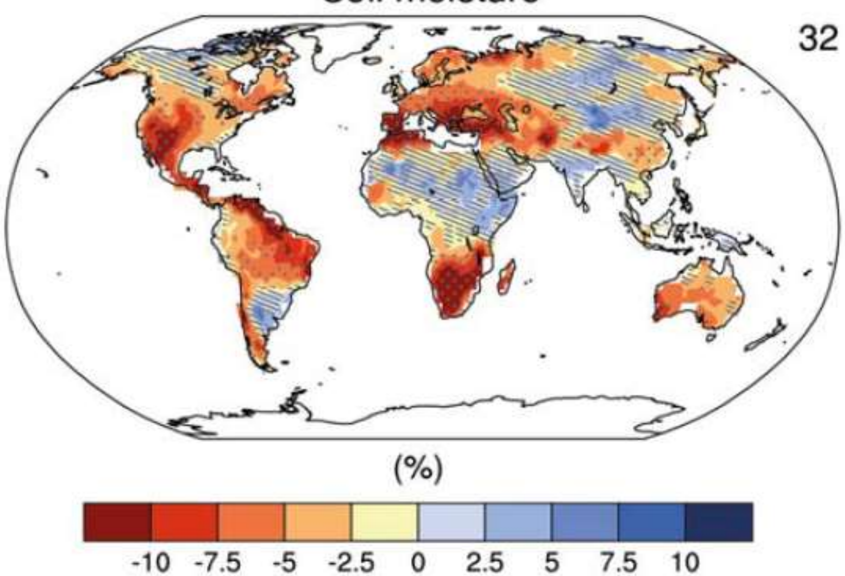
- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??

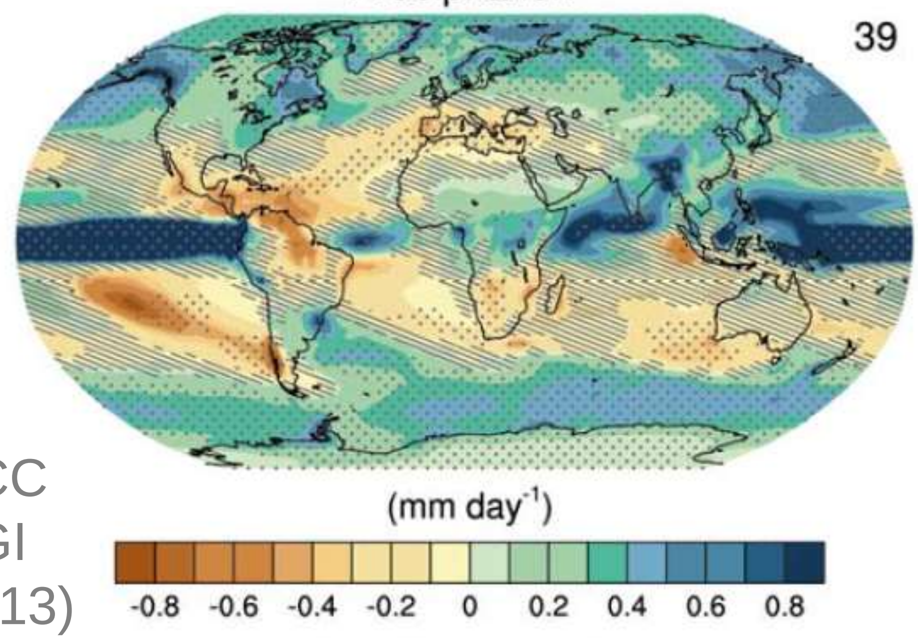
Precipitation intensity



Soil moisture

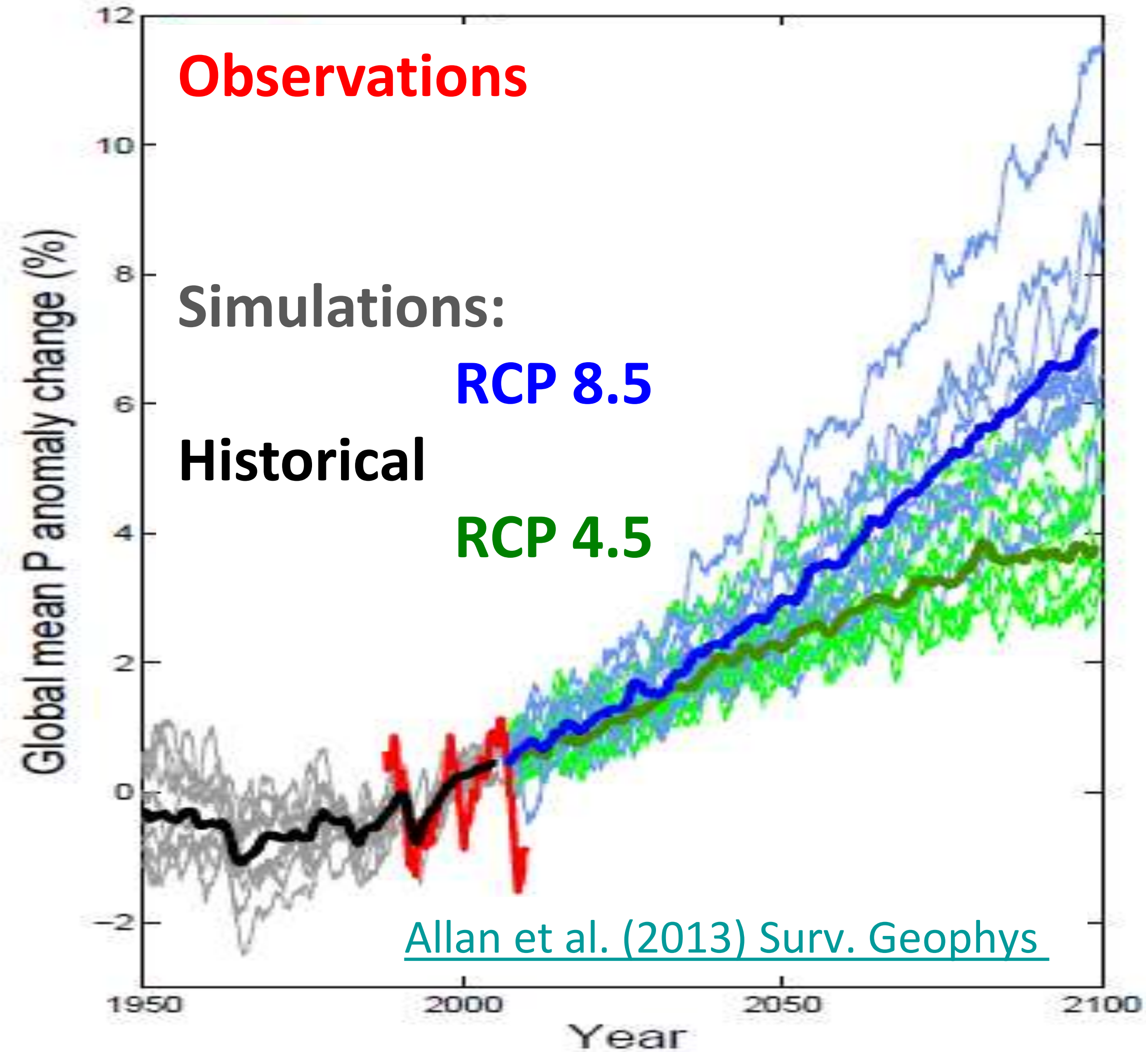


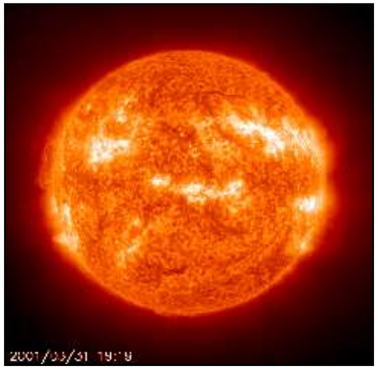
Precipitation



IPCC WGI (2013)

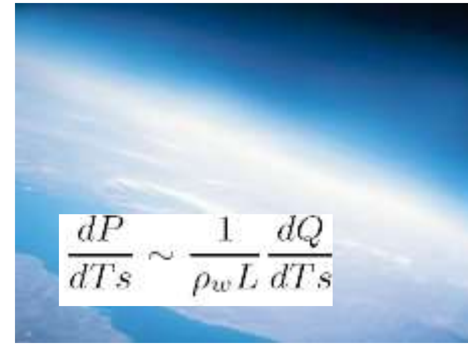
How will global precipitation respond to climate change?





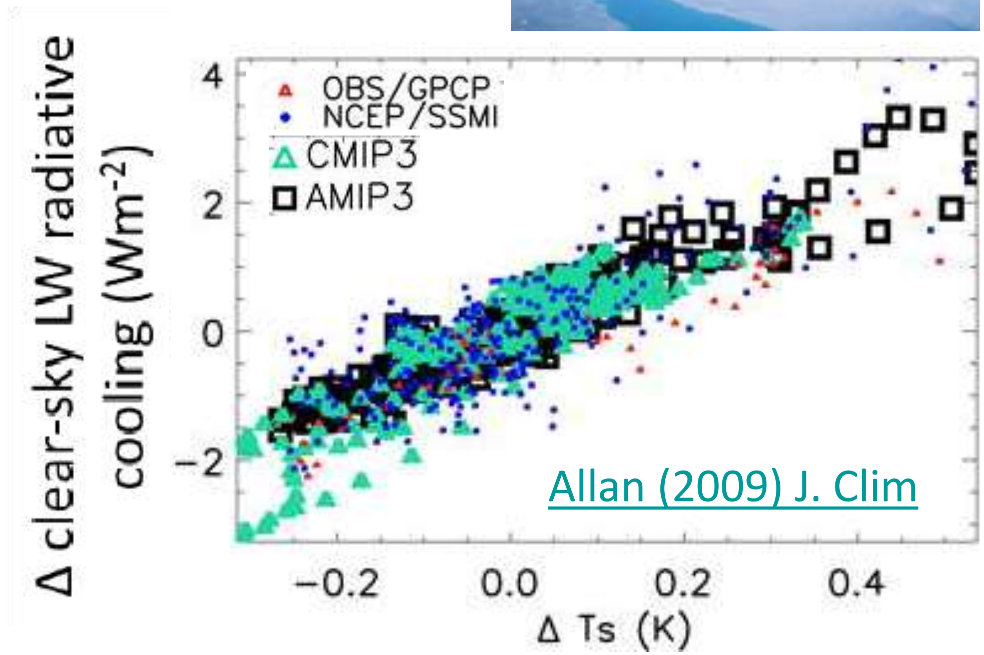
See also Hawkins & Sutton (2010) Clim. Dyn

Confident global precipitation increases with warming



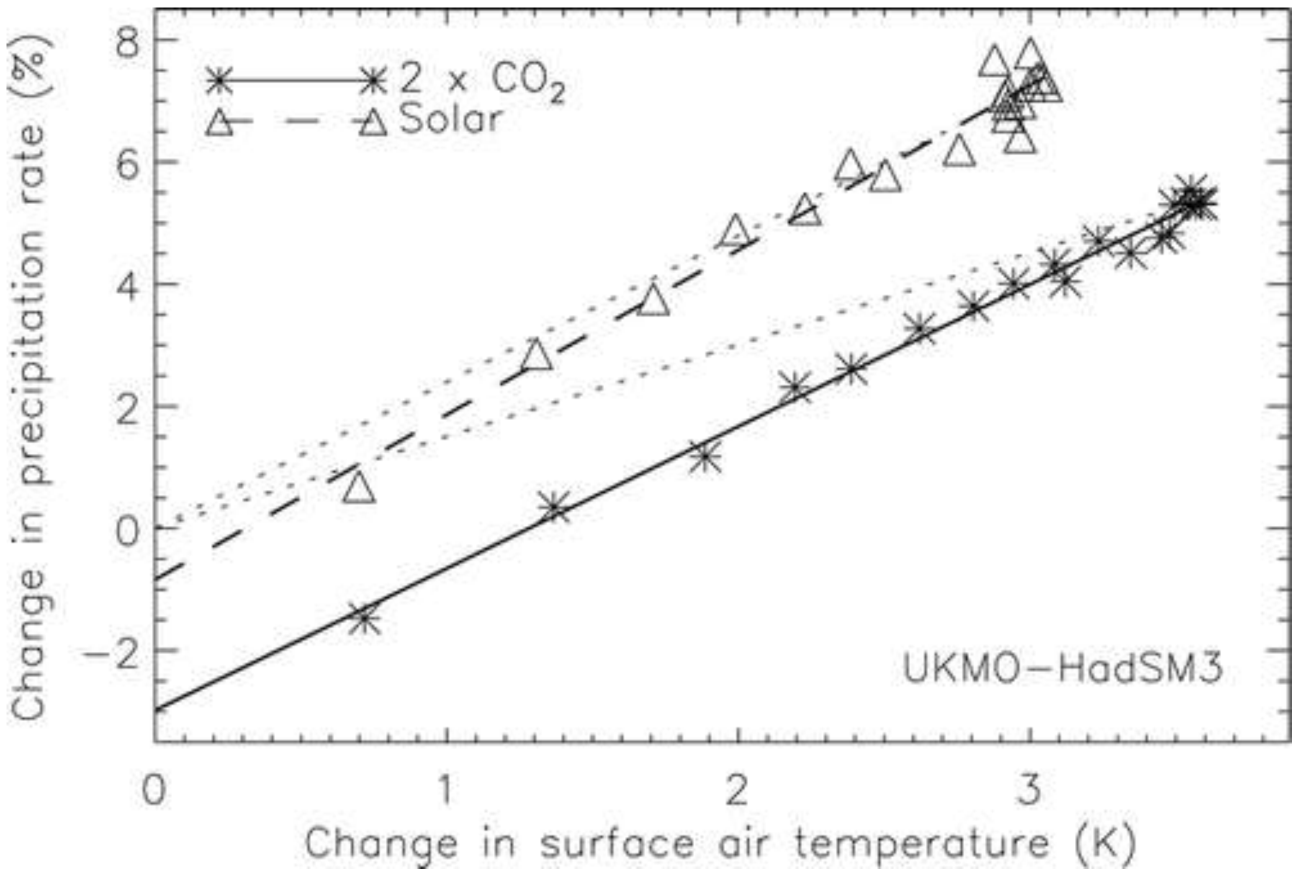
- Enhanced atmospheric radiative cooling with warming
  - Clear-sky dominates
  - Model agreement
  - Radiative transfer and thermodynamics

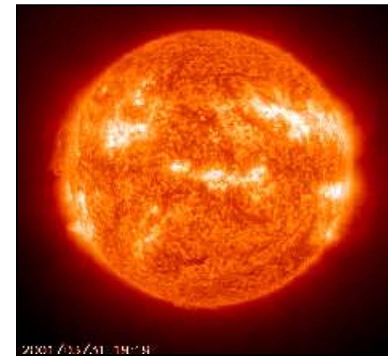
  Lambert & Webb (2008) GRL ; Previdi (2010) ERL ; Huang et al. (2013) J Clim



- Energy balance constrains increase in precipitation → e.g. Allen and Ingram (2002) *Nature* ; Stephens & Ellis (2008) J. Clim ; O'Gorman et al. (2012) Surv. Geophys

Improved understanding: radiative forcing & precipitation response





Andrews et al. (2009) J Climate

See also: Allen and Ingram (2002) *Nature* ; O'Gorman et al. (2012) Surv. Geophys ; Pendergrass & Hartmann (2012) GRL

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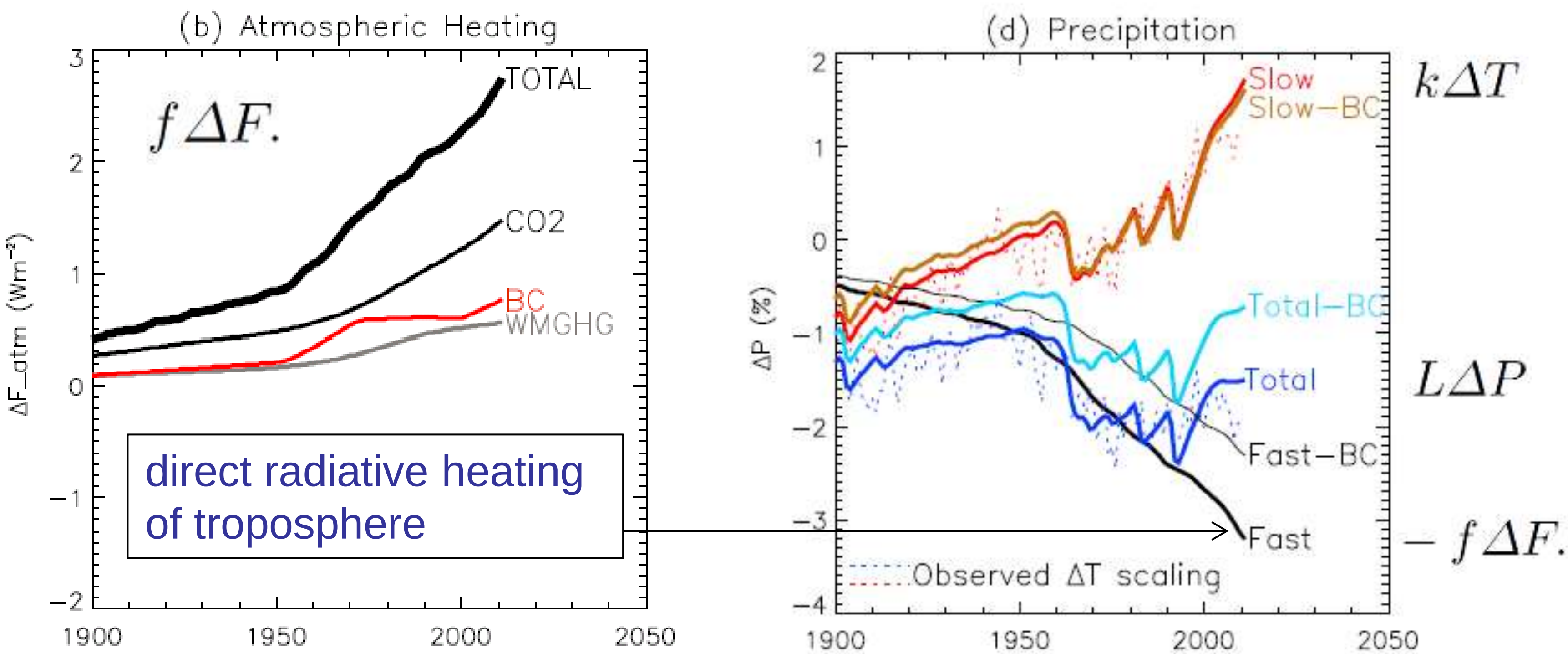
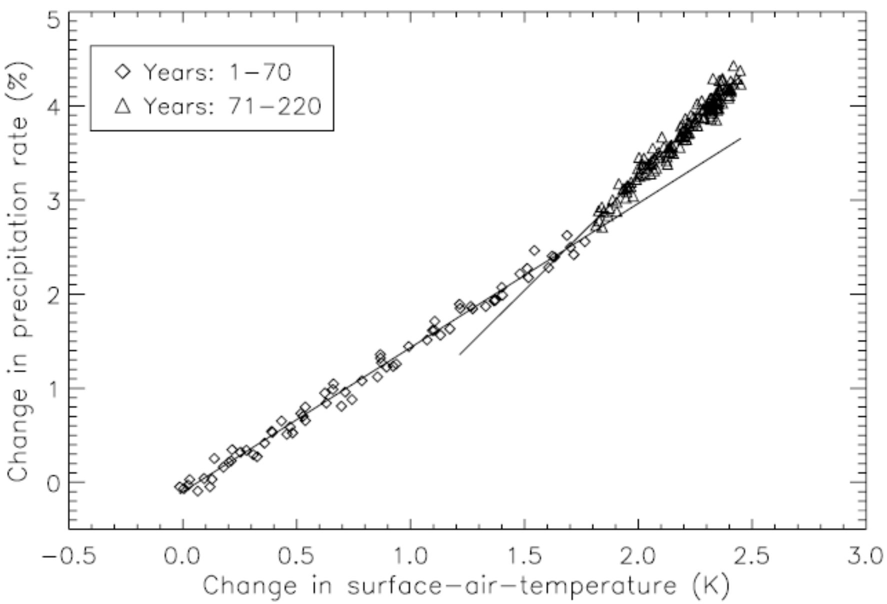
A simple model of precipitation change

$$L\Delta P \sim k\Delta T - f\Delta F.$$

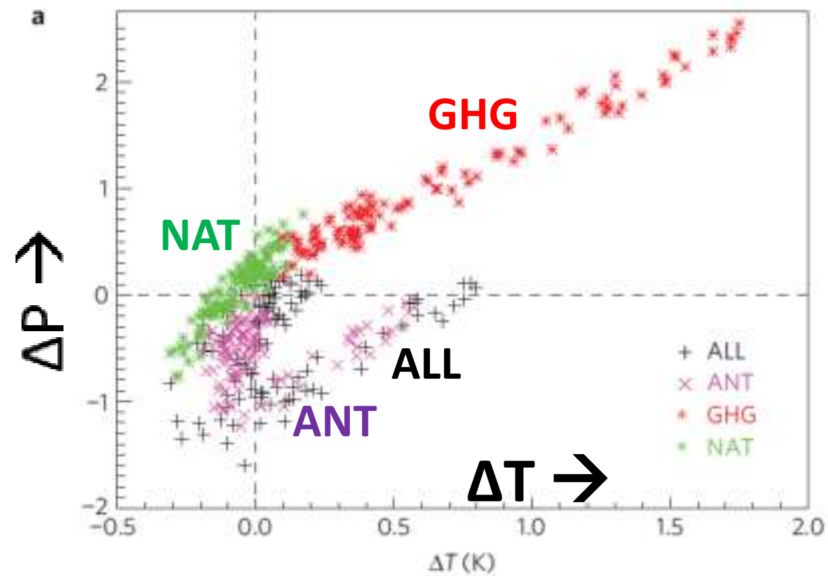


Allan et al. (2013) Surv. Geophys, using ***f*** calculated by Andrews et al. (2010) GRL ; see also Kvalevåg et al. (2010) GRL

Implications for transient responses



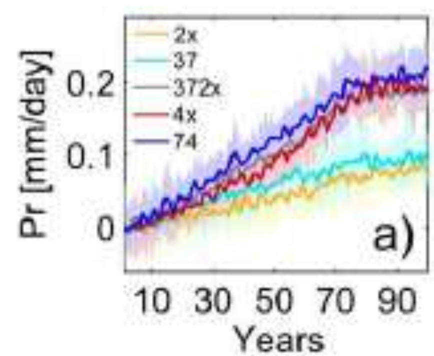
CMIP3 coupled model ensemble mean:
Andrews et al. (2010) Environ. Res. Lett.



Wu et al. (2013) Nature-Climate

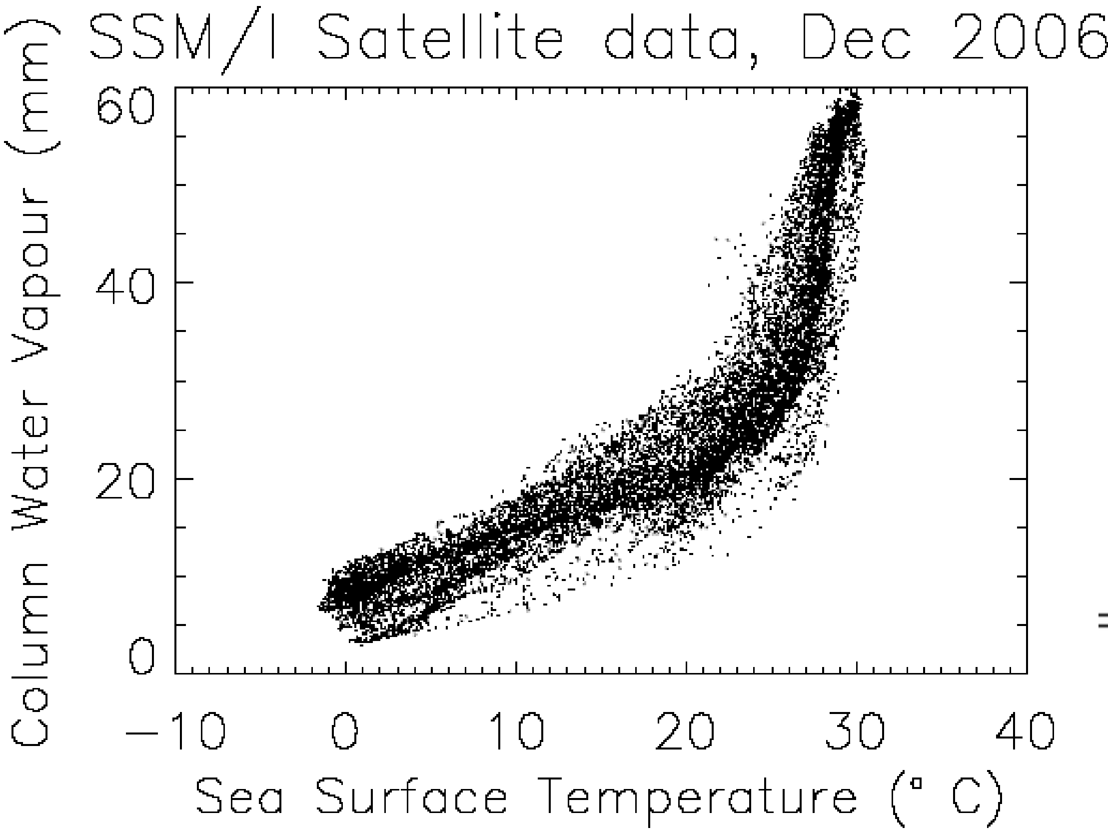
- **Above:** GHG-aerosol influence on precipitation
- **Left:** precipitation ramp-up on CO_2 ramp-down

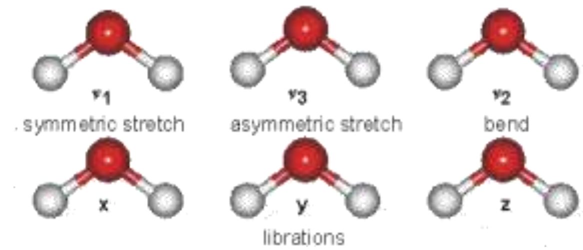
Degree of hysteresis determined by forcing related fast responses and linked to ocean heat uptake



Work also by: McInerney & Moyer ; Schaller et al. (2013) ESDD

The role of water vapour



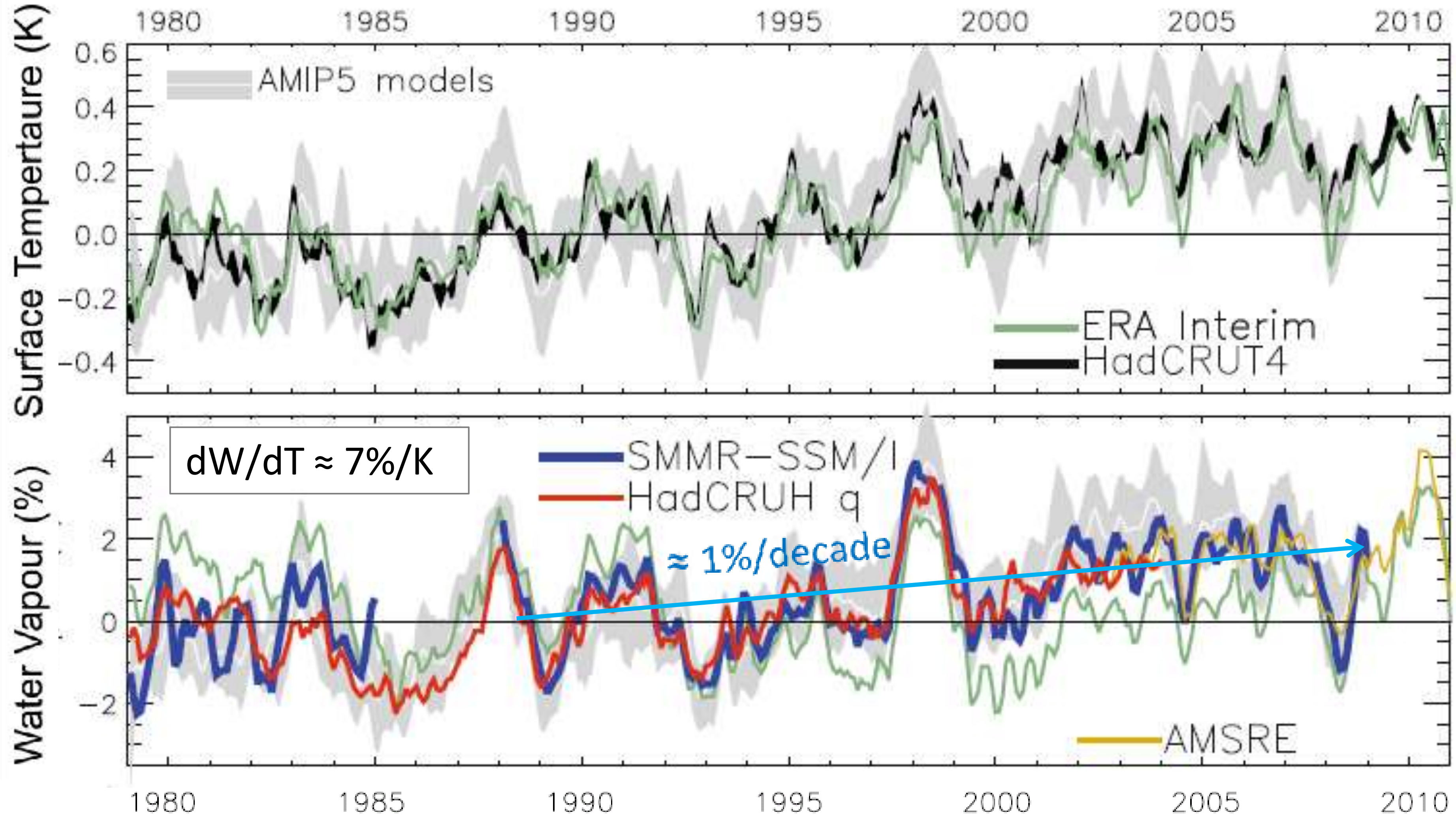


$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2}$$

$$= \begin{cases} 0.14K^{-1} & T = 200K \\ 0.07K^{-1} & T = 273K \\ 0.06K^{-1} & T = 300K \end{cases}$$

- Physics: Clausius-Clapeyron
- Low-level water vapour concentrations increase with atmospheric warming at about 6-7%/K
  - Wentz & Shabel (2000) *Nature*; Raval & Ramanathan (1989) *Nature*

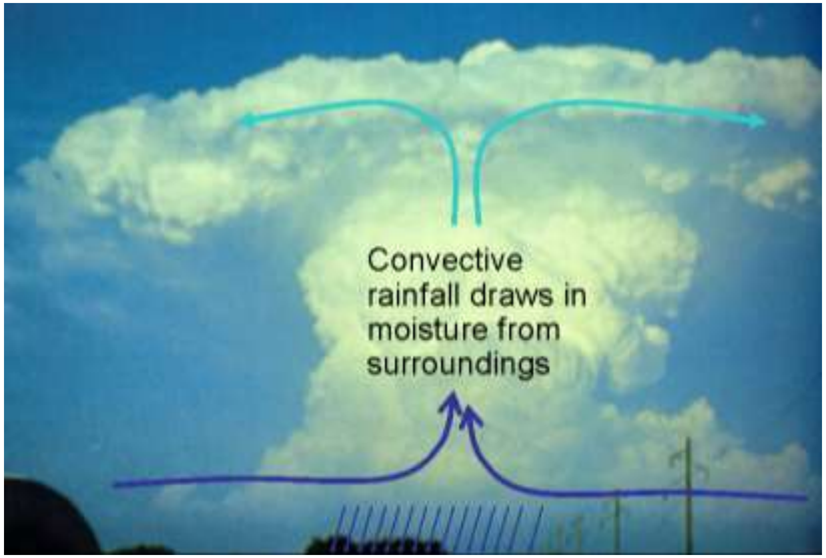
Global changes in water vapour



Allan et al. (2013) Surv. Geophys

Global mean estimates (use SMMR-SSM/I, AMSRE and ERA Interim over land and high latitudes)

Extreme Precipitation



- Moisture convergence fuels large-scale rainfall events

e.g. *Trenberth et al. (2003) BAMS*

- Intensification of rainfall with warming

e.g. Allan & Soden (2008) Science

- Amplifying latent heat feedbacks?

e.g. *Berg et al. (2013) Nature Geo*

- Time/space scale important
- Observational constraints? →

e.g. *O'Gorman (2012) Nature Geosci*; Liu & Allan (2012) JGR

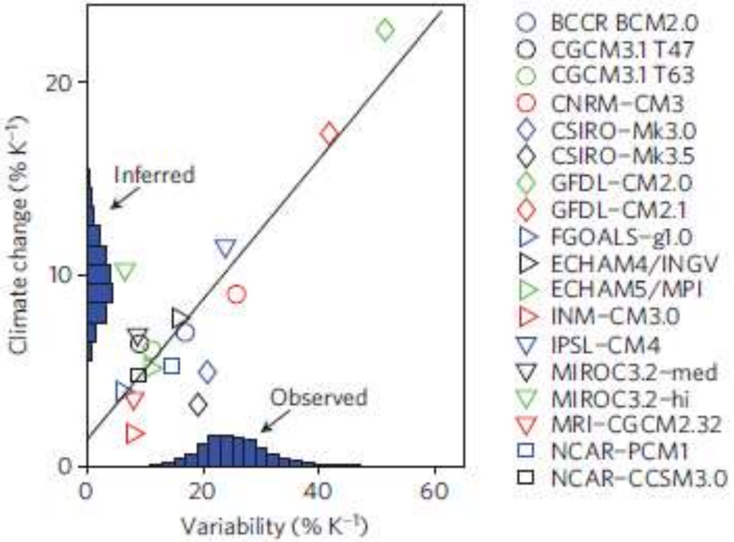
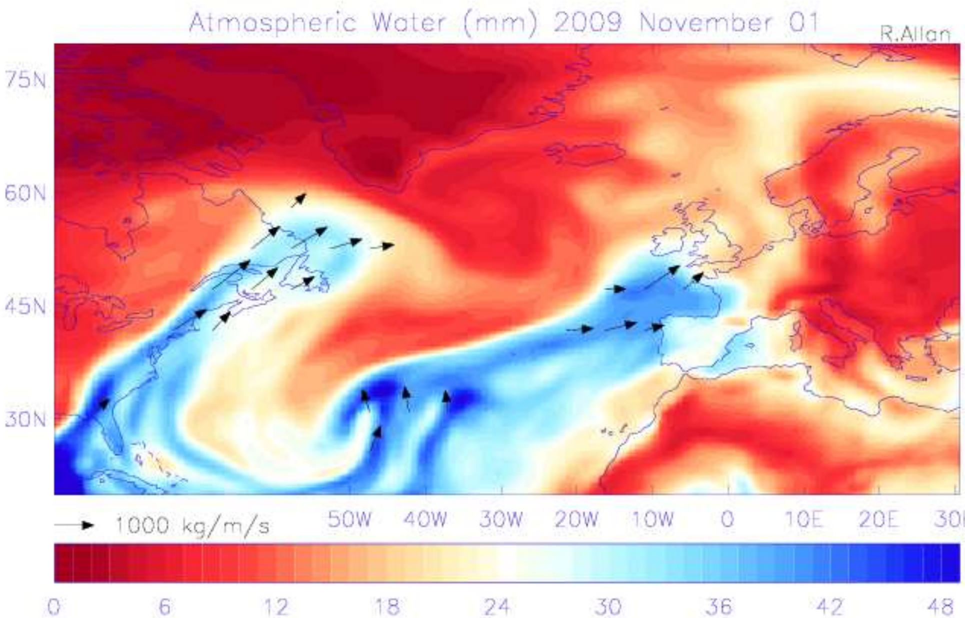
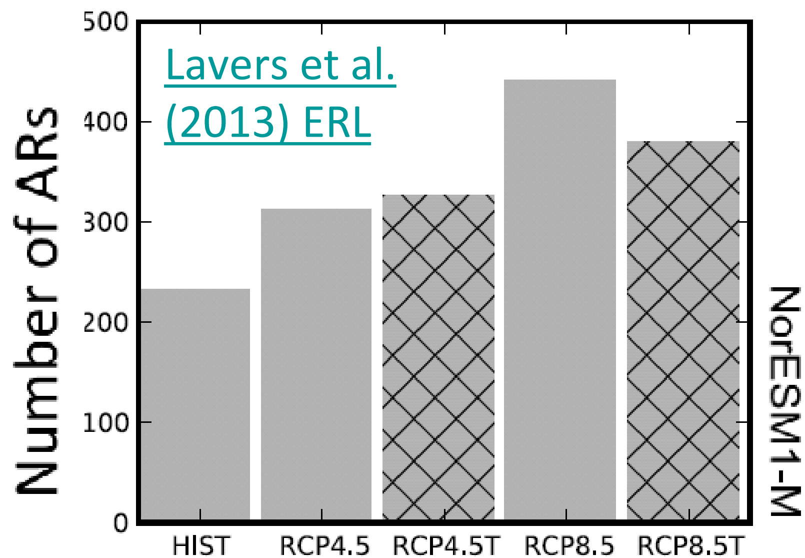


Figure 2 | Sensitivities (% K^{-1}) of the 99.9th percentile of precipitation for variability versus climate change in the CMIP3 simulations. The solid

Linking flooding impacts to atmospheric precursors

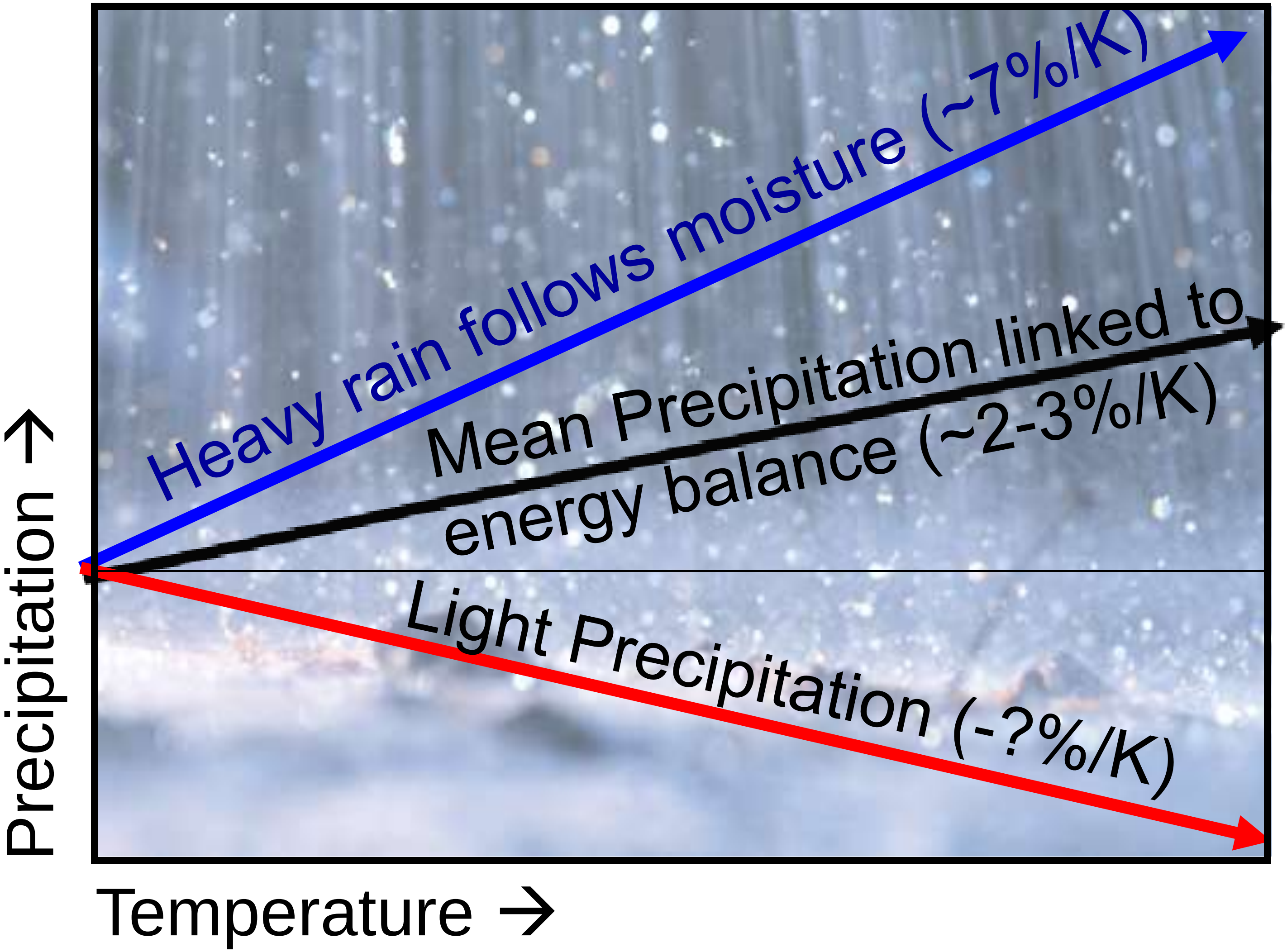


- UK winter flooding linked to strong moisture transport events
  - Cumbria November 2009 (Lavers et al. 2011 GRL)
  - "Atmospheric Rivers" (ARs) in warm conveyor



- Future increase in moisture explains most (but not all) of intensification of AR events
  - Confident in the mechanisms and physics involved

Contrasting precipitation response expected



e.g. Allen and Ingram (2002) *Nature* ; Held & Soden (2006) *J Climate*

Moisture Balance

$$\frac{\delta F}{F} \approx \frac{\delta e_s}{e_s} \approx \alpha \delta T. \quad \alpha \approx 0.07\ \mathrm{K}^{-1}$$

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

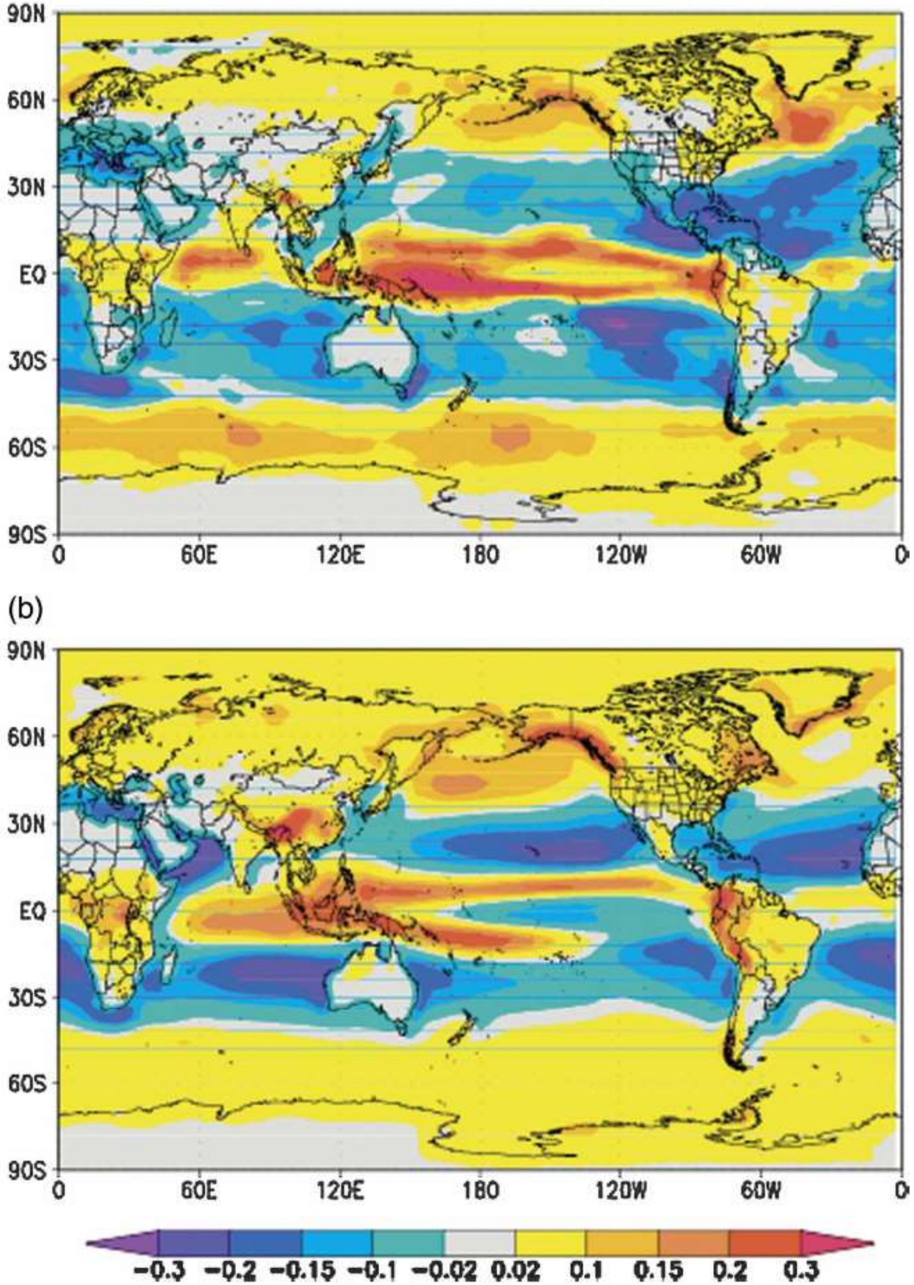


FIG. 7. The annual-mean distribution of $\delta(P - E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

Enhanced moisture transport *F* leads to amplification of

(1) P–E patterns (left)

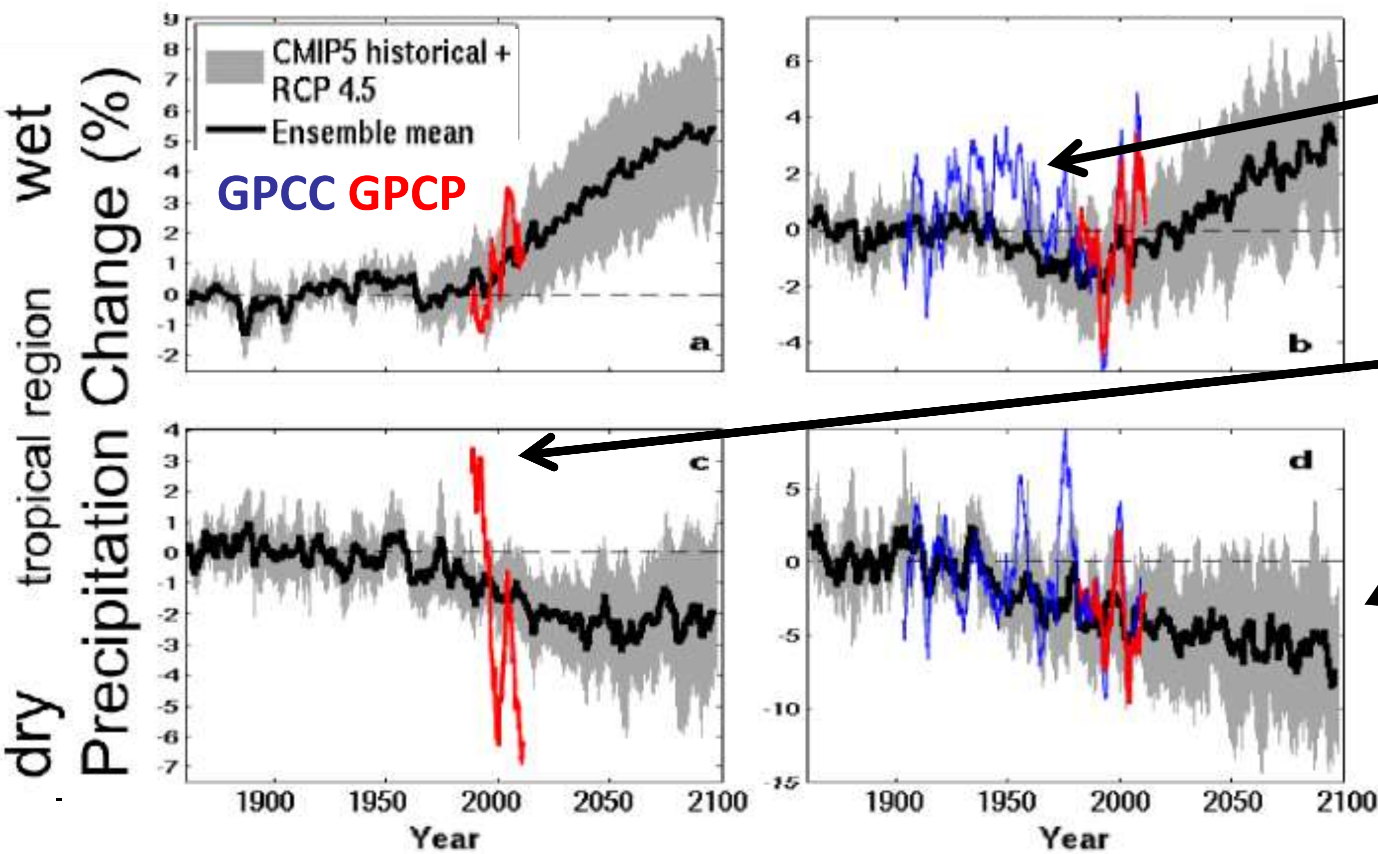
Held & Soden (2006) *J Climate*

(2) ocean salinity patterns

Durack et al. (2012) *Science*

See also Mitchell et al. (1987) *QJRMS*

CMIP5 simulations: Wettest tropical grid-points get wetter, driest drier



Wet land: strong ENSO influence

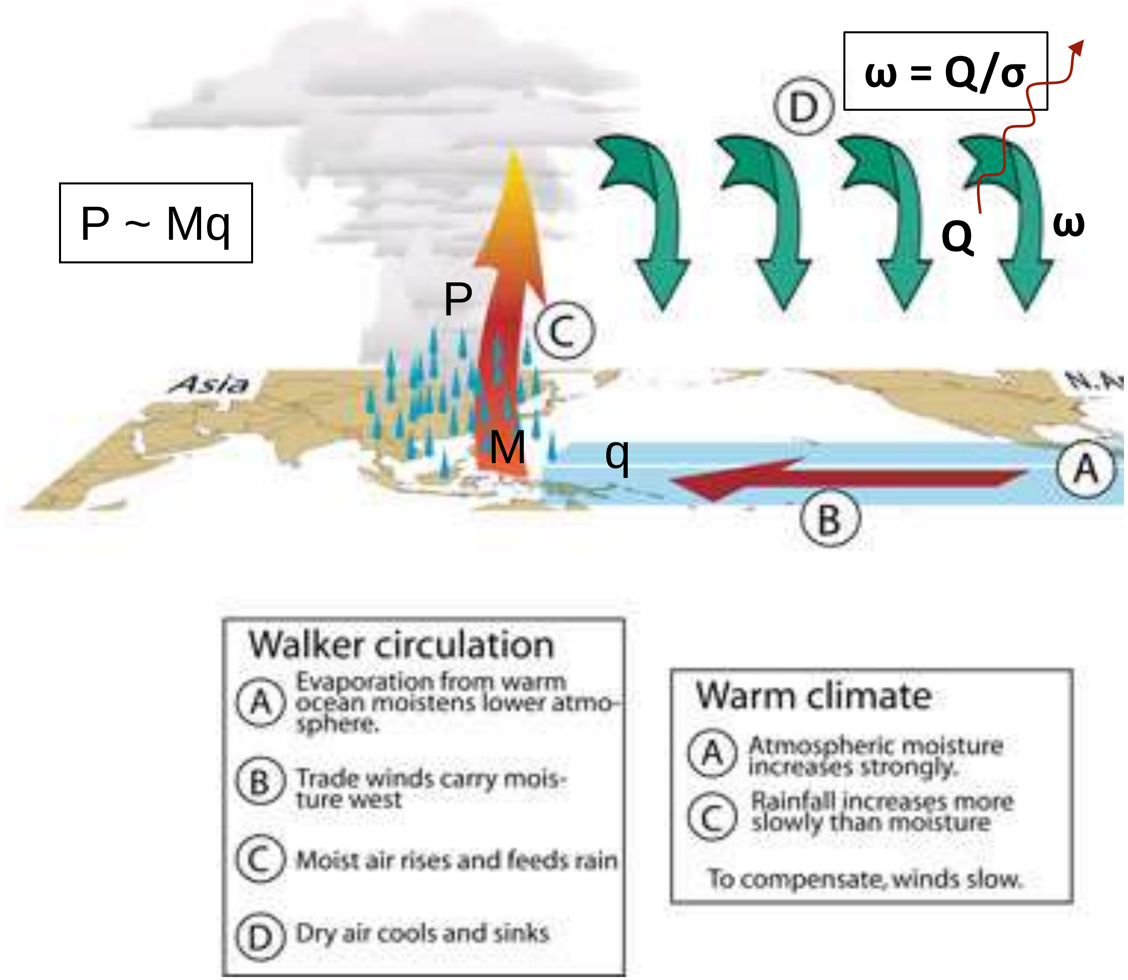
Pre 1988 GPCP observations over ocean don't use microwave data

Robust drying of dry tropical land

30% wettest gridpoints vs 70% driest each month

Liu and Allan (2013) ERL; *see also:* *Chou et al. (2013) Nature Geosci*; *Chadwick et al. (2013) J Clim* ; *Allan (2012) Clim. Dyn.*

Circulation response



Schematic from Gabriel Vecchi

First argument:

$$P \sim Mq$$

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

Bony et al. (2013) Nat Geosci

Chadwick et al. (2012) J Clim

Second argument:

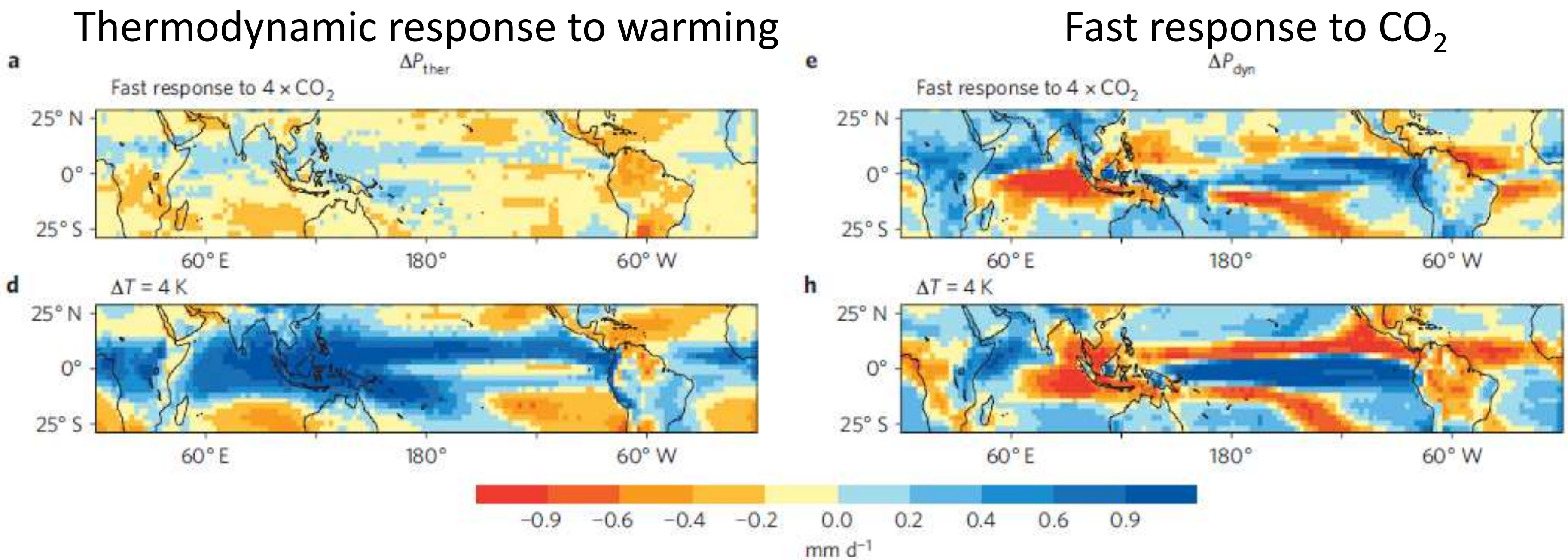
$$\omega = Q/\sigma$$

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

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

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

Walker circulation response to fast and slow precipitation effects

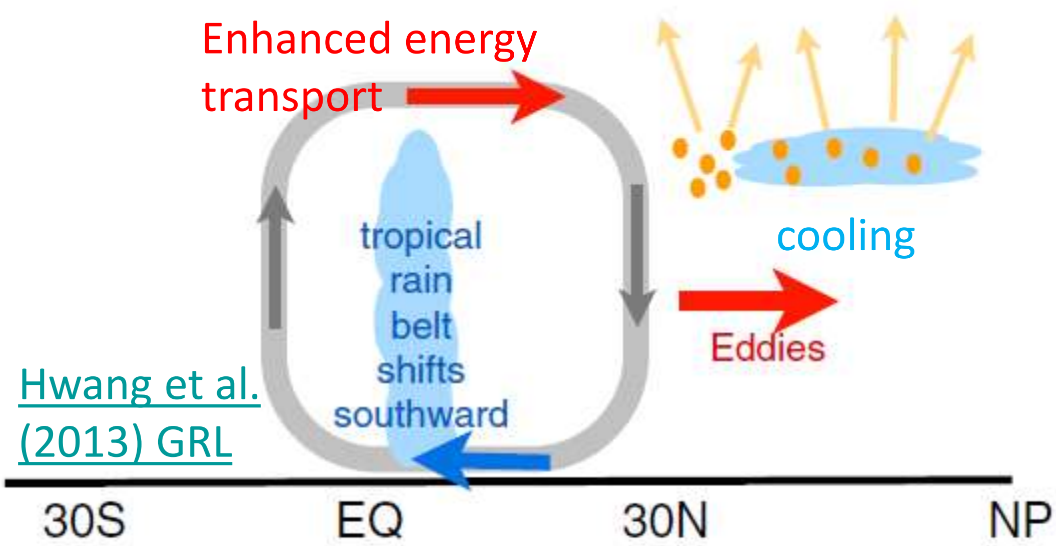


Bony et al. (2013) *Nature Geosciences* Both fast and slow responses to CO_2 forcings induce reduced Walker circulation in response to P = Mq constraint

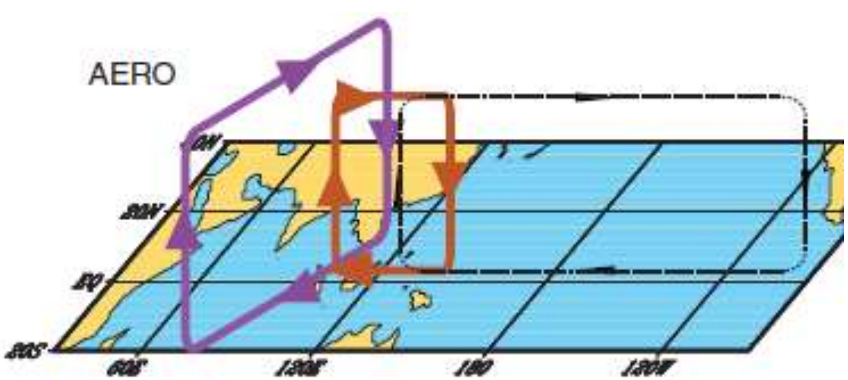
Reduced Walker circulation: Vecchi et al. (2006) *Nature* Recent strengthening of circulation? Merrifield (2011) *J Clim*; Sohn et al. (2011) *Clim Dyn*; L'Heureux et al. (2013) *Nature Climate*

Aerosol & regional circulation response

- N Hemisphere Aerosol cooling 1950-1980s
- Induces southward movement of ITCZ
- Reduced Sahel rainfall →
- Recovery after 1980s e.g. Wild 2012 BAMS
- +Asymmetric volcanic forcing e.g. Haywood et al. (2013) Nature Climate

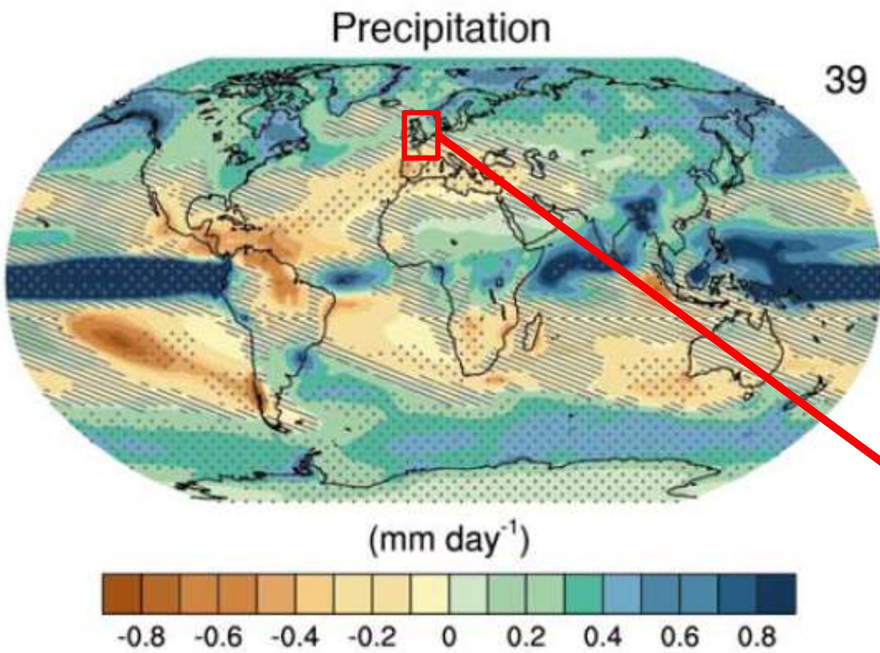


Hwang et al. (2013) GRL

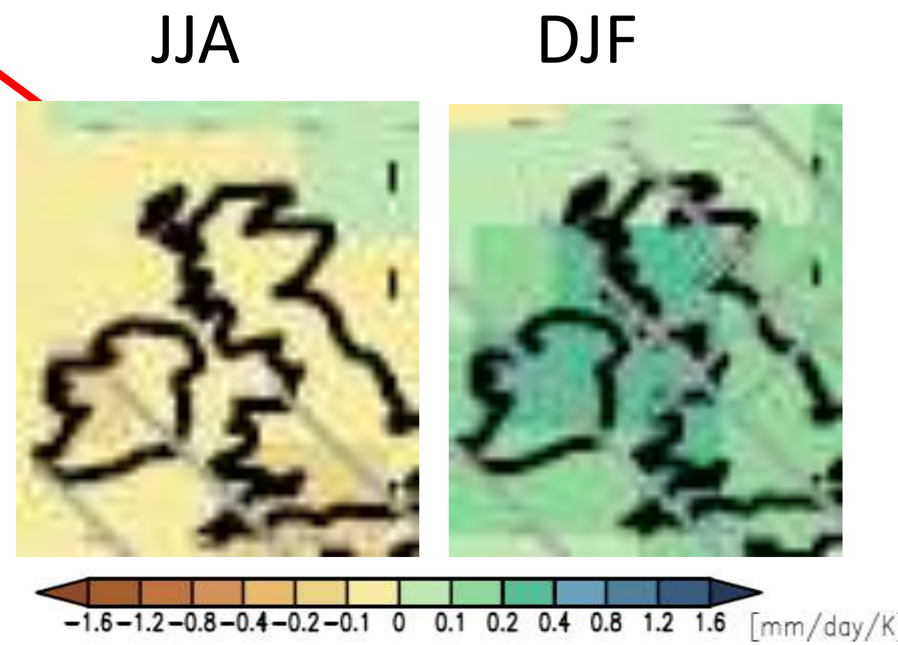


- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science
- Links to Horn of Africa drought ? Williams et al. (2011) Clim Dyn

Challenge: Regional projections



Shifts in circulation systems are crucial to regional changes in water resources and risk yet predictability is often poor (but see [Power et al. (2012) J Clim](#))

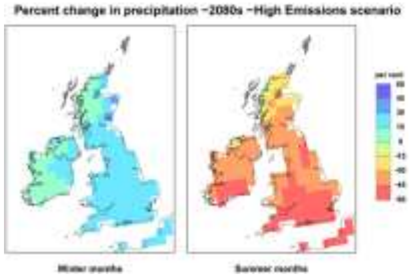


How will jet stream positions and monsoons respond to warming? e.g. [Levermann et al. (2009) PNAS](#)

How will primary land-surface and ocean-atmosphere feedbacks affect the local response to global warming?

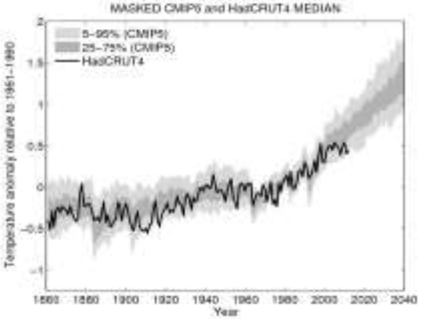
Outstanding Issues

- Observing systems can't monitor changes in precipitation & radiation adequately
- Are regional responses predictable?



- Will extreme precipitation outpace Clausius Clapeyron constraint?

- What are changes in radiative forcings and their associated fast adjustments?
- Implications for climate geoengineering
- What is the effect of the global surface temperature hiatus on the water cycle?



Conclusions

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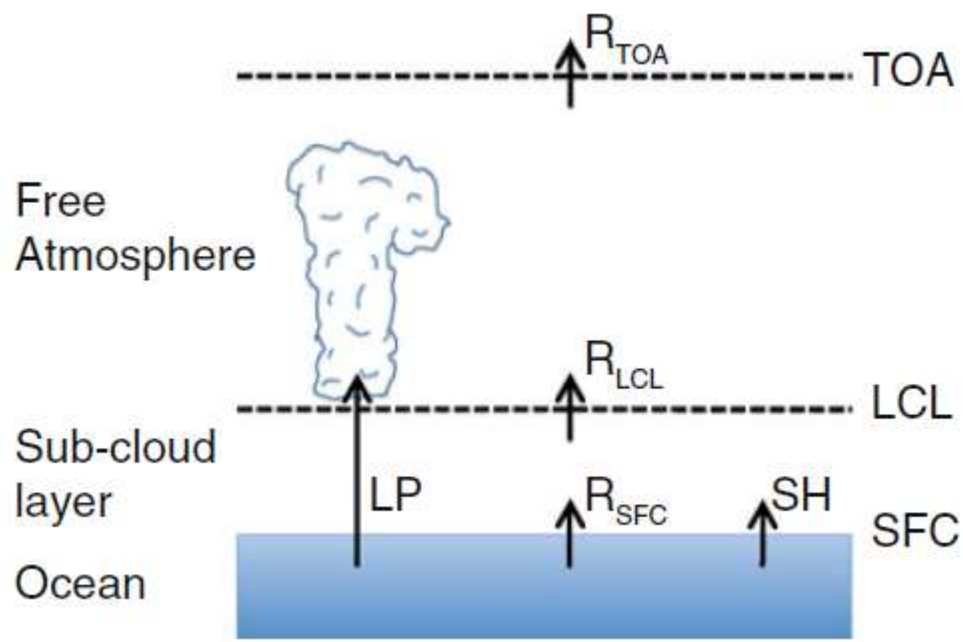
- Radiative energy balance is fundamental to climate response

Energy and moisture balance powerful constraints on global water cycle

- Global precipitation rises with surface warming (~2-3%/K)
- Direct effects of radiative forcing from greenhouse gases/ absorbing aerosol cause rapid adjustments in E and P (+cloud)
- Current & future increases in wet and dry extremes
  - Linked to rises in low-level moisture of about 7%/K
  - Combined energy and moisture balance constraints via circulation
- **Aerosol radiative forcing** appears key in determining global and circulation-driven precipitation responses
- How SST patterns and the land surface respond to rising CO_2 is crucial for improving regional predictions

Radiative energy budget of the atmosphere and hydrological response

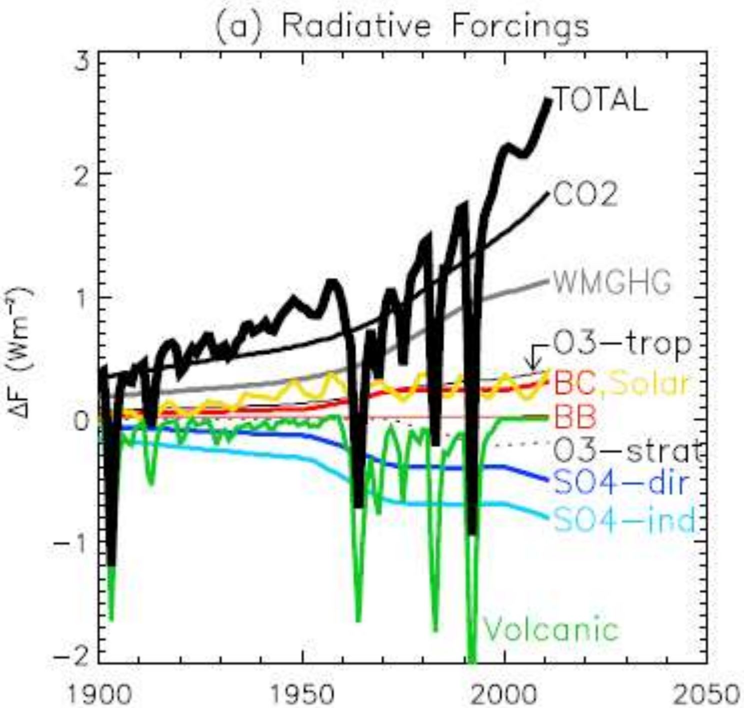
- Adjustments in latent heating LP (precipitation) for change in radiative energy budget ΔR above LCL (lifting condensation level)
- ΔR below LCL → adjustments in SH (sensible heat flux) important



O'Gorman et al. (2012) Surv. Geophys; after Takahashi (2009) JAS.
See also Manabe & Wetherald (1975) JAS

Simple model of precipitation change

Thanks to Keith Shine and Evgenios Koukouvagias



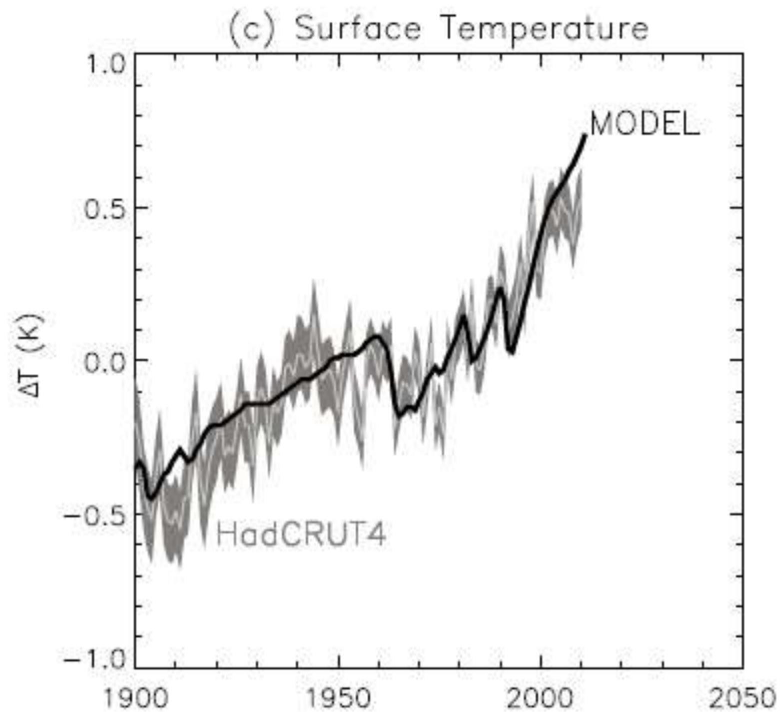
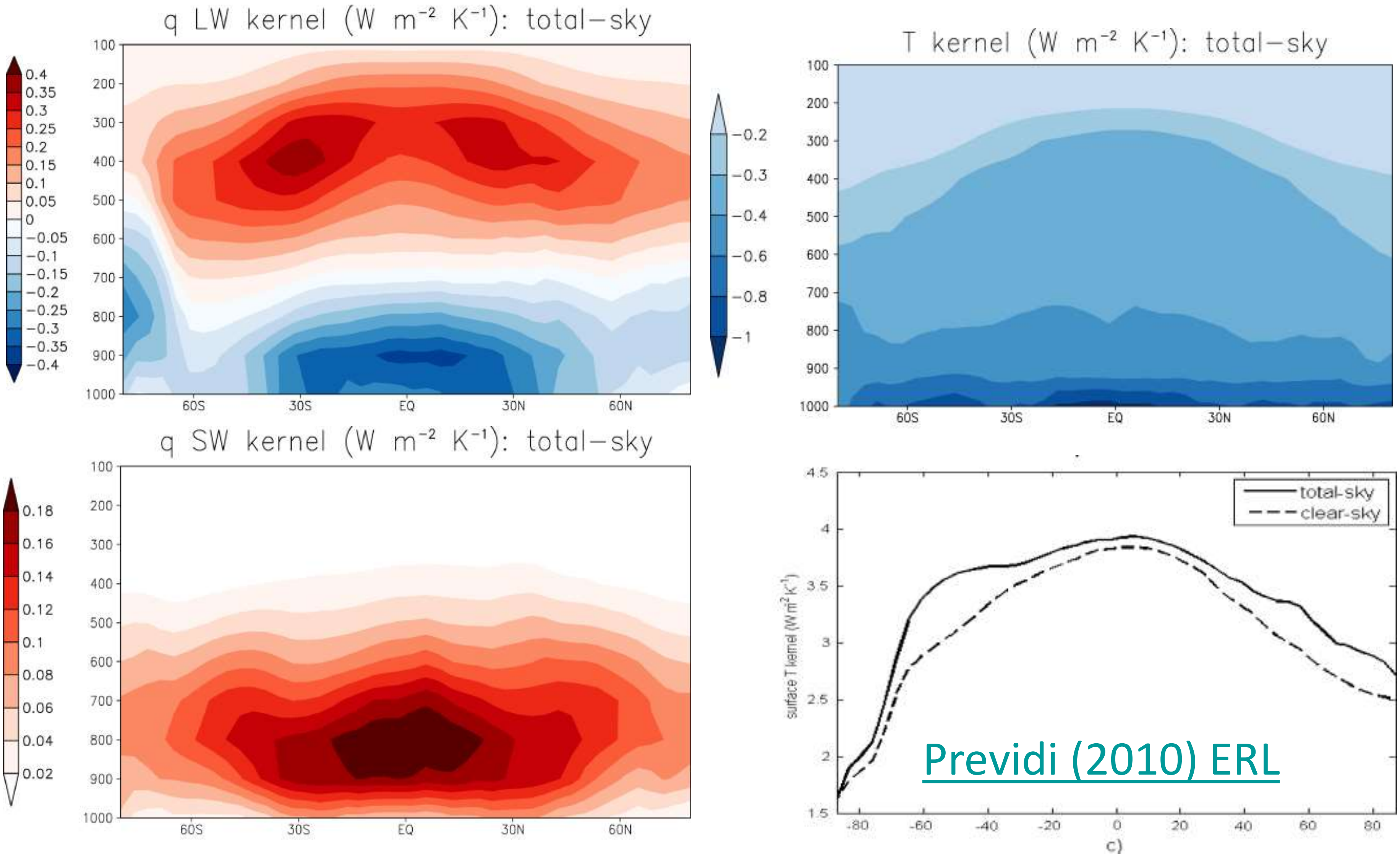


Table 1 Prescribed values of atmospheric forcing scaling parameter $f = \Delta F_{atm}/\Delta F$

Forcing	CO_2	Other WMGHG	O_3 trop.	O_3 strat.	SO_4 (all)	BB	BC	Solar
f	0.8	0.5	−0.3	0.0	0.0	−0.9	2.5	0.2

Well-Mixed Greenhouse Gases (WMGHG) includes CH_4, N_2O and CFCs; SO_4 includes all sulfate aerosol forcings (direct, indirect and volcanic). *BB* biomass burning aerosol, *BC* black carbon aerosol

Altitude dependence of response (kernels)



See also O’Gorman et al. (2012) Surv. Geophys

Quantifying Hydrological Feedbacks

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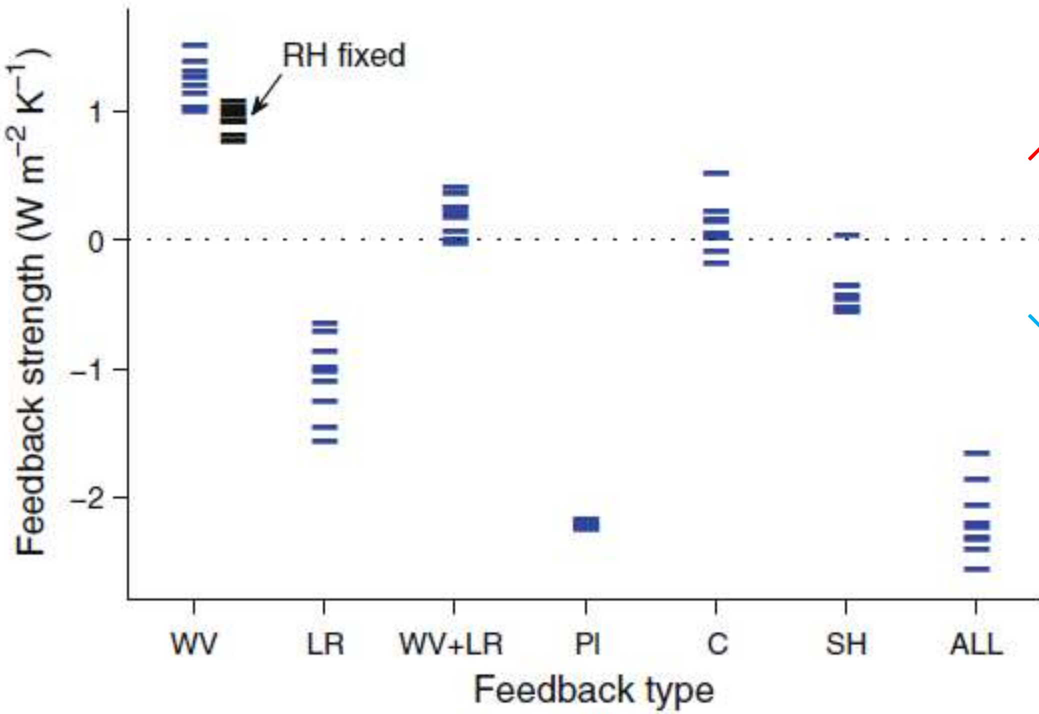

↑ Radiative heating

↓ Radiative cooling

~ –2 $Wm^{-2}K^{-1}$

Fig. 4 Feedbacks (*blue dashes*) on the atmospheric energy budget in coupled simulations with nine climate models. *Positive values* indicate a gain in energy for the atmospheric column and a negative feedback on precipitation. Feedbacks shown are water vapor (WV), lapse rate (LR), the sum of water vapor and lapse rate (WV + LR), Planck (Pl), cloud (C), surface sensible heat flux (SH), and the sum ALL = WV + LR + Pl + C + SH. Albedo feedback is negligible and is not shown. *Black dashes* show the water vapor feedback for invariant relative humidity (RH)

O'Gorman et al. (2012) Surv. Geophys; see also Previdi (2010) ERL