Department of Meteorology

University of Reading

CHANGES IN EARTH'S ENERGY BALANCE AND IMPLICATIONS FOR THE WATER CYCLE

~~Venue: Fancy Paris Conference~~ GU01

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

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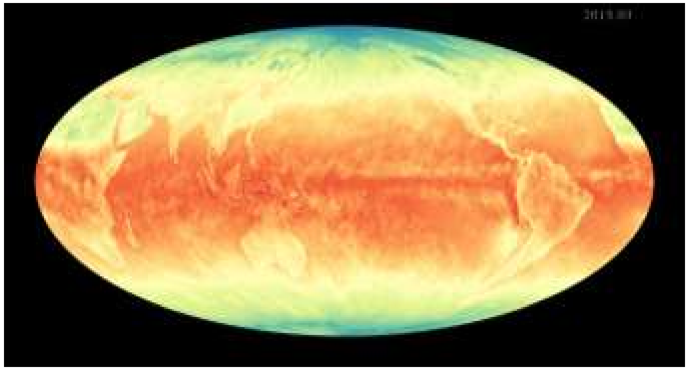
NERC SCIENCE OF THE ENVIRONMENT

Met Office



INTRODUCTION

- Earth's energy budget determines the trajectory and magnitude of climate change
- Both a powerful constraint on and diagnostic of the water cycle globally and regionally

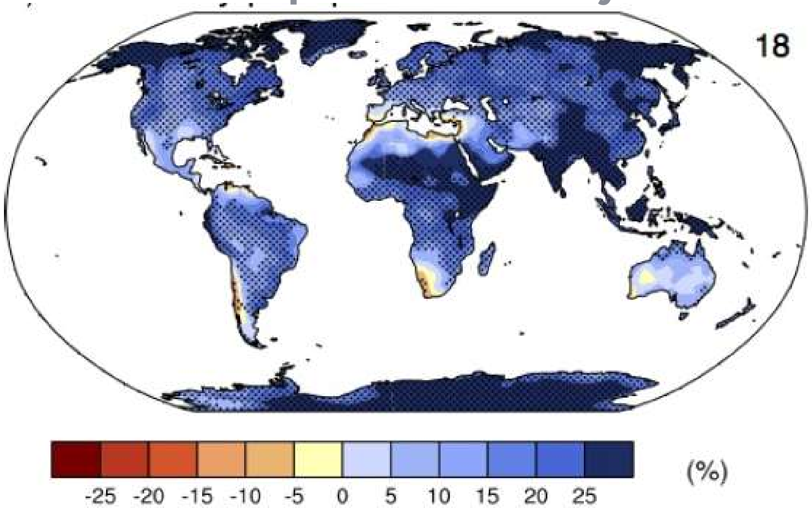
Flows of energy and moisture between land/ocean, northern/southern hemispheres and high/low latitudes fundamental for determining climate that societies depend upon

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

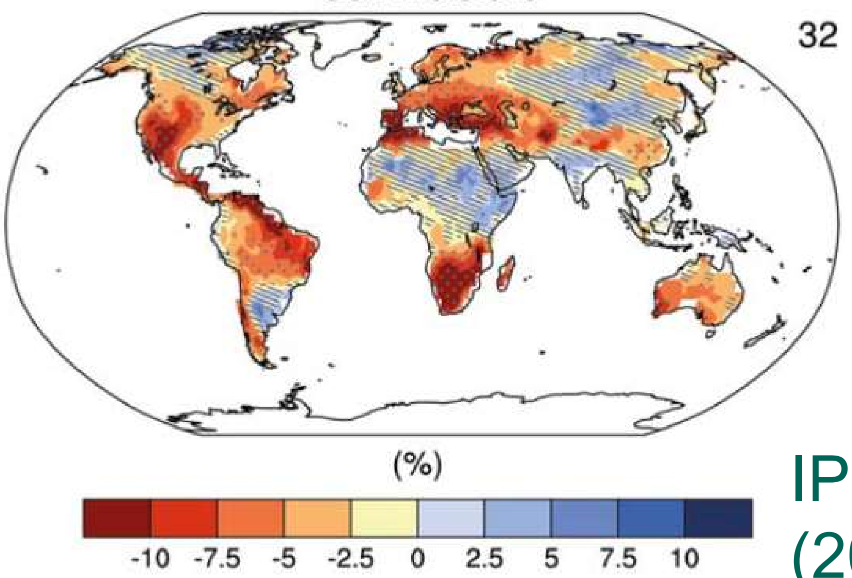
HOW WILL WATER CYCLE CHANGE?

- More global mean precip.
- More intense rainfall
- More intense droughts
- Intensification of wet and dry seasons?
- Regional projections??

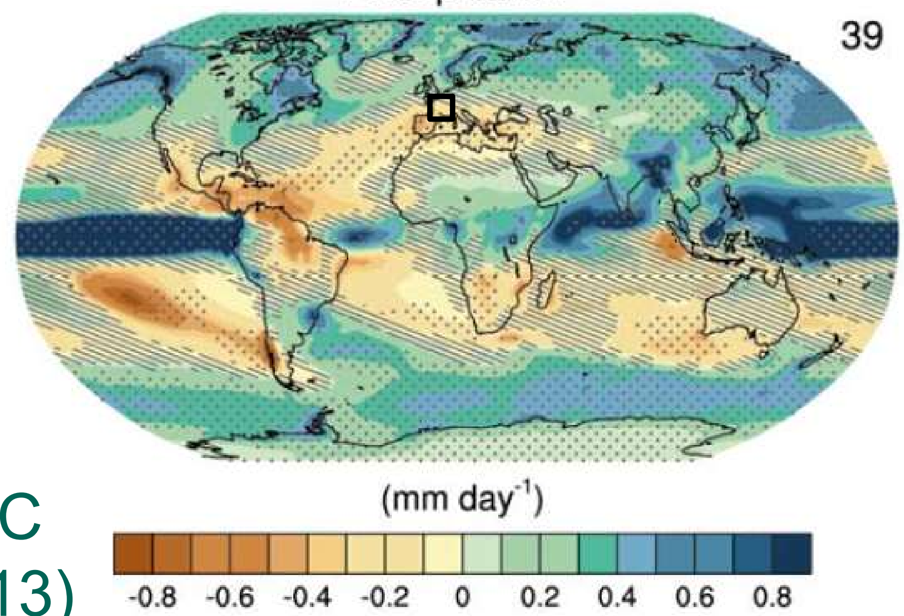
Precipitation intensity



Soil moisture



Precipitation



IPCC (2013)

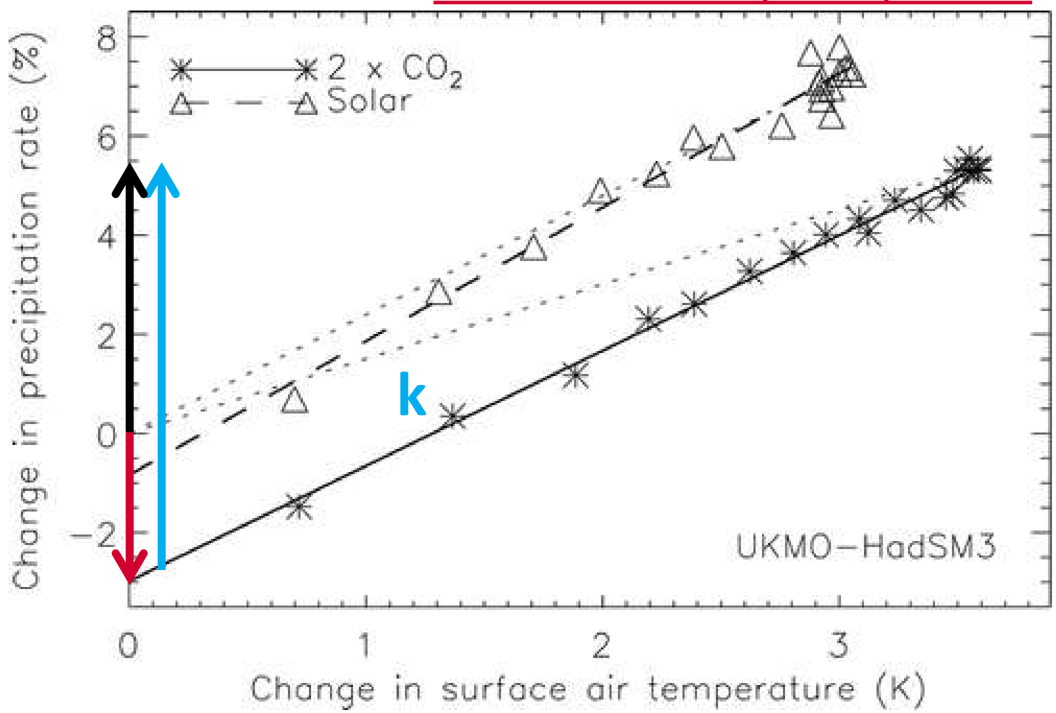
EARTH'S ENERGY BUDGET AND PRECIPITATION RESPONSE

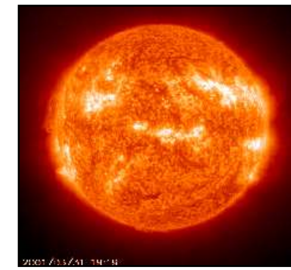
Andrews et al. (2009) J Clim

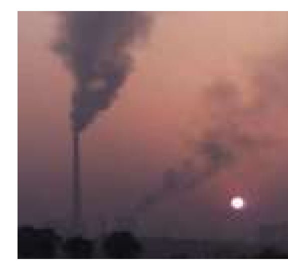
$L\Delta P \approx k\Delta T - f_F \Delta F$

ahem?

ΔSH

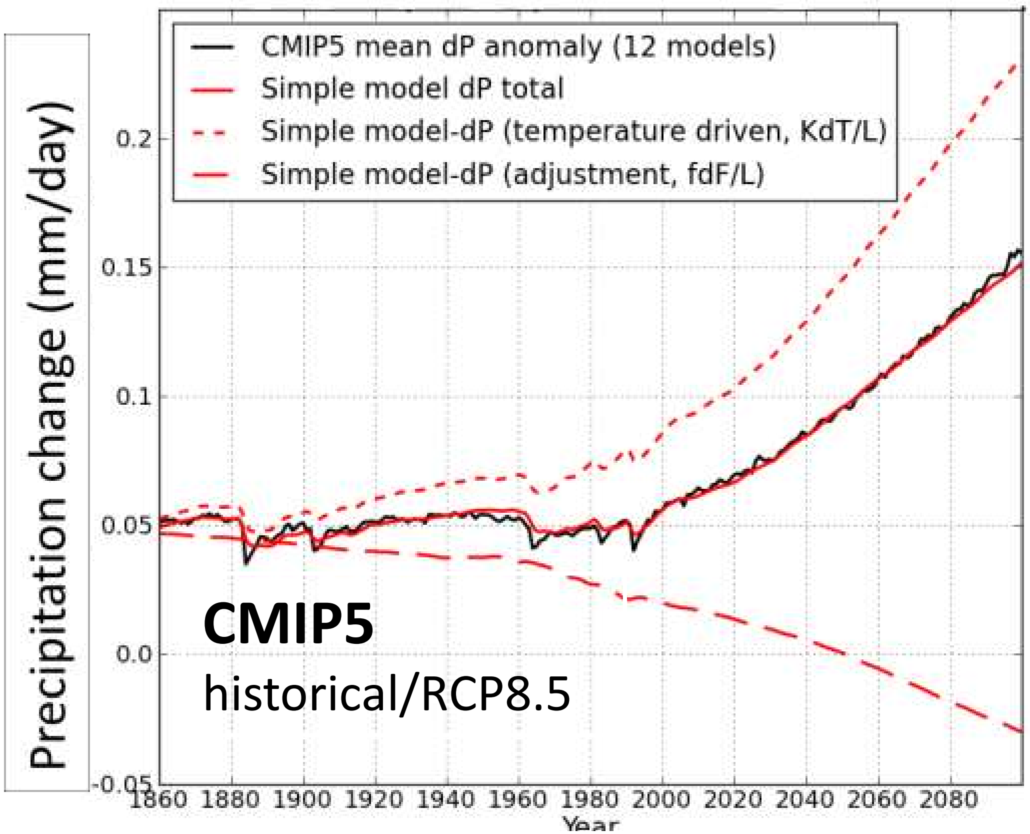






See also: Allen and Ingram (2002) Nature ; O'Gorman et al. (2012) Surv. Geophys ; Bony et al. 2014 Nature Geosci.

SIMPLE MODEL FOR GLOBAL PRECIPITATION



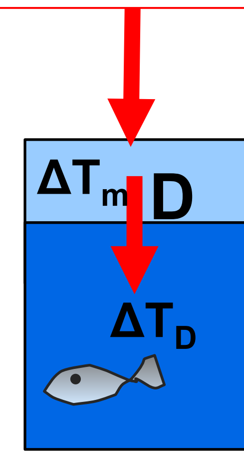
After [Allan et al. (2014) Surv. Geophys]() and [Thorpe and Andrews (2014) ERL]()

Using simple model:

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

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

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

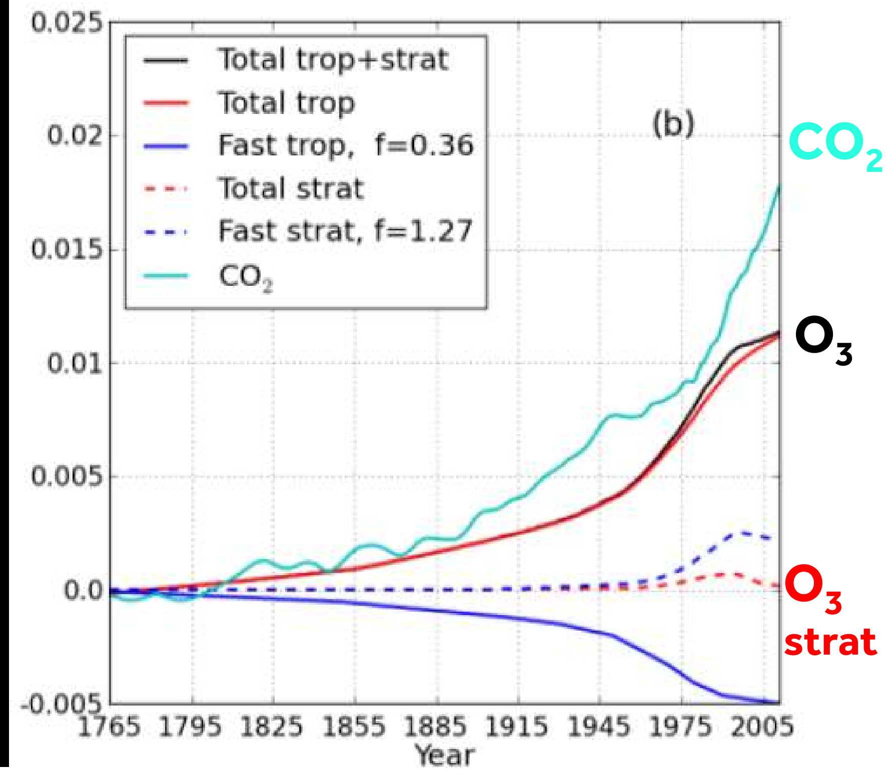


$$D = c(\Delta T_m - \Delta T_D)/d$$

Zahra Mousavi
(PhD project)

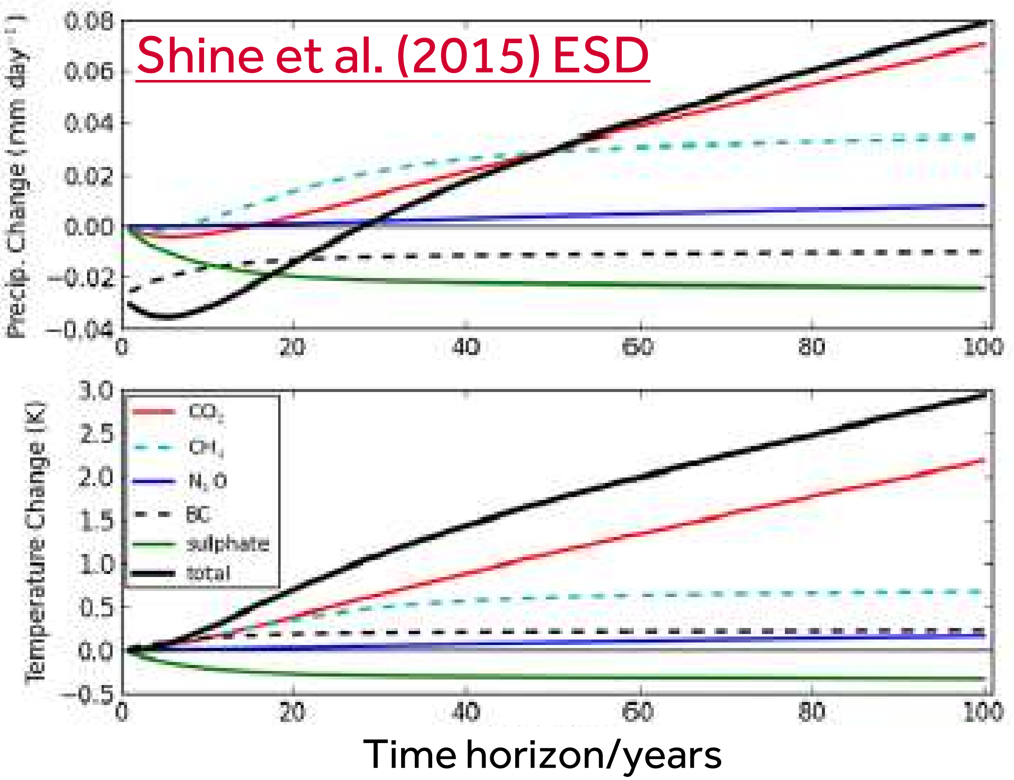
DISPROPORTIONATE GLOBAL PRECIPITATION RESP[redacted]NSE TO OZONE

- Detailed modelling of radiative response to ozone changes (ECLIPSE project inc. Bill Collins, Keith Shine, Nicolas Bellouin)
- Precipitation response to ozone changes >50% that due to CO_2, even though the RF is only ~20%
- Increased ozone pollution at low levels effective at increasing P
- Stratospheric ozone depletion also contributes to increased P



MacIntosh et al. (2016) GRL

METRICS FOR GLOBAL PRECIPITATION



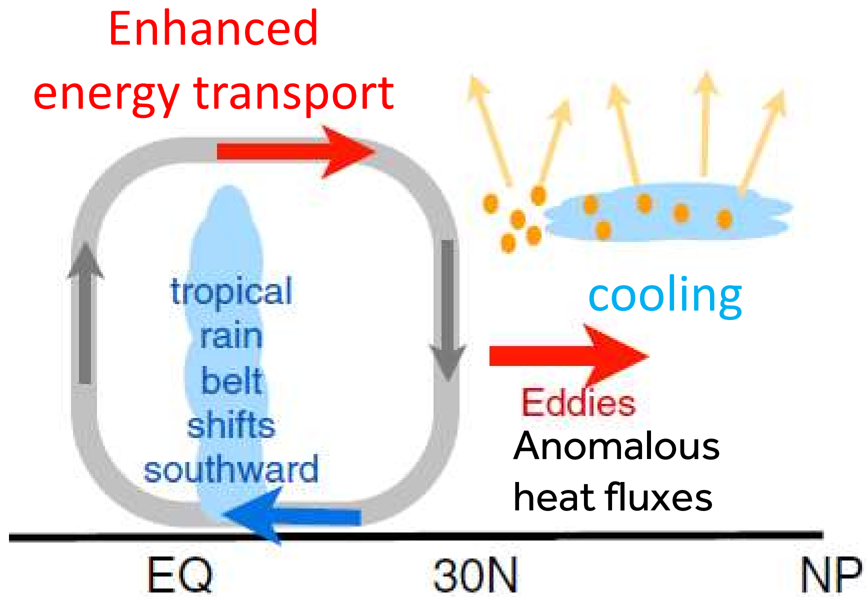
- Metrics linking change in precipitation to emissions
- Precipitation and temperature response to constant emissions after 2008
- But what about regional changes?

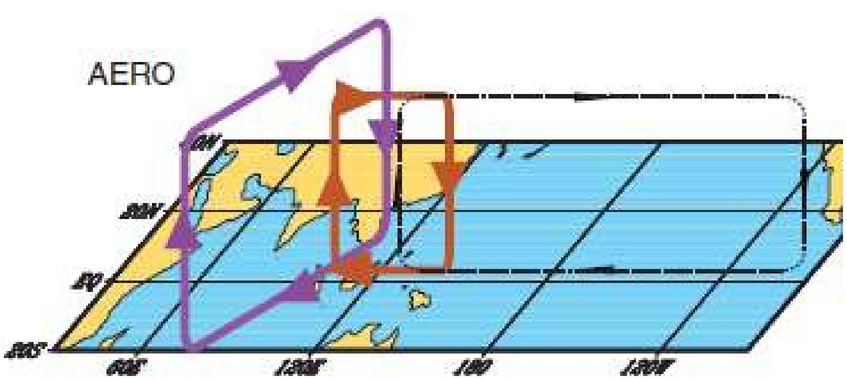
$$\mathrm{AGPP}_{\mathrm{S}}^{x}(H) = 0.034\left(k\mathrm{AGTP}_{\mathrm{S}}^{x}(H) - f_x A_x \tau_x\left(1 - \exp\left(-H/\tau_x\right)\right)\right)$$

Using Absolute Global Temperature Potential (AGTP) due to sustained emissions and radiative forcing over time horizon, H.

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

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

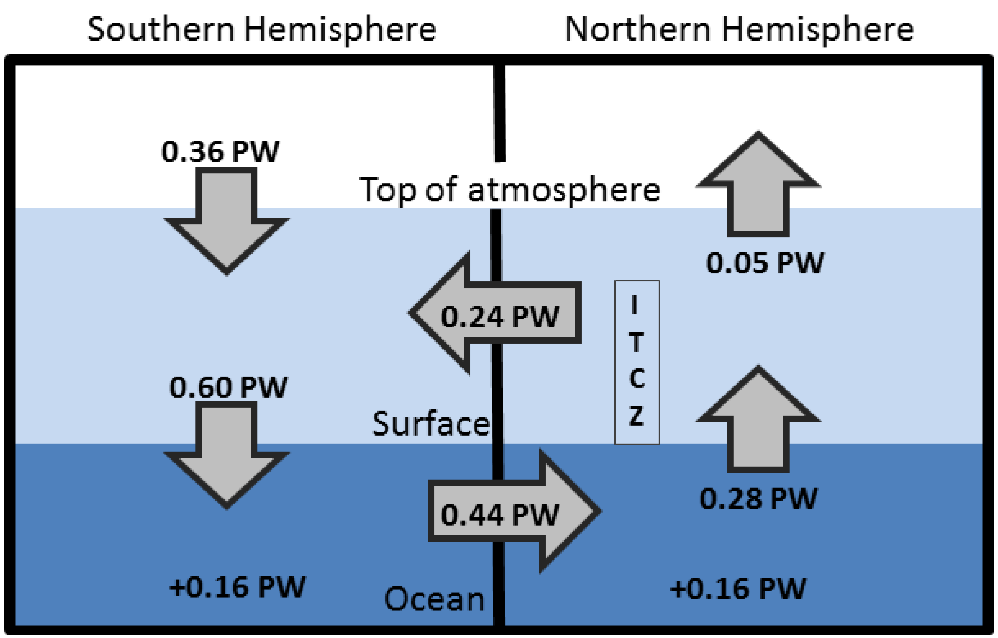


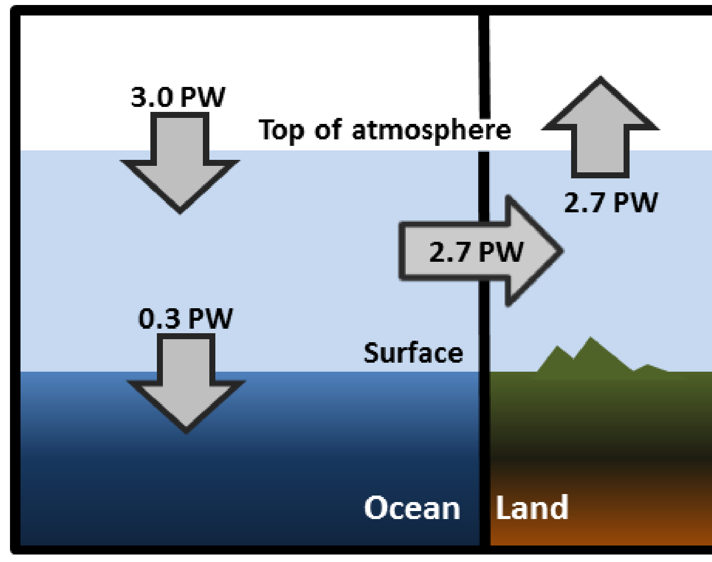


- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science (left)
- Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn
- GHGs & Sahel rainfall recovery?

Dong & Sutton (2015) Nature Clim.

OBSERVED ASYMMETRY IN EARTH'S ENERGY BUDGET

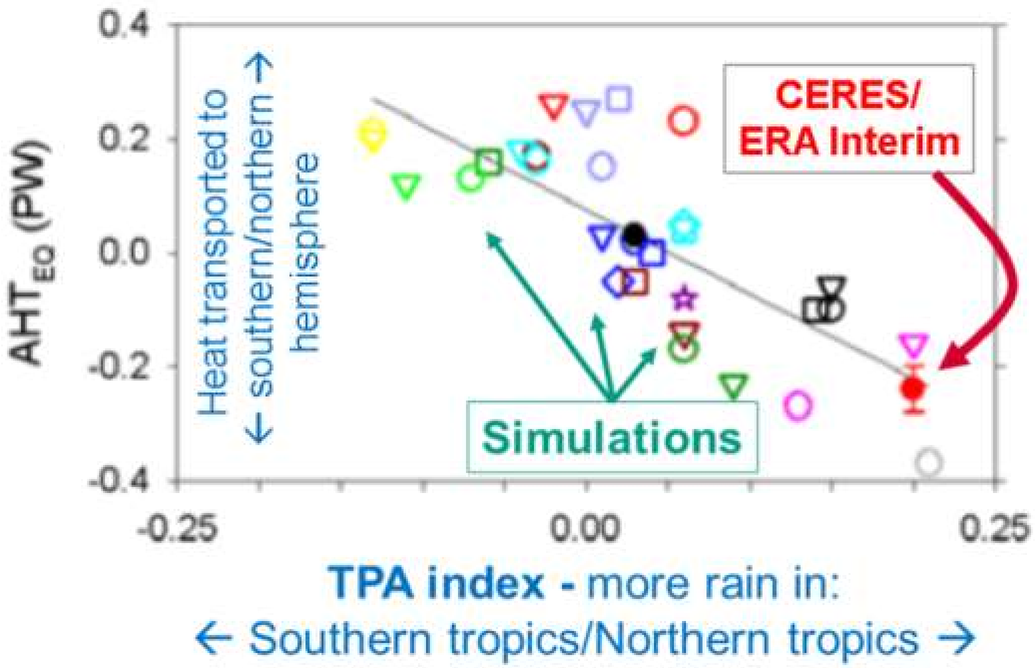




Adapted from Liu et al. (2015) JGR (above) & Loeb et al. (2015) Clim. Dyn. (left)

- 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)

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

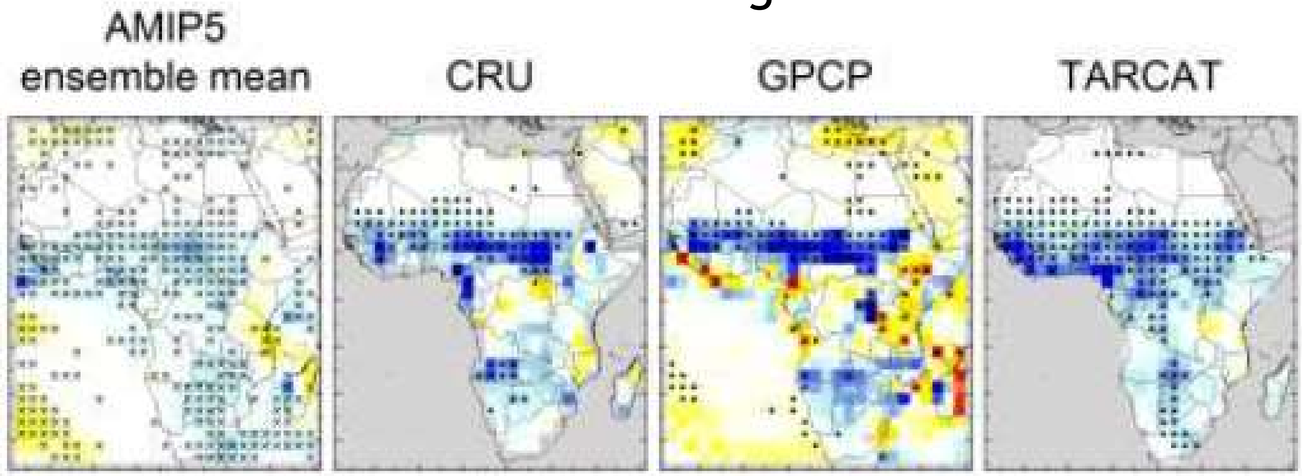
Also: Haywood et al. (2016) GRL

Ahmad Alkamali
BSc project

AFRICA RAINFALL AND CIRCULATION CHANGES

- Africa rainfall sensitive to radiative forcings, inter-hemispheric heating & internal variability
- Africa susceptible to changes in water cycle: monitoring essential (TAMSAT group)
- West Africa – particularly complex mix of pollution /cloud/dynamics: observations essential: DACCIWA project (inc. Christine Chiu et al.) Knippertz et al. 2015

- Recent changes in Africa rainfall:

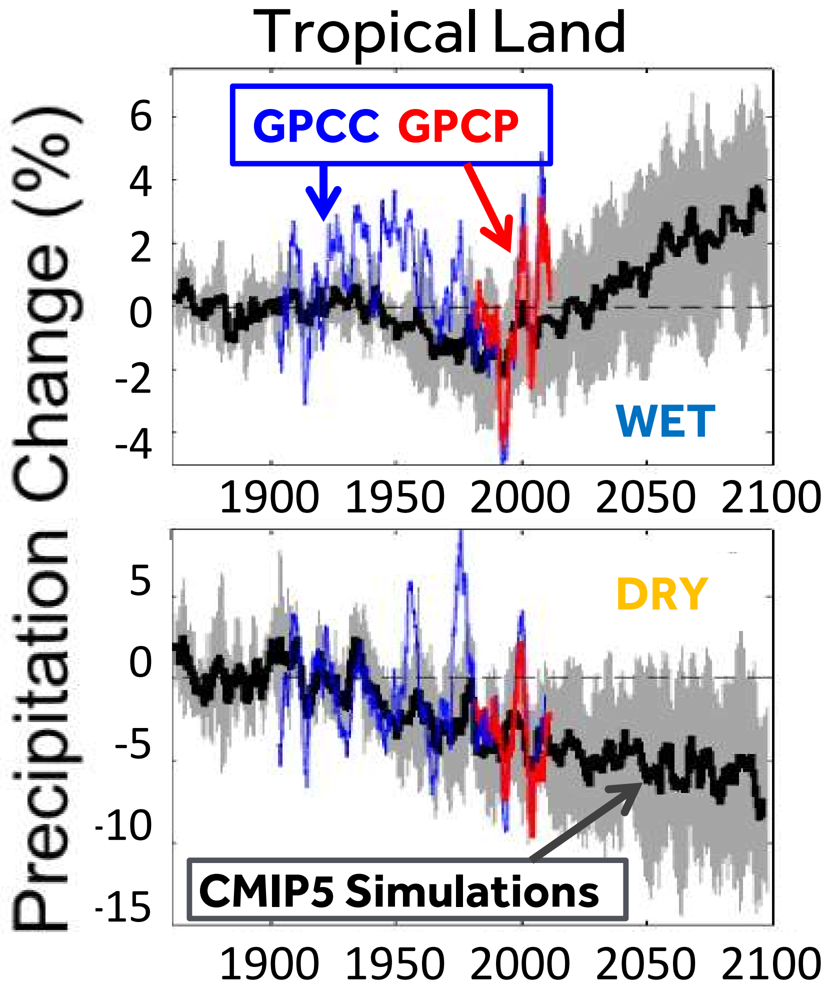


Maidment et al. (2015) GRL

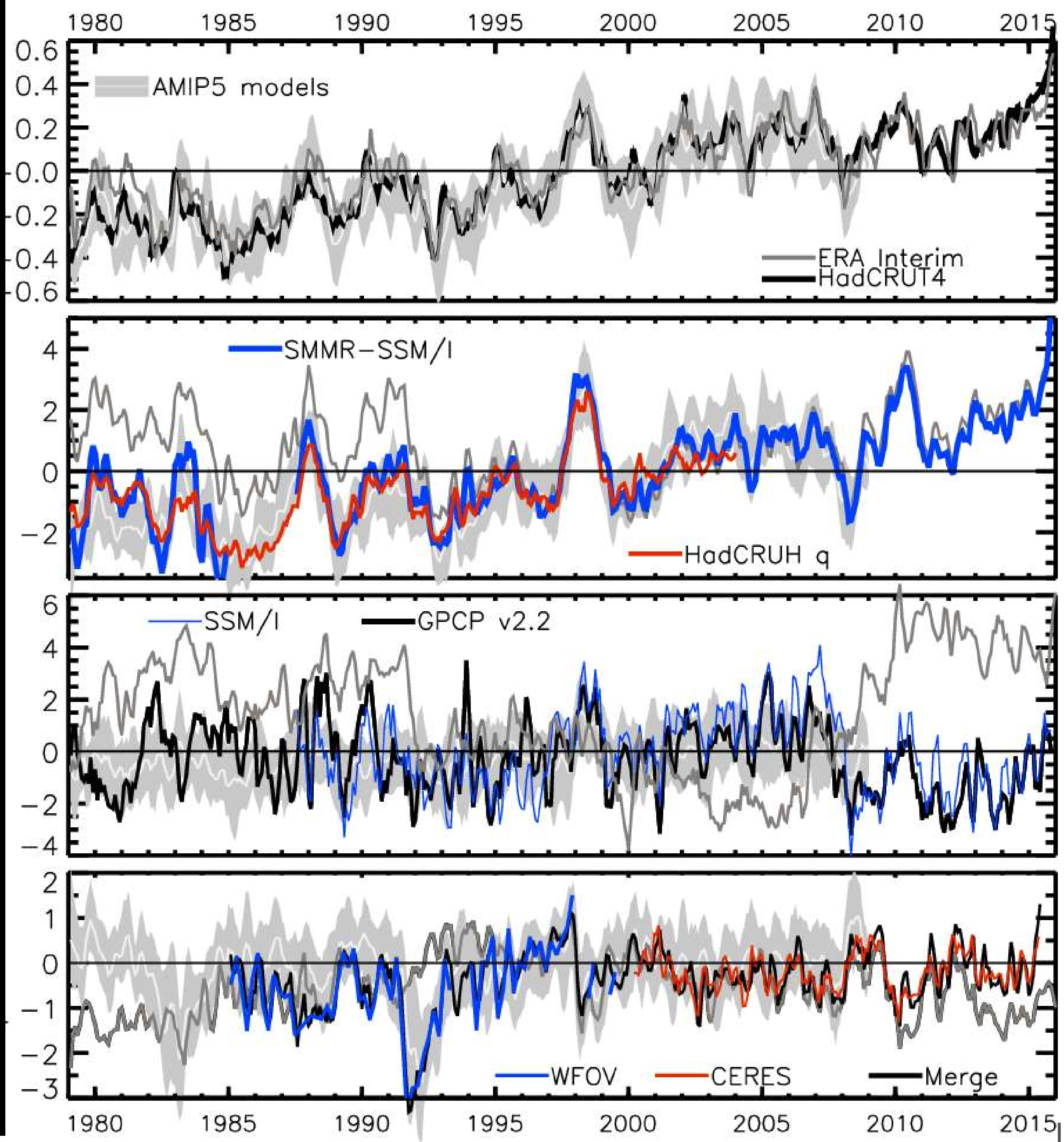
Seasonality: Caroline Dunning PhD project

MOISTURE TRANSPORT AND INTENSIFICATION OF WET/DRY SEASONS

- 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 dry *and* wet 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 ; Kumar et al. 2016)
- Changes in circulation dominate locally (e.g. Scheff & Frierson 2012; Chadwick et al. 2013; Muller & O'Gorman 2011; Allan 2014)



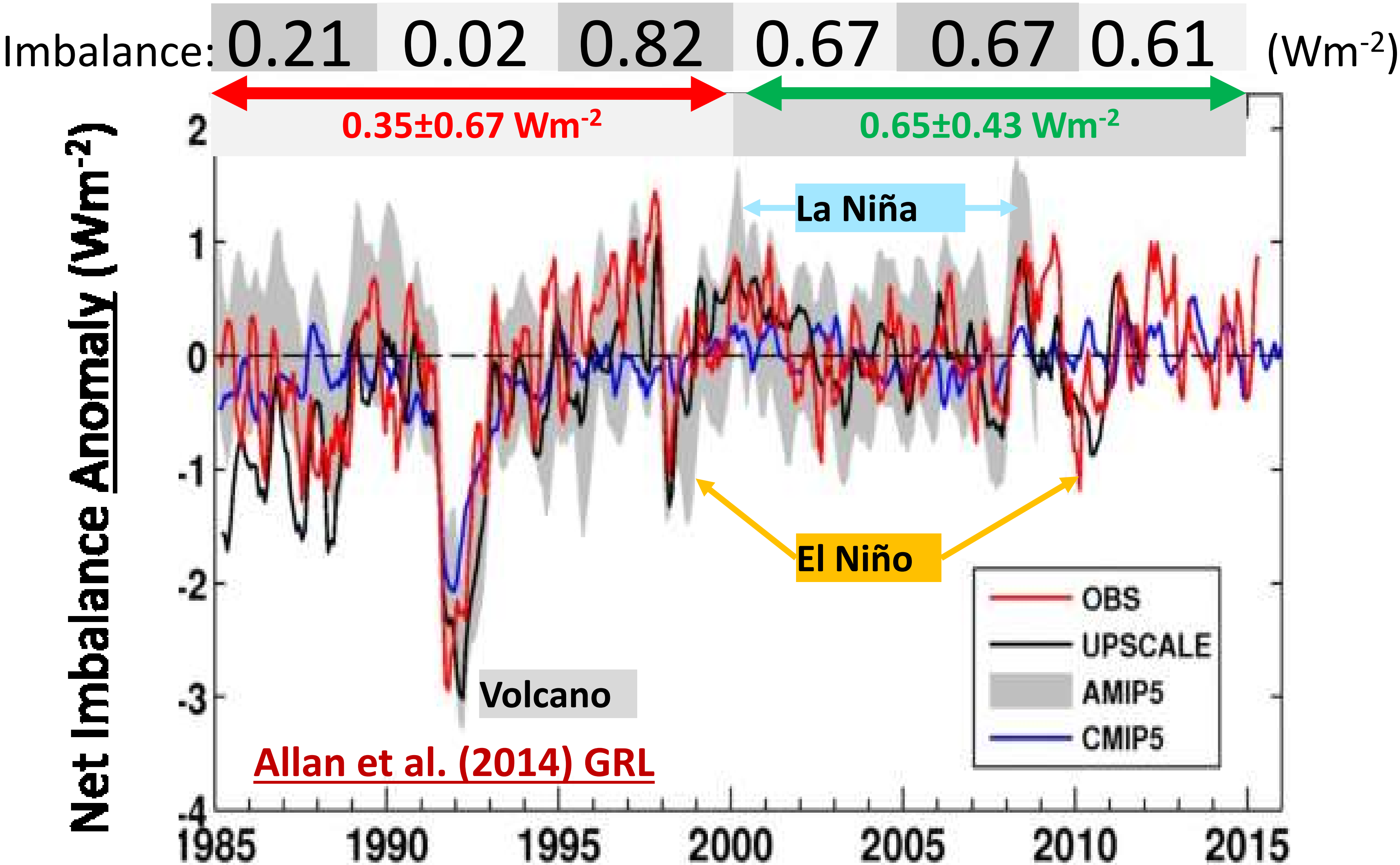
Liu & Allan 2013 ERL



TRACKING GLOBAL CLIMATE CHANGE

Update from [Allan et al. (2014) Surv. Geophys](#) & [Allan et al. (2014) GRL](#)

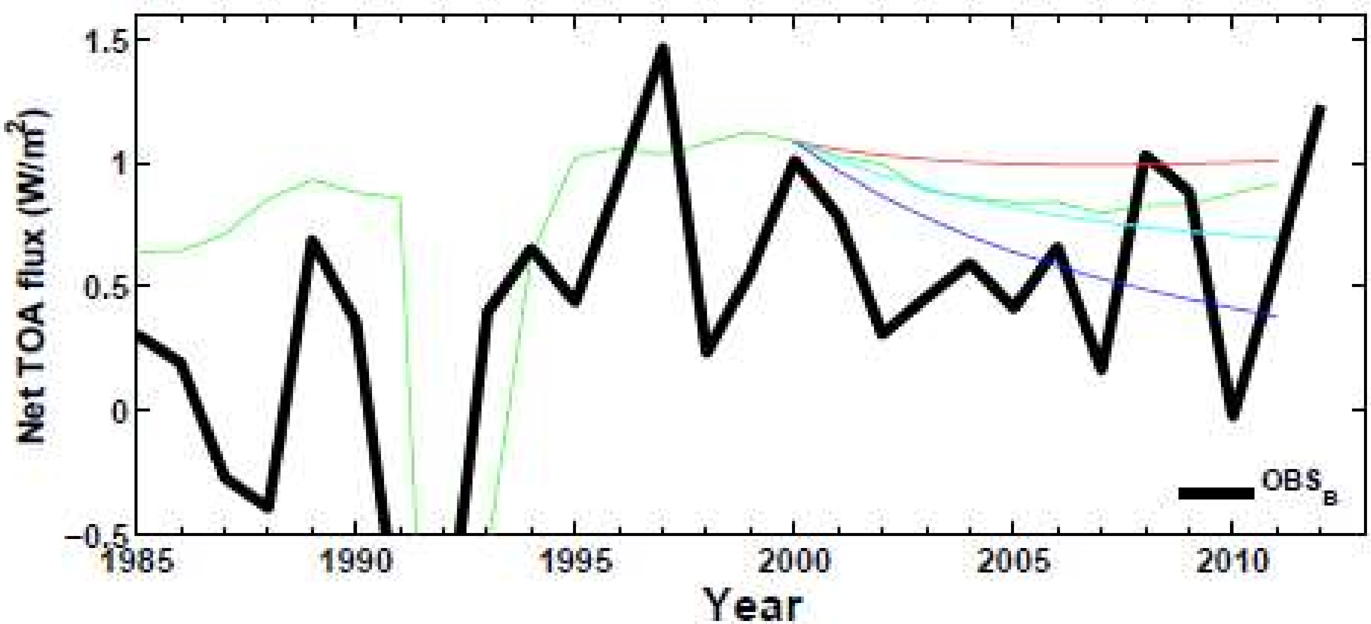
HOW IS EARTH'S ENERGY BALANCE CHANGING?



See also: Wielicki et al. (2002) Science; Wong et al. (2006) J Climate; Harries & Belotti (2010) J. Climate ; Loeb et al. (2012) Nature Geosci

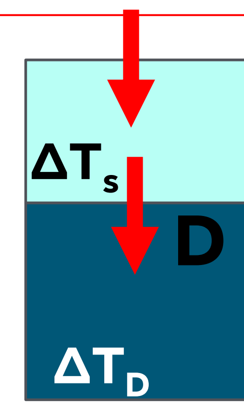
UNDERSTANDING CHANGES IN NET IMBALANCE

N



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

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



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

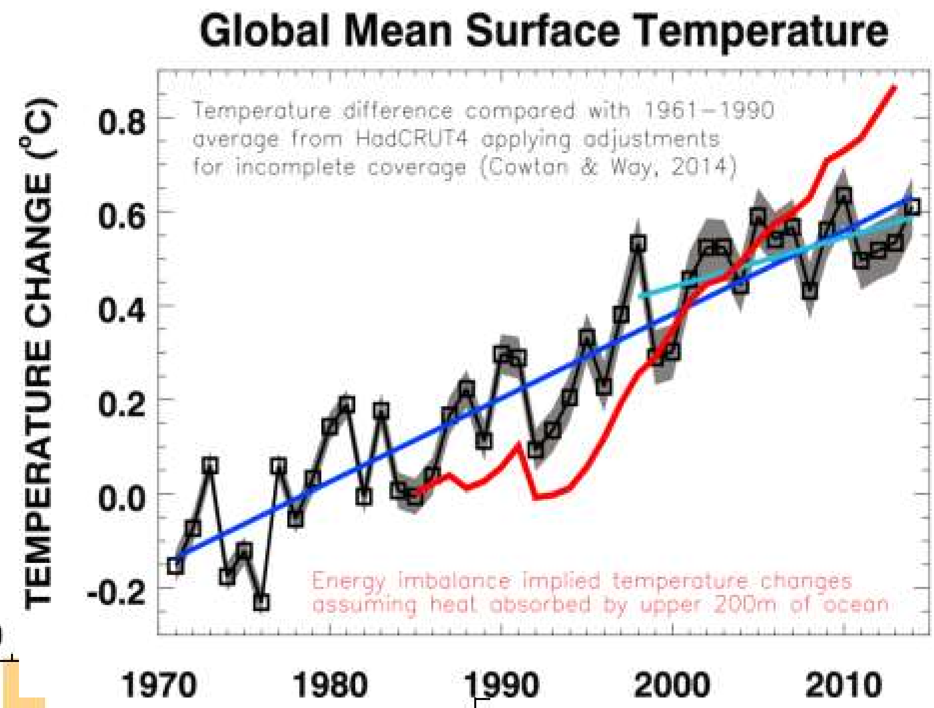
$$\frac{d\Delta T_D}{dt}=\frac{D}{C_D}$$

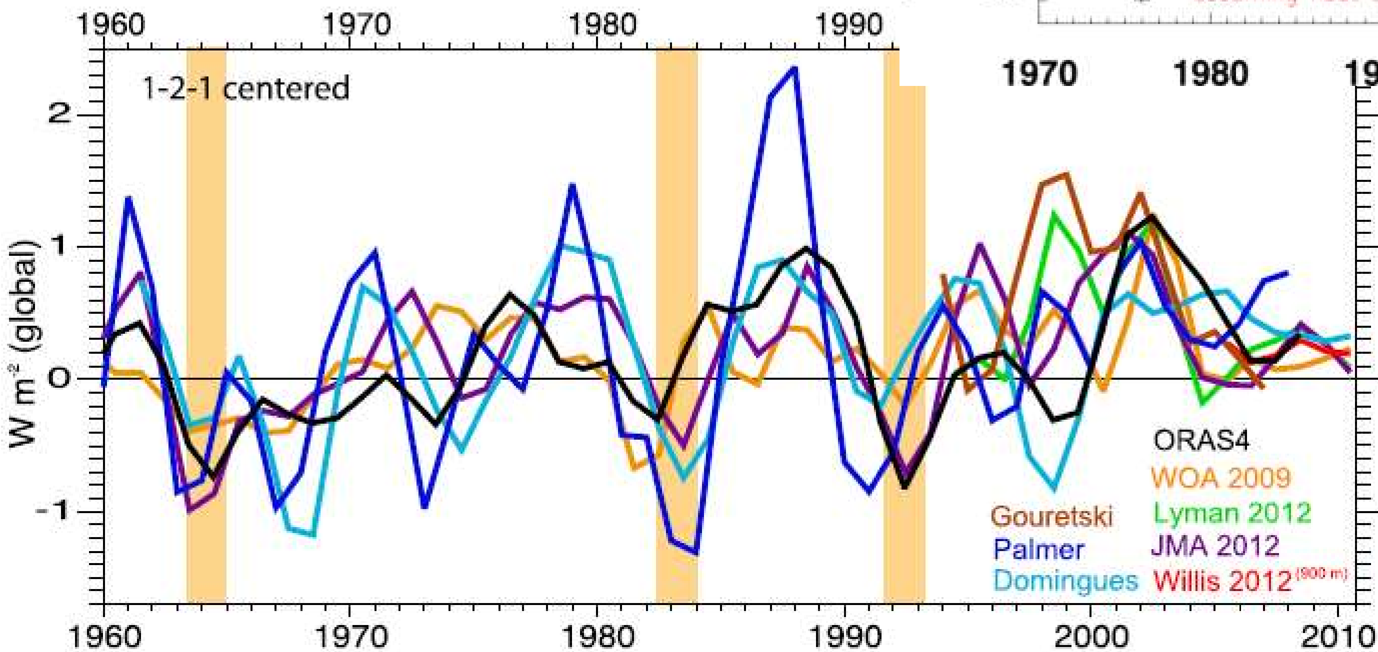
$$\frac{d\Delta T_s}{dt}=\frac{N-D}{C_m}=\frac{\Delta F-Y\Delta T_s-D}{C_m}$$

$$D=k(\Delta T_s-\Delta T_D)$$

AT WHAT RATE IS EARTH HEATING?

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

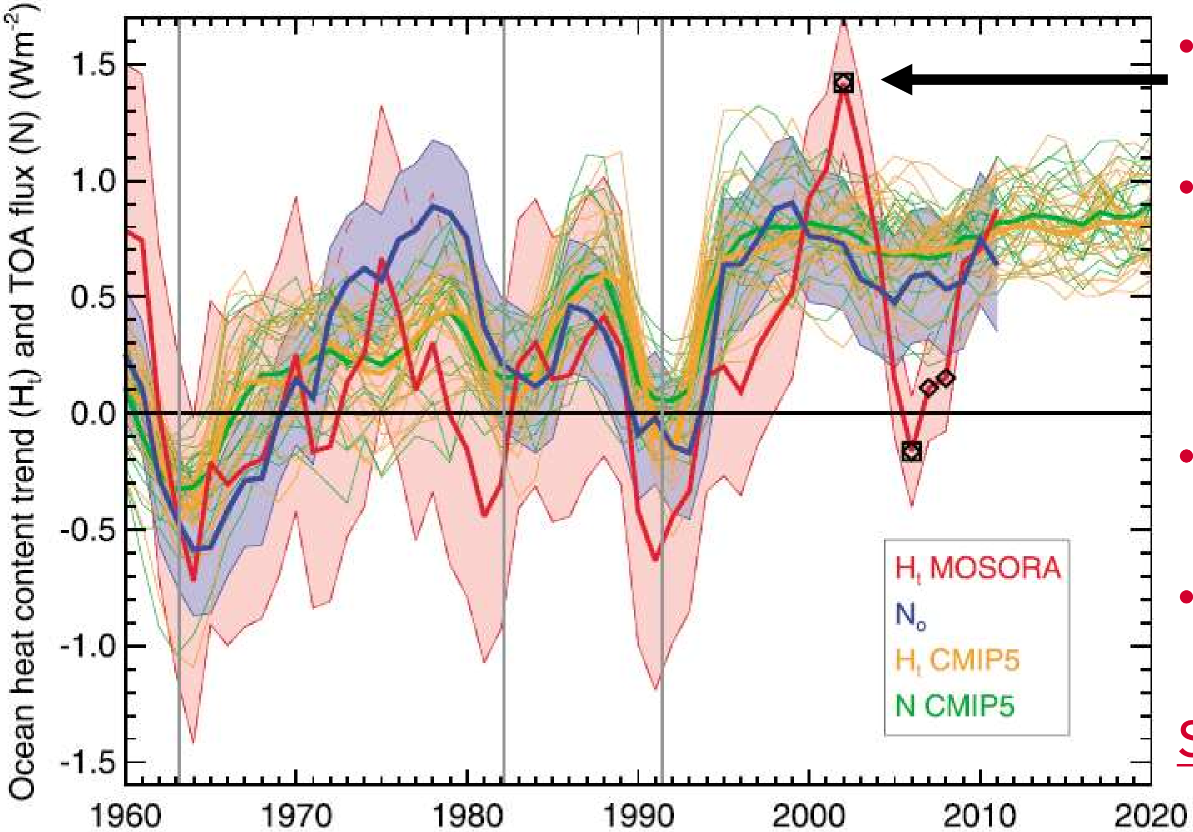




Upper ocean heating rate (Wm^{-2})

Trenberth et al. (2014) J Clim see also Loeb et al. (2012) Nat. Geosci; Glecker et al. Nature Clim.

DISCREPANCY BETWEEN RADIATION BUDGET AND OCEAN HEATING?

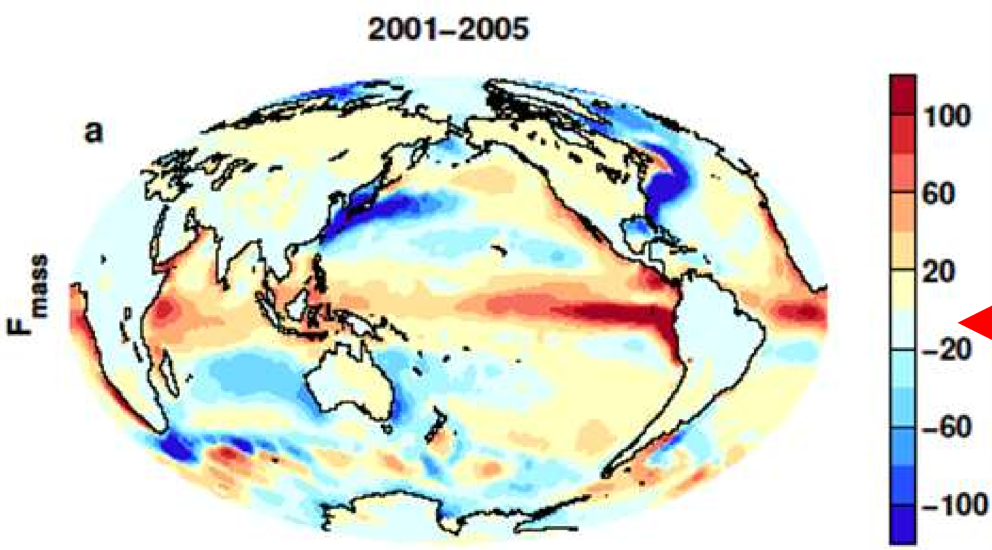


- Large ocean heating anomaly in 2002
- Inconsistent with radiation budget observations and simulations
- Changing observing system influence?
- Slight drop in net flux 1999-2005?

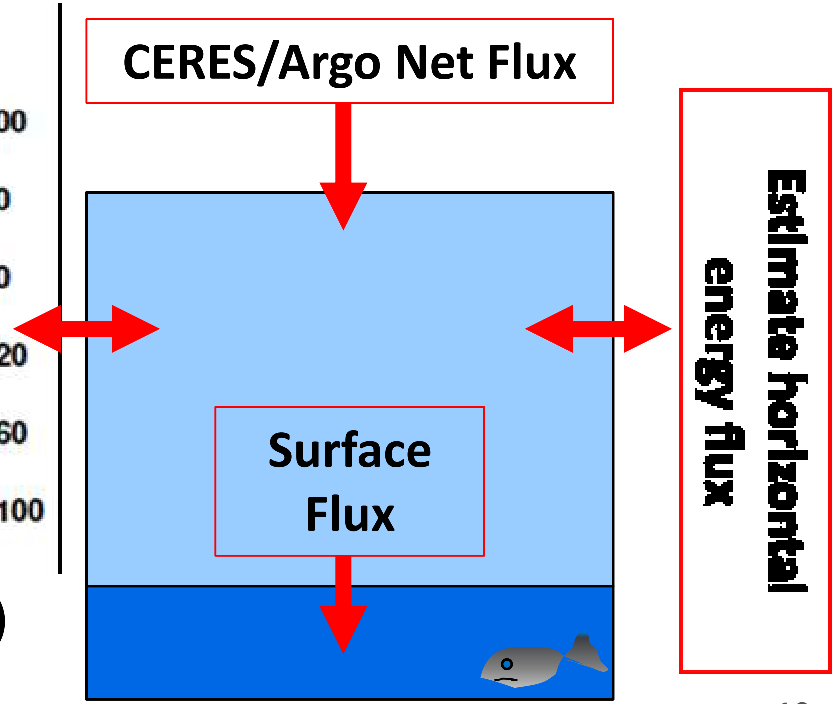
Smith et al. (2015) GRL

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

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



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

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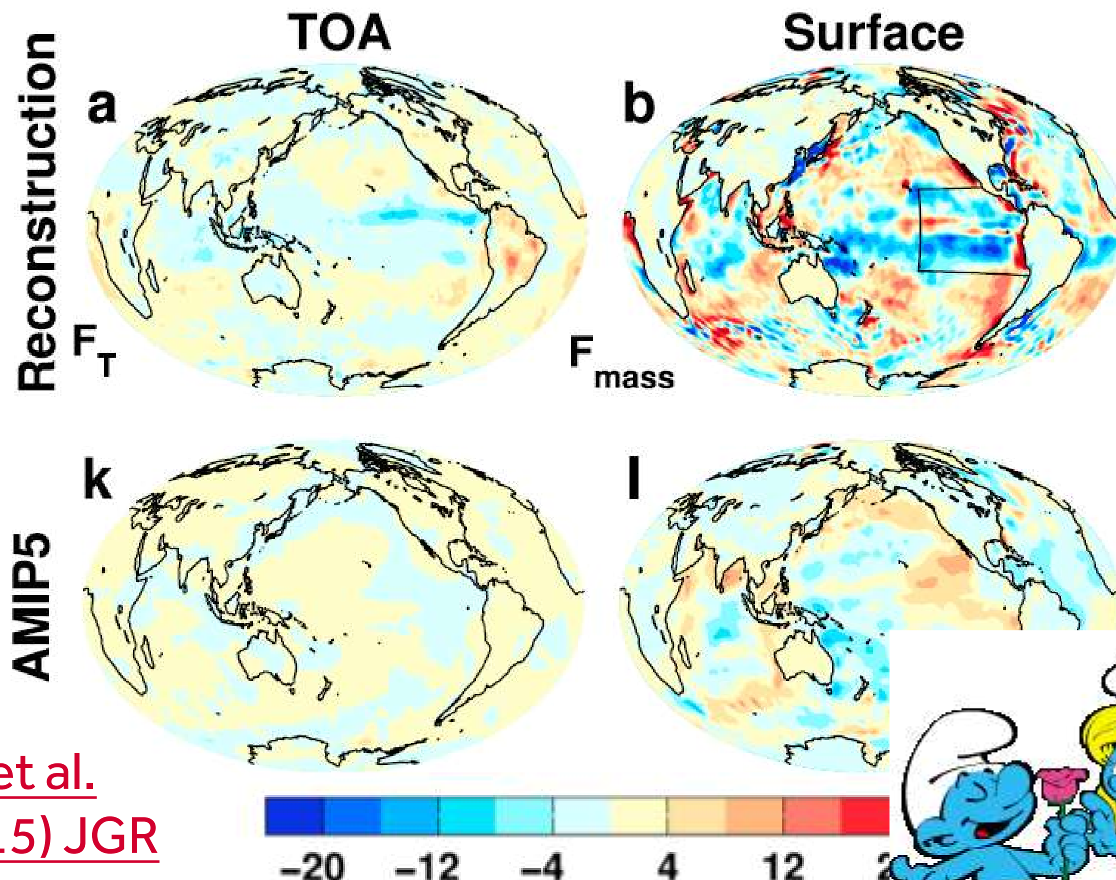
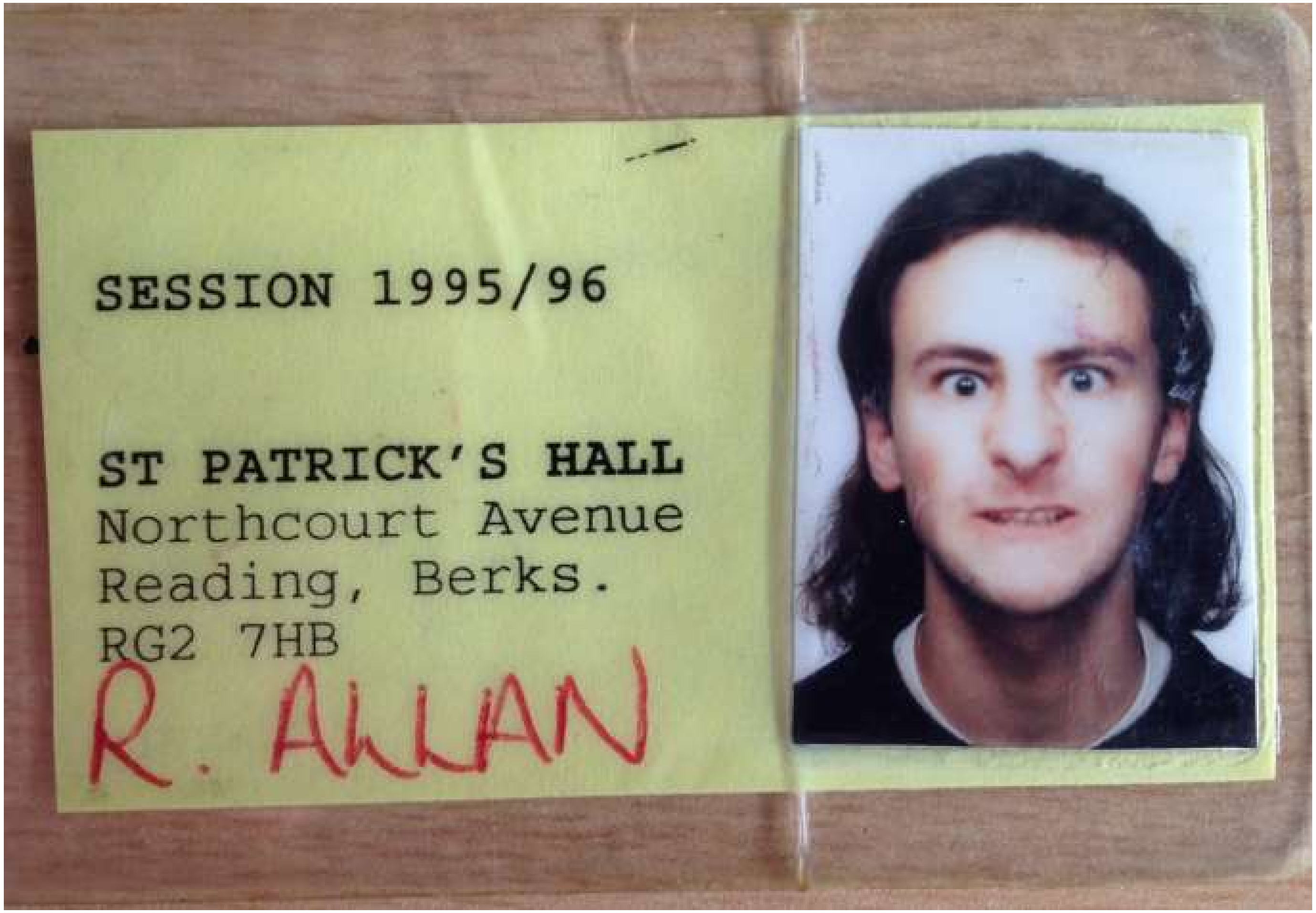


- Changes in energy fluxes 1986-2000 to 2001-2008
- Surface energy flux dominated by atmos. transports
- More investigation of mechanisms & feedbacks by…

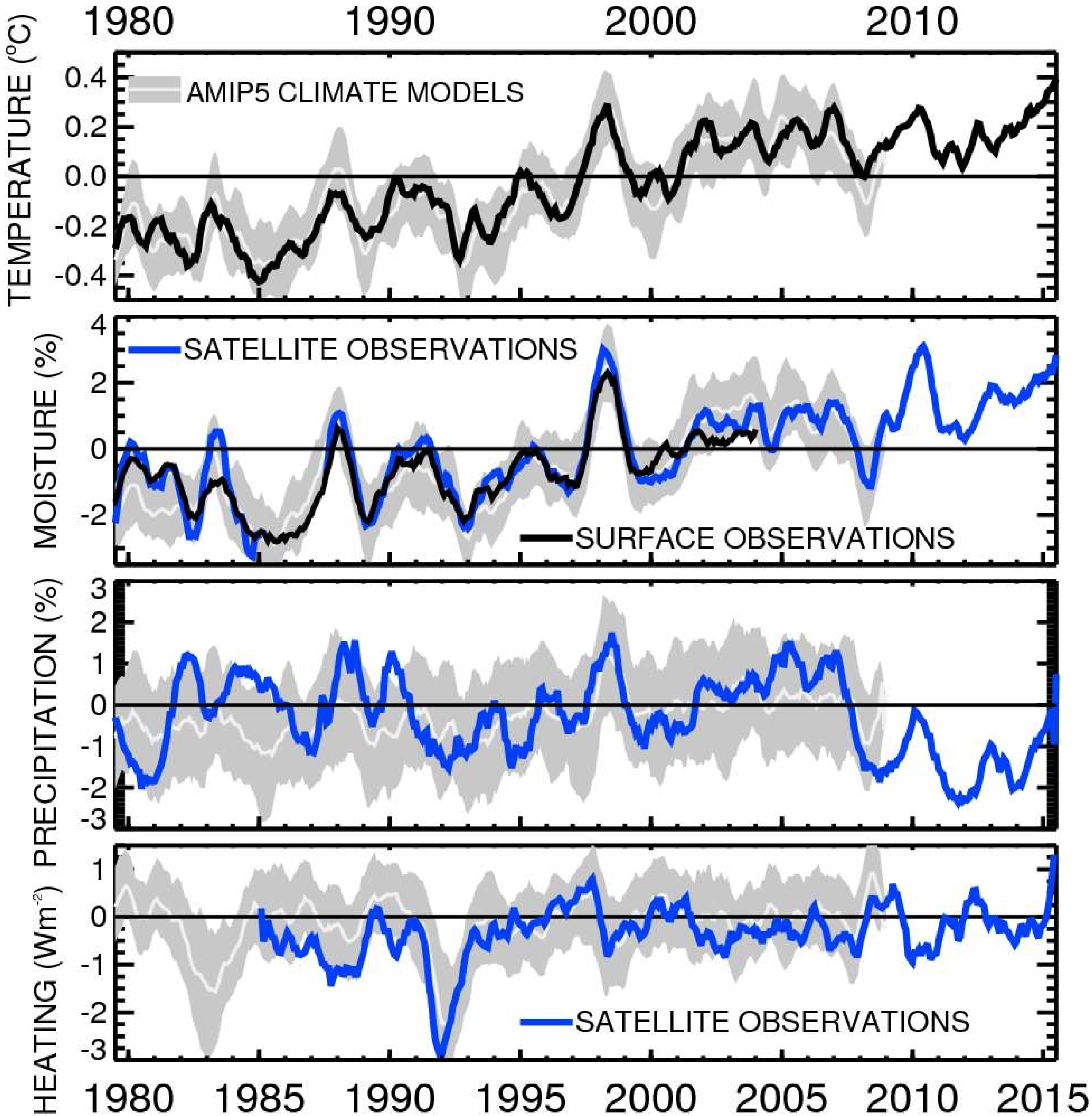
Liu et al. (2015) JGR

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 and can we constrain climate sensitivity & feedbacks on internal variability? DEEP-C and SMURPHS projects…



CLAP IMMEDIATELY!!!



1980
1990
2000
2010
TEMPERATURE (°C)
0.4
0.2
0.0
-0.2
-0.4
AMIP5 CLIMATE MODELS
MOISTURE (%)
4
2
0
-2
SATELLITE OBSERVATIONS
SURFACE OBSERVATIONS
PRECIPITATION (%)
3
2
1
0
-1
-2
-3
HEATING (Wm⁻²)
1
0
-1
-2
-3
SATELLITE OBSERVATIONS
1980
1985
1990
1995
2000
2005
2010
2015