Current Changes in Earth's Energy Imbalance and the Global Water Cycle

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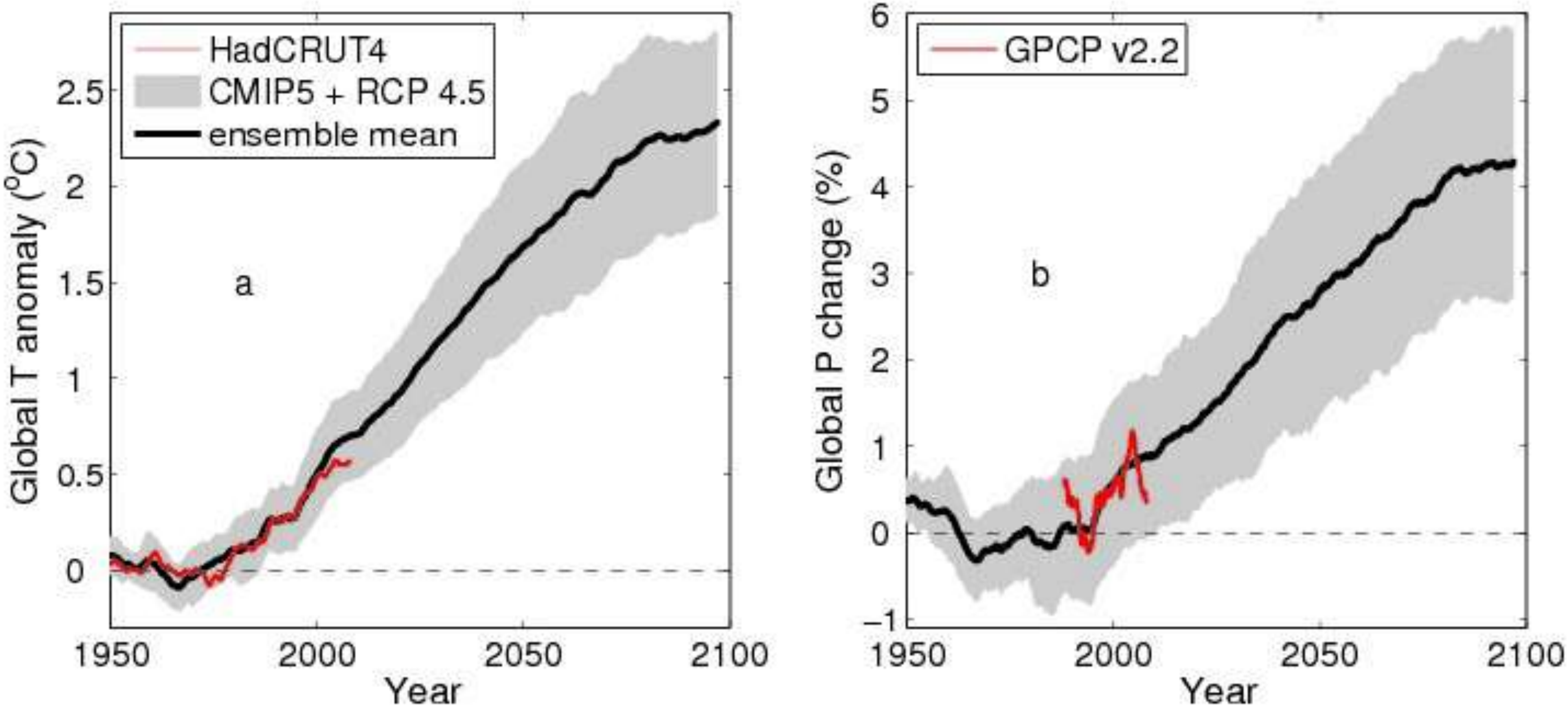
NCAS-Climate/NCEO

Thanks to Chunlei Liu, David Lavers, Matthias Zahn, Norman Loeb, John Lyman, Greg Johnson, Brian Soden, Viju John

University of Reading | National Centre for Atmospheric Science, Natural Environment Research Council | National Centre for Earth Observation, Natural Environment Research Council | Walker Institute

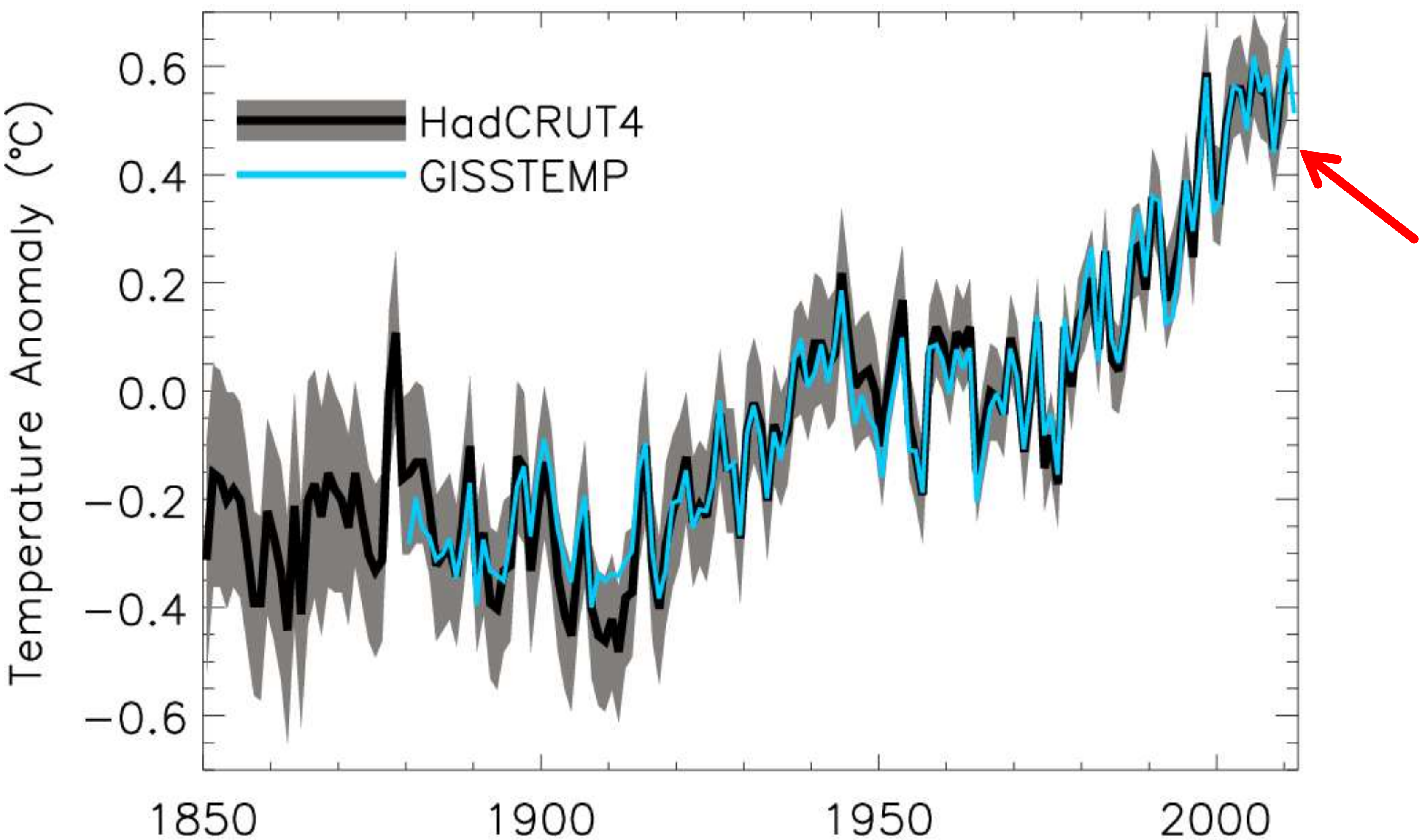
How is global climate change doing?



Part 1: Global Heating

Part 2: Global Water Cycle

Decline in rate of surface warming?



Global annual average temperature anomalies relative to 1951–1980 mean (shading denotes lower and upper 95% uncertainty range for HadCRUT4)

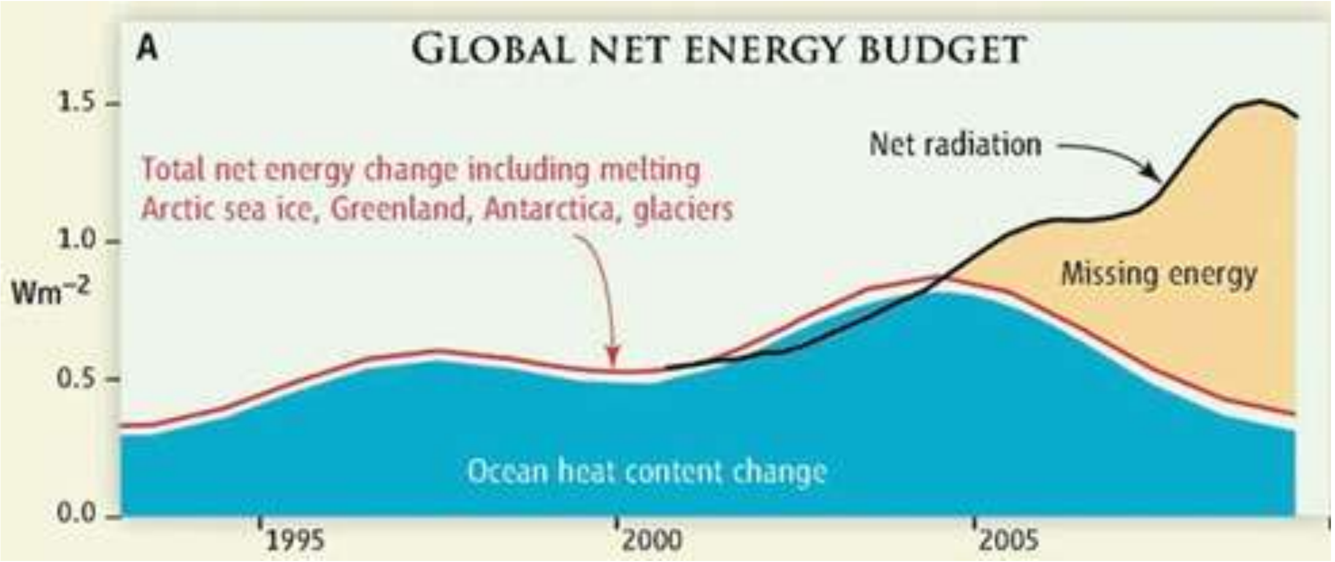
Radiative forcing or energy redistribution?

- Small, persistent volcanic forcing?
  - e.g. Solomon et al. (2011) Science
- Sulphur emissions?
  - e.g. Kaufmann et al. (2011) PNAS
- Stratospheric water vapour?
  - e.g. Solomon et al. (2010) Science
- Solar output?
- Cloud forcing/feedbacks & El Nino?
- Ocean circulation e.g. Modelling studies:

  Meehl et al. (2011) Nature Climate Change ,
  Palmer et al. (2010) GRL ,
  Katsman and van Oldenborgh (2011) GRL

Missing energy?

- Trenberth and Fasullo (2010, Science) highlighted an apparent large discrepancy between net radiation and ocean heat content changes



We undertook a reanalysis of the satellite and ocean record over the period 2000-2010…

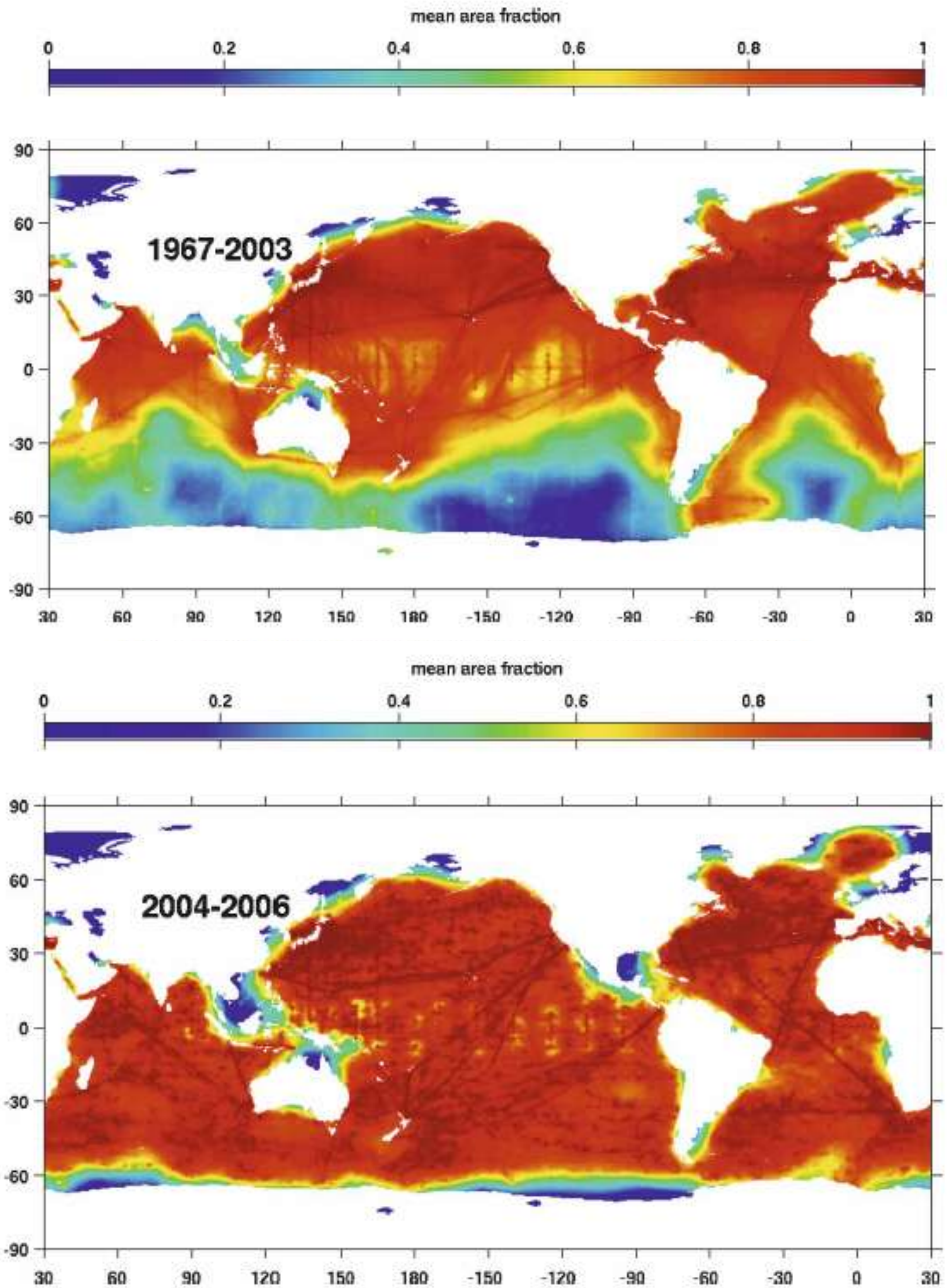


FIG. 4. Mean of annual "observed" area coverage from 2004 to 2006.

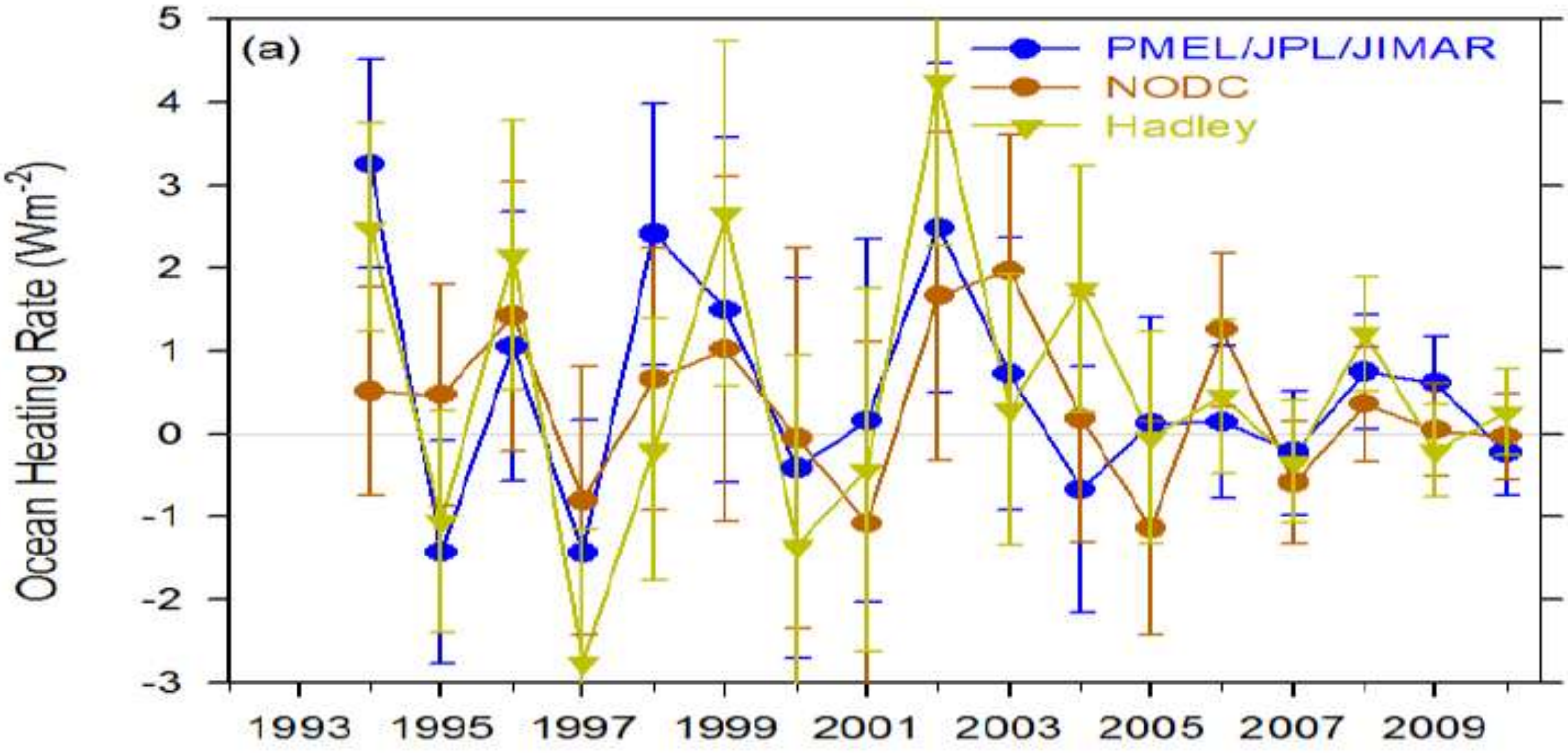
Ocean Heat Content data

- Use weighted integral to account for changes in data coverage
- Ensures transition to ARGO era does not introduce spurious variability
- Integrate ocean heat content trend over time and divide by Earth's surface area → Wm^{-2}

Lyman & Johnson (2008) J Clim

Ocean heat content data uncertainty

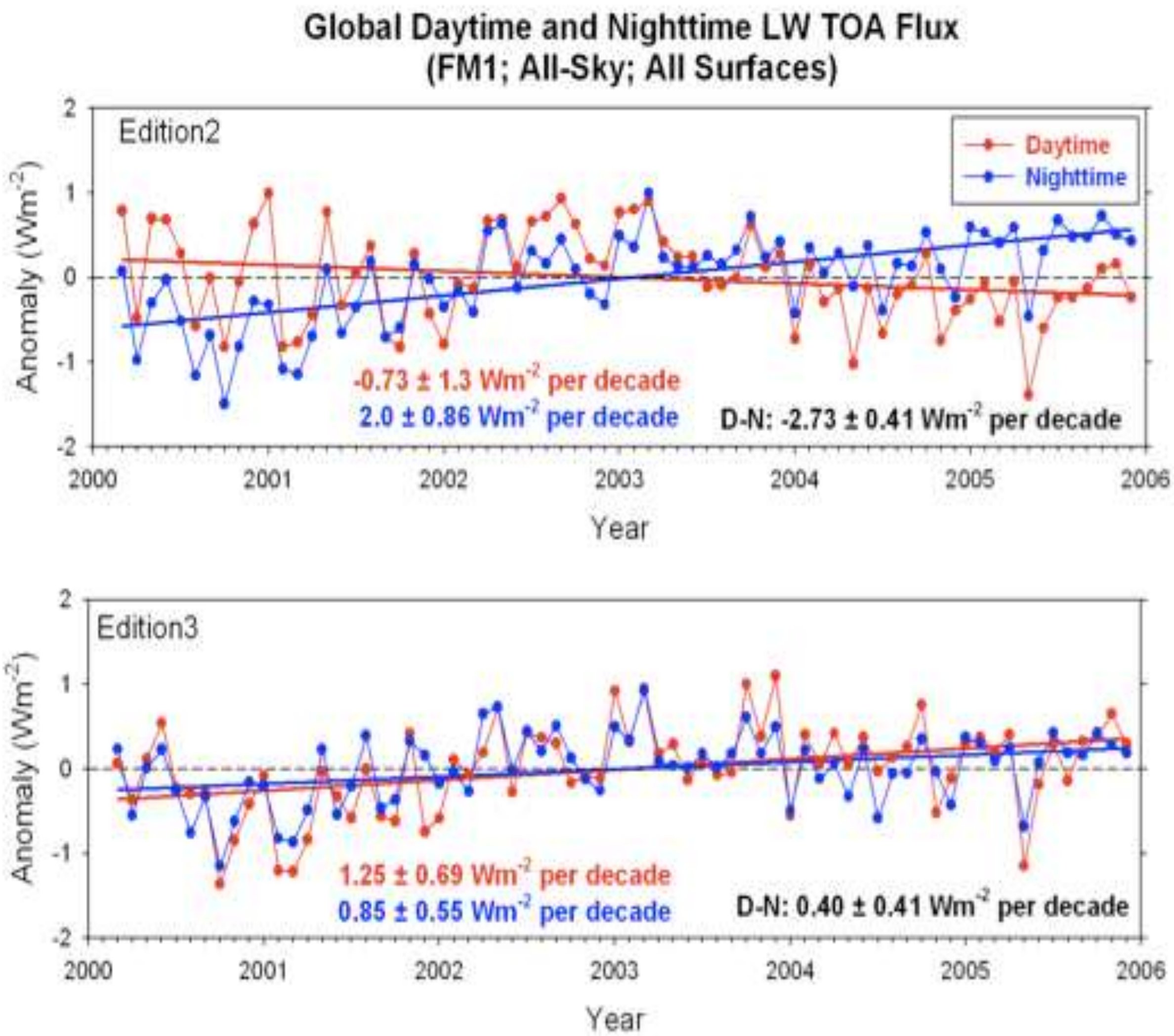
- Accounting for considerable sampling/structural uncertainty we find no evidence for a robust decline in ocean heating rate since 2005



Loeb et al. (2012) Nat. Geosci

Updated CERES satellite data

- Global Earth Radiation Balance
- Correction for degradation of shortwave filter
- Correction also improves physical consistency of trends in daytime longwave

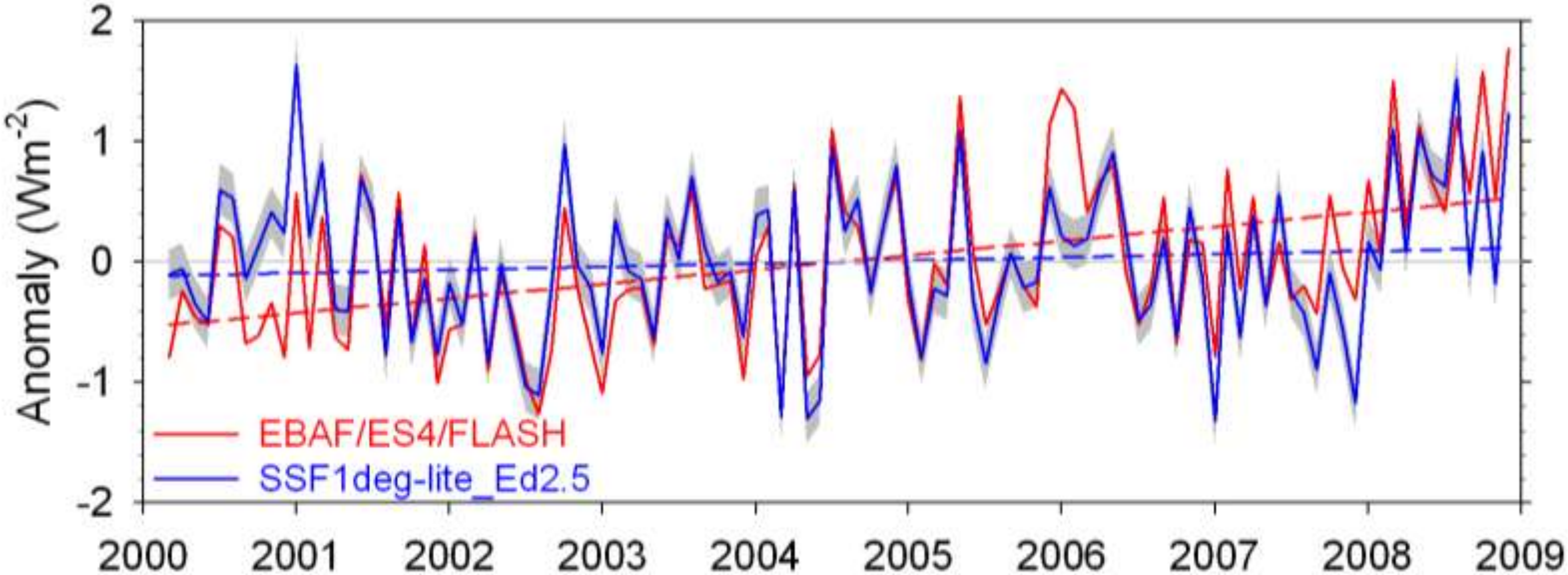


We use version CERES_EBAF-TOA_Ed2.6r

Trends in net radiation

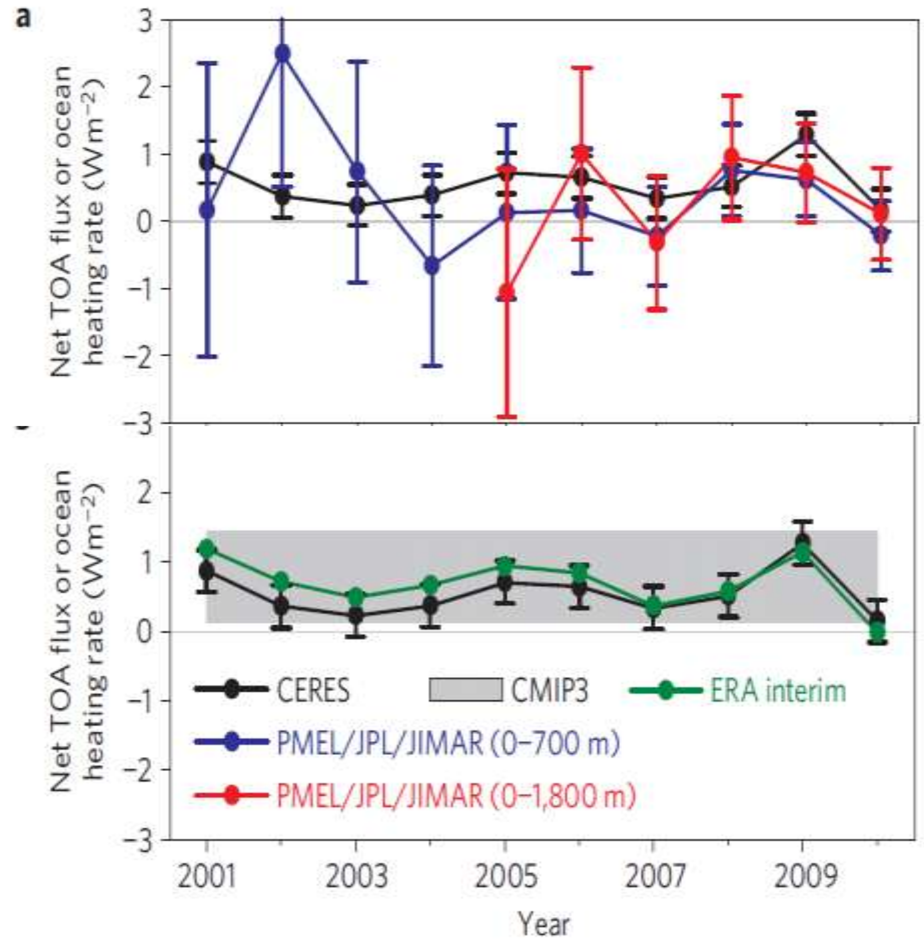
- Errors in satellite sensors and inappropriate use of satellite products explain much of large rise in net radiative flux shown by Trenberth and Fasullo (2010)

global net radiation anomalies



Combining Earth Radiation Budget and Ocean Heat Content data

- Tie 10-year CERES record with SORCE TSI and ARGO-estimated heating rate 2005-2010
- Best estimates for additional storage terms
- Variability relating to ENSO reproduced by CERES and ERA Interim
- Estimate of decade long net energy imbalance of **0.50±0.43 Wm^{-2}**

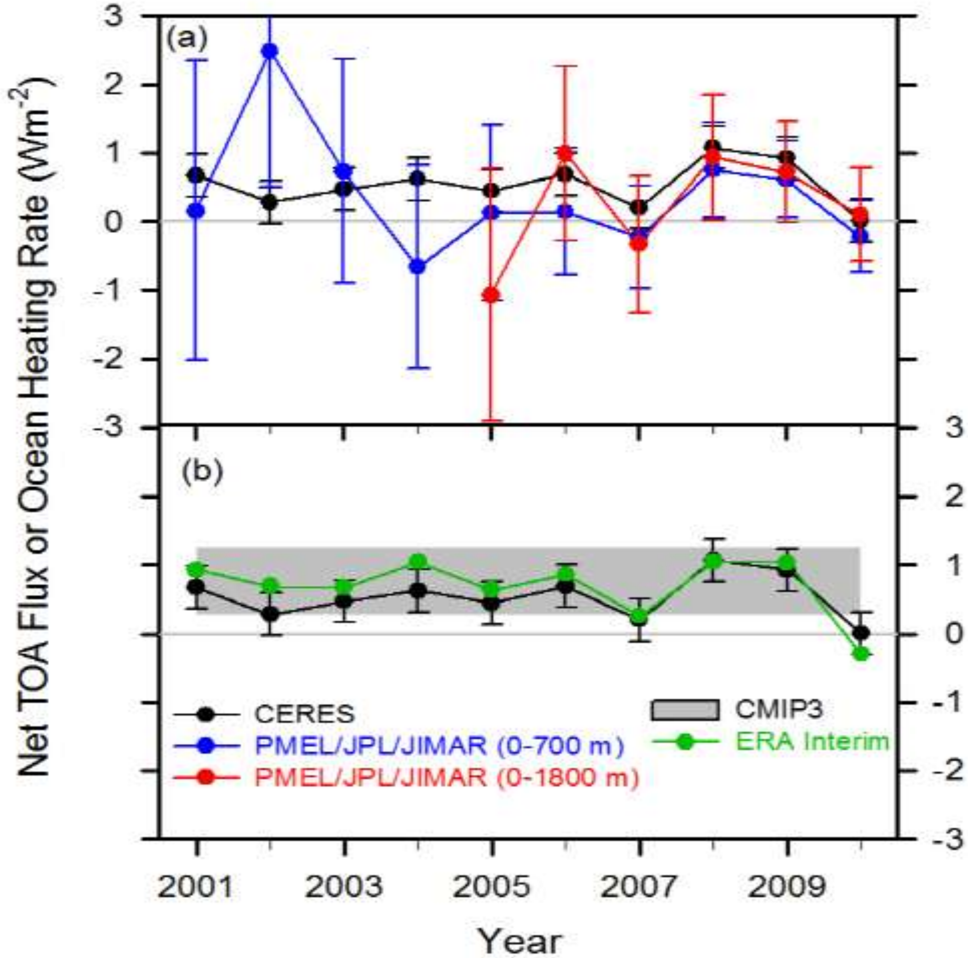


Loeb et al. (2012) Nat. Geosci.
See also Hansen et al. (2011) ACP

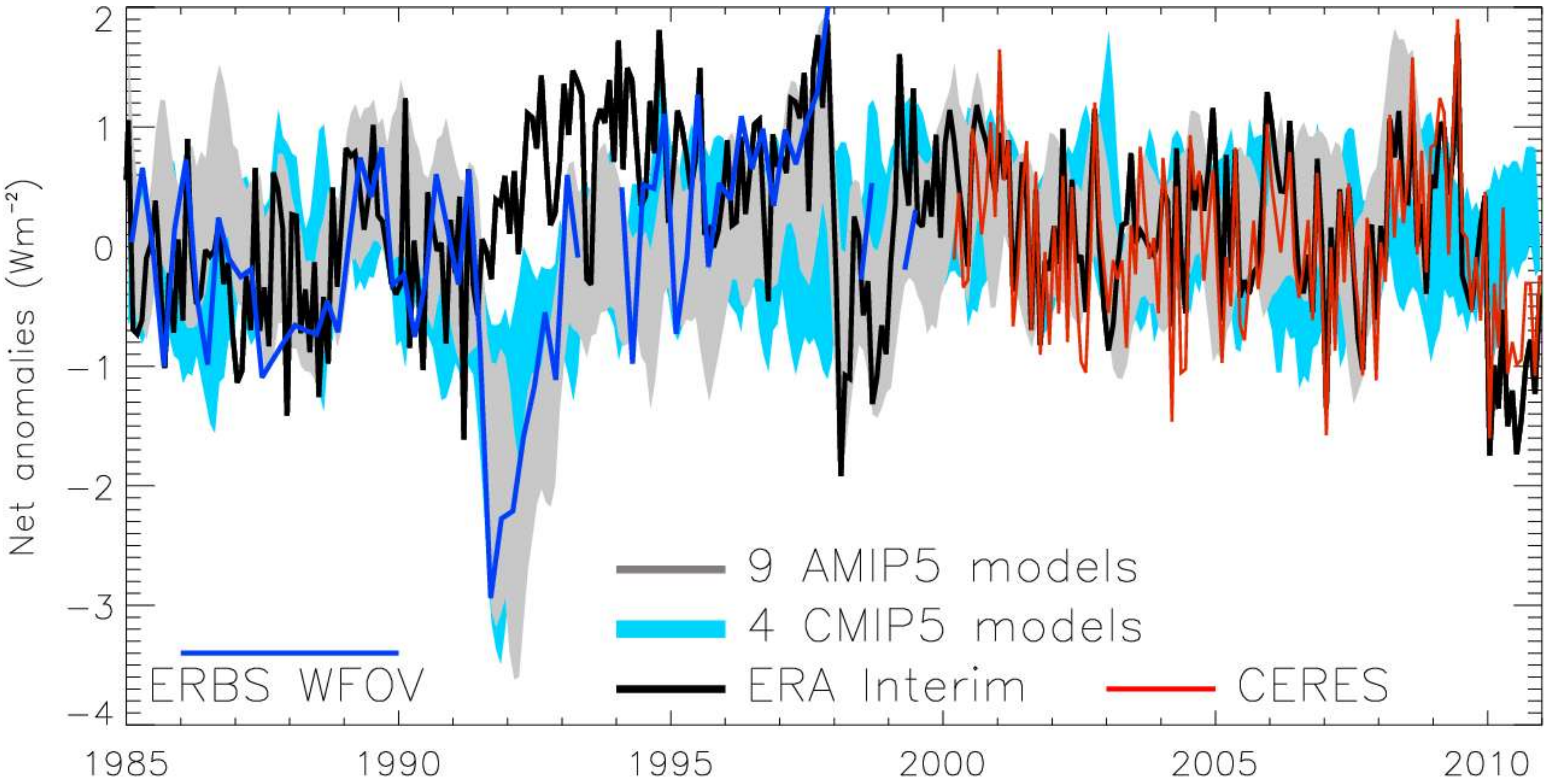
Combining Earth Radiation Budget and Ocean Heat Content data (2)

- Replotted so that CERES and ERA Interim sample 6-months later than ARGO

- Is there a lag in the system?
- Where in ocean is energy accumulating?
- Mechanism?



Variation in net radiation since 1985



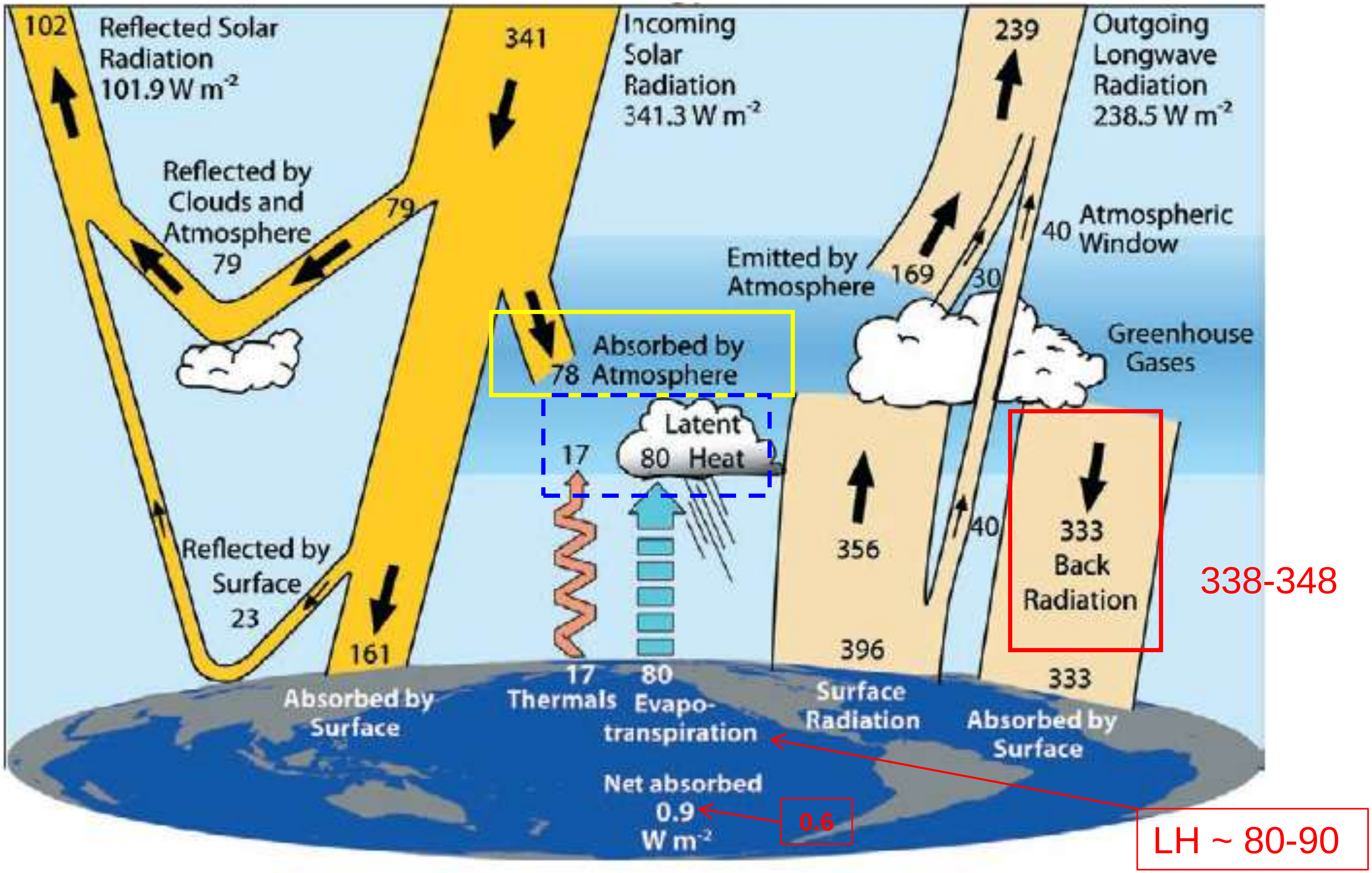
60S-60N, after Allan (2011) Meteorol. Apps

Conclusions (1)

- Previously highlighted "missing energy" explained by ocean heat content uncertainty combined with inappropriate net radiation satellite products
- Heating of Earth continues at rate of ~0.5 Wm^{-2}
  - Negative radiative forcing does not appear to contribute strongly
- Implications/mechanisms?
  - Energy continues to accumulate below the ocean surface
  - Strengthening of Walker circulation, e.g. Merrifield (2011) J Clim?
  - Implications for hydrological cycle, e.g. Simmons et al. (2010) JGR?
- New NERC project: **D**iagnosing **E**arth's **E**nergy **P**athways in the **C**limate System (DEEP-C)

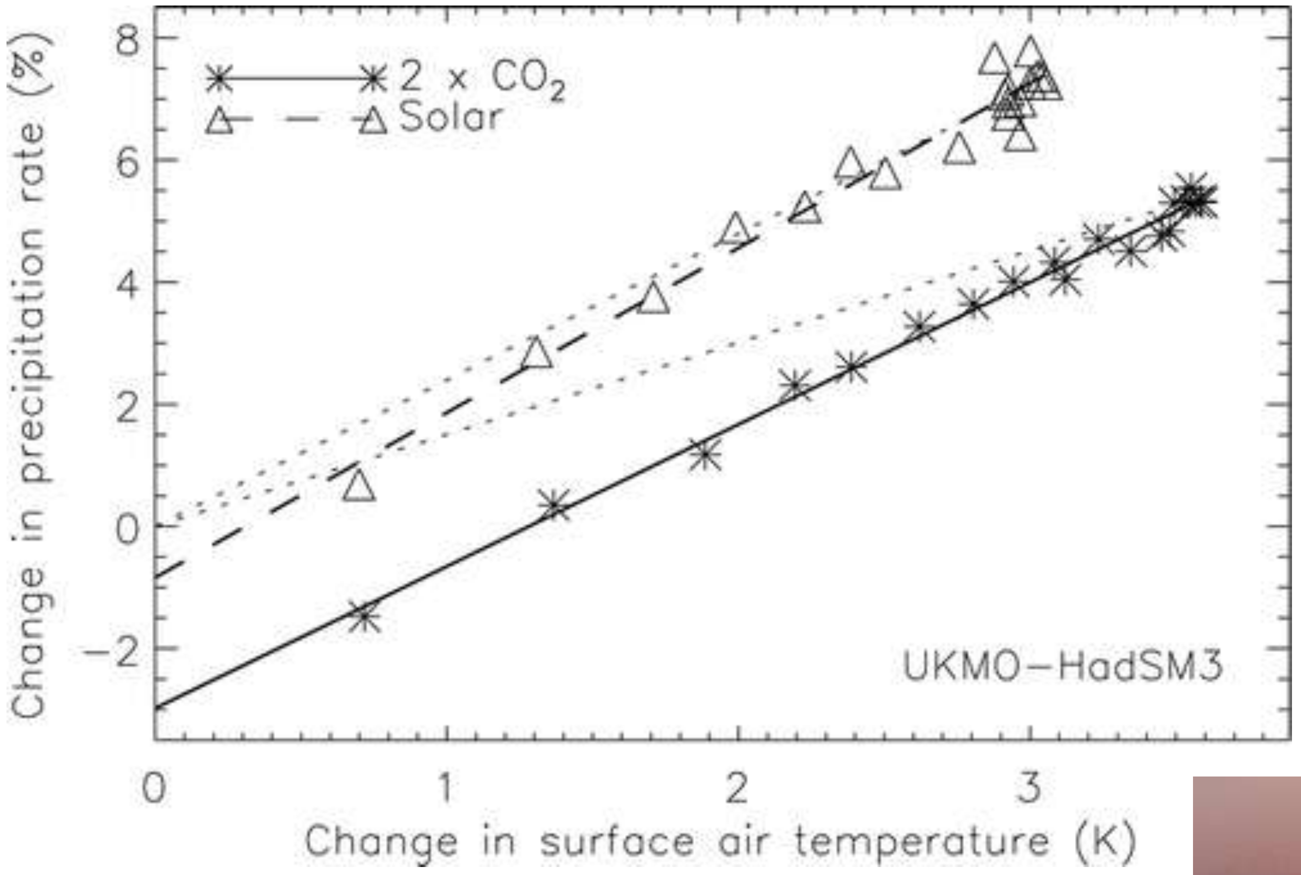
  + NOC Southampton/Met Office/Jonathan Gregory/Till Kuhlbrodt)

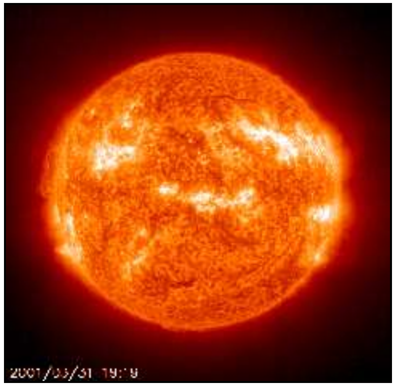
What has Earth's Energy Budget got to do with current changes in the Global Water Cycle?



Trenberth et al. (2009) BAMS, but see update by Wild et al. (2012) Clim. Dynamics

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) k ~ 2 $Wm^{-2}K^{-1}$

(ii) f dependent upon type of radiative forcing *ΔF*

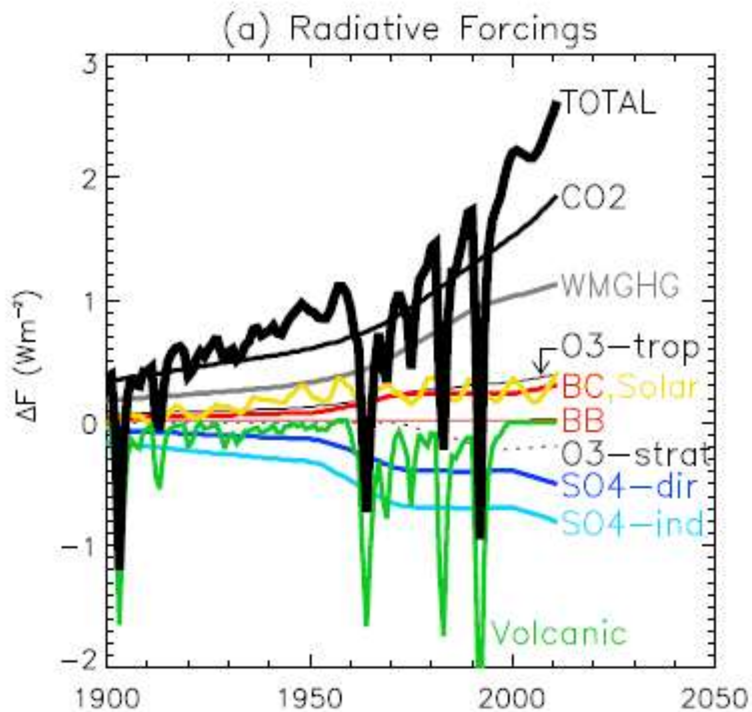
Precipitation change *ΔP* determined by:

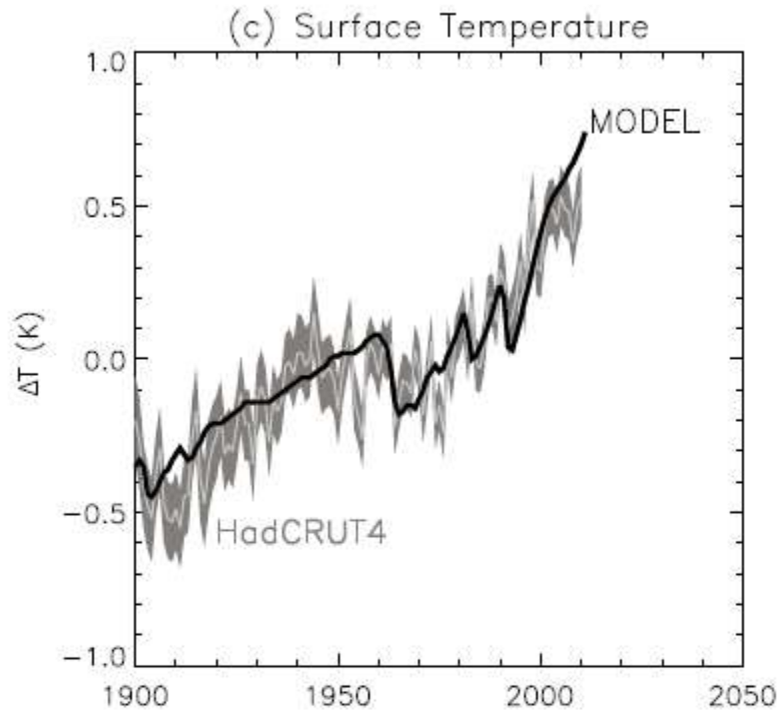
(i) "slow" response to warming *ΔT* (enhanced radiative cooling of warmer troposphere)

(ii) "fast" direct influence of radiative forcing on tropospheric energy budget (rapid adjustment)

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

A simple model of precipitation change





Thanks to Keith Shine and Evgenios Koukouvagias

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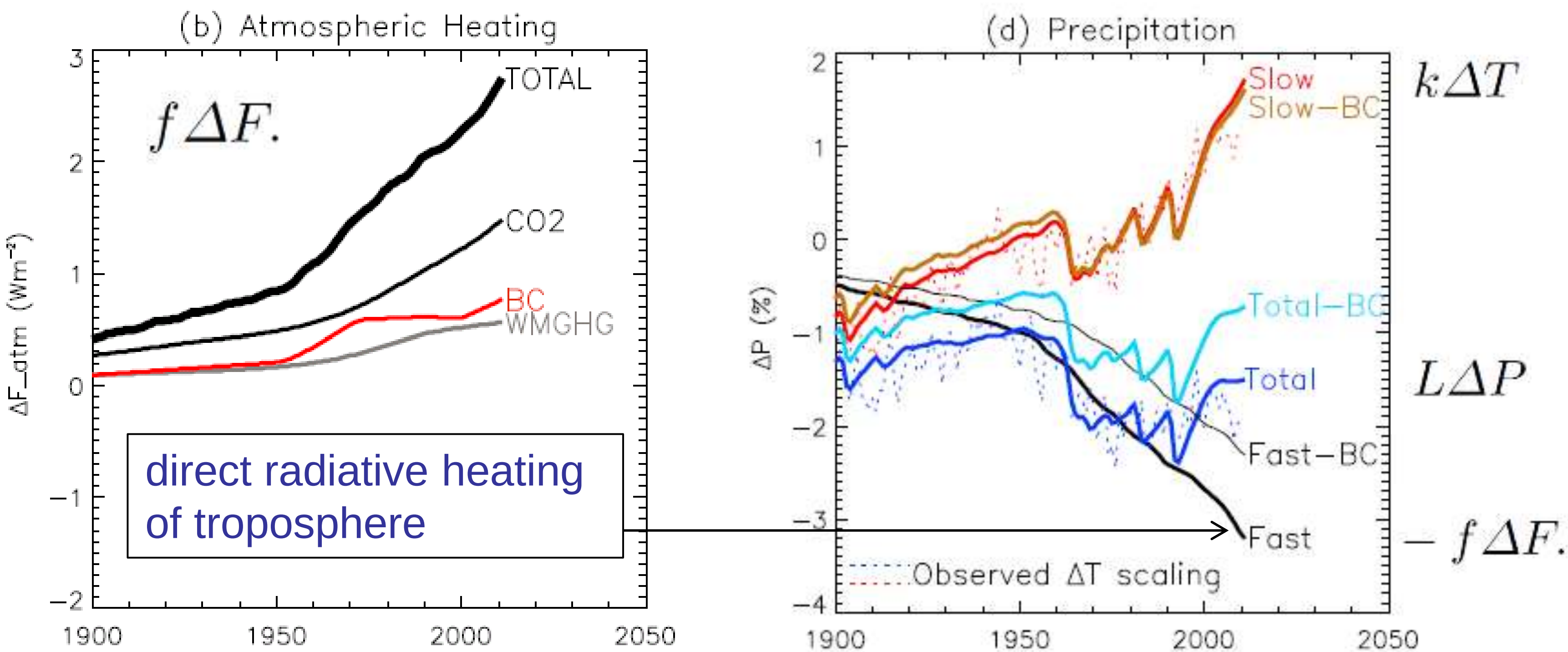
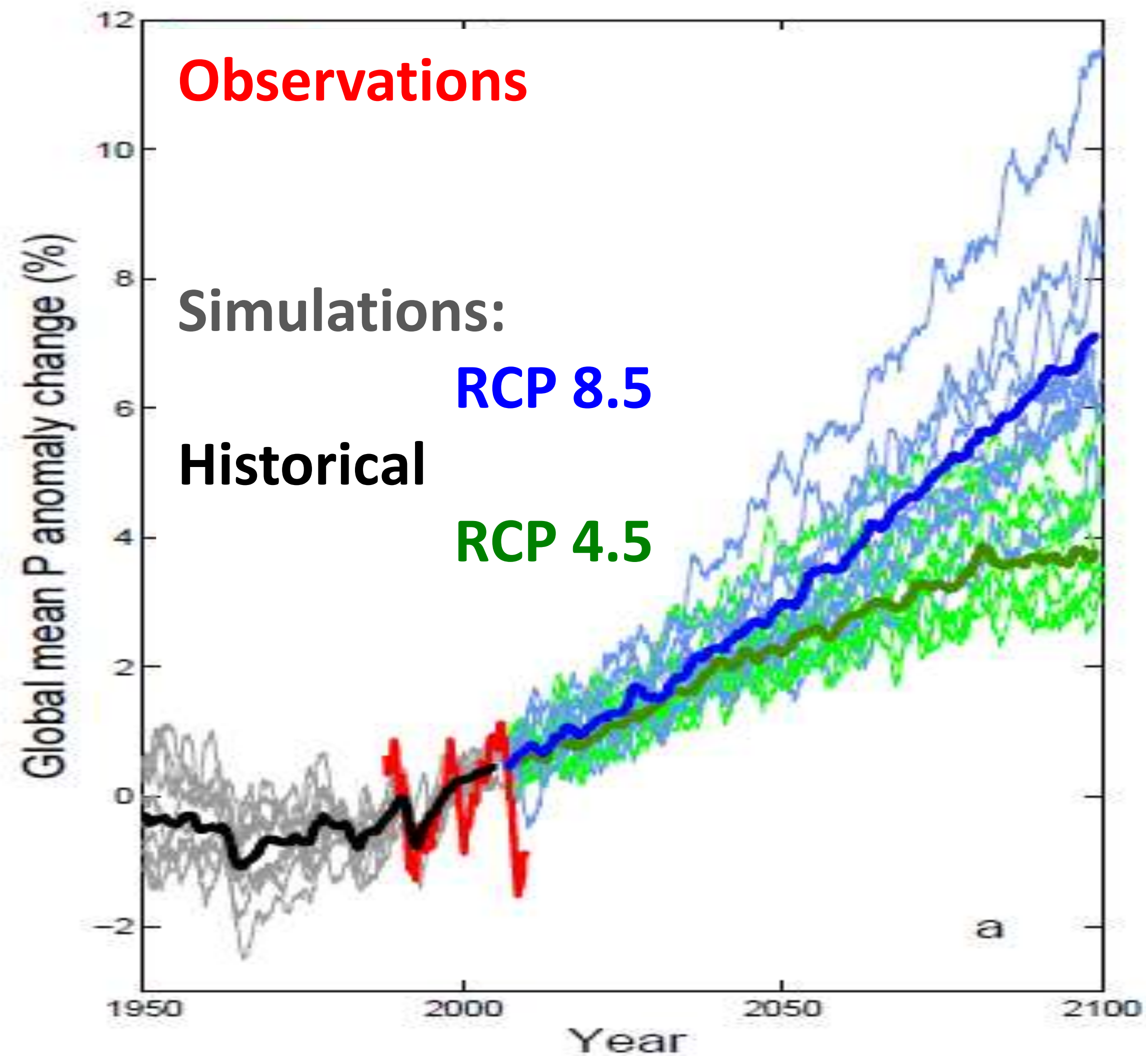
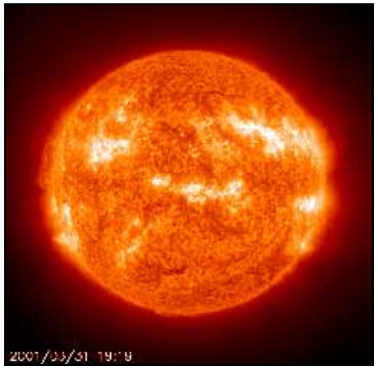


Allan et al. (2013) Surv. Geophys, using calculations from *Andrews et al. (2010) GRL*

Thanks to Keith Shine and Evgenios Koukouvagias

How will global precipitation respond to climate change?





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

Climate model projections

NATURAL ENVIRONMENT RESEARCH COUNCIL

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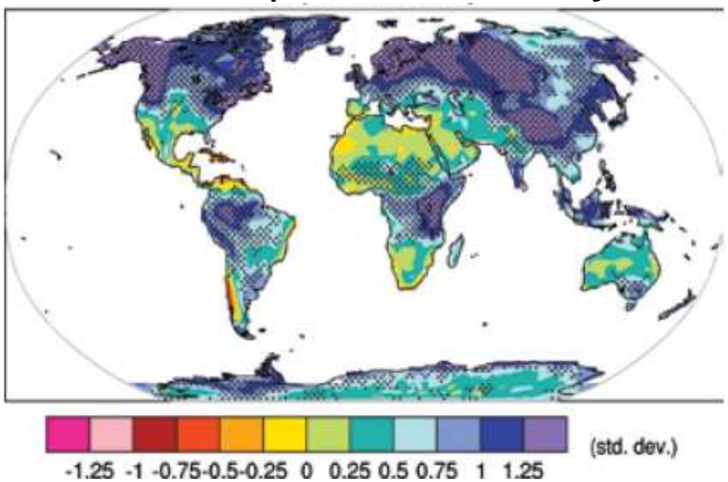
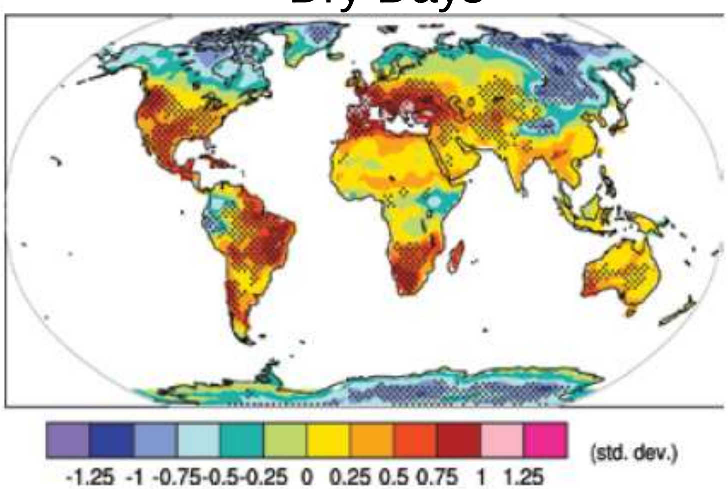
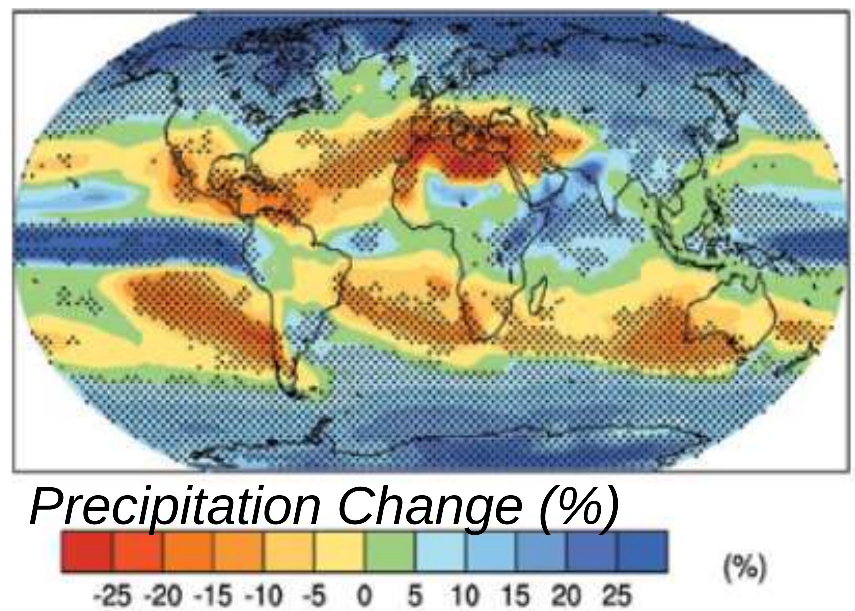
- Increased Precipitation
- More Intense Rainfall
- More droughts
- Wet regions get wetter, dry regions get drier?
- Regional projections??

Precipitation Intensity



Dry Days

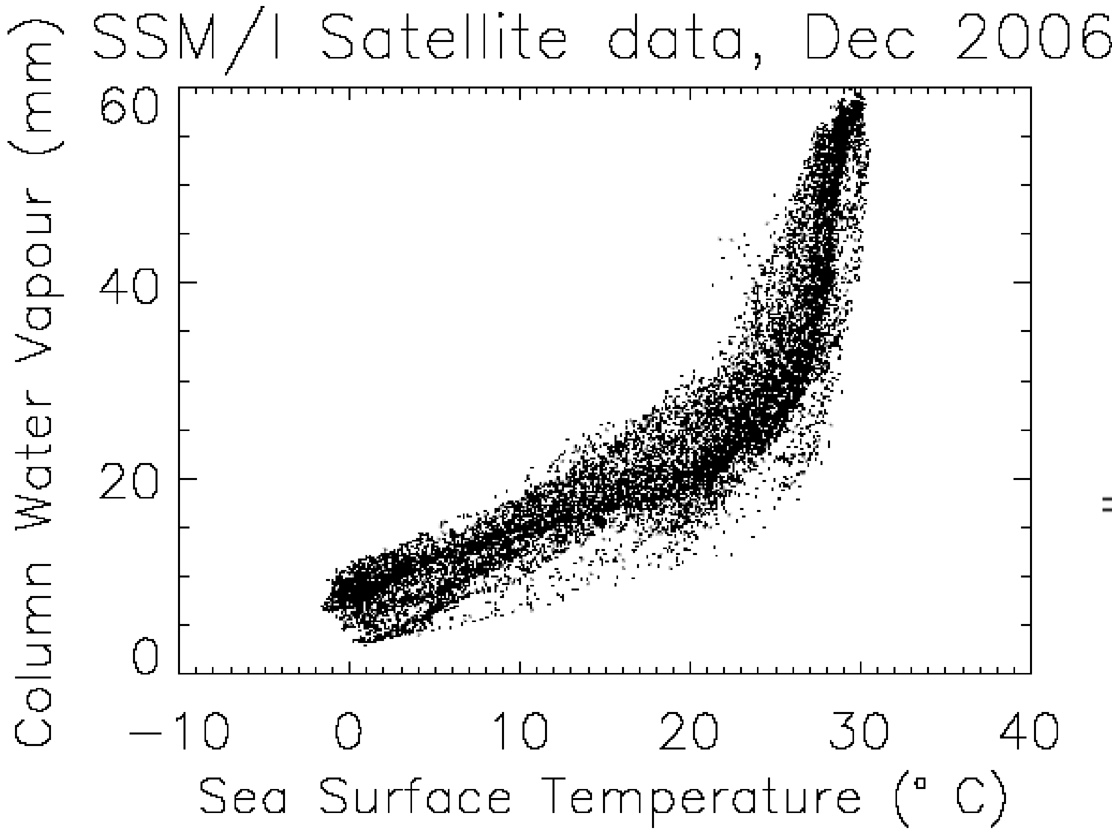




Precipitation Change (%)

IPCC WGI (2007)

The role of water vapour

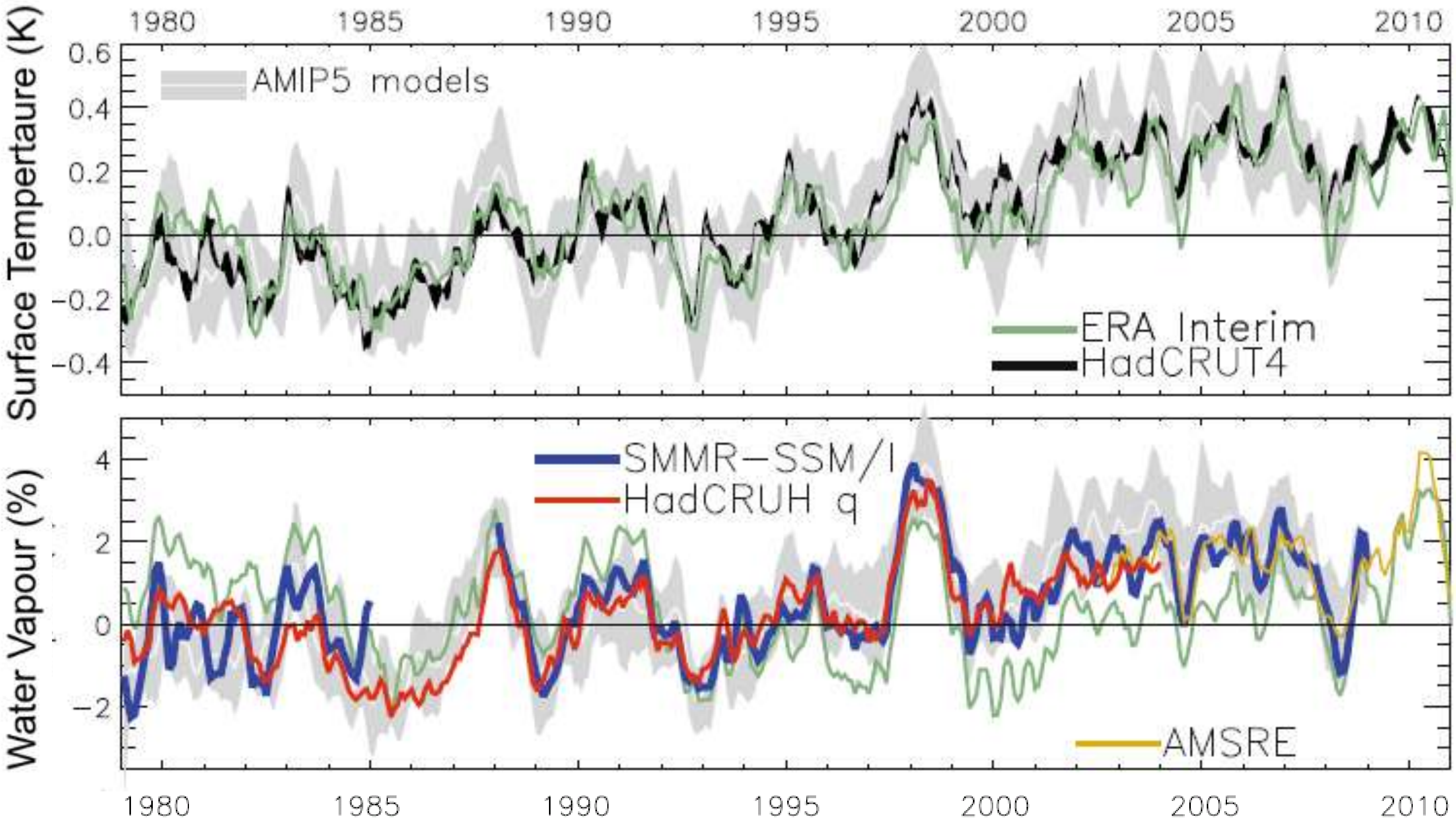


$$\frac{1}{e_s}\frac{de_s}{dT} = \frac{L}{R_v T^2}$$

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

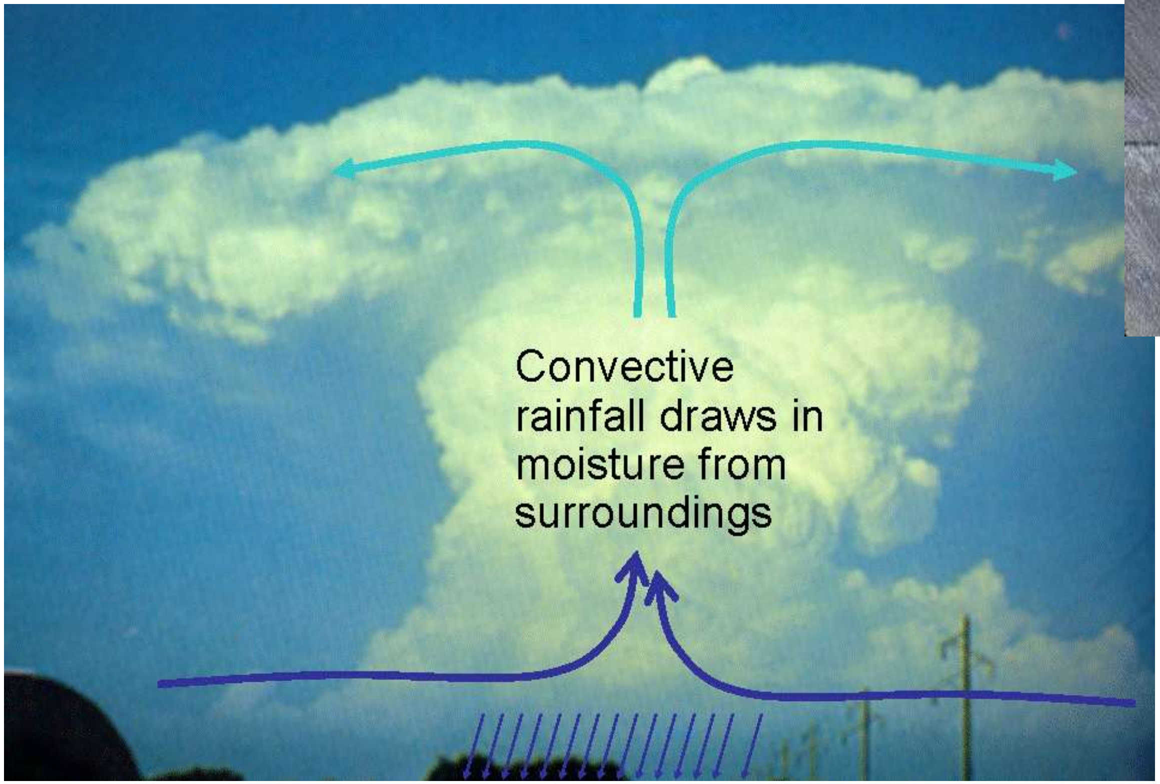
- Physics: Clausius-Clapeyron
- Low-level water vapour concentrations increase with atmospheric warming at about 6-7%/K
  - Wentz and Shabel (2000) *Nature*; Raval and Ramanathan (1989) *Nature*

Global changes in water vapour



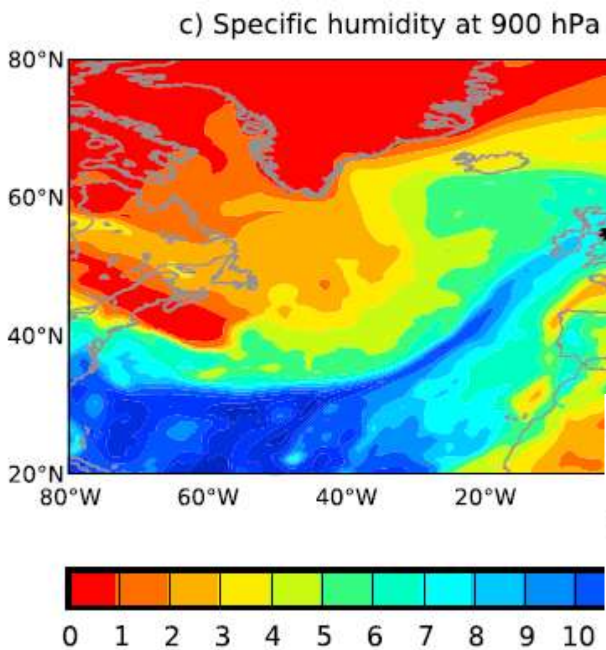
Allan et al. (2013) Surv. Geophys

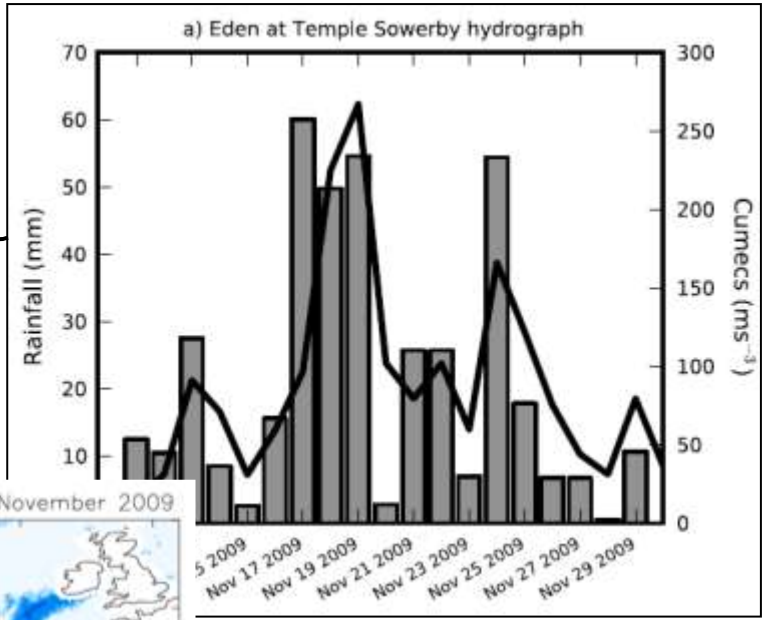
Extreme Precipitation

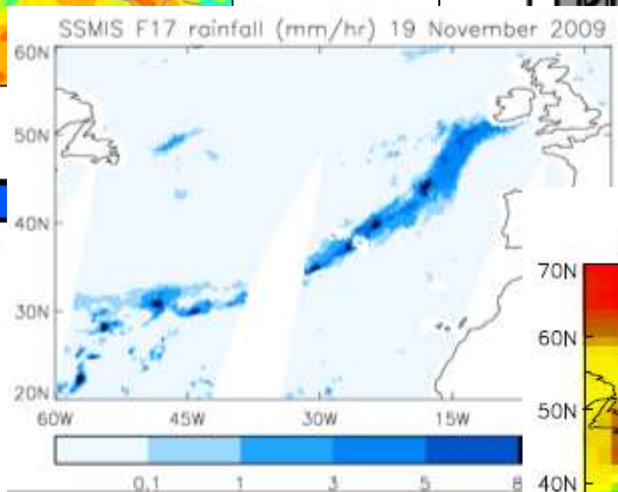


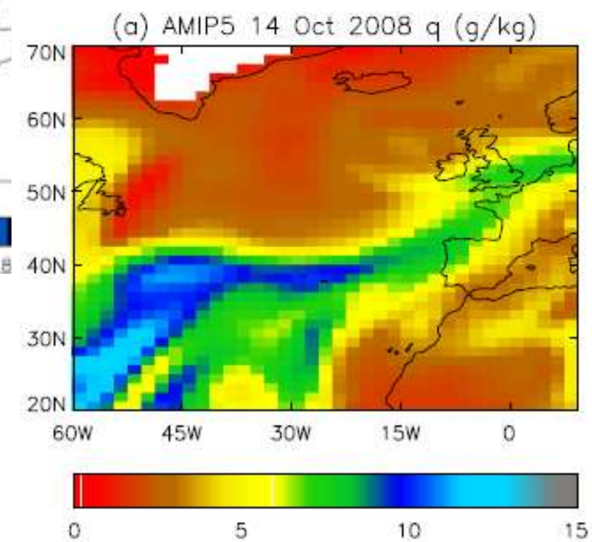
- Large-scale rainfall events fuelled by moisture convergence
  e.g. *Trenberth et al. (2003) BAMS*
- Intensification of rainfall with global warming
  e.g. Allan and Soden (2008) Science

Precipitation extremes









$$IVT = \sqrt{\left(\frac{1}{g}\int_{1000}^{300} qu\, dp\right)^2 + \left(\frac{1}{g}\int_{1000}^{300} qv\, dp\right)^2}$$

NERC HydEF project

Linking UK flooding to large-scale precursors

e.g. 2009 Cumbria floods

Lavers et al. (2011) GRL, Lavers et al. (2012) JGR

Using observed interannual variability to evaluate climate model simulations of precipitation extremes

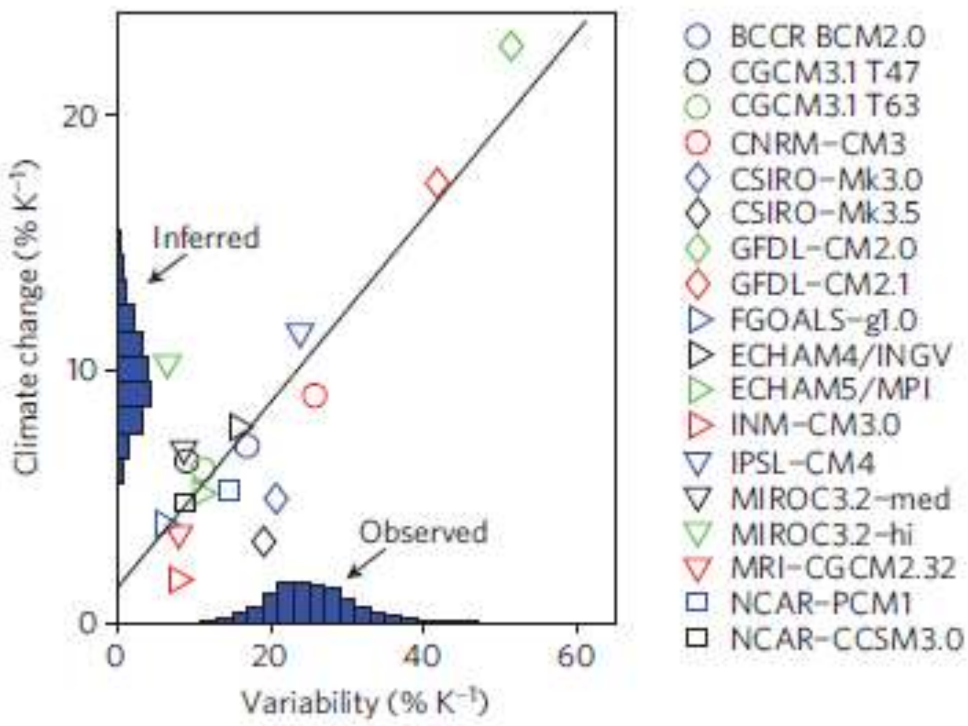


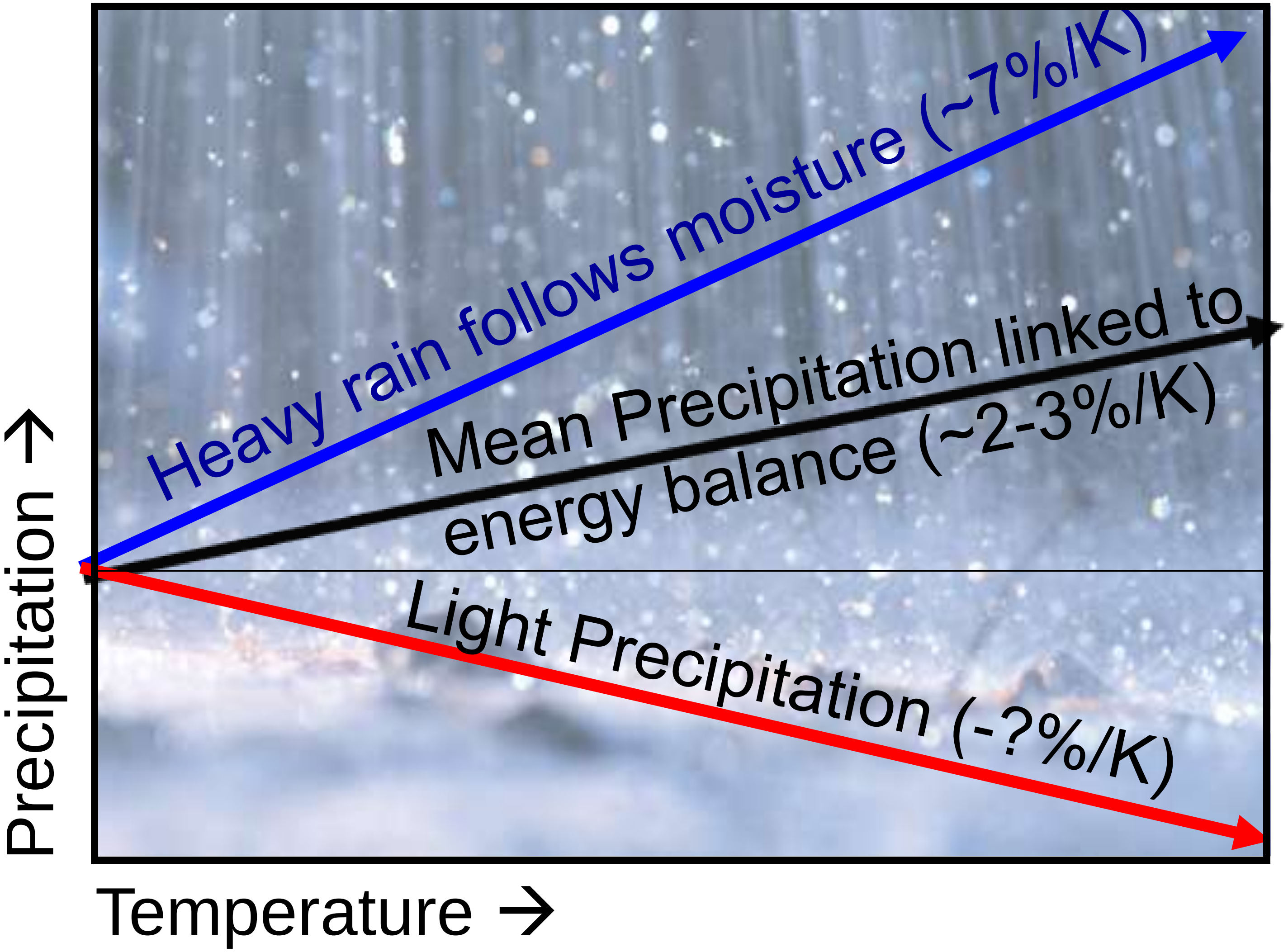
Figure 2 | Sensitivities (% K^{-1}) of the 99.9th percentile of precipitation for variability versus climate change in the CMIP3 simulations. The solid

Can observations be used to constrain the projected responses in extreme precipitation?

O'Gorman (2012) *Nature Geosciences*

See also Allan & Soden (2008) *Science*; Liu & Allan (2012) JGR

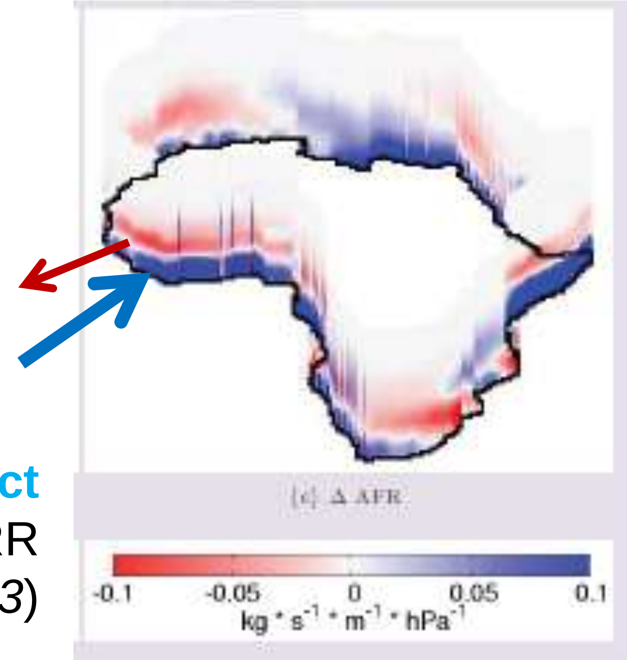
Contrasting precipitation response expected



e.g. Allen and Ingram (2002) *Nature*; Allan (2011) *Nature*

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

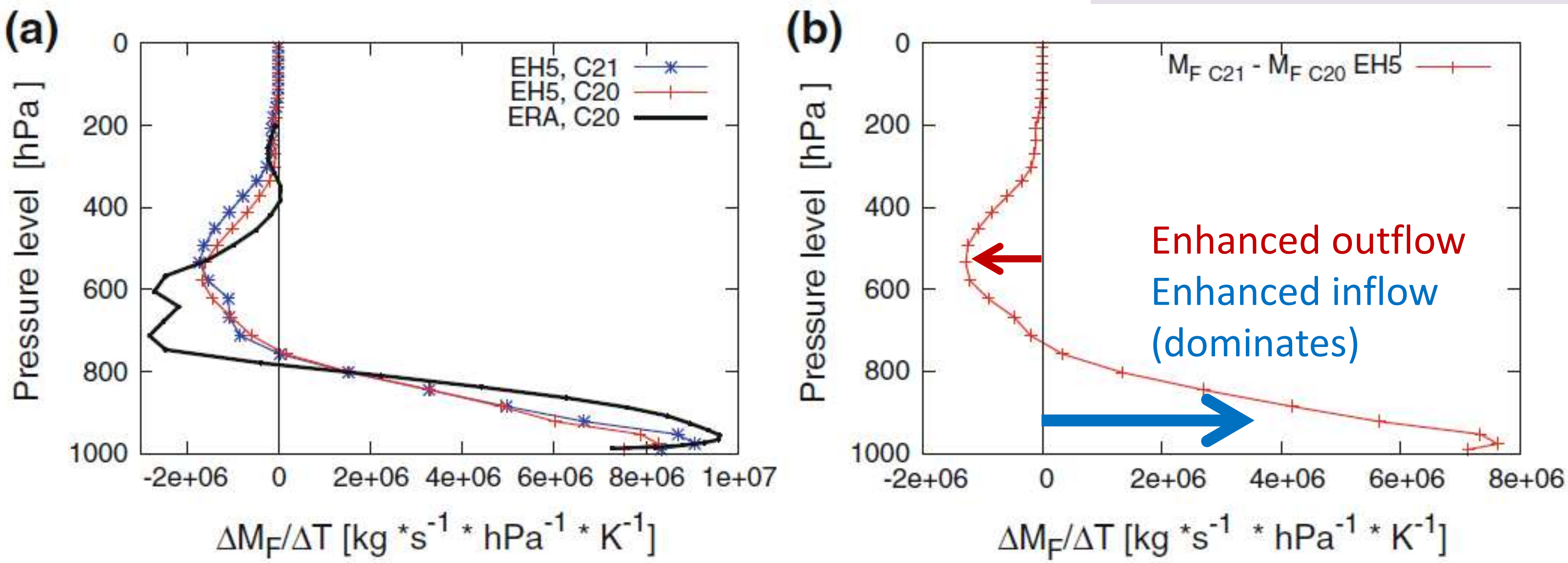
$$\frac{\partial w}{\partial t} + \nabla \cdot \frac{1}{g}\int_0^{p_s} \mathbf{v} q \, dp = E - P,$$



PREPARE project

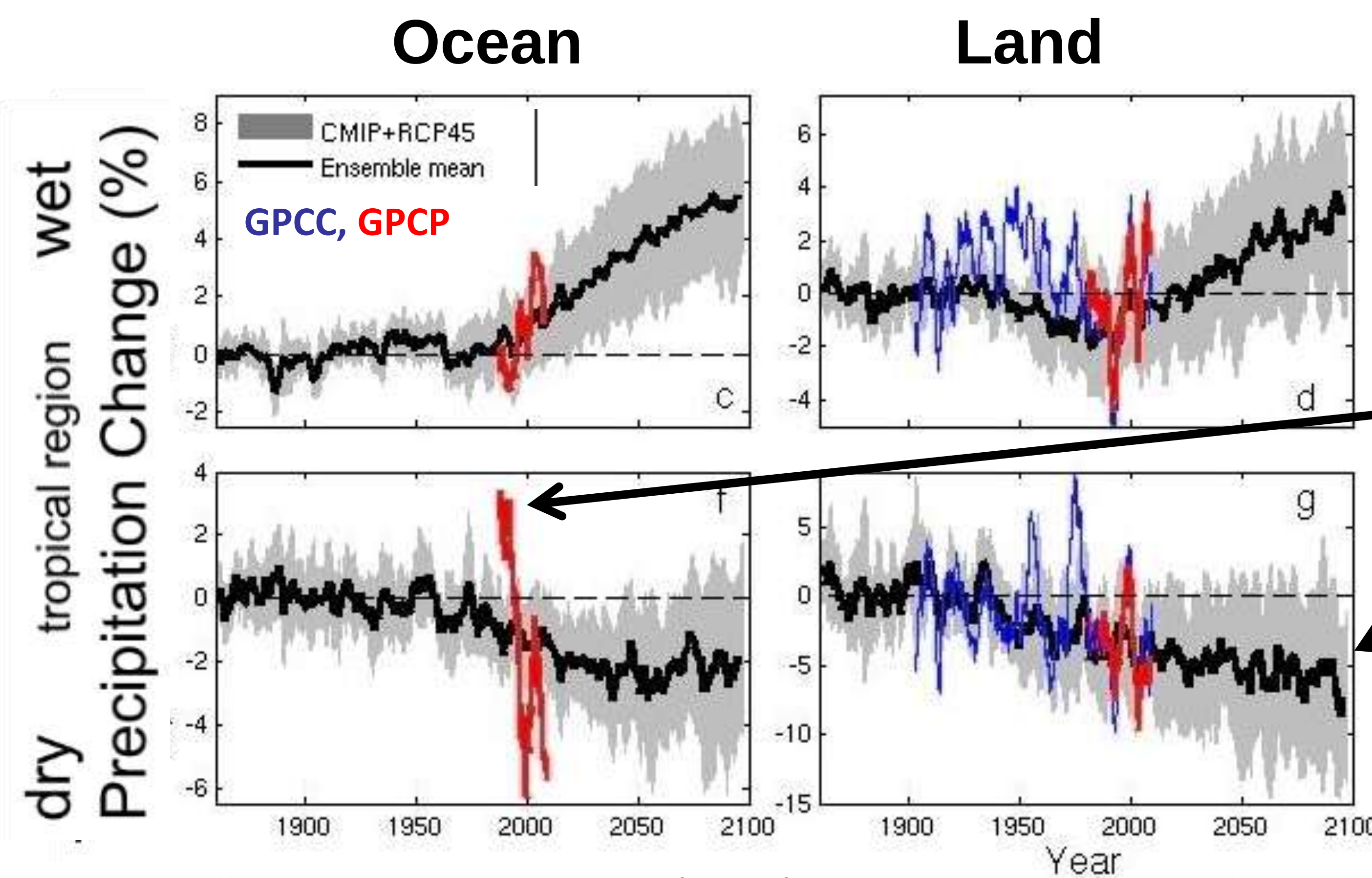
Zahn & Allan, submitted to WRR

See also Demory et al. (2013)



see also: Zahn and Allan (2013) J Clim

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



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

Robust drying of dry tropical land

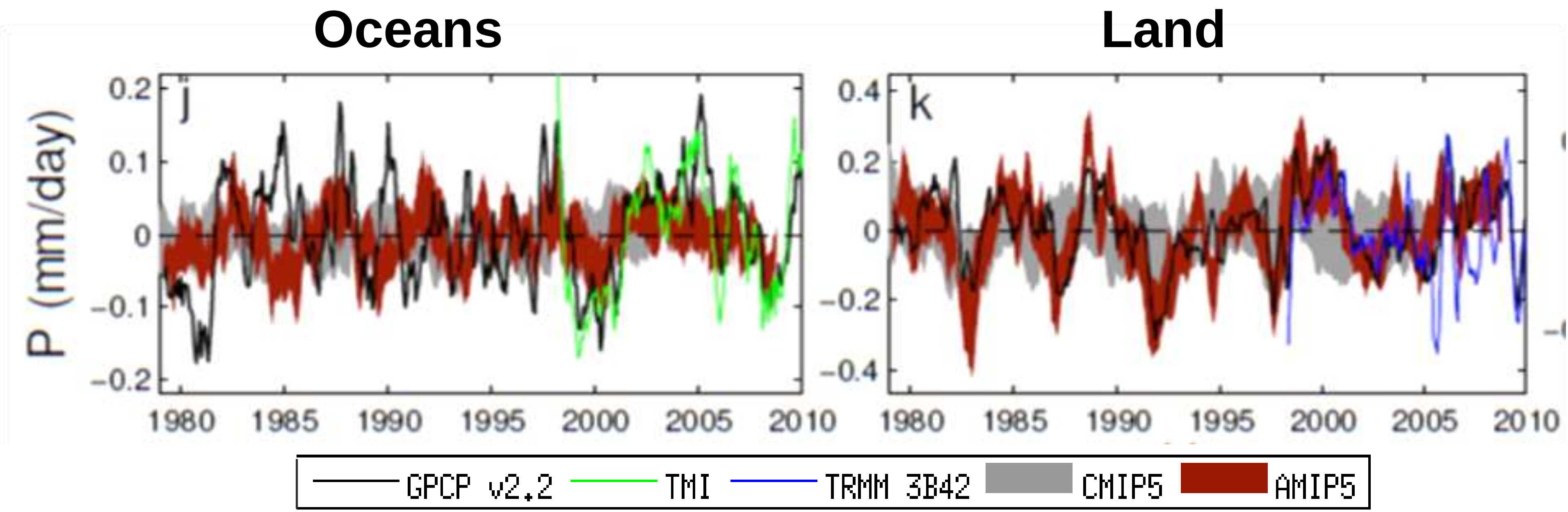
30% wettest gridpoints vs 70% driest each month

Liu and Allan *in prep;* [Allan et al. (2010) ERL.] *See also Chadwick et al. (2013) J Clim,* *[Allan (2012) Clim. Dyn.]*, *Balan Sarojin et al. (2013) GRL*

Challenge: Observing systems

Observed precipitation variability over the oceans is questionable. Over land, gauges provide a useful constraint.

Combining observational platforms is a powerful strategy *e.g. microwave, gravity, ocean heat content, reanalysis transports*



[Liu, Allan, Huffman (2012) GRL](#)

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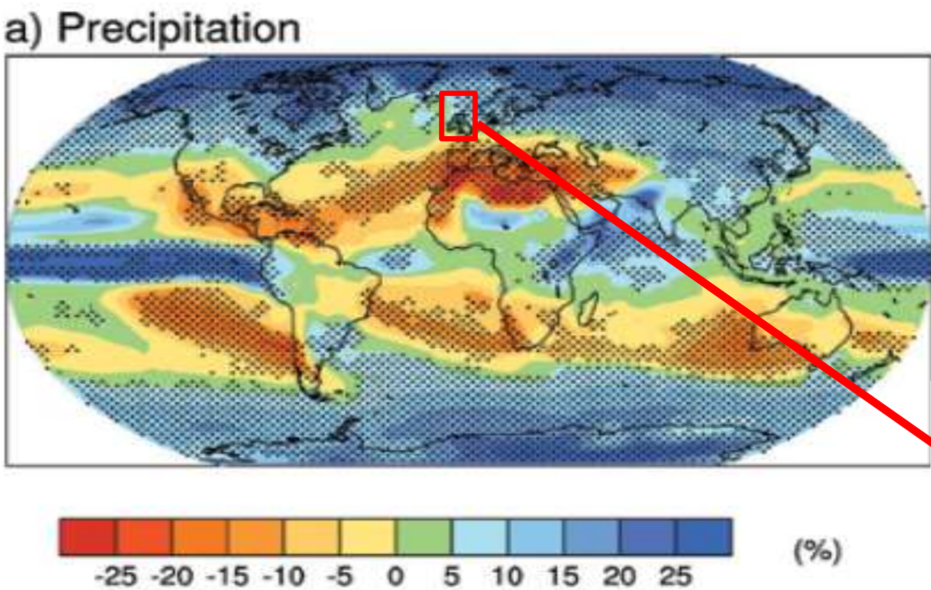
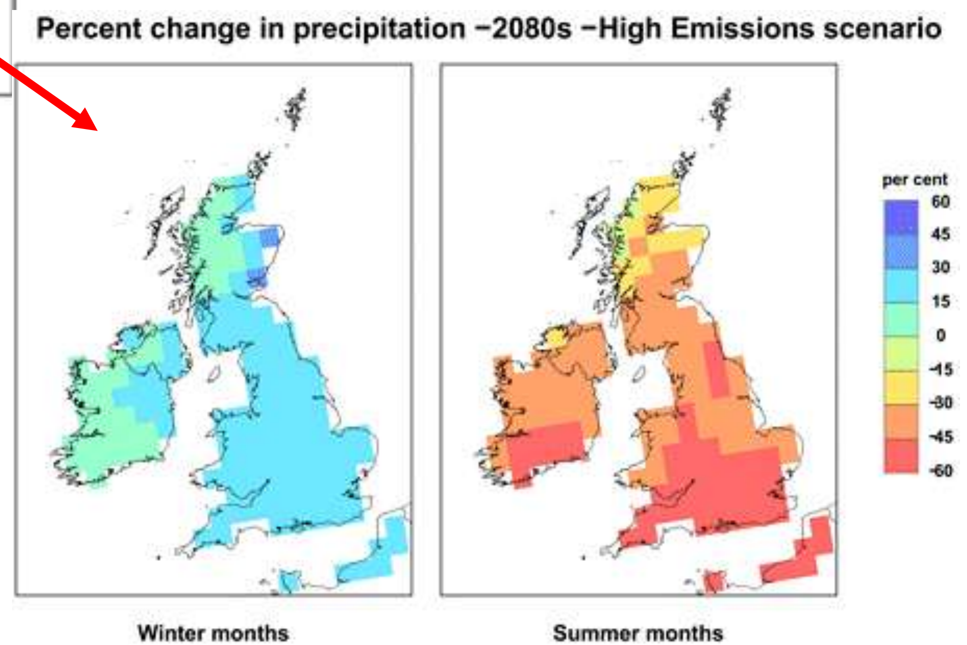
Challenge: Regional projections



Shifts in circulation systems are crucial to regional changes in water resources and risk yet predictability is often poor.



How will monsoons and jet stream positions respond to warming?

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

Conclusions

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- Energy balance is fundamental to climate response

Energy and moisture balance powerful constraints on global water cycle

- Heating of Earth continues at rate of **~0.5 Wm^{-2}** over the last decade despite stable Surface Temperature
- Global precipitation rises due to surface warming (~2%/K) offset slightly by direct effect of GHG forcing on troposphere
- Current increases in wet and dry extremes
  - Linked to rises in low-level moisture of about 7%/K
- **Aerosol radiative forcing** appear key in determining global and circulation-driven precipitation responses
  - Interesting regional trends e.g. Africa: *see Ross Maidment's seminar*
- Further details available from www.met.reading.ac.uk/~sgs02rpa:

Loeb et al. (2012) Nature Geosci and Allan et al. (2013) Surv. Geophys

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