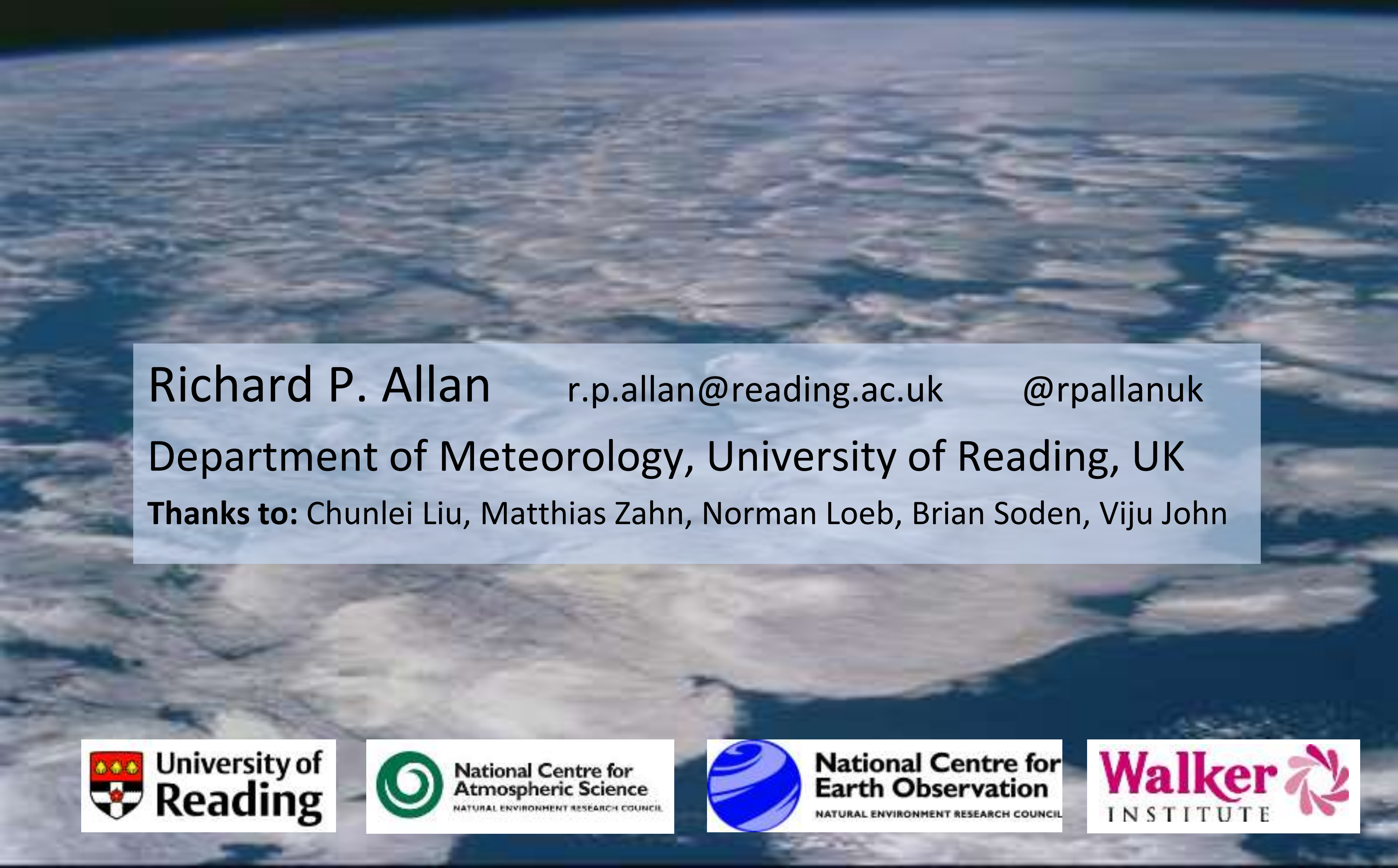
Radiative constraints on current and future changes in the global water cycle



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

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Walker INSTITUTE

Young(er) scientists!

Troublemakers

Gordon Research Conferences

Connecticut College

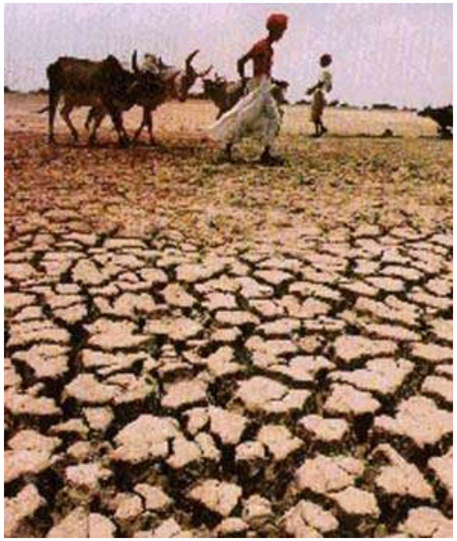
Solar Radiation and Climate

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

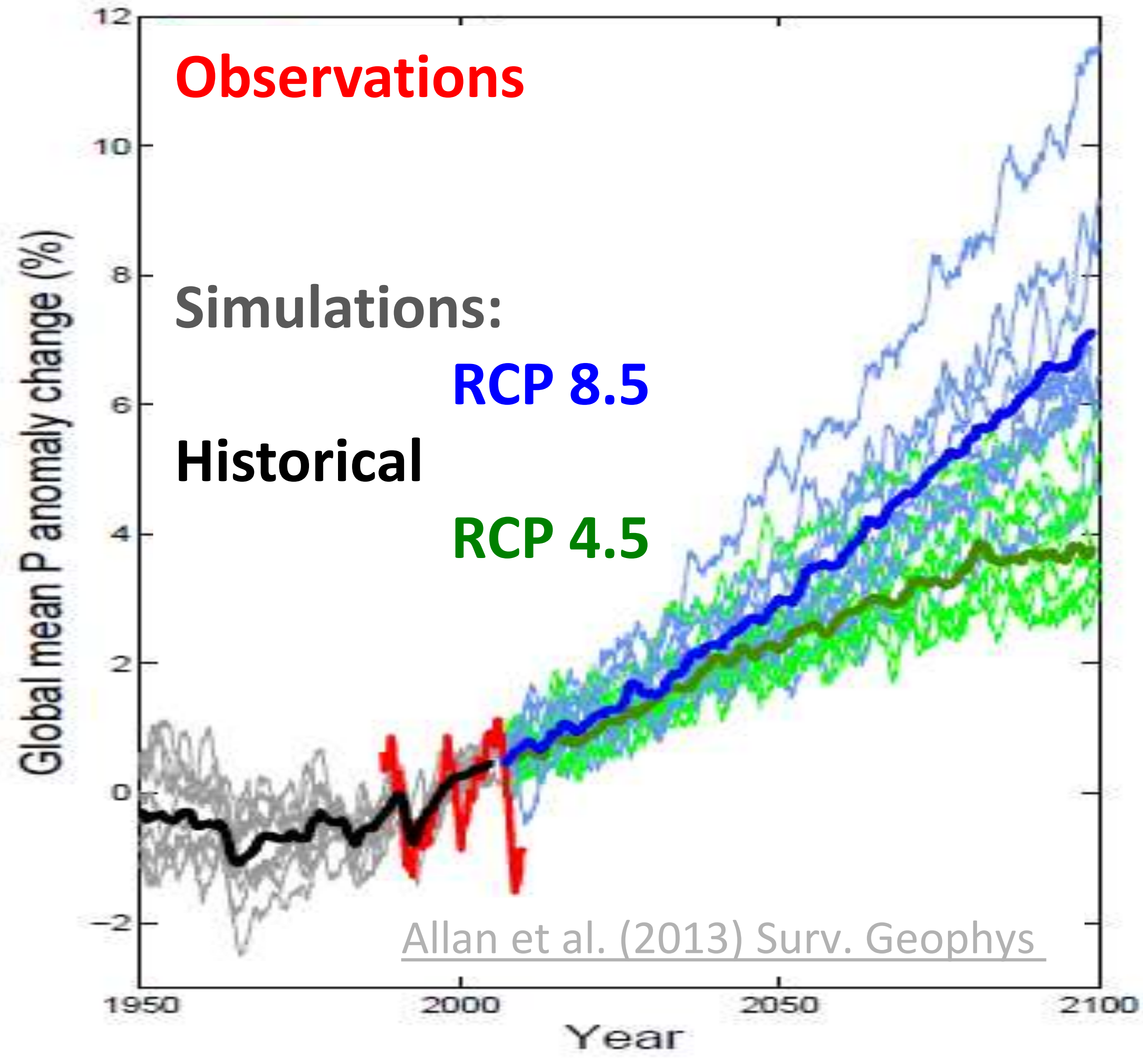
June 24-29, 2000

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

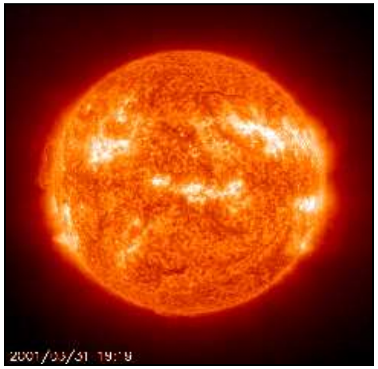


How will global precipitation respond to climate change?



Allan et al. (2013) Surv. Geophys

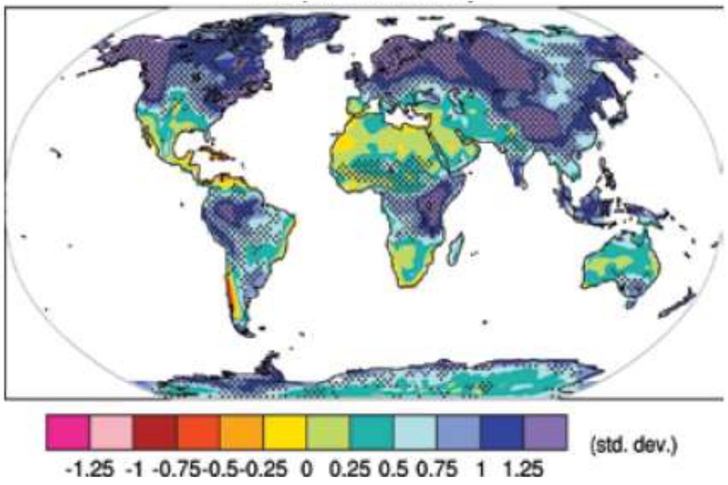
See also Hawkins & Sutton (2010) Clim. Dyn



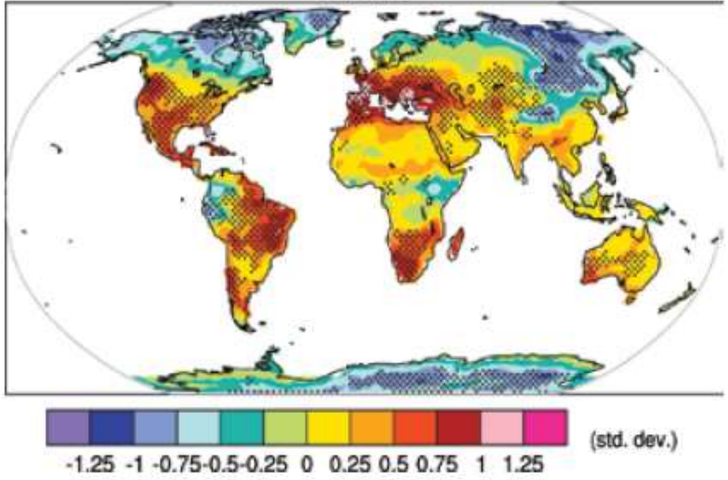
Climate model projections

University of Reading

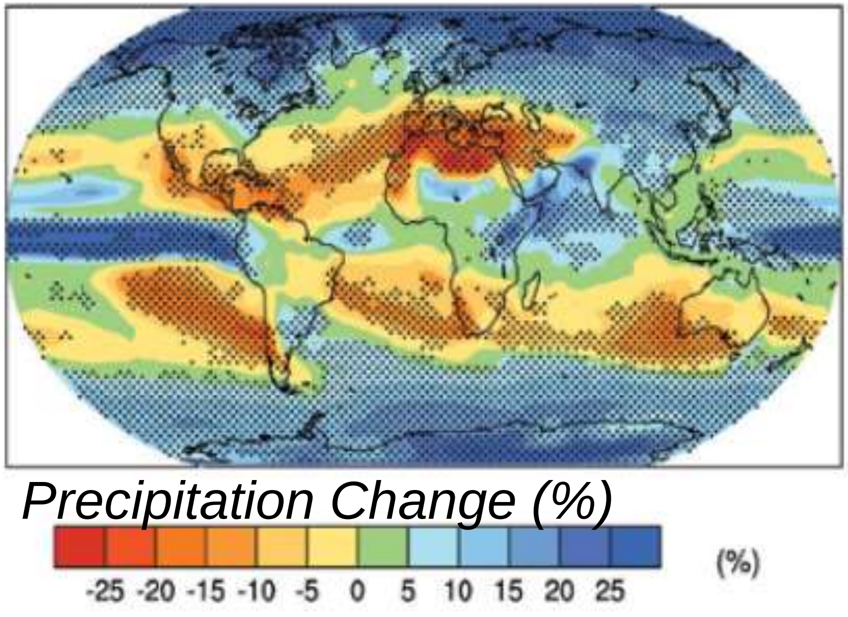
Precipitation Intensity



Dry Days

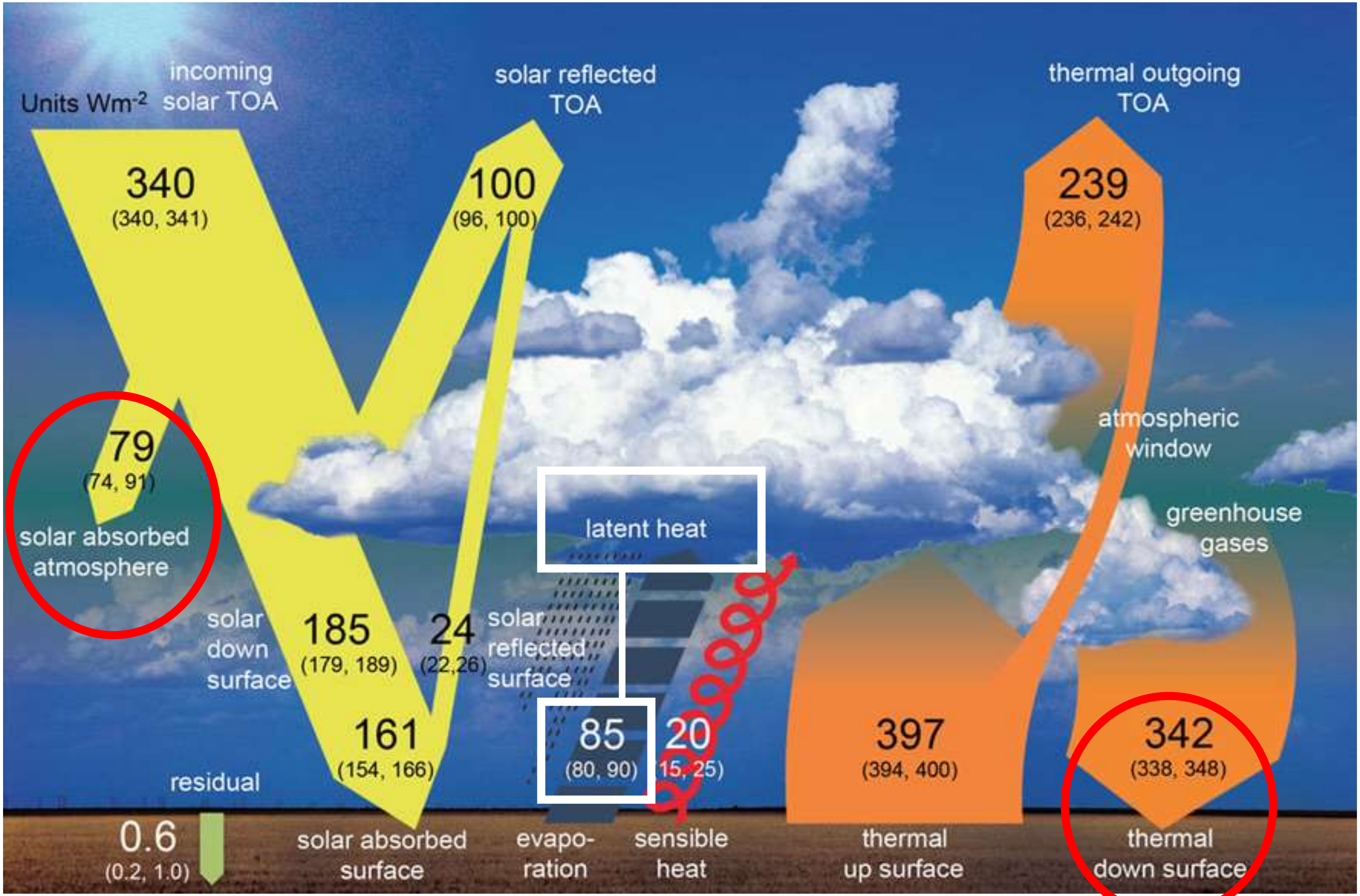


- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??


Precipitation Change (%)

IPCC WGI (2007)

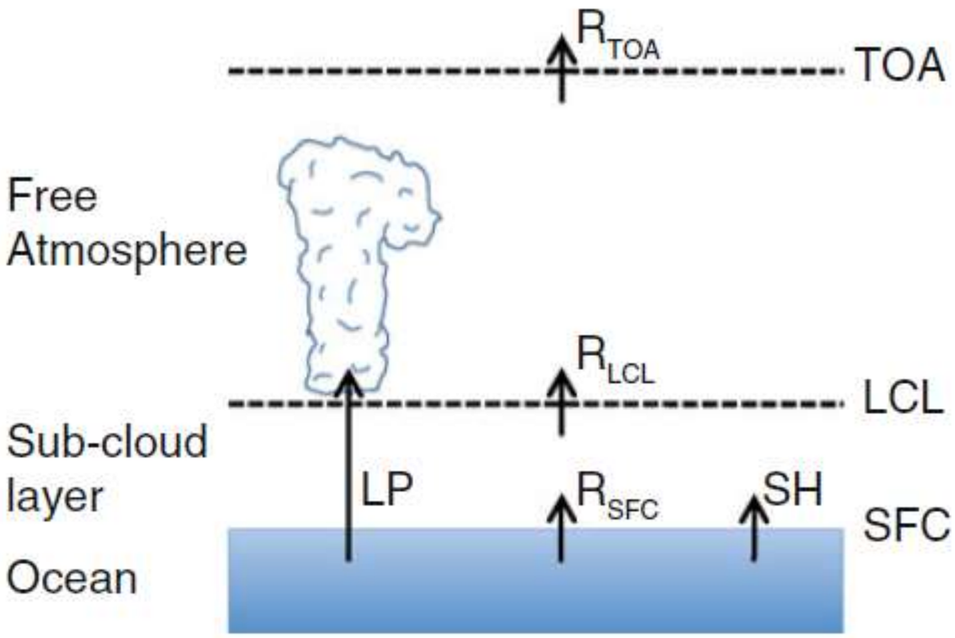
Earth's Energy Budget & the Global Water Cycle



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

Radiative energy budget of the atmosphere and hydrological response

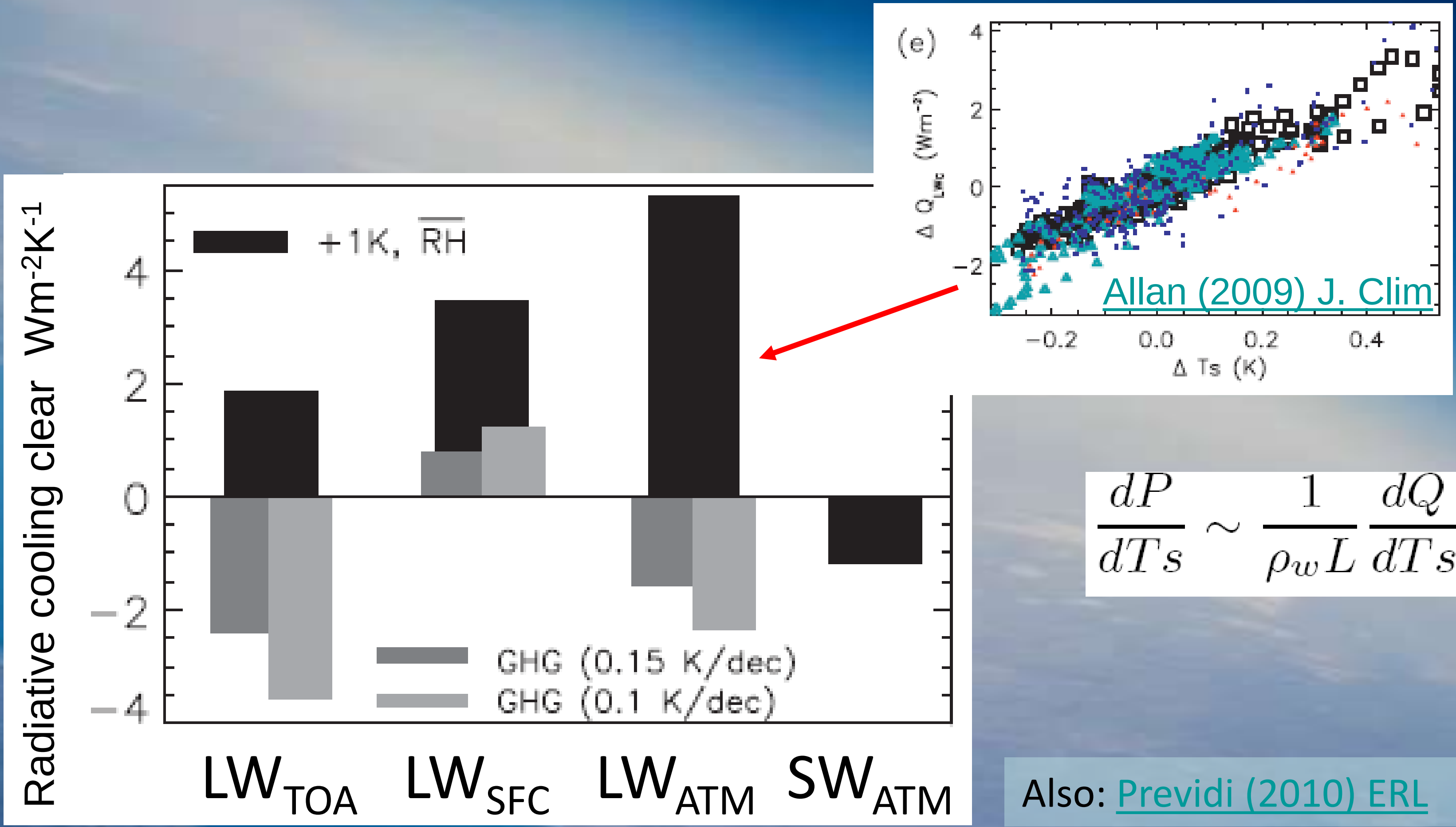
- Adjustments in latent heating LP (precipitation) for change in radiative energy budget ΔR above LCL (lifting condensation level)
- ΔR below LCL → adjustments in SH (sensible heat flux) important



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 (~2-3 $Wm^{-2}K^{-1}$) and resulting increase in latent heating (precipitation) to balance (~2 $\%K^{-1}$)

e.g. Lambert & Webb (2008) GRL; Stephens & Ellis (2008) J. Clim;

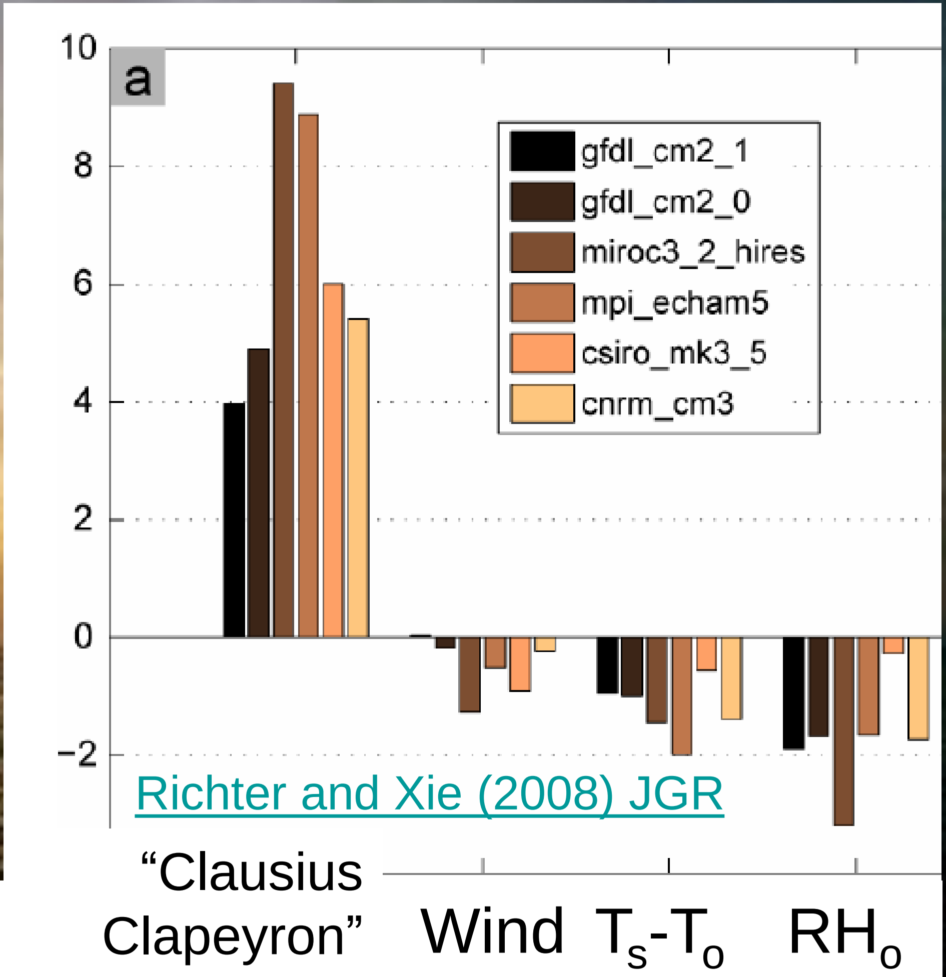


Allan (2009) J. Clim

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

Also: Previdi (2010) ERL

Evaporation



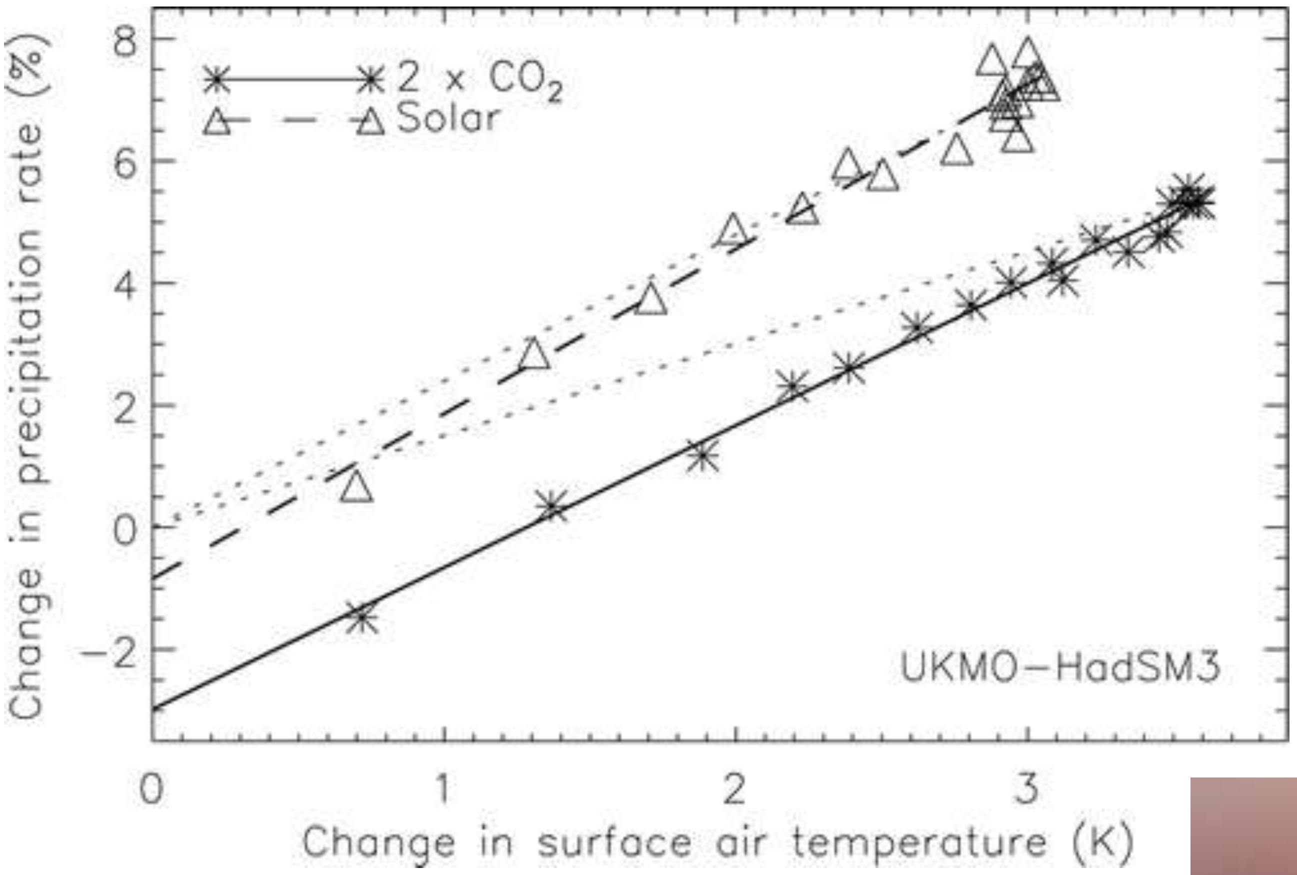
Richter and Xie (2008) JGR

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

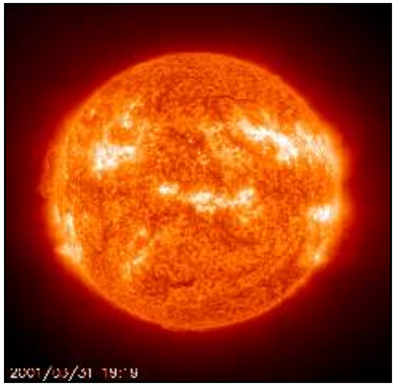
“Muted” Evaporation changes in models are explained by small adjustments in Boundary Layer:

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



Energetic constraint upon global precipitation

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

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

(ii) $\boldsymbol{f}$ dependent upon nature of radiative forcing ΔF

Precipitation change ΔP determined by:

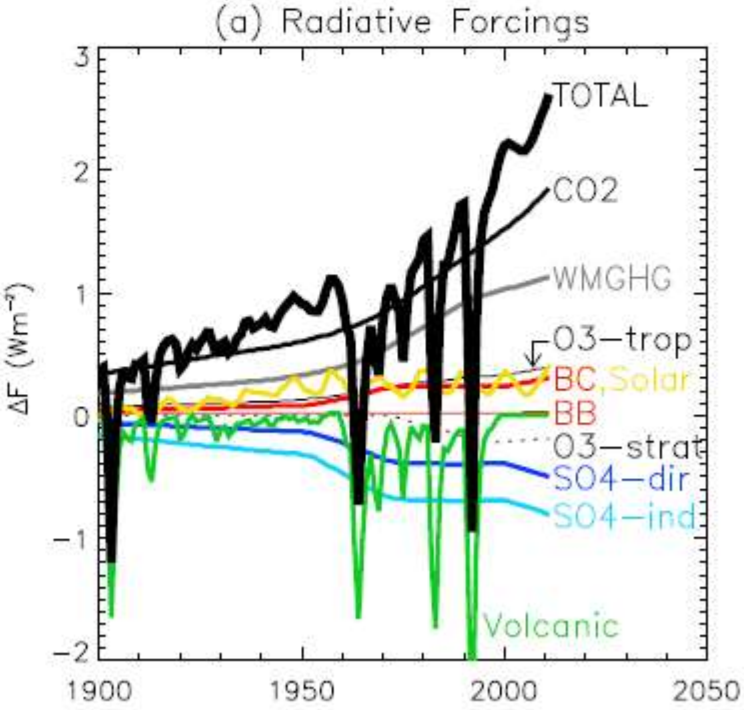
(i) “slow” response to warming ΔT (enhanced radiative cooling of warmer troposphere)

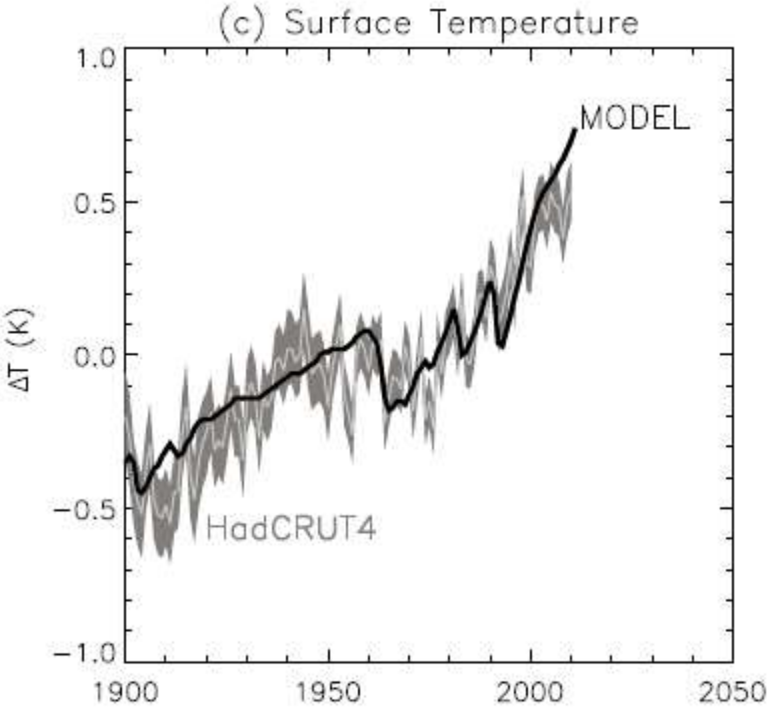
(ii) “fast” direct influence of radiative forcing on surface/tropospheric energy budget (rapid adjustment)

See Allen and Ingram (2002) *Nature* *for detailed discussion*

Simple model of precipitation change

Thanks to Keith Shine and Evgenios Koukouvagias





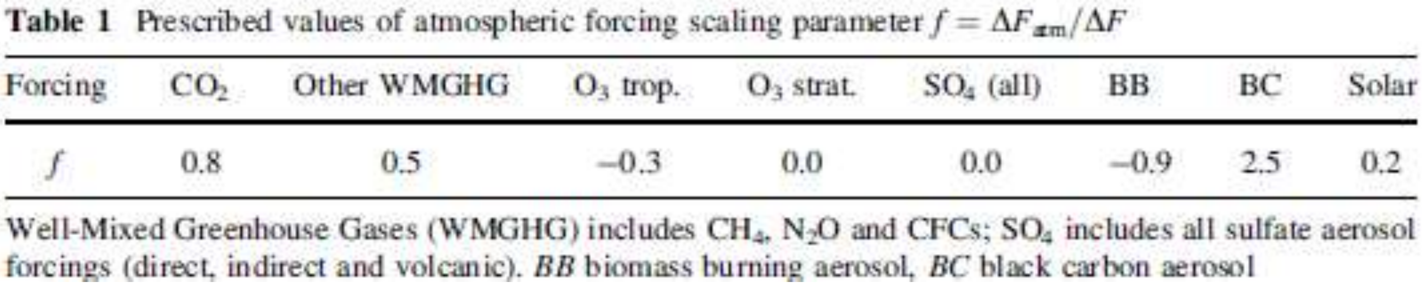


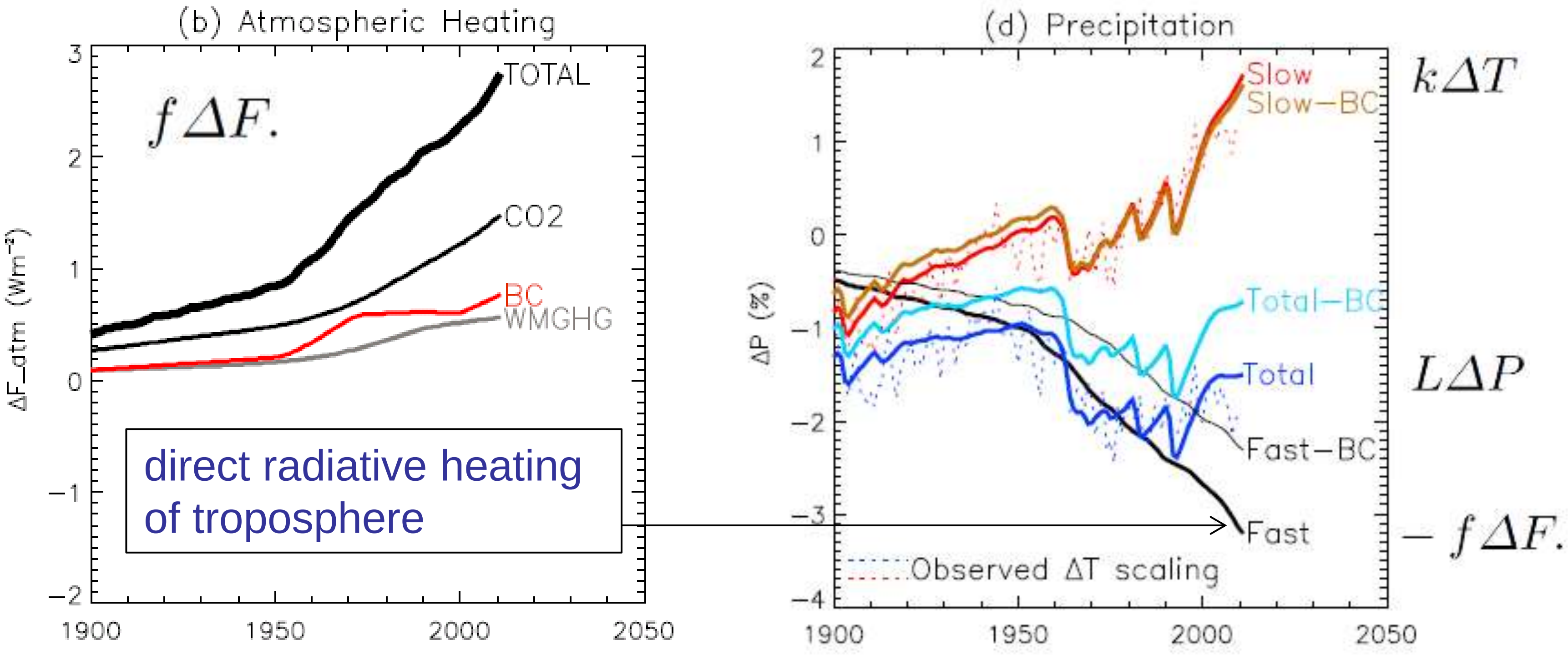
Table 1 Prescribed values of atmospheric forcing scaling parameter $f = \Delta F_{atm}/\Delta F$

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

A simple model of precipitation change

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



direct radiative heating of troposphere

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

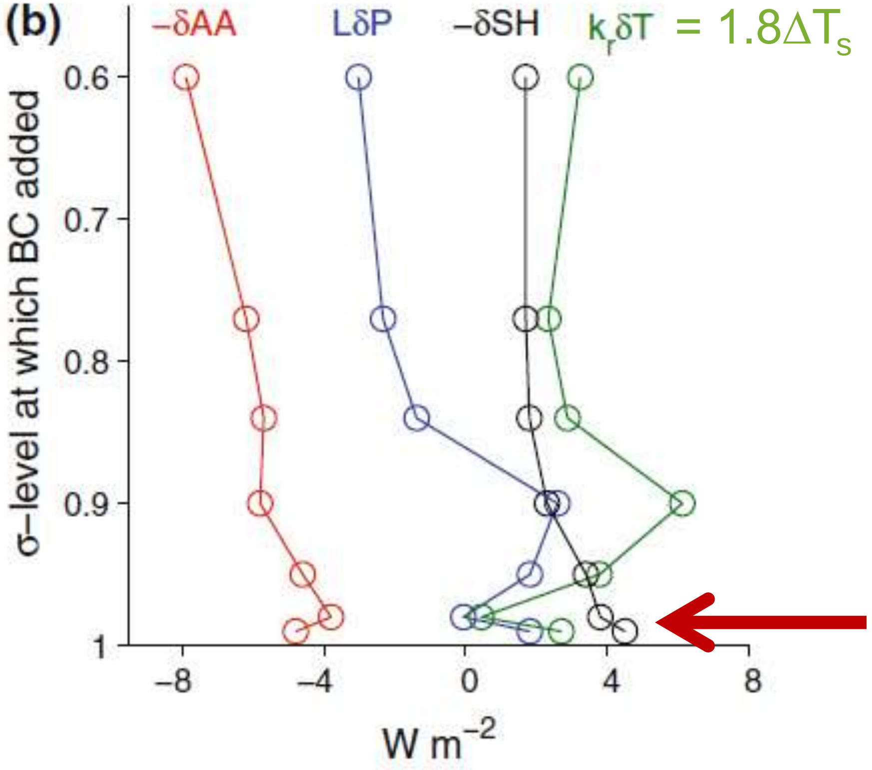
It matters where you put your radiative forcing

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:

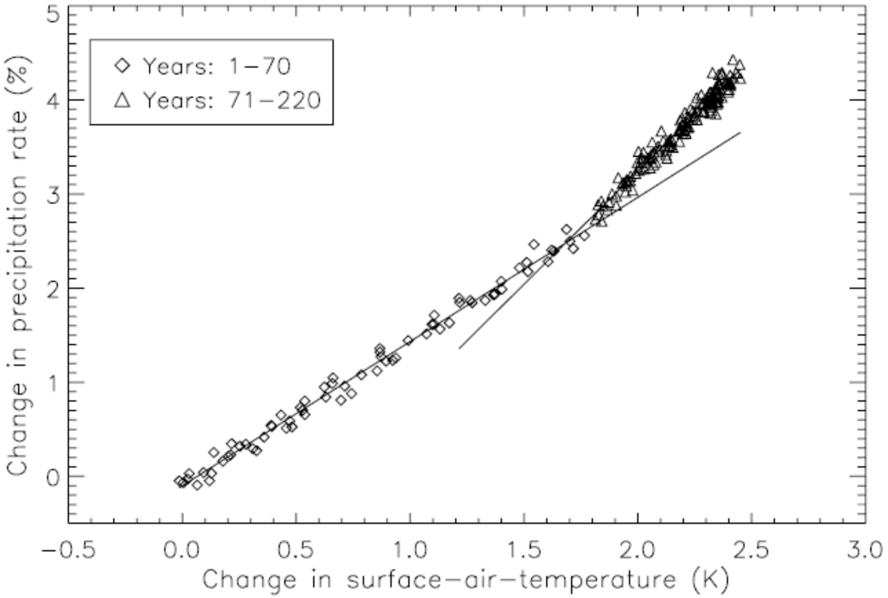
  HF=kdT-dAA-dSH

Geographical location also important for regional response

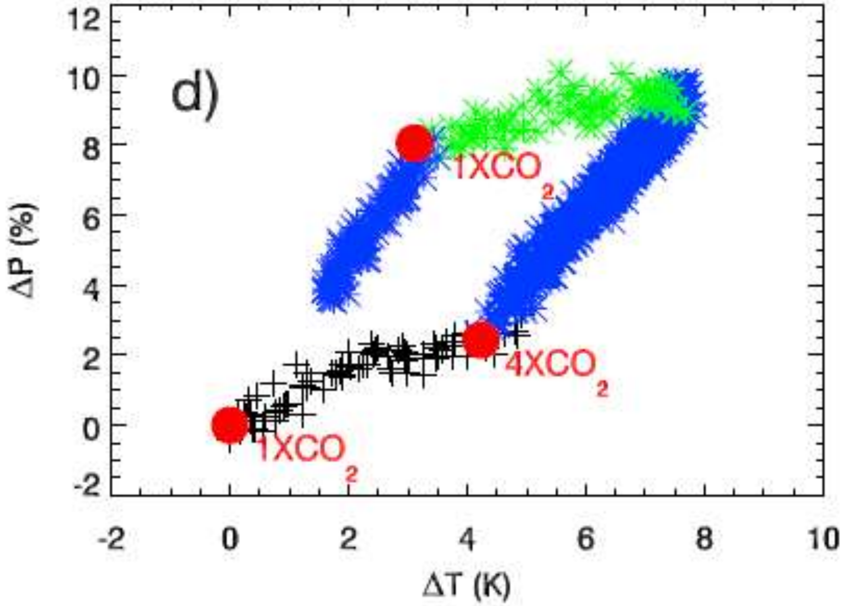


O’Gorman et al. (2012) Surv. Geophys; after Ming et al. (2010) GRL
See also Pendergrass & Hartmann (2012) GRL; Previdi (2010) ERL

Implications for transient responses

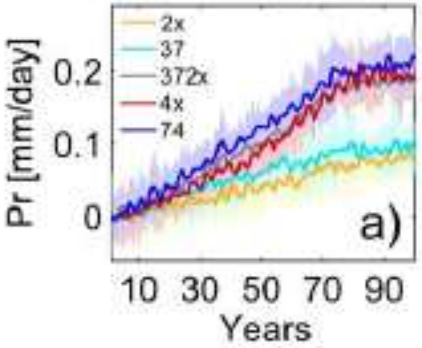


CMIP3 coupled model ensemble mean: Andrews et al. (2010) Environ. Res. Lett.



HadCM3: Wu et al. (2010) GRL

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



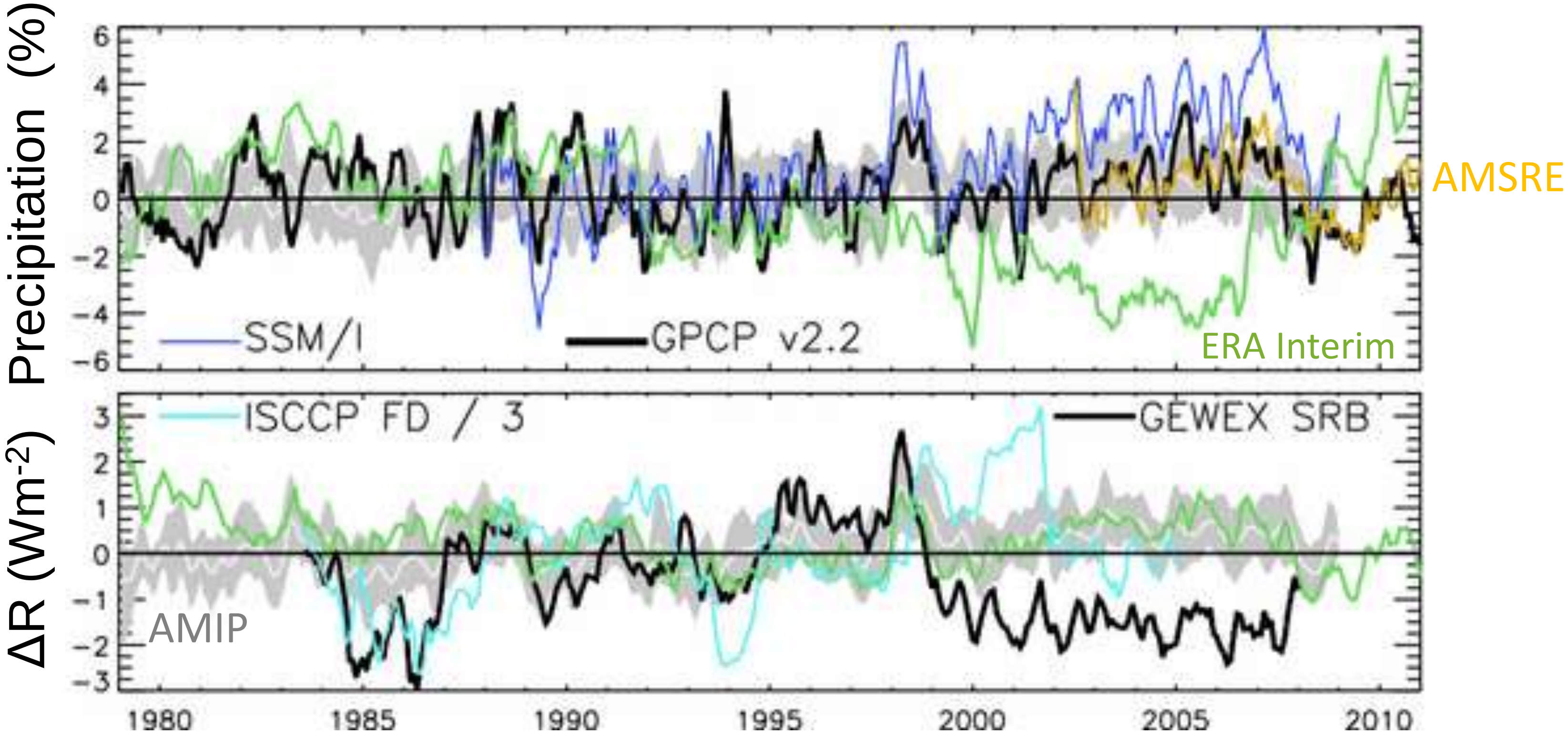
Degree of hysteresis determined by forcing related fast responses and linked to ocean heat uptake

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

How is global precipitation and radiative cooling currently changing?

GPCP

dP/dT ≈ 2.8 %/K

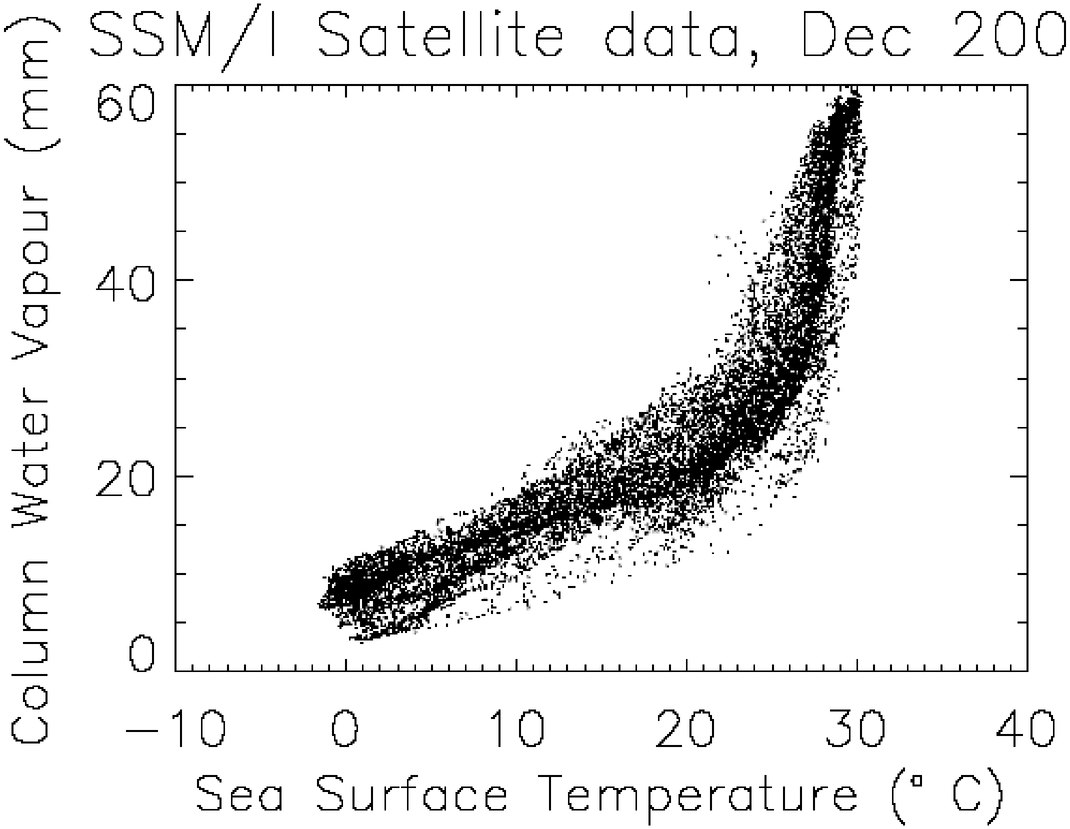


Allan et al. (2013) Surv. Geophys

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

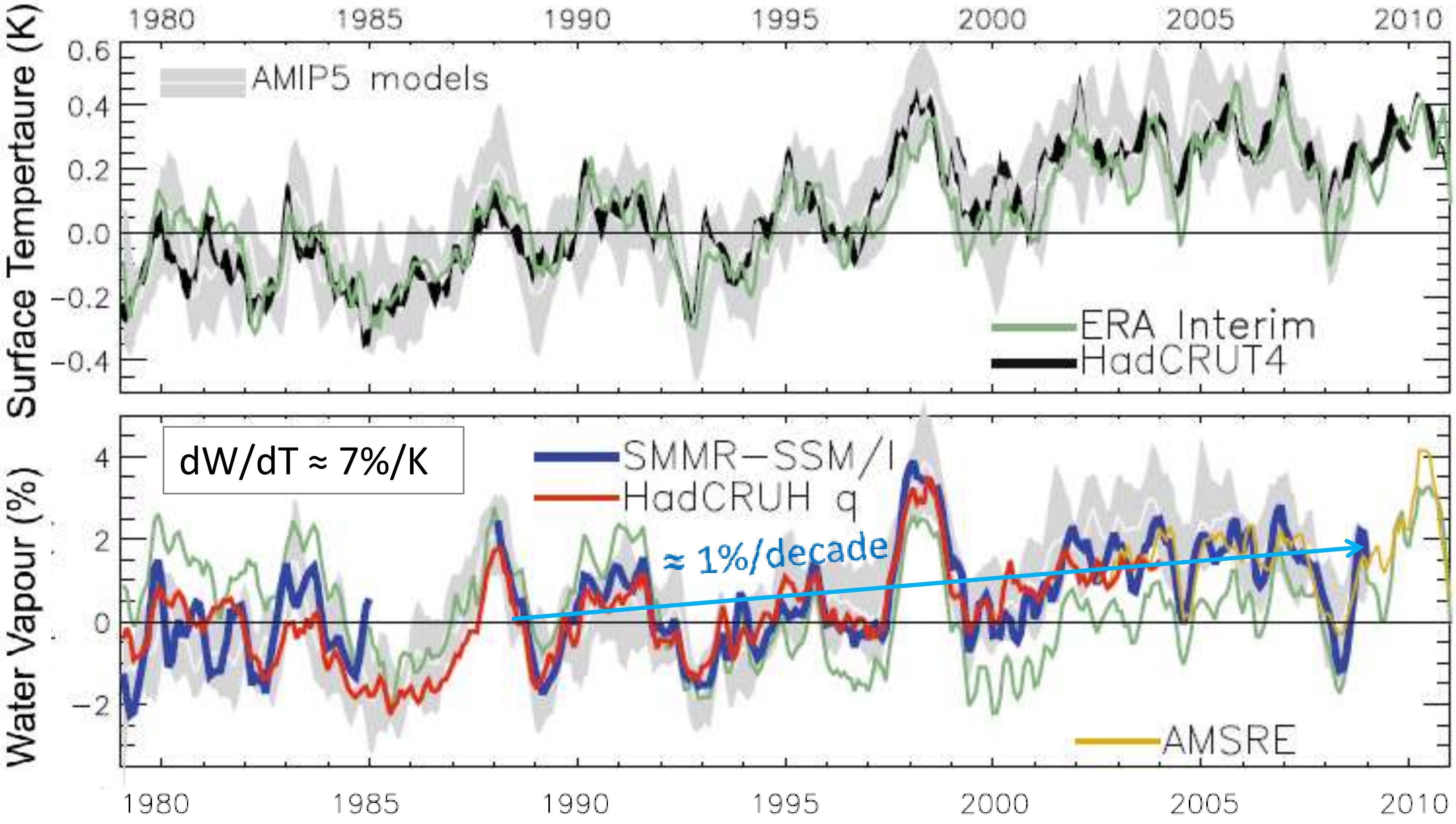


$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2}$$

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

- 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 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

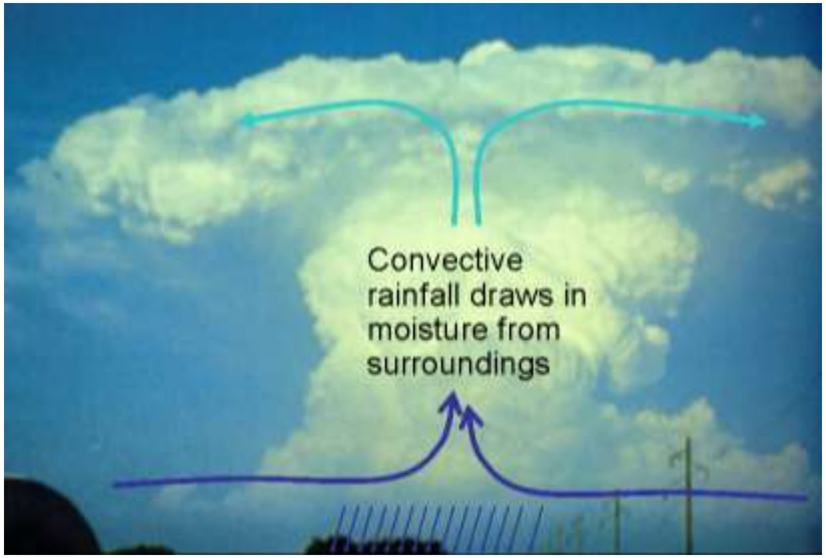
e.g. Allan & Soden (2008) Science

- 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



Convective rainfall draws in moisture from surroundings

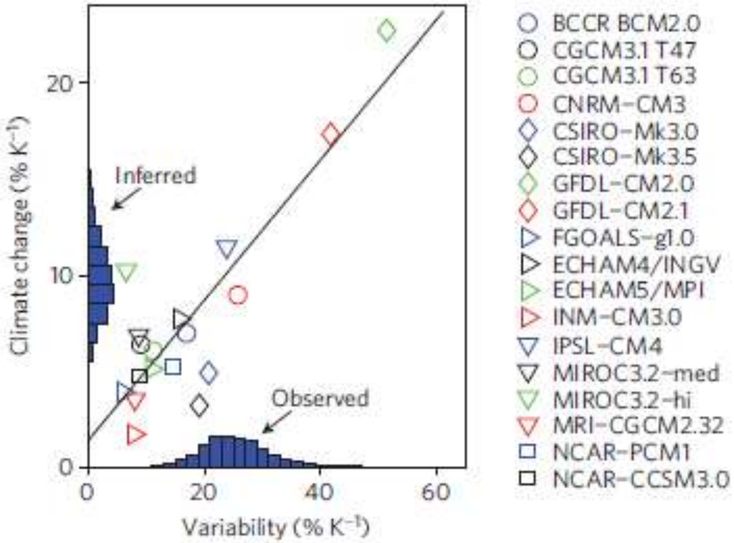
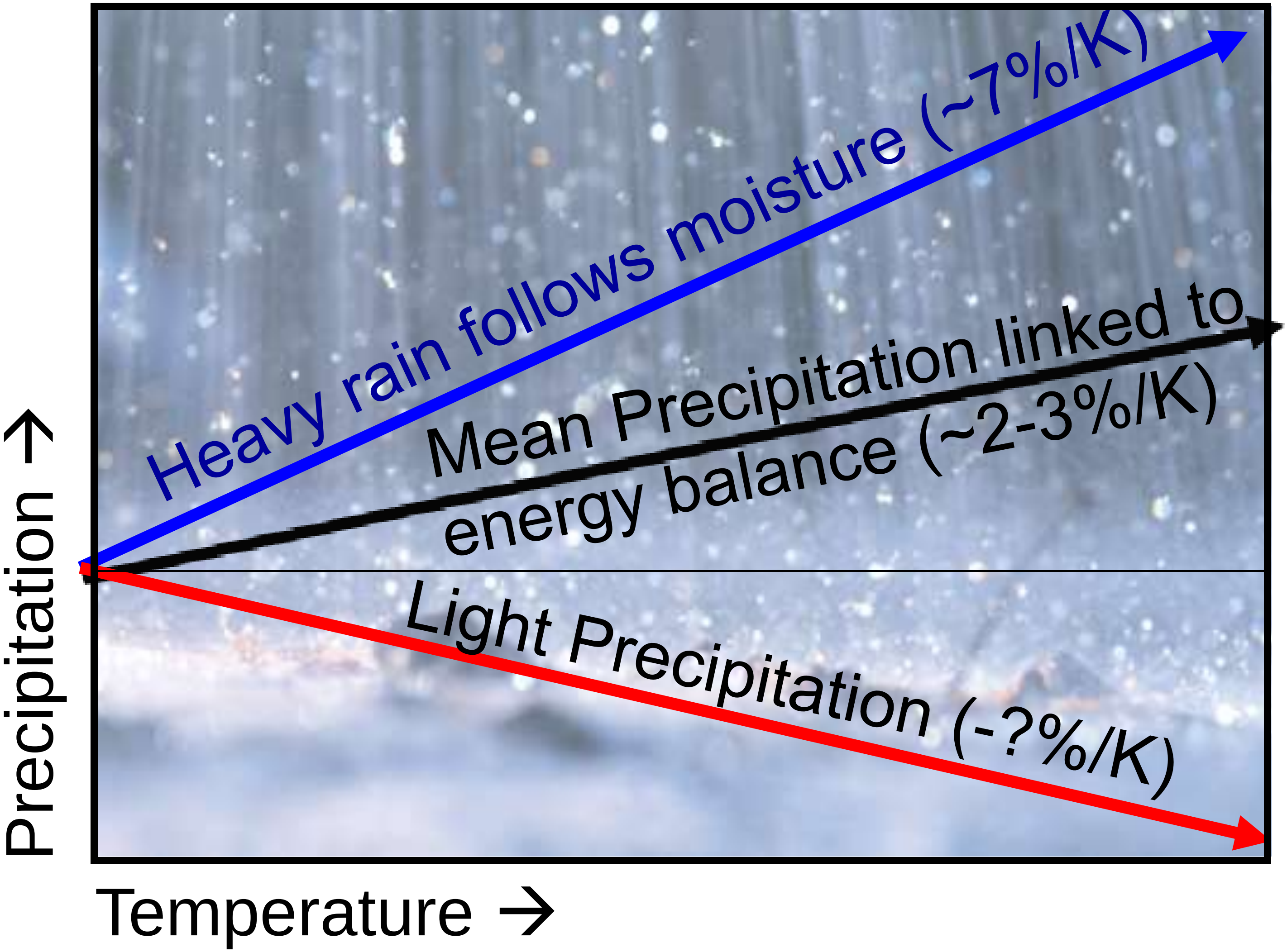


Figure 2 | Sensitivities (% K^{-1}) of the 99.9th percentile of precipitation for variability versus climate change in the CMIP3 simulations. The solid

Contrasting precipitation response expected



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

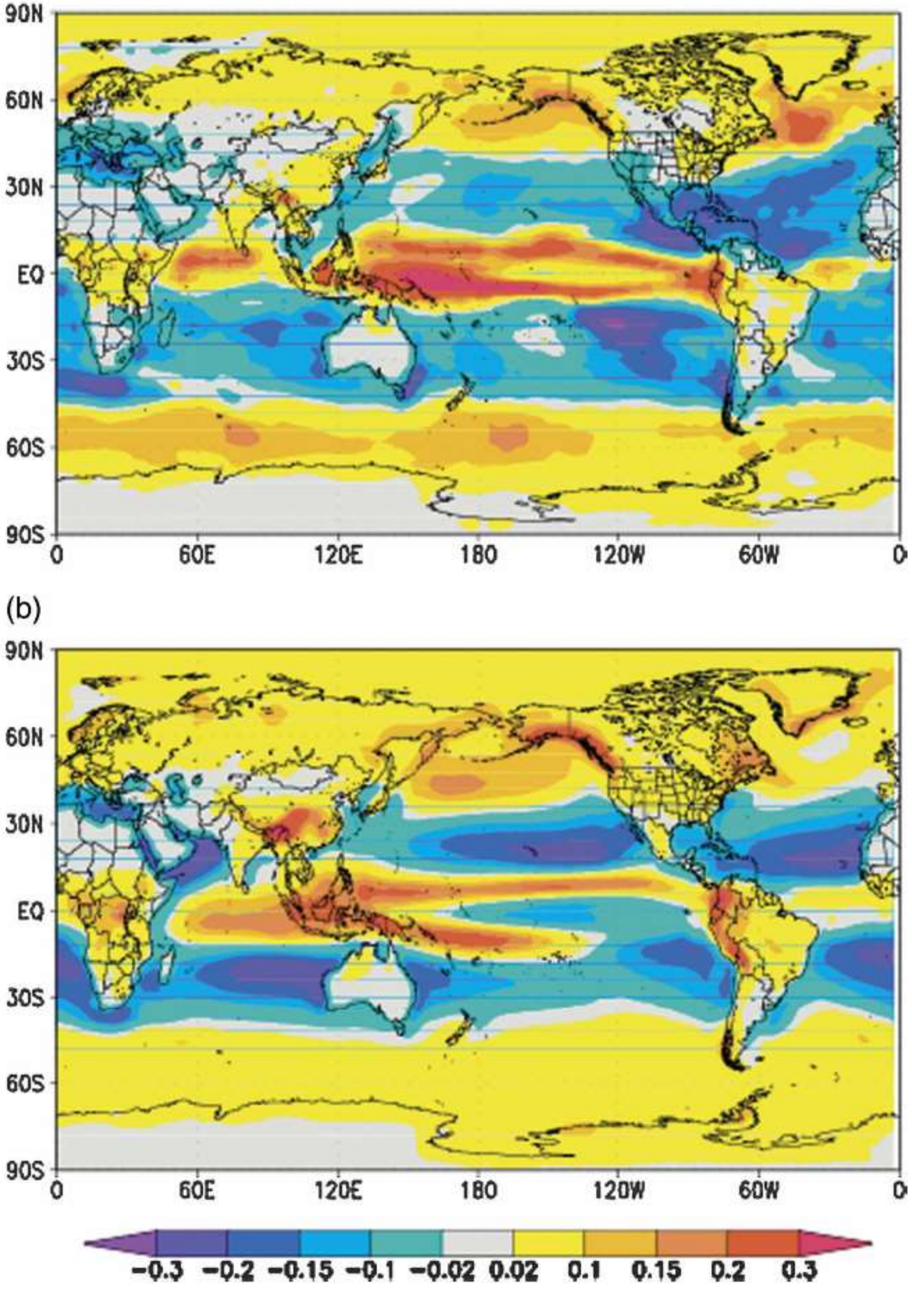


FIG. 7. The annual-mean distribution of $\delta(P-E)$ from the ensemble mean of (a) PCMDI AR4 models and (b) the thermodynamic component predicted from (6) from the SRES A1B scenario.

Moisture Balance

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

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

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) *QJRMS*

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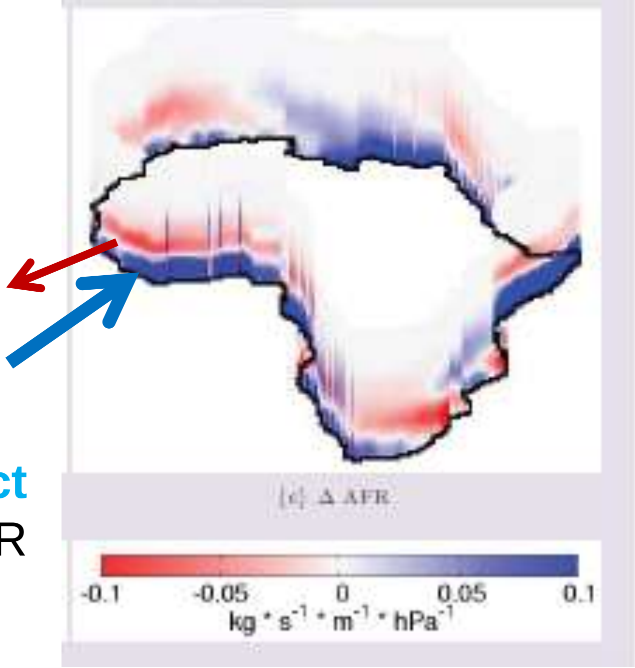
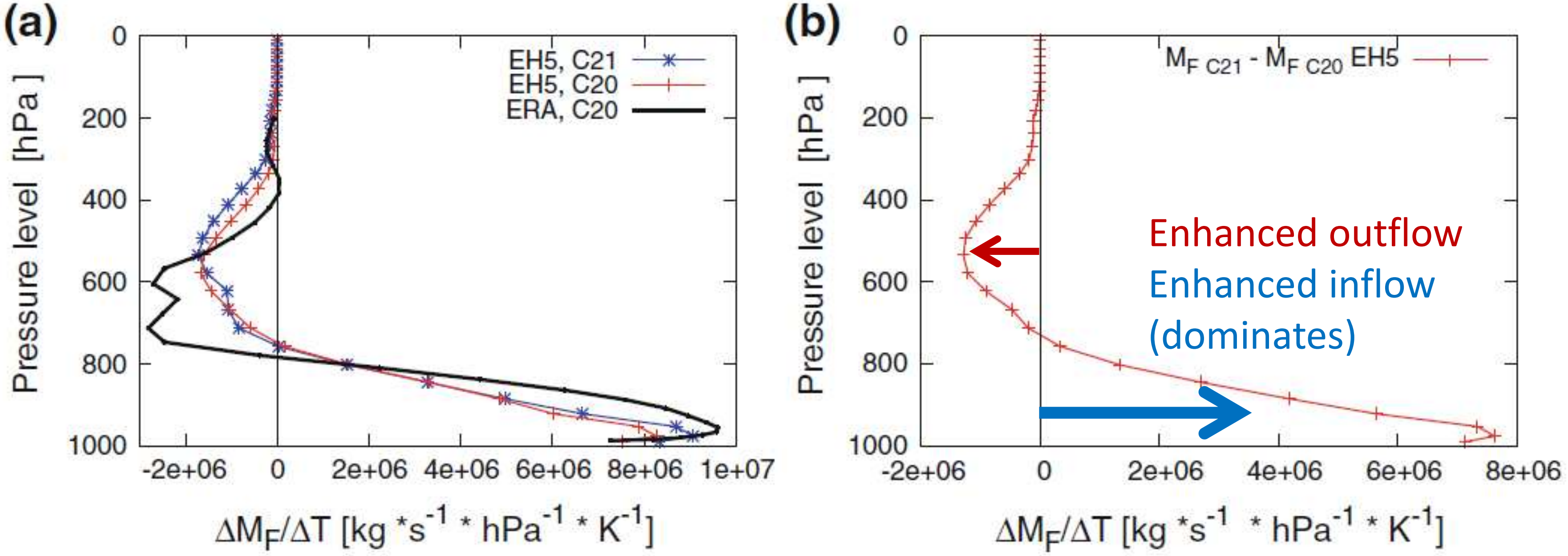
Enhanced moisture transports into the "wet" tropics, high latitudes and continents

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



PREPARE project

Zahn & Allan, submitted to WRR



Enhanced outflow

Enhanced inflow (dominates)

Allan et al. (2013) Surv. Geophys see also: Zahn and Allan (2013) J Clim

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

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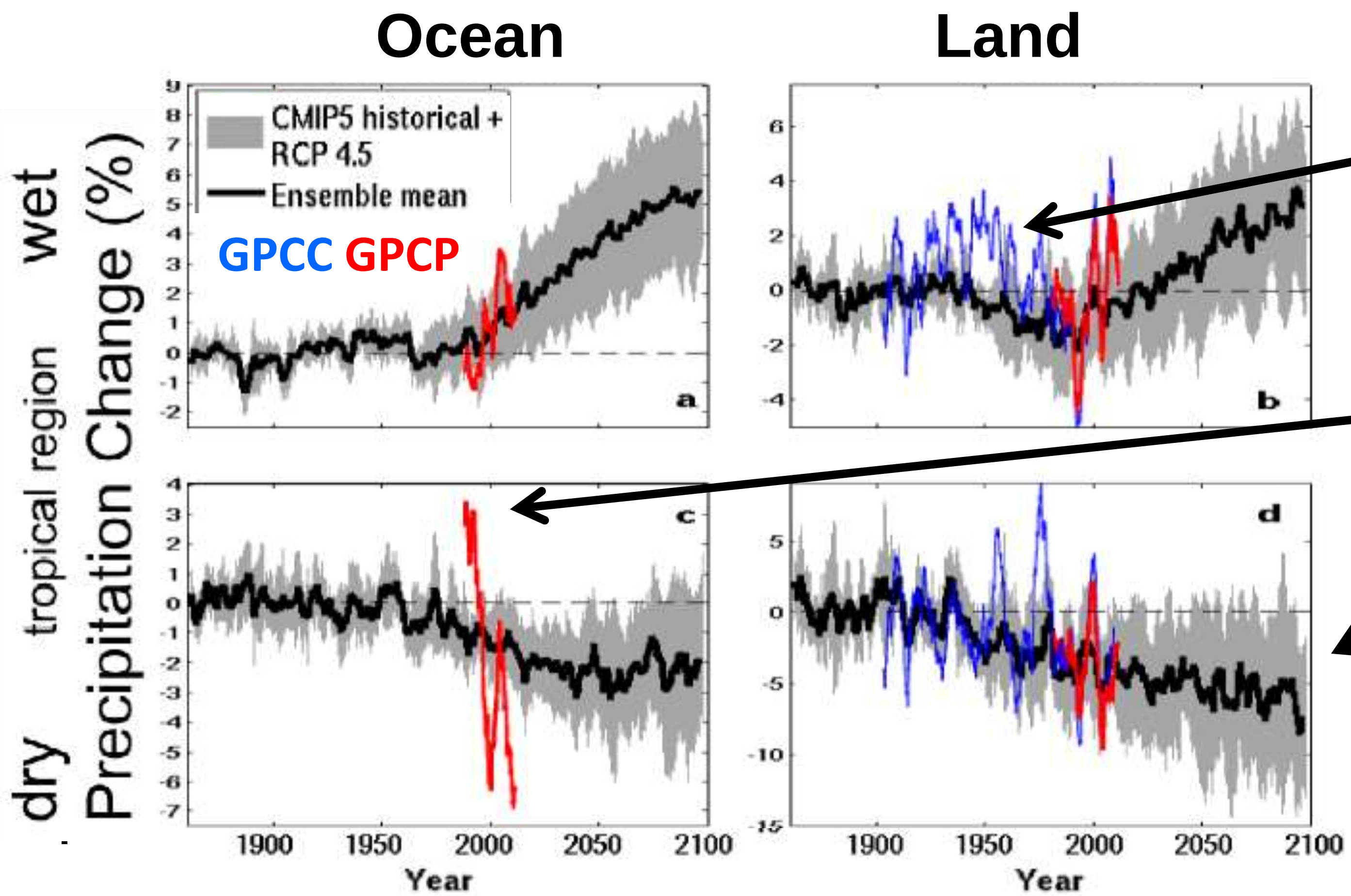
Changing water cycle



Wet land: strong ENSO influence

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

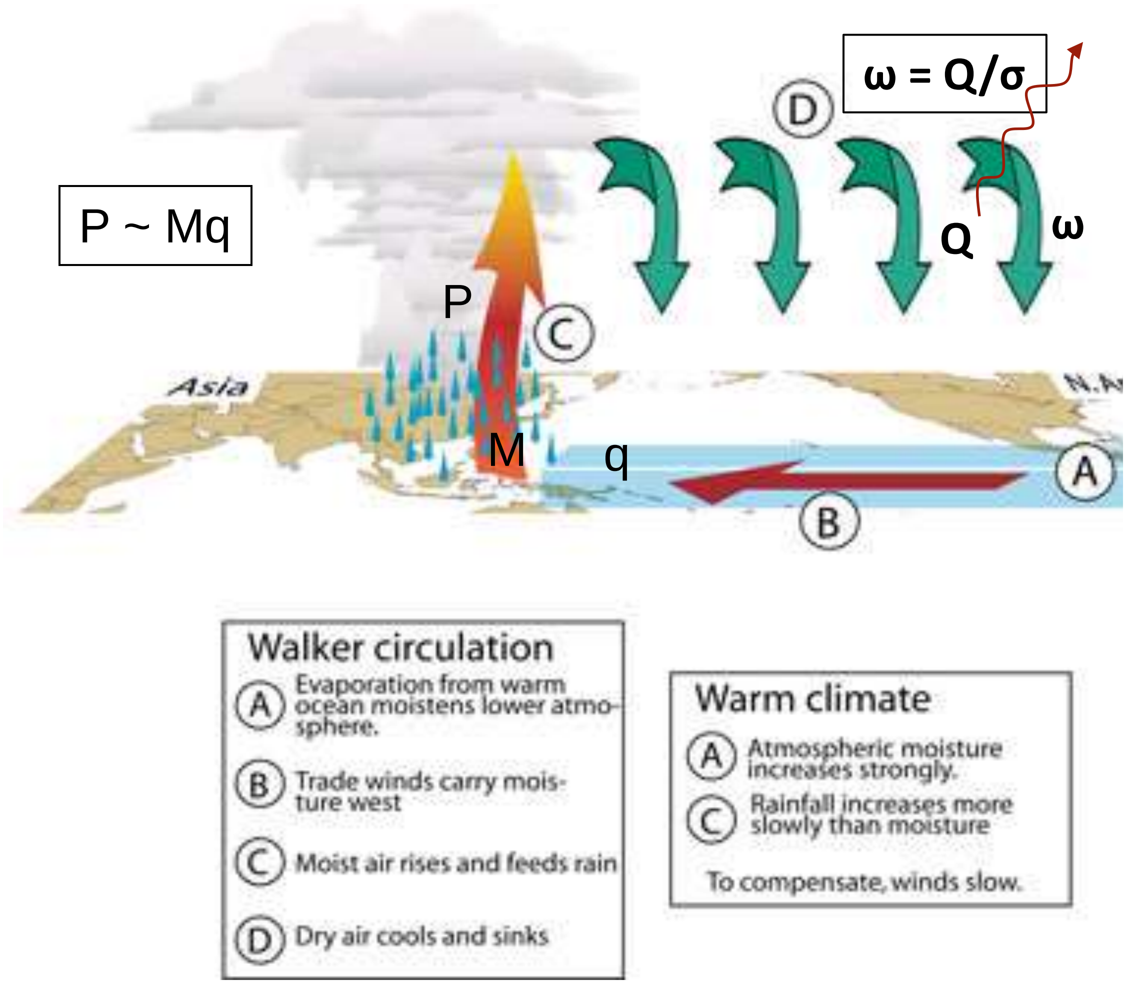
Robust drying of dry tropical land

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.*

Horyuji PAGODA
HydrOlogical cYcle Understanding via Process-bAsed GlObal Detection, Attribution and prediction

Circulation response



Walker circulation

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

Warm climate

- Ⓐ Atmospheric moisture increases strongly.
- Ⓒ 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:

$$\boldsymbol{\omega = Q/\sigma}$$

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

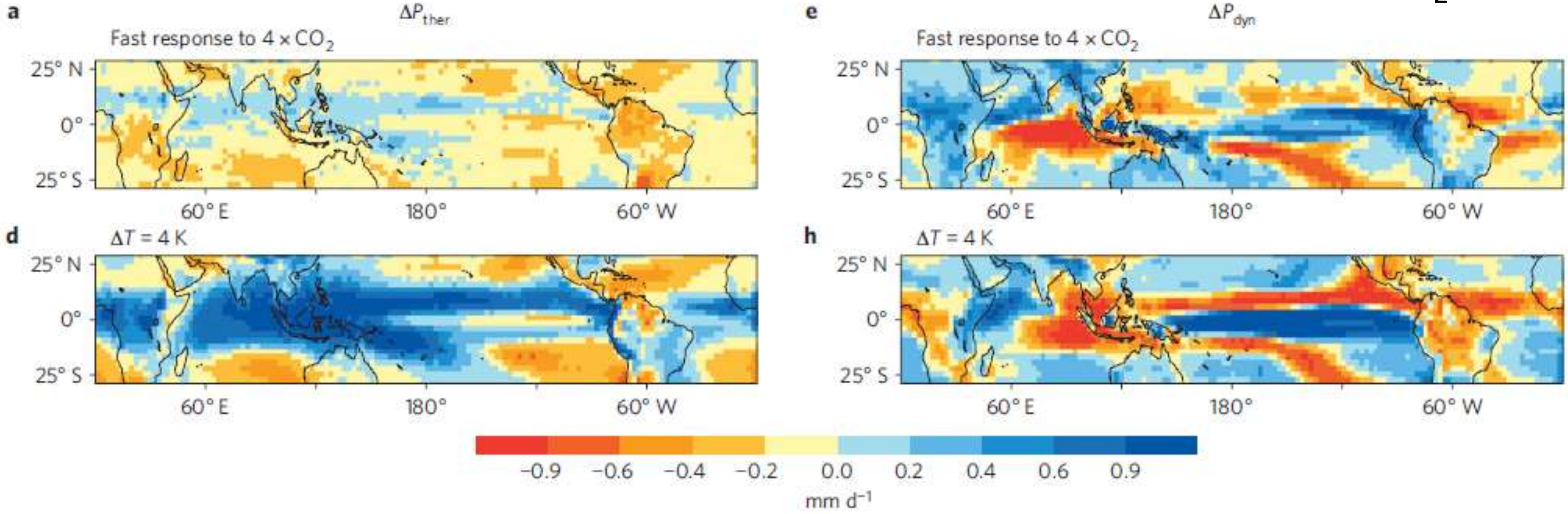
If Γ follows MALR → increased σ. This offsets Q effect on ω.

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

Walker circulation response to fast and slow precipitation effects

Thermodynamic response to warming

Fast response to CO_2

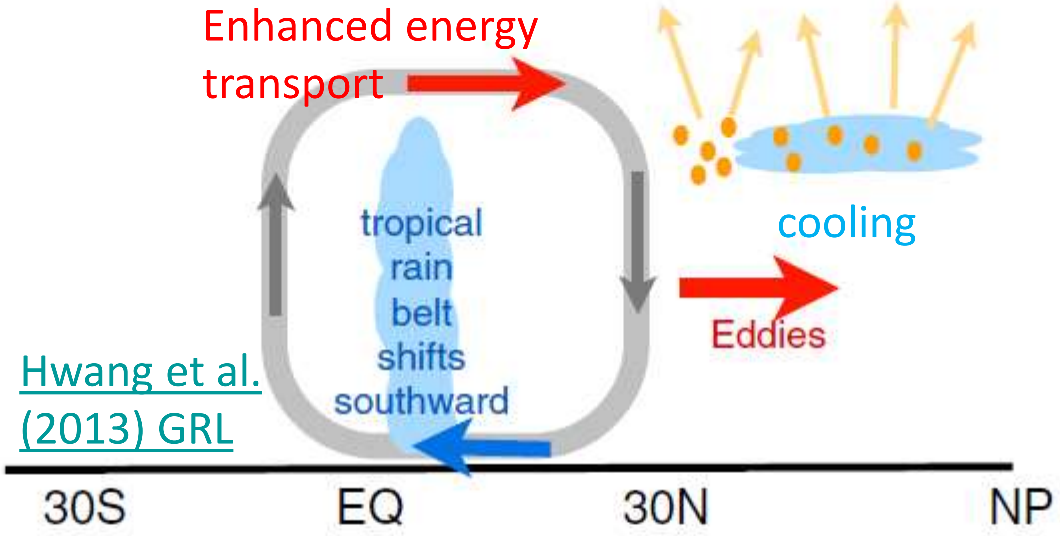


Bony et al. (2013) *Nature Geosciences* (see talk on Tuesday!)
Both fast and slow responses to CO_2 forcings induce reduced Walker circulation in response to P = Mq constraint

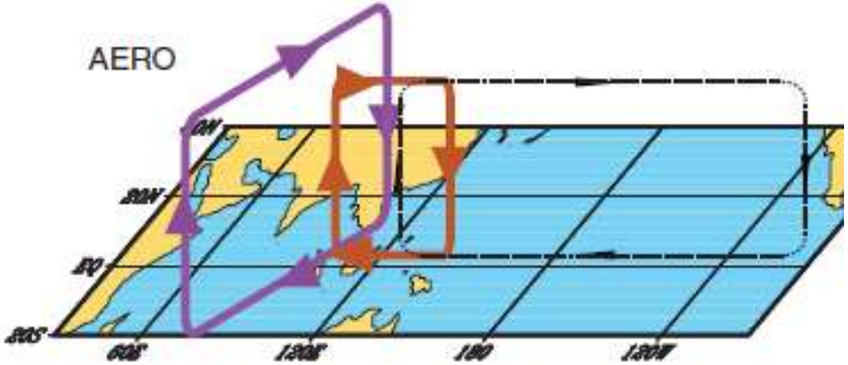
Reduced Walker circulation: Vecchi et al. (2006) *Nature* Recent strengthening of circulation? Merrifield (2011) *J Clim*; Sohn et al. (2011) *Clim Dyn*; L'Heureux et al. (2013) *Nature Climate*

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

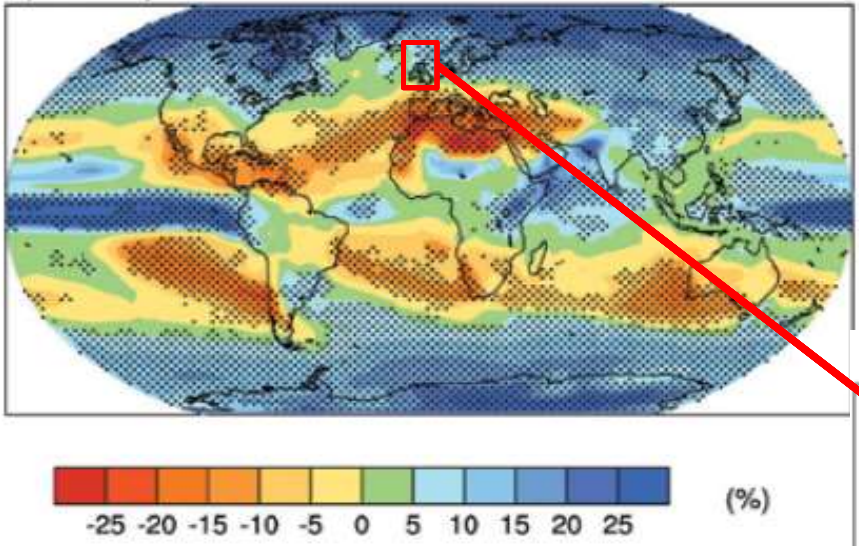


Hwang et al. (2013) GRL



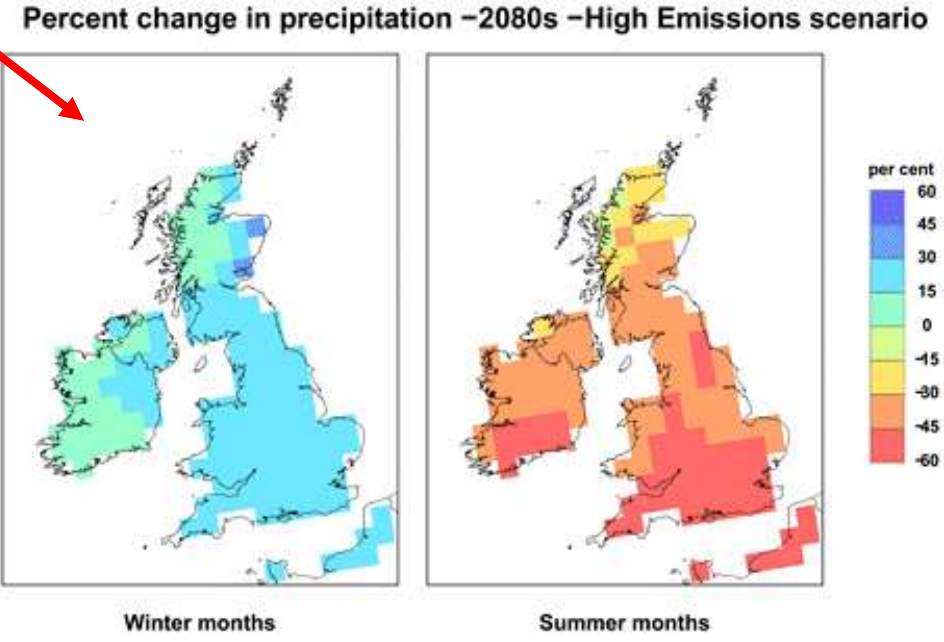
- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science
- Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn

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]( ))



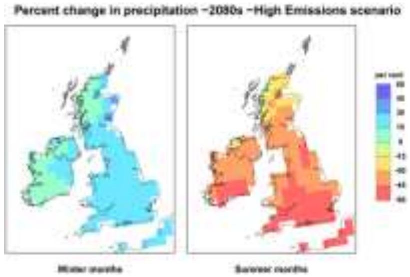
Percent change in precipitation –2080s –High Emissions scenario

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?

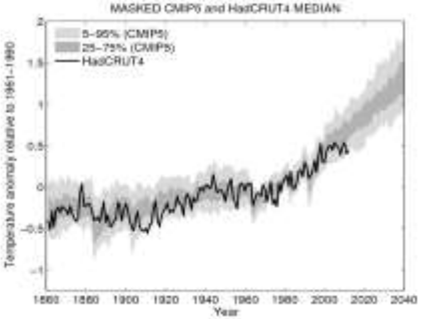
Outstanding Issues

- 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?



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 (~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 ≈ 0.6 Wm^{-2} over the last decade despite stable Surface Temperature

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Extra slides

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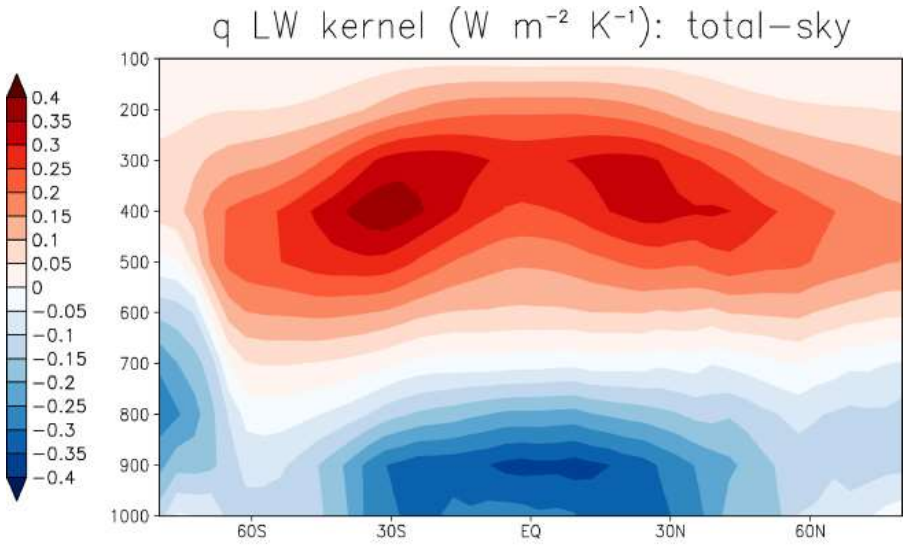
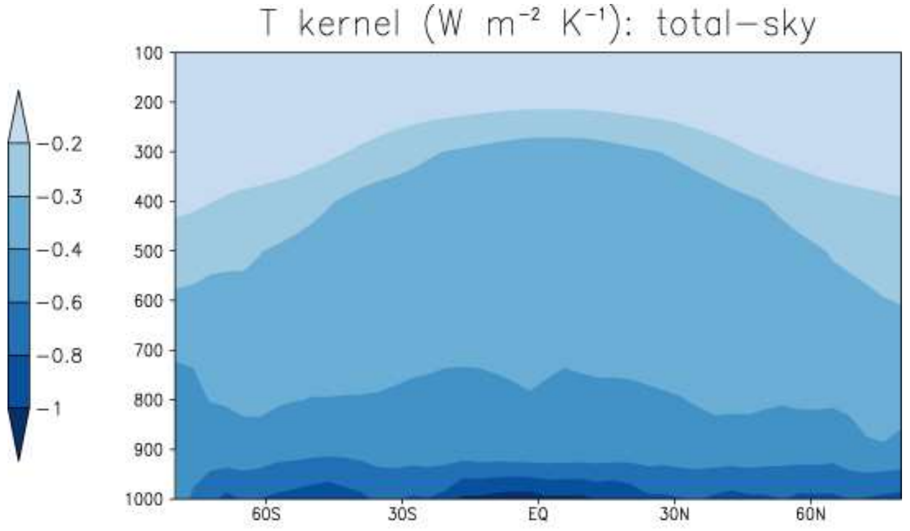
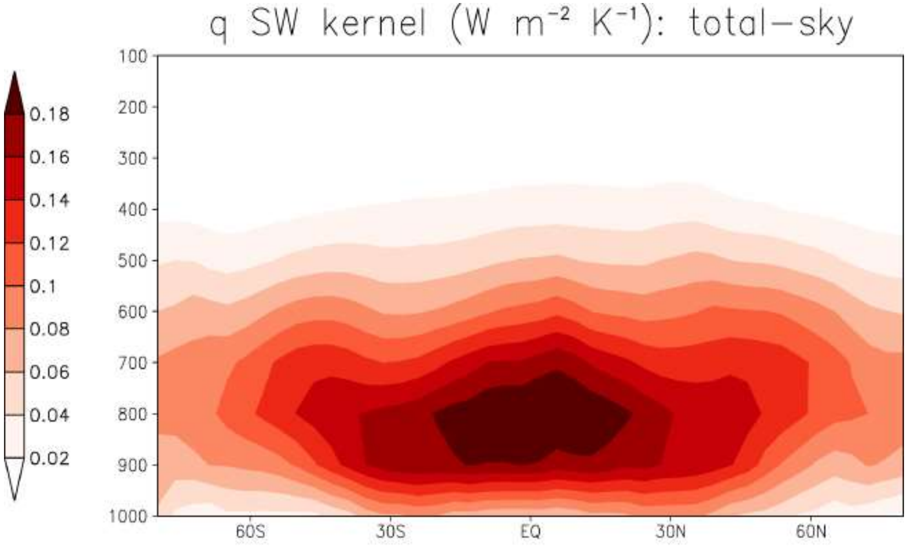
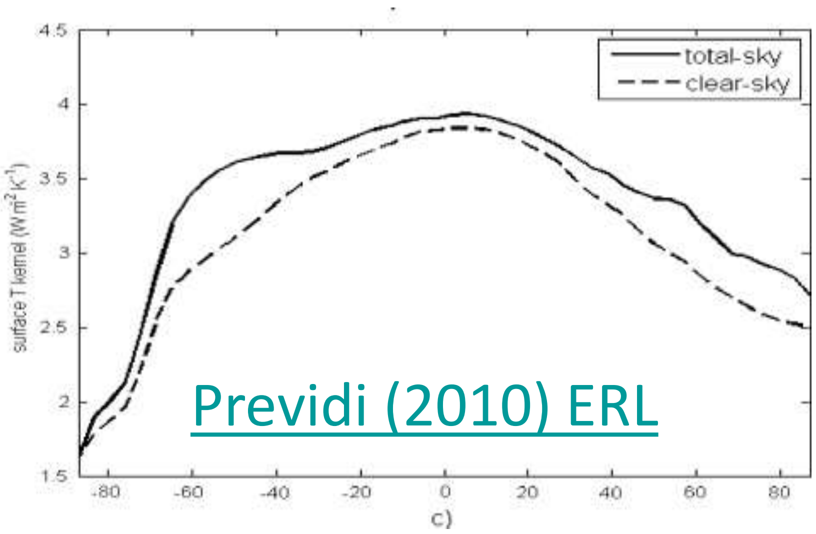
Altitude dependence of response (kernels)


q LW kernel (W m^{-2} K^{-1}): total−sky


T kernel (W m^{-2} K^{-1}): total−sky


q SW kernel (W m^{-2} K^{-1}): total−sky



Previdi (2010) ERL

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

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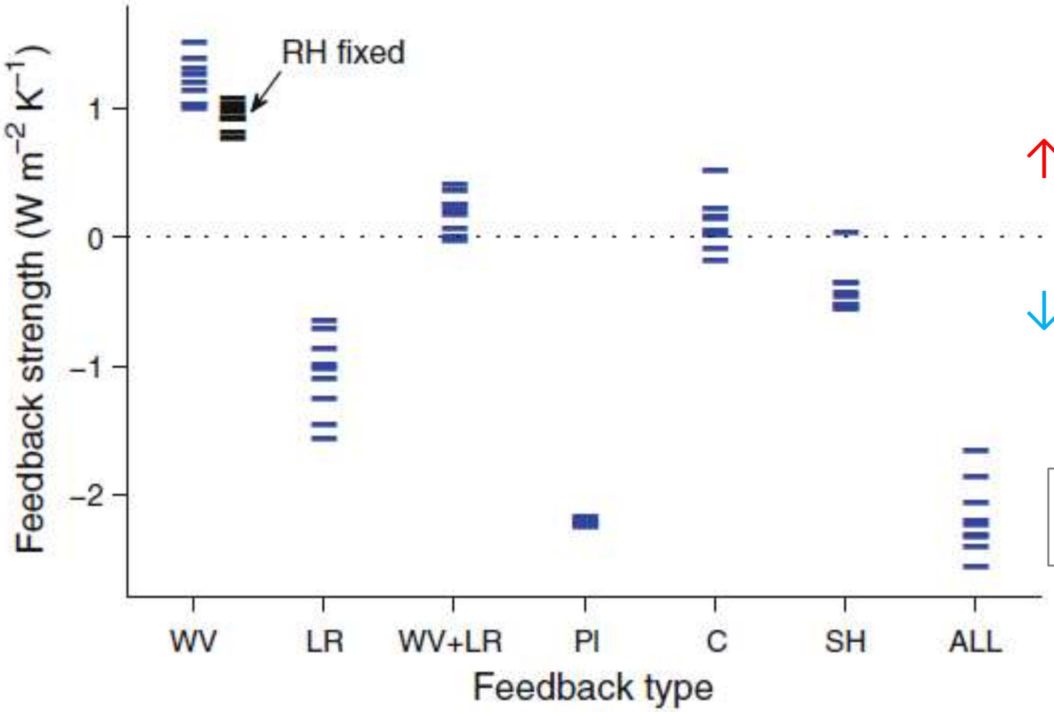
Quantifying Hydrological Feedbacks



↑ 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

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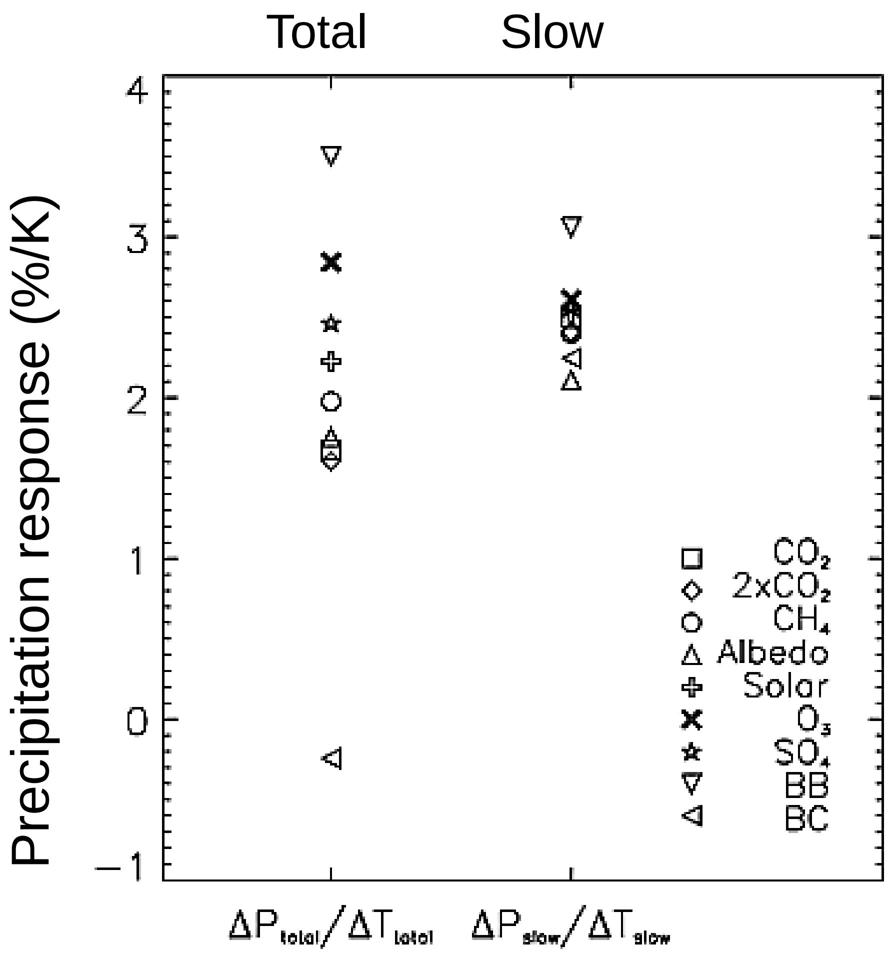
Forcing related fast responses



Andrews et al. (2010) GRL; see also Kvalevåg 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; Cao et al. 2012 ERL
- 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

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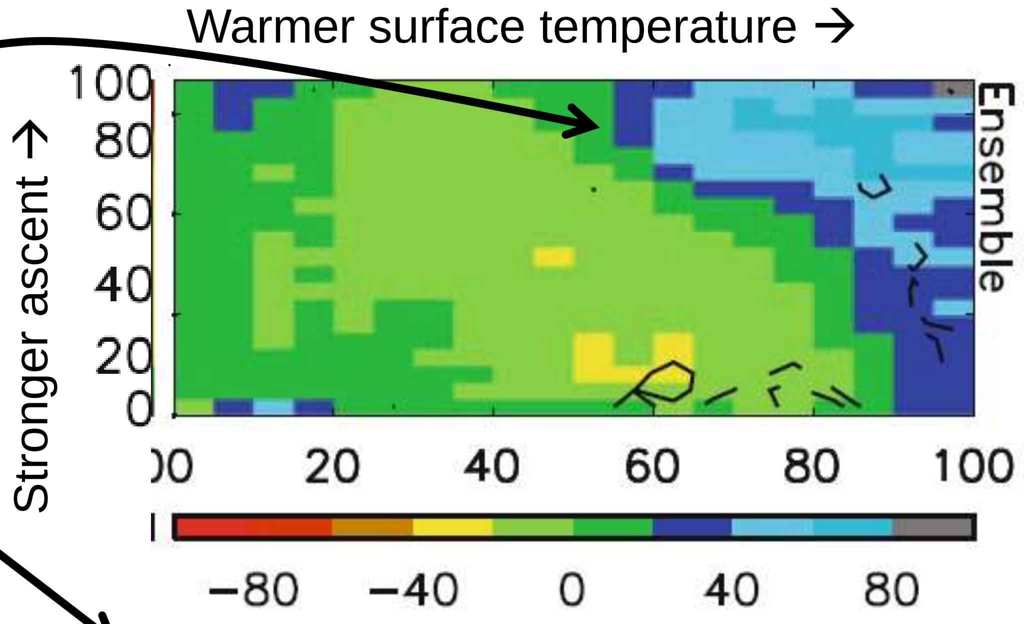
Fingerprints of precipitation response by dynamical regime

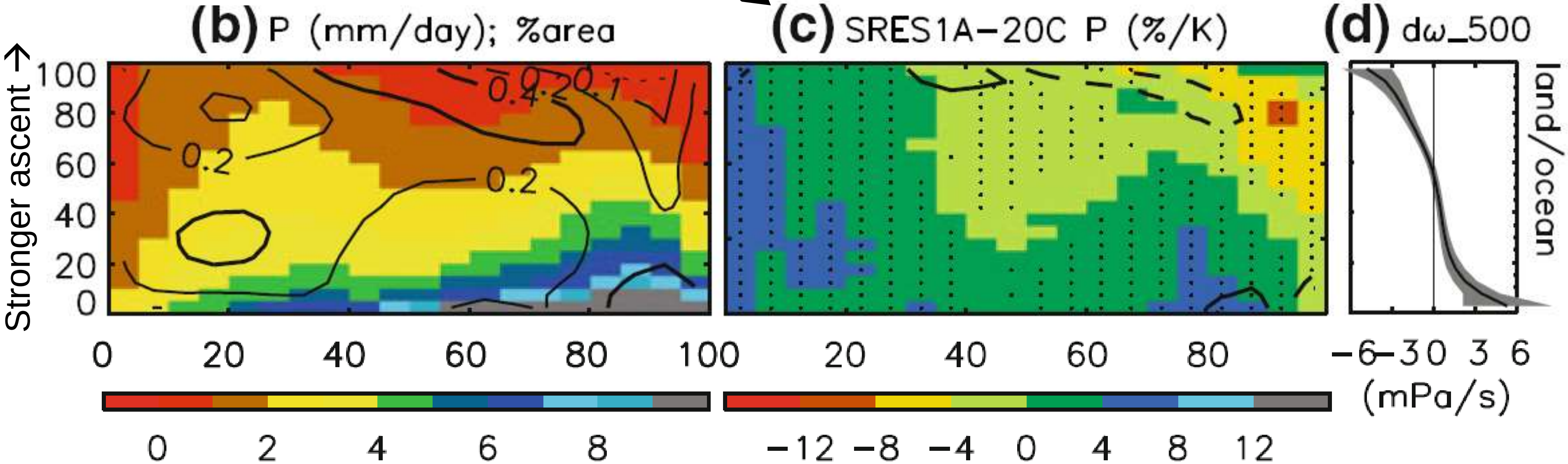
University of Reading

PREPARE project



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

Allan (2012) Clim. Dyn.



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NATURAL ENVIRONMENT RESEARCH COUNCIL

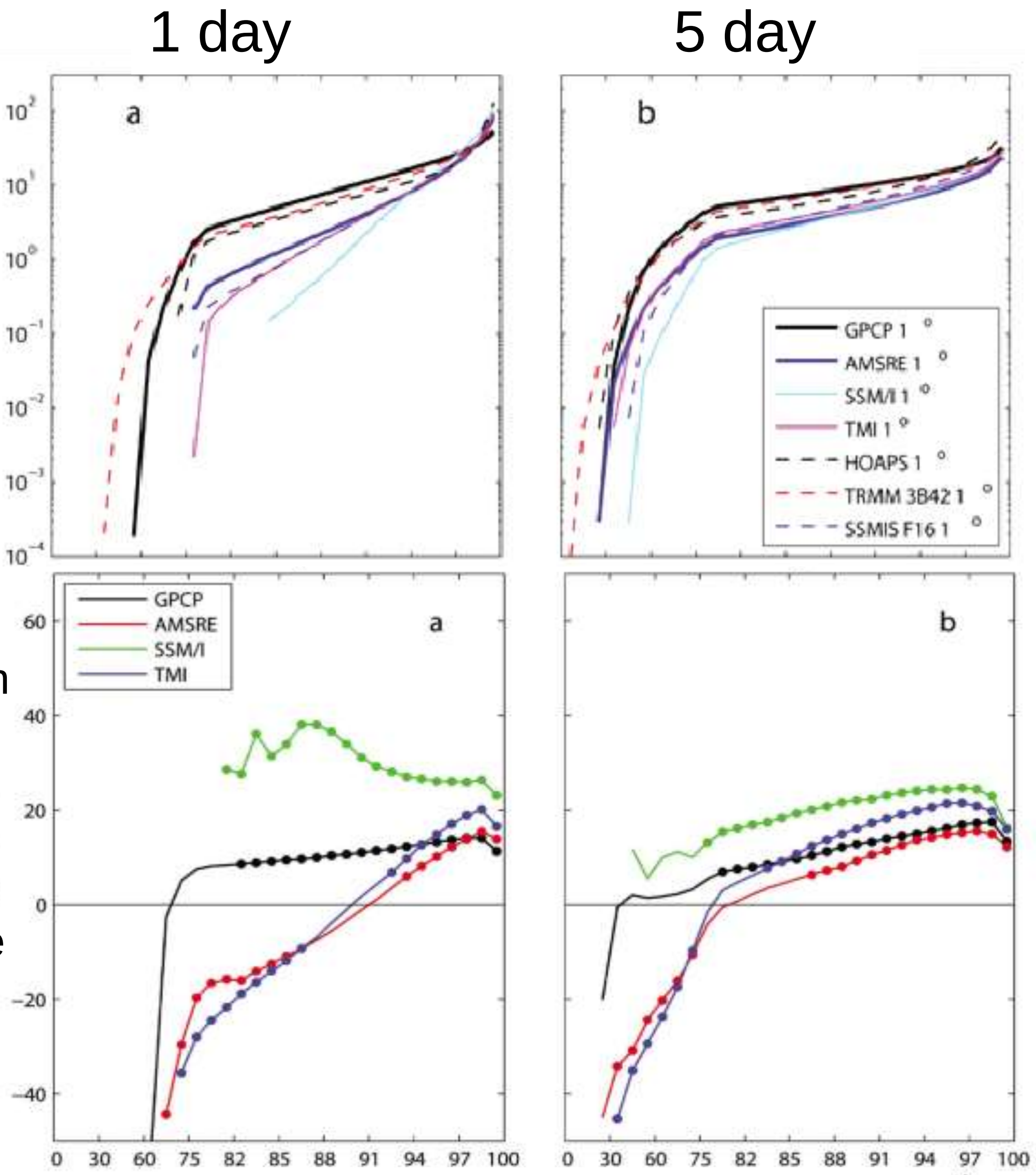
Changing water cycle

Uncertainty in observed P intensity & response

(tropical oceans)

Precipitation intensity (mm/day)

Precipitation intensity change with mean surface temperature (%/day)



Precipitation intensity percentile (%)

Liu & Allan (2012) JGR

Horyuji PAGODA

HydrOlogical cYcle Understanding via Process-bAsed GlObal Detection, Attribution and prediction

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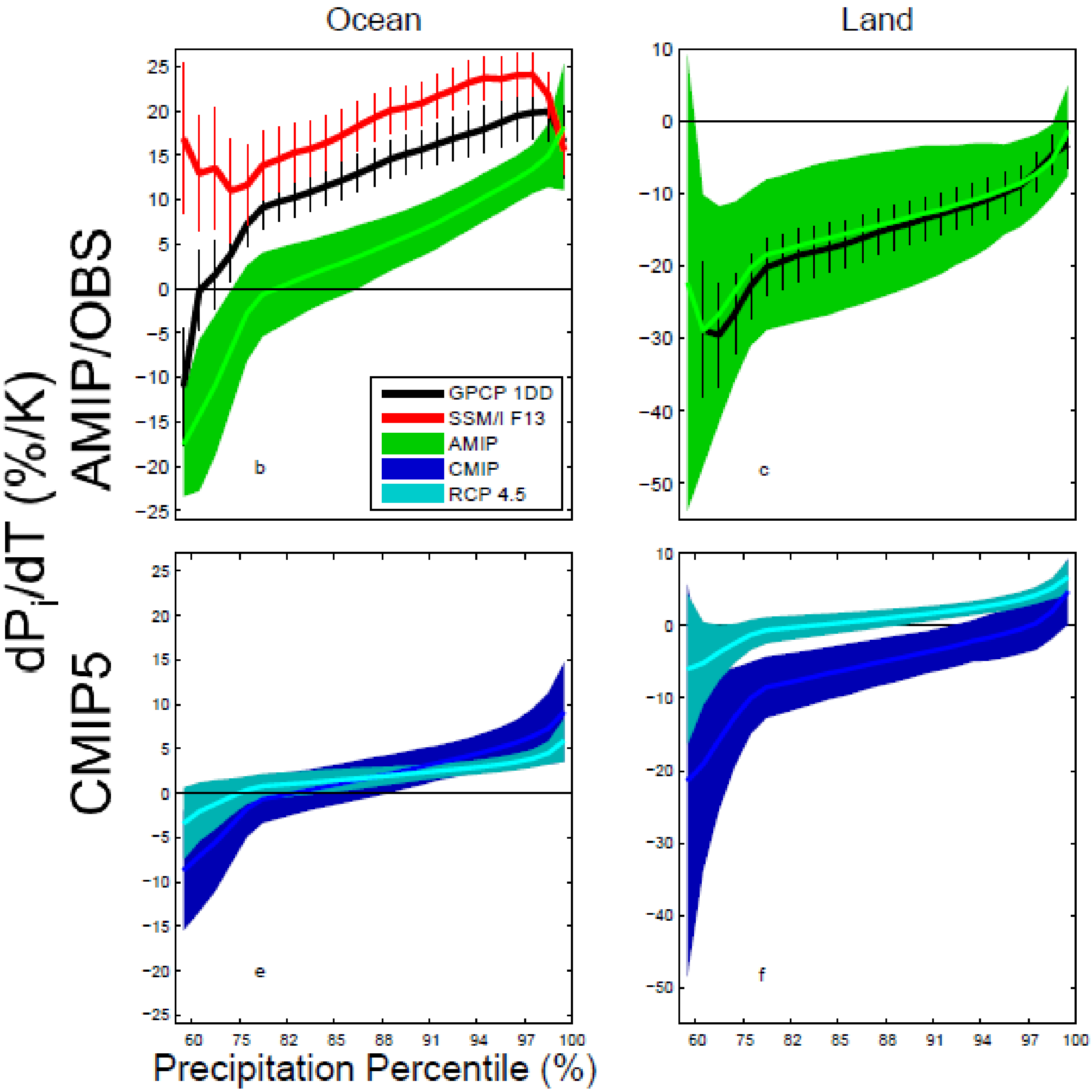
Response of Precipitation intensity distribution to warming:

Observations and CMIP5, 5-day mean

Is present day variability a good proxy for climate response?



Allan et al. (2013) Surv. Geophys