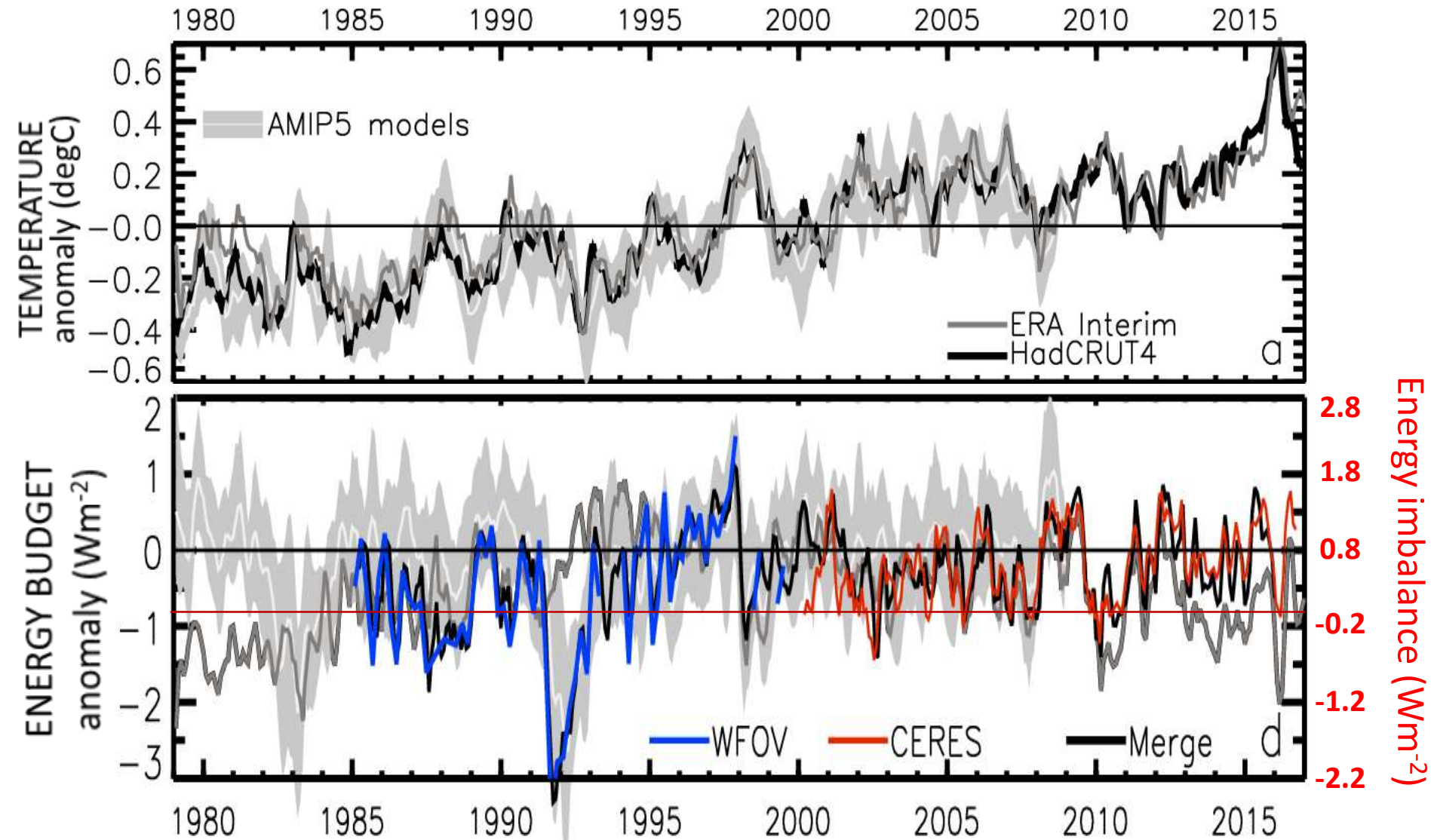


# Current changes in Earth's energy budget

**Richard Allan, Chunlei Liu - University of Reading**

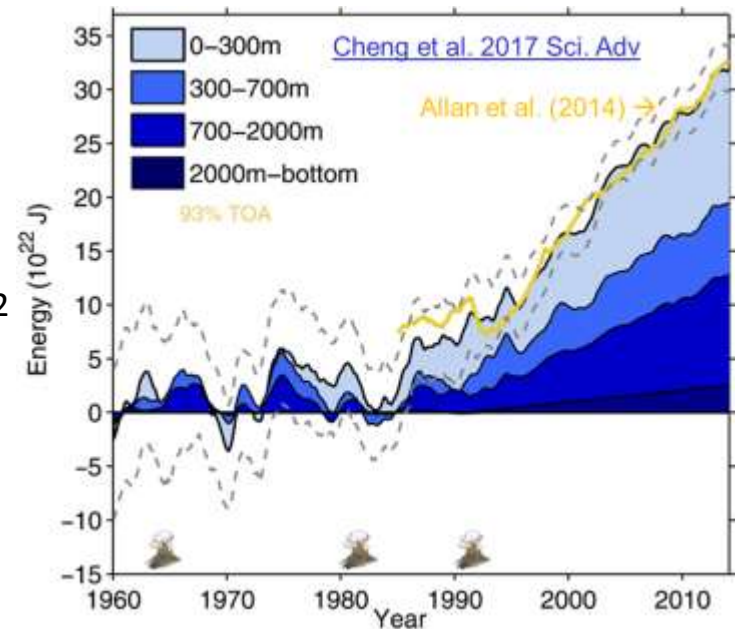
*SMURPHS meeting NOCS, May 2017*

# Variations in Earth's energy imbalance & surface temperature since 1980s



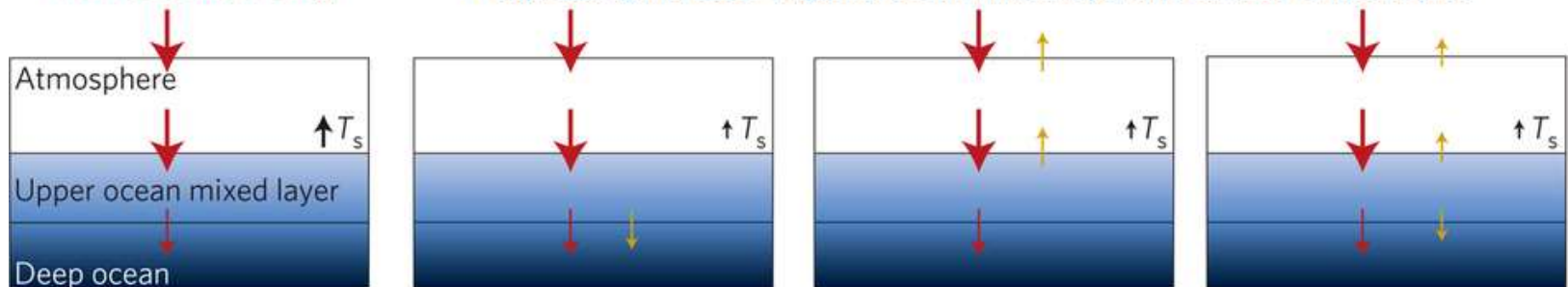
# Improved global energy imbalance estimates

- More accurate global imbalance from ocean and satellite observations: [Cheng et al. 2017](#):
- Observed variability 1985-2016 explained by SST and radiative forcing ([Allan et al. 2014](#))
- Steady ocean heating since 2000:  $0.6\text{-}0.8\text{Wm}^{-2}$  ([Johnson et al. 2016](#); [Trenberth et al. \(2016\) J Clim](#))
- Radiative forcing/internal variability influence TOA radiation ([Palmer & McNeall 2014](#); [Huber/Knutti 2014](#); [Xie/Kosaka 2017](#))
- Upper ocean heat budget explains surface temperature: [Hedemann et al. 2017 NatureCC](#)



Net energy accumulation from radiative forcing

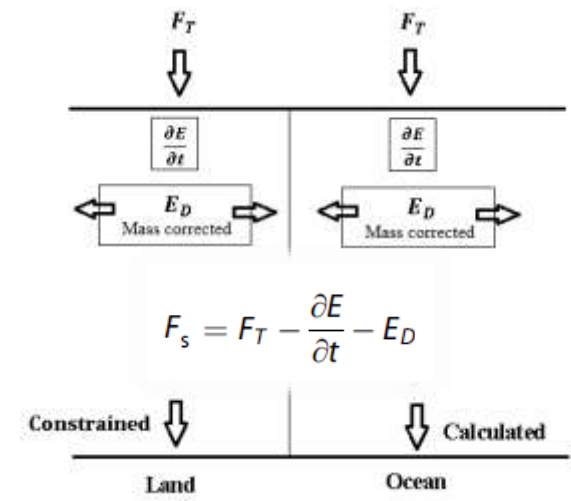
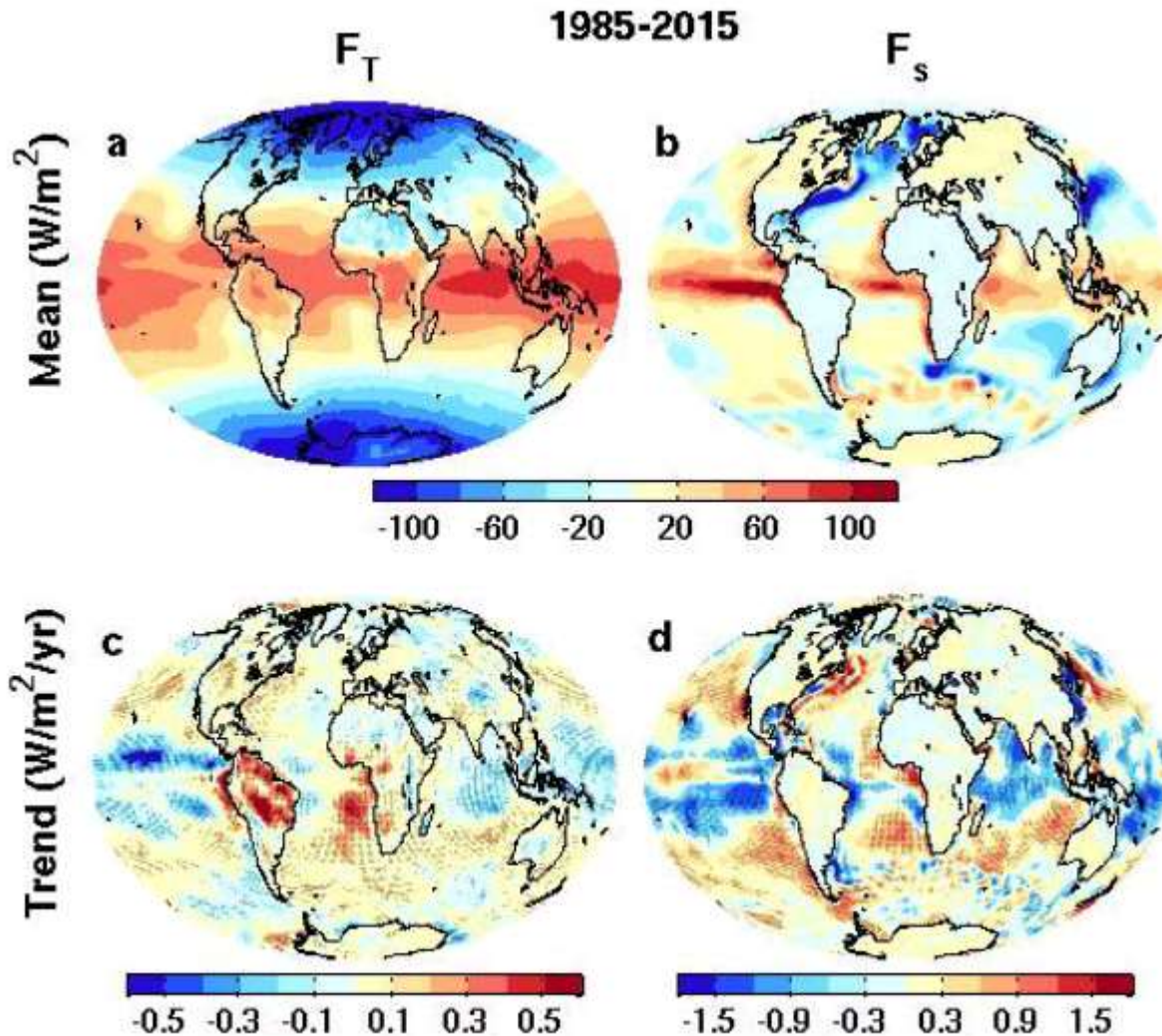
Unforced climate fluctuation alters energy budget of the upper ocean mixed layer, suppressing increases in global ocean mixed layer and surface temperatures



[Allan \(2017\) Nature Climate Change](#)

# Surface/TOA energy fluxes & trends

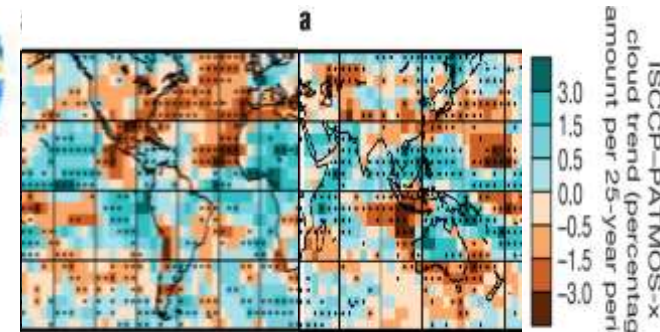
top of atmosphere      surface



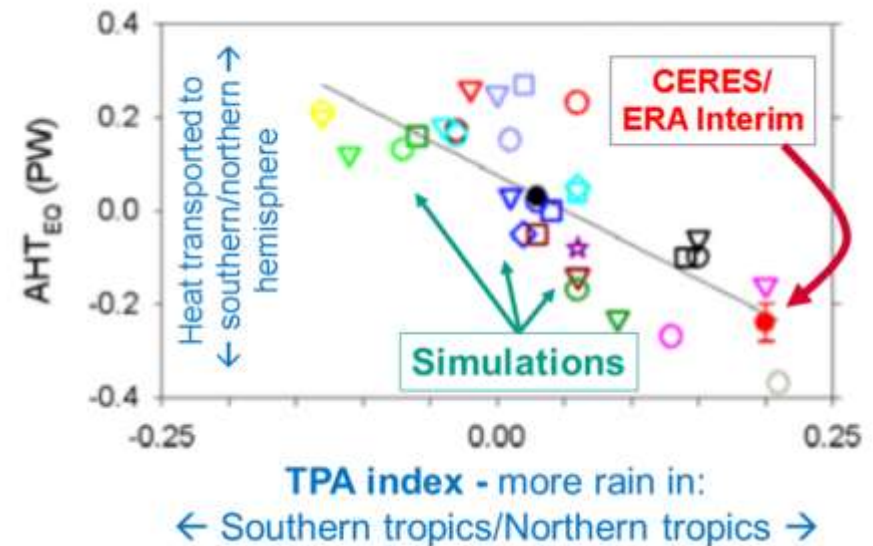
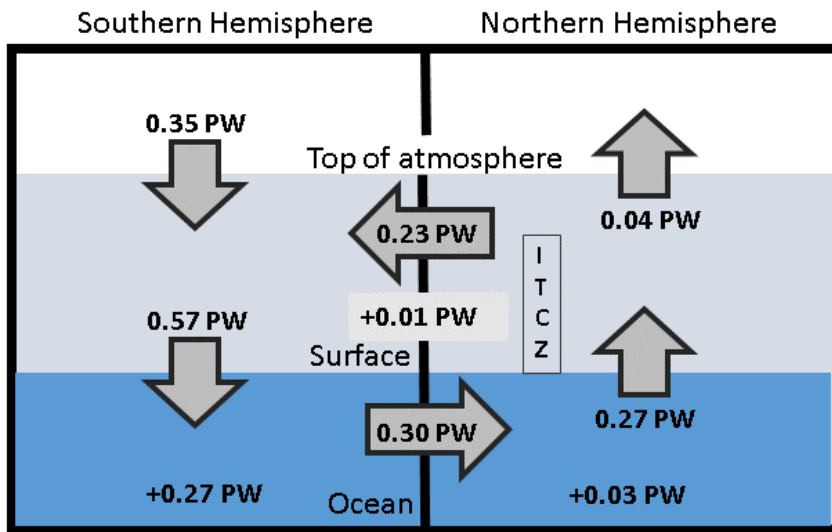
Surface energy flux [dataset](#) combining TOA reconstruction with reanalysis energy transports: [Liu et al. \(2015\) JGR](#)

Liu et al. (2017) submitted to JGR  
 Data: <http://dx.doi.org/10.17864/1947.111>

[Norris et al \(2016\) Nature](#)  
*Changes in cloudiness*



# Inter-hemispheric energy imbalance/transport and precipitation biases in CMIP5 models

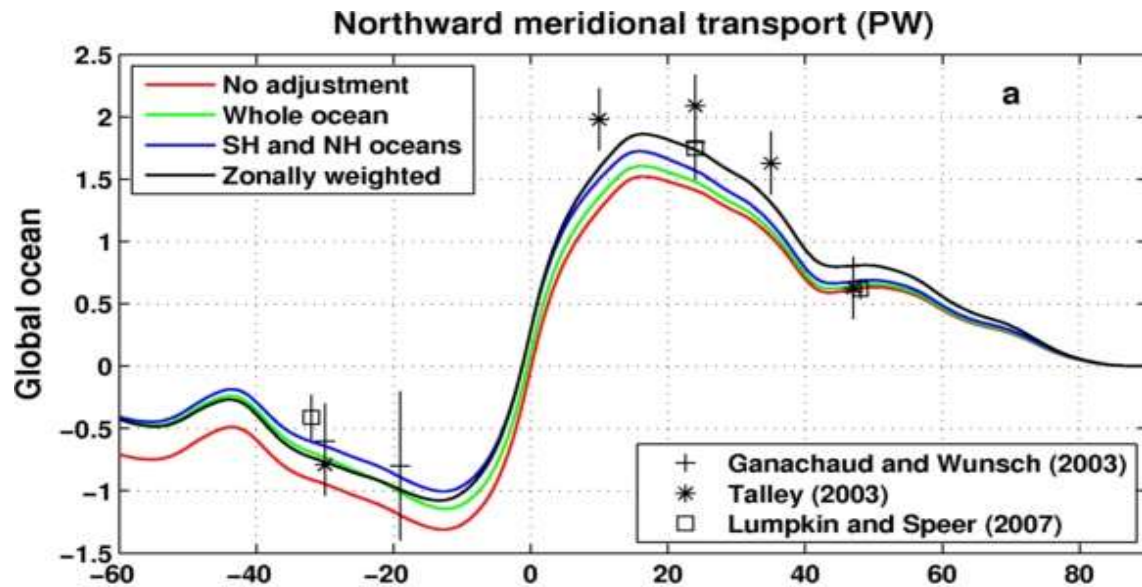


- Observed inter-hemispheric imbalance in Earth's energy budget 2000-15 (Liu et al. **submitted** update of [Loeb et al. \(2016\) Clim. Dyn](#) using [Roemmich et al. \(2015\) Nature Climate](#) ocean heating)
- Implied ocean heat transport less than [Loeb et al. \(2016\)](#) & [Frierson et al. 2013](#)

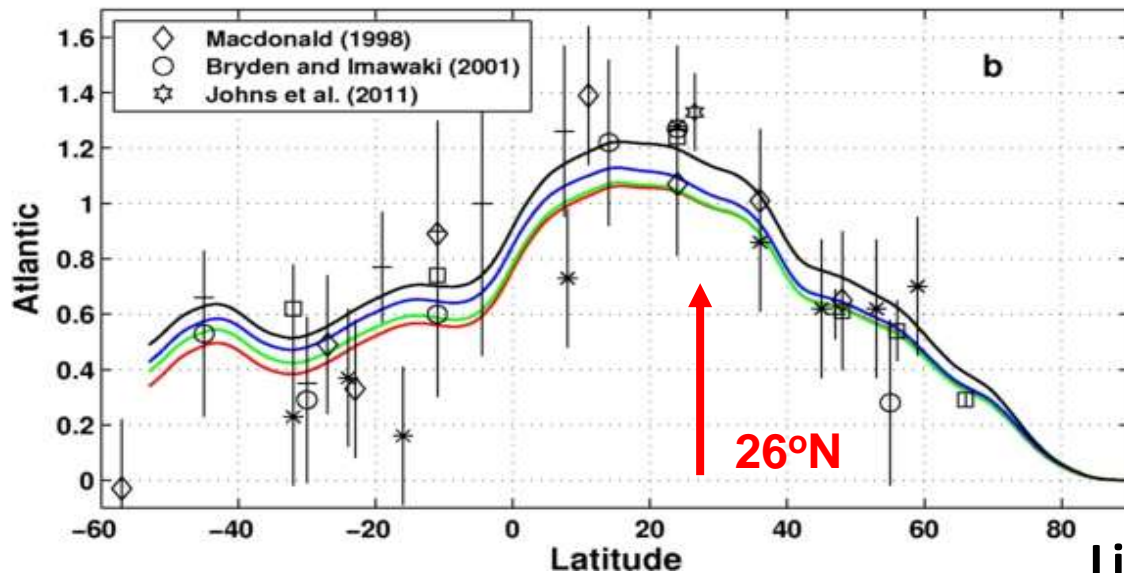
Cross-equatorial heat transport by atmosphere & hemispheric precipitation asymmetry linked [Loeb et al. \(2016\) Clim. Dyn](#)

See also: [Haywood et al. \(2016\) GRL](#); [Hawcroft et al. \(2016\) Clim. Dyn.](#)

# Comparison of Meridional Heat Transport



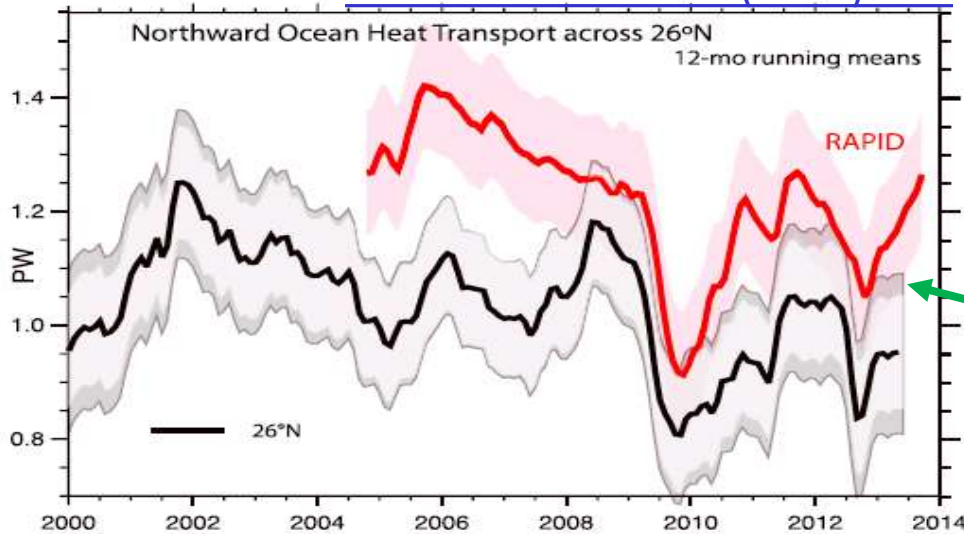
- Inferred from  $F_s$  (Liu et al.) & ocean heating ([Roemmich et al 2015](#)) 2006-2013



- Sensitivity of method to land flux correction

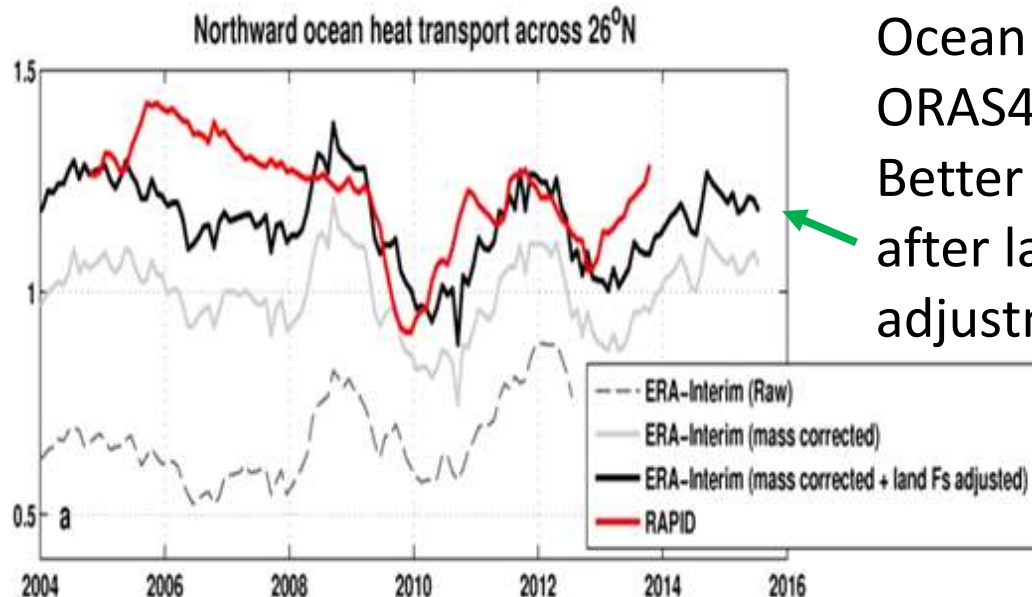
# Inferred ocean heat transport@26°N

Trenberth & Fasullo (2017) GRL



Compare indirect method with RAPID observations

Is [TF2017](#) discrepancy due to lack of land  $F_s$  adjustment?



Ocean heating from ORAS4 (0-700m).  
Better agreement after land  $F_s$  adjustment

2004-2013

RAPID 1.23 PW

TF2017 1.00 PW

Liu et al: 1.16 PW

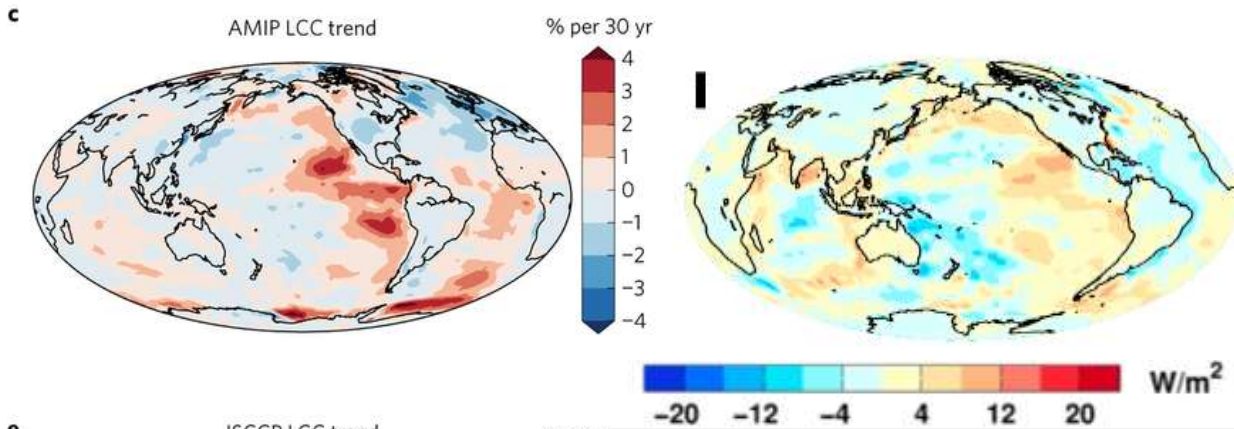
*large uncertainty*

Liu et al. (2017) submitted to JGR

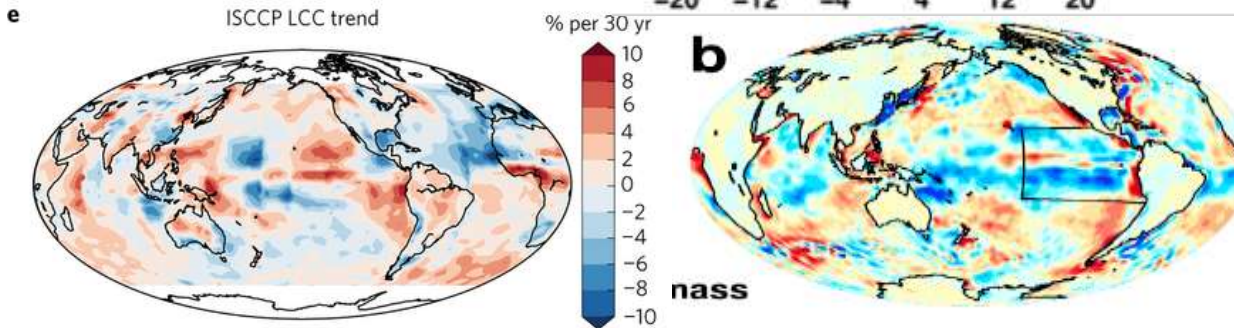
# Feedbacks on internal and forced climate change involving regional energy budget

Low Cloud Cover trend **1980s-2000s** Surface energy flux change

AMIP MODELS



OBSERVATIONS



[Zhou et al. \(2016\) Nature Geosci](#)

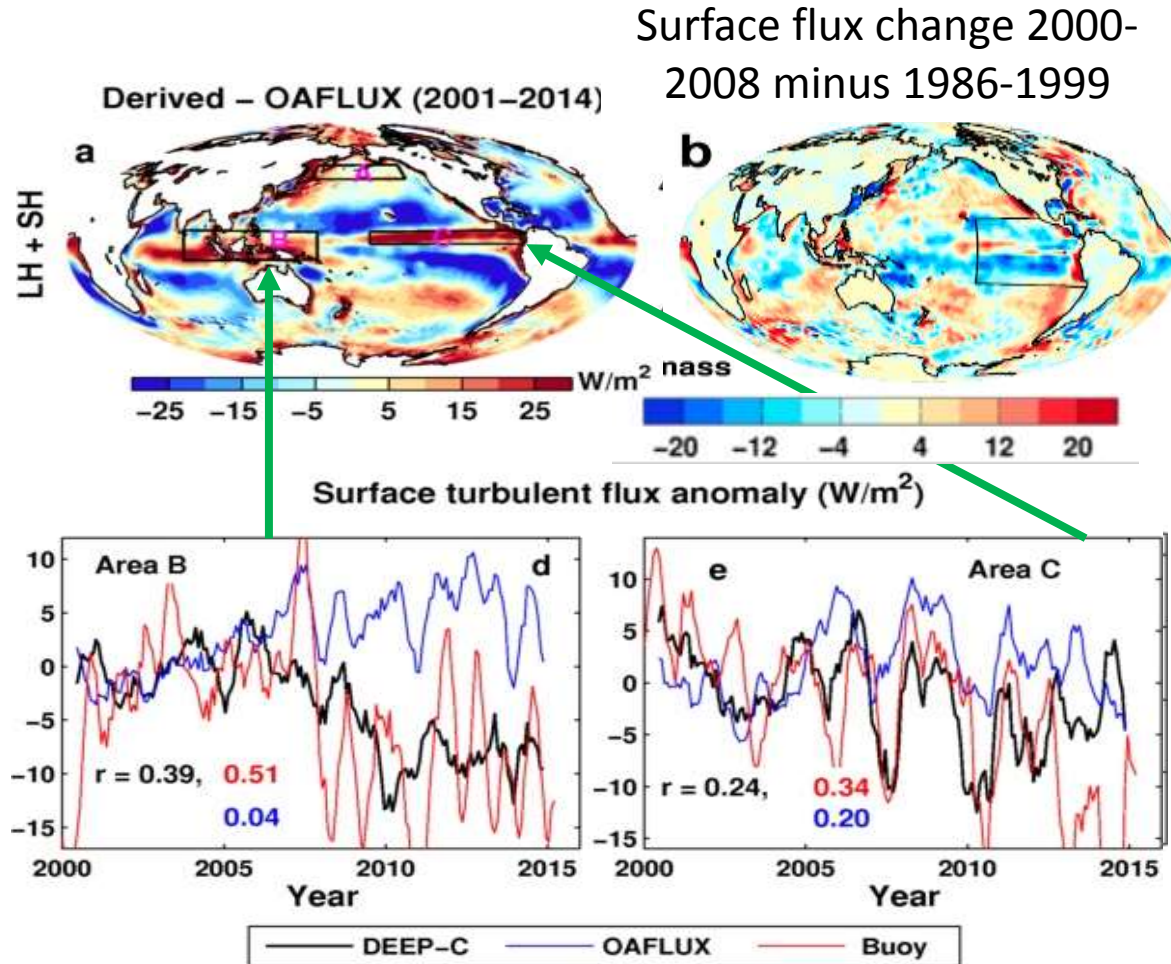
[Liu et al. \(2015\) JGR](#)

Distinct feedbacks on internal variability & forced change e.g. [Brown et al. 2016 J. Clim](#); [Xie et al. 2015 Nature Geosci](#);

Spatial patterns of warming crucial for feedbacks & climate sensitivity e.g. [He & Soden \(2016\) J. Clim](#); [Richardson et al. \(2016\) Nature Clim Change](#); [Gregory & Andrews \(2016\) GRL](#)



# Evaluation of turbulent flux changes



Kato et al (2013) J Clim

CERES



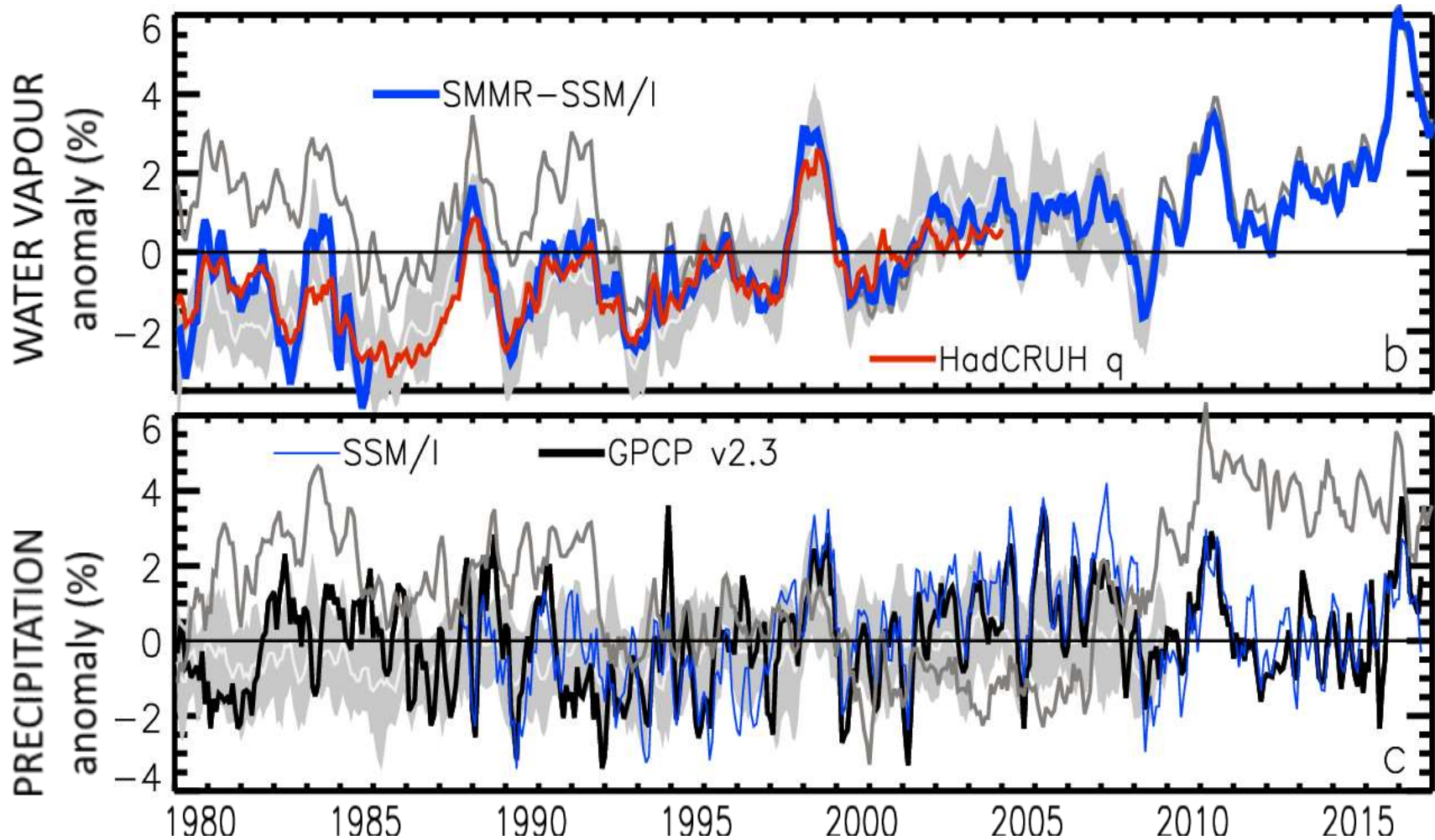
- Turbulent flux:  $F_s - F_{RAD}$
- OAFlux systematically lower (removed)
- Good agreement in anomaly variability
- Buoy data agree better with our product than with OAFlux
- Are trends in reanalysis winds reliable?

# Global energy budget: advances

- More accurate multi-decadal global estimates of Earth's energy budget and its variability (e.g. [Cheng et al. 2017](#) Sci. Adv.; [Allan et al. 2014](#) GRL)
  - Better indicator of global climate change than surface temperature but gaps in observing deep ocean (e.g. [Palmer 2017](#) CCCR)
  - Link to observed cloudiness? e.g. [Norris et al \(2016\) Nature](#)
- Link between energy imbalance and surface warming depends on energy budget of upper mixed ocean layer ([Roberts et al. 2015 JGR](#); [Hedemann et al. 2017](#) Nature Climate Change; [Xie & Kosaka 2017](#) CCCR)
  - Better appreciation of mechanisms of decadal global climate variability
- Distinct feedbacks on internal variability/forced change ([Brown et al. 2016 J. Clim](#); [Xie et al. 2015 Nature Geosci](#); [Zhou et al. \(2016\) Nature Geosci](#))
  - Obs. estimates of climate sensitivity ([Richardson et al. \(2016\) Nature Climate](#))
  - Spatial patterns of warming crucial ([Gregory and Andrews \(2016\) GRL](#))
- Advances in observing/understanding inter-hemispheric energy imbalance/transport and links to CMIP5 precipitation biases ([Frierson et al. 2013](#); [Loeb et al. 2016 Clim. Dyn](#); [Stephens et al. 2016 CCCR](#))
  - Possible constraint on realism of climate models ([Haywood et al. \(2016\) GRL](#))



# Changes in global water cycle



# Role of Atlantic/Pacific Variability?

Radiative Forcing/Imbalance  
[Johnson et al. \(2016\)](#) ; [Checa-Garcia et al. \(2016\)](#) ; [Huber & Knutti \(2014\)](#) ; [Santer et al. \(2015\)](#)

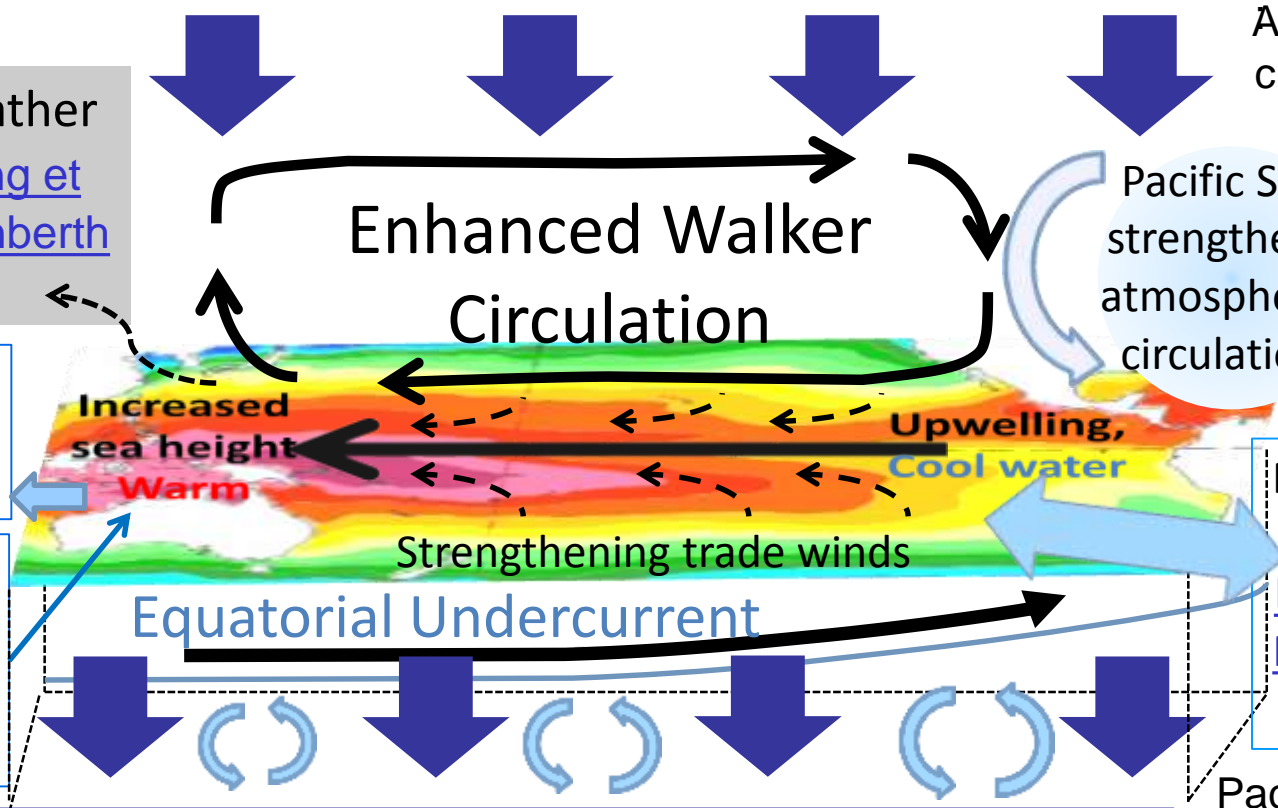
Aerosol forcing of circulation ([Smith et al. 2016](#))

Continued heating from greenhouse gases

Unusual weather patterns ([Ding et al. 2014](#); [Trenberth et al. 2014b](#))

? Heat flux to Indian ocean  
[Lee et al 2015](#)

Increased precipitation  
Decreased salinity



Pacific SST strengthens atmospheric circulation

Remote forcing from Atlantic:  
[Li et al. \(2016\)](#) ;  
[McGregor et al. \(2014\)](#)

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

Pacific dominates?  
[Mann et al. \(2016\)](#)  
[Kosaka & Xie \(2013\)](#)  
[England et al. \(2014\)](#)

See also: [Merrifield \(2010\)](#).; [Sohn et al. \(2013\)](#) .; [L'Heureux et al. \(2013\)](#) . Change; [Watanabe et al. \(2014\)](#) ; [Balmaseda et al. \(2013\)](#) ; [Trenberth et al. \(2014\)](#) .; [Llovel et al. \(2014\)](#) ; [Durack et al. \(2014\)](#) ; [Nieves et al. \(2015\)](#) ; [Brown et al. \(2015\) JGR](#) ; [Somavilla et al. \(2016\)](#) ; [Liu et al. \(2016\)](#)