

Radiative constraints on current and future changes in the global water cycle

Richard P. Allan r.p.allan@reading.ac.uk @rpallanuk

Department of Meteorology, University of Reading, UK

Thanks to: Chunlei Liu, Matthias Zahn, Norman Loeb, Brian Soden, Viju John



Young(er) scientists!



Troublemakers

Gordon Research Conferences

Connecticut College

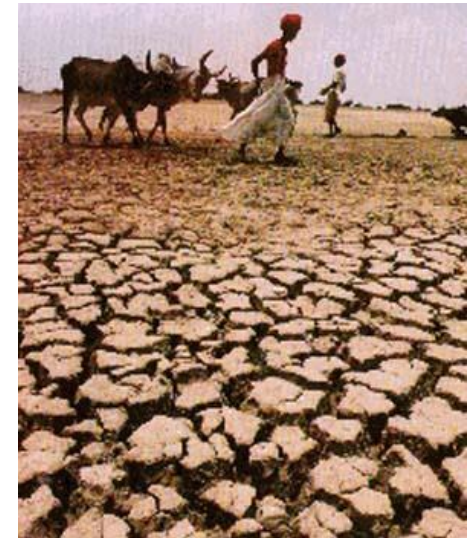
Solar Radiation and Climate

Co-Chairs: Bruce Wielicki & ~~Thomas Ackerman~~ V. Ramaswamy

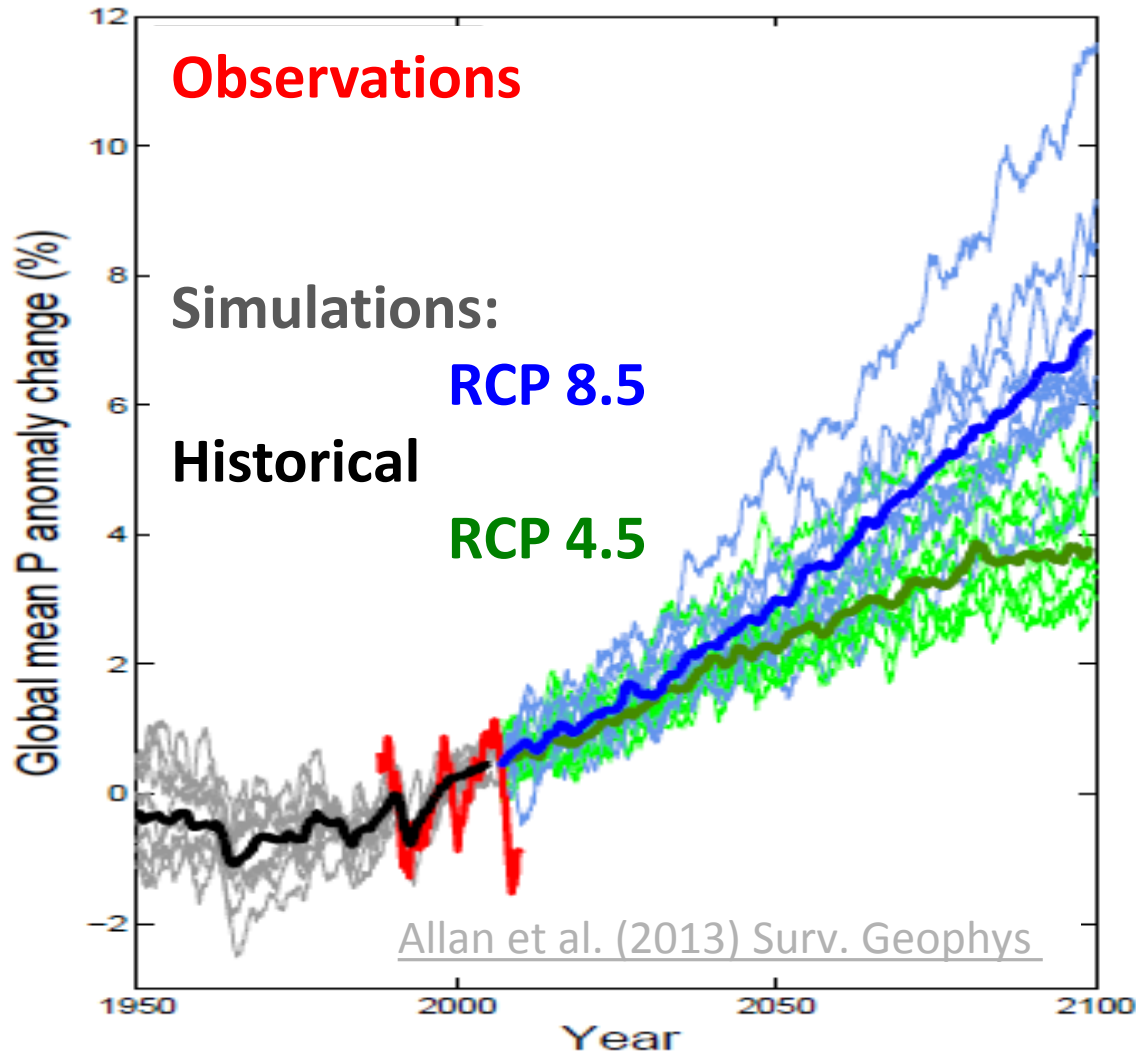
June 24-29, 2000

Introduction

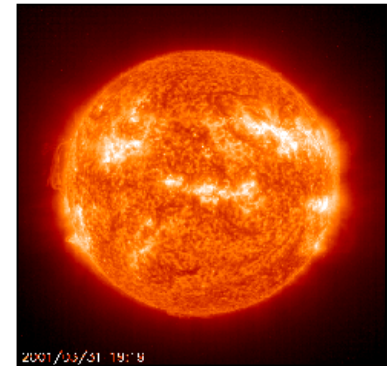
***“Observational records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems.”
IPCC (2008) Climate Change and Water***



How will global precipitation respond to climate change?

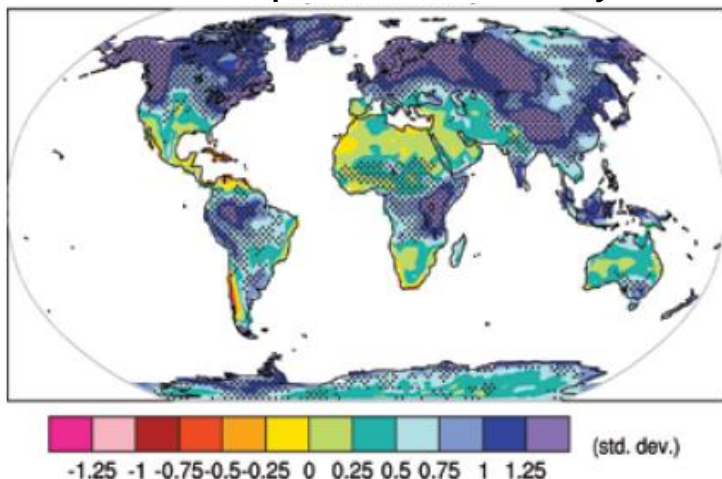


See also [Hawkins & Sutton \(2010\) Clim. Dyn](#)

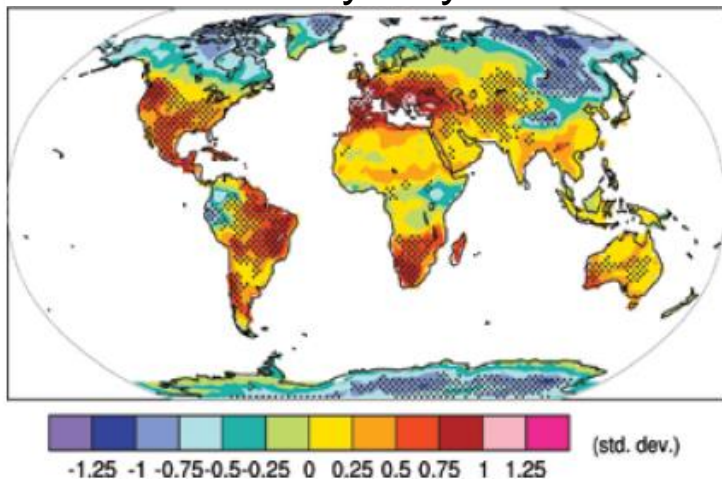


Climate model projections

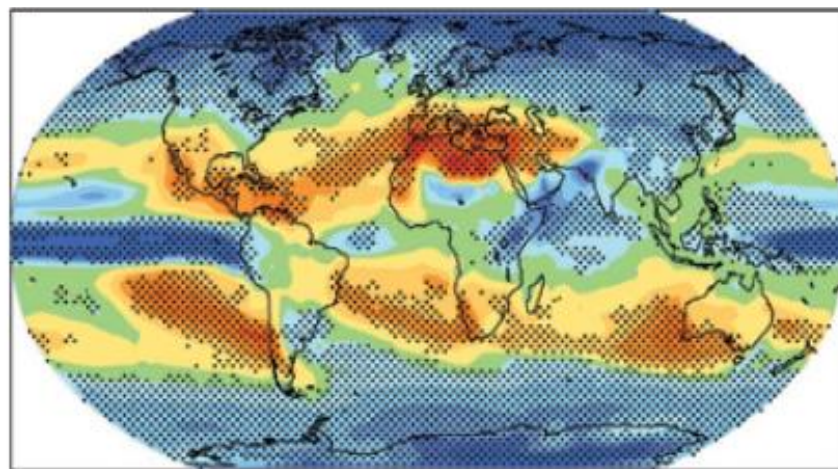
Precipitation Intensity



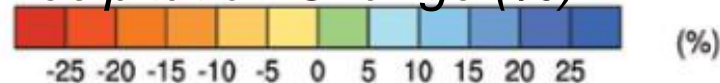
Dry Days



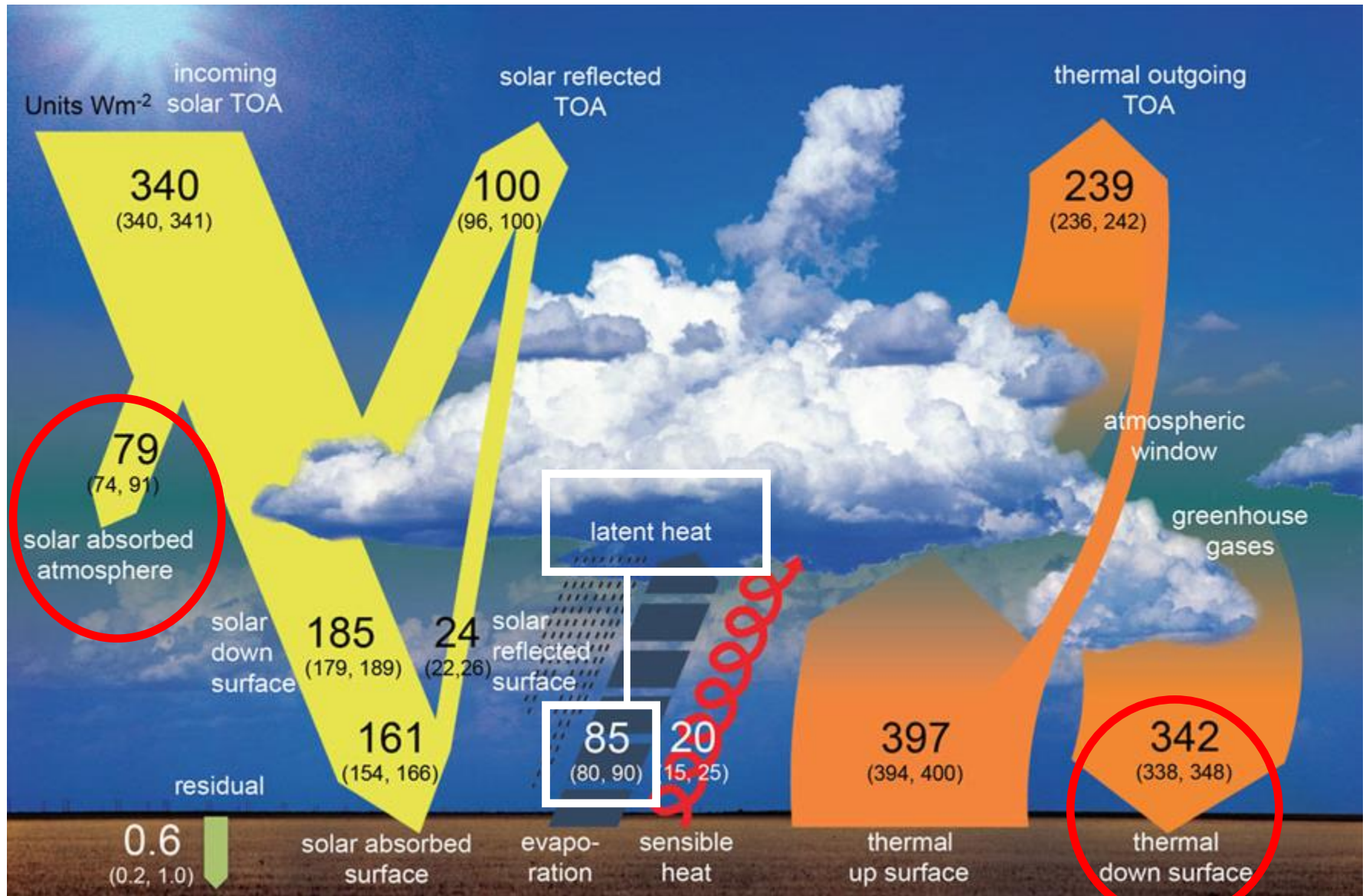
- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??



Precipitation Change (%)



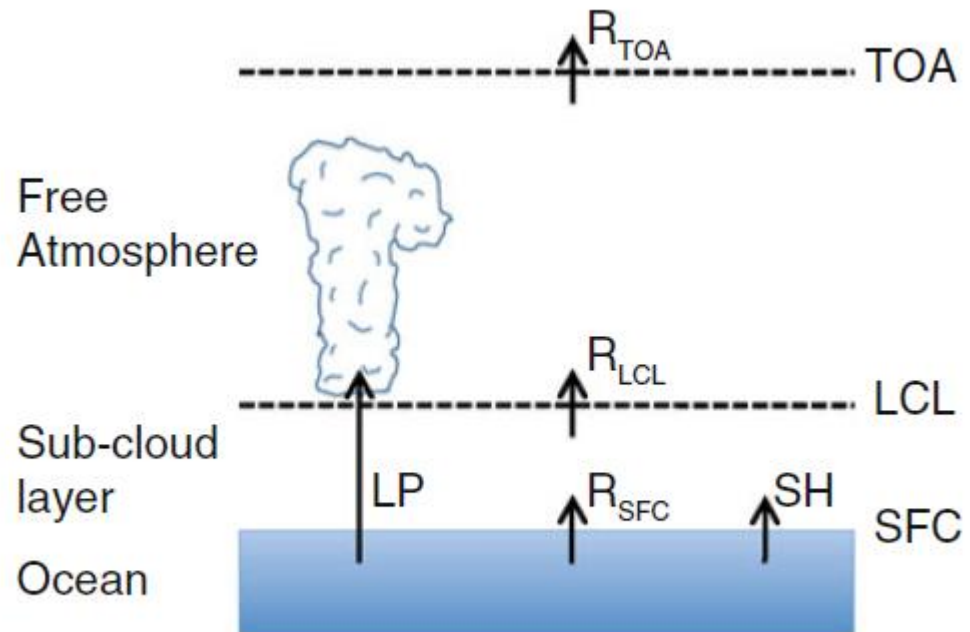
Earth's Energy Budget & the Global Water Cycle



[Wild et al. \(2012\) Clim. Dynamics](#) (see talk Tuesday!). Also: [Trenberth et al. \(2009\) BAMS](#)

Radiative energy budget of the atmosphere and hydrological response

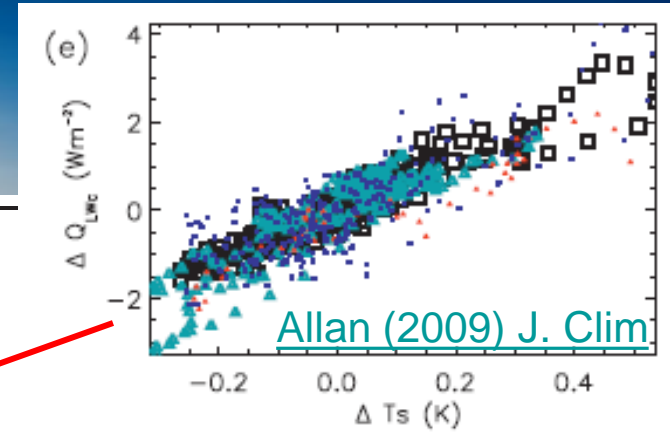
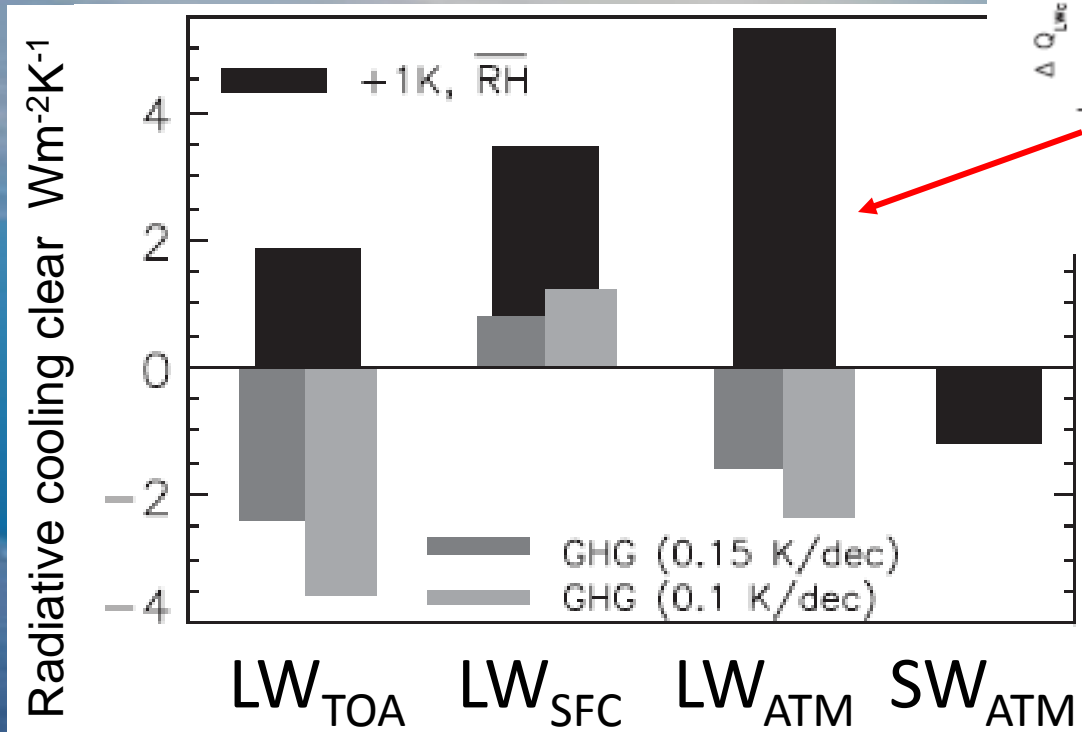
- Adjustments in latent heating LP (precipitation) for change in radiative energy budget ΔR above LCL (lifting condensation level)
- ΔR below LCL \rightarrow adjustments in SH (sensible heat flux) important



[O’Gorman et al. \(2012\) Surv. Geophys;](#)
after [Takahashi \(2009\) JAS.](#)

See also [Manabe & Wetherald \(1975\) JAS](#)

Models simulate robust **clear-sky radiation** response to warming ($\sim 2\text{-}3 \text{ Wm}^{-2}\text{K}^{-1}$) and resulting increase in latent heating (precipitation) to balance ($\sim 2 \text{ \%K}^{-1}$) e.g. Lambert & Webb (2008) [GRL](#); Stephens & Ellis (2008) [J. Clim](#);

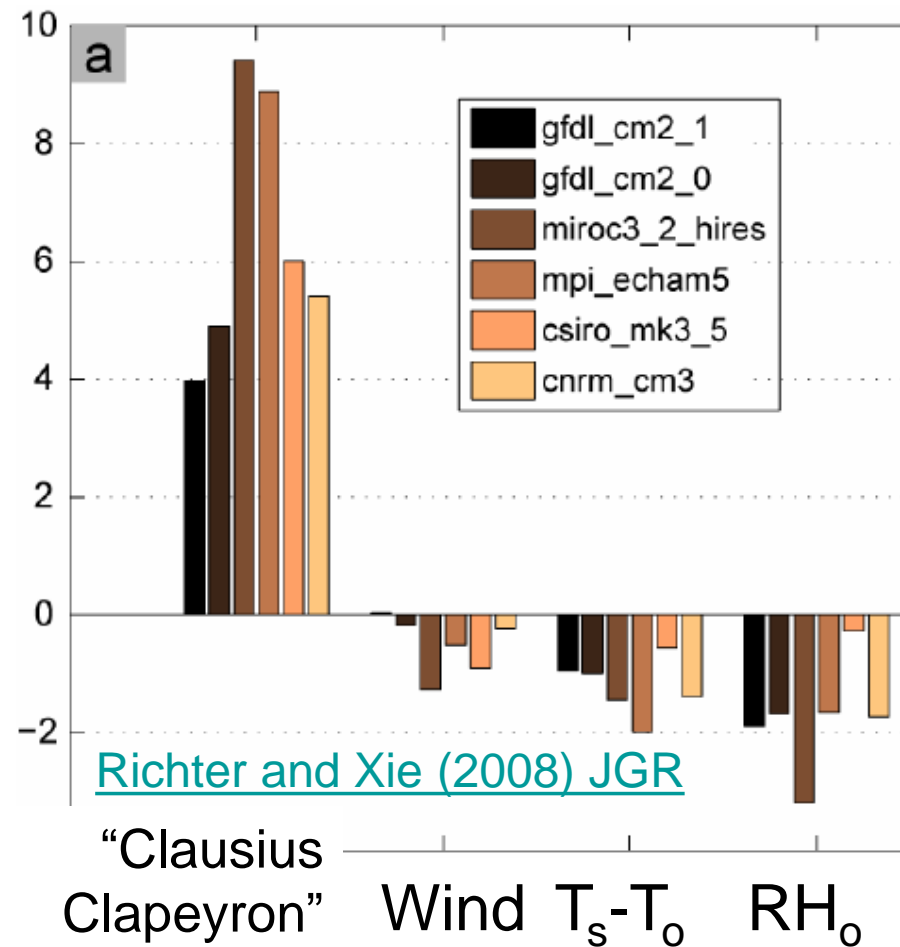


$$\frac{dP}{dT_s} \sim \frac{1}{\rho_w L} \frac{dQ}{dT_s}$$

Also: [Previdi \(2010\) ERL](#)
[Huang et al. \(2013\) J Clim](#)

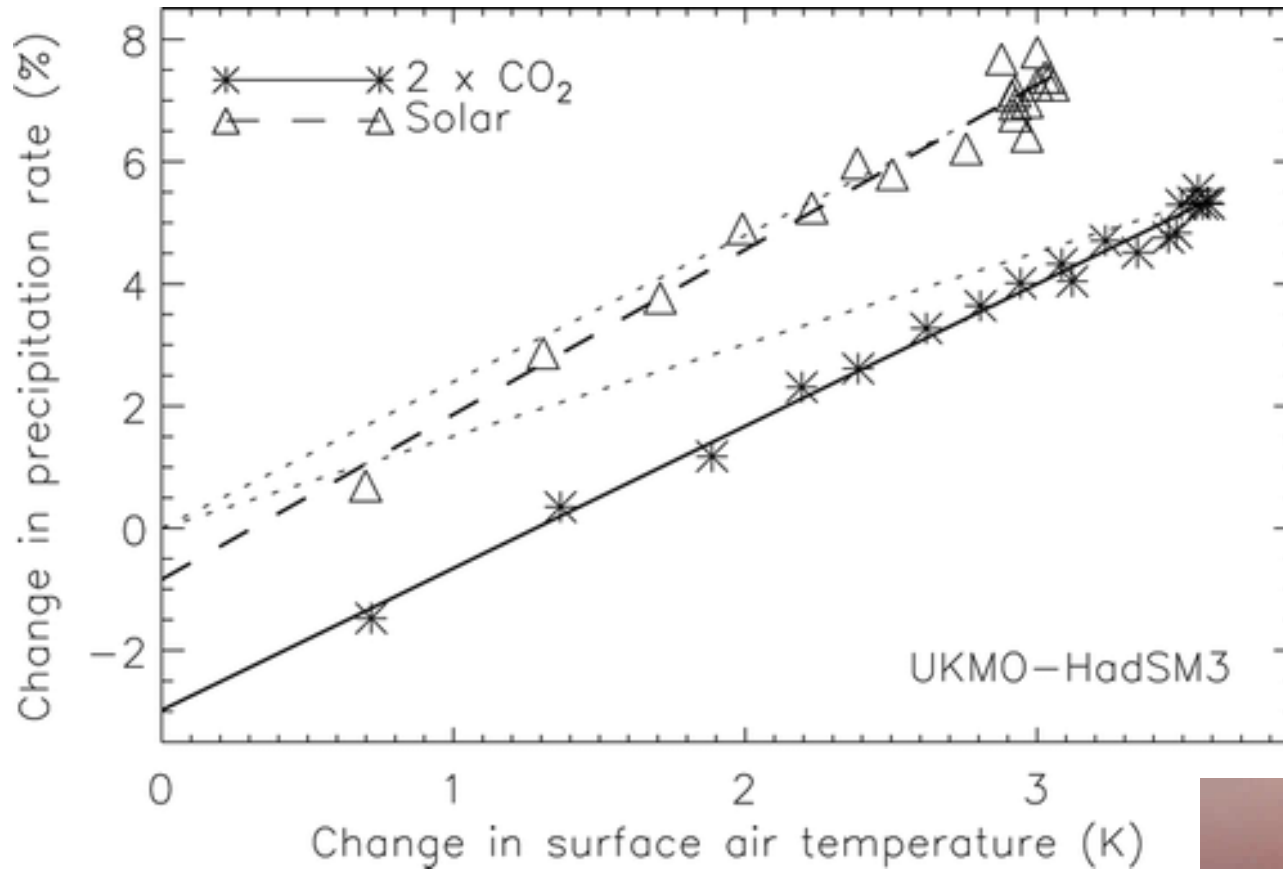
Evaporation

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

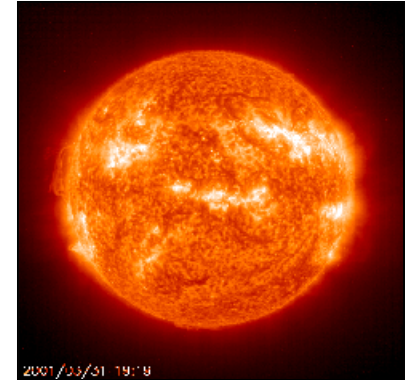


- “Muted” Evaporation changes in models are explained by small adjustments in Boundary Layer:
- 1) declining wind stress
 - 2) reduced surface temperature lapse rate ($T_s - T_o$)
 - 3) increased surface relative humidity (RH_o)

Direct influence of radiative forcing and climate response on precipitation changes

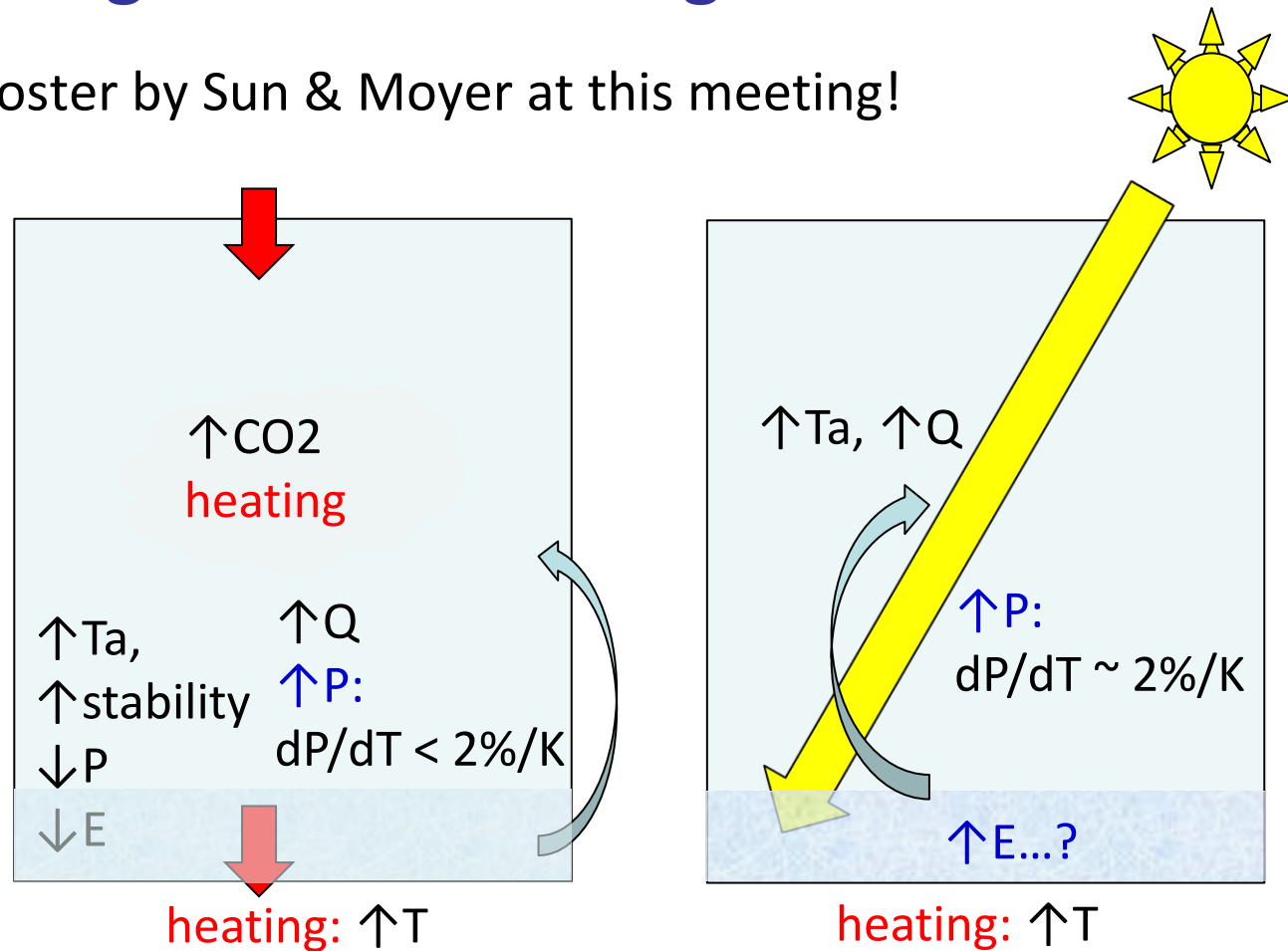


[Andrews et al. \(2009\) J Climate](#)



Fast precipitation adjustments to contrasting radiative forcing

See also poster by Sun & Moyer at this meeting!



See [Cao et al. 2012 ERL](#) for more details:

Contrasting land/ocean responses (heat capacity)

Energetic constraint upon global precipitation

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

(i) $k \sim 2 \text{ Wm}^{-2}\text{K}^{-1}$ depends on spatial pattern of warming

(ii) f dependent upon nature of radiative forcing ΔF

Precipitation change ΔP determined by:

- (i) “slow” response to warming ΔT (enhanced radiative cooling of warmer troposphere)
- (ii) “fast” direct influence of radiative forcing on surface/tropospheric energy budget (rapid adjustment)

See [Allen and Ingram \(2002\) *Nature*](#) for detailed discussion

Simple model of precipitation change

Thanks to Keith Shine and Evgenios Koukouvagias

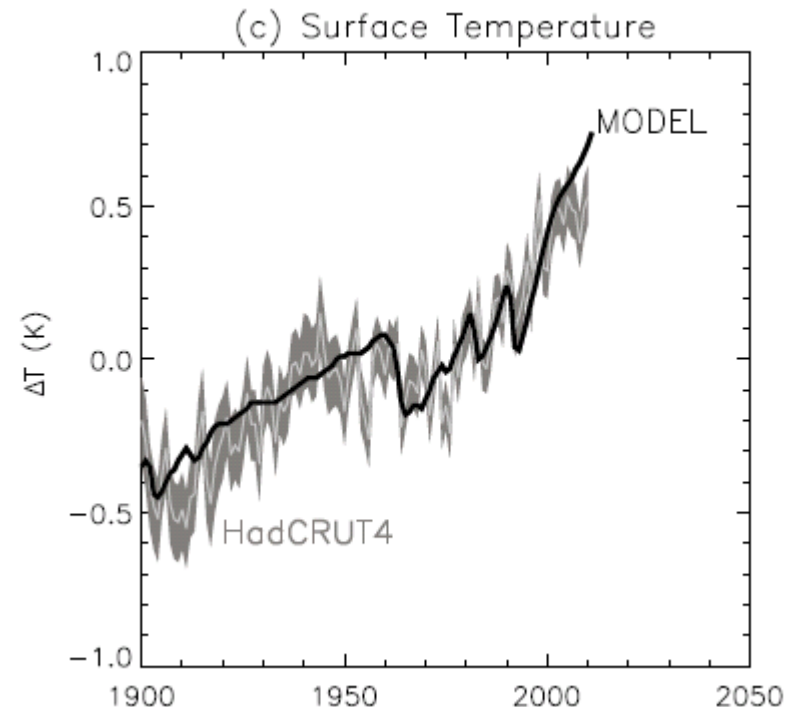
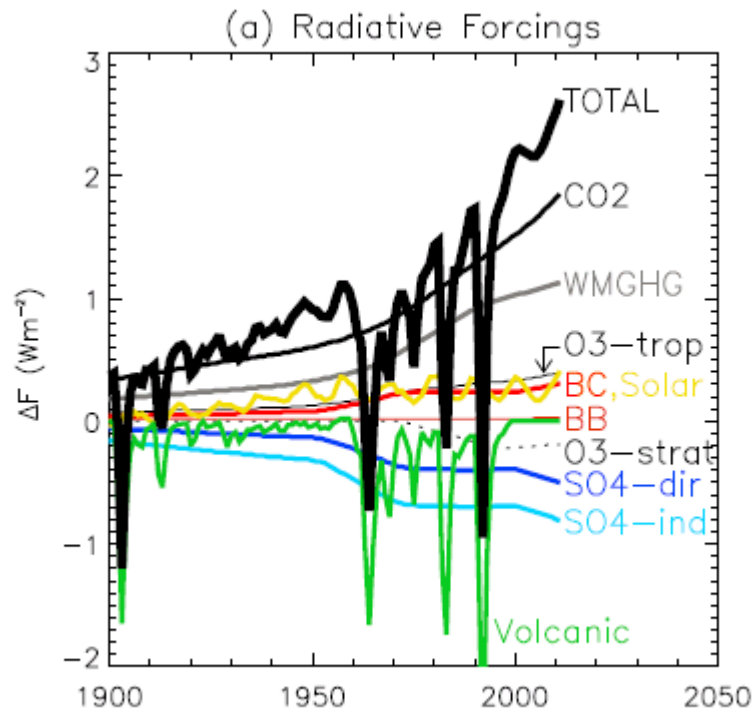


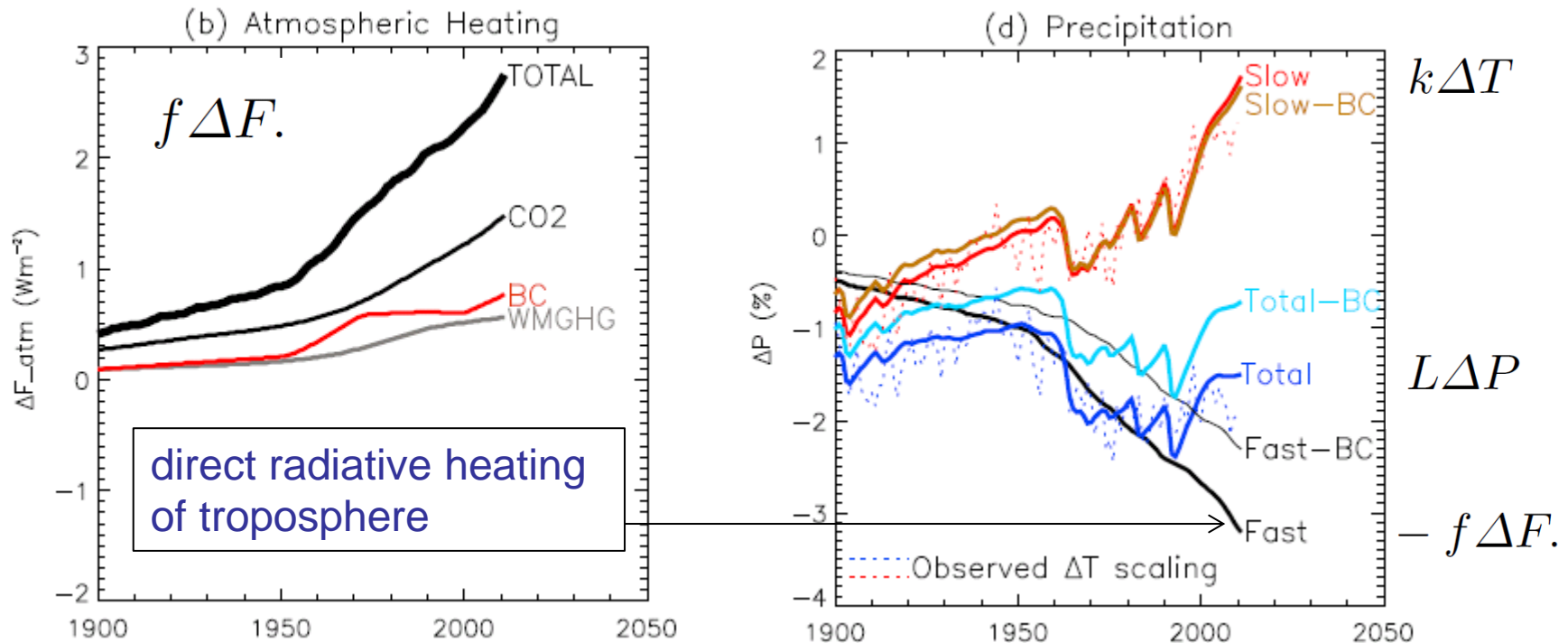
Table 1 Prescribed values of atmospheric forcing scaling parameter $f = \Delta F_{\text{atm}}/\Delta F$

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 CH₄, N₂O and CFCs; SO₄ includes all sulfate aerosol forcings (direct, indirect and volcanic). *BB* biomass burning aerosol, *BC* black carbon aerosol

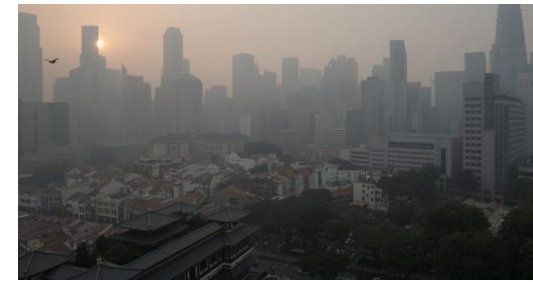
A simple model of precipitation change

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



[Allan et al. \(2013\) Surv. Geophys.](#), using f calculated by [Andrews et al. \(2010\) GRL](#)
see also [Kvalevåg et al. \(2010\) GRL](#)

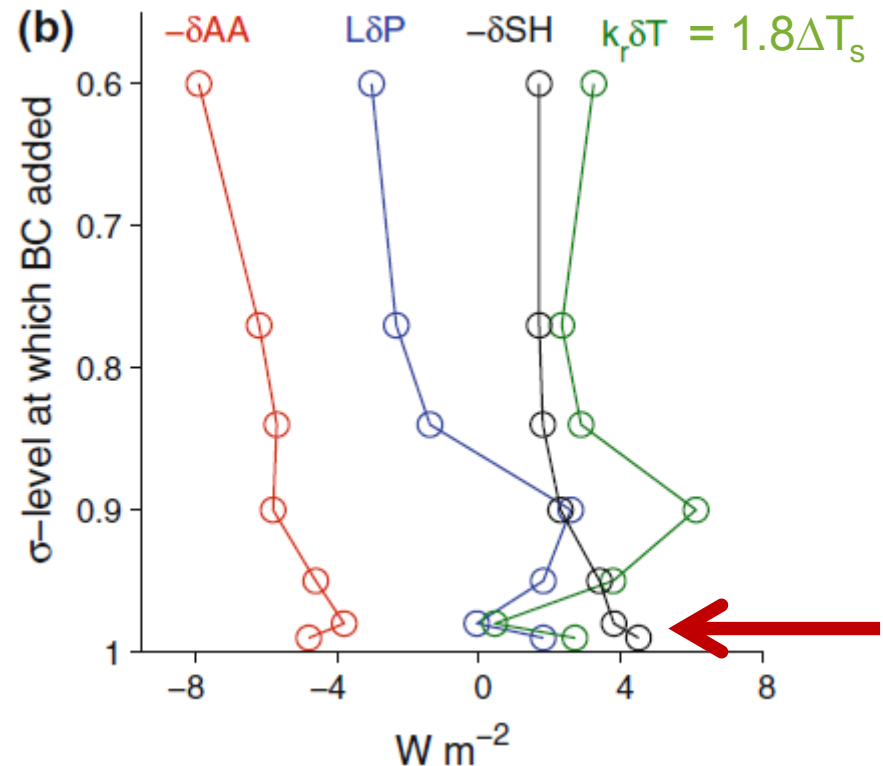
It matters where you put your radiative forcing



Surface sensible heat flux adjustment (rather than latent heat adjustment) increasingly important for absorbing aerosol within boundary layer e.g. Black Carbon (BC) [Ming et al. \(2010\) GRL](#) →

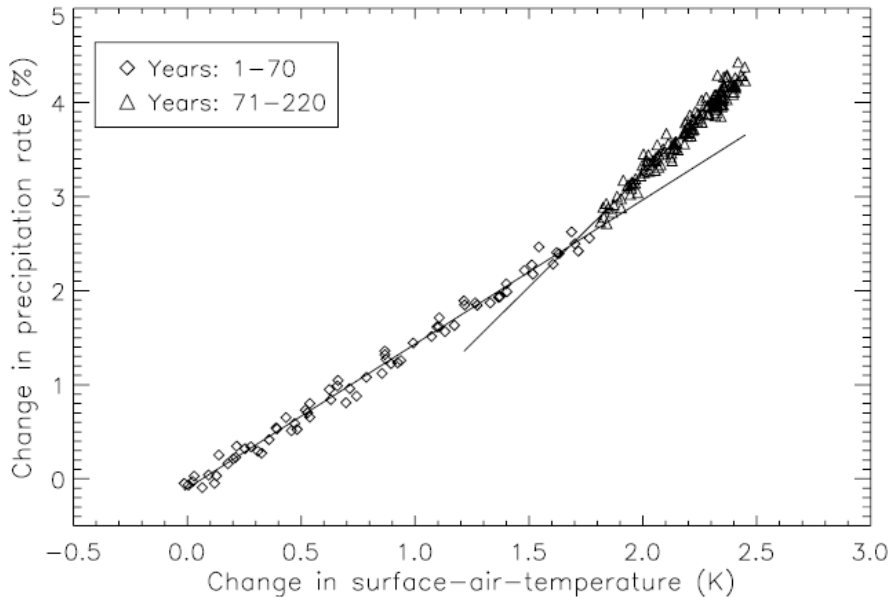
- Hydrological Forcing:
 $HF = kdT - dAA - dSH$

Geographical location also important for regional response



[O’Gorman et al. \(2012\) Surv. Geophys](#); after [Ming et al. \(2010\) GRL](#)
See also [Pendergrass & Hartmann \(2012\) GRL](#); [Previdi \(2010\) ERL](#)

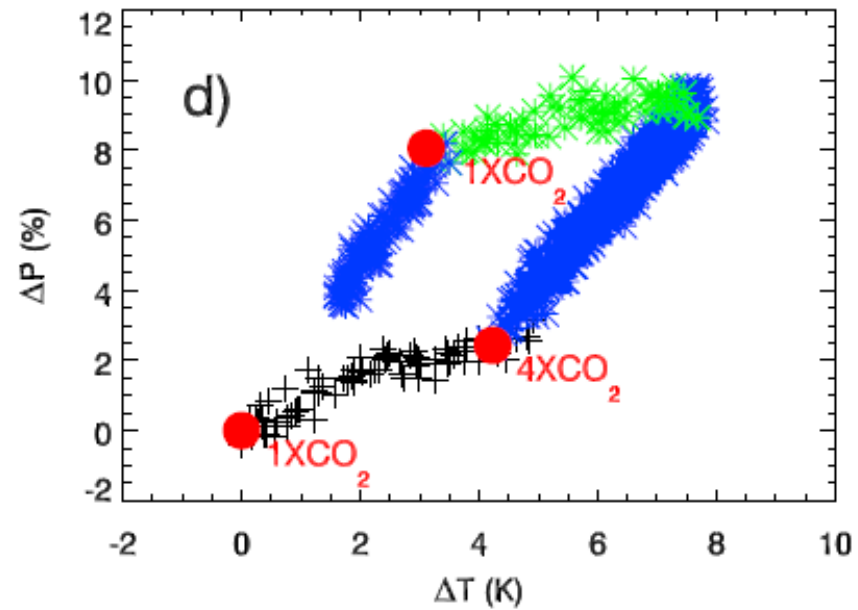
Implications for transient responses



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

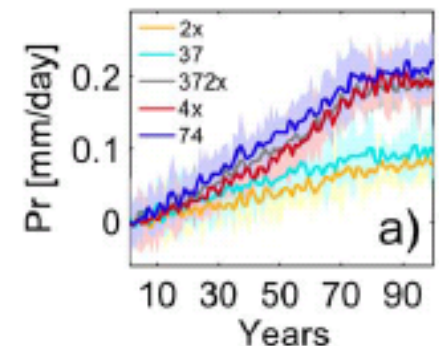
Degree of hysteresis determined by forcing related fast responses and linked to ocean heat uptake

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

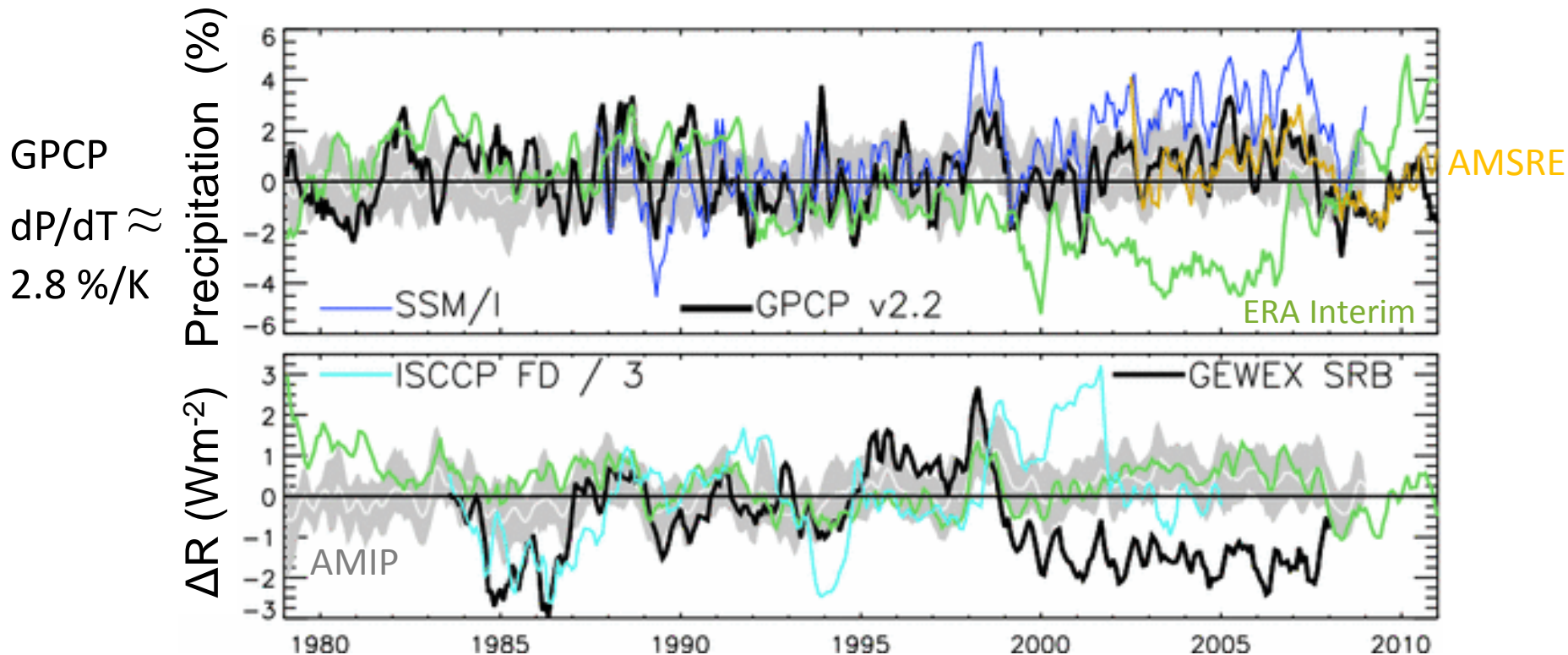


HadCM3: [Wu et al. \(2010\) GRL](#)

- CO₂ forcing experiments
- Initial precipitation response suppressed by CO₂ forcing
- Stronger response after CO₂ rampdown



How is global precipitation and radiative cooling currently changing?

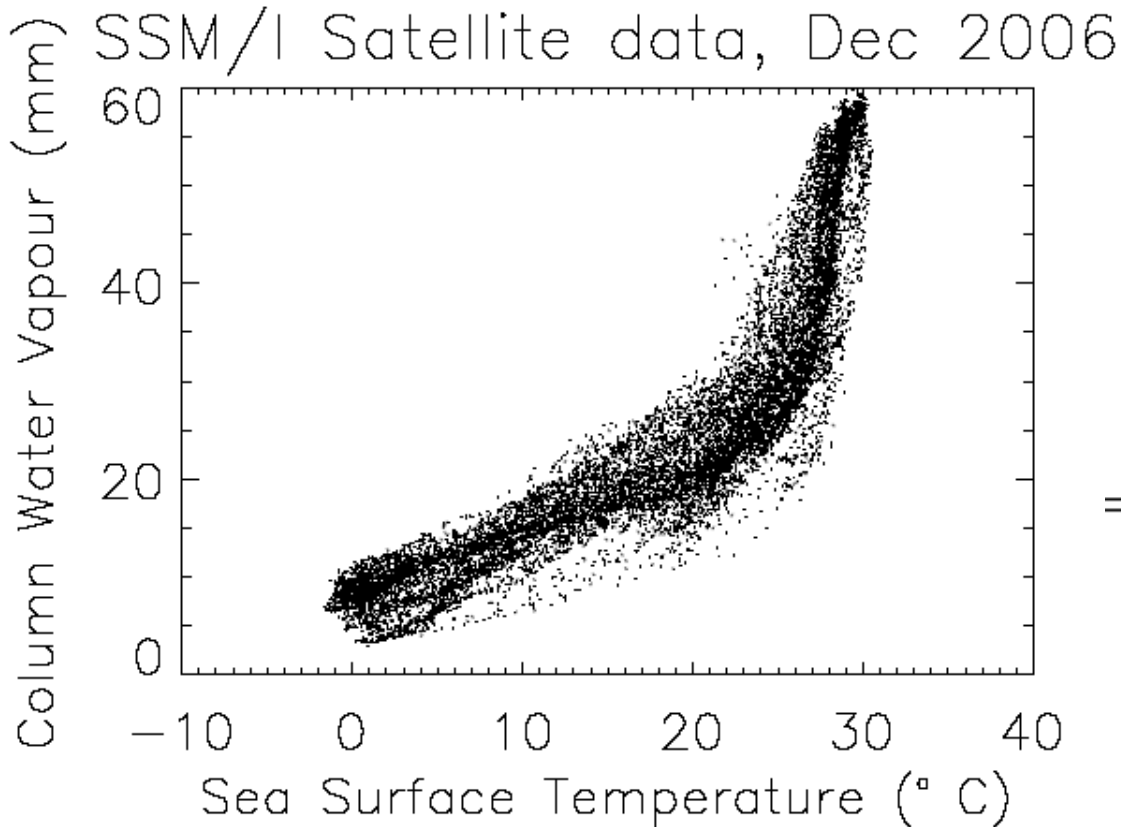


[Allan et al. \(2013\) Surv. Geophys](#)

1988-2008: Precipitation trends not significant

Global mean estimates (use ERA Interim over land and high latitudes for SSM/I & AMSRE)

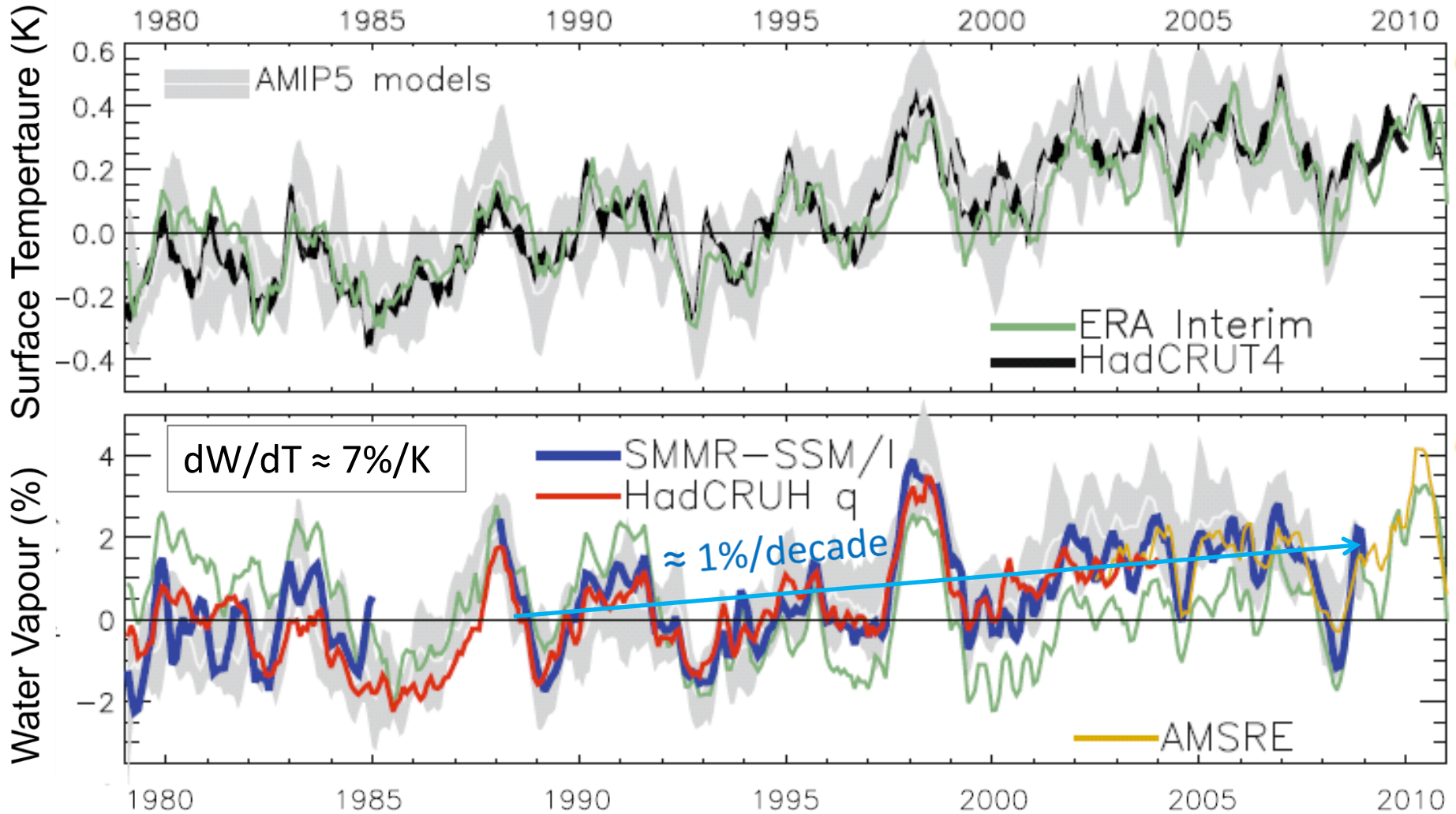
The role of water vapour



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

- 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](#)

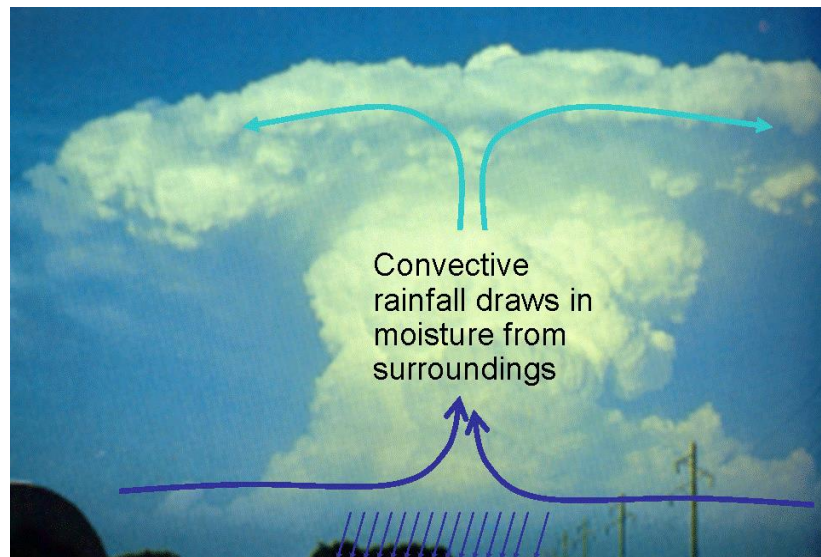
Global changes in water vapour



[Allan et al. \(2013\) Surv. Geophys](#)

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

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](#)

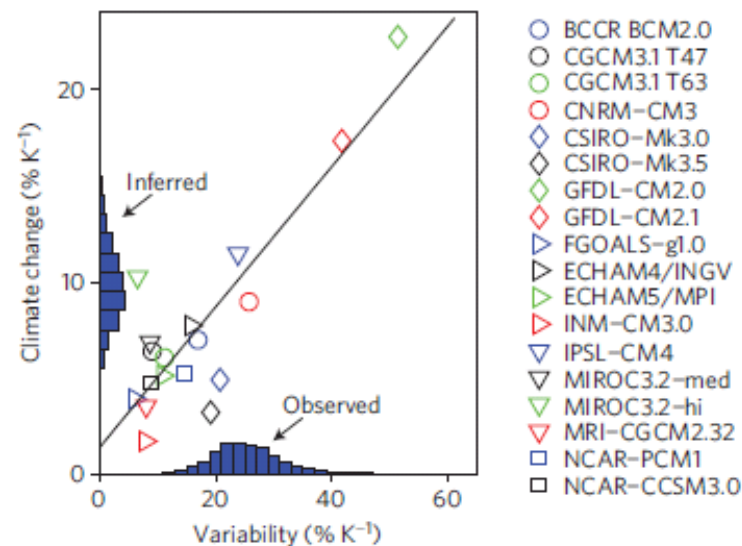
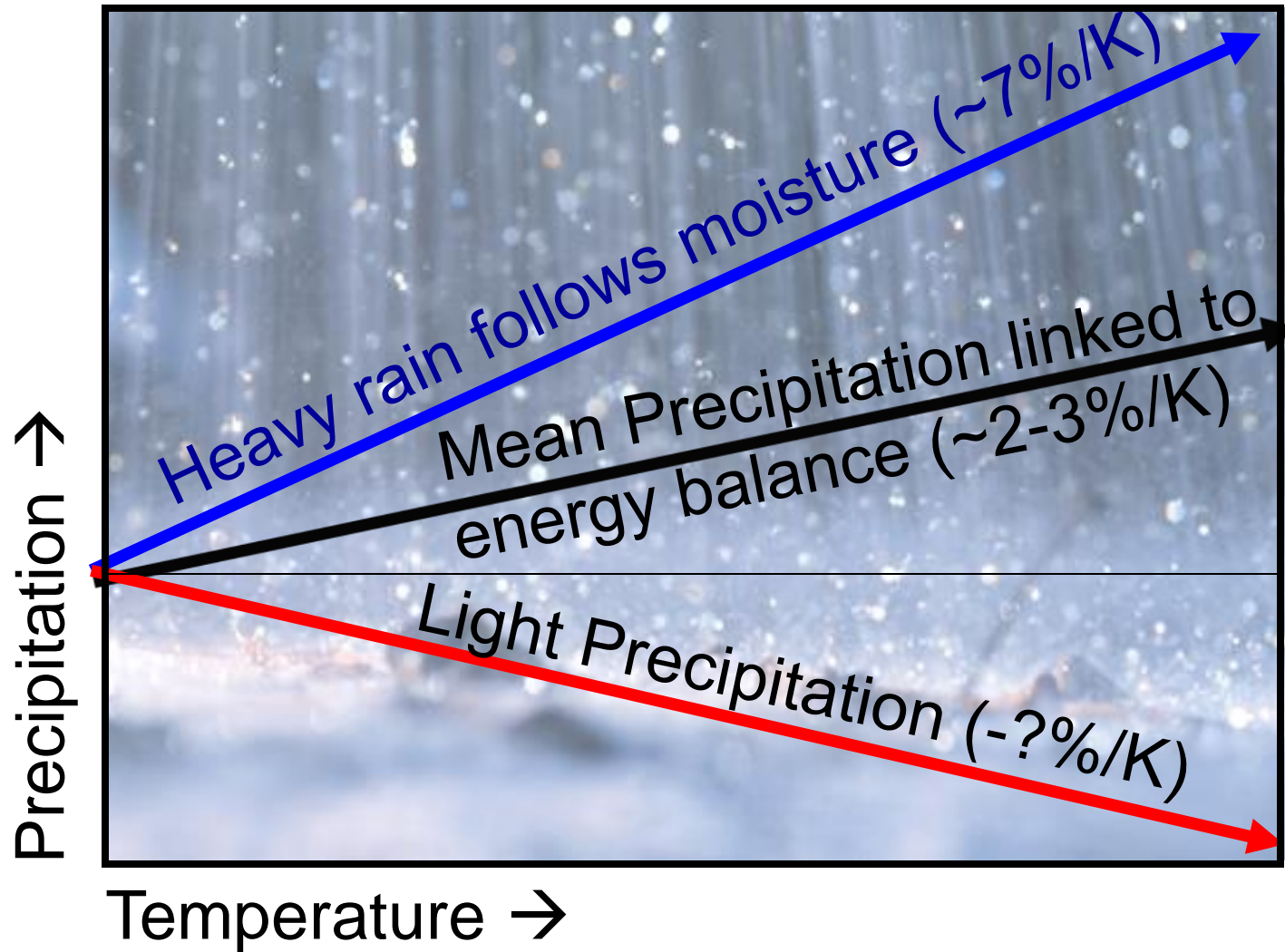


Figure 2 | Sensitivities ($\% K^{-1}$) of the 99.9th percentile of precipitation for variability versus climate change in the CMIP3 simulations. The solid

Contrasting precipitation response expected



e.g. [Allen and Ingram \(2002\) *Nature*](#) ; [Allan et al. \(2010\) *Environ. Research Lett.*](#)

Moisture Balance

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

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

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. \(1987\) *QJRM*](#)

r.p.allan@reading.ac.uk

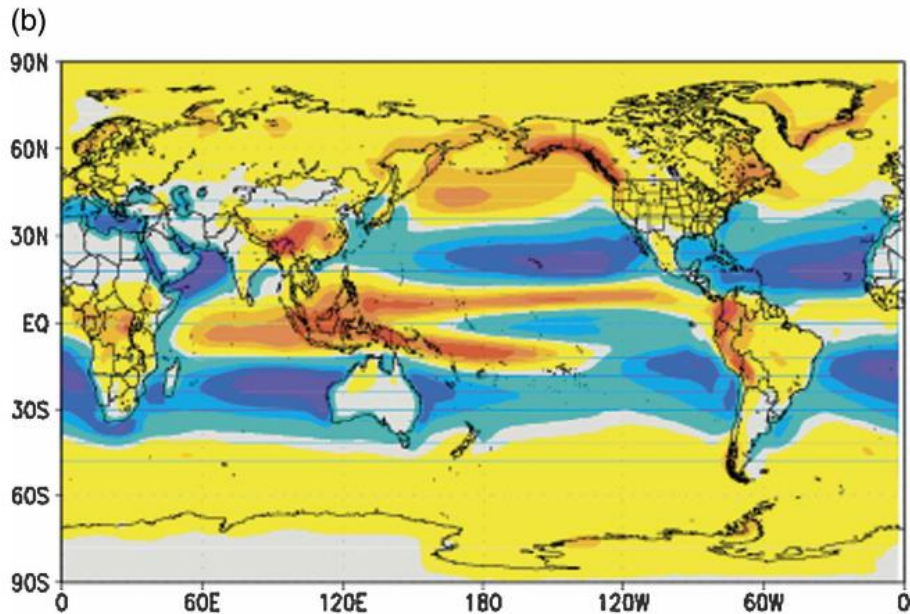
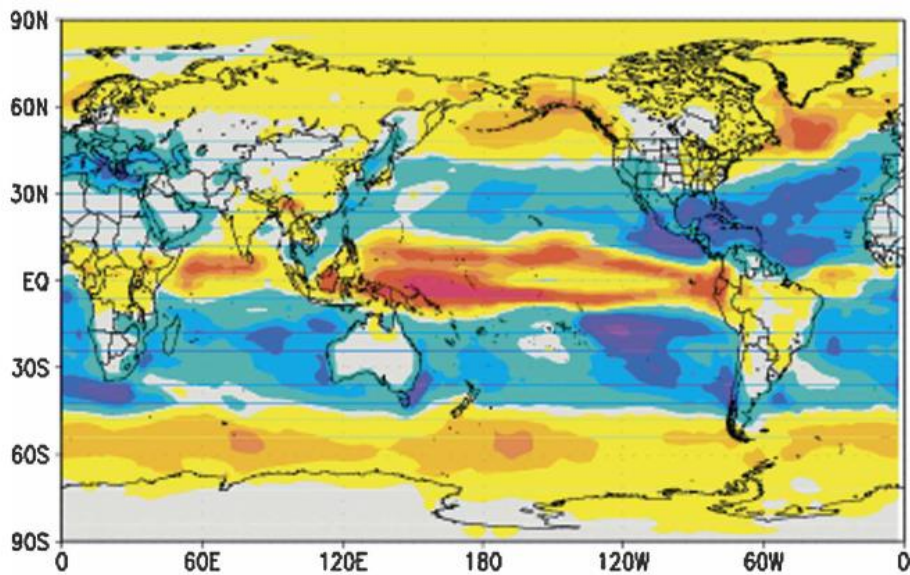


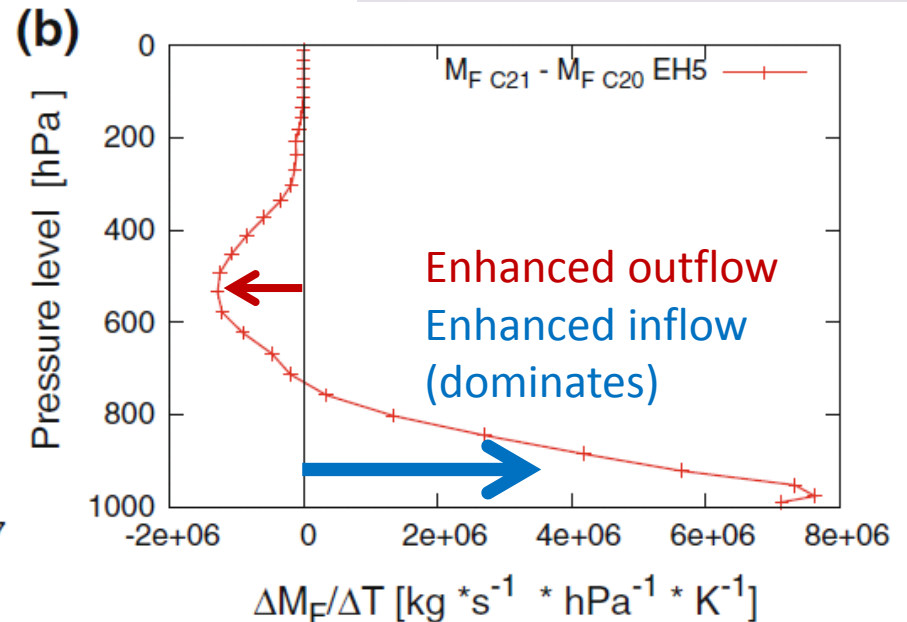
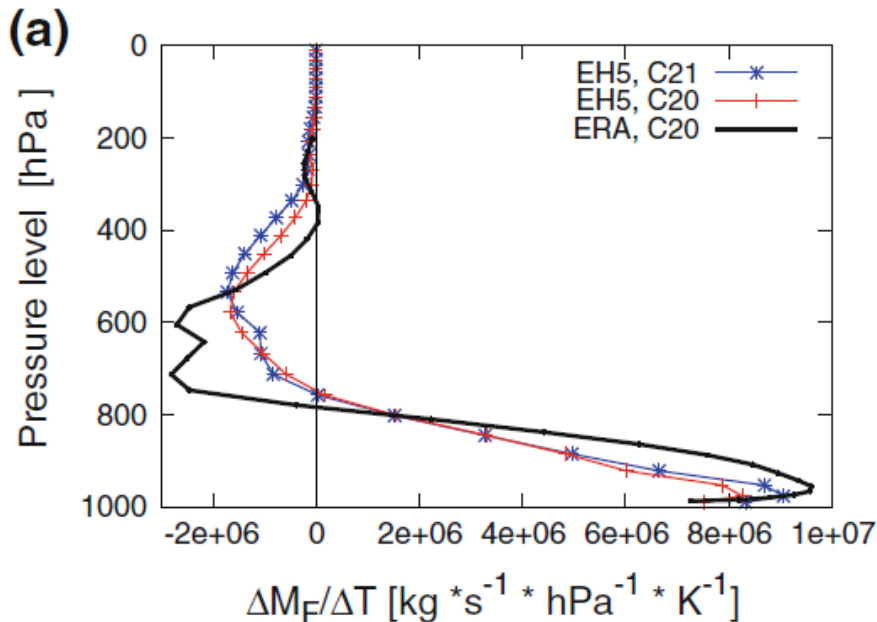
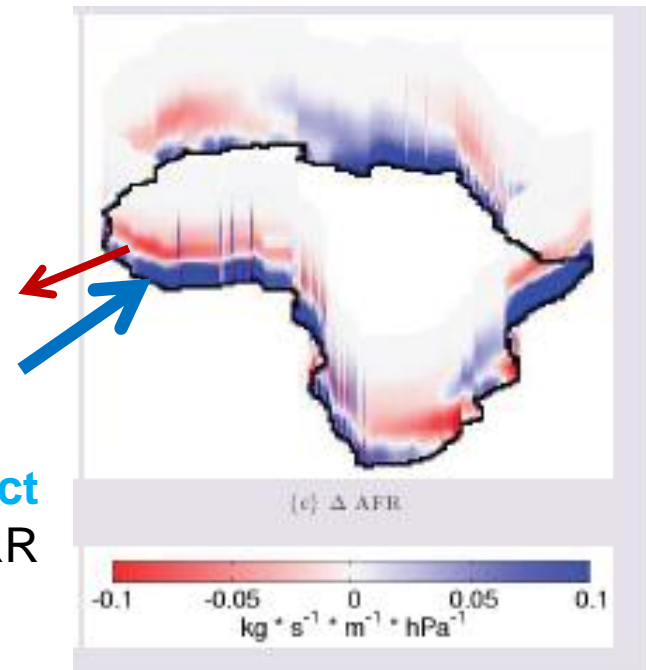
FIG. 7. The annual-mean distribution of $\delta(P - E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

Enhanced moisture transports into the “wet” tropics, high latitudes and continents

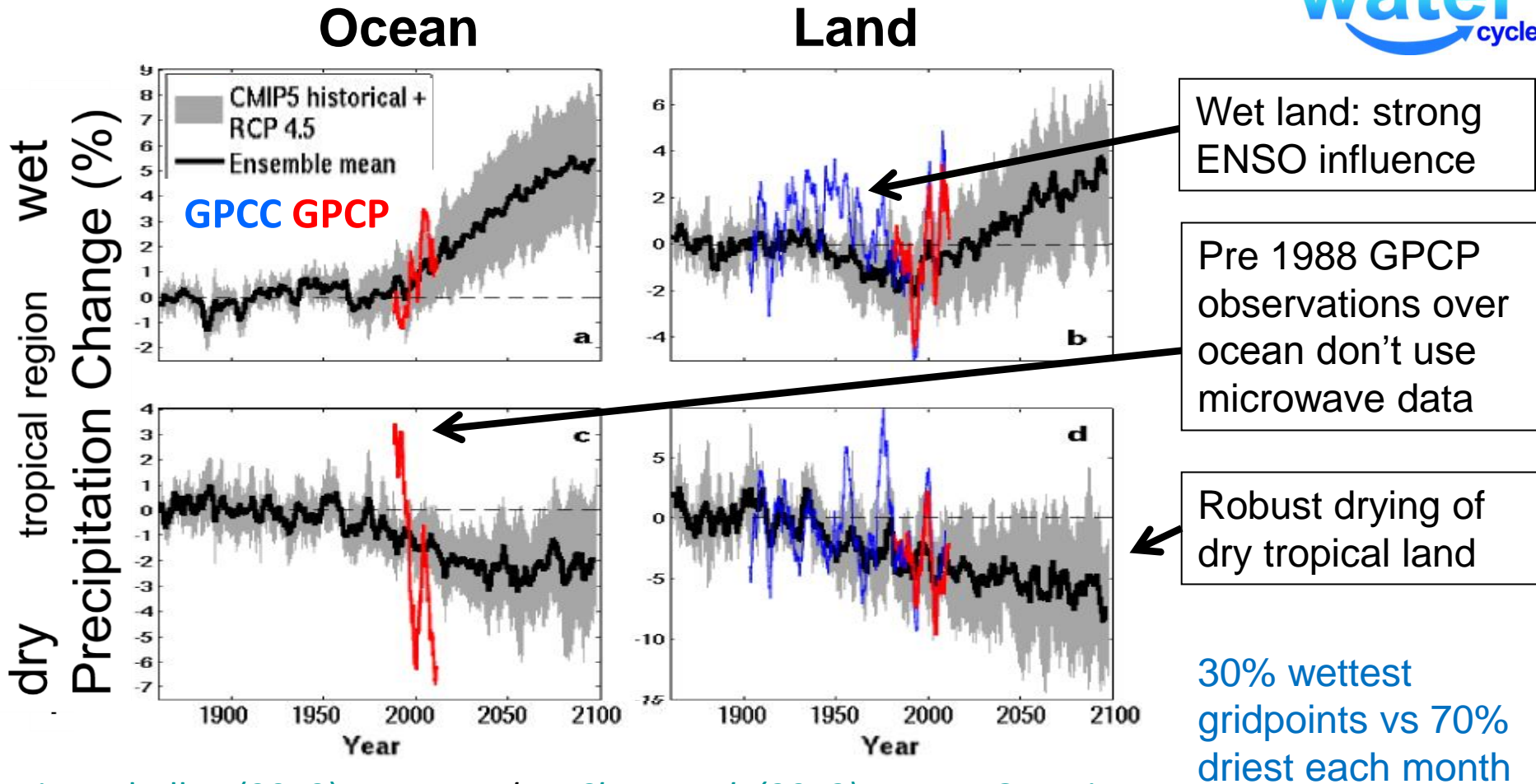
$$\frac{\partial w}{\partial t} + \nabla \cdot \frac{1}{g} \int_0^{P_s} \mathbf{v}q dp = E - P,$$

PREPARE project

Zahn & Allan, submitted to WRR

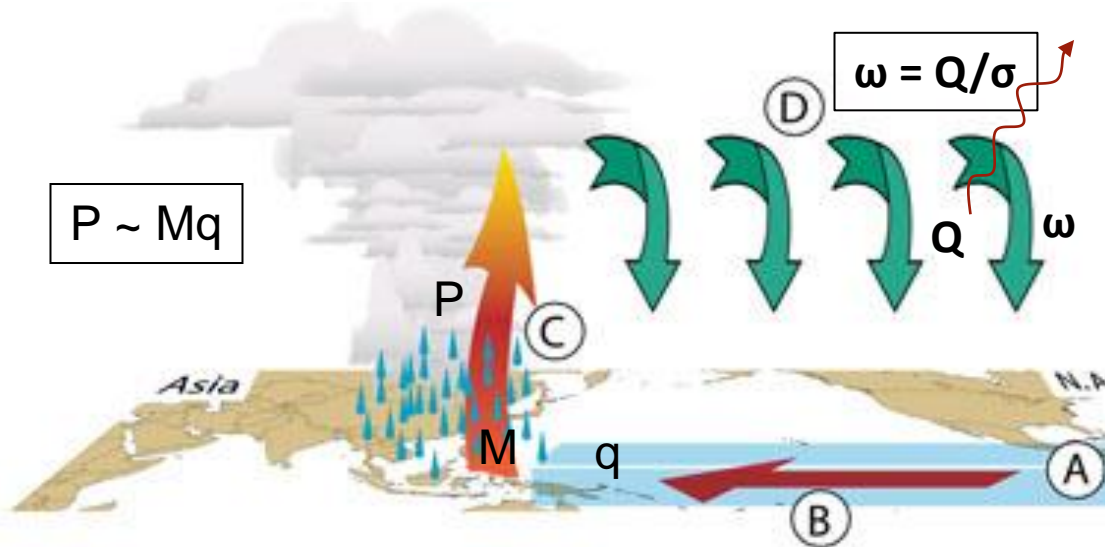


CMIP5 simulations: Wettest tropical grid-points get wetter, driest drier



[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



Walker circulation

- (A) Evaporation from warm ocean moistens lower atmosphere.
- (B) Trade winds carry moisture west
- (C) Moist air rises and feeds rain
- (D) Dry air cools and sinks

Warm climate

- (A) Atmospheric moisture increases strongly.
- (C) Rainfall increases more slowly than moisture

To compensate, winds slow.

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:

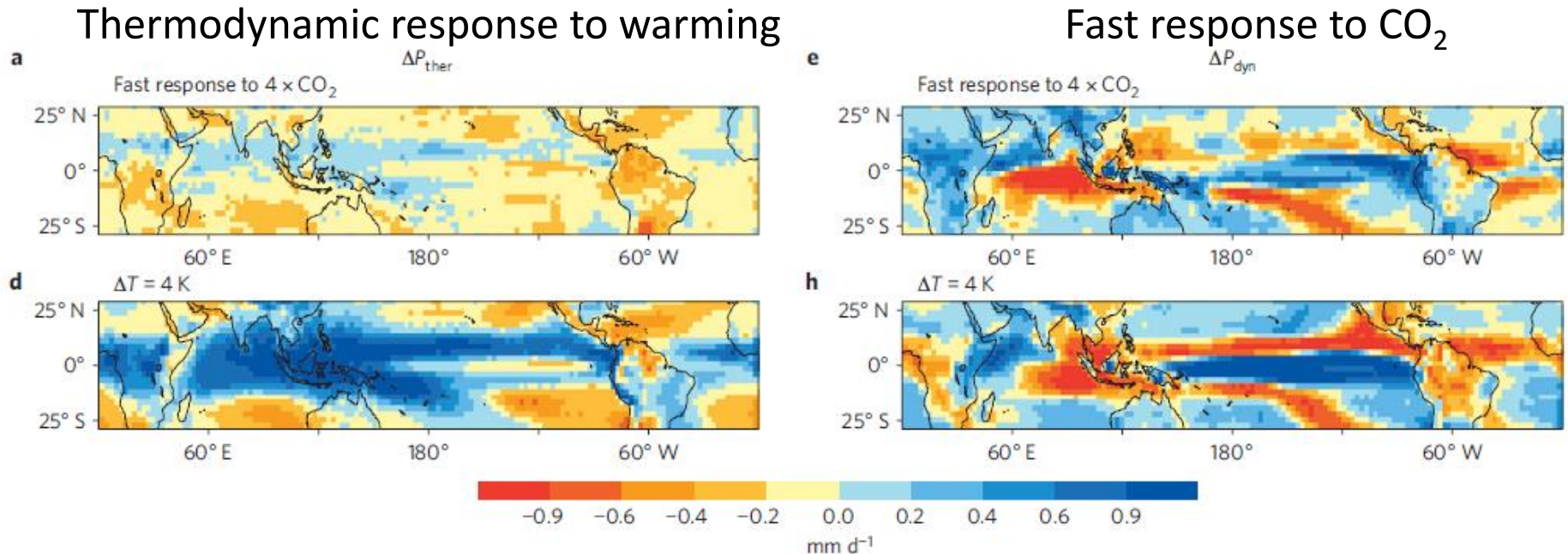
$$\omega = Q/\sigma$$

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

If Γ follows MALR \rightarrow 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



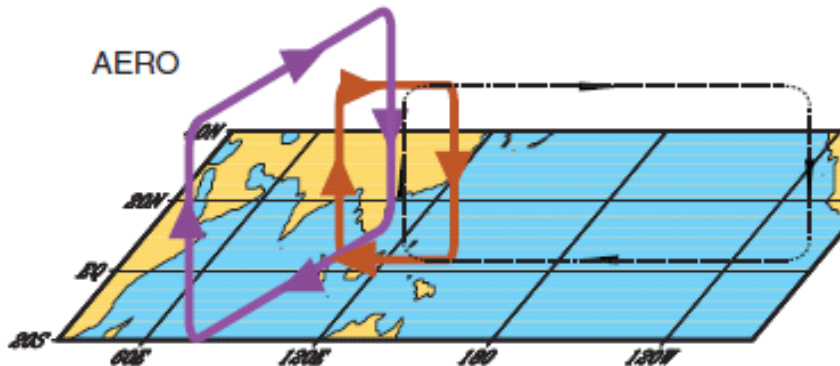
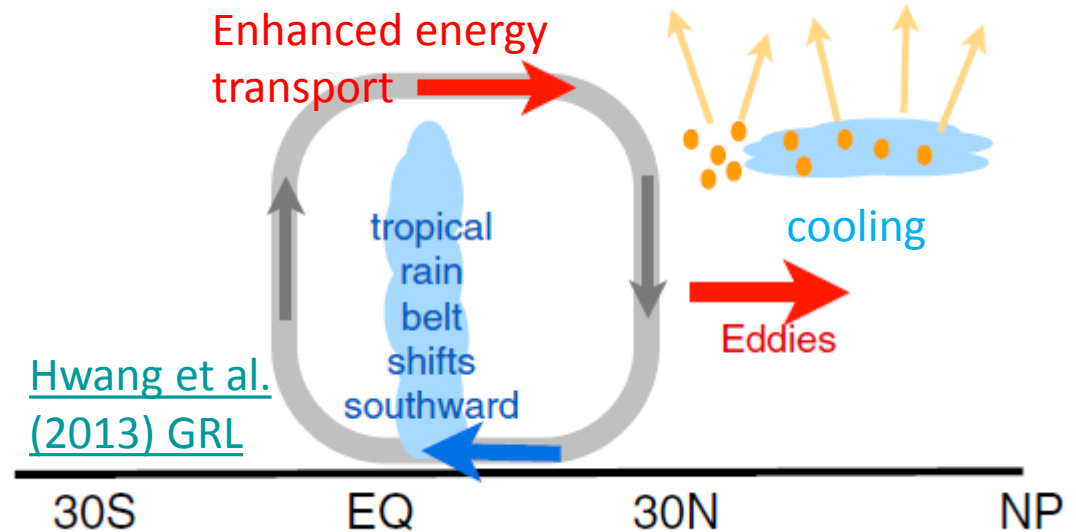
[Bony et al. \(2013\) *Nature Geosciences*](#) (see talk on Tuesday!)

Both fast and slow responses to CO₂ 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

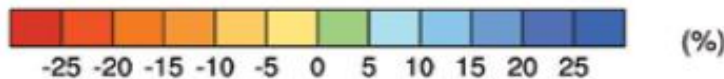
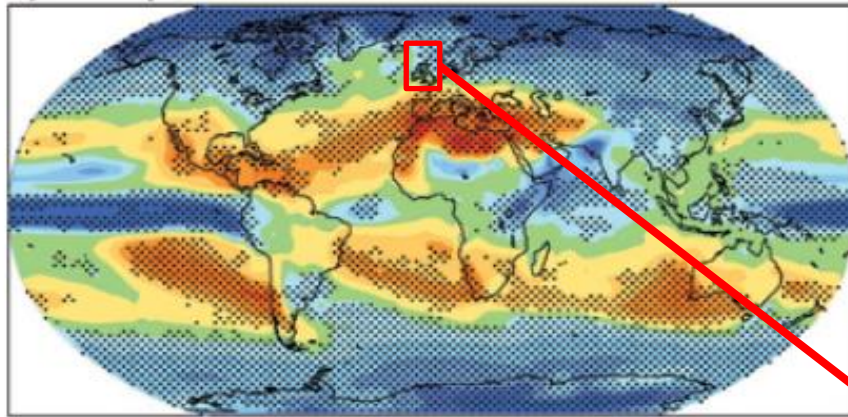
- N Hemisphere Aerosol cooling 1950-1980s
- Induces southward movement of ITCZ
- Reduced **Sahel rainfall** →
- Recovery after 1980s e.g. [Wild 2012 BAMS](#)
- +Asymmetric volcanic forcing e.g. [Haywood et al. \(2013\) Nature Climate](#)



- Sulphate aerosol effects on Asian monsoon e.g. [Bollasina et al. 2011 Science](#)
- Links to drought in Horn of Africa? [Park et al. \(2011\) Clim Dyn](#)

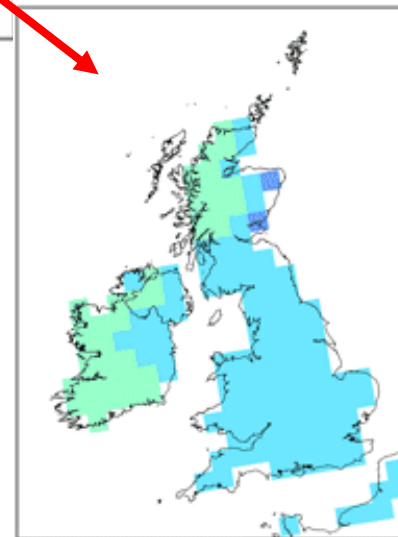
Challenge: Regional projections

a) Precipitation

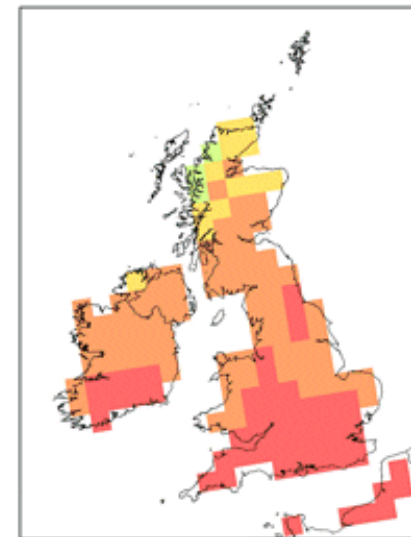


Shifts in circulation systems are crucial to regional changes in water resources and risk yet predictability is often poor (but see [Power et al. \(2012\) J Clim](#))

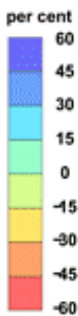
Percent change in precipitation –2080s –High Emissions scenario



Winter months



Summer months

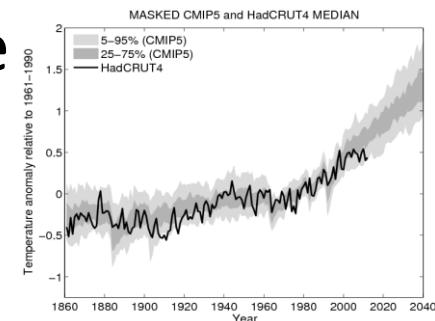
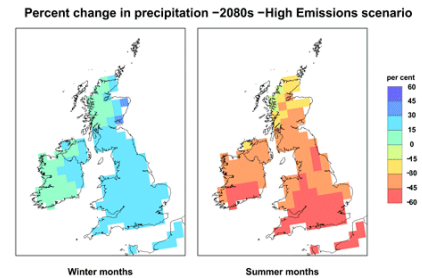


How will jet stream positions and monsoons respond to warming? e.g. [Levermann et al. \(2009\) PNAS](#)

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
- Regional responses are unpredictable
- Extreme precipitation is outpacing Clausius Clapeyron constraint
- What are changes in radiative forcings and their associated fast adjustments?
- Implications for geoengineering of climate
- What is the effect of the global surface temperature hiatus on the water cycle?



Mechanisms during SST warming hiatus?

After calculations from 4XCO₂ from

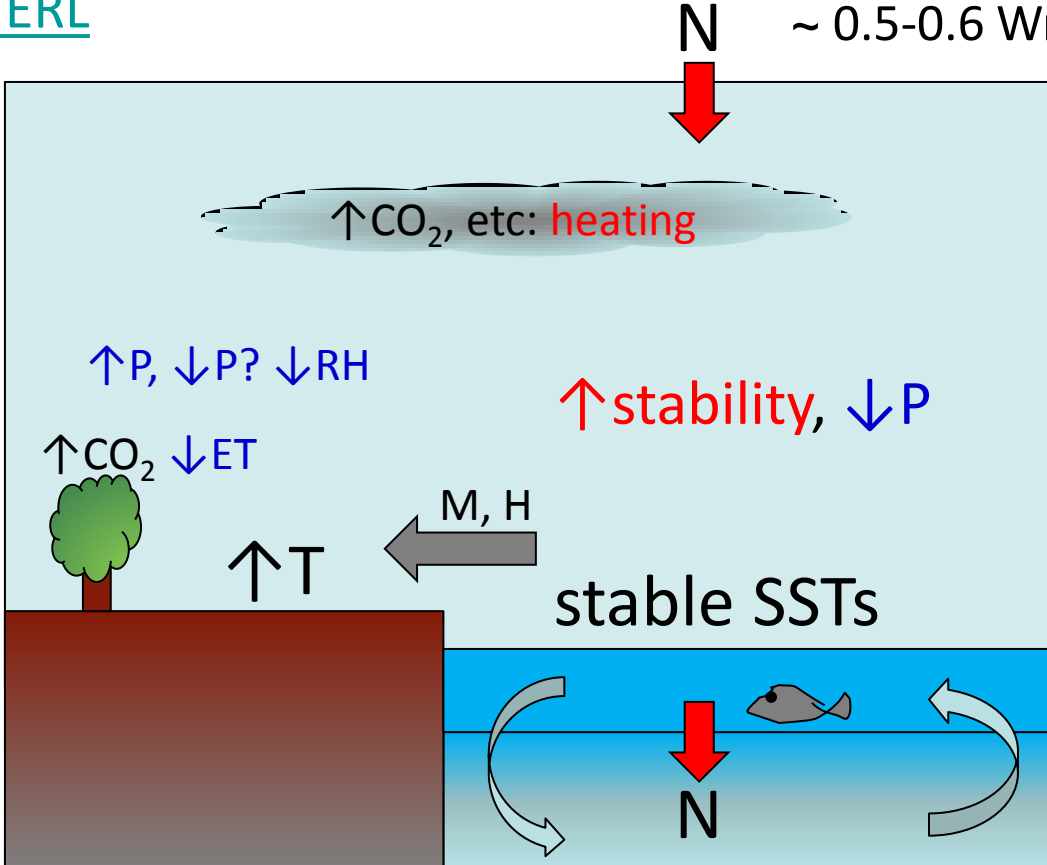
[Cao et al. 2012 ERL](#)

↑ Monsoonal circulations:

[Levermann et al. \(2009\) PNAS](#)

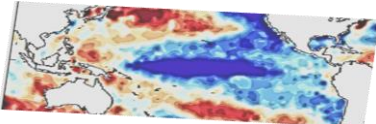
Energy flows:
[Muller & O’Gorman \(2011\) Nature Clim.](#)

CO₂ bio. Effects – small over 15yrs?
[Andrews et al. 2010 Clim. Dyn](#) ; [Dong et al. \(2009\) J. Clim](#)



[Loeb et al. \(2012\) Nature Geo](#)

↑ Walker circ?
[Sohn et al. \(2012\) Clim Dyn](#)



IPO pattern
e.g. [Meehl et al. \(2012\) Nat. Clim.](#)

Change from EP to CP El Nino?

[Xiang et al. \(2013\) Clim Dyn](#)

r.p.allan@reading.ac.uk

Conclusions

- Radiative energy balance is fundamental to climate response
- Energy and moisture balance powerful constraints on global water cycle
- Global precipitation rises with surface warming ($\sim 2\%/K$)
- 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
- **Heating of Earth continues** at rate of $\approx 0.6 \text{ Wm}^{-2}$ over the last decade **despite stable Surface Temperature**