Current Changes in Earth's energy and water cycles

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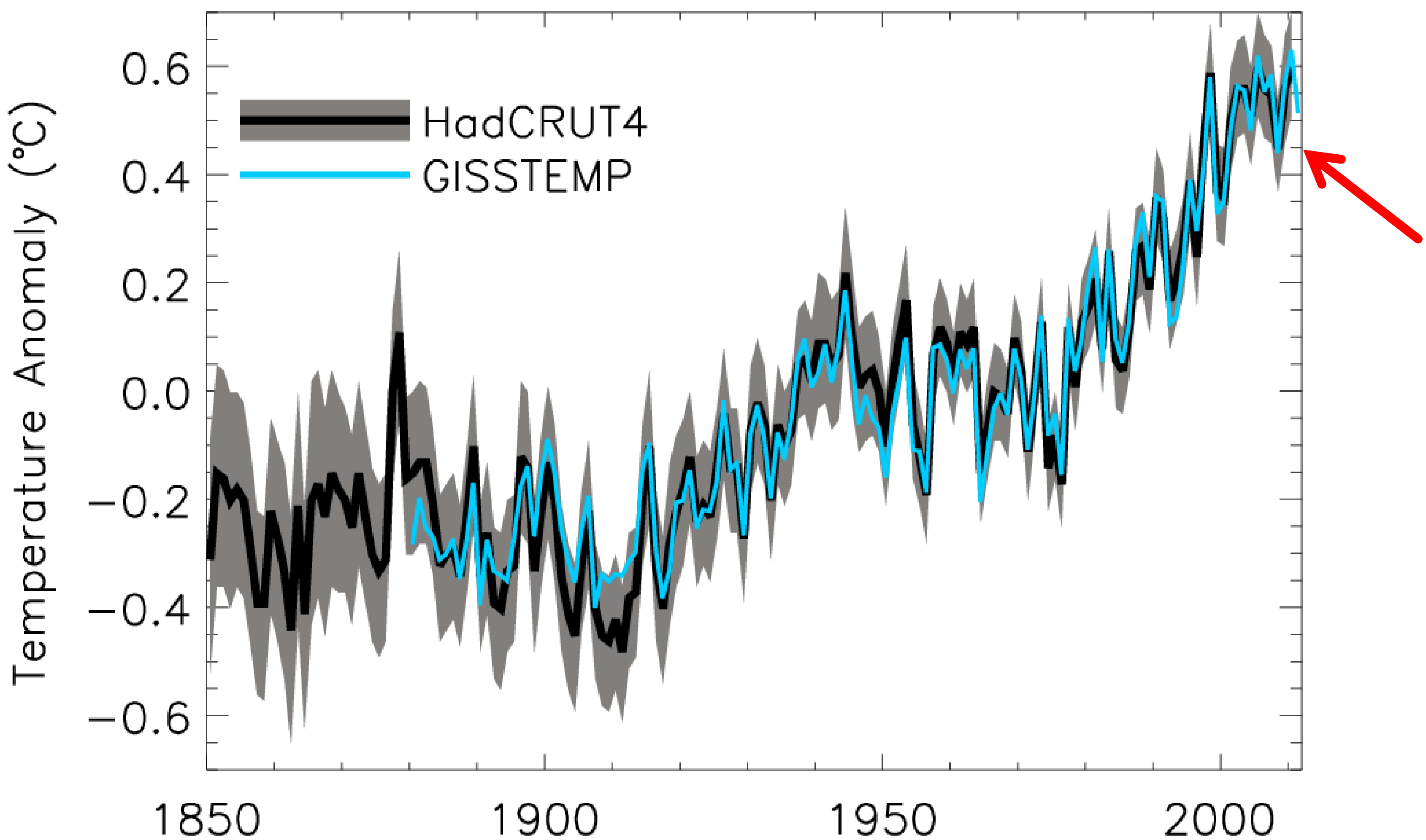
Also thanks to Chunlei Liu, David Lavers, Matthias Zahn, Norman Loeb, John Lyman, Greg Johnson, Brian Soden

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?

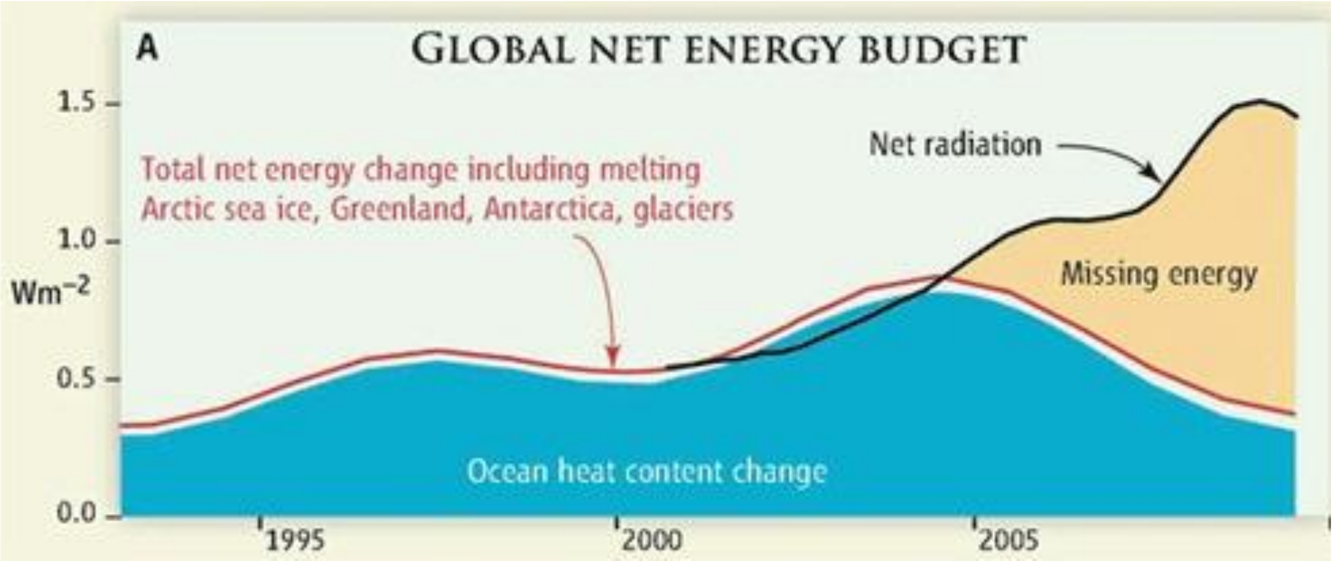
- Small, persistent volcanic forcing?
  - e.g. Solomon et al. (2011) Science
- Sulphur emissions?
  - e.g. Kaufmann et al. (2011) PNAS

- Stratospheric water vapour?
  - e.g. Solomon et al. (2010) Science
- 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…

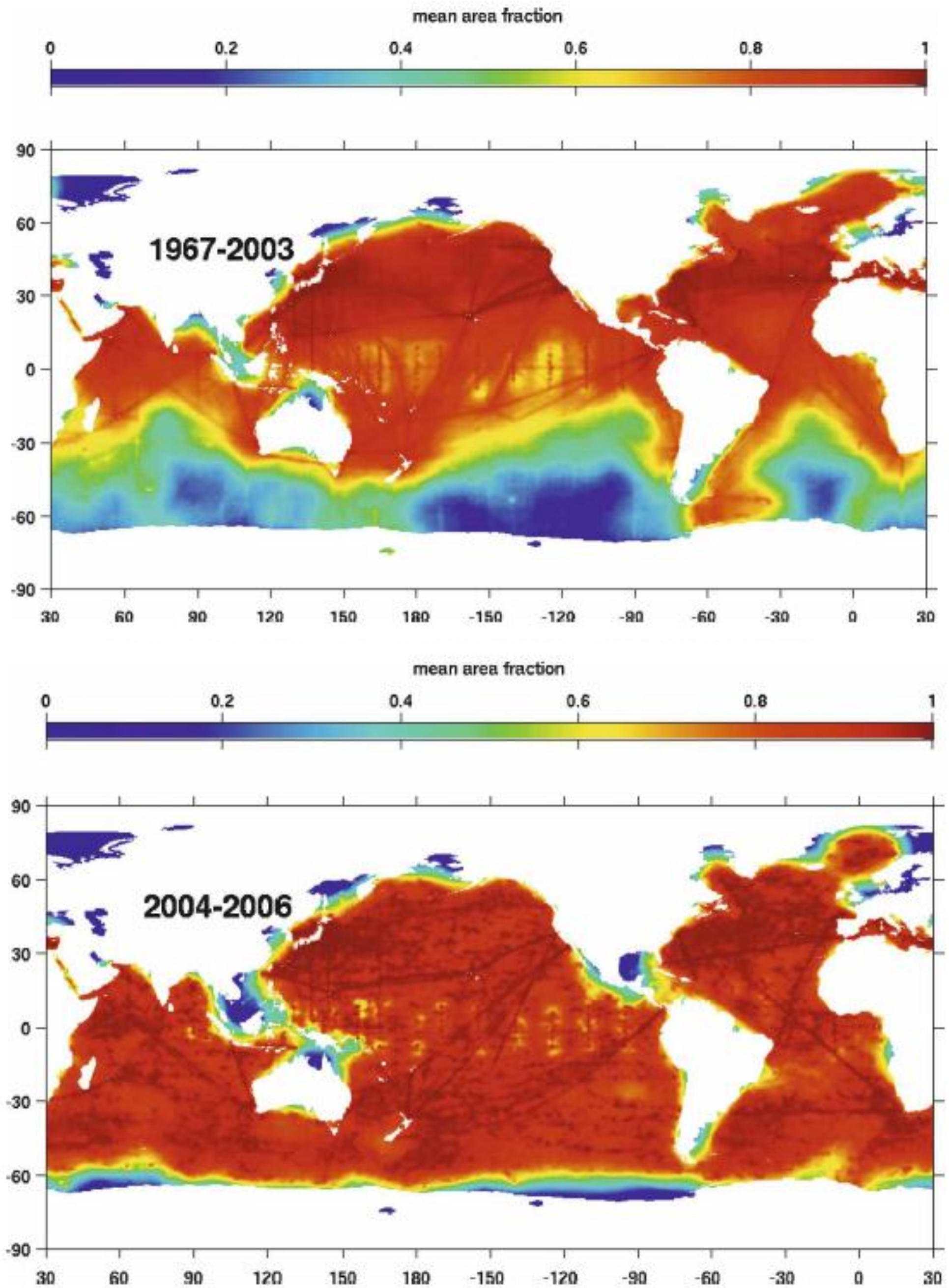


FIG. 4. Mean of annual "observed" area coverage from 2004 to 2006.

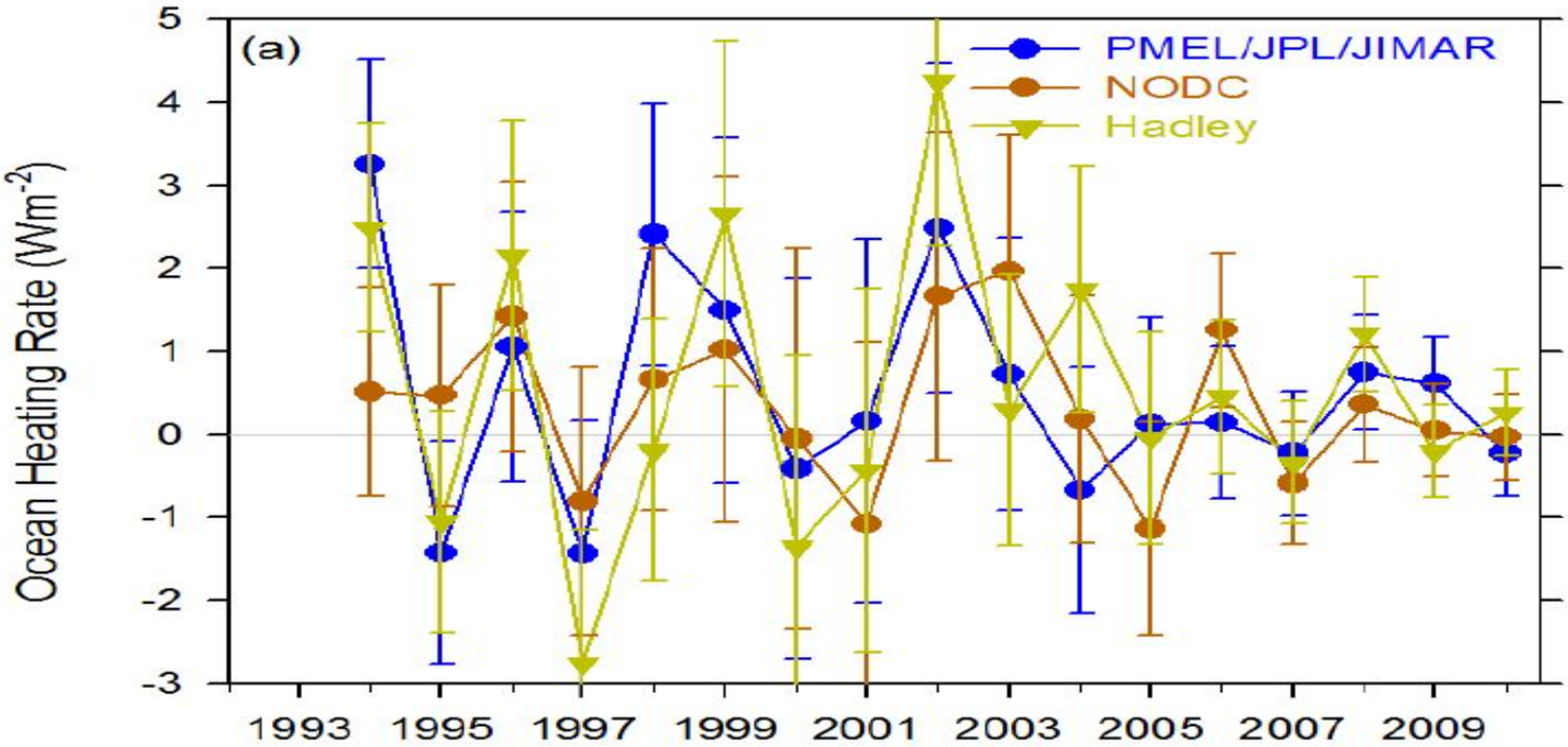
Ocean Heat Content data

- 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

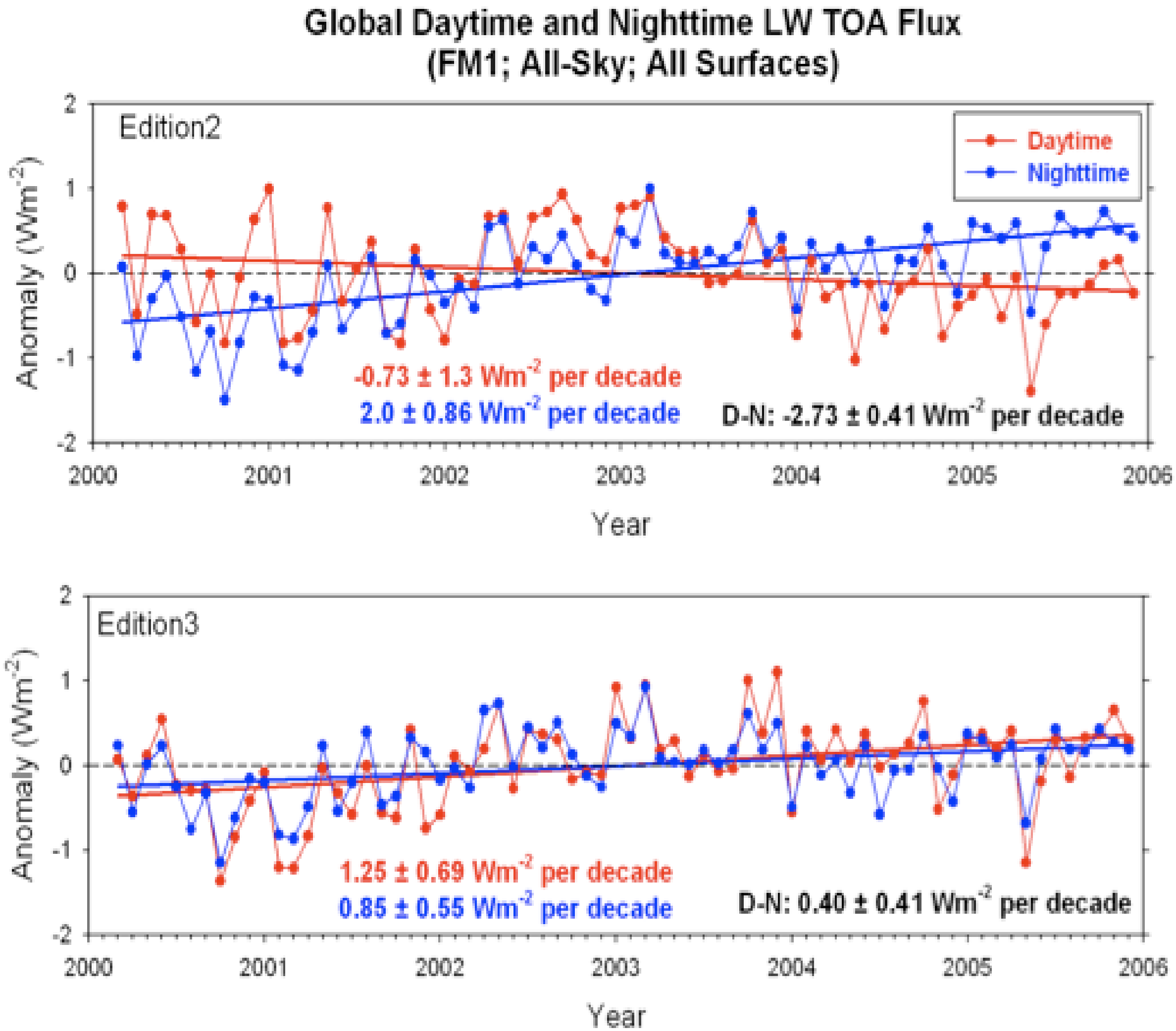
- Accounting for considerable sampling/structural uncertainty we find no evidence for a robust decline in ocean heating rate since 2005



Loeb et al. (2012) Nat. Geosci

Updated CERES satellite data

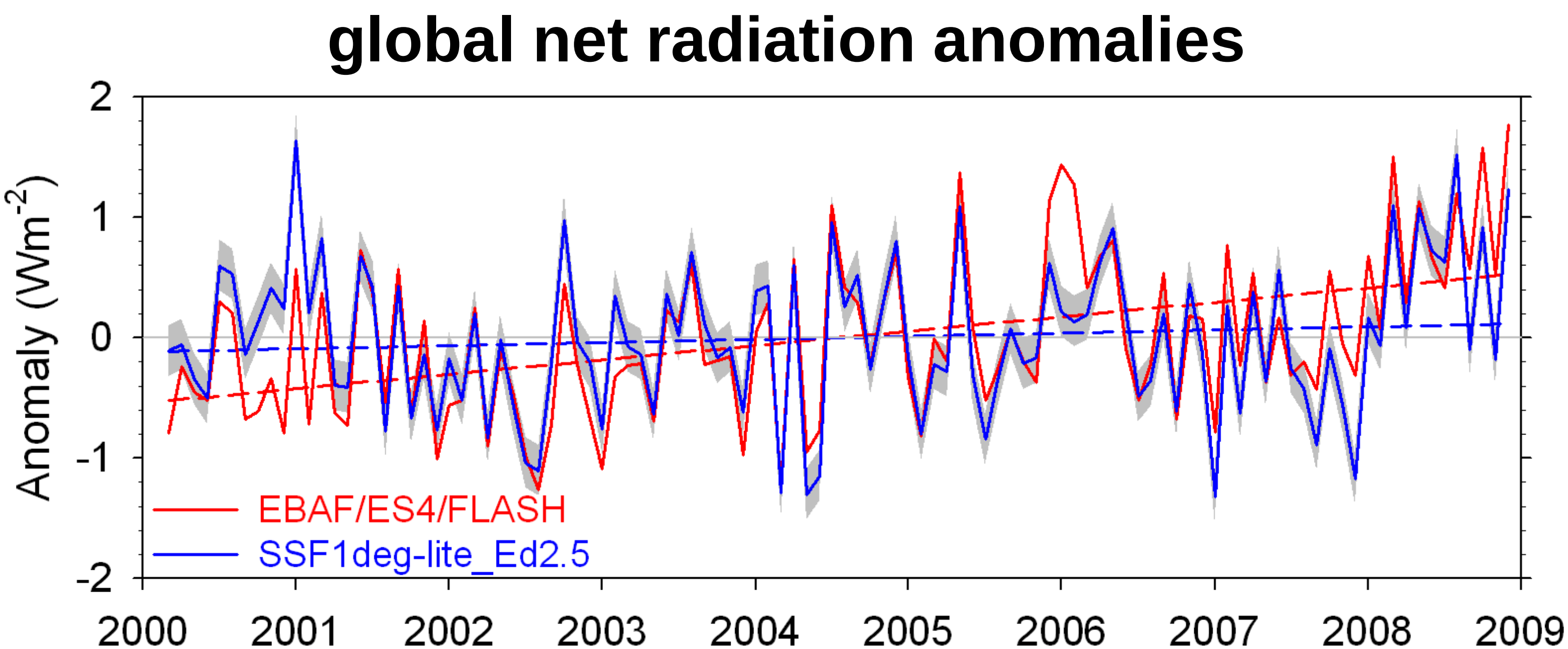
- Global Earth Radiation Balance
- Correction for degradation of shortwave filter
- Correction also improves physical consistency of trends in daytime longwave



We use version CERES_EBAF-TOA_Ed2.6r

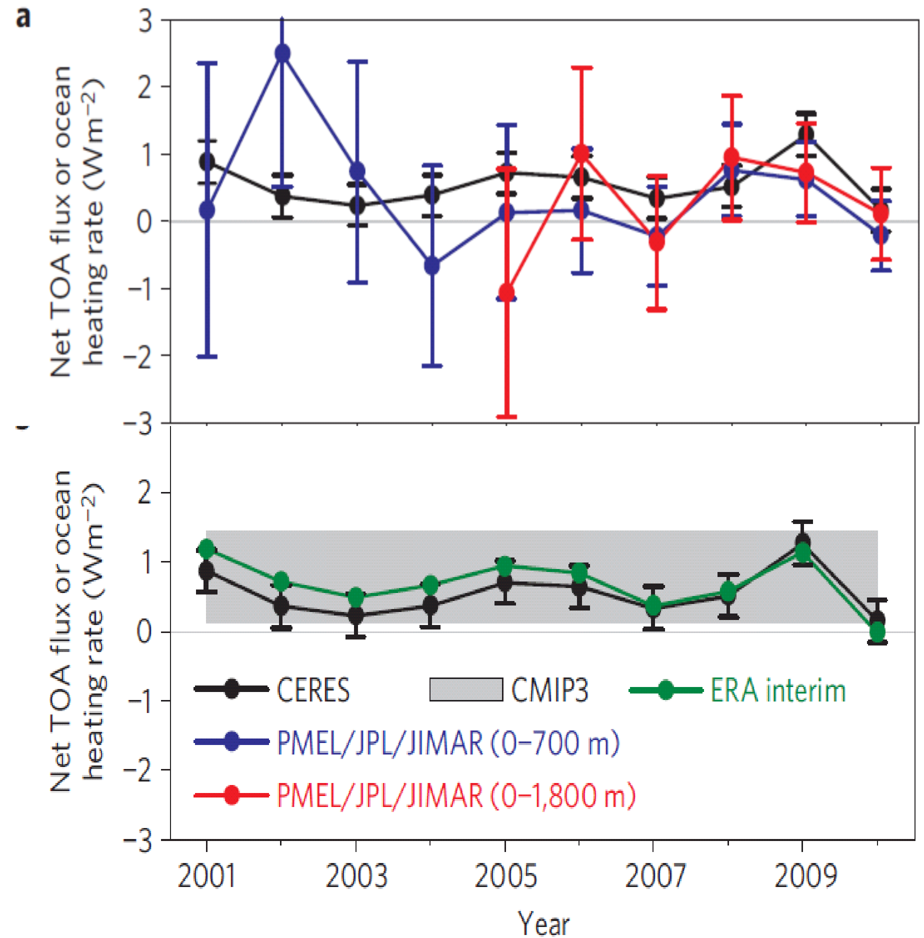
Trends in net radiation

- 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)



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 **0.54±0.43 Wm⁻²**

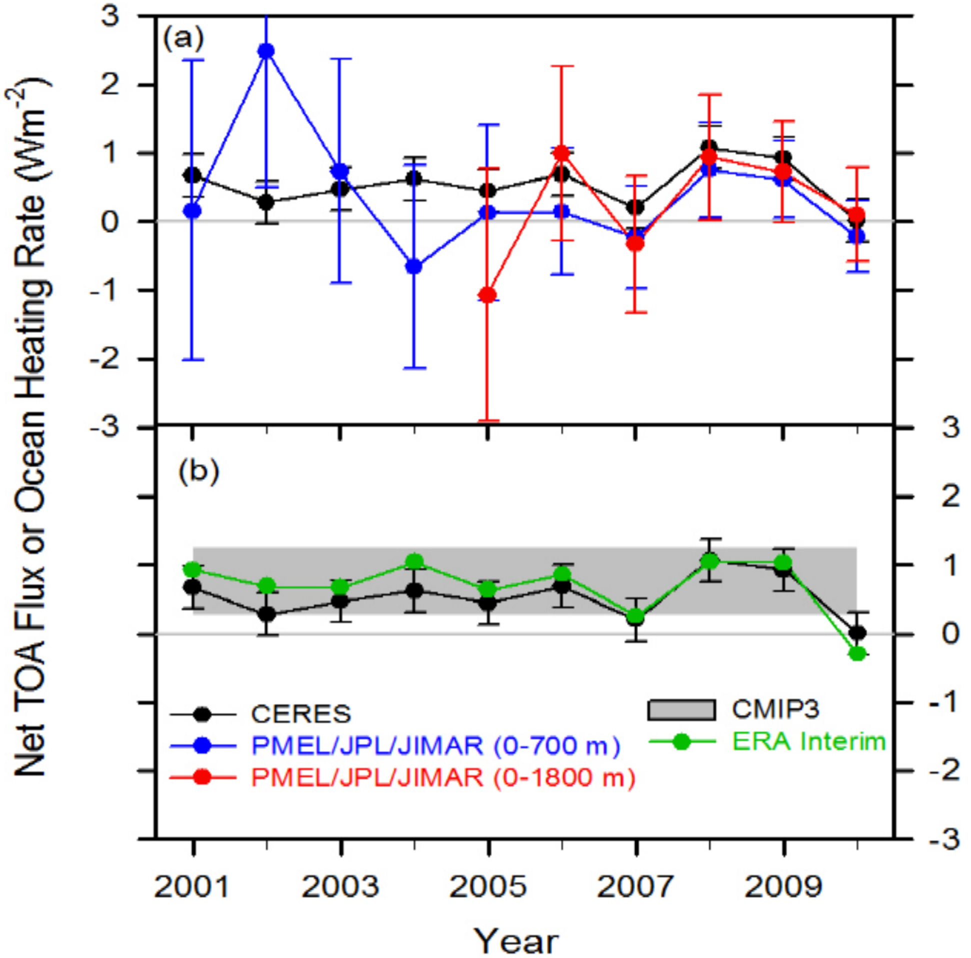


Loeb et al. (2012) Nat. Geosci.

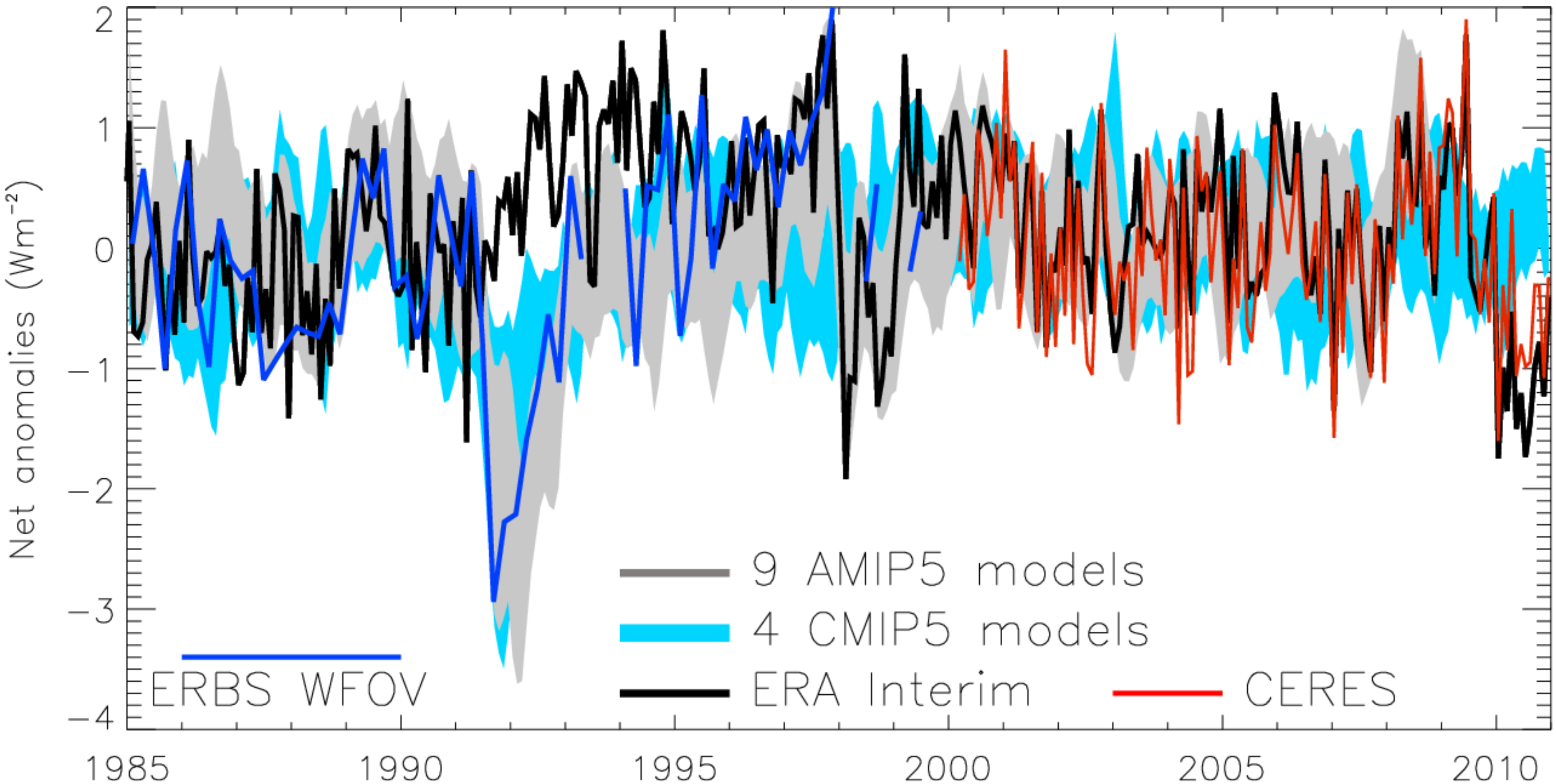
Combining Earth Radiation Budget and Ocean Heat Content data (2)

- 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

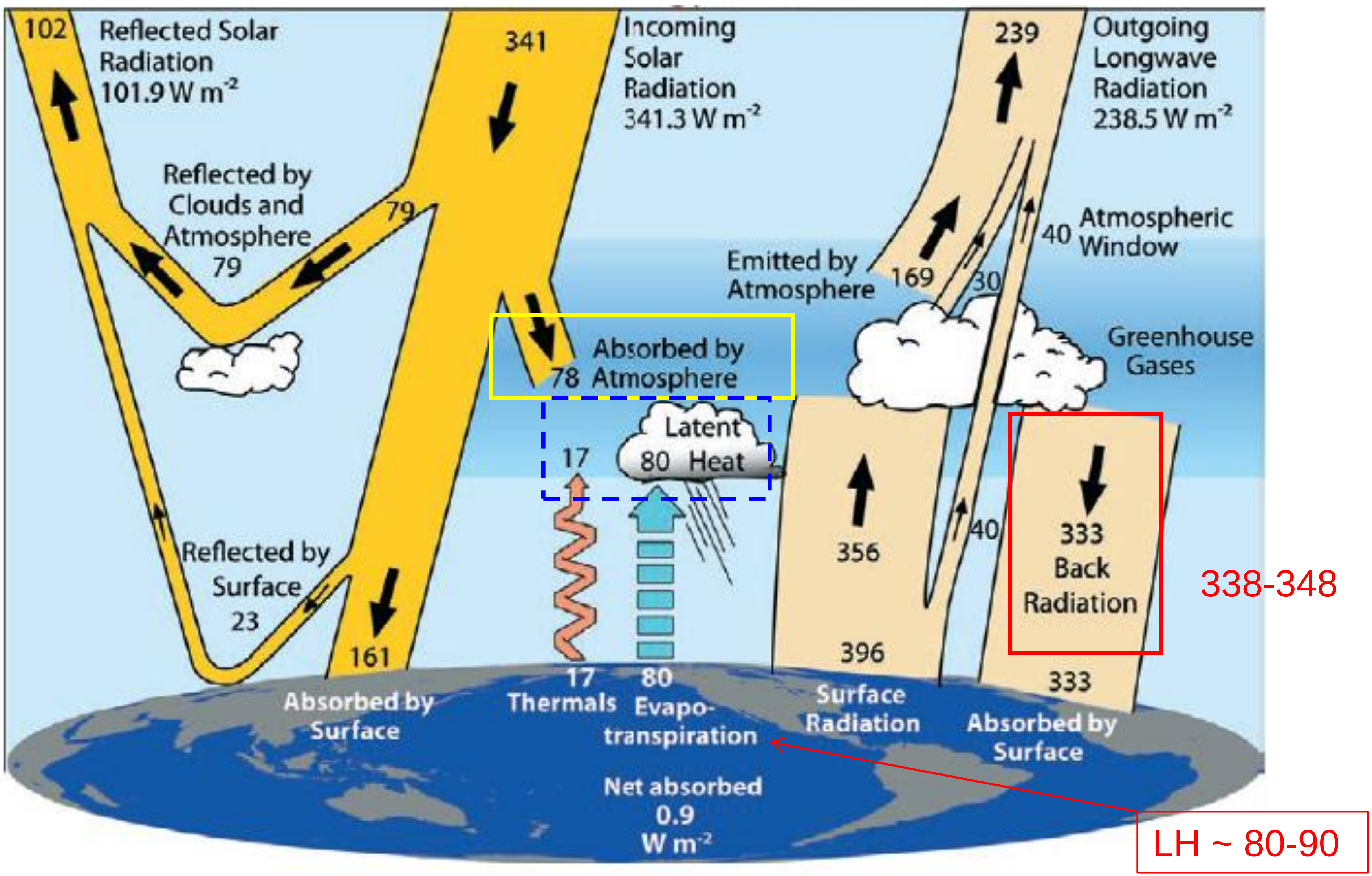


60S-60N, after Allan (2011) Meteorol. Apps

Conclusions (1)

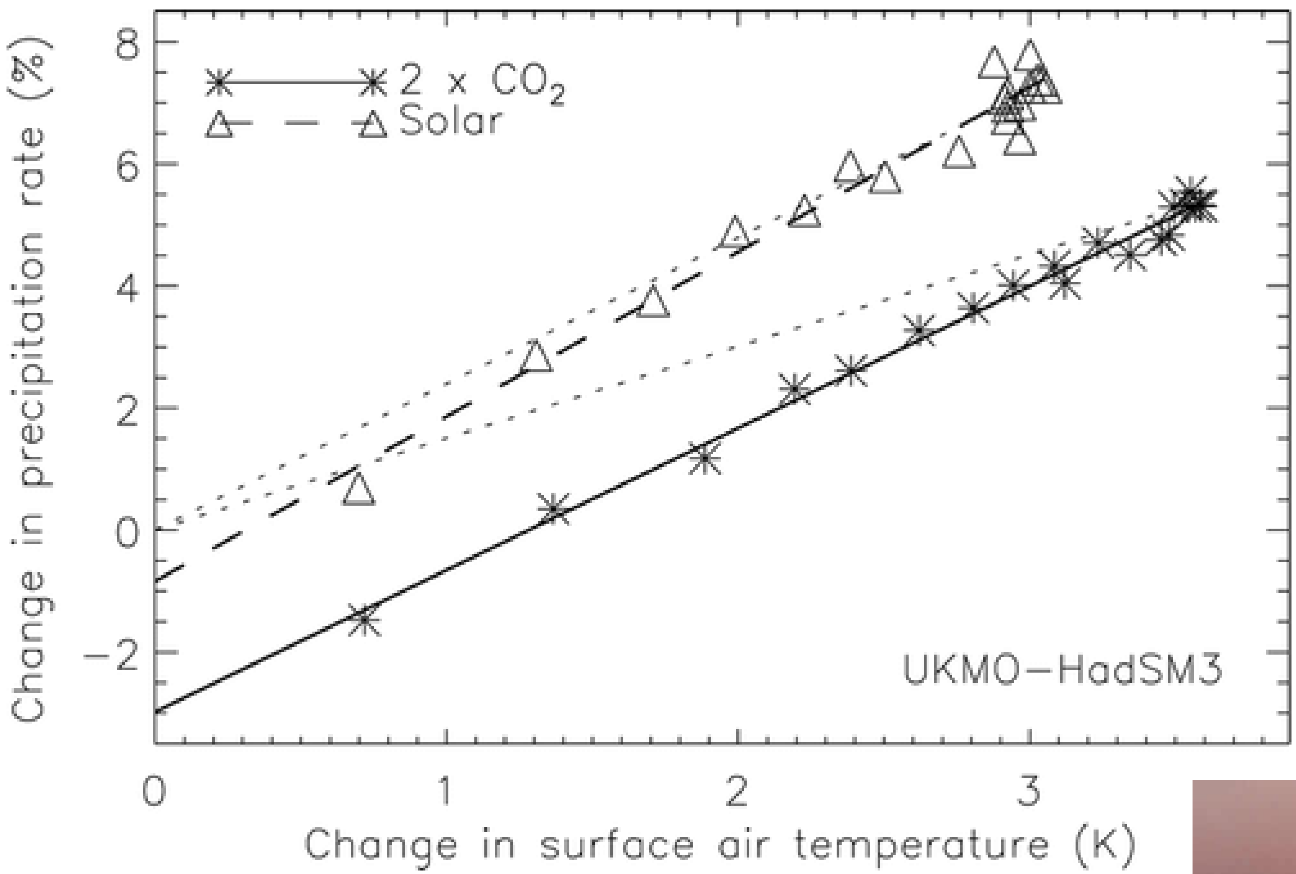
- Previously highlighted "missing energy" explained by ocean heat content uncertainty combined with inappropriate net radiation satellite products
- Heating of Earth continues (~0.5 Wm^{-2})
  - Negative radiative forcing does not appear to strongly contribute
- Implications:
  - Energy continues to 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?

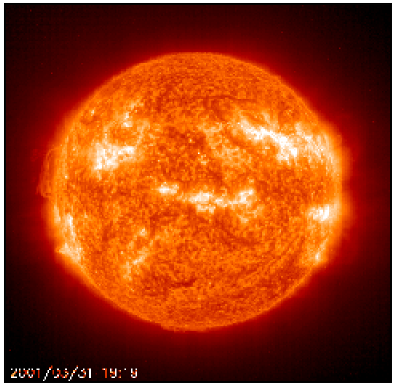
What has Earth's Energy Budget got to do with current changes in the Global Water Cycle?



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 $Wm^{-2}K^{-1}$

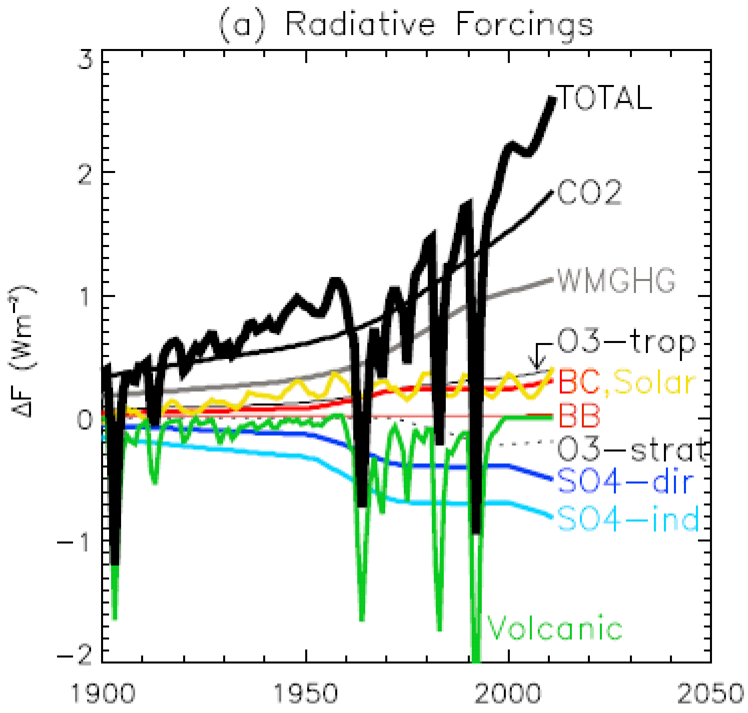
(ii) f dependent upon type of radiative forcing *ΔF*

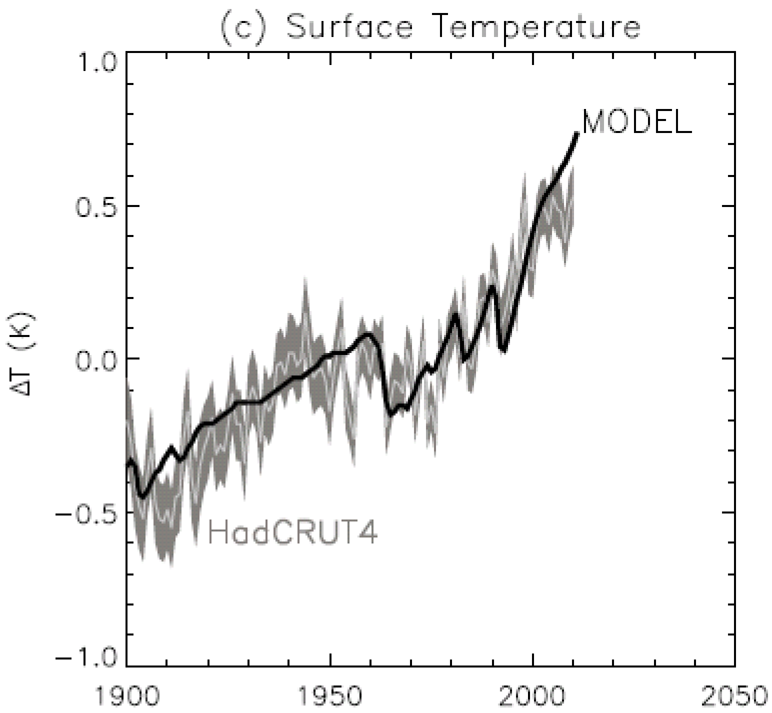
Precipitation change *ΔP* determined by:

(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)

A simple model of precipitation change





Allan et al. (2013) Surv. Geophys, in press

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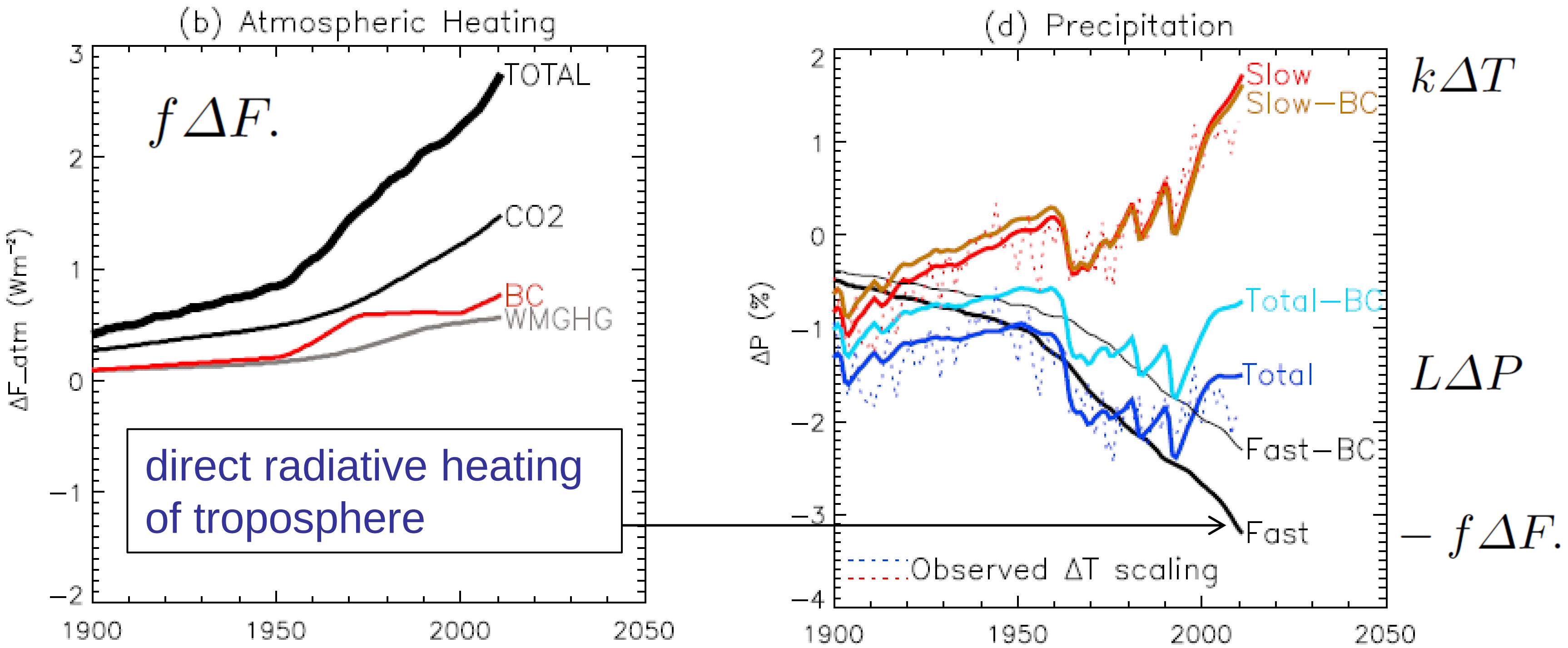
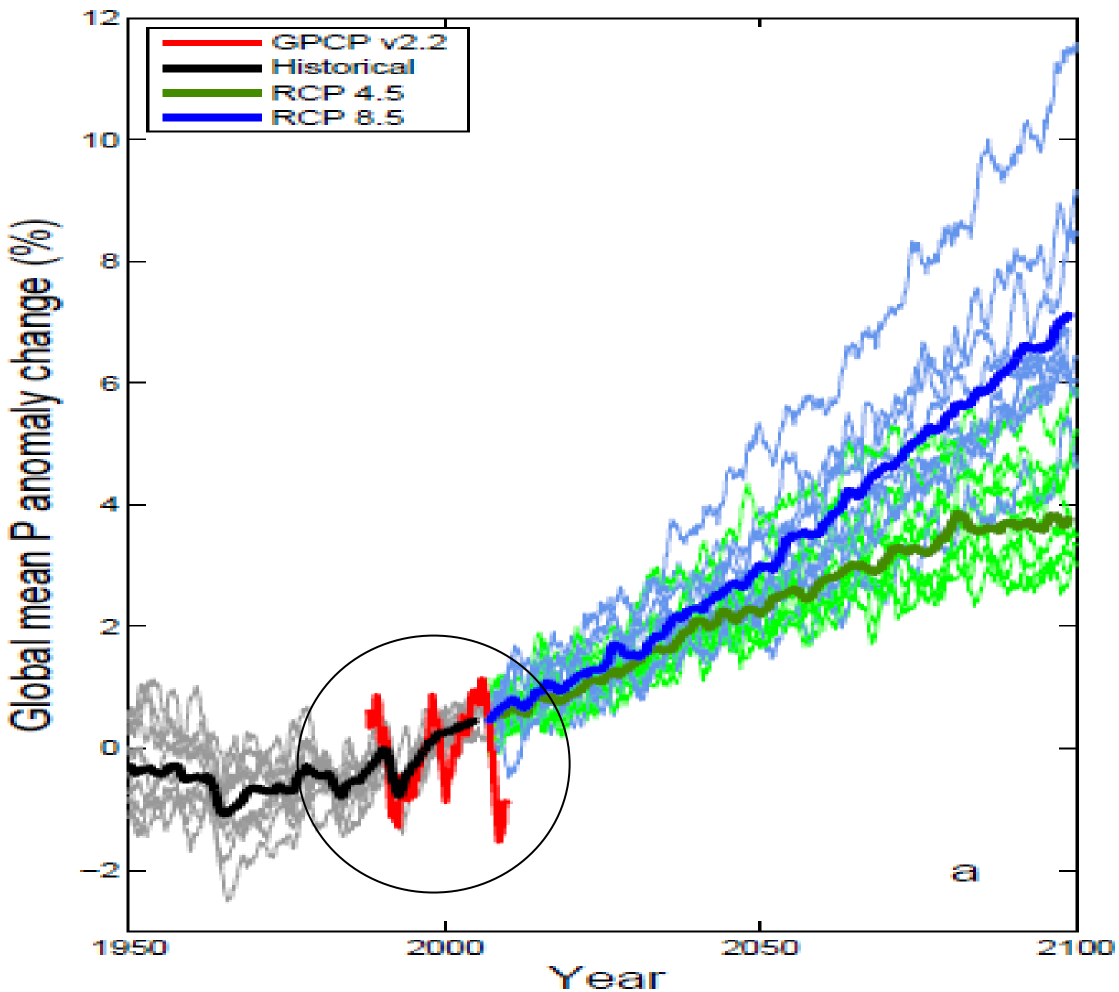


Allan et al. (2013) Surv. Geophys, in press

How does/will global to regional precipitation respond to climate change?



Allan et al. (2013) Surv. Geophys. in press.

See also: Hawkins & Sutton (2010) Clim. Dyn.

Global constraints: energy balance

(Allen & Ingram 2002)

- Surface T
- Radiative forcing (GHG, AA) (Andrews et al. 2010)

Regional constraints:

- Water vapour transports (Held & Soden 2006)
- Radiative forcing

Land vs ocean (Cao et al. 2012)

Circulation change

- Feedbacks

Land vs ocean

Circulation change

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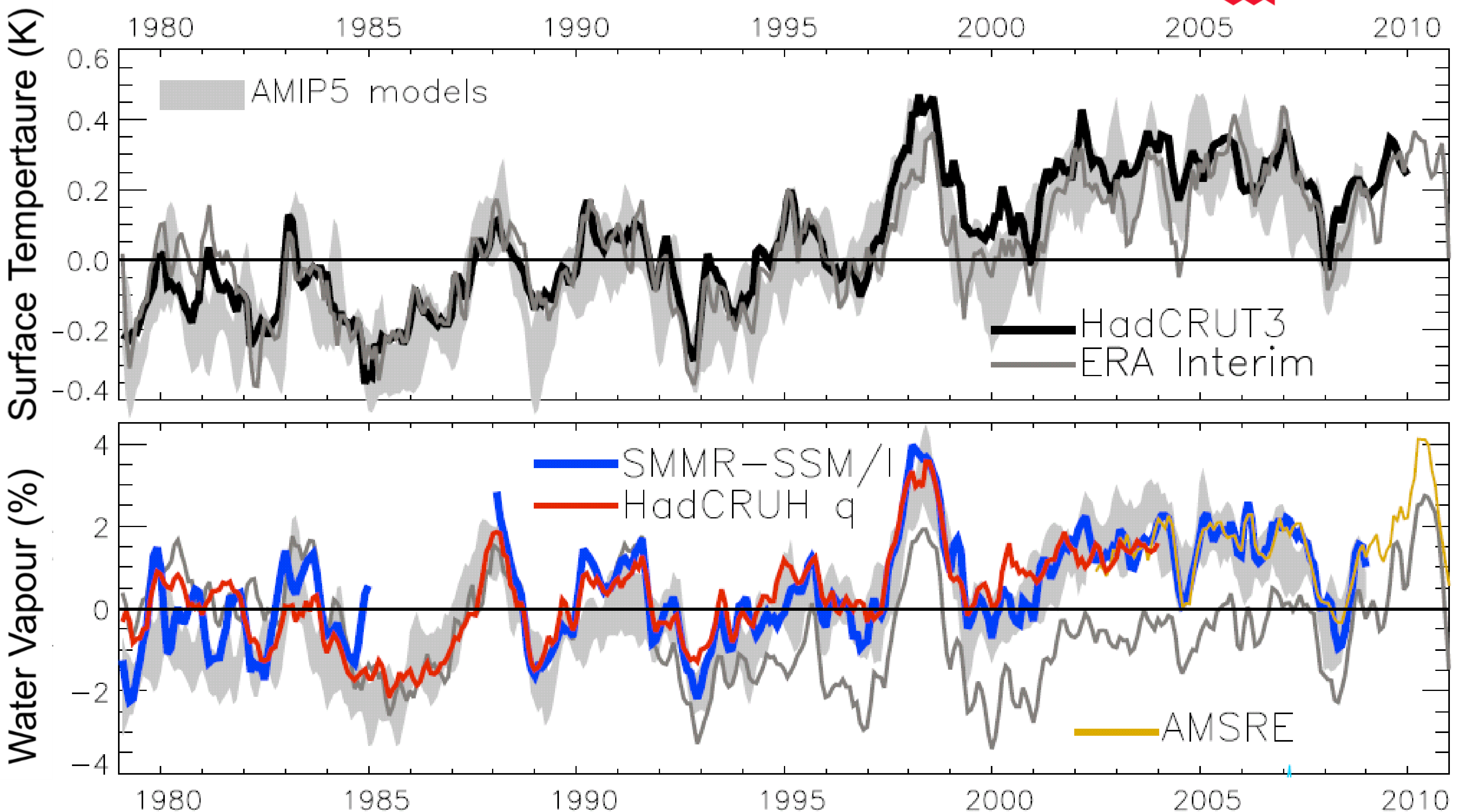
Global changes in water vapour



Allan et al. (2013) Surv. Geophys; see also O'Gorman et al. (2012); John et al. (2009)

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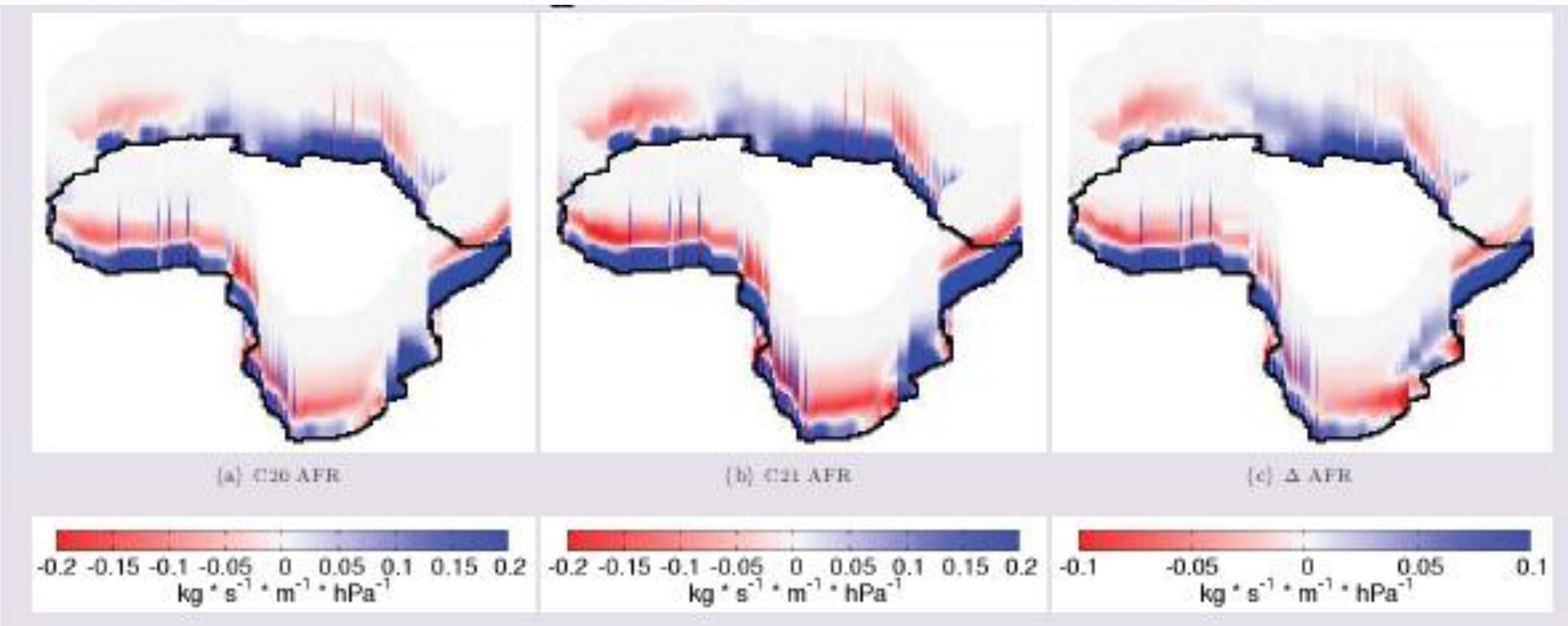
Enhanced moisture transports (moisture balance constraint)

20C | 21C | 21C-20C



PREPARE project
Zahn and Allan, submitted to WRR

see also: [Zahn and Allan (2013) J Clim]

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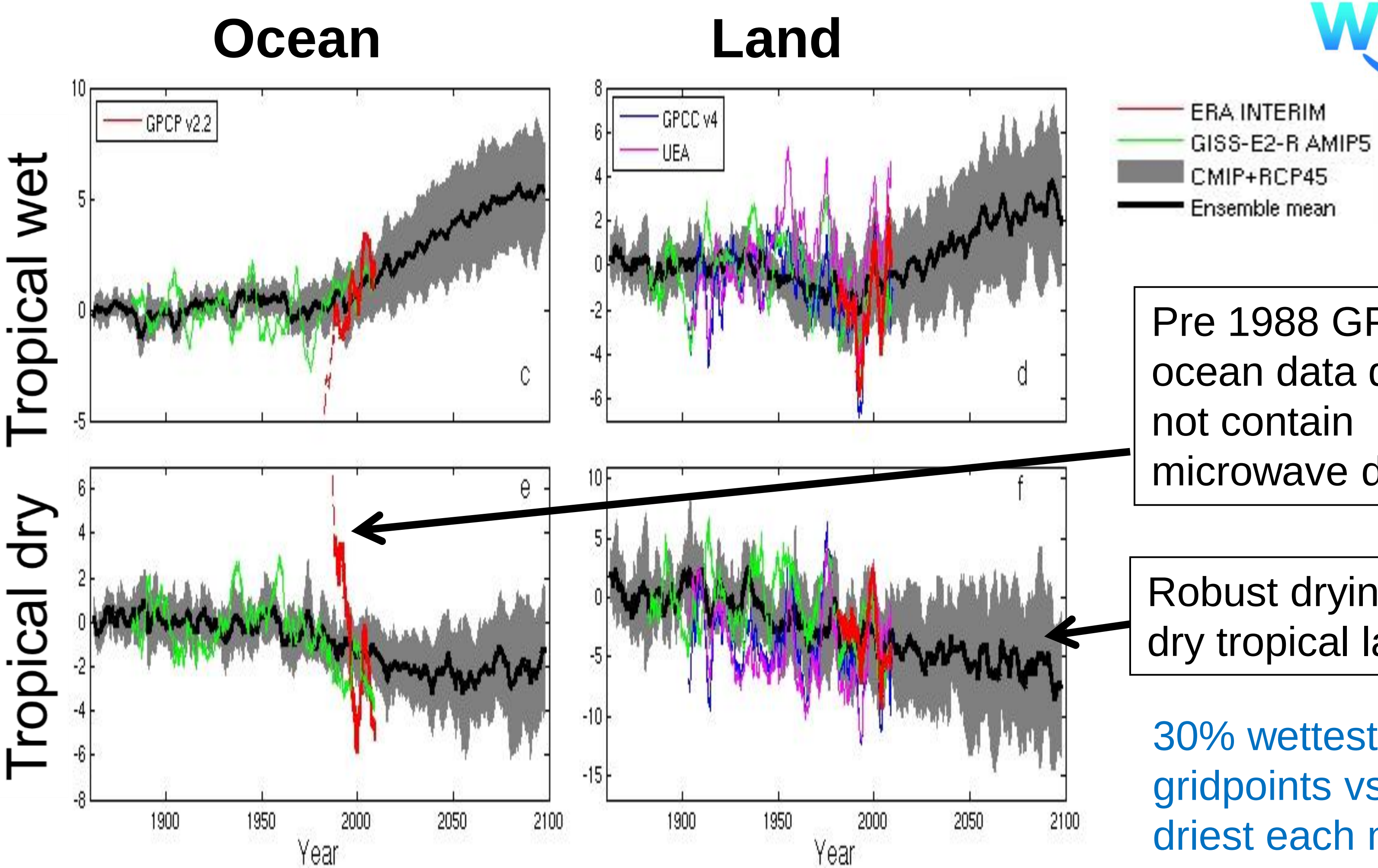
CMIP5 simulations: Wet regions get wetter, dry regions get drier



Pre 1988 GPCP ocean data does not contain microwave data

Robust drying of dry tropical land

30% wettest gridpoints vs 70% driest each month

Liu and Allan *in prep; see also* Allan et al. (2010) ERL.

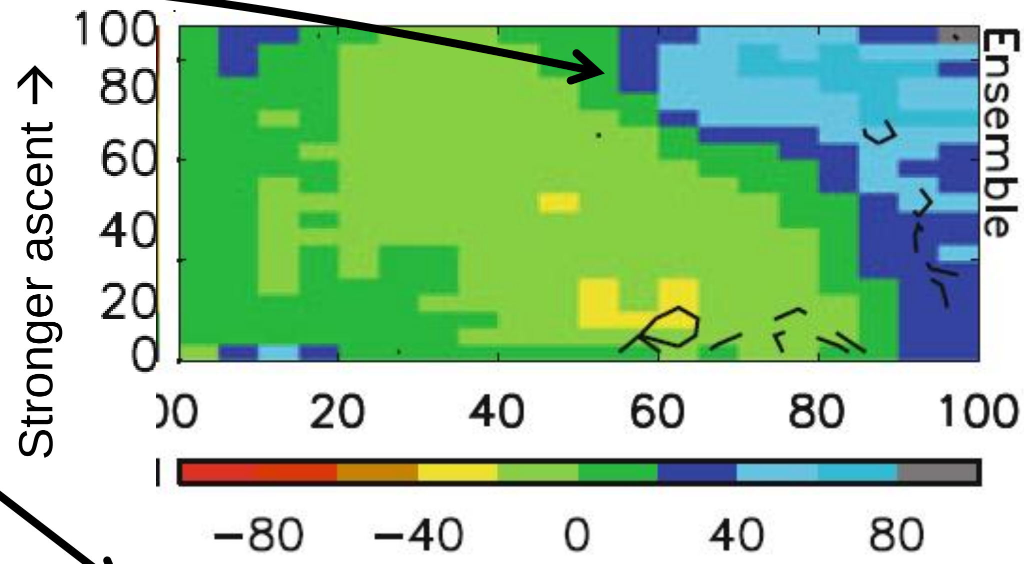
Fingerprints of precipitation response by dynamical regime

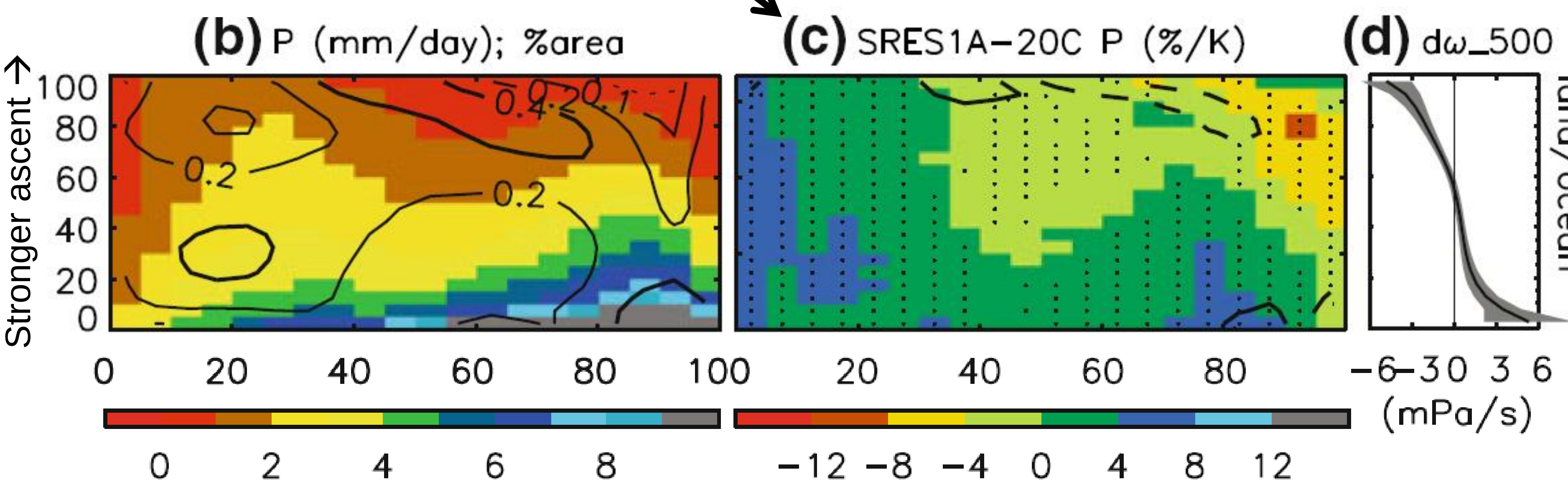
University of Reading

PREPARE project

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

Allan (2012) Clim. Dyn.





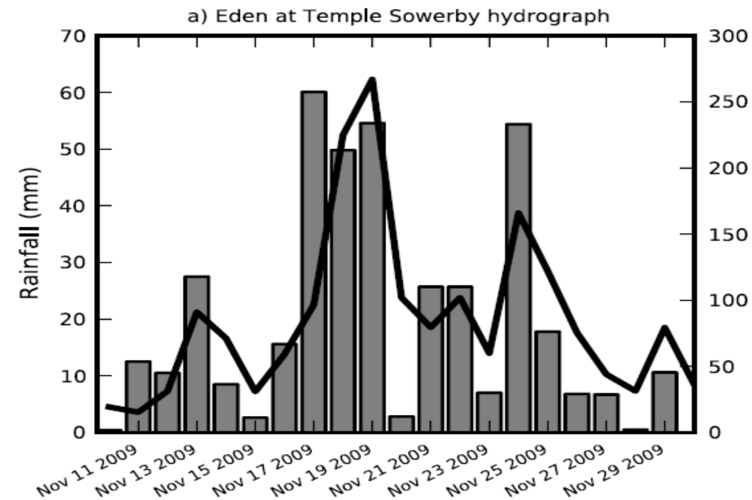
Applications: Linking flooding to moisture transports (HydEF)

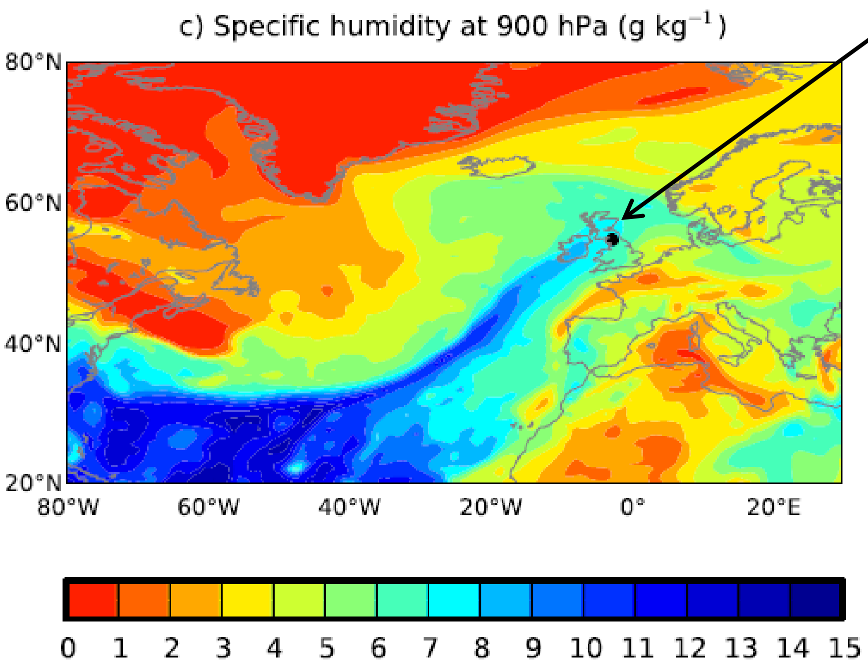
NATURAL ENVIRONMENT RESEARCH COUNCIL

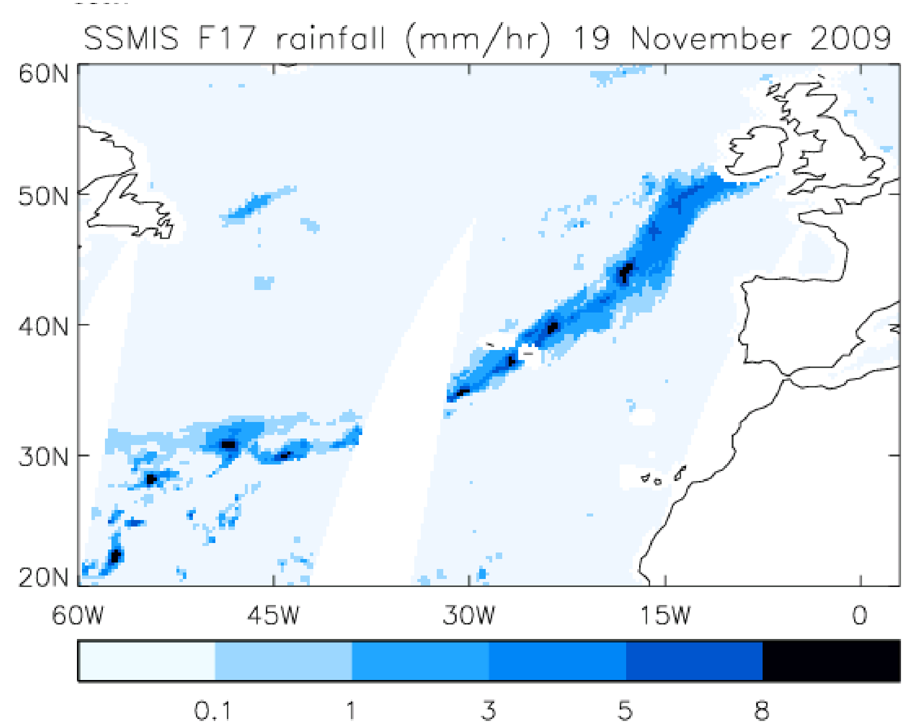
Changing water cycle

University of Reading

HydEF project: Importance of large-scale atmospheric precursors for flooding e.g. 2009 Cumbria floods







[Lavers et al. (2011) Geophys. Res. Lett.]

Identifying “Atmospheric Rivers” simulated by climate models

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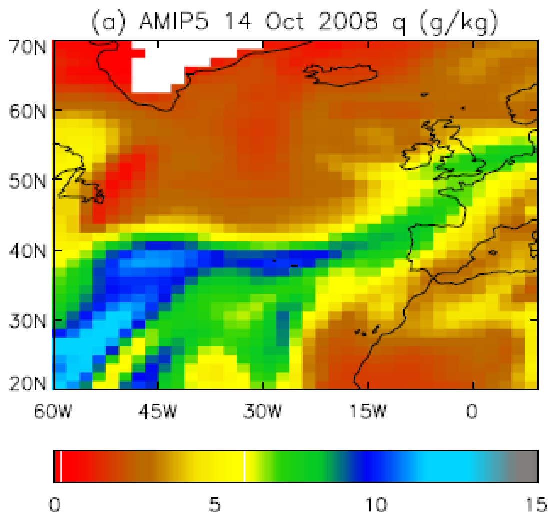
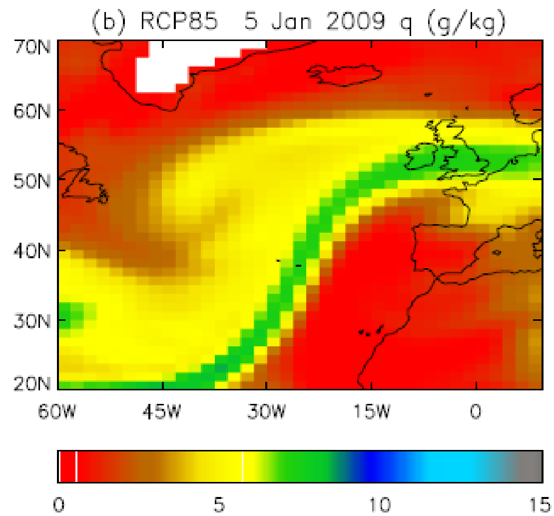
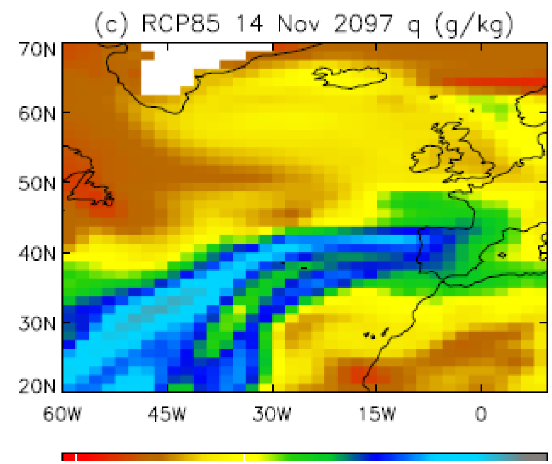
AMIP



CMIP



← Coarse-scale climate models able to capture flood-generating mid-latitude systems



- Will thermodynamics dominate over changes in dynamics under climate change? →

…work in progress (HydEF)

Allan et al. (2013) Surv. Geophys, in press

Evaluating climate model simulations of precipitation extremes

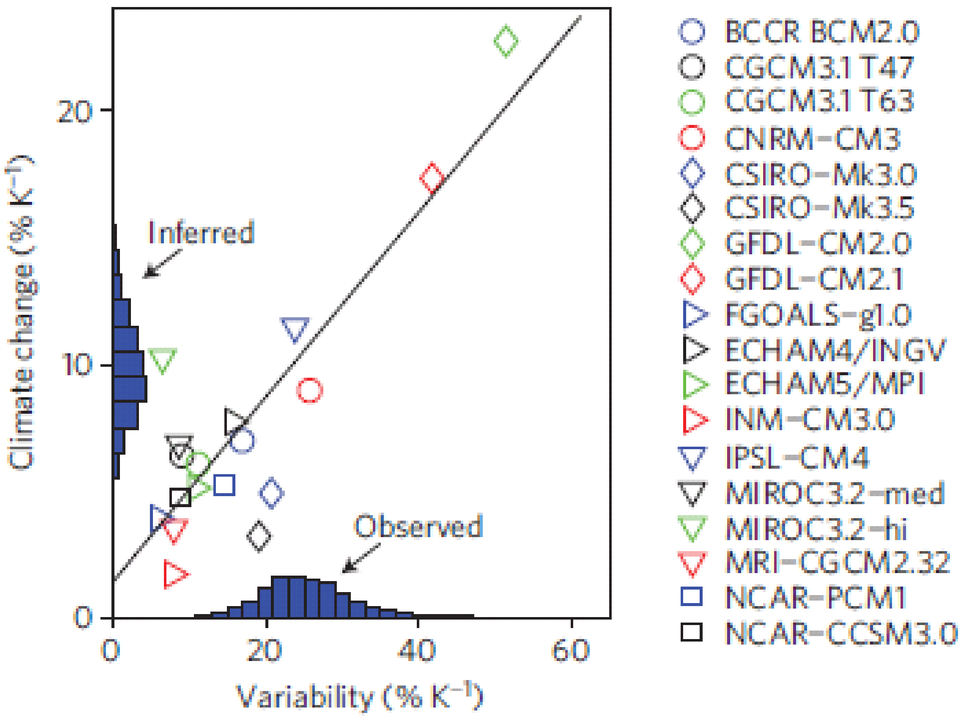


Figure 2 | Sensitivities (% K^{-1}) of the 99.9th percentile of precipitation for variability versus climate change in the CMIP3 simulations. The solid

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

O'Gorman (2012) *Nature Geosciences*

See also Allan & Soden (2008) *Science*

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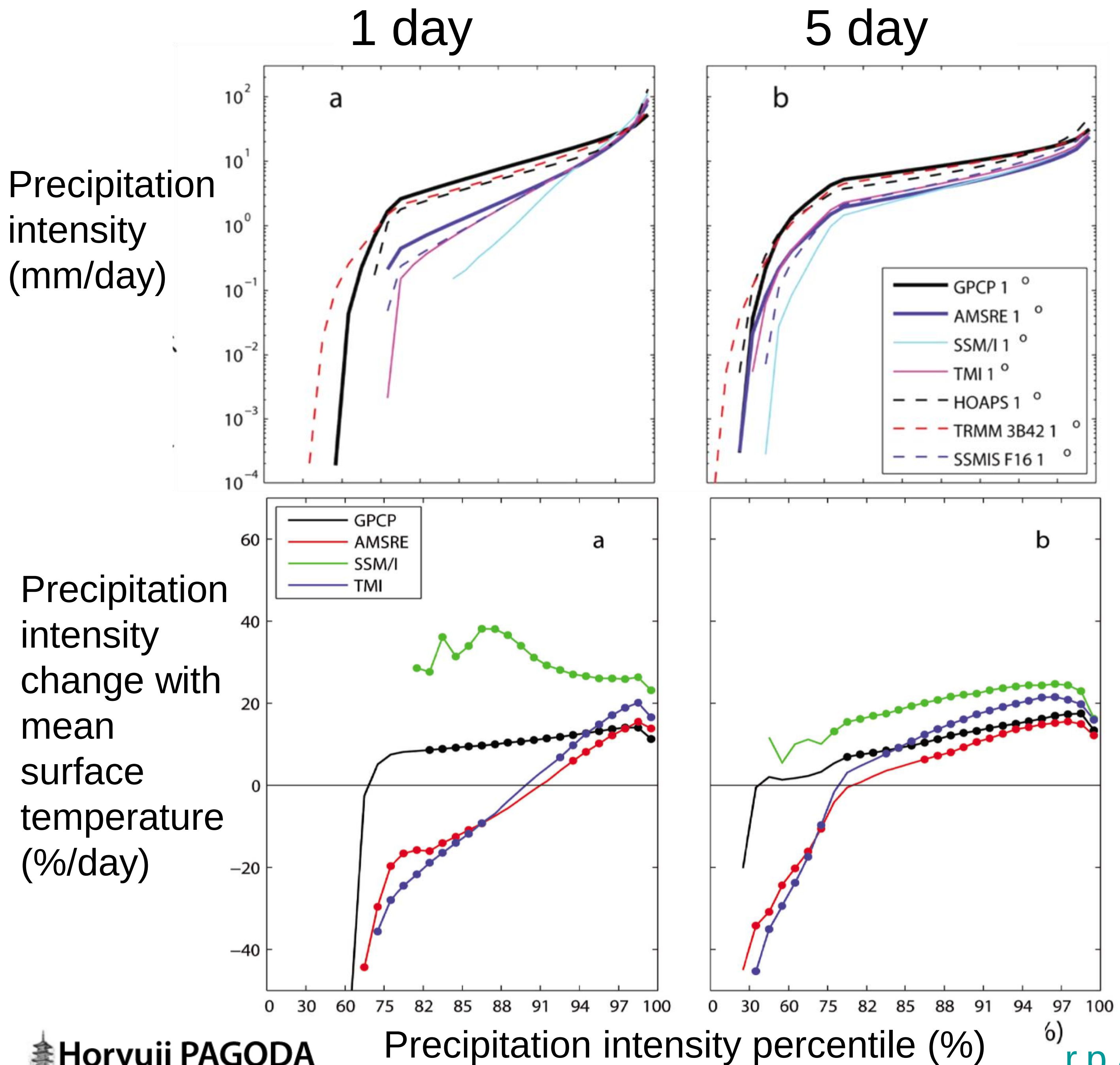

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Changing water cycle

Uncertainty in observed P intensity & response

(tropical oceans)

Liu & Allan (2012) JGR

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

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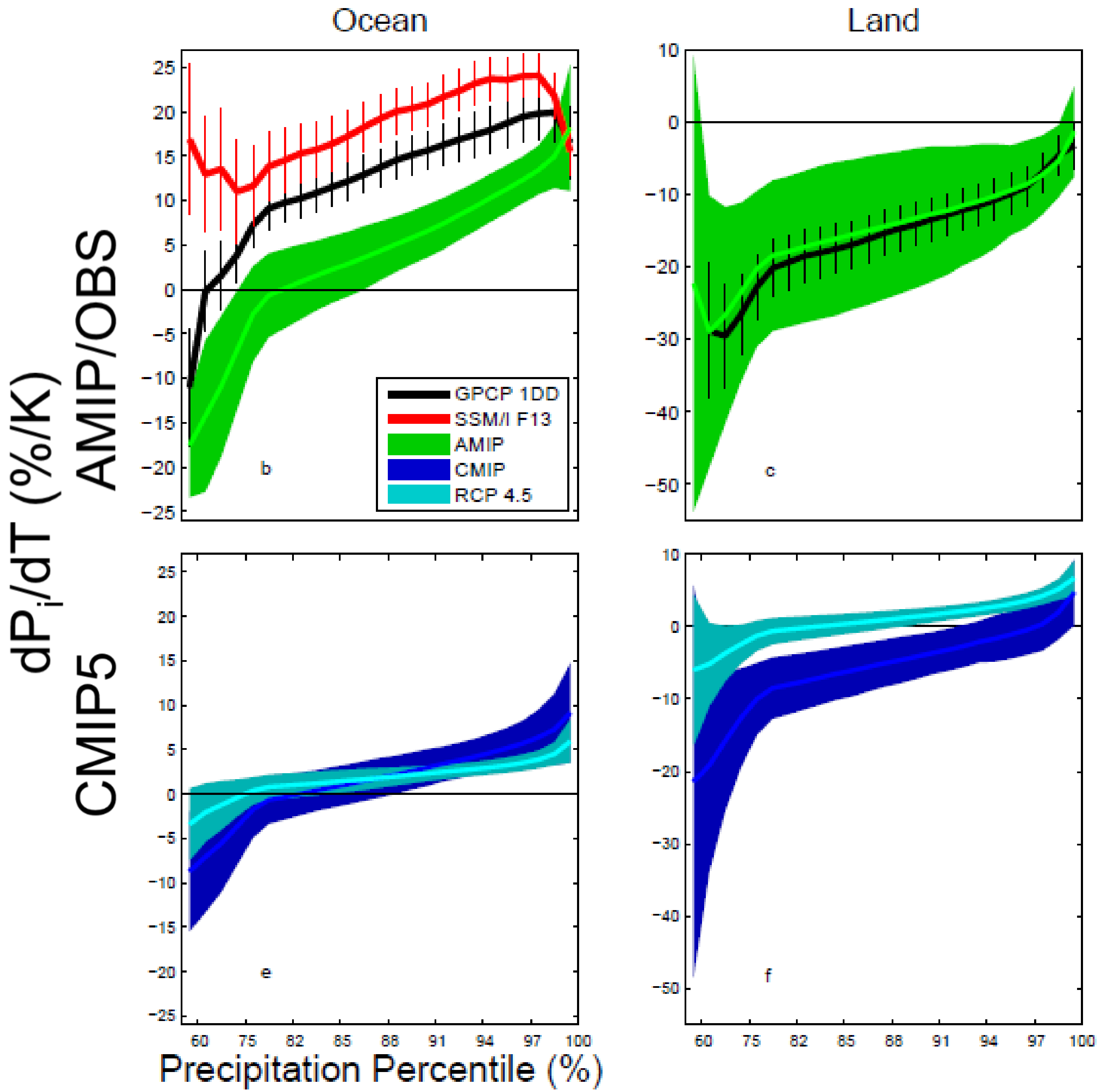
Response of Precipitation intensity distribution to warming:

Observations and CMIP5, 5-day mean

Is present day variability a good proxy for climate response?

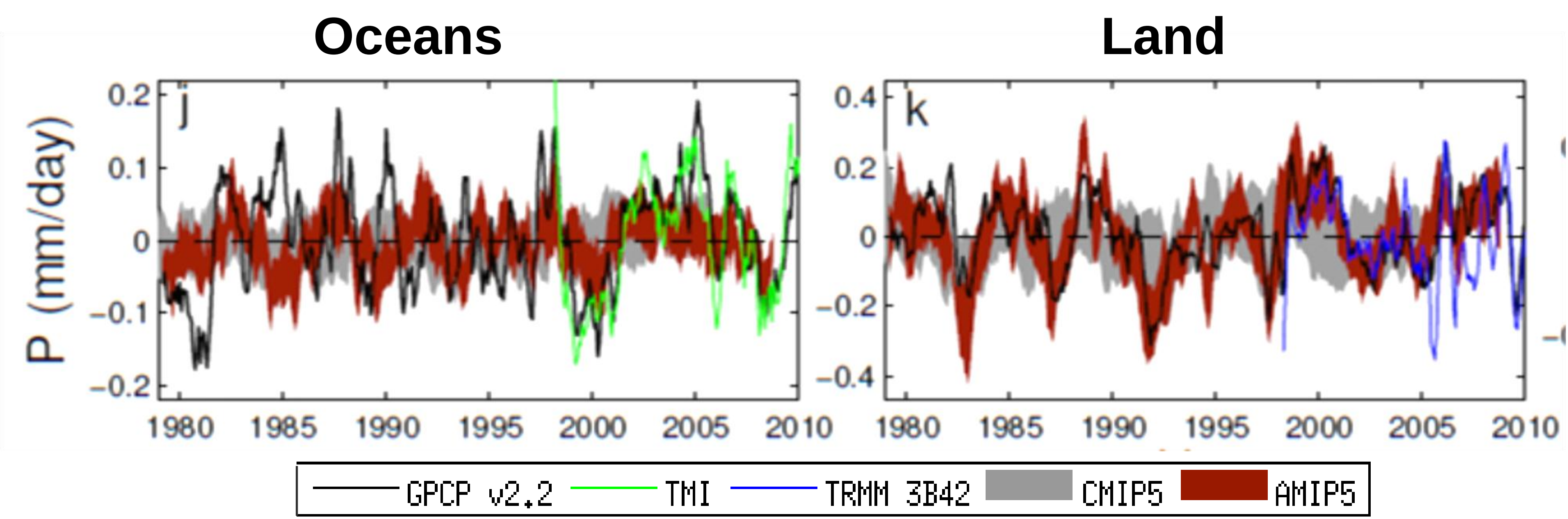


Allan et al. (2013) Surv. Geophys, in press, see also Allan and Soden (2008) Science

Observing systems: a challenge

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

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Conclusions

- Energy balance is fundamental to climate response, in particular for the water cycle
- Observations indicate a positive imbalance of ~0.6 Wm^{-2} over the last decade despite stable surface Temperature
- Energy and moisture balance powerful constraints on global-regional water cycle
- Current increases in wet and dry extremes
  - Linked to rises in low-level moisture of about 7%/K
- Global precipitation rises due to surface warming (~2%/K) offset slightly by direct effect of GHG forcing on troposphere
- Aerosol radiative forcing key in determining circulation-driven precipitation responses

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