Department of Meteorology

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CURRENT CHANGES IN EARTH'S RADIATION BUDGET AND CLIMATE

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Thanks to Chunlei Liu, Norman Loeb, Doug Smith, Matt Palmer

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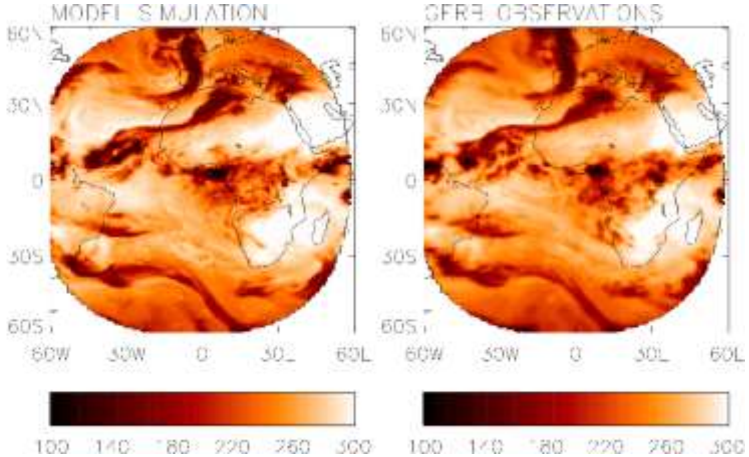
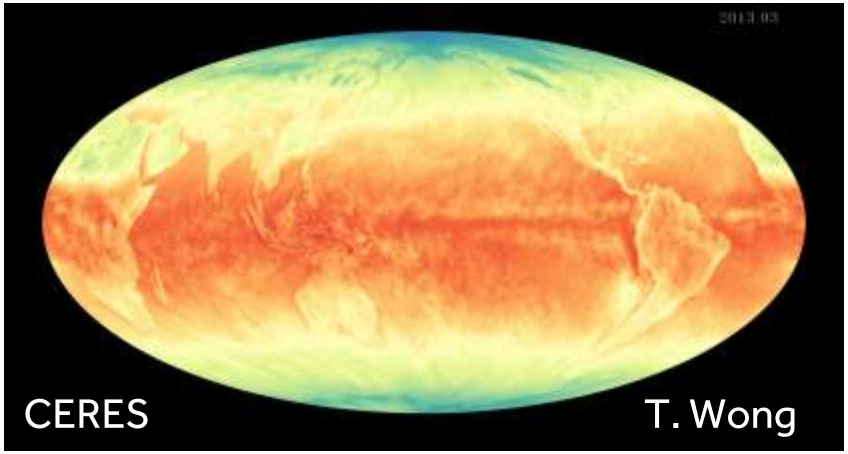
NERC SCIENCE OF THE ENVIRONMENT

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



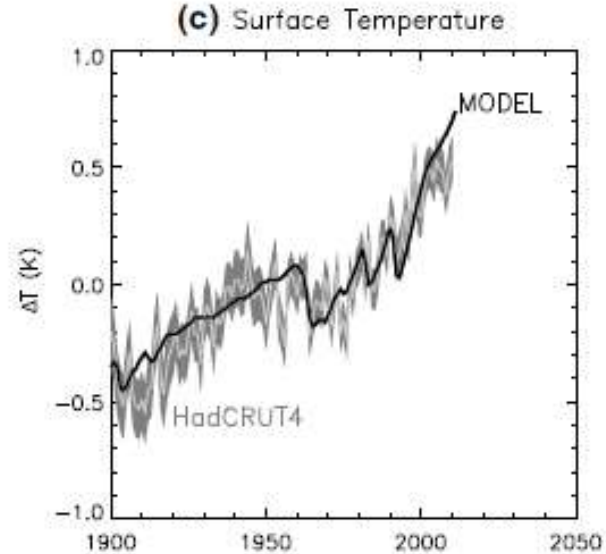


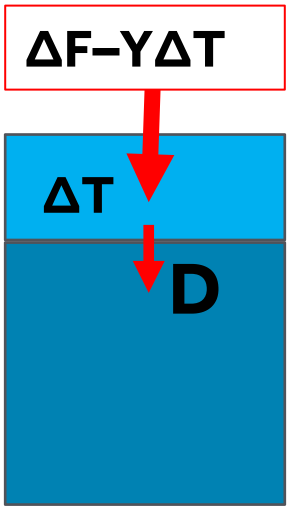
A SIMPLE ENERGY BALANCE MODEL OF EARTH'S CLIMATE

- 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

$$\frac{\mathrm{d}\Delta T_\mathrm{m}}{\mathrm{d}t} = \frac{1}{C_\mathrm{m}}(\Delta F - Y\Delta T_\mathrm{m} - D)$$

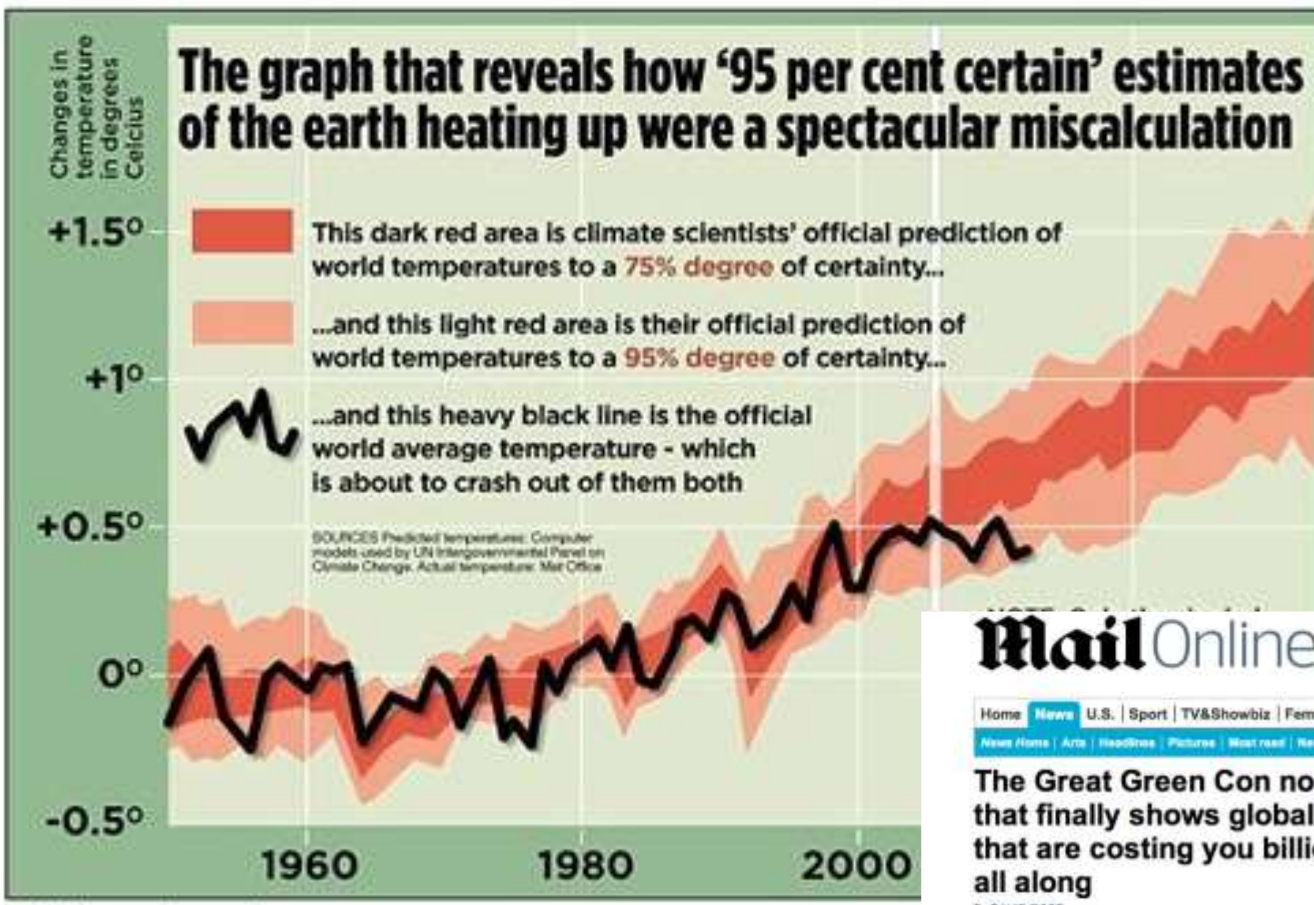
$$D = c(\Delta T_\mathrm{m} - \Delta T_\mathrm{D})/d$$





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

SURFACE WARMING: INCOMPLETE PICTURE OF CLIMATE CHANGE



Mail on Sunday 16th March 2013

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The Great Green Con no. 1: The hard proof that finally shows global warming forecasts that are costing you billions were WRONG all along

By DAVID ROSE

PUBLISHED: 23:37, 16 March 2013 | UPDATED: 13:41, 18 March 2013

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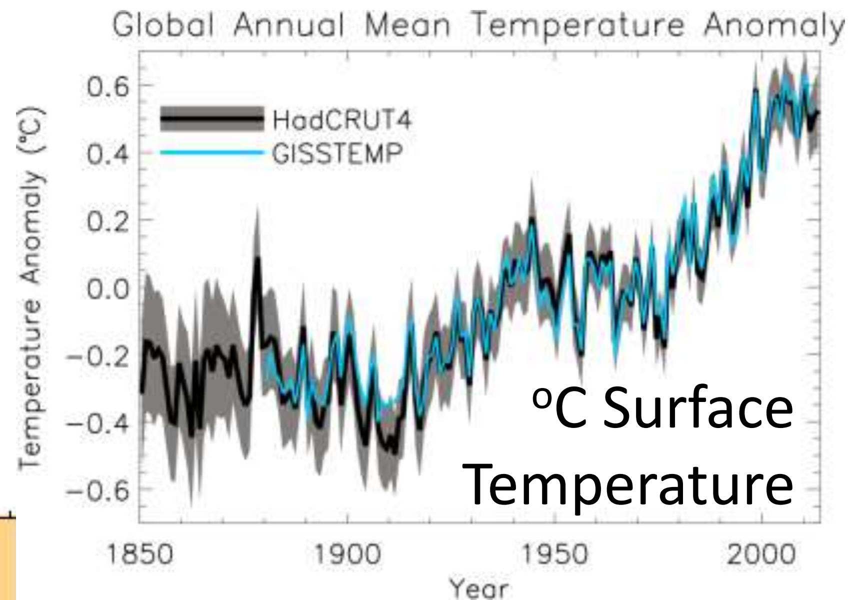
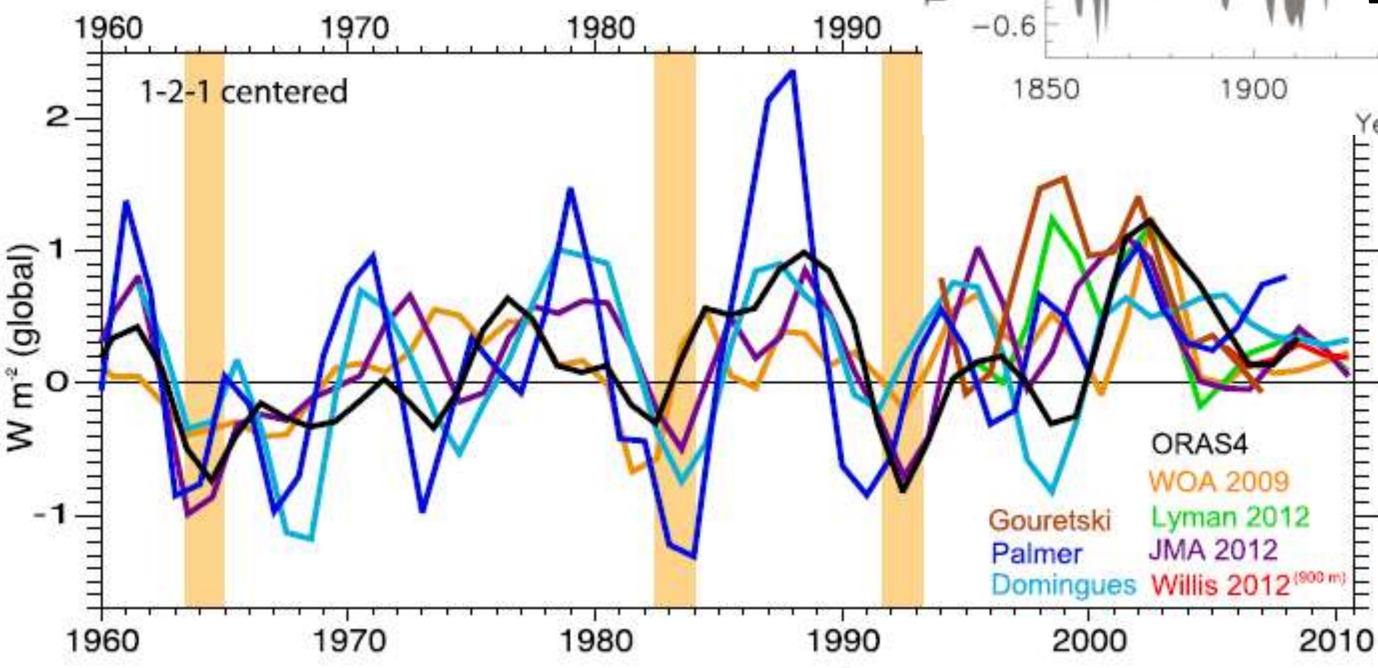
No, the world ISN'T getting warmer (as you may have noticed). Now we reveal the official data that's making scientists suddenly change their minds about climate doom. So will eco-funded MPs stop waging a green crusade with your money? Well... what do YOU think?

AT WHAT RATE IS EARTH HEATING?



°C Surface Temperature

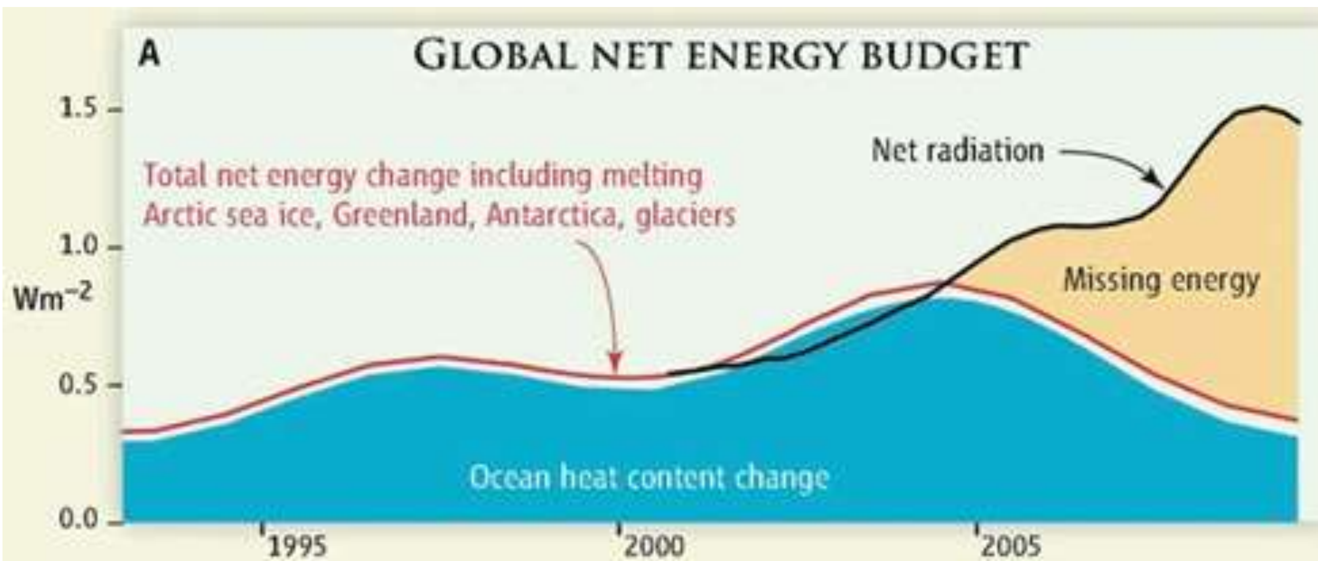


Upper ocean (Wm^{-2})

[Trenberth et al. (2014) J Clim]

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…

COMBINED CERES/ARGO DATA

- Incoming Solar: SORCE Level 3 V10
- Reflected Shortwave/Outgoing Longwave from EBAF
  - (v2.6r → v2.8 → V3...)
- Added errors in quadrature to give ± 0.43 Wm^{-2}
  - Argo 0-2000m dOHCA/dt = 0.47 ± 0.38 Wm^{-2} (2005-2010)
  - >2000m ~ 0.07 ± 0.05 Wm^{-2}
  - Heating/melting ice, heating land/atmos ~ 0.04 ± 0.02 Wm^{-2}
  - CERES standard error ± 0.2 Wm^{-2}

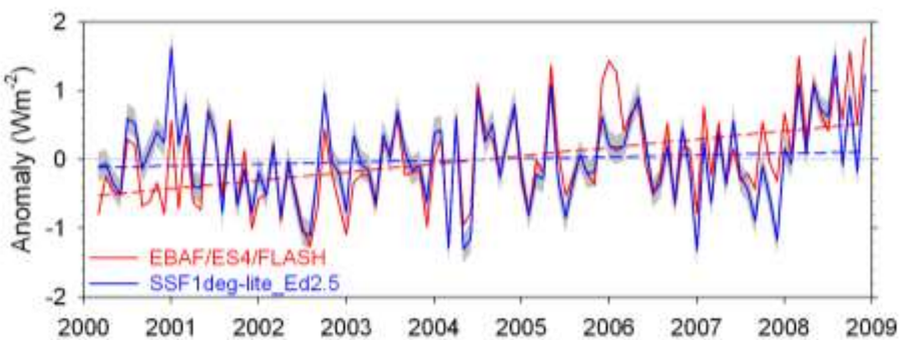
LETTERS
nature geoscience

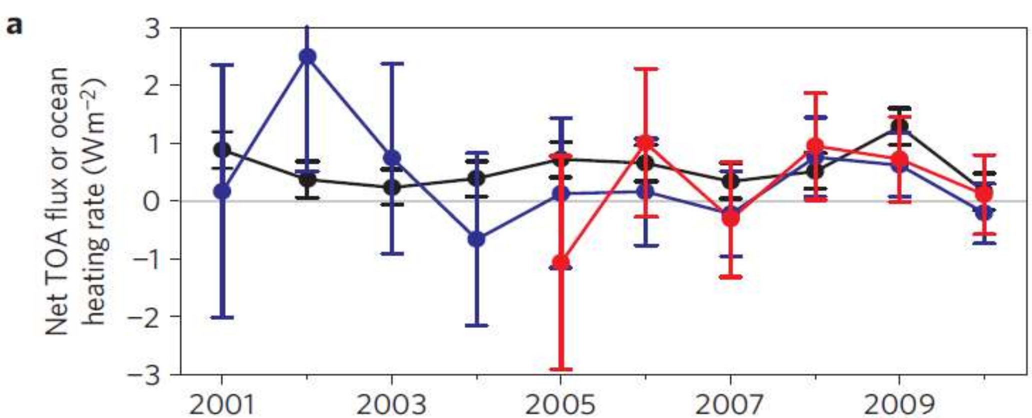
PUBLISHED ONLINE: 22 JANUARY 2012 | DOI: 10.1038/NGEO1375

Observed changes in top-of-the-atmosphere radiation and upper-ocean heating consistent within uncertainty

Norman G. Loeb[1]*, John M. Lyman[2,3], Gregory C. Johnson[3], Richard P. Allan[4], David R. Doelling[1], Takmeng Wong[1], Brian J. Soden[5] and Graeme L. Stephens[6]

CONSISTENT CHANGES IN NET HEATING WITHIN UNCERTAINTY



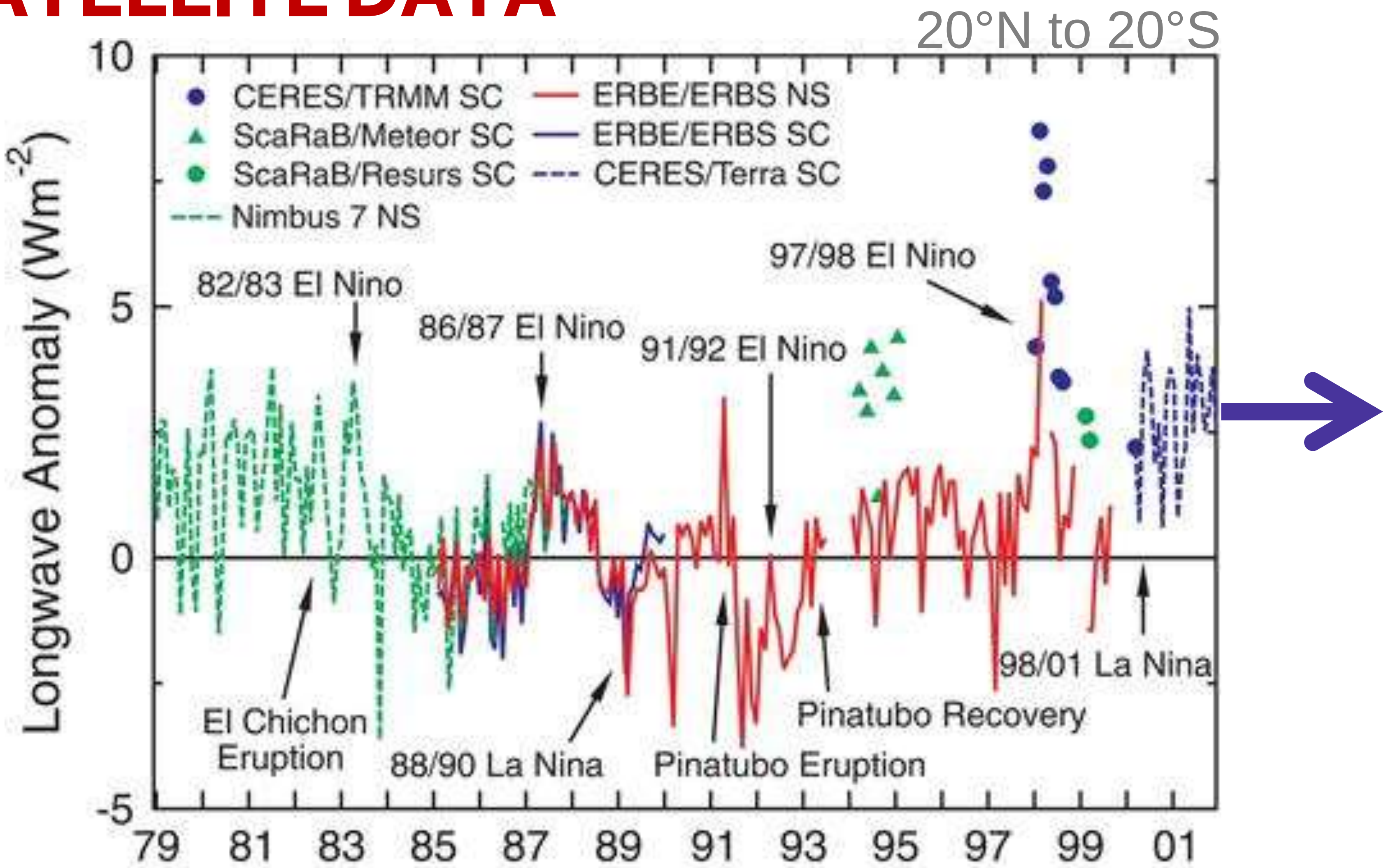


[Loeb et al. (2012) Nat. Geosci]

- Using appropriate CERES dataset that accounts for degradation of SW filter and ocean heat content data we found:
  - No evidence of a decline in ocean heating
  - Stable net radiative imbalance of 0.50 ± 0.43 Wm^{-2}
  - Consistent variability within large uncertainty

…but what about before 2000?

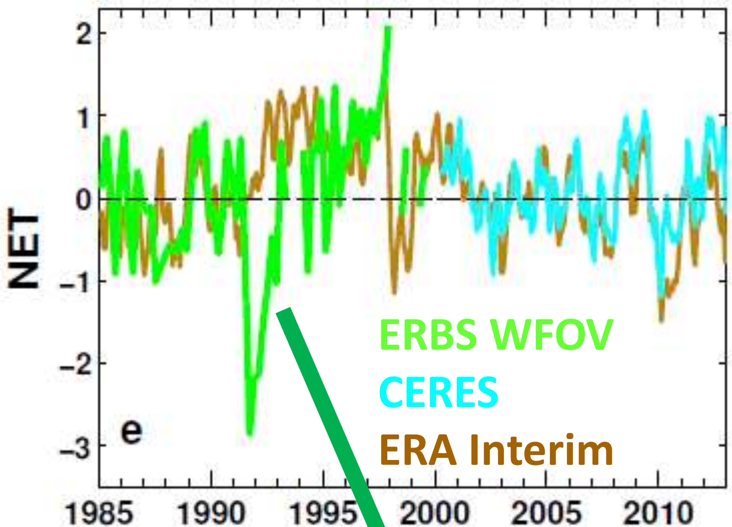
EARTH RADIATION BUDGET SATELLITE DATA



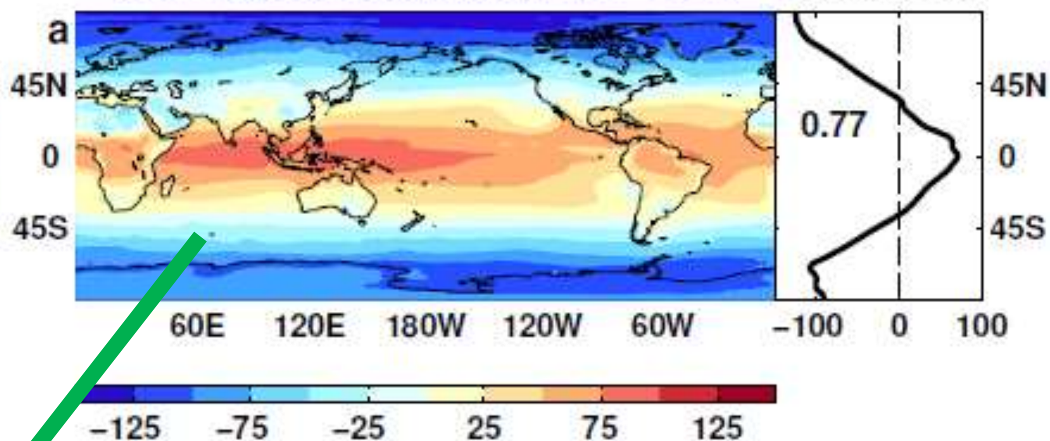
[Wong et al. (2006) J Clim]; [Wielicki et al. (2002) Science]; [Harries & Belotti (2010) J. Clim]

RECONSTRUCTING GLOBAL RADIATIVE FLUXES PRIOR TO 2000

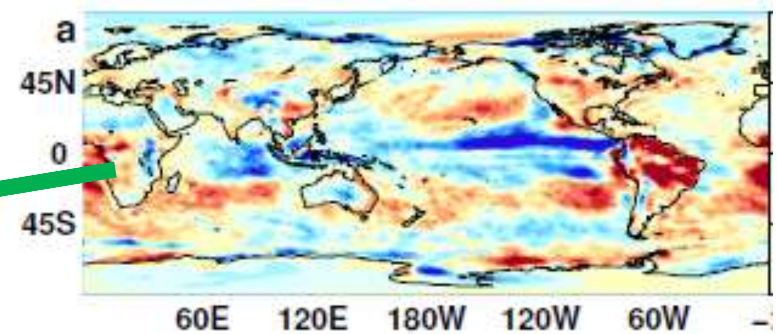
ERBS/CERES variability



CERES monthly climatology



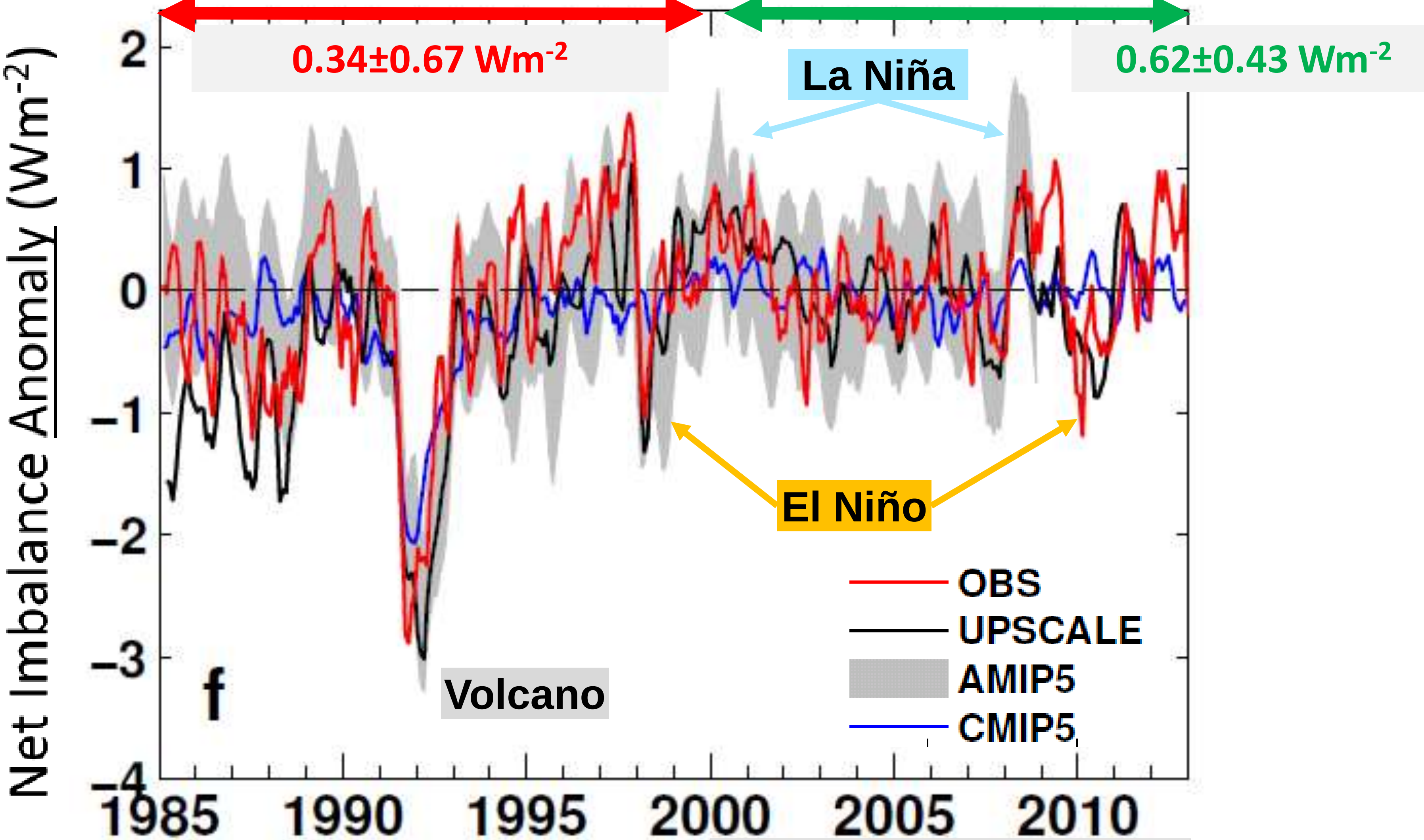
ERA Interim spatial anomalies



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

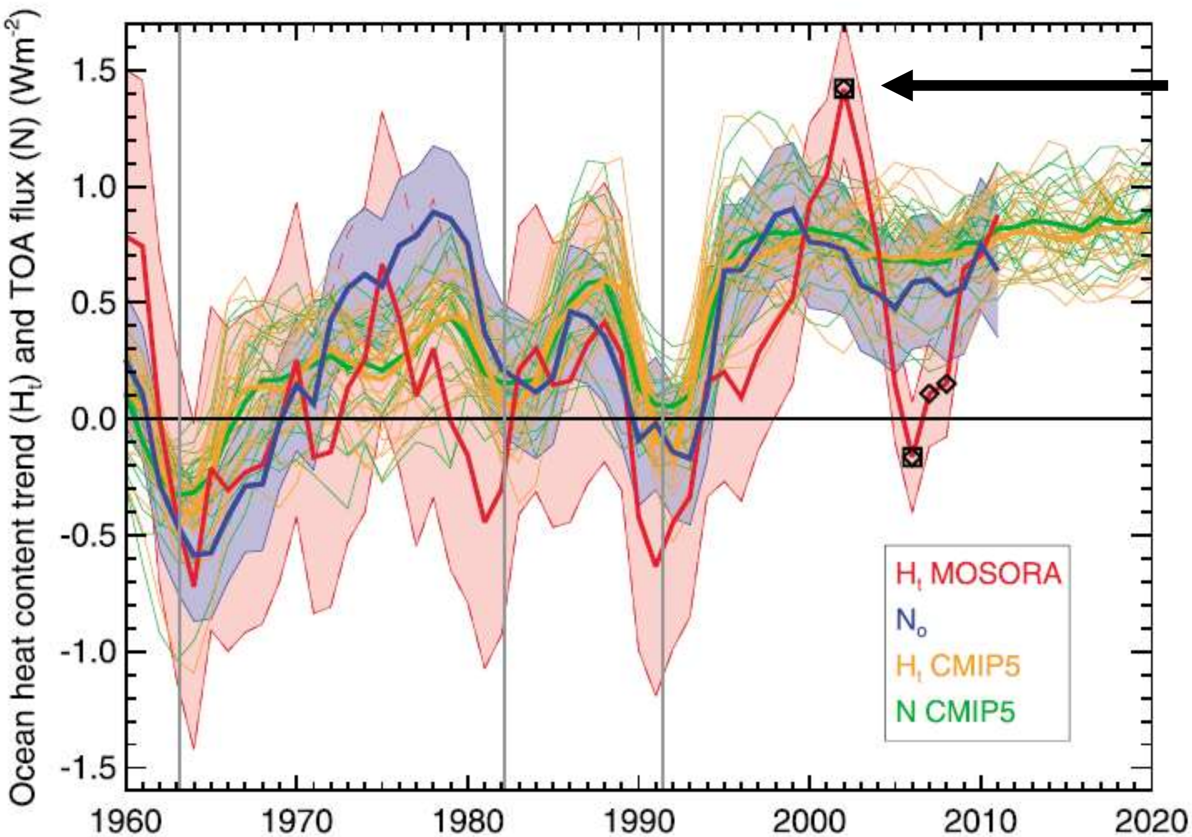
CHANGES IN NET RADIATIVE IMBALANCE

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



Allan et al. (2014) GRL

DISCREPANCY BETWEEN RADIATION BUDGET & OCEAN HEATING

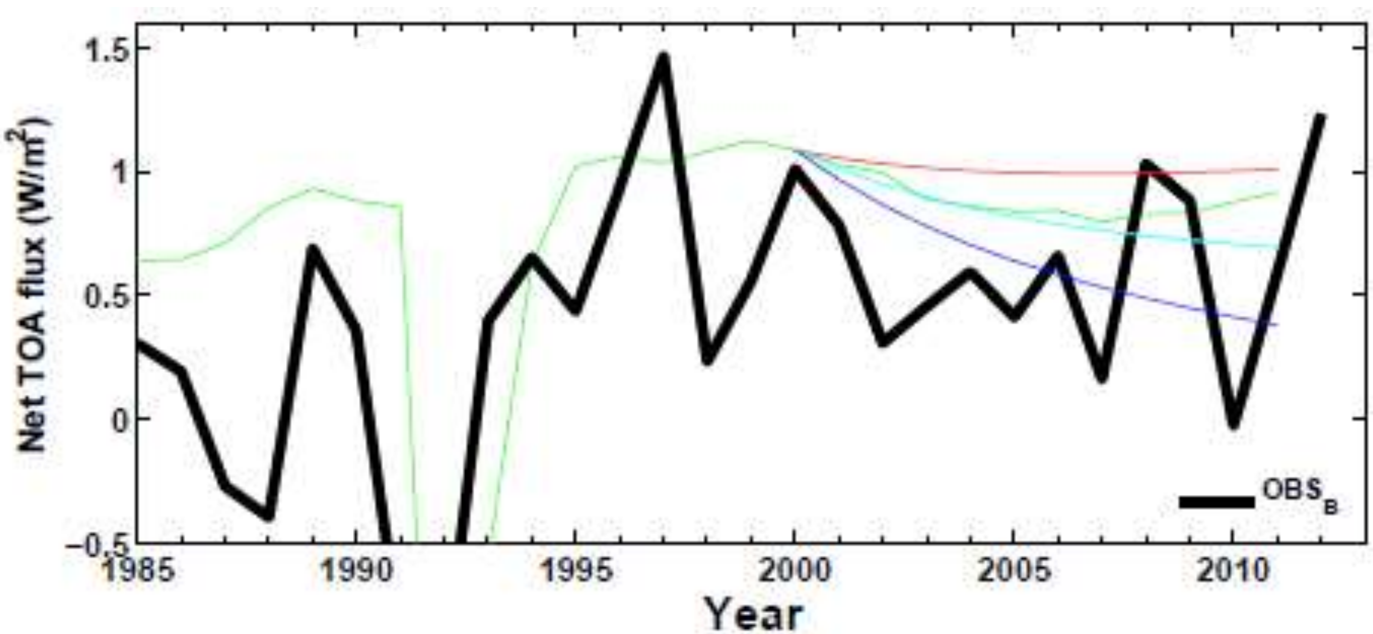


- Large ocean heating anomaly in 2002
- Inconsistent with radiation budget observations and simulations
- Changing observing system influence?
- Slight drop in net flux 1999-2005?

Smith et al. (2015) GRL

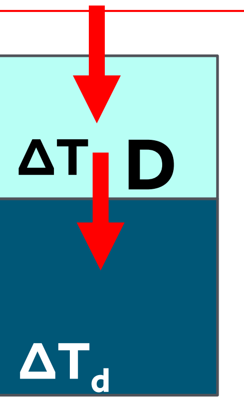
UNDERSTANDING CHANGES IN NET IMBALANCE

N



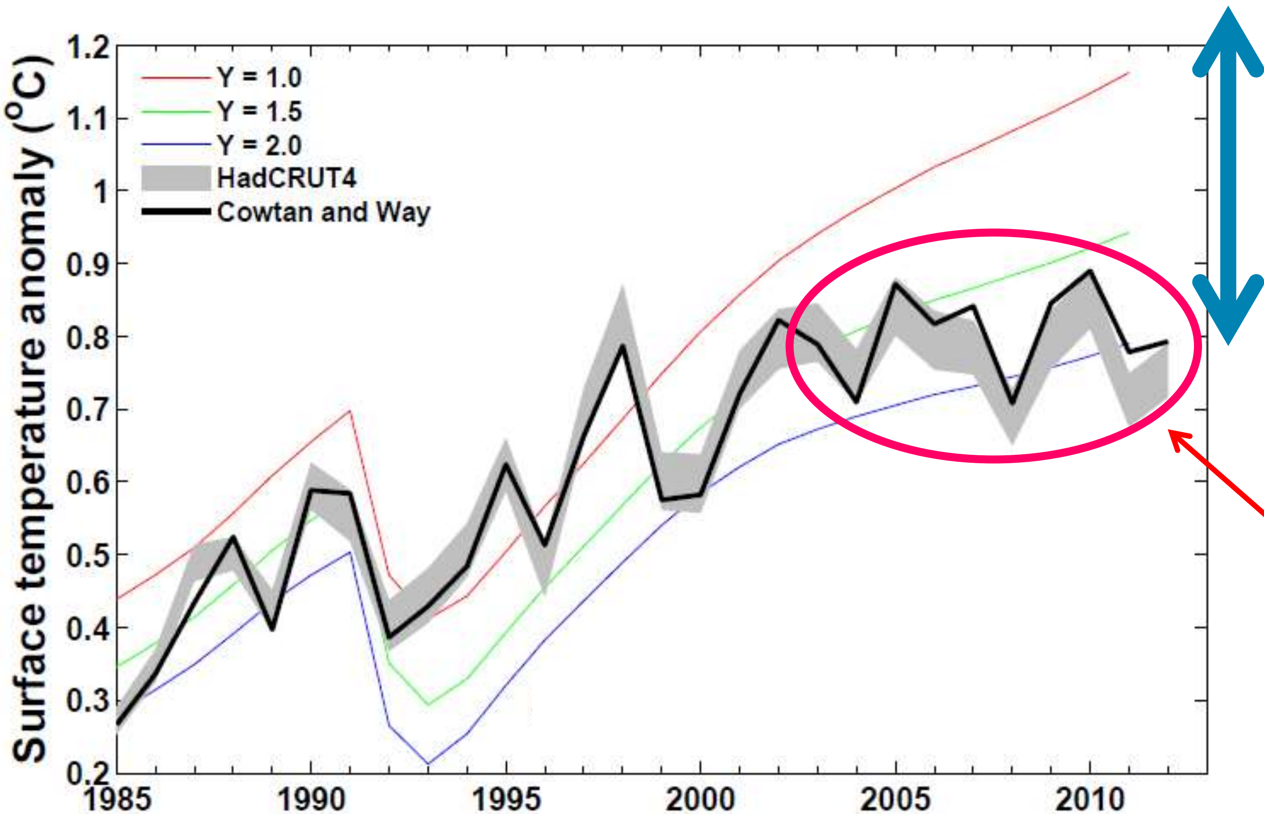
+ve RF trend
AR5 RF
0 RF trend
-ve RF trend

$\boxed{N=\Delta F-Y\Delta T}$



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

IMPLICATIONS FOR CLIMATE SENSITIVITY?

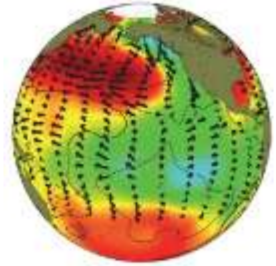


Allan et al. (2014) GRL supplementary

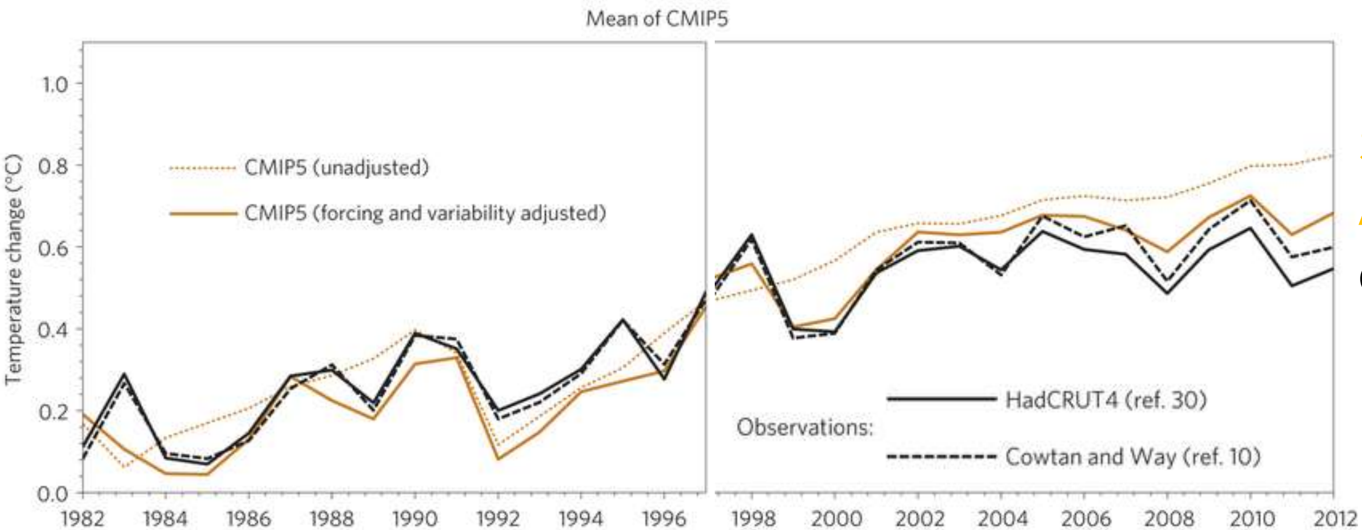
?Can comparisons tell us about how sensitive climate is to radiative forcing Otto et al. (2013) Nature Geosci

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

EXPLAINING THE SLOWDOWN



- Declining solar forcing (e.g. [Hansen et al. 2013 PLOSONE]) , more small volcanos (e.g. [Ridley et al. 2014 GRL]) & more La Niñas/cold NH land in winter vs late 1990s appear to explain:
  - Slowing in surface warming (e.g. [Foster & Rahmstorf 2012)]
  - Slower surface warming compared with coupled simulations (e.g. [Risbey et al. 2014] ; [Huber & Knutti 2014])



Simulations

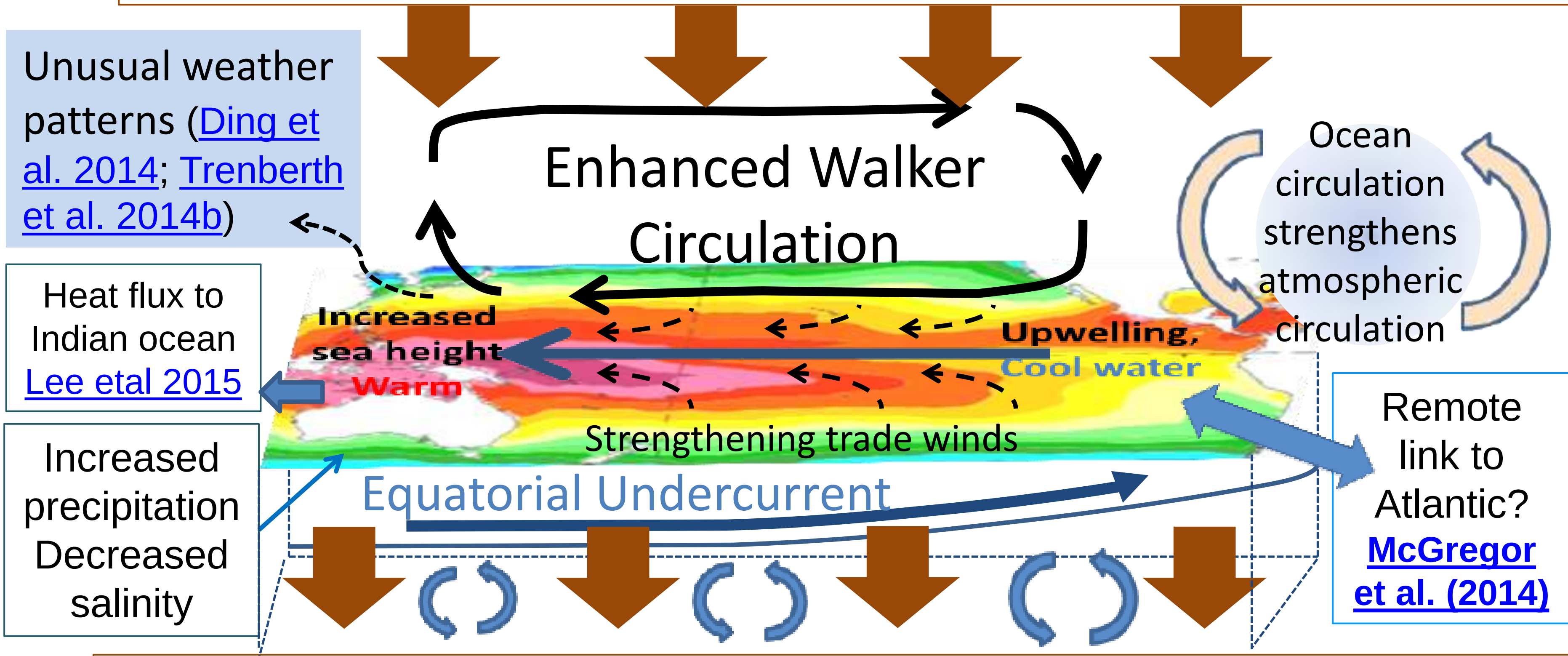
Adjusted Simulations

Observations

Huber & Knutti 2014

Role of Pacific Ocean Variability

Continued heating from rising greenhouse gas concentrations



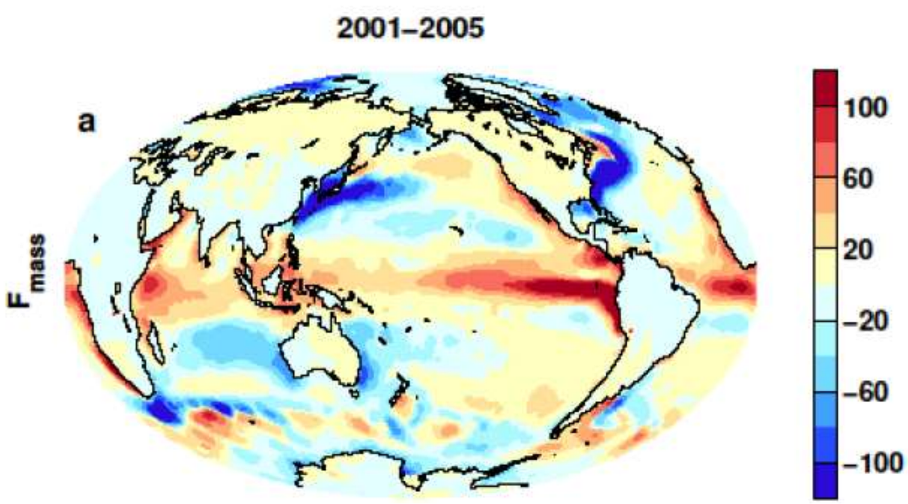
Enhanced mixing of heat below 100 metres depth by accelerating shallow overturning cells and equatorial undercurrent

See: Merrifield (2010) J. Clim.; Sohn et al. (2013) Clim. Dyn.; L'Heureux et al. (2013) Nature Clim. Change; Kosaka and Xie (2013) Nature; England et al. (2014) Nature Clim. Change; Watanabe et al. 2014 Nature Clim. Change; Balmaseda et al. (2013) GRL; Trenberth et al. (2014) J. Clim.

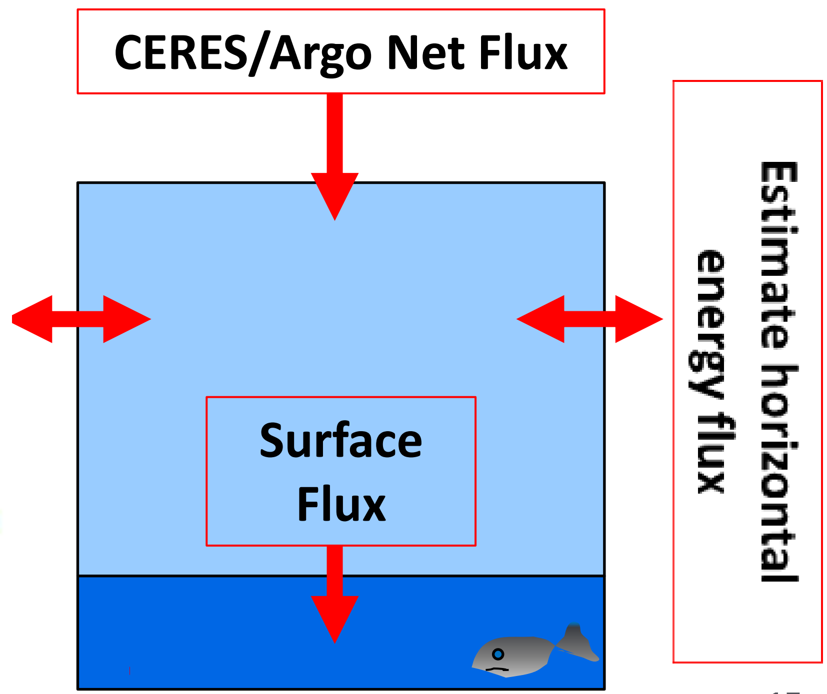
WHERE IS THE HEAT GOING?

NEW ESTIMATES OF SURFACE ENERGY FLUX

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

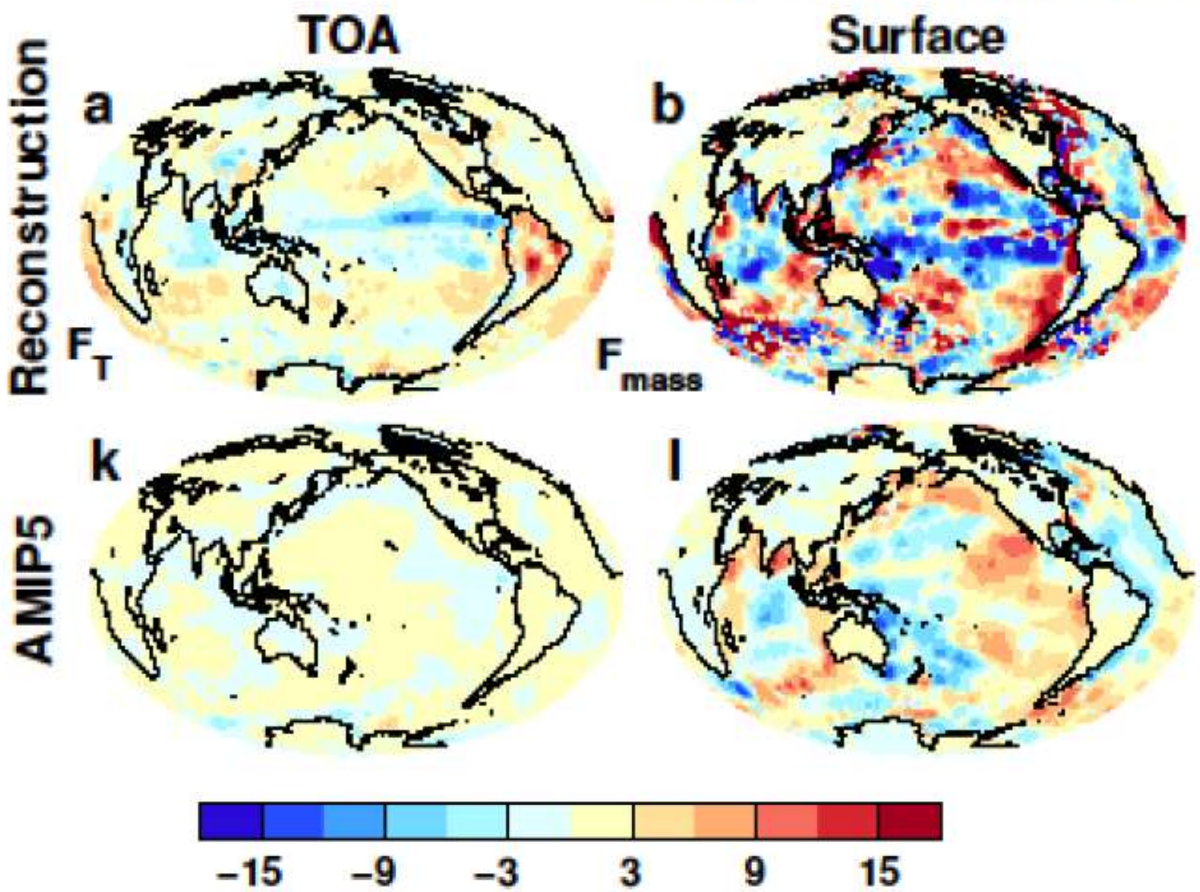


Net surface downward energy flux (Wm^{-2})
Liu et al. (2015) in prep



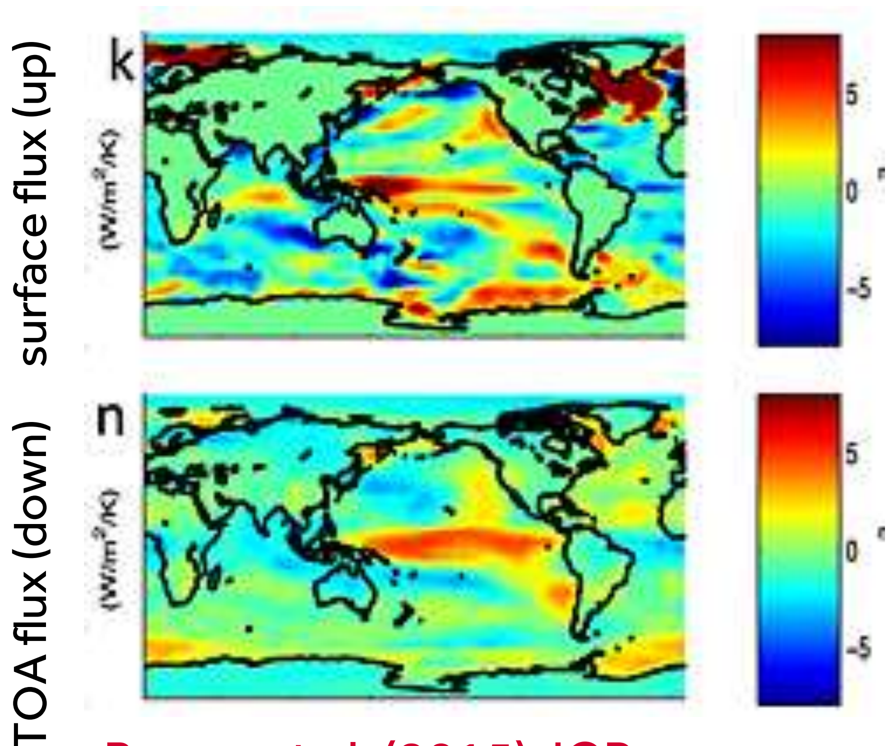
WHERE IS THE HEAT GOING?

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?

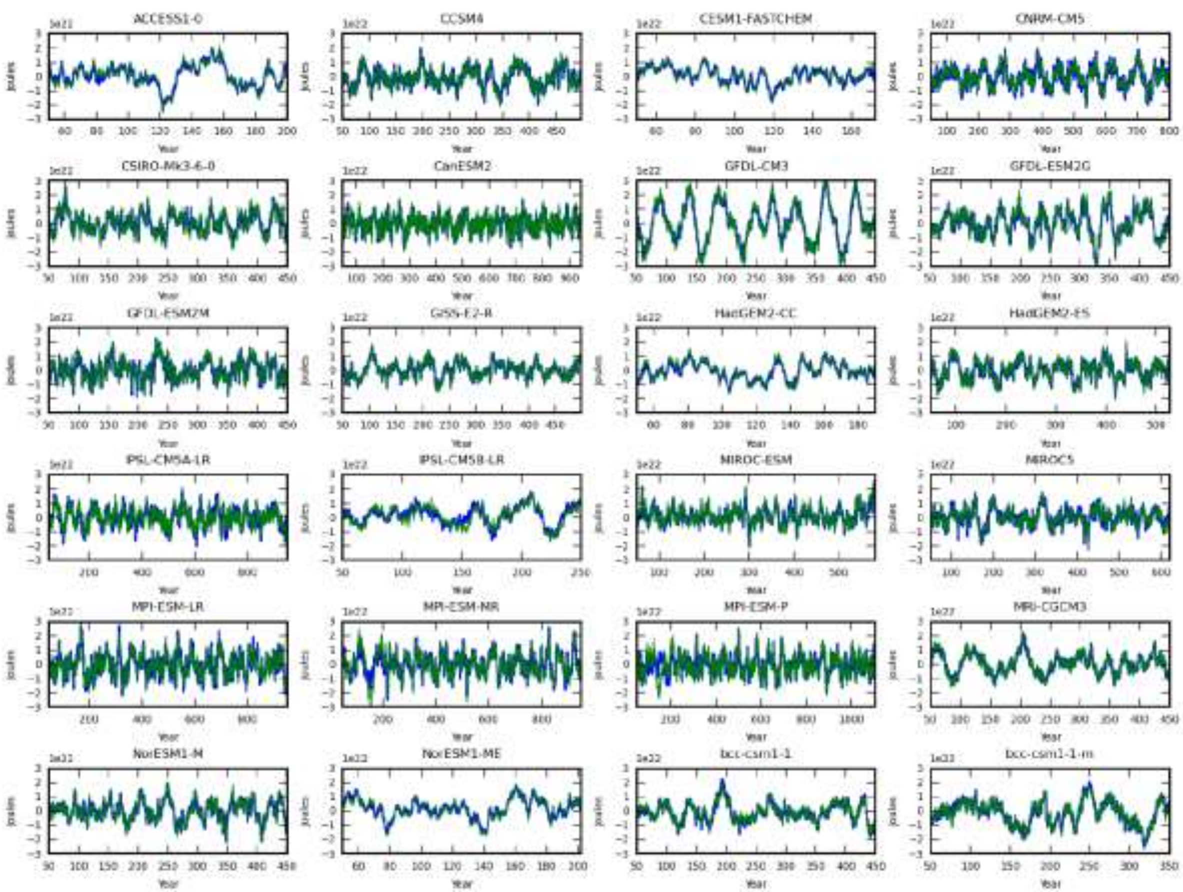


Brown et al. (2015) JGR

← **top:** 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?

UNFORCED VARIABILITY IN EARTH'S ENERGY BUDGET

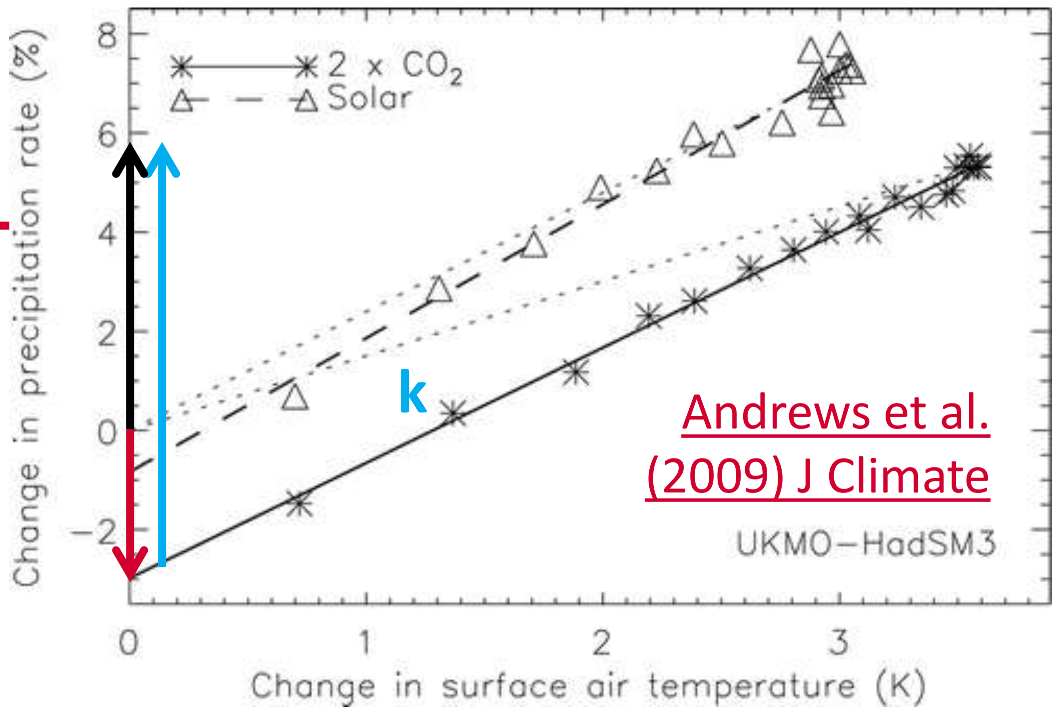


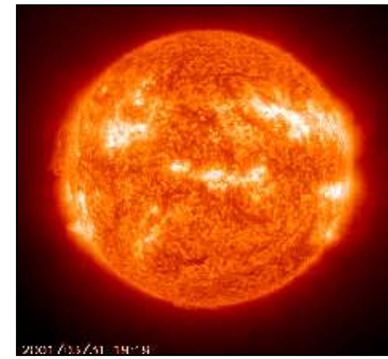
- Diverse range of unforced variability in CMIP5 pre-industrial control simulations
- **Left:** variations in total energy content of Earth's climate system across CMIP5 simulations

Palmer & McNeall (2014) ERL

EARTH'S ENERGY BUDGET AND PRECIPITATION RESPONSE

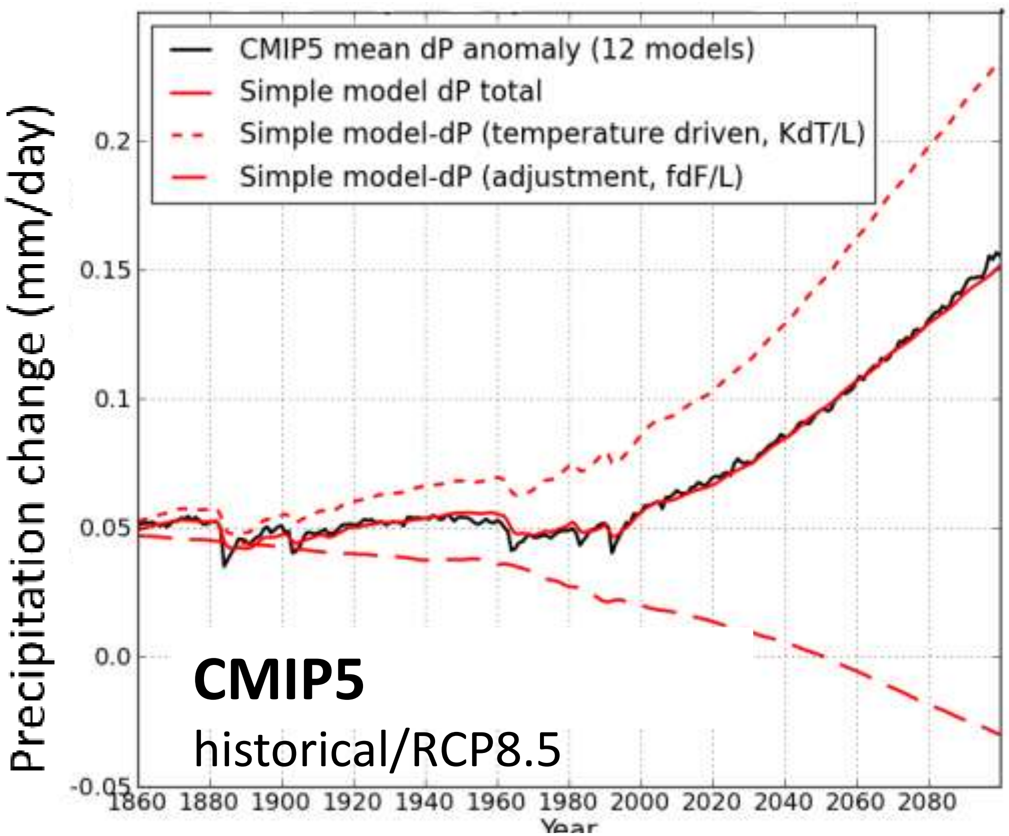
$$L\Delta P \approx k\Delta T - f_F\Delta F$$





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

SIMPLE MODEL FOR GLOBAL PRECIPITATION

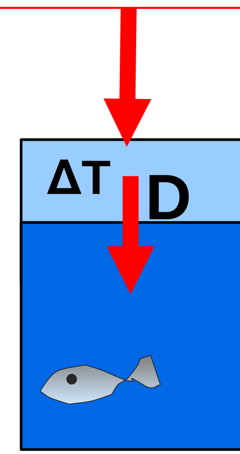


Using simple model:

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

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

$$\boxed{N = \Delta F - Y\Delta T}$$

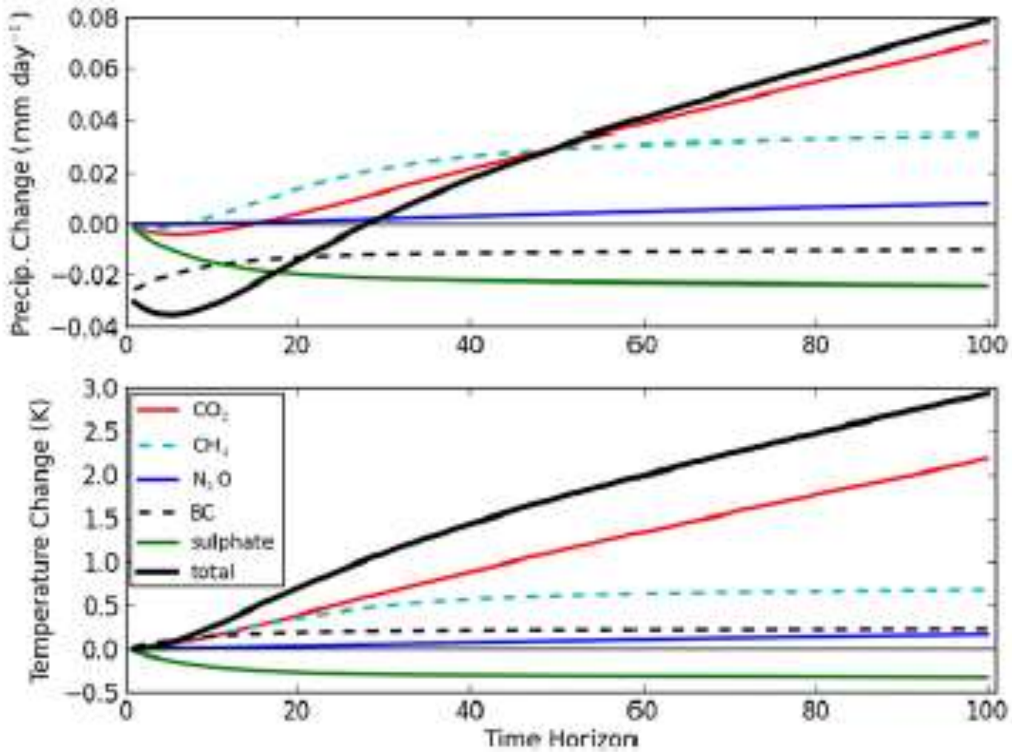


$$D = c(\Delta T_m - \Delta T_D)/d$$

Zahra Mousavi
(PhD project)

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

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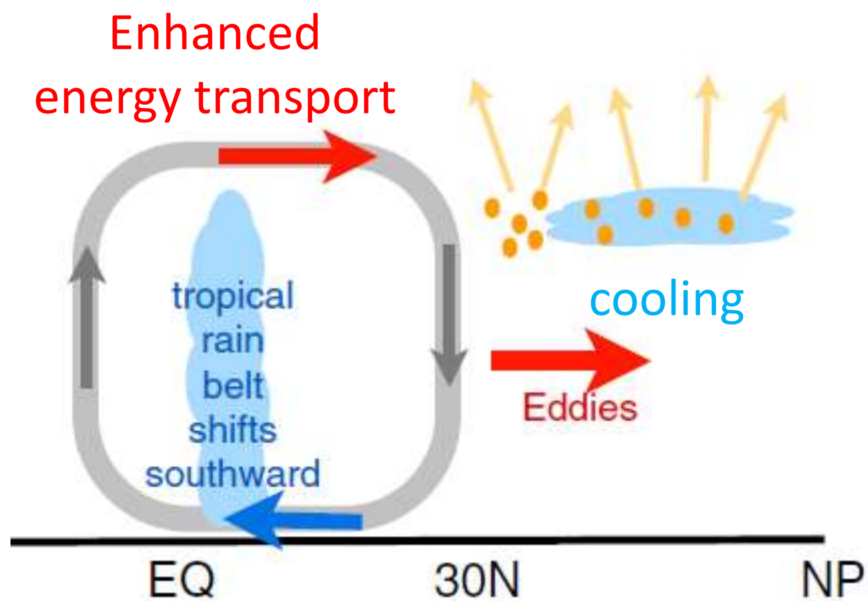
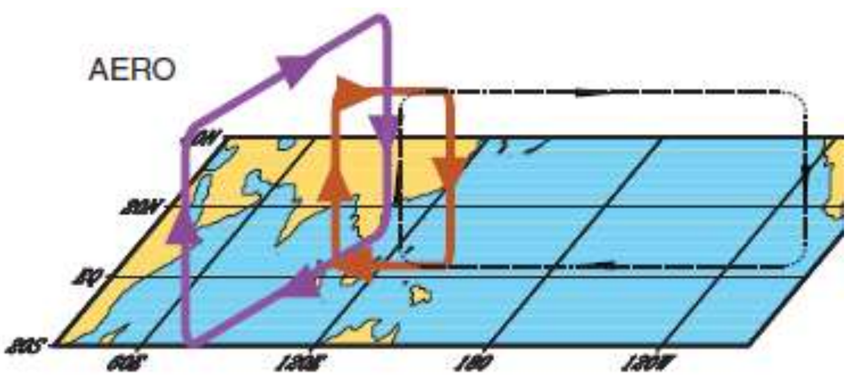
- Regional precipitation changes sensitive to asymmetries in Earth's energy budget
- N. Hemisphere cooling: stronger heat transport into hemisphere
- Reduced Sahel rainfall from:
  - Anthropogenic aerosol cooling 1950-1980s: Hwang et al. (2013) GRL →
  - Asymmetric volcanic forcing e.g. Haywood et al.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

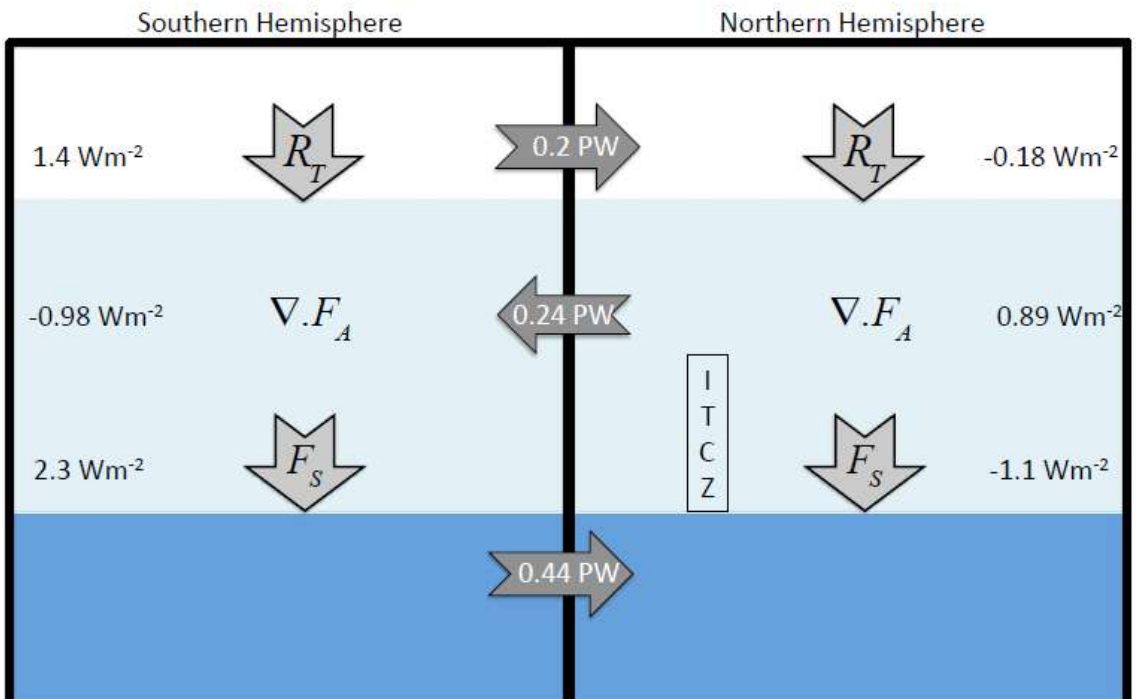




- Sulphate aerosol effects on Asian monsoon e.g. Bollasina et al. 2011 Science (left)
- Links to drought in Horn of Africa? Park et al. (2011) Clim Dyn
- GHGs & Sahel rainfall recovery?

Dong & Sutton (2015) Nature Clim.

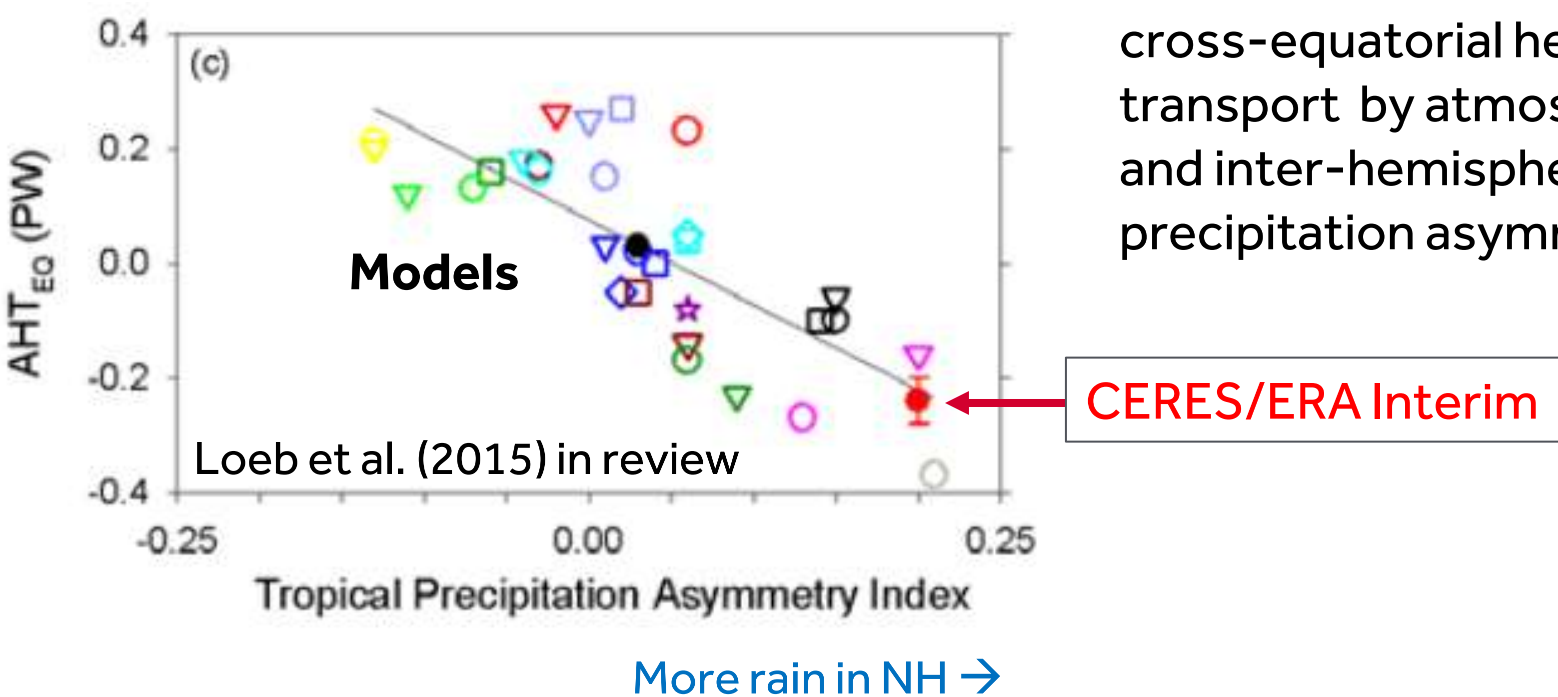
OBSERVED ASYMMETRY IN EARTH'S ENERGY BUDGET



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)

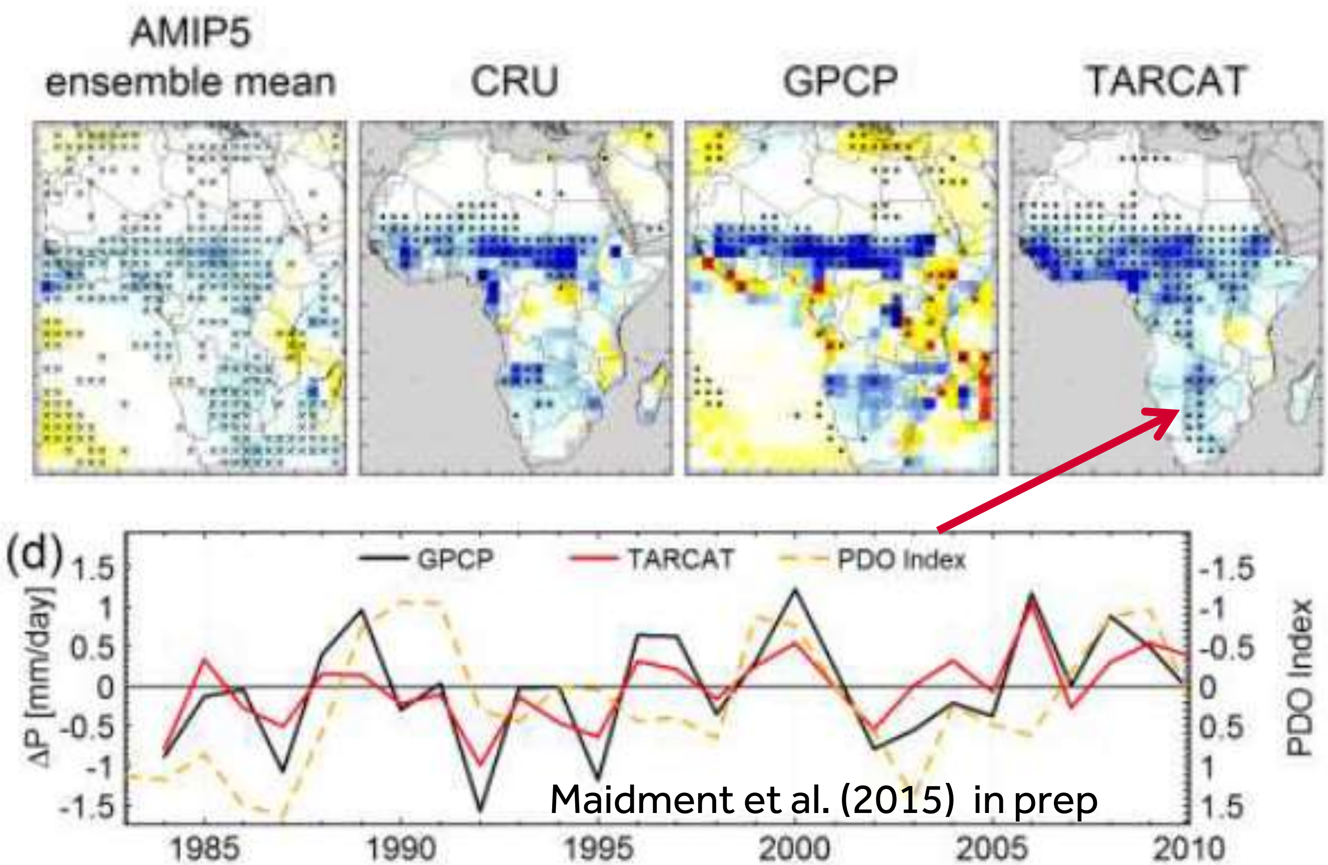
EQUATORIAL HEAT TRANSPORT AND MODEL PRECIPITATION BIAS



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

RECENT TRENDS IN AFRICA RAINFALL

- Evaluating and understanding recent changes in Africa rainfall [Maidment et al. (2014) JGR]
- PhD project extending this work: impact-relevant metrics for Africa (Caroline Dunning)



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FUTURE WORK

- Time-scales associated with net imbalance (Harries & Futyan 2006 GRL)
- Can we reconcile ocean heating and top of atmosphere imbalance?
- Observational constraint on radiative feedbacks & climate sensitivity
- What controls decadal variability: “hiatus” and “surge” events?
- Feedbacks associated with unforced variability
  - Cloud and latent heat fluxes in the Pacific e.g. Brown et al. 2014 GRL
- Do patterned radiative forcings force distinct feedback responses?
- To what extent does inter-hemispheric imbalance control rainfall patterns? e.g. Hwang et al. (2012) GRL