Department of Meteorology

CHANGES IN EARTH'S ENERGY IMBALANCE & IMPLICATIONS FOR WATER CYCLE

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Thanks to Chunlei Liu, Norman Loeb and all co-authors

National Centre for Earth Observation
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NERC SCIENCE OF THE ENVIRONMENT

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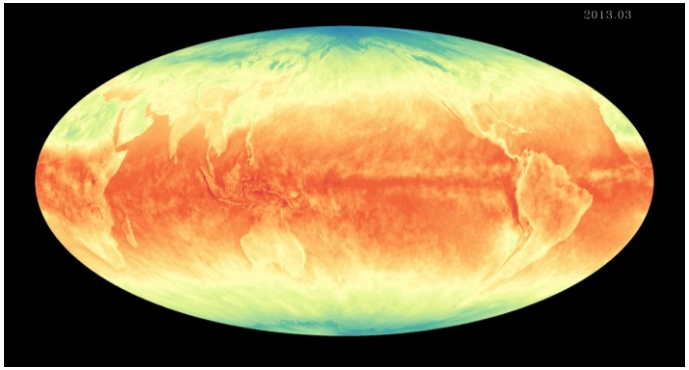


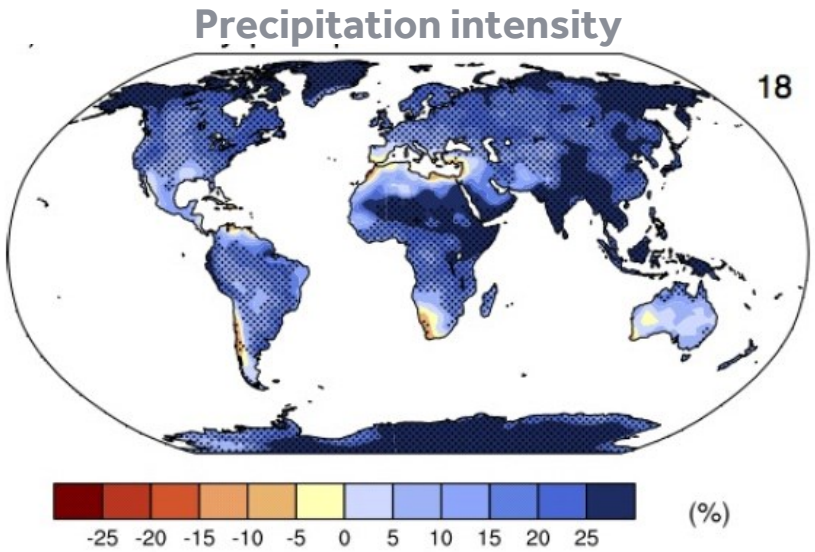
INTRODUCTION

- Earth's energy budget determines the trajectory and magnitude of climate change
- Powerful constraint and also diagnostic of the water cycle globally and regionally

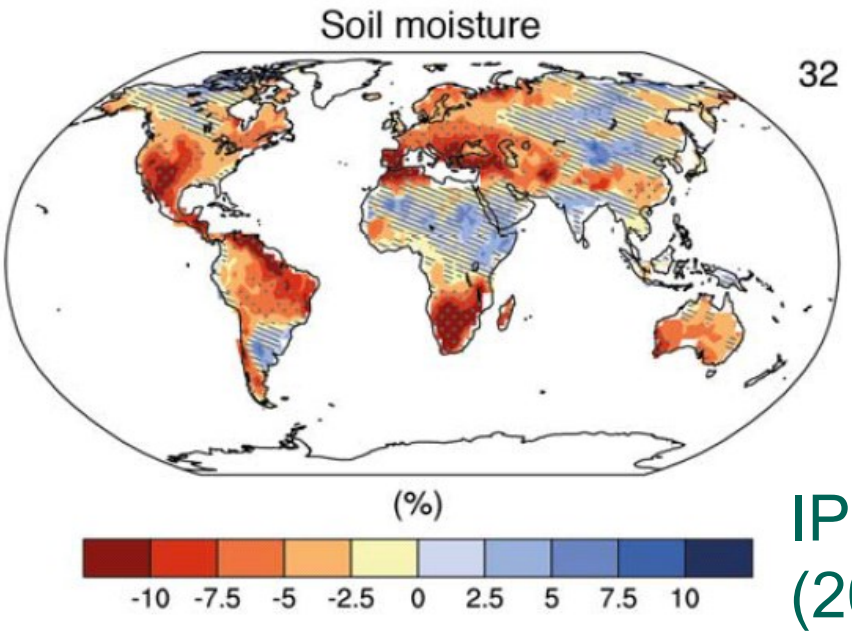
  Flows of energy and moisture between land/ocean, northern/southern hemispheres and high/low latitudes fundamental for the climate that societies depend upon

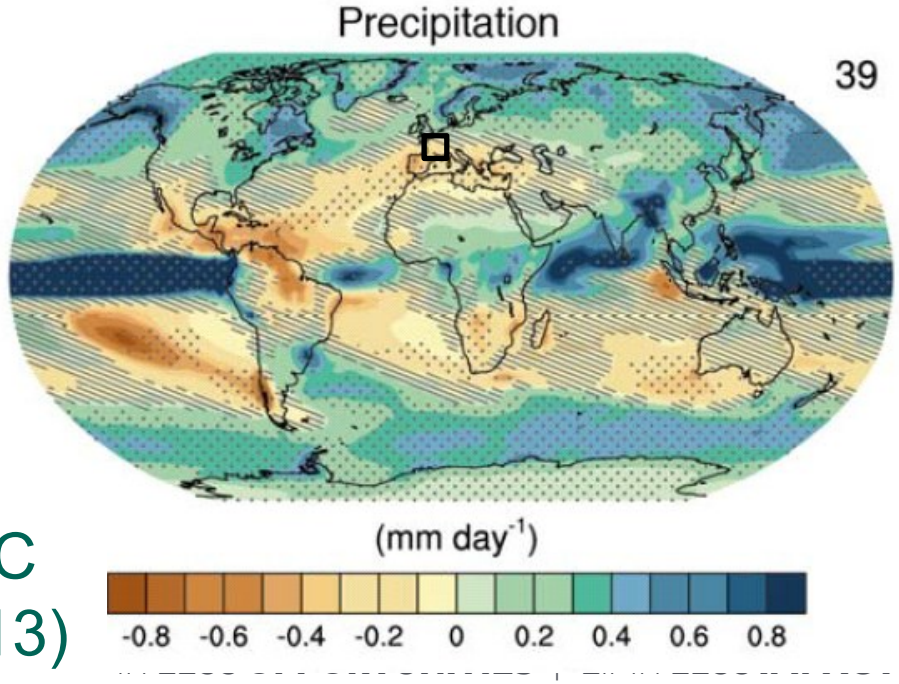
- How is Earth's energy imbalance currently changing and what are the implications for the global water cycle?

HOW WILL WATER CYCLE CHANGE?



- Increased Precipitation
- More Intense Rainfall
- More intense droughts
- Intensification of wet and dry seasons?
- Regional projections??

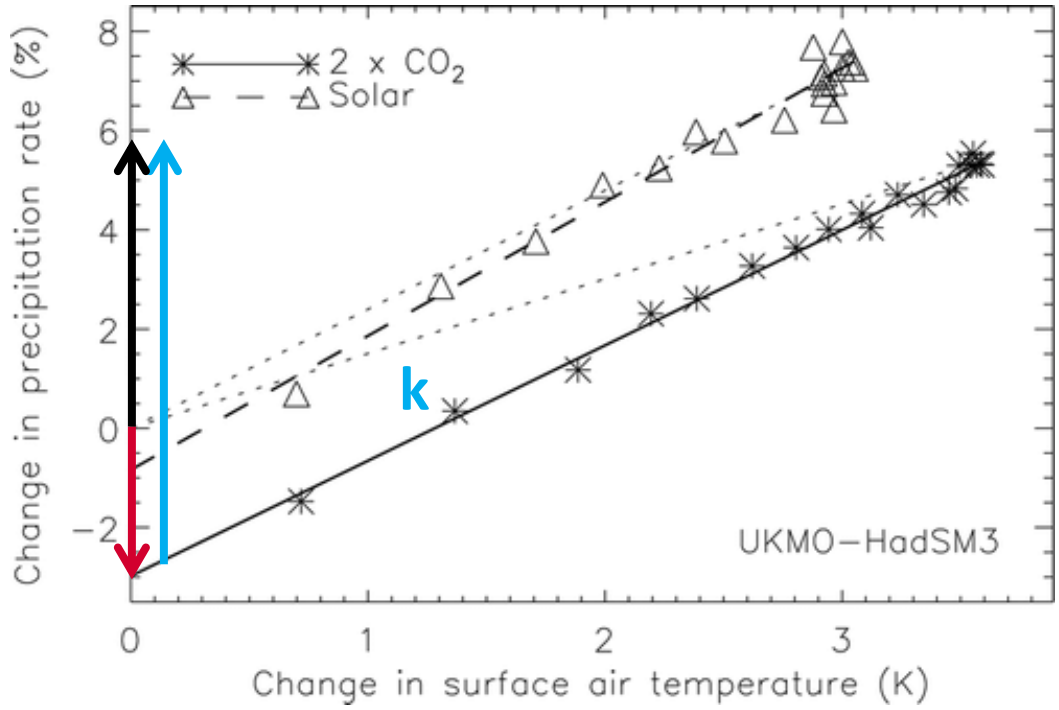




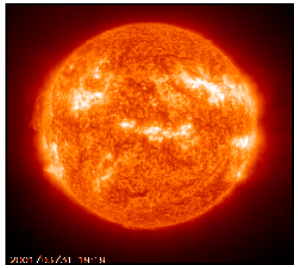
IPCC (2013)

EARTH'S ENERGY BUDGET AND PRECIPITATION RESPONSE

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

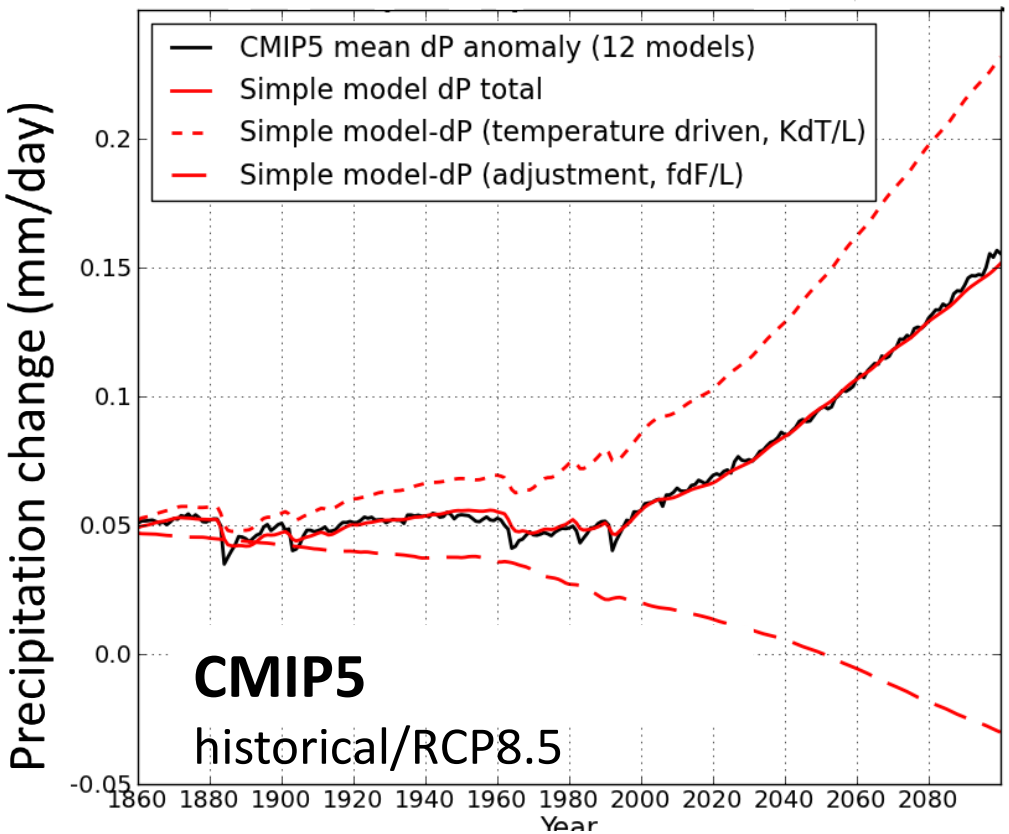


Andrews et al. (2009) J Clim



See also: Allen and Ingram (2002) Nature ; O'Gorman et al. (2012) Surv. Geophys ; Bony et al. 2014 Nature Geosci.

SIMPLE MODEL FOR GLOBAL PRECIPITATION



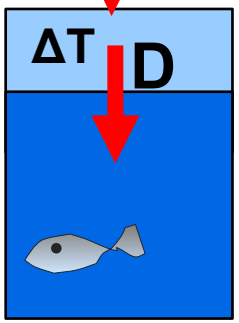
After Allan et al. (2014) Surv. Geophys and Thorpe and Andrews (2014) ERL

Using simple model:

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

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

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

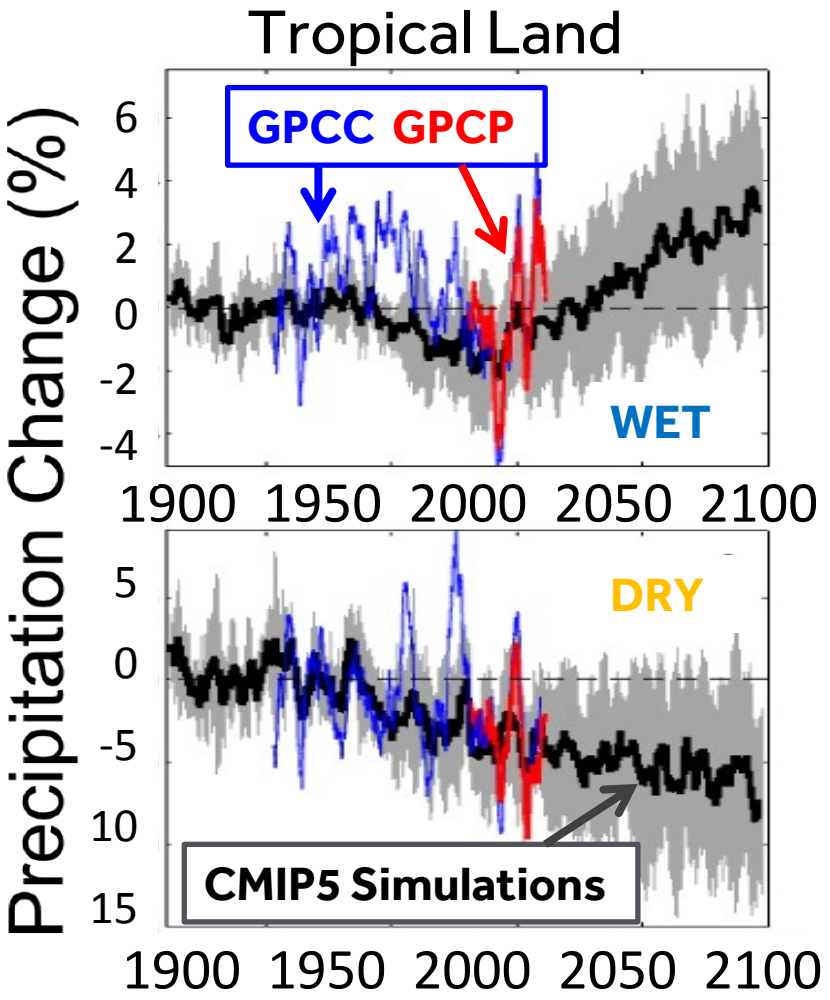


$$D = c(\Delta T_m - \Delta T_D)/d$$

Zahra Mousavi (PhD project)

MOISTURE TRANSPORT AND INTENSIFICATION OF WET/DRY SEASON

- Increased moisture with warming implies amplified P-E (e.g. Held & Soden 2006)
- Multi-annual P-E > 0 over land implies increased P-E (e.g. Greve et al. 2014)
- Changes in T/RH gradients also important (Byrne & O'Gorman 2015)
- P-E < 0 in dry season over land: more intense wet/dry seasons? (Chou et al. 2013; Liu & Allan 2013; Kumar et al. 2014)
- Aridity metrics more relevant (Scheff & Frierson 2015; Greve & Seneviratne 2015 Roderick et al. 2014)
- Changes in circulation dominate locally (e.g. Scheff & Frierson 2012; Chadwick et al. 2013; Muller & O'Gorman 2011)

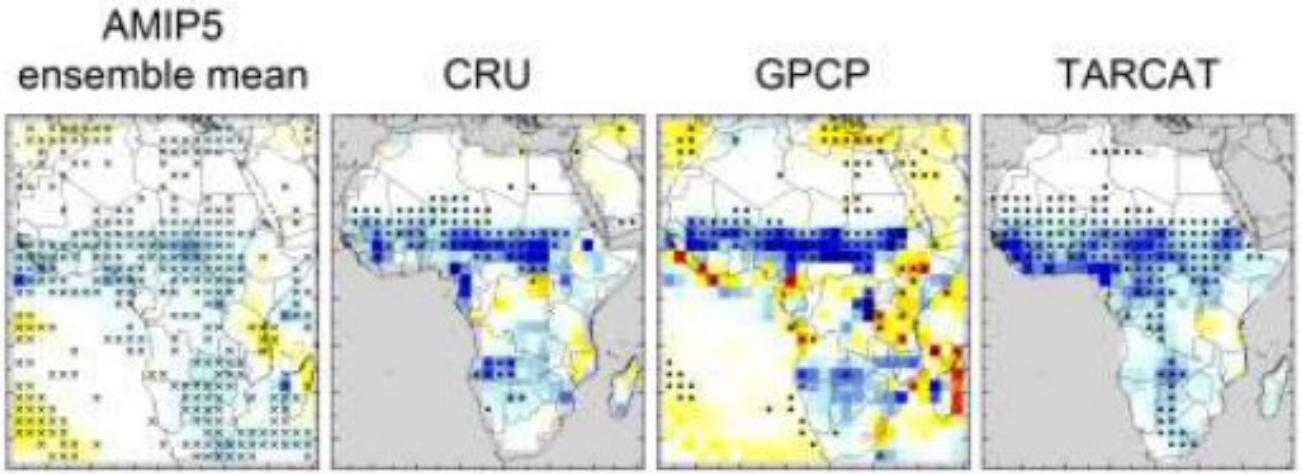


Liu & Allan 2013

RECENT TRENDS IN RAINFALL ACROSS AFRICA

- Africa particularly susceptible to changes in water cycle
- West Africa – particularly complex mix of pollution/cloud/dynamics

DACCIWA project - Knippertz et al. 2015 BAMS

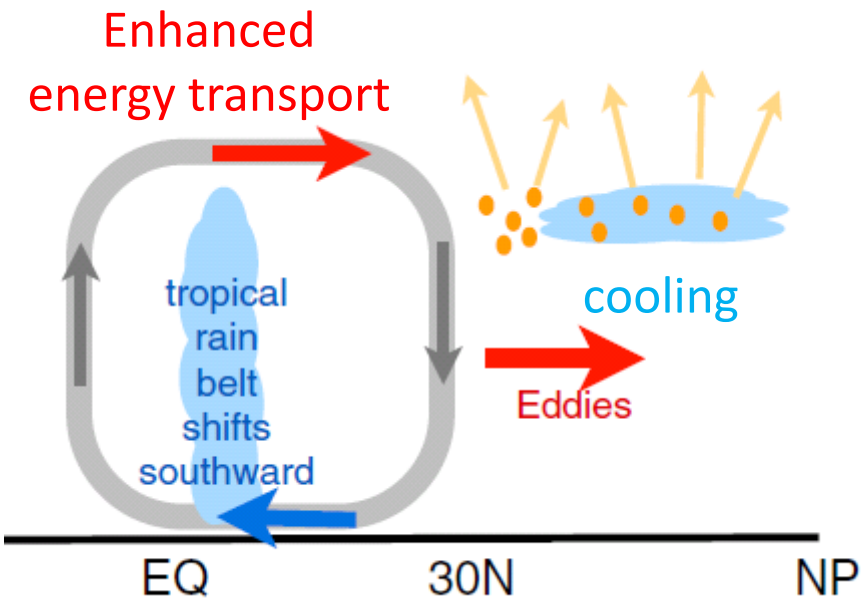


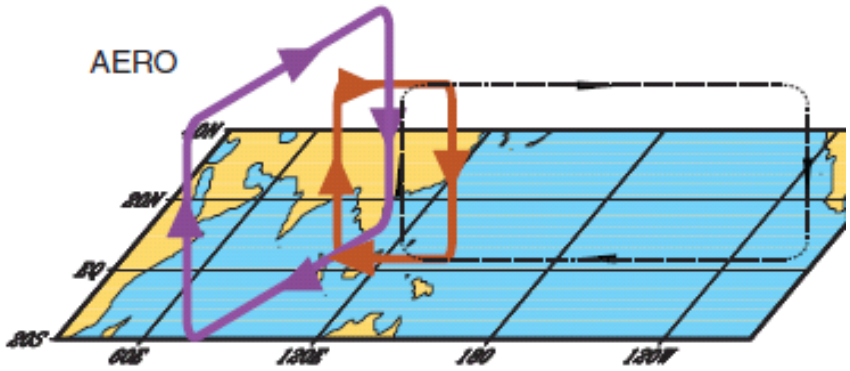
Maidment et al. (2015) GRL

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

- 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

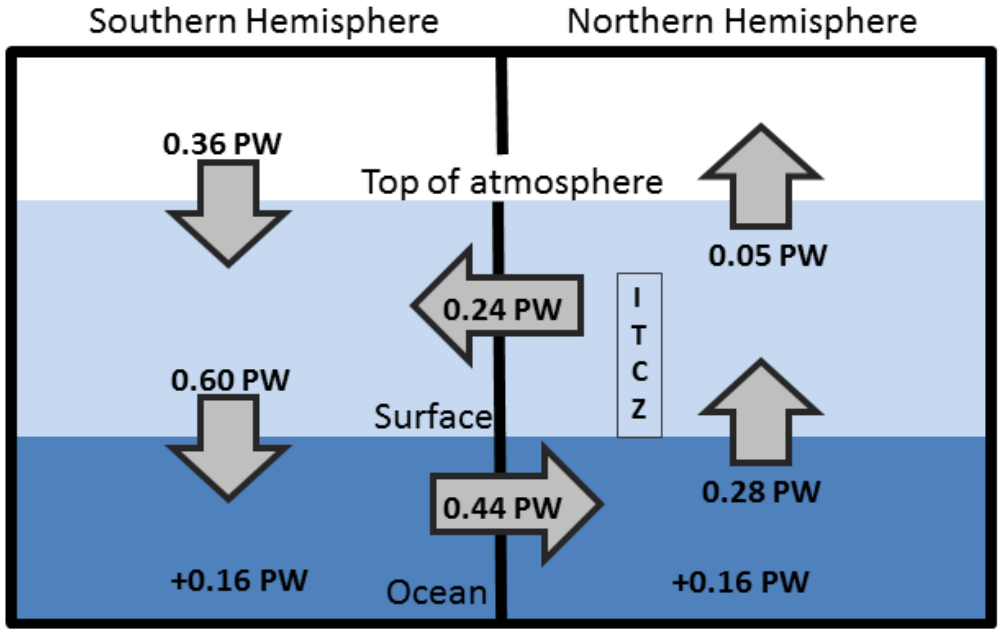


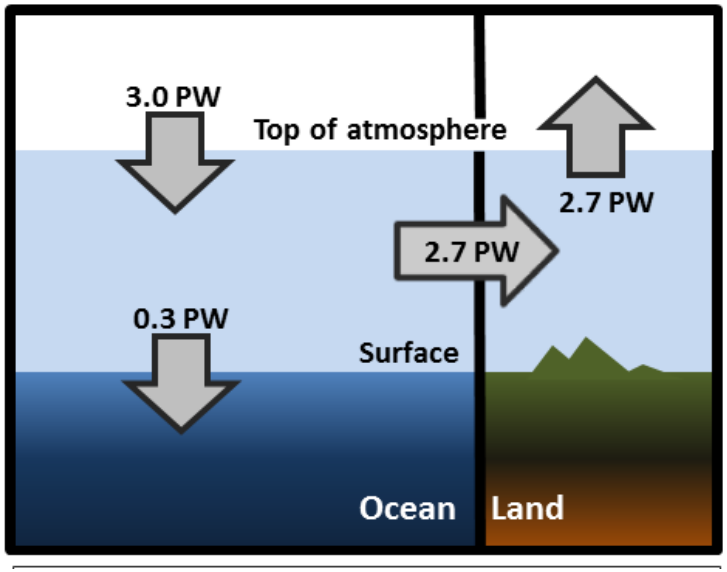


- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science (left)
- Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn
- GHGs & Sahel rainfall recovery?

Dong & Sutton (2015) Nature Clim.

OBSERVED ASYMMETRY IN EARTH'S ENERGY BUDGET

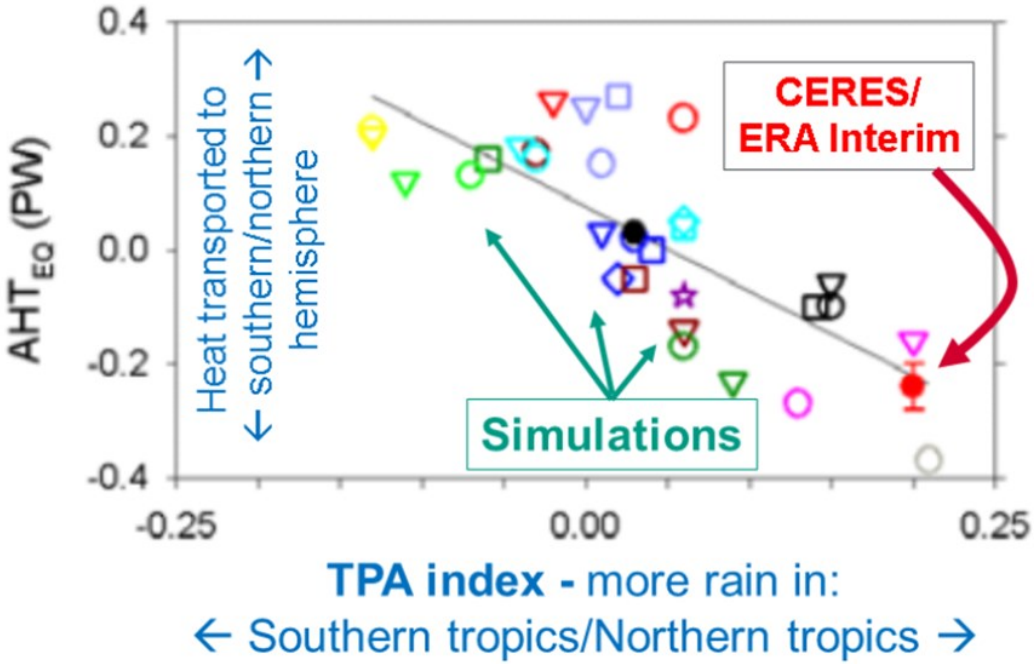




Adapted from Liu et al. (2015) JGR (above) & Loeb et al. (2015) Clim. Dyn. (left)

- 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)
- Inter-hemispheric heat transports determine and are influenced by position of ITCZ (e.g. Frierson et al. 2013) – more in next talk!!

CROSS-EQUATORIAL HEAT TRANSPORT LINKED TO MODEL PRECIPITATION BIAS

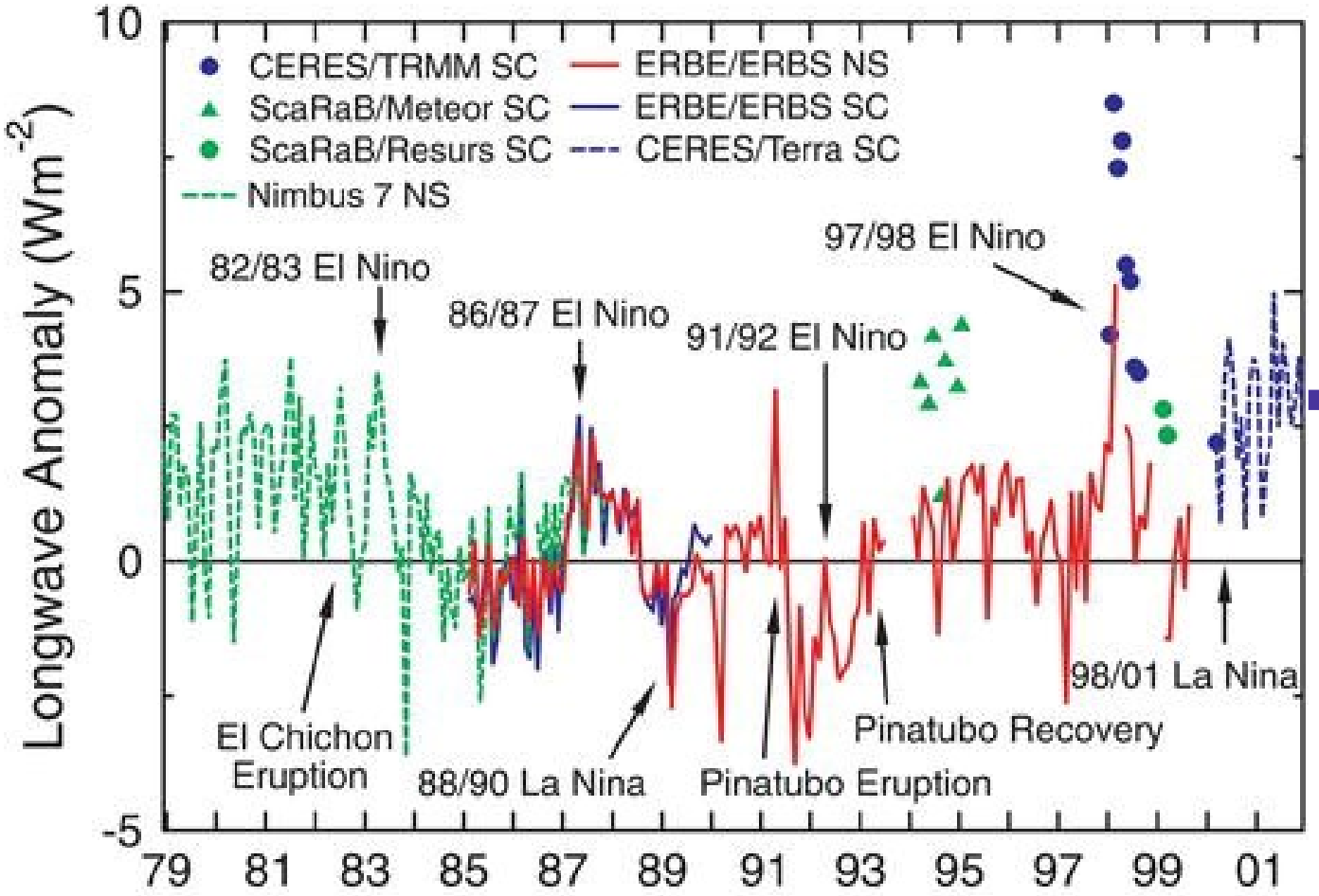


Estimated cross equatorial atmospheric heat transport in peta Watts (AHT_{EQ}) against an index of tropical precipitation asymmetry (TPA) between hemispheres in simulations and observations

- Clear link between bias in cross-equatorial heat transport by atmosphere and inter-hemispheric precipitation asymmetry Loeb et al. (2015) Clim. Dyn.

See talk in afternoon!

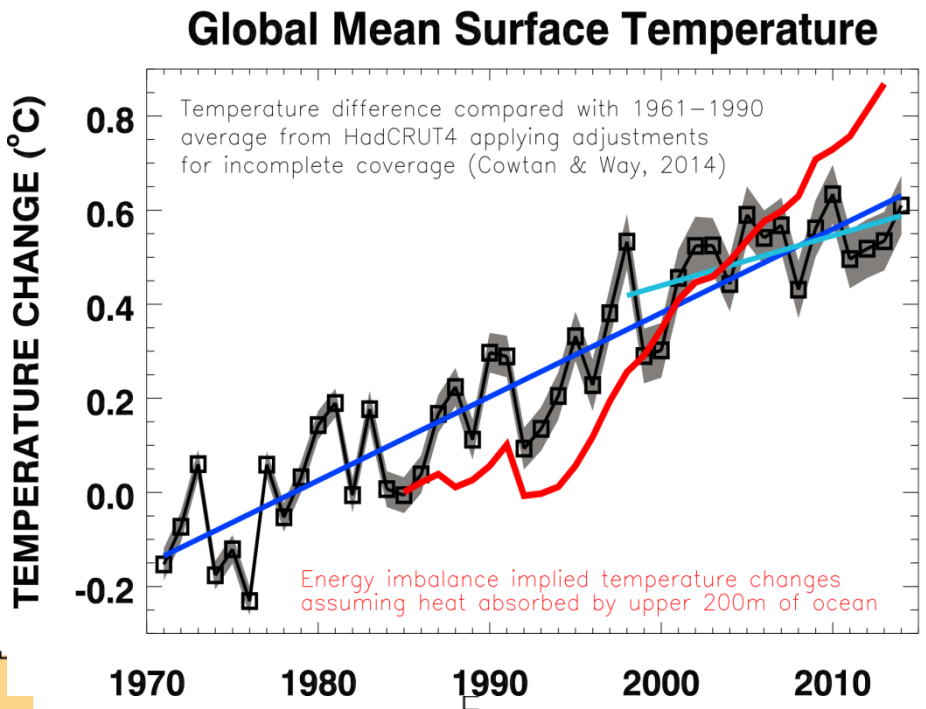
HOW IS EARTH'S ENERGY BALANCE CHANGING & WHAT ARE IMPLICATIONS?

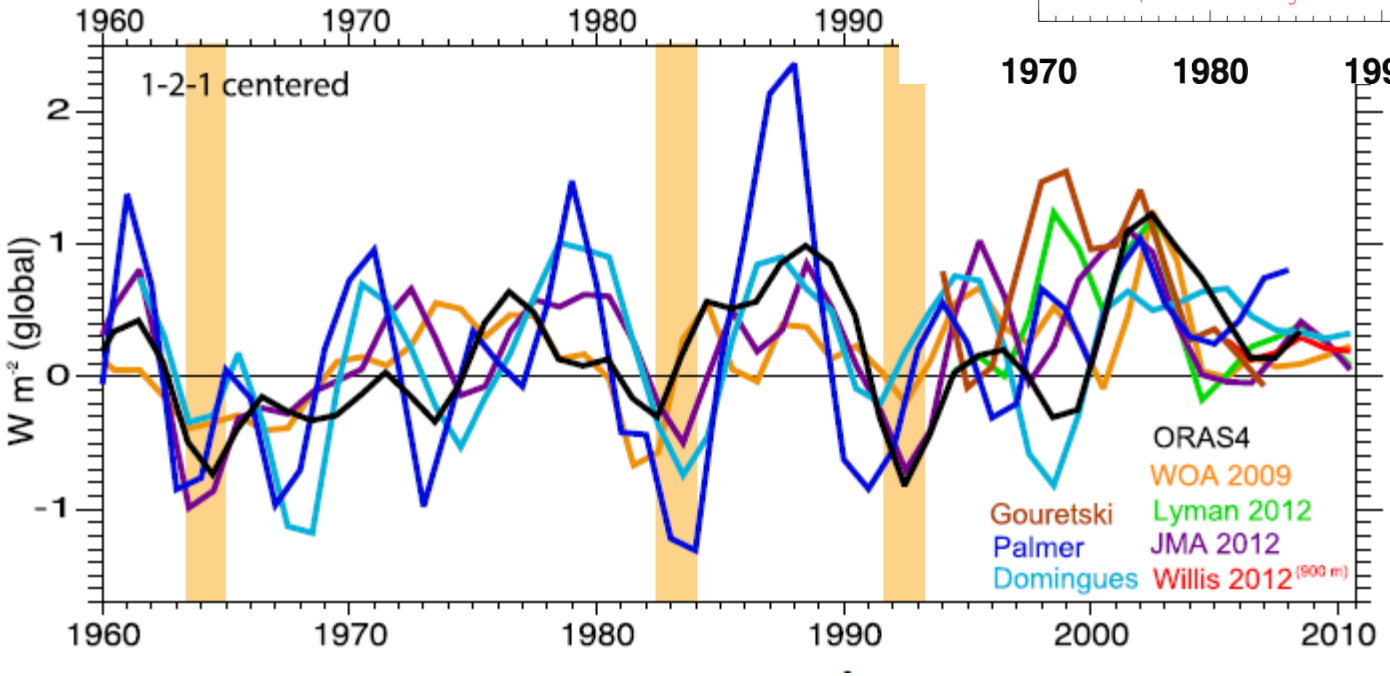


Wong et al. (2006) J Clim; Wielicki et al. (2002) Science

AT WHAT RATE IS EARTH HEATING?

What are implications for climate sensitivity and the global water cycle?



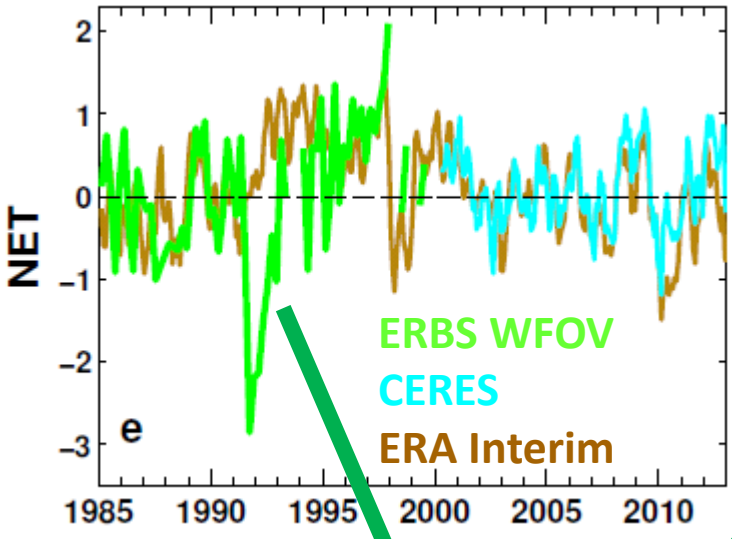


Upper ocean heating rate (Wm^{-2})

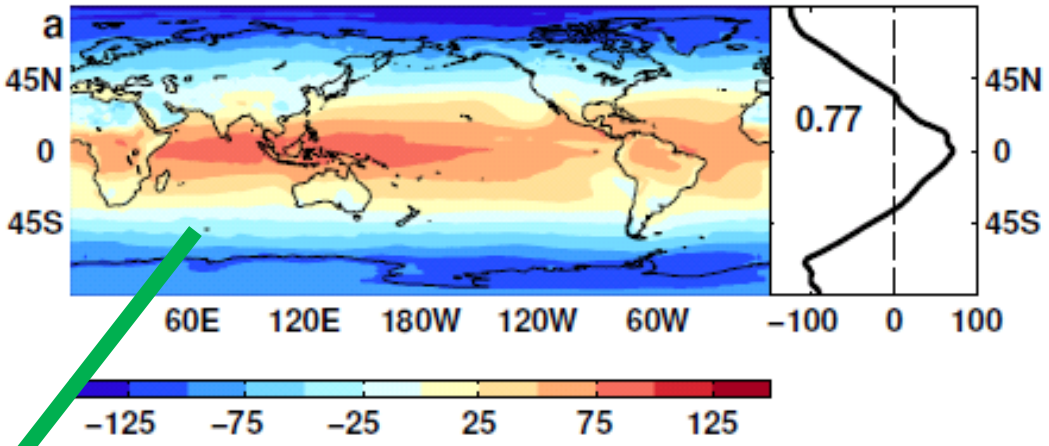
Harries & Belotti (2010) J. Clim | Loeb et al. (2012) Nat. Geosci | Trenberth et al. (2014) J Clim

RECONSTRUCTING GLOBAL RADIATIVE FLUXES SINCE 1985

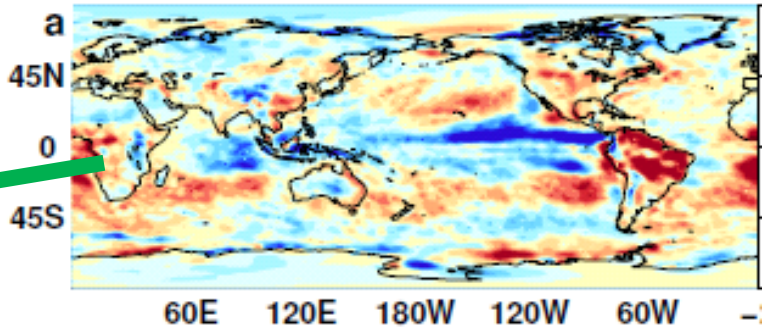
ERBS/CERES variability



CERES monthly climatology



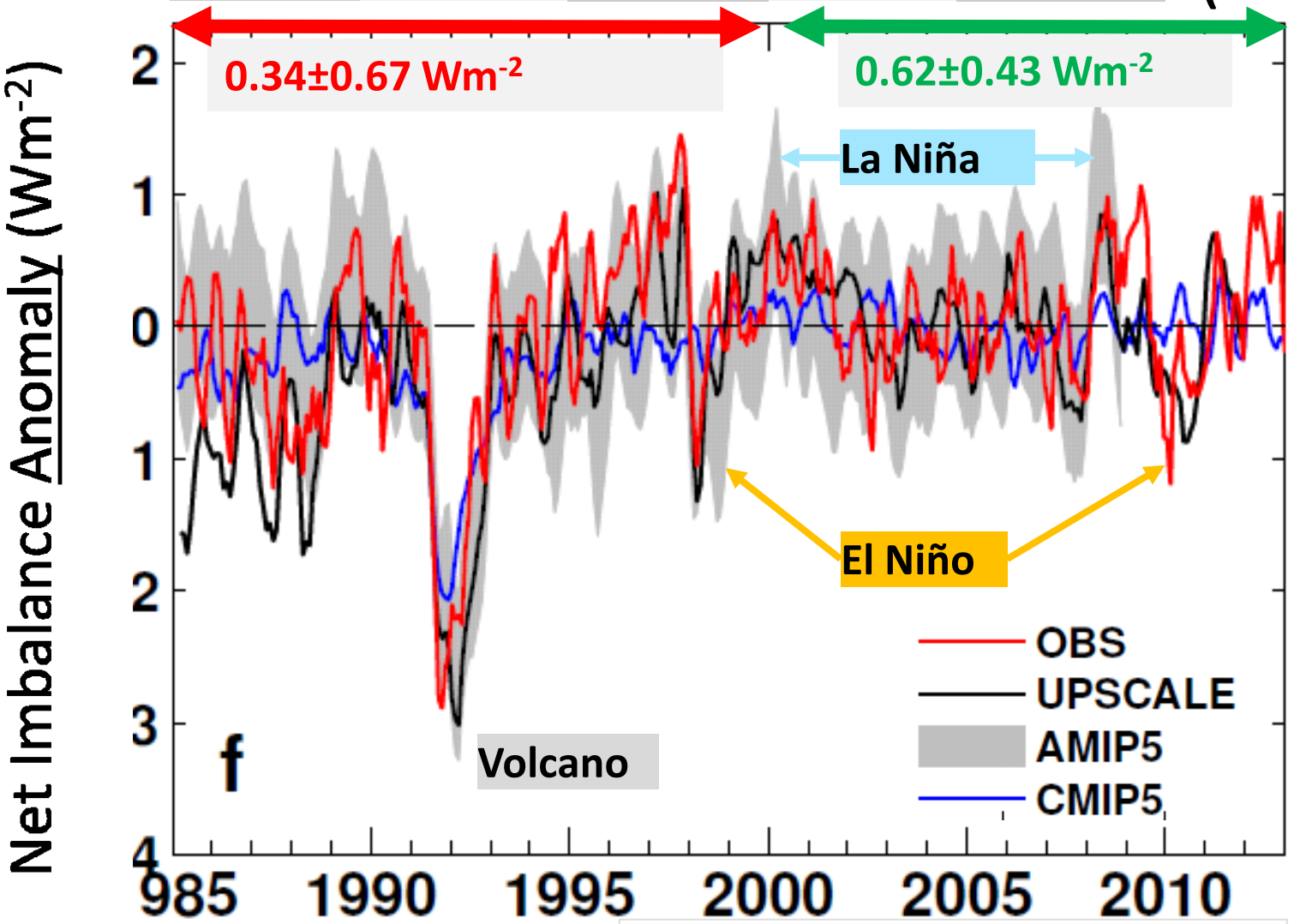
ERA Interim spatial anomalies



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

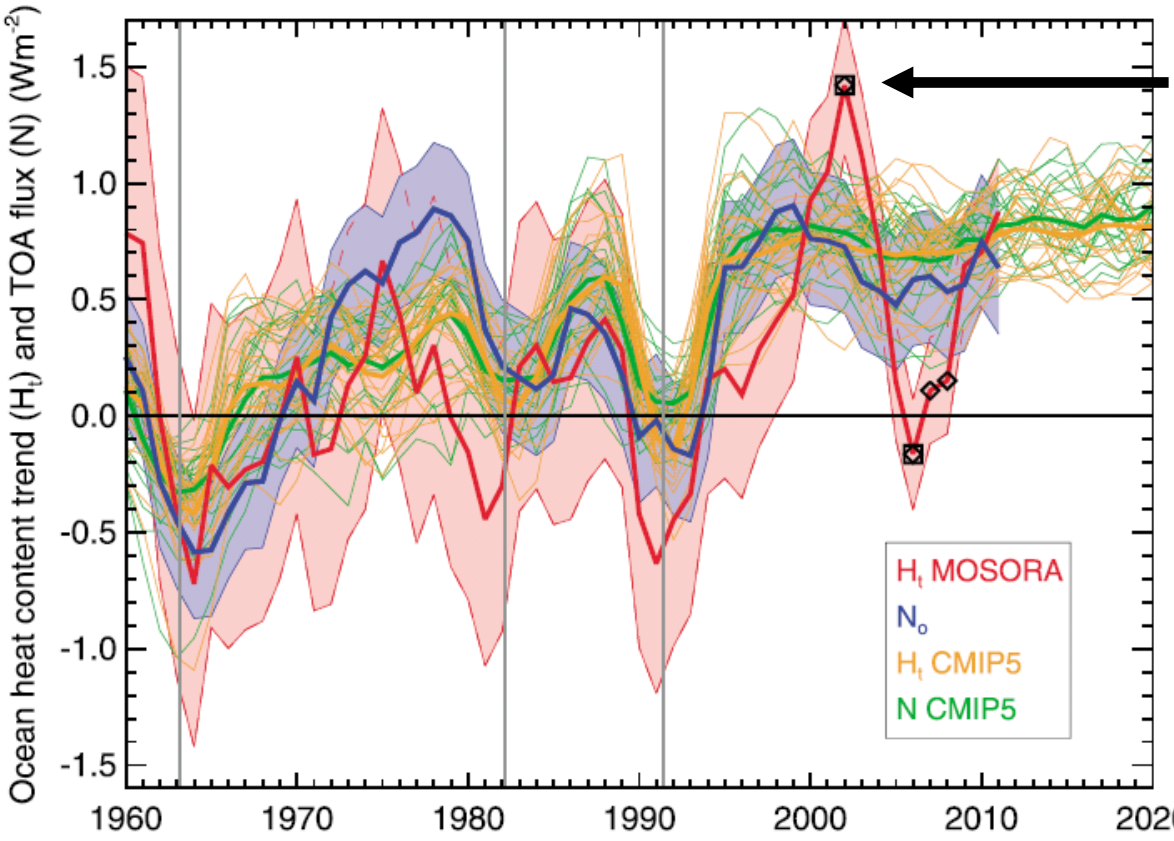
CHANGES IN IMBALANCE IN MODELS/OBS

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



Allan et al. (2014) GRL

DISCREPANCY BETWEEN RADIATION BUDGET & OCEAN HEATING

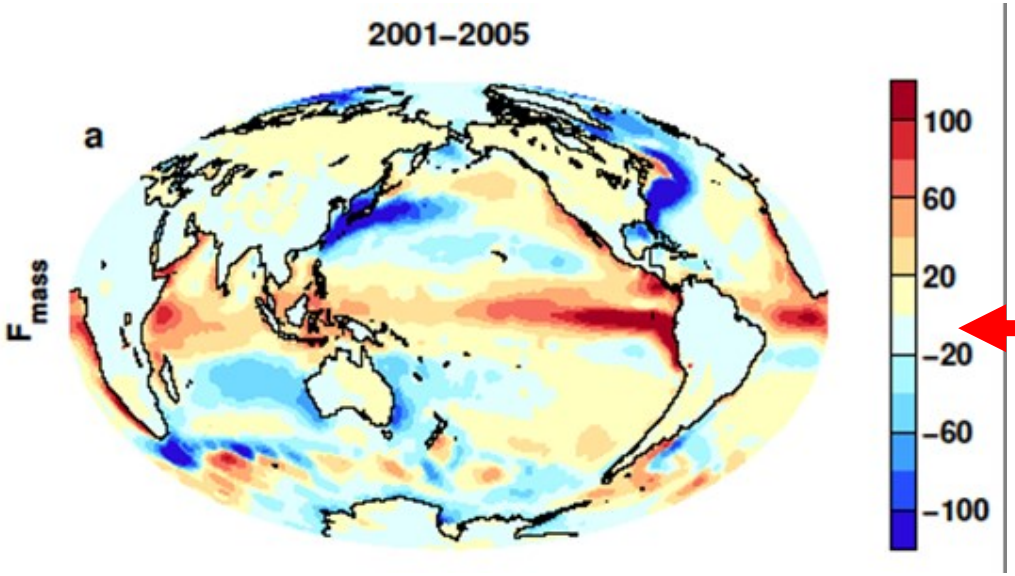


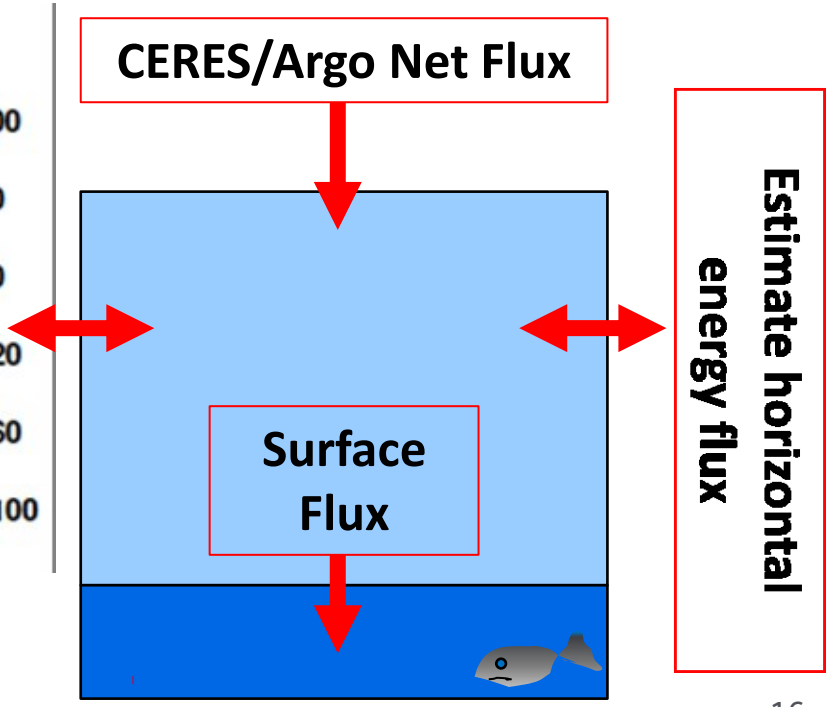
- Large ocean heating anomaly in 2002
- Inconsistent with radiation budget observations and simulations
- Changing observing system influence?
- Slight drop in net flux 1999-2005?

Smith et al. (2015) GRL

INDIRECT ESTIMATES OF AIR-SEA ENERGY FLUXES FROM SATELLITE/REANALYSES

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

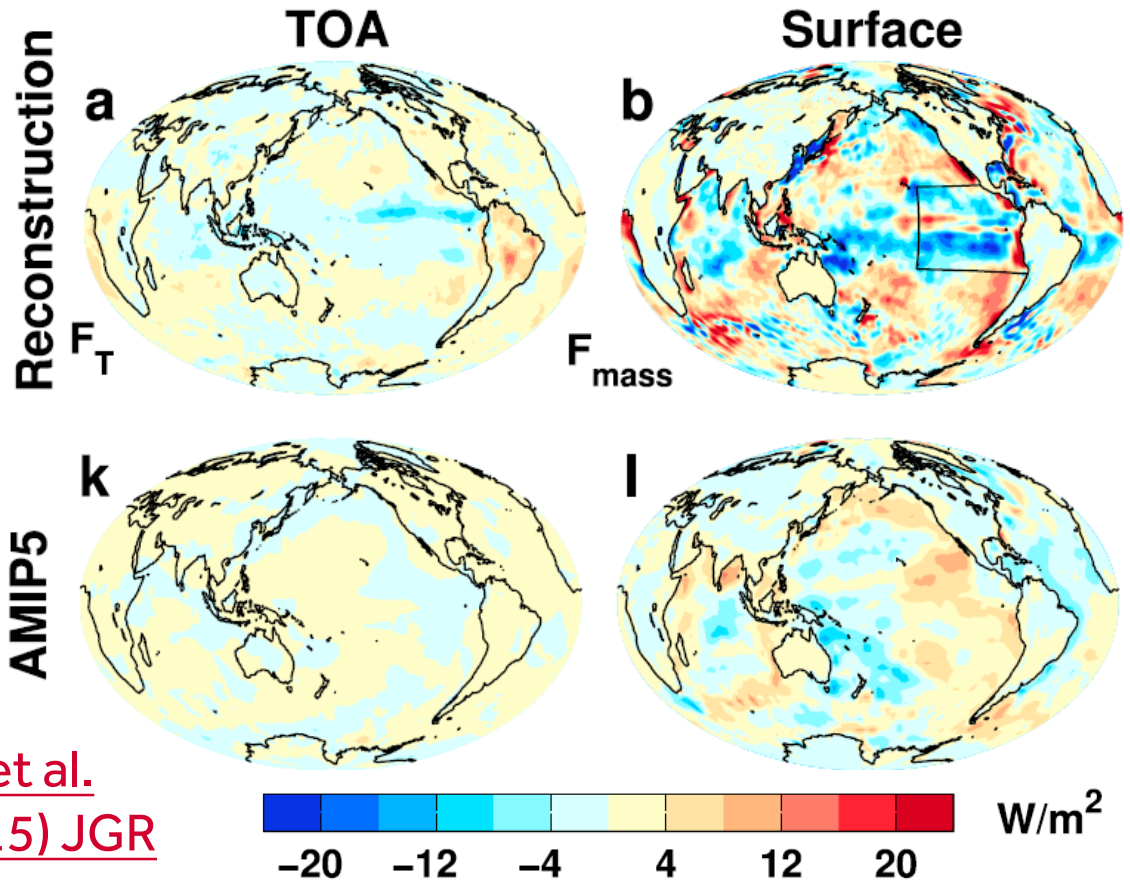




Net surface downward energy flux (Wm^{-2})
Liu et al. (2015) JGR
see also: Loeb et al. (2015) Clim. Dyn , Trenberth et al. (2001) Clim. Dyn.

WHERE IS THE HEAT GOING?

CHANGES IN SURFACE ENERGY FLUX



Liu et al. (2015) JGR

- 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?

CONCLUSIONS

- Heating of Earth continues at rate of ~0.6 Wm^{-2}
  - Manifest as positive imbalance in Southern Hemisphere
  - Variability from radiative forcings & ocean changes
- Radiative transfer & Thermodynamics explain increased global precipitation with warming ≈ 2%/K
  - Radiative forcings also directly affect water cycle responses
  - Greenhouse gas & absorbing aerosol forcing supress global precipitation response to warming ("hydrological sensitivity")
- Inter-hemispheric heating, moisture budget & unforced variability dictate regional responses and determine climate model biases
  - Decadal changes in ITCZ and global atmospheric/ocean circulation
  - Has the "hiatus" affected water cycle?
  - How do changes in cloud/circulation fit in?
  - Where is energy going? NERC DEEP-C project...