Department of Meteorology

University of Reading

EARTH'S ENERGY AND WATER CYCLES: ONGOING PROJECTS

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Summary of current research projects and results

National Centre for Atmospheric Science
NATURAL ENVIRONMENT RESEARCH COUNCIL

National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

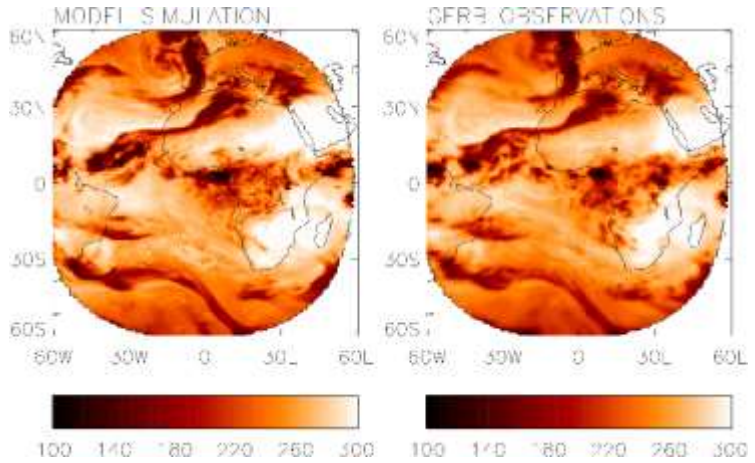
NERC SCIENCE OF THE ENVIRONMENT

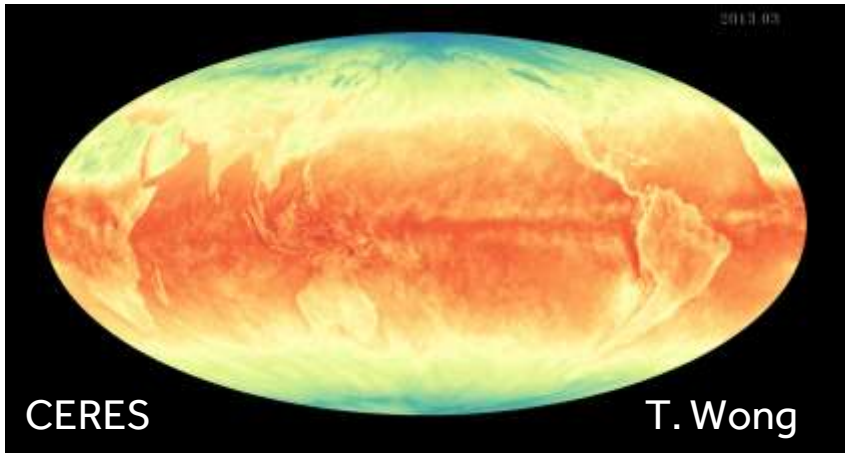
CURRENT AND RECENT PROJECTS

- NERC CWC projects (PAGODA, HYDEF)
- DEEP-C – Understanding changes in Earth's energy balance in the context of current climate change and variability (NERC)
- SINATRA – Work task on atmospheric precursors to intense summer rainfall (NERC FFIR programme)
- DACCIWA – Clouds, Radiation & Aerosol over West Africa (EU)
- 3D Shortwave Radiative Kernels of Marine Boundary-layer Clouds (DoE)
- NCEO – Cloud, Radiation & Precip studies & prep for Earthcare
- TAMSAT – changes in Africa rainfall including PhD project
- Simple model for precipitation (PhD project)

EARTH'S RADIATIVE ENERGY BUDGET AND CLIMATE

- Earth's radiative energy budget represents a nexus between radiative forcings, feedbacks & climate response
- Powerful constraint upon hydrological cycle
- Versatile diagnostic of the impact of clouds, aerosol, water vapour greenhouse effect and atmospheric circulation



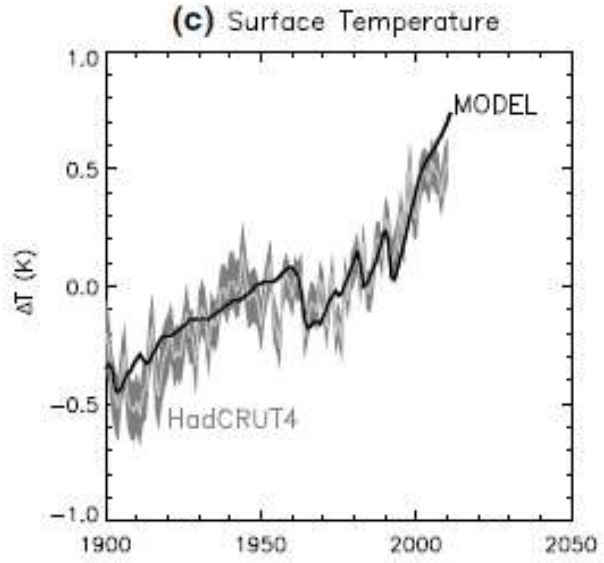


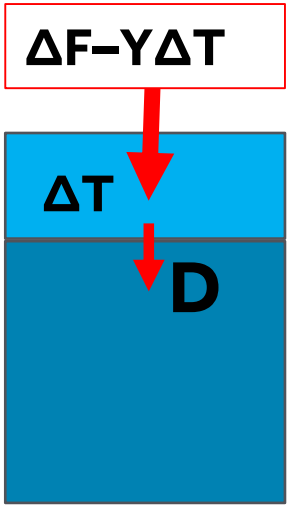
A SIMPLE ENERGY BALANCE MODEL OF EARTH'S CLIMATE

- Oceans dominate the heat capacity of climate system
- Temperature change linked to radiative forcings (ΔF) and response which depends on feedbacks Y.
- Heat uptake by the deep ocean is important in the timescale and variability of climate change
- Simple models are useful for interpreting climate change

$$\frac{d\Delta T_m}{dt} = \frac{1}{C_m}(\Delta F - Y\Delta T_m - D)$$

$$D = c(\Delta T_m - \Delta T_D)/d$$





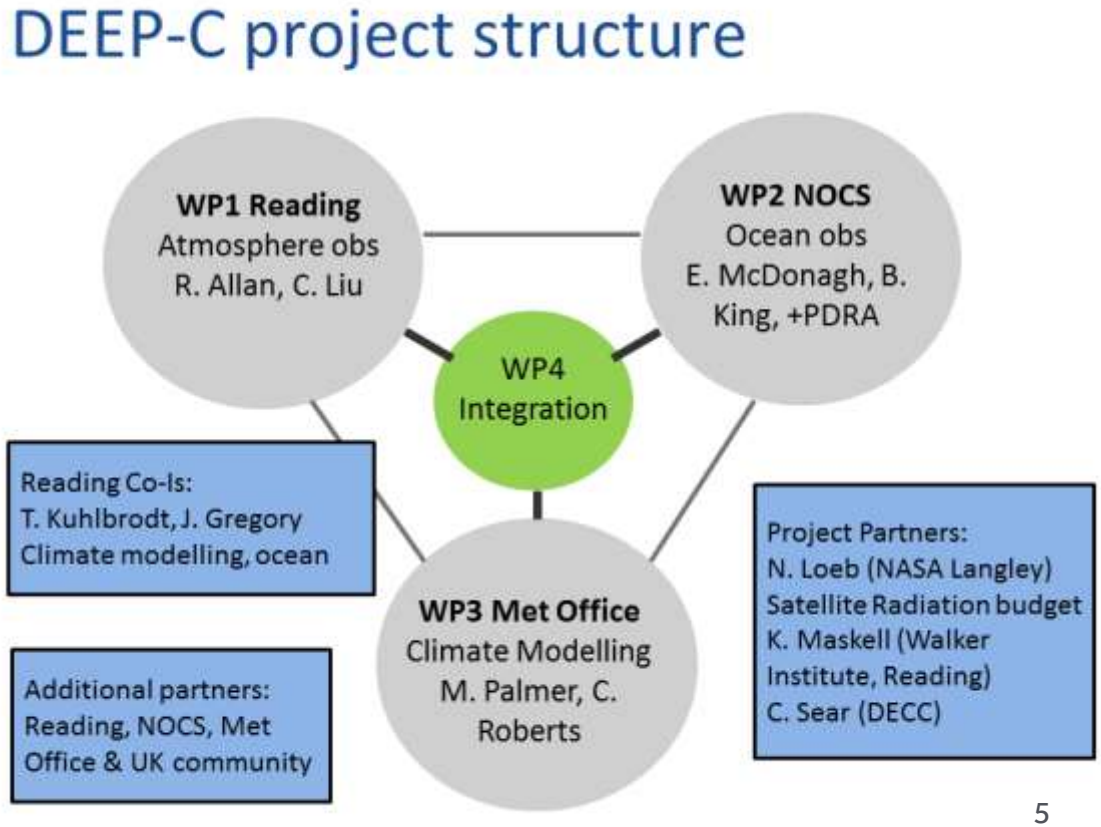
e.g. Allan et al. (2014) Surv. Geophys

DIAGNOSING EARTH'S ENERGY PATHWAYS IN THE CLIMATE SYSTEM: DEEP-C

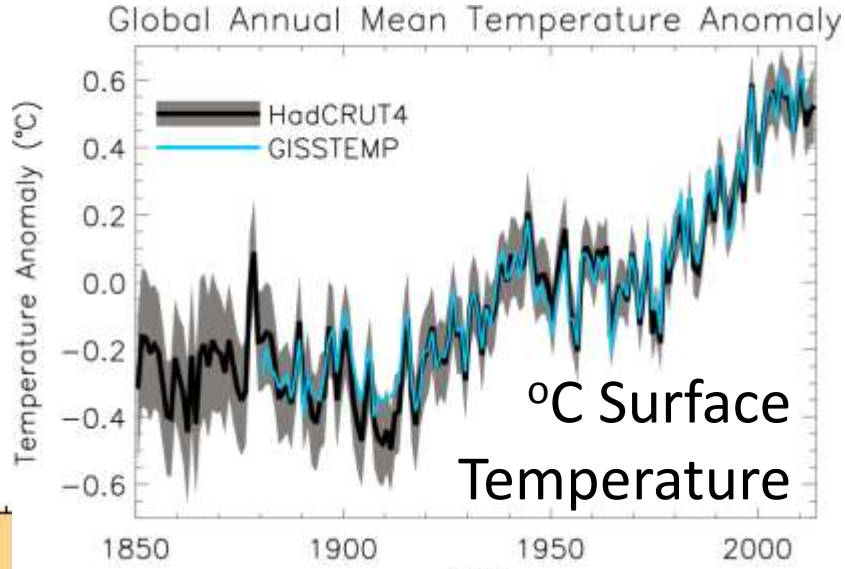
- 4-year NERC consortium (Reading/Met Office/NOC) tackling the questions:

1. What explains apparent slowing in global surface warming rate since around 2000
2. Where is excess energy due to rising greenhouse gas concentrations currently accumulating in the climate system?

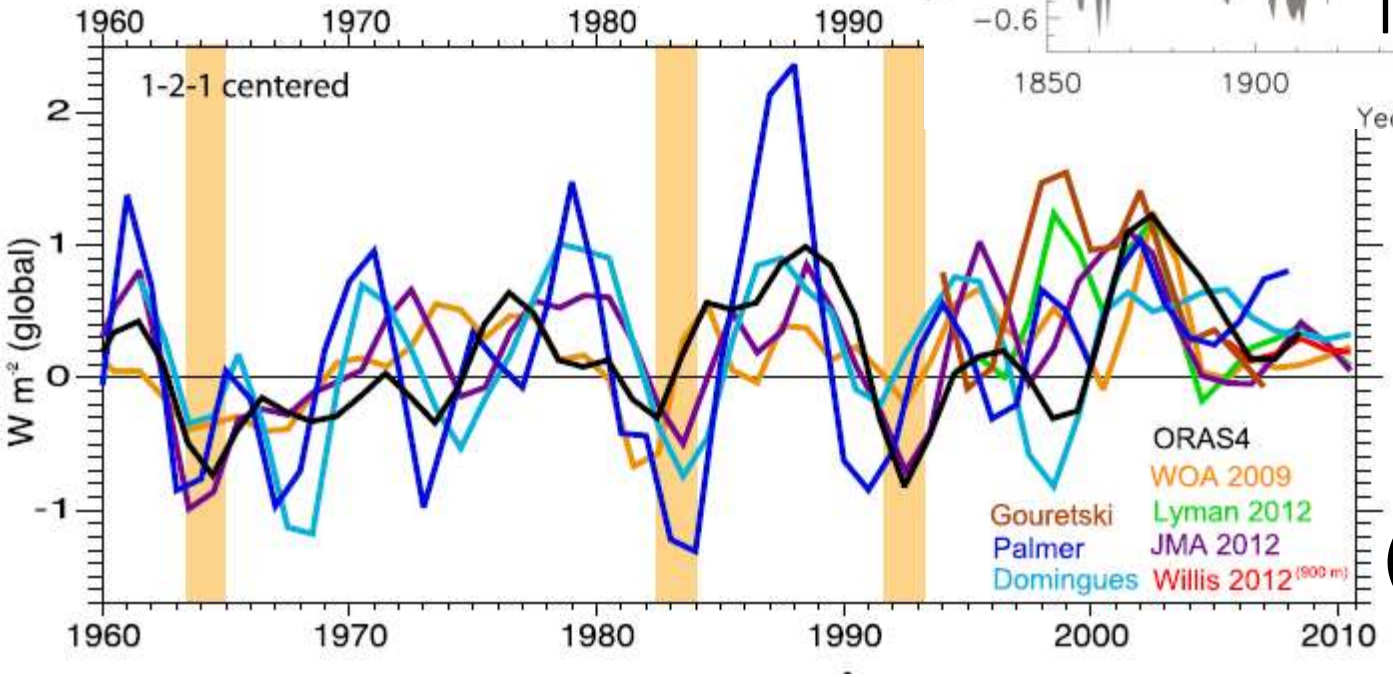
~sgs02rpa/research/DEEP-C.html



AT WHAT RATE IS EARTH HEATING?



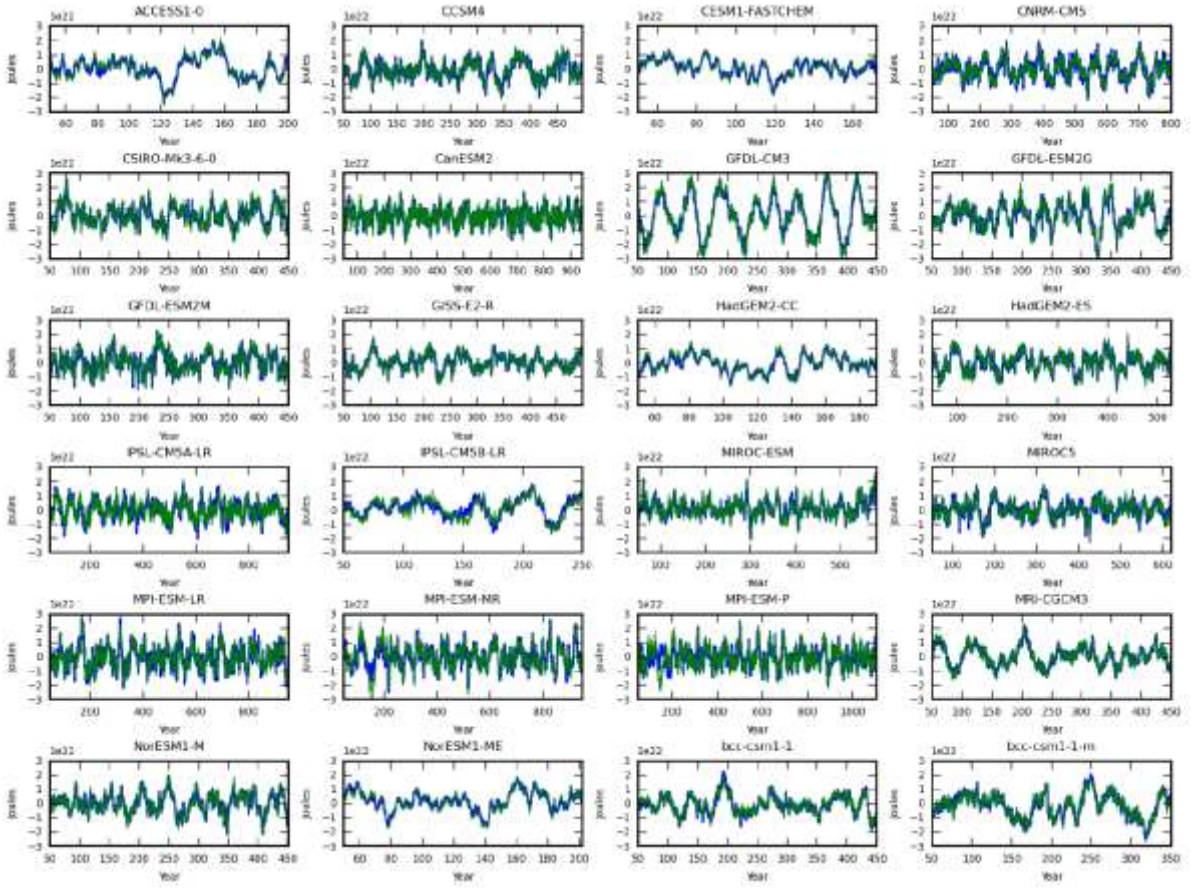
°C Surface Temperature



Upper ocean (Wm^{-2})

Trenberth et al. (2014) J Clim

UNFORCED VARIABILITY IN EARTH'S ENERGY BUDGET

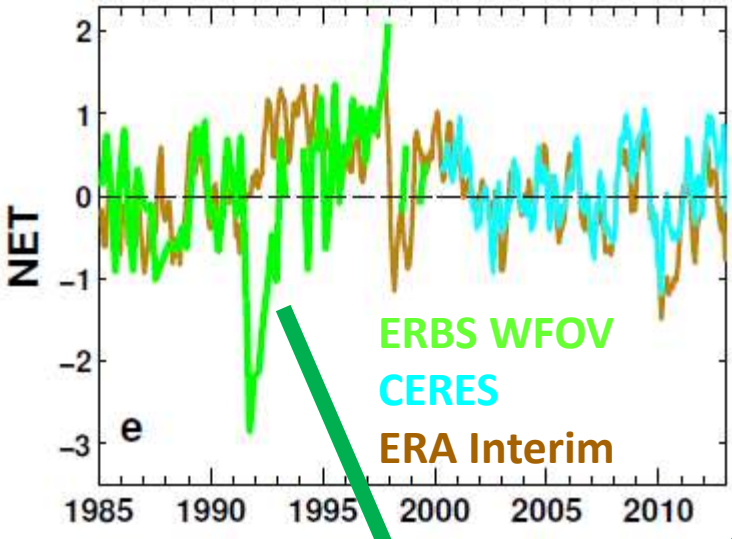


- Diverse range of unforced variability in CMIP5 pre-industrial control simulations
- **Left:** variations in total energy content of Earth's climate system across CMIP5 simulations

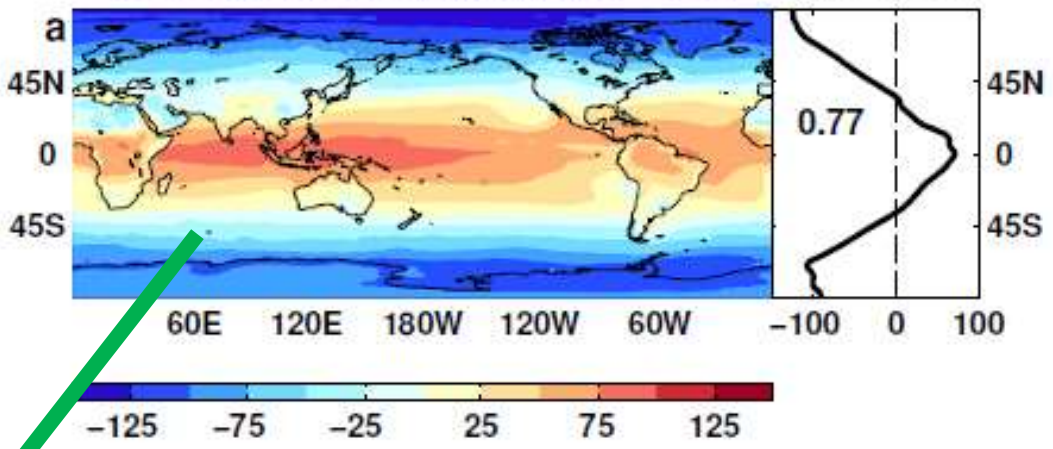
Palmer & McNeall (2014) ERL

RECONSTRUCTING GLOBAL RADIATIVE FLUXES SINCE 1985

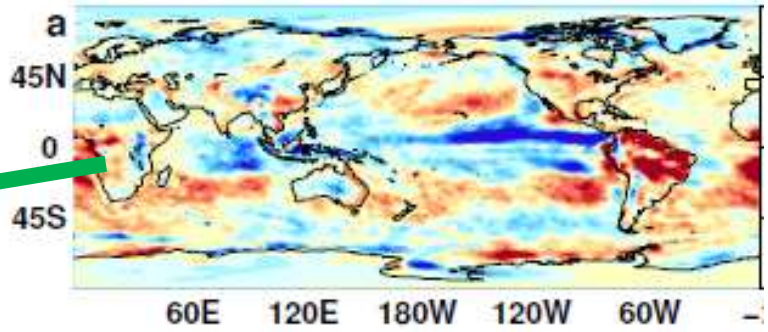
ERBS/CERES variability



CERES monthly climatology



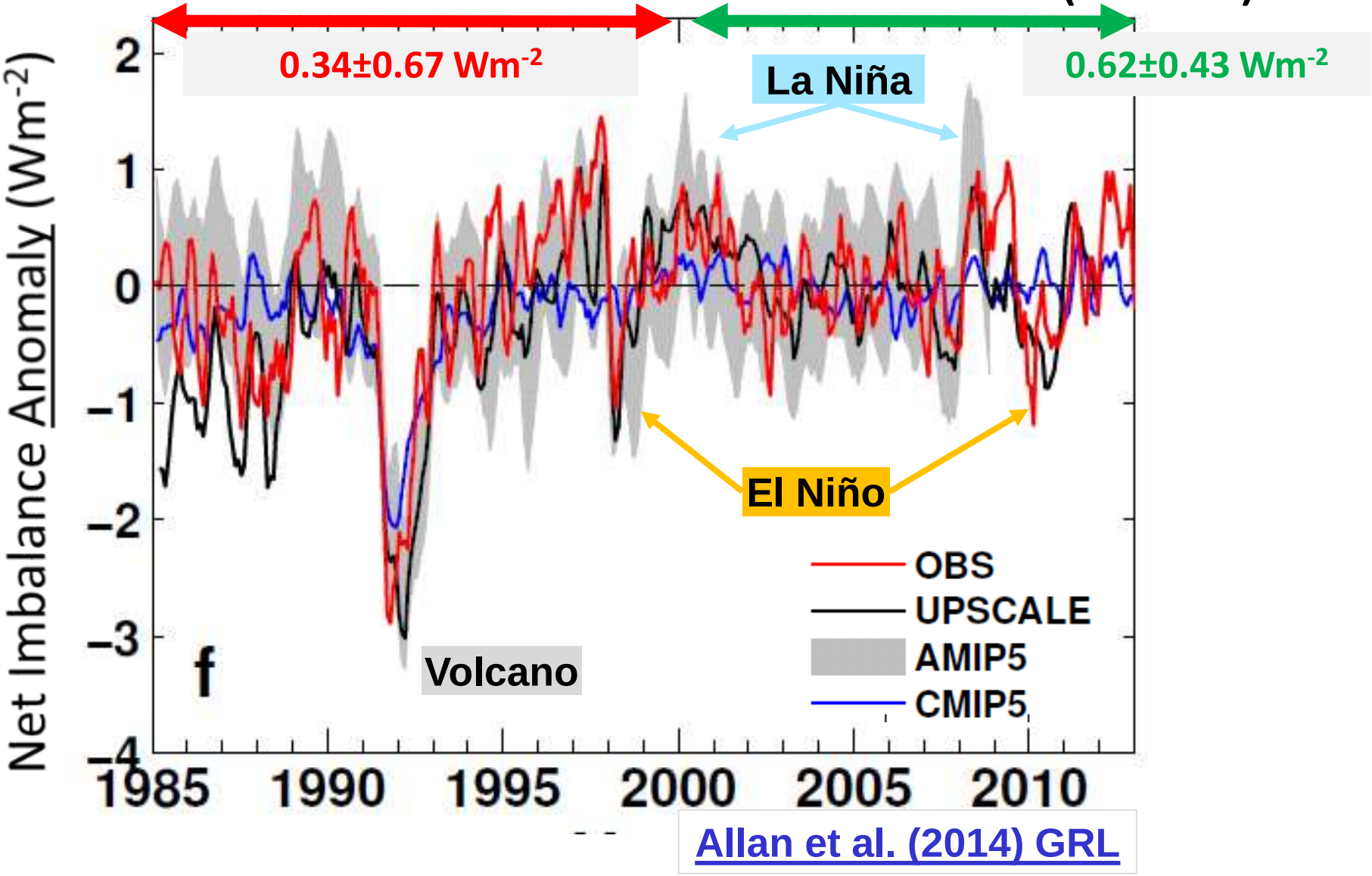
ERA Interim spatial anomalies



Combine CERES/ARGO accuracy, ERBS WFOV stability and reanalysis circulation patterns to reconstruct radiative fluxes

EARTH CONTINUES TO HEAT UP

Imbalance: 0.23 0.00 0.78 0.63 0.63 (Wm^{-2})



Allan et al. (2014) GRL

UNDERSTANDING CHANGES IN NET IMBALANCE

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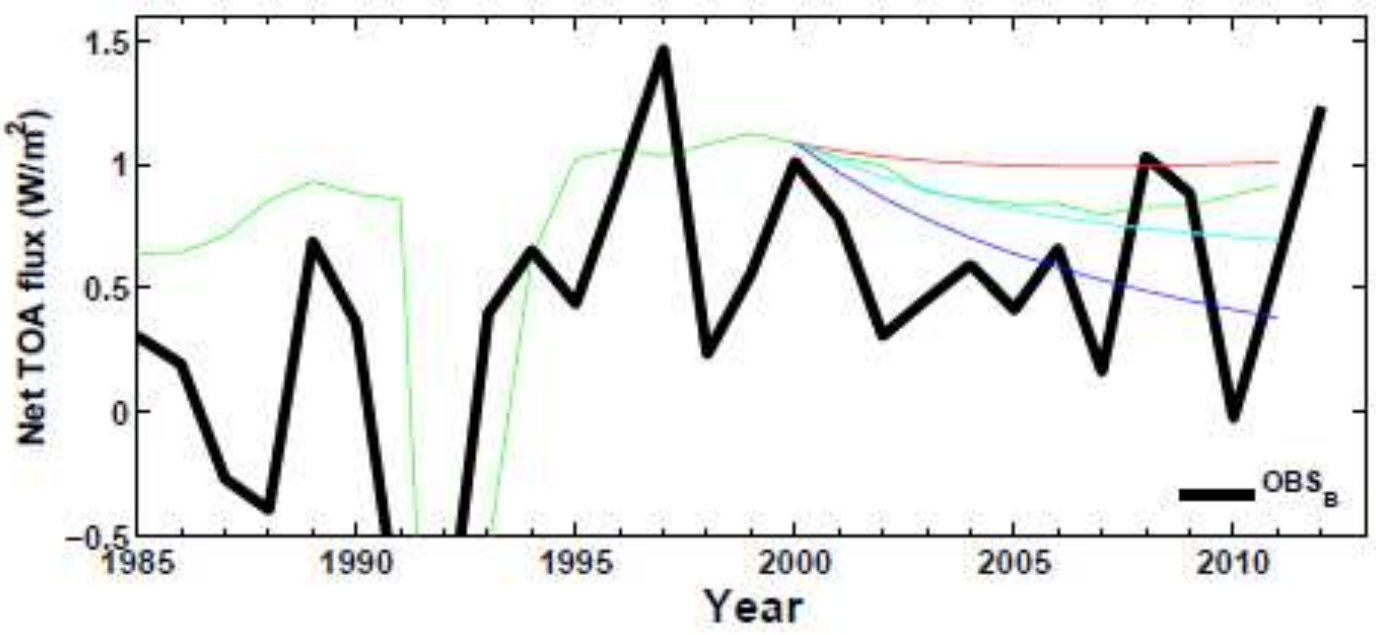
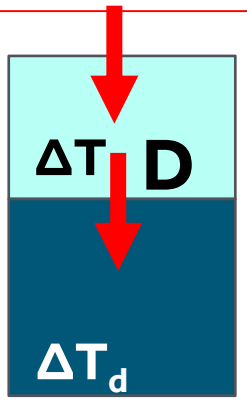
N



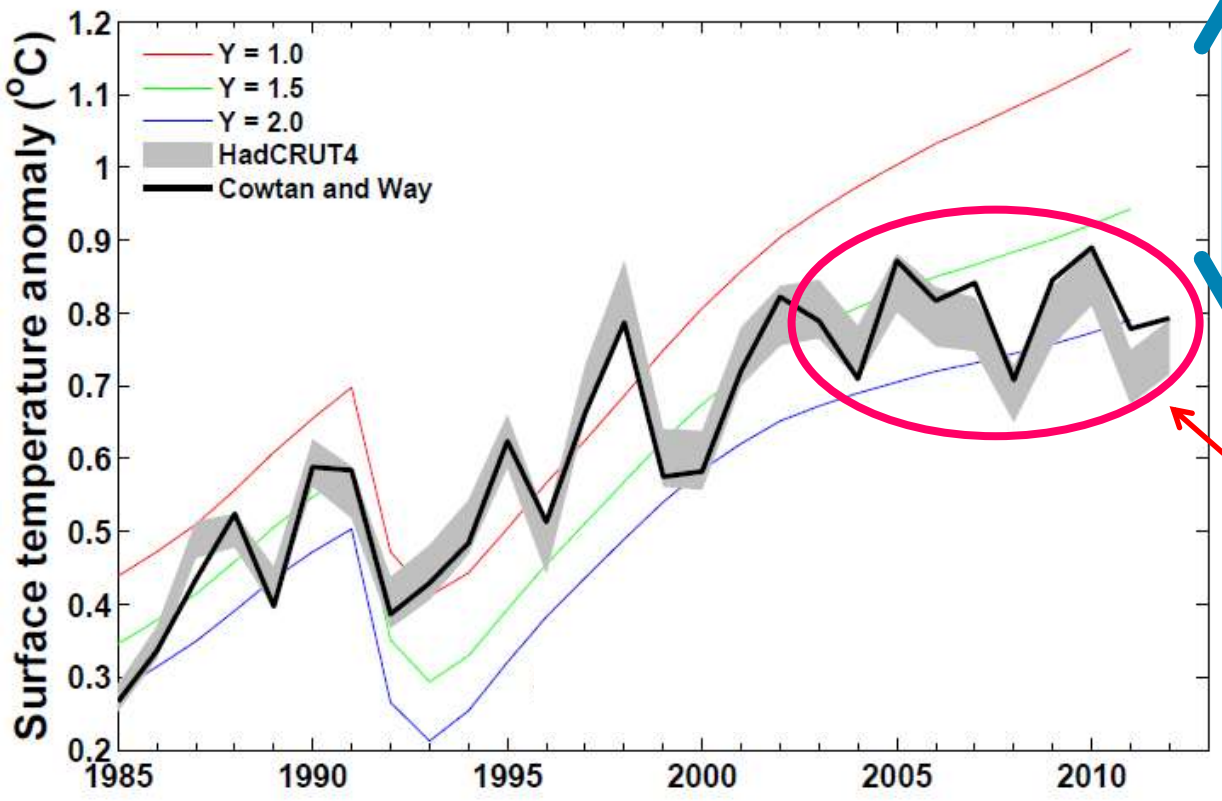
+ve RF trend
AR5 RF
0 RF trend
-ve RF trend

$N = \Delta F - Y\Delta T$



Analysis using simple energy balance model
Allan et al. (2014) GRL supplementary

IMPLICATIONS FOR CLIMATE SENSITIVITY?

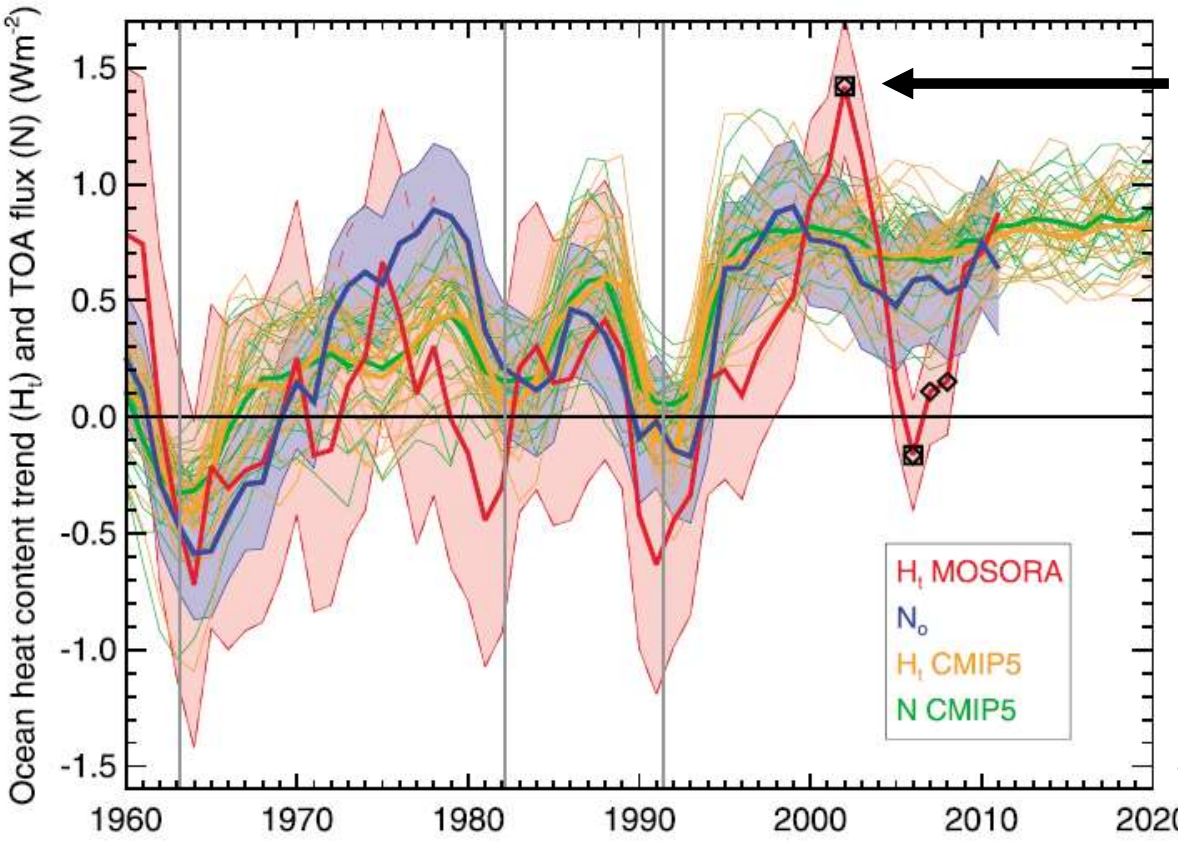


Allan et al. (2014) GRL supplementary

?Can comparisons tell us about how sensitive climate is to radiative forcing Otto et al. (2013) Nature Geosci

Infilling data gaps influences surface temperature trends (Cowtan & Way, 2013 QJRMS) and ocean heat content (Lyman & Johnson 2014 J. Clim.)

DISCREPANCY BETWEEN RADIATION BUDGET & OCEAN HEATING



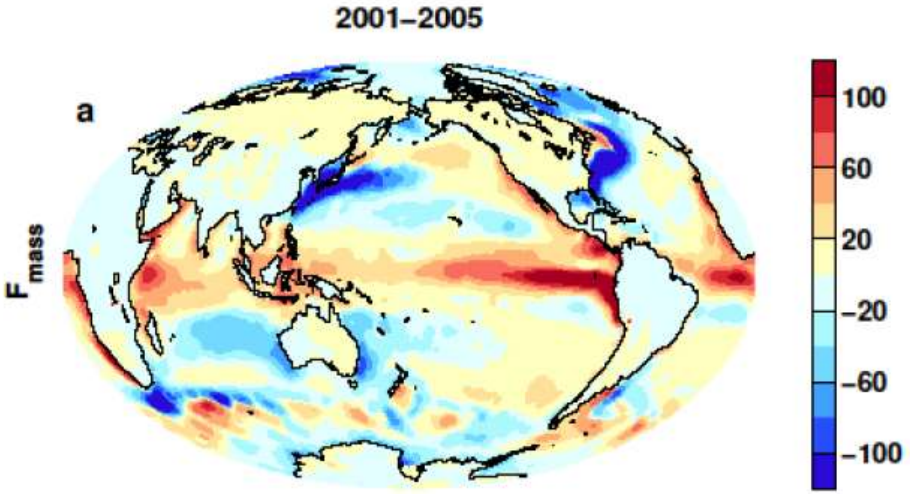
- Large ocean heating anomaly in 2002
- Inconsistent with radiation budget observations and simulations
- Changing observing system influence?
- Slight drop in net flux 1999-2005?

Smith et al. (2015) GRL

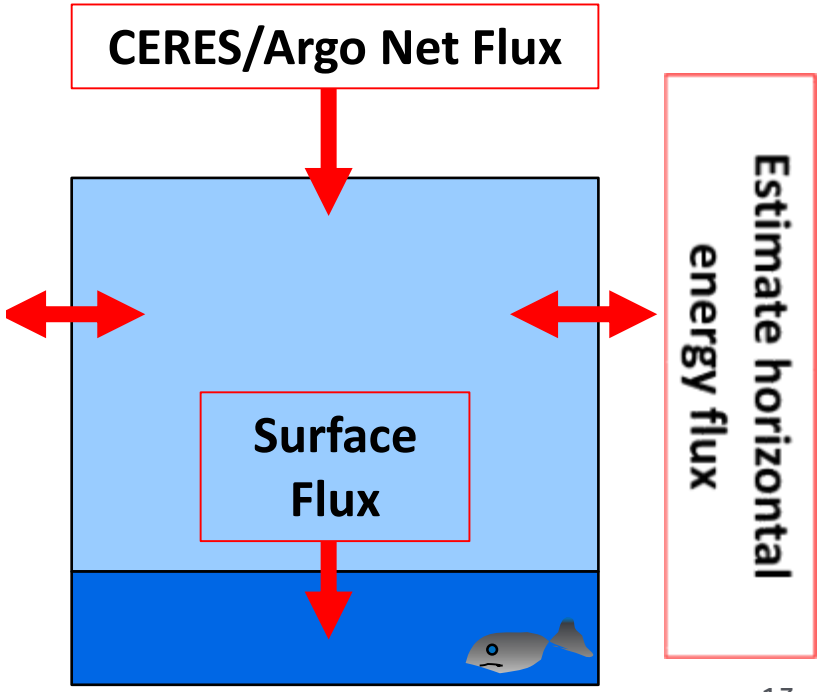
WHERE IS THE HEAT GOING?

NEW ESTIMATES OF SURFACE ENERGY FLUX

$$F_{SFC} = F_{TOA} - \frac{\partial TE}{\partial t} - \nabla \cdot \frac{1}{g} \int_0^1 V(Lq + C_p T + \varphi_s + k) \frac{\partial p}{\partial \eta} d\eta$$

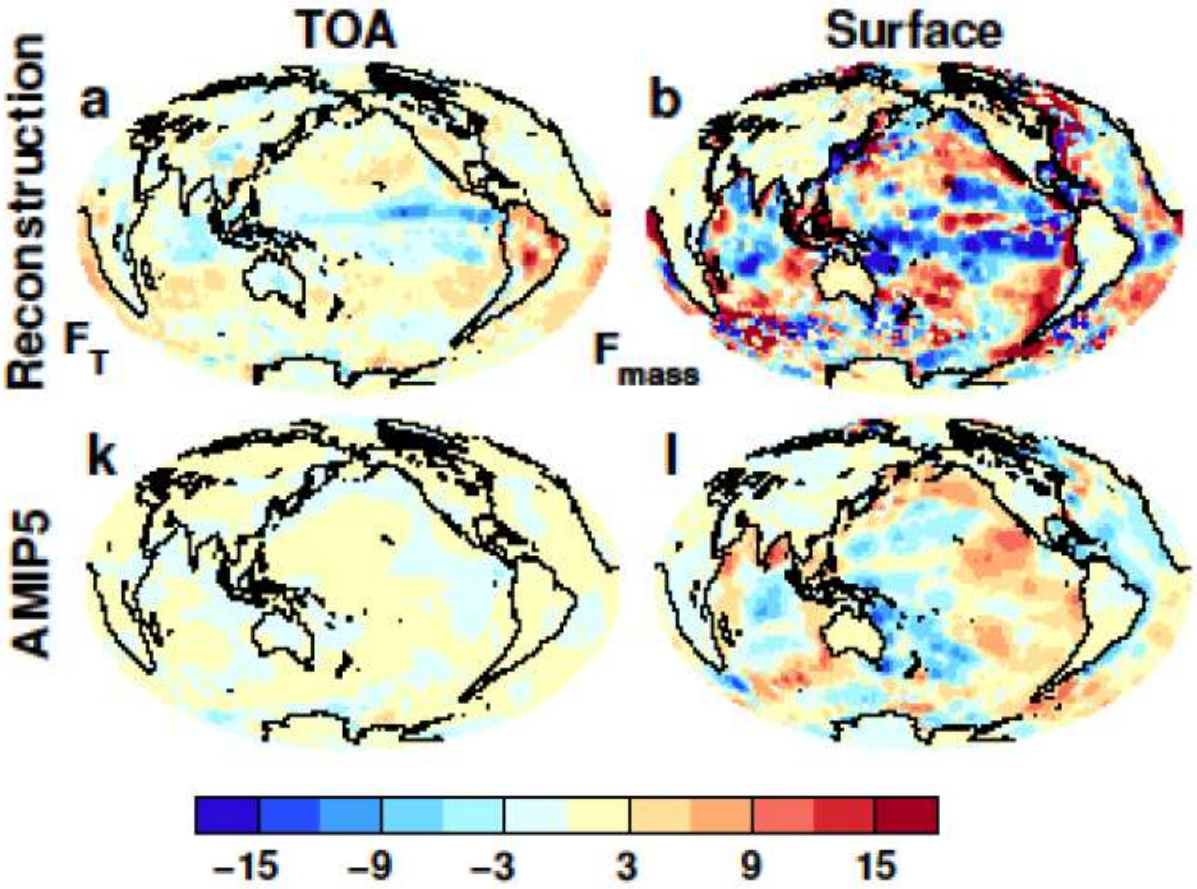


Net surface downward energy flux (Wm^{-2})
Liu et al. (2015) in prep



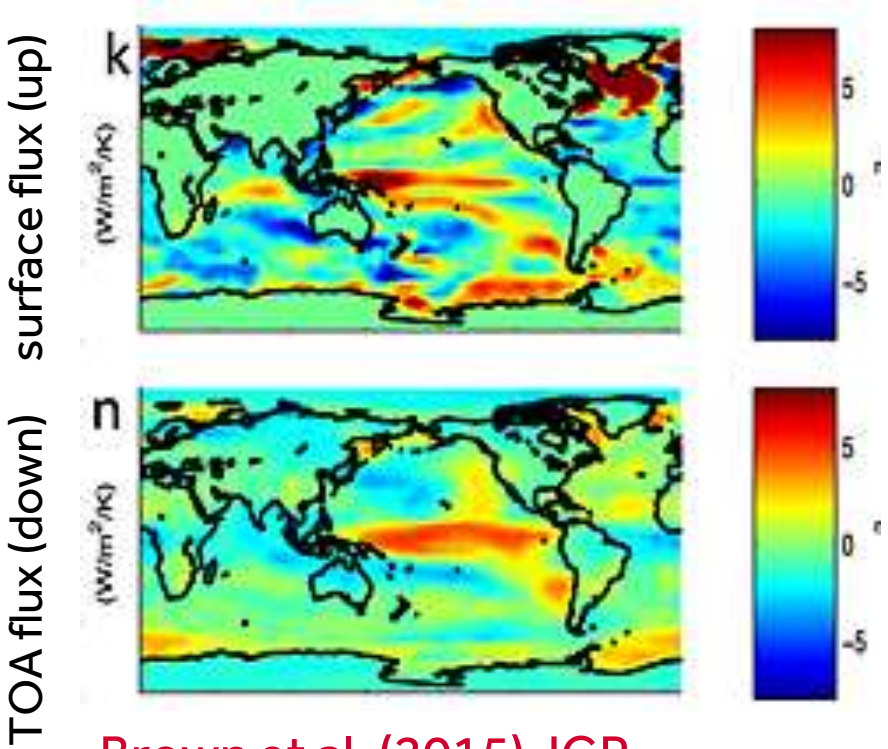
WHERE IS THE HEAT GOING?

CHANGES IN SURFACE ENERGY FLUX



- Changes in energy fluxes 1986-2000 to 2001-2008
- Surface energy flux dominated by atmospheric transports
- Contrasting model pattern of change
- Are reanalysis transports reliable?

FEEDBACKS ON INTERNAL VARIABILITY?



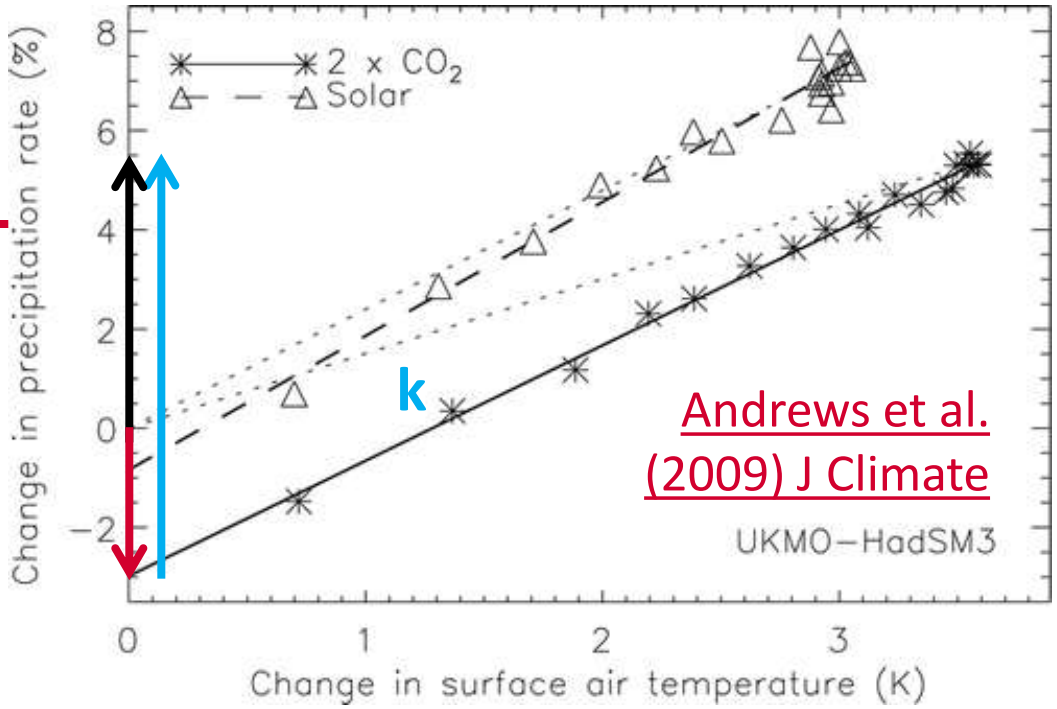
Brown et al. (2015) JGR

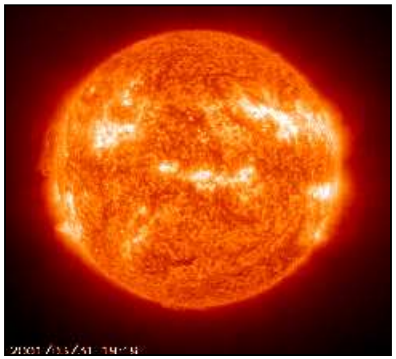
← **Right:** less heat flux out of east Pacific during warm phases?

- Models may underestimate interdecadal variability
- Are there positive heat flux feedbacks which amplify internal climate variability?

EARTH'S ENERGY BUDGET AND PRECIPITATION RESPONSE

$$\underline{L\Delta P} \approx \underline{k\Delta T} - \underline{f_F \Delta F}$$

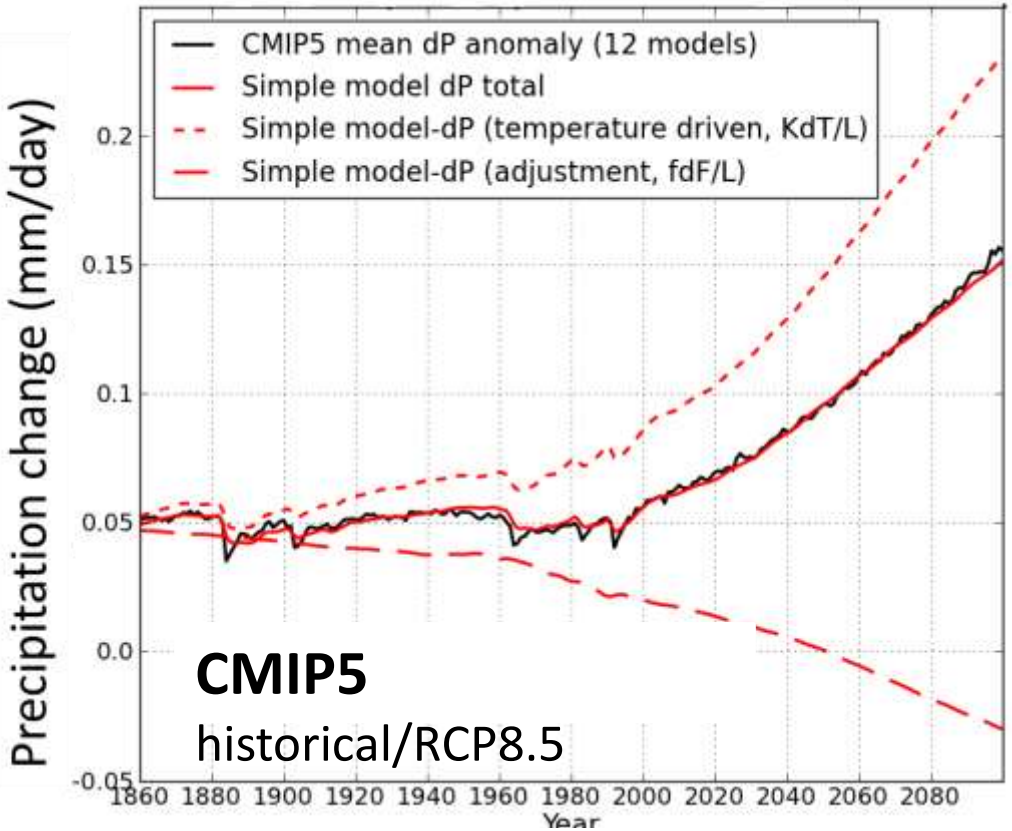




See also: Allen and Ingram (2002) *Nature* ; O'Gorman et al. (2012) Surv. Geophys ; Pendergrass & Hartmann (2012) GRL

SIMPLE MODEL FOR GLOBAL PRECIPITATION

PhD project (Zahra Mousavi, Keith Shine)



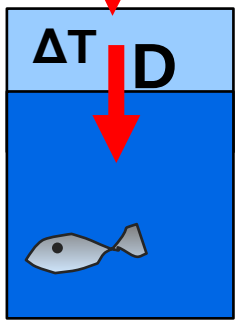
After Allan et al. (2014) Surv. Geophys and Thorpe and Andrews (2014) ERL

Using simple model:

$$L\Delta P = k\Delta T - f_F \Delta F$$

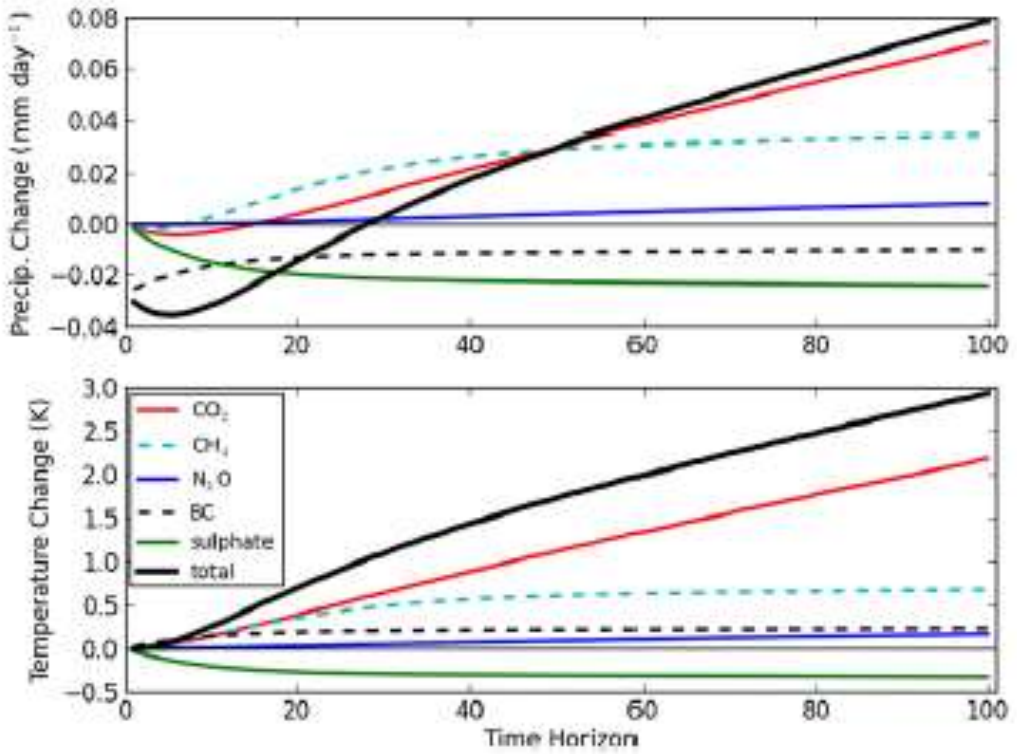
$$\frac{d\Delta T_m}{dt} = \frac{1}{C_m}(\Delta F - Y\Delta T_m - D)$$

$$N = \Delta F - Y\Delta T$$



$$D = c(\Delta T_m - \Delta T_D)/d$$

METRICS FOR GLOBAL PRECIPITATION



- Metrics linking emissions to precipitation response
- Precipitation and temperature response to constant emissions after 2008

Shine et al. (2015) in prep:

EARTH'S ENERGY BUDGET & REGIONAL CHANGES IN THE WATER CYCLE

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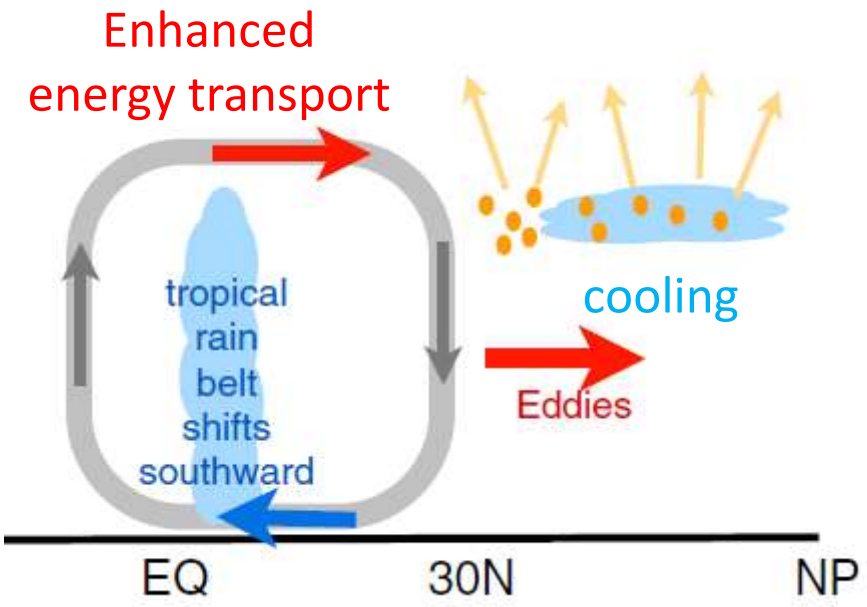
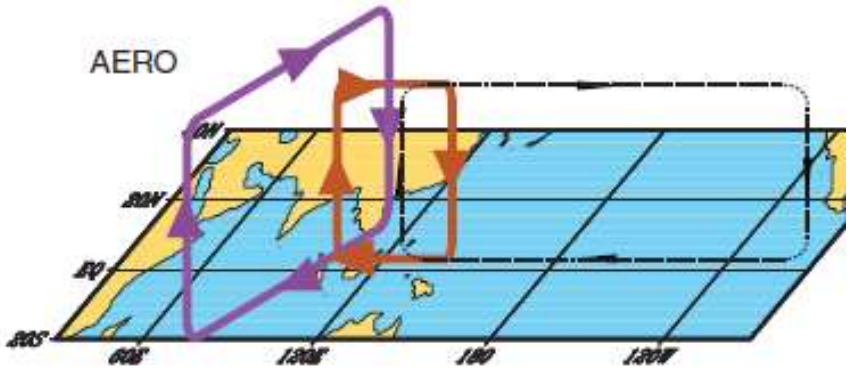
- Regional precipitation changes sensitive to asymmetries in Earth's energy budget
- N. Hemisphere cooling: stronger heat transport into hemisphere
- Reduced Sahel rainfall from:
- Anthropogenic aerosol cooling 1950-1980s: Hwang et al. (2013) GRL →
- Asymmetric volcanic forcing e.g. Haywood et al. (2013) Nature Climate

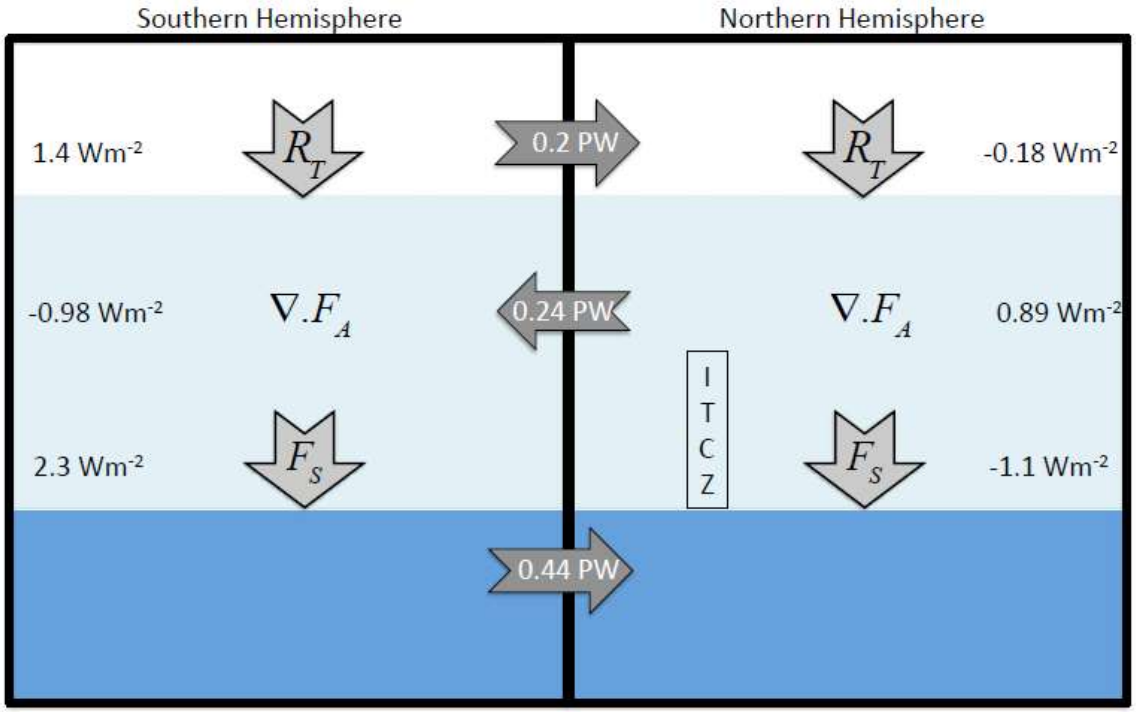




- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science (left)
- Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn
- GHGs & Sahel rainfall recovery?

Dong & Sutton (2015) Nature Clim.

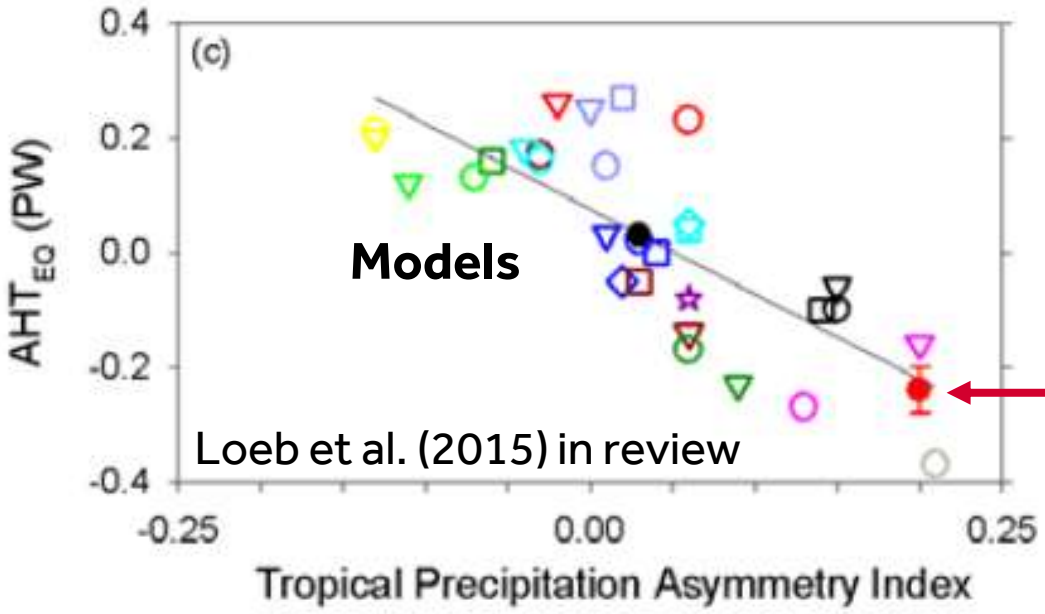
OBSERVED ASYMMETRY IN EARTH'S ENERGY BUDGET



Loeb et al. (2015) in review

- Observed inter-hemispheric imbalance in Earth's energy budget
- Not explained by albedo: brighter NH surface but more clouds in SH (Stephens et al. 2015)
- Imbalance explains position of ITCZ (Frierson et al. 2013)

EQUATORIAL HEAT TRANSPORT AND MODEL PRECIPITATION BIAS



More rain in NH →

- Clear link between bias in cross-equatorial heat transport by atmosphere and inter-hemispheric precipitation asymmetry

CERES/ERA Interim

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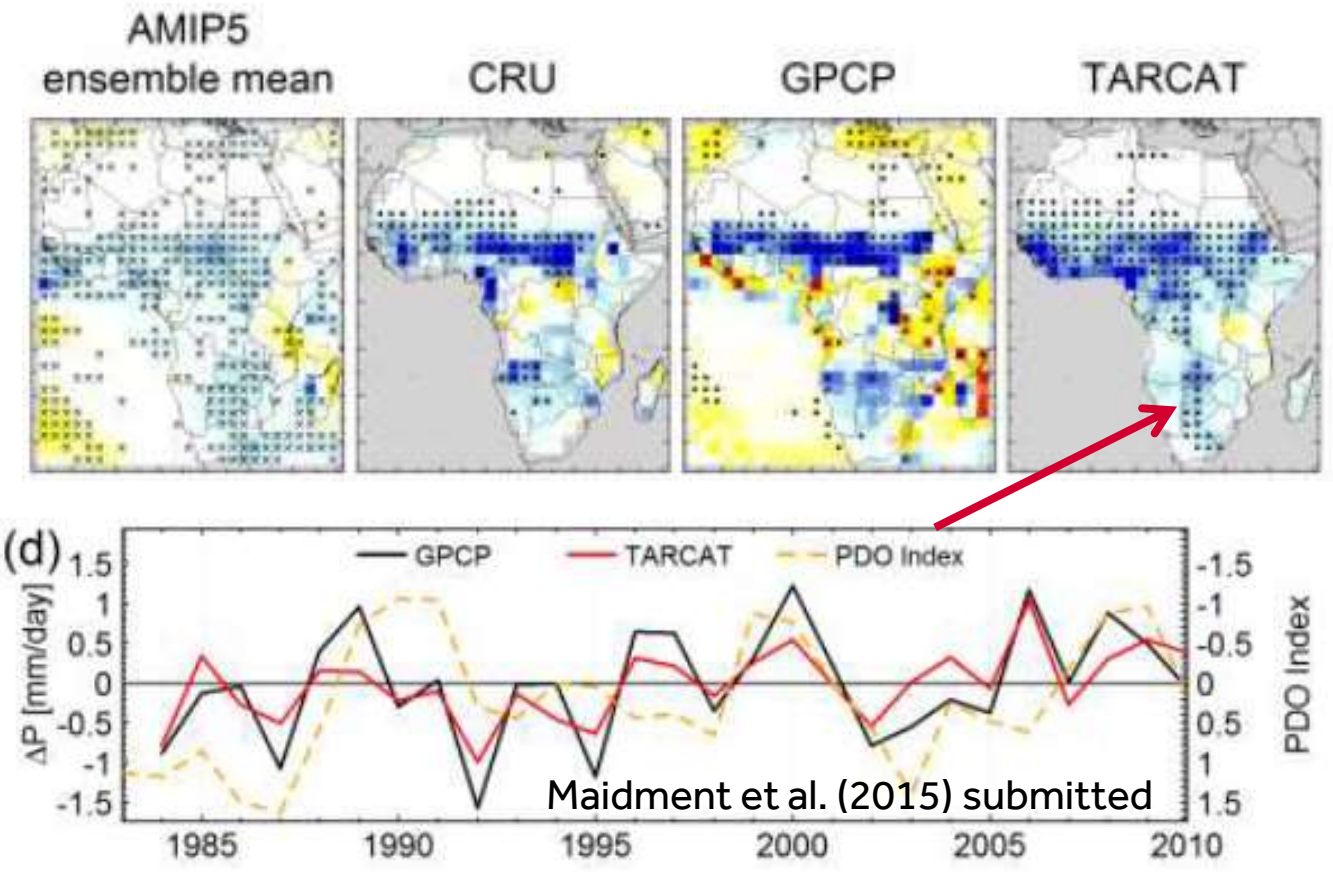
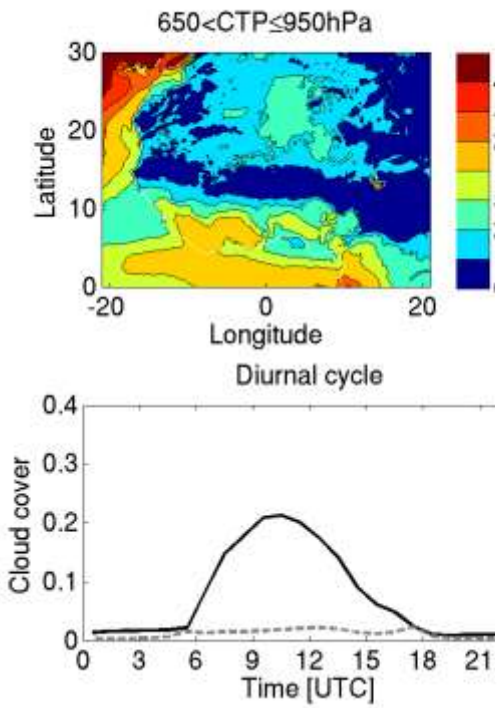
TAMSAT PROJECTS: RECENT TRENDS IN AFRICA RAINFALL

- Evaluating and understanding recent changes in Africa rainfall (Ross Maidment, Emily Black)
- PhD project extending this work: changes in impact-relevant metrics for Africa (Caroline Dunning, Emily Black)



DYNAMICS-AEROSOL-CHEMISTRY-CLOUD INTERACTIONS IN WEST AFRICA (DACCIWA)

- EU consortium lead by Peter Knipperts (see Knipperts et al. 2015 BAMS)
- Radiation Budget & Clouds: Christine Chiu, Thorwald Stein, Peter Hill



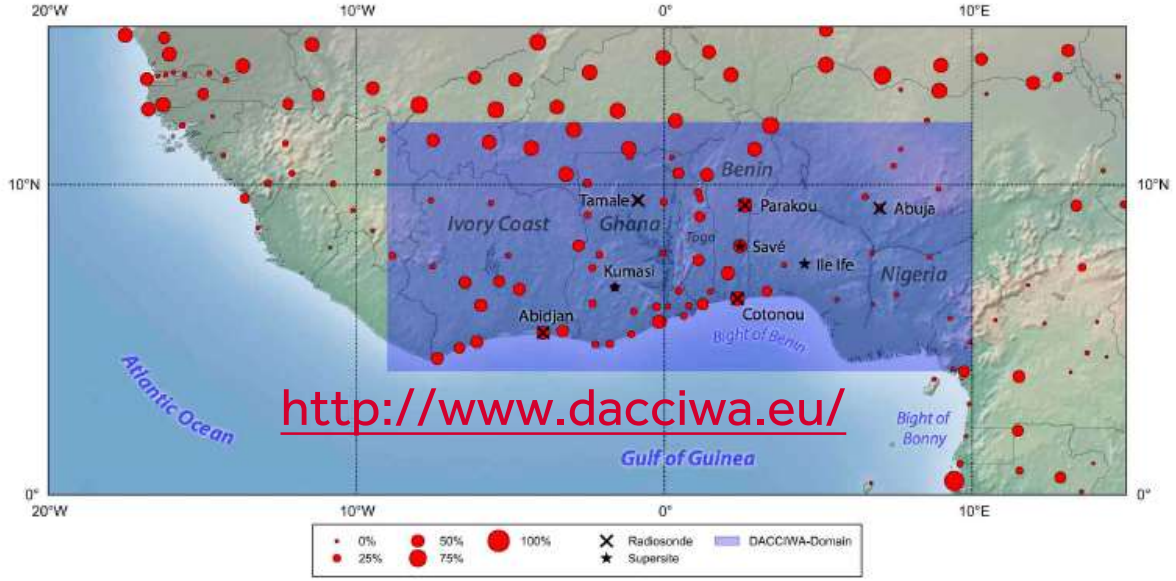
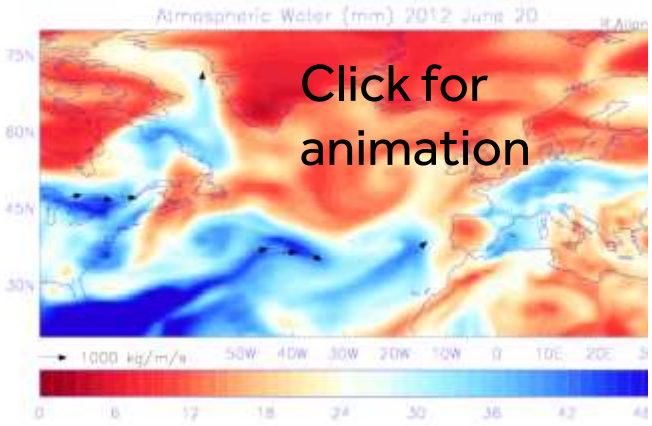


Figure 1.4: Geographical overview of the DACCIWA study area highlighted in blue. Supersites and planned radiosonde stations (black markers) and synoptic weather stations (red dots, proportional to available number of reports in the WMO Global Telecommunication System from 1998–2012).

SUSCEPTIBILITY OF CATCHMENTS TO INTENSE RAINFALL & FLOODING (SINATRA)

- 4-year NERC consortium
- Work task 1.3 looking at precursors to summer flooding (Adrian Champion)
- Initial work concentrating on moisture transport



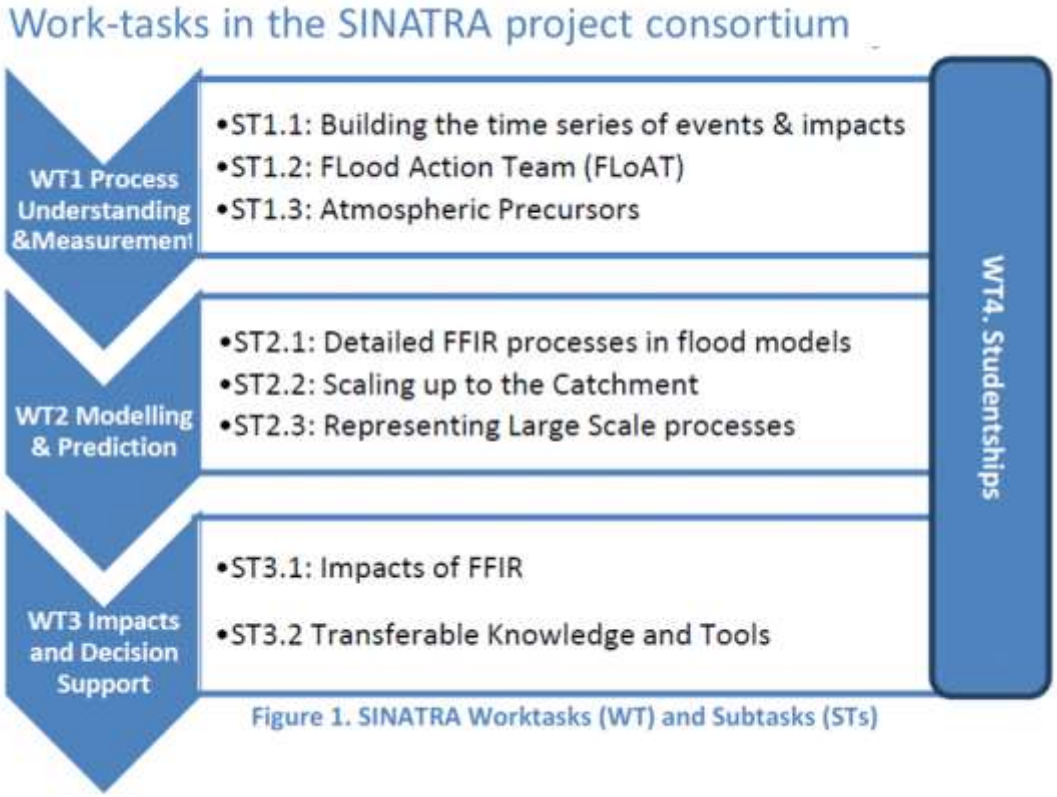
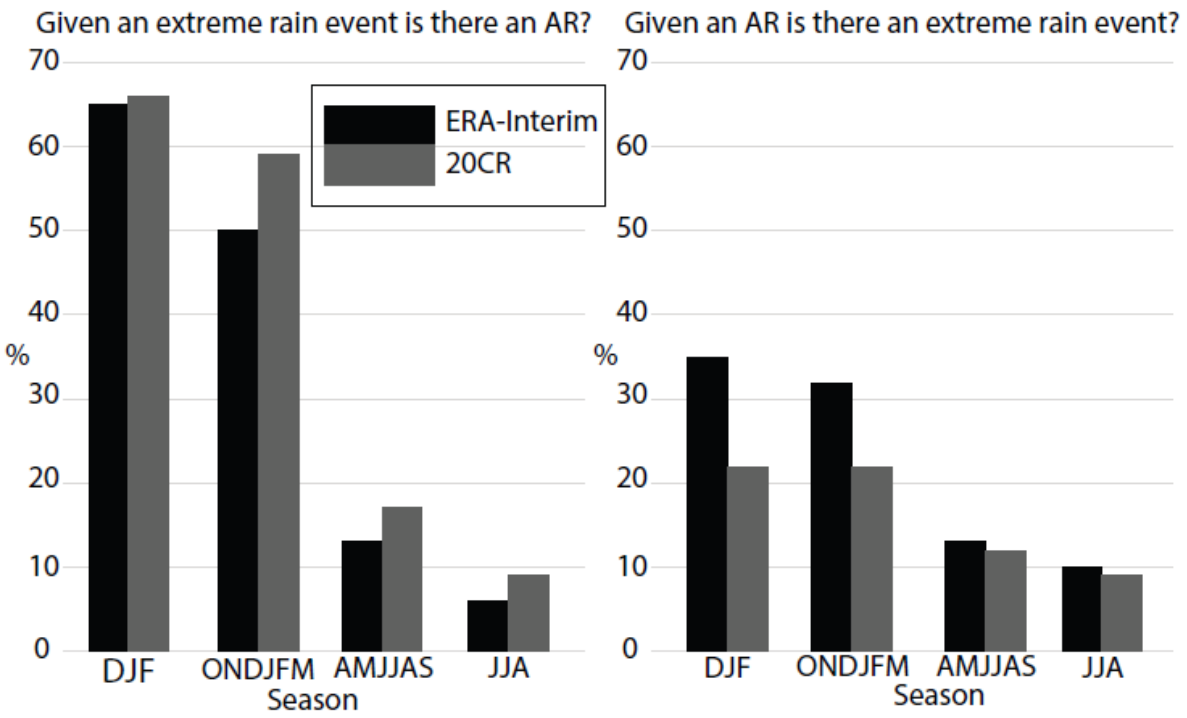


Figure 1. SINATRA Worktasks (WT) and Subtasks (STs)

ATMOSPHERIC RIVERS DON'T EXPLAIN HEAVY SUMMER RAINFALL EVENTS

- Initially investigated influence of intense moisture transport events (Atmospheric Rivers or ARs)
- Relatively few ARs associated with extreme rainfall
- Very few extreme daily rainfall events in summer linked to ARs



Champion et al. submitted

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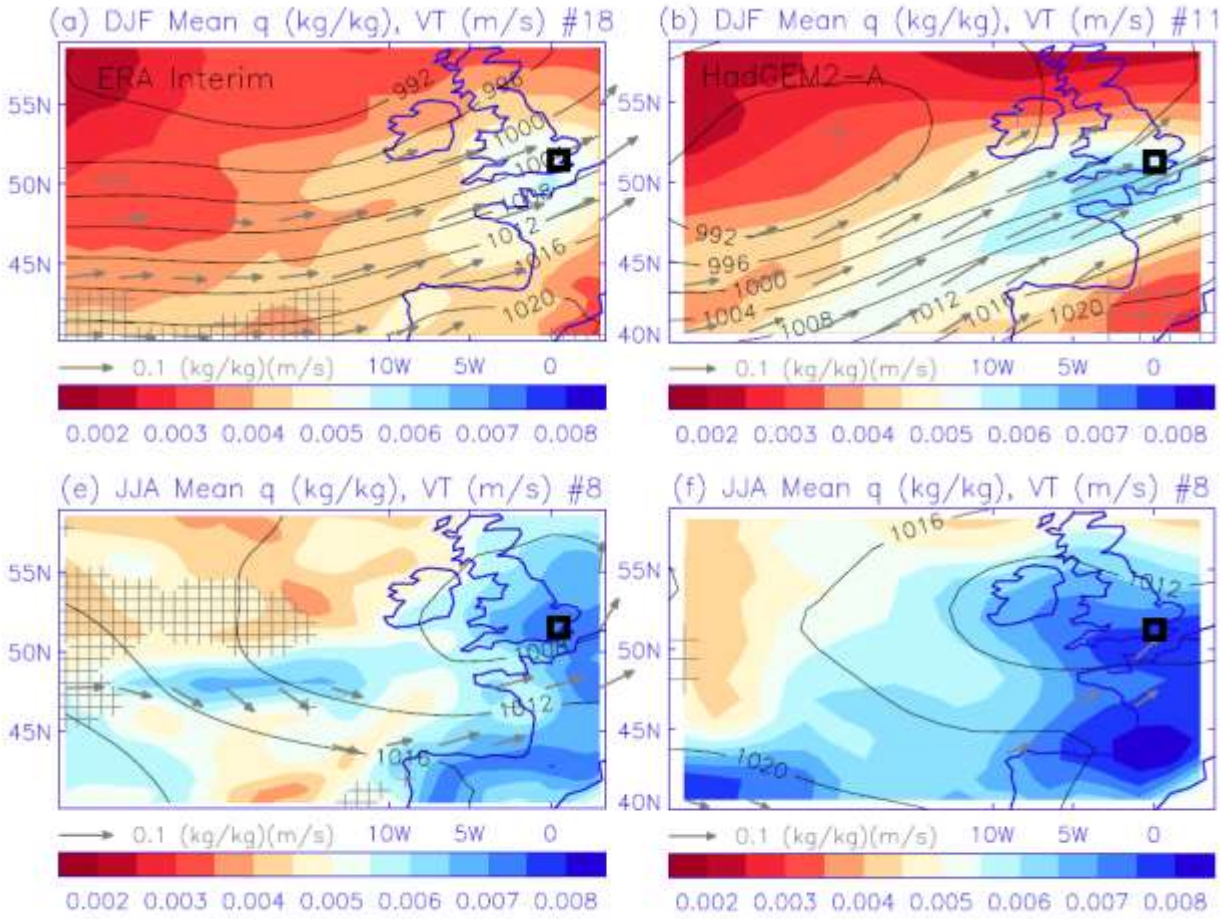
MOISTURE CHARACTERISTICS ASSOCIATED WITH HEAVY DAILY RAINFALL EVENTS

- Initial evaluation of moisture characteristics associated with heavy daily rainfall
- Dependence on region/season
- Now moving to hourly data and CAPE-based diagnostics



CONCLUSIONS

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- Earth's energy imbalance
  - Heating of Earth continues at rate of ~0.6 Wm^{-2}
  - Variability from radiative forcings & unforced ocean changes
  - Where is the excess energy going in the oceans?
  - Toward reconciled ocean heating and radiation budget changes
  - Do feedbacks amplify/extend hiatus/surge events?
- Energy budget constraint on precipitation responses
  - Simple models for global precipitation
  - Greenhouse gas & absorbing aerosol forcing supress global precipitation response to warming ("hydrological sensitivity")
- Inter-hemispheric heating, moisture budget & unforced variability affect regional responses and climate model biases
  - Radiative forcing & unforced variability influence African rainfall trends
- Local-scale precursors and characteristics crucial for impacts