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EVALUATING BIASES & VARIABILITY IN CLOUDS, PRECIPITATION AND EARTH'S ENERGY BALANCE

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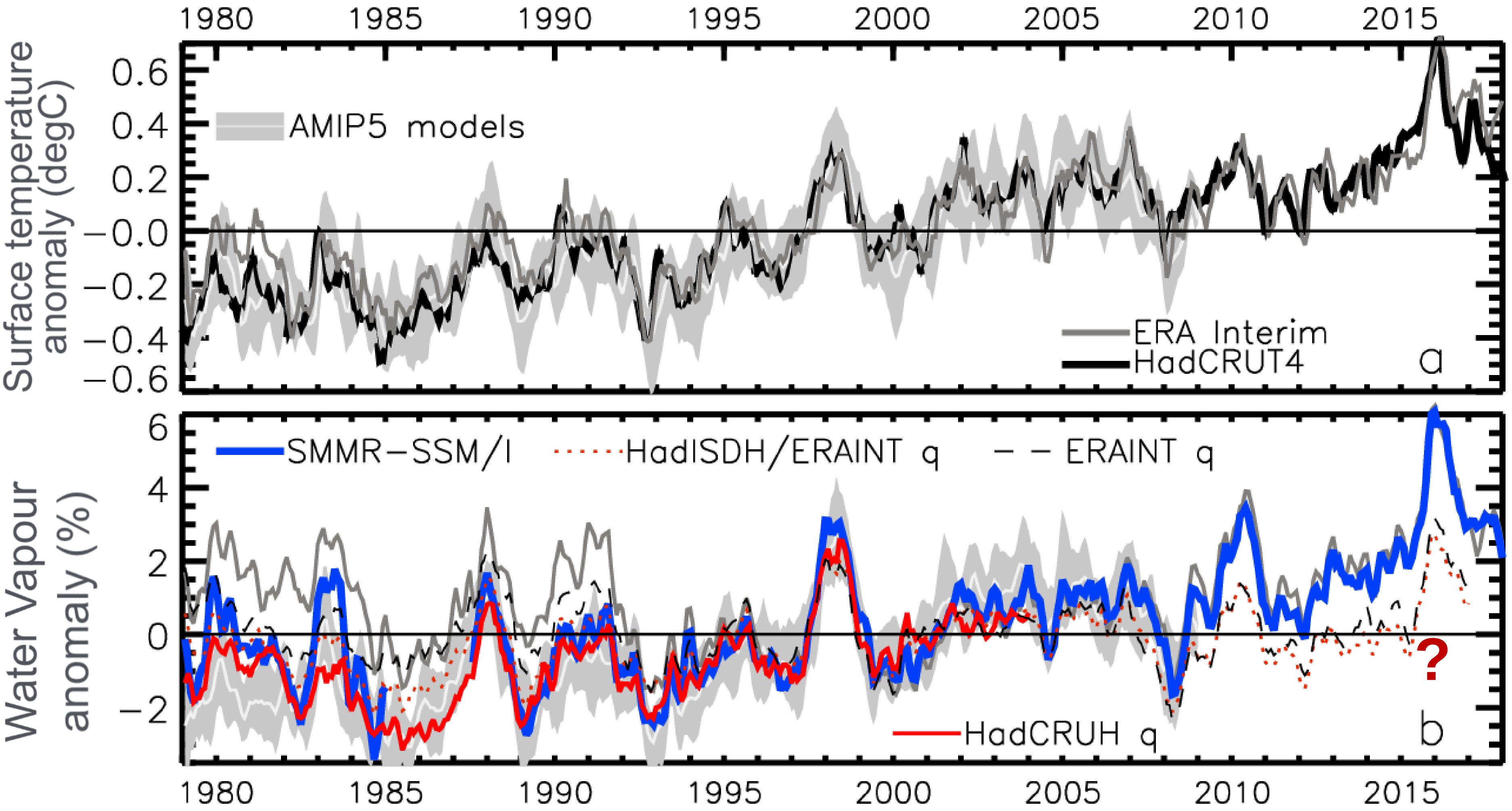
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL

INTRODUCTION

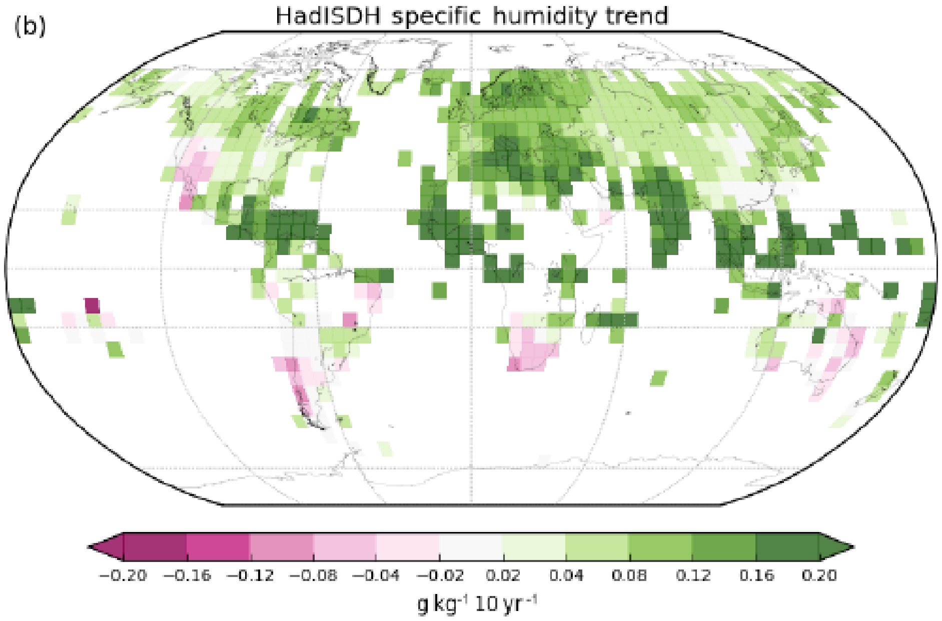
- Greenhouse gas emissions have driven a warming of around 1^{o}C since pre-industrial times; the hydrological cycle is beginning to intensify but global precipitation has barely begun to increase
- Satellite data is vital in assessing recent climate change globally, monitoring ongoing change but also evaluating and helping to improve model processes crucial for future projections (your work is vital!)
- There are simple physical processes determining global and regional responses that can be evaluated with observations
- Different diagnostics are important for the detection of climate change, physical understanding of processes and predicted impacts from regional changes in the water cycle but all are linked

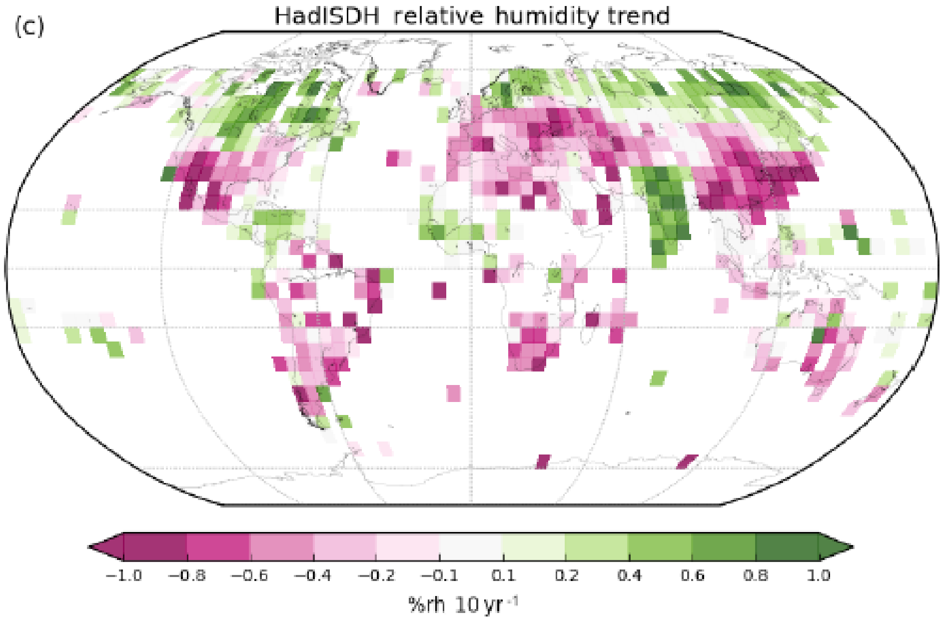
RECENT GLOBAL CLIMATE VARIABILITY



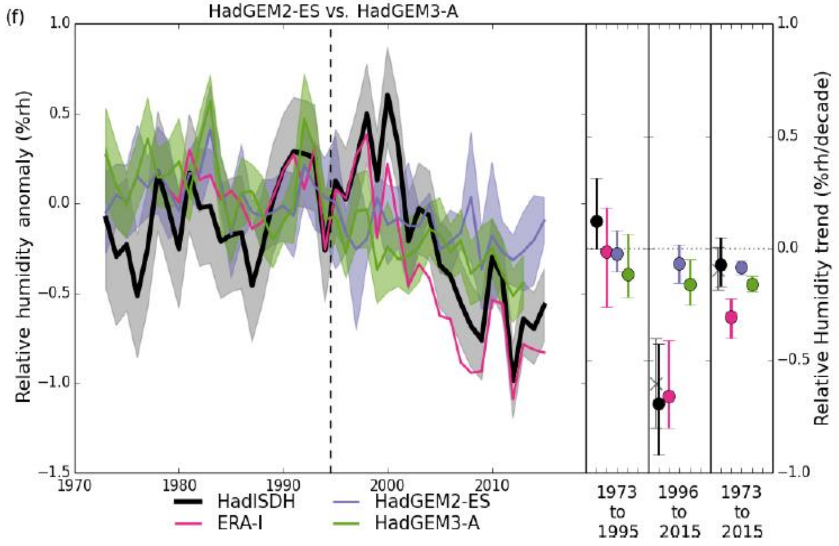
After Allan et al.(2014) Surv. Geophys; land humidity, see Willett et al. (2014) Clim. Past
UTH changes, see John et al. (2017) in BAMS state of climate

NEAR SURFACE HUMIDITY TRENDS



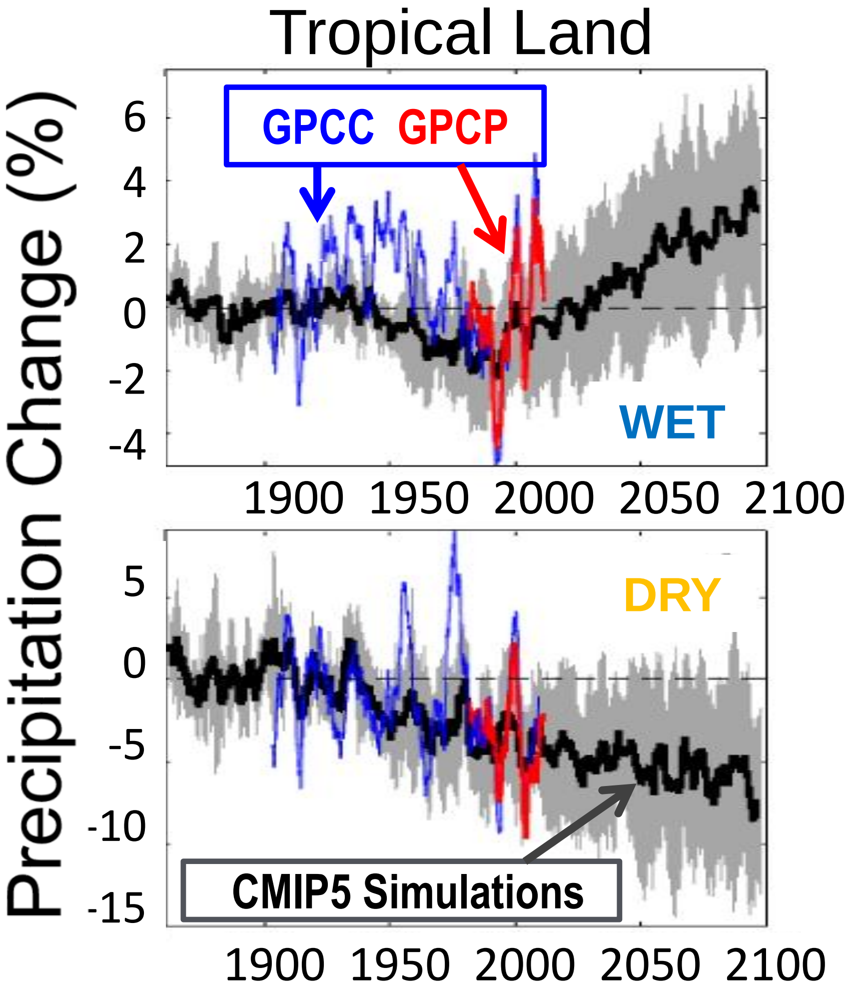


- HadISD specific and relative humidity trends (Dunn et al. 2017 ESD)
- Declining RH over land since ~2000.
- Not captured by CMIP5 simulations but is when models forced with SST
- Explained by land/sea warming contrast: O'Gorman & Byrne (2018) PNAS



MOISTURE TRANSPORT AND INTENSIFICATION OF WET/DRY SEASONS

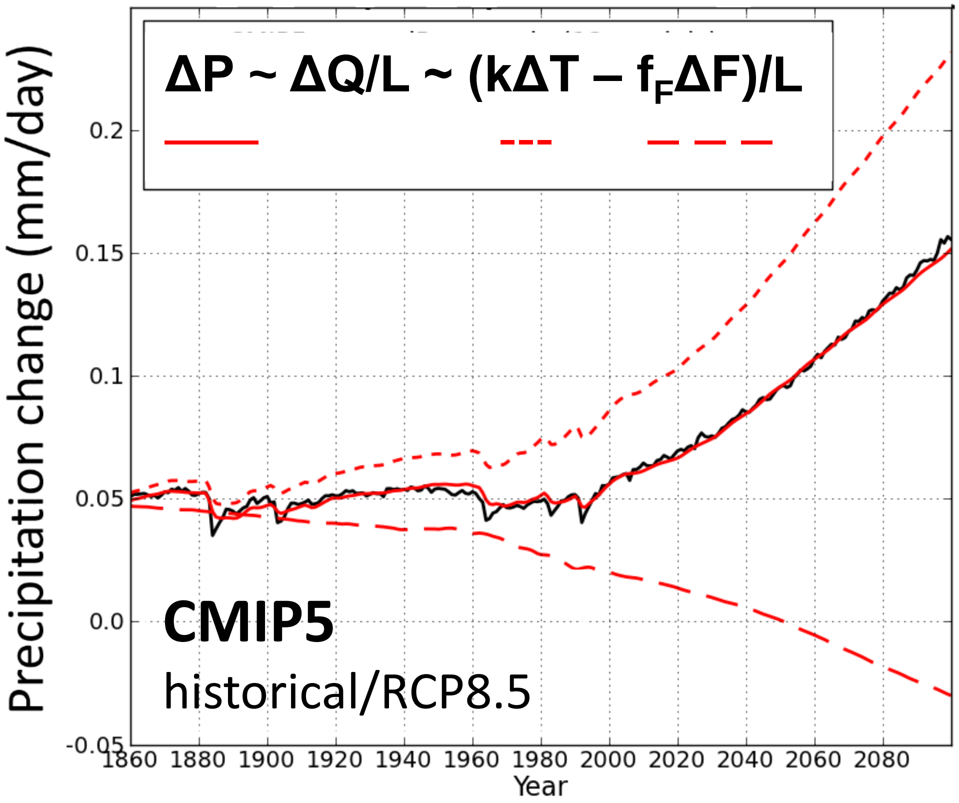
- Increased moisture with warming implies amplified P-E (e.g. Held & Soden 2006) & more moisture transport: dry→wet regimes
- Multi-annual P-E > 0 over land implies increased P-E (e.g. Greve et al. 2014)
- Changes in T/RH gradients also important (Byrne & O'Gorman 2015)
- P-E < 0 in dry season over land: 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 ; Milly & Dunne 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

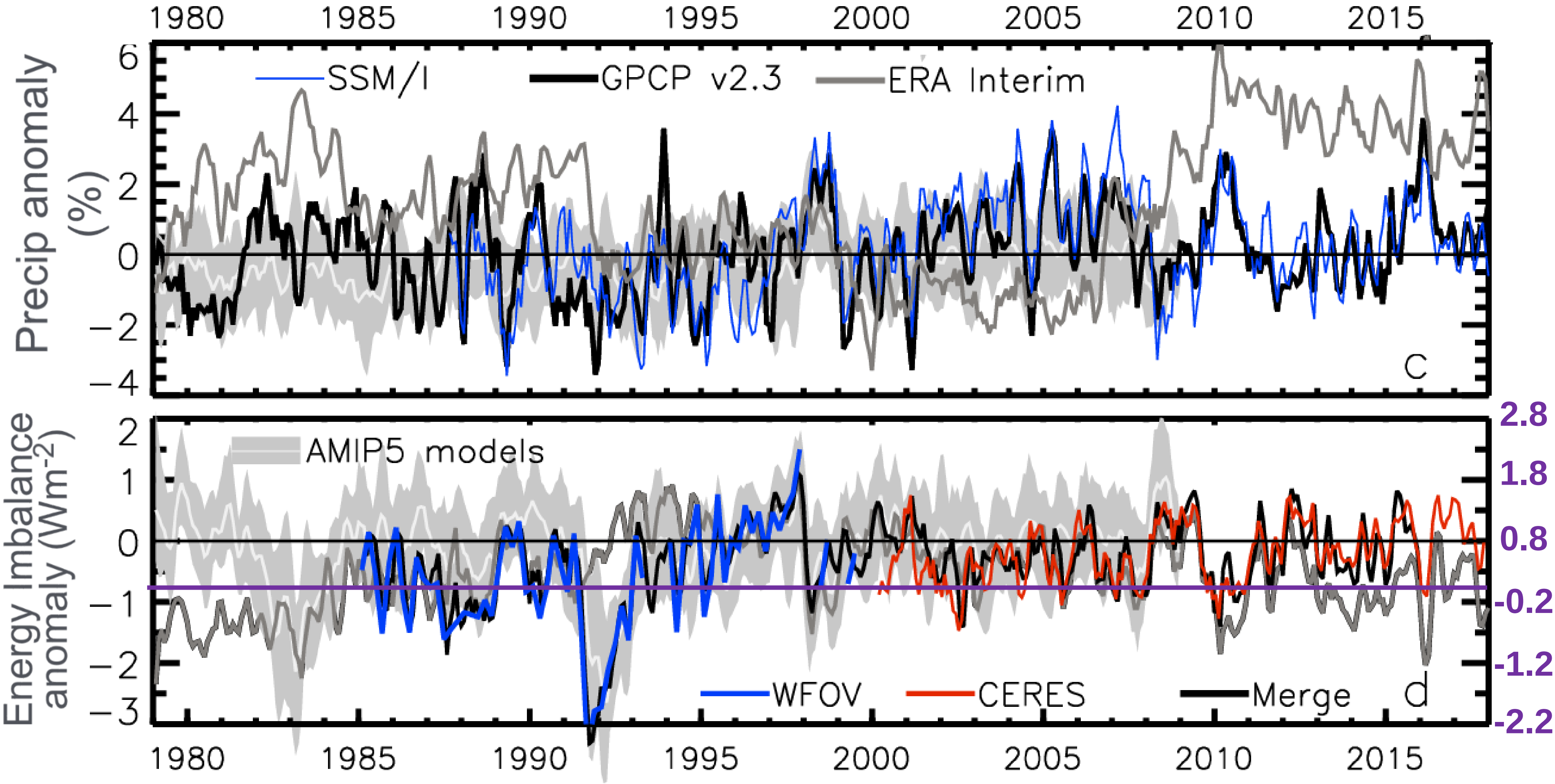
GLOBAL PRECIPITATION DETERMINED BY ENERGY BUDGET

- Atmospheric latent heating from precipitation (**LP)** balanced by radiative cooling (**Q)** (…minus sensible heating, SH)
- A warmer atmosphere radiates energy away more effectively, increasing precipitation (**$k\Delta T$ ---)**
- Atmospheric heating by greenhouse gases & absorbing aerosol reduce precipitation (**$f_F\Delta F$ – – –)**
- These effects compensate explaining why global precipitation has only just started to increase (e.g. Allan et al. (2014) Surv. Geophys) and SH is temporarily a significant term (Myhre et al. (2018) Nature Comms)



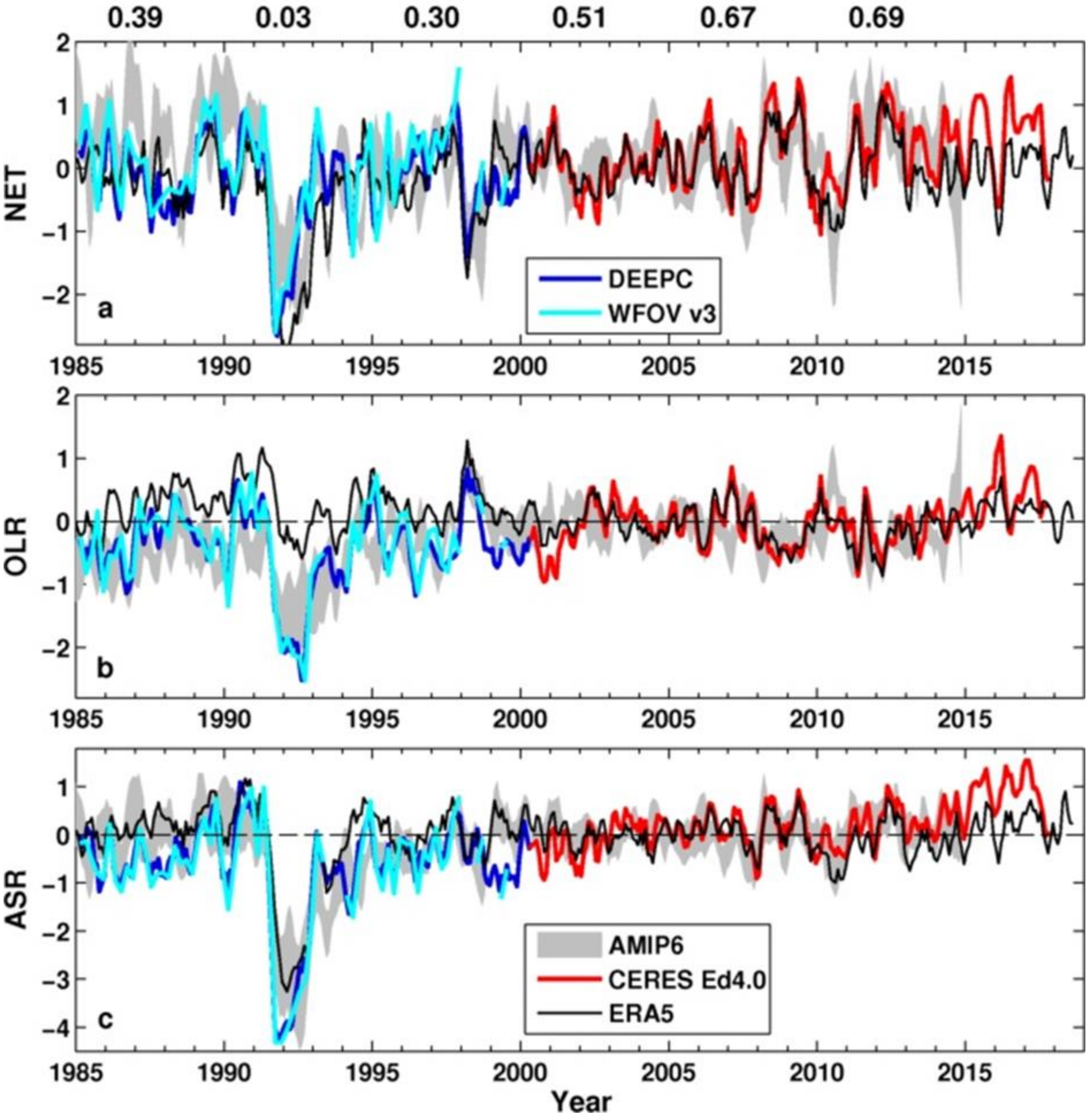
After Allan et al. (2014) Surv. Geophys and Thorpe and Andrews (2014) ERL

PRECIP & ENERGY BUDGET CHANGES



Update from Allan et al.(2014) Surv. Geophys.; Allan et al. (2014) GRL

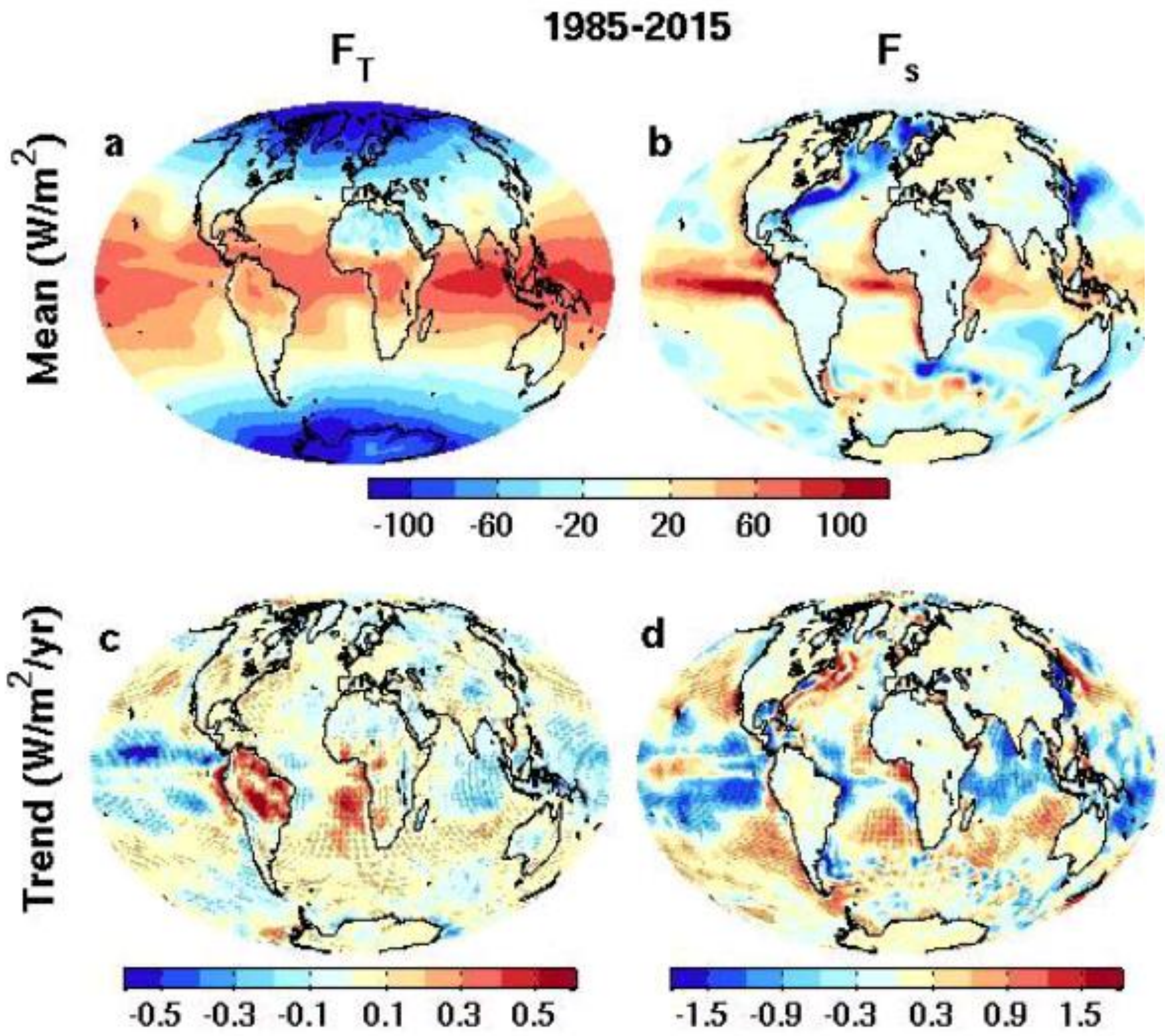
CURRENT ENERGY BUDGET CHANGES

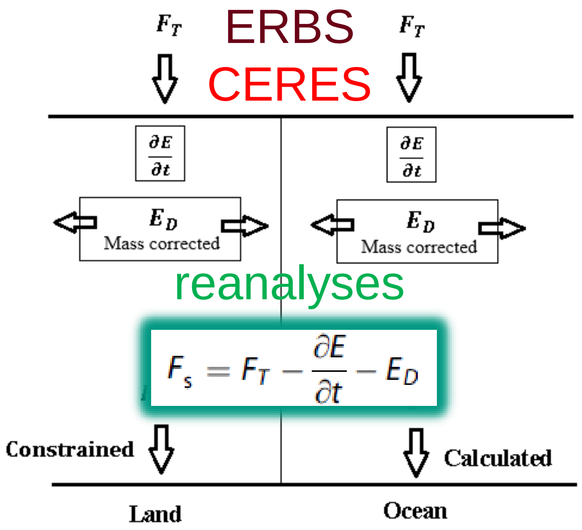


- Preliminary comparison with AMIP6 and ERA5
- Large uncertainty in pre-CERES EEI remains
- ERA5 does not capture observed ASR increase after warming slowdown (e.g. Loeb et al. 2018)
- AMIP vs reconstruction:
  - NET: r = 0.46
  - OLR: r = 0.57
  - ASR: r = 0.70
- Consistent with ocean heat content (Cheng et al. 2017 Sci. Adv.) lower than new independent estimate by Resplandy et al. (2018) Nature

NEW GLOBAL SURFACE FLUX ESTIMATES

top of atmosphere surface





ERBS

CERES

reanalyses

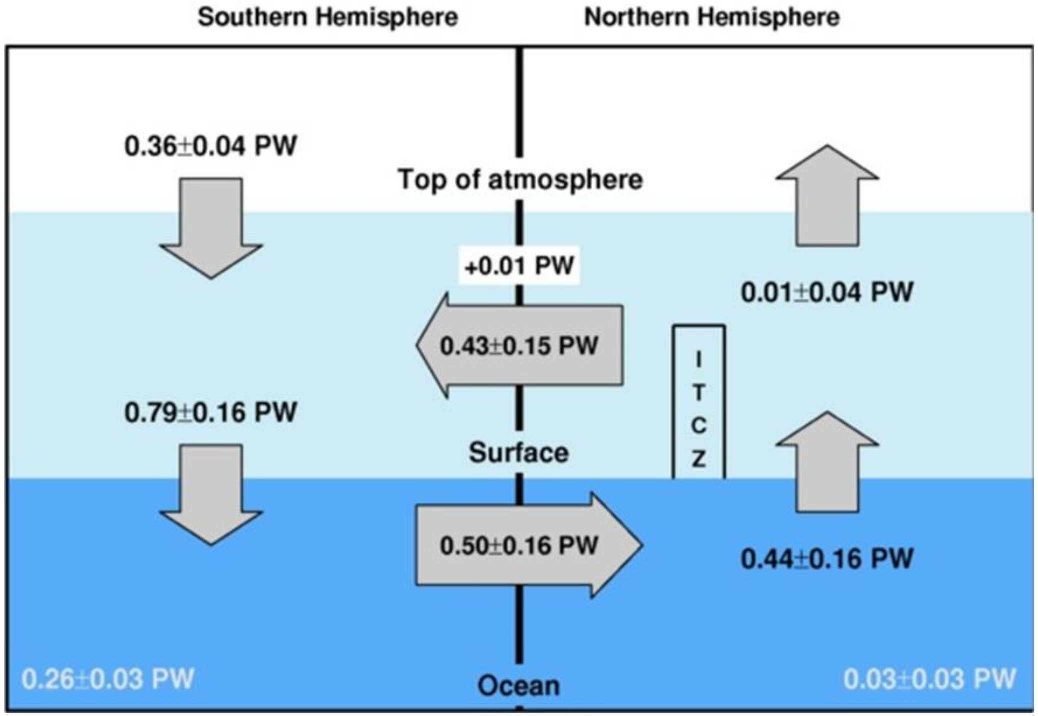
$$\boxed{F_s = F_T - \frac{\partial E}{\partial t} - E_D}$$

Surface energy flux dataset combines top of atmosphere satellite reconstruction with reanalysis energy transports: Liu et al. (2015) JGR

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

HEMISPHERIC ASYMMETRY IN EARTH’S ENERGY BUDGET

- Mean position of the tropical rainy belt in northern hemisphere determined by northward energy transport by ocean e.g. Frierson et al. (2013) Nature Geosci

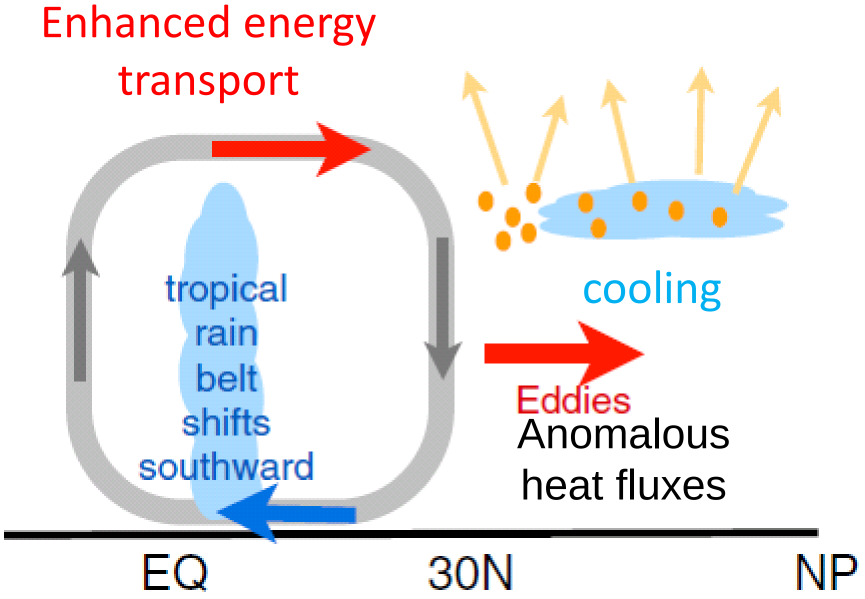


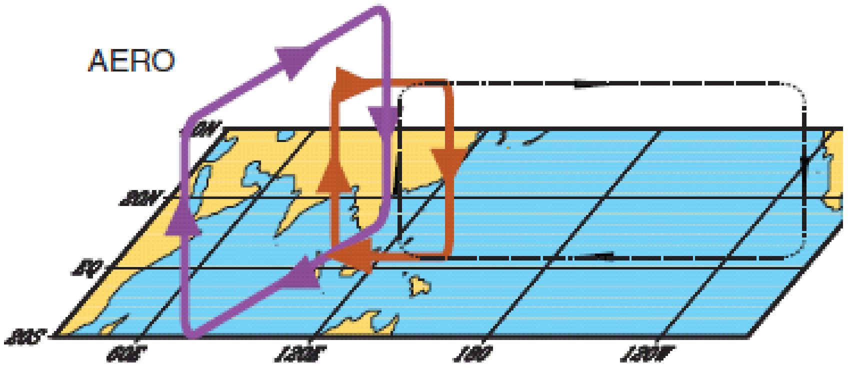
Important to quantify hemispheric energy budget:

← Inferred 2006-2013 cross equatorial energy flux (updated from Liu et al. 2017 & Loeb et al. (2015) Clim. Dyn using ocean heating from Roemmich et al. (2015) Nature Clim or ORAS4 reanalysis

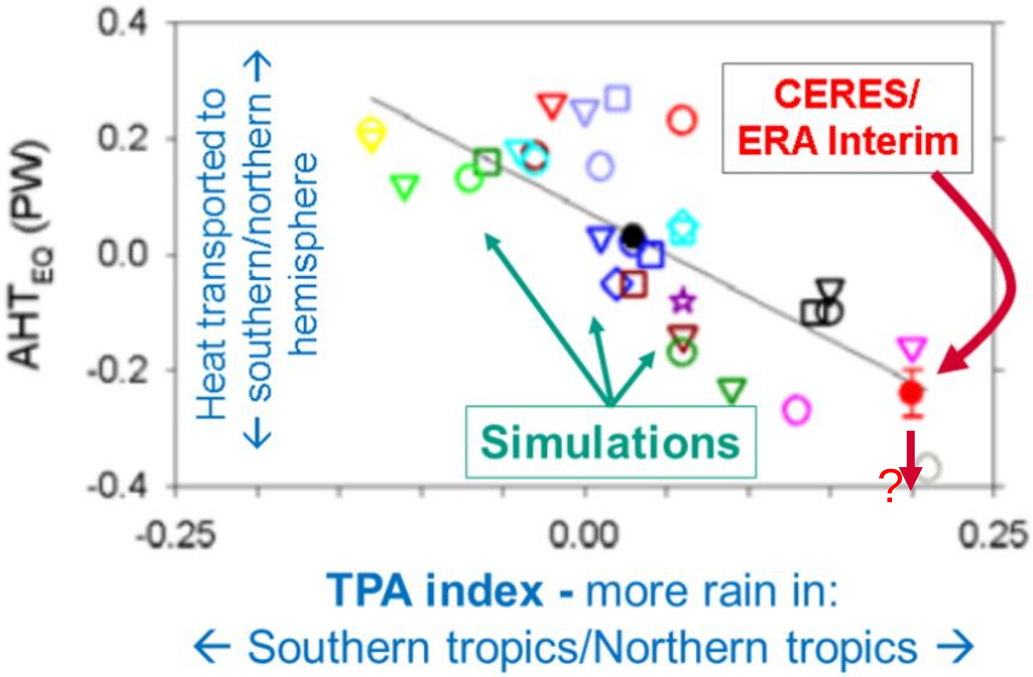
EARTH'S ENERGY BUDGET & REGIONAL CHANGES IN THE WATER CYCLE

- Historical shifts in tropical rainy belts also linked to high latitude volcanic eruptions (Haywood et al. (2013) Nature Clim) & anthropogenic aerosol-cloud interactions (Chung & Soden (2017) Nature Geosci.; Wilcox et al. ERL 2013; Hwang et al. (2013) GRL) but greenhouse gas forcing may now dominate (Dong & Sutton 2015 NatureCC)
- Sulphate aerosol also affects Asian monsoon e.g. Bollasina et al. 2011 Science & may link to drought in Horn of Africa Park et al. (2011) Clim Dyn though internal variability dominates Chung et al. (2019) NatureClim





CROSS-EQUATORIAL HEAT TRANSPORT & PRECIPITATION BIAS LINKED



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

← Many climate models simulate incorrect sign of cross equatorial energy flow and northern minus southern hemispheric precipitation difference

Loeb et al. (2015) Clim. Dyn

Also: Haywood et al. (2016) GRL

Hawcroft et al. (2016) Clim. Dyn.

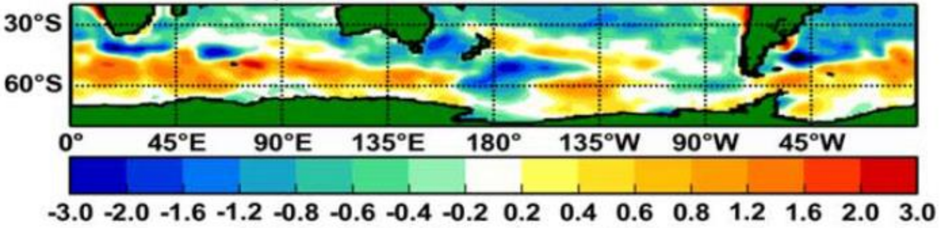
- Many processes contribute to hemispheric asymmetry…

CLIMATE MODEL BIASES IN SOUTHERN OCEAN INFLUENCE ASYMMETRY

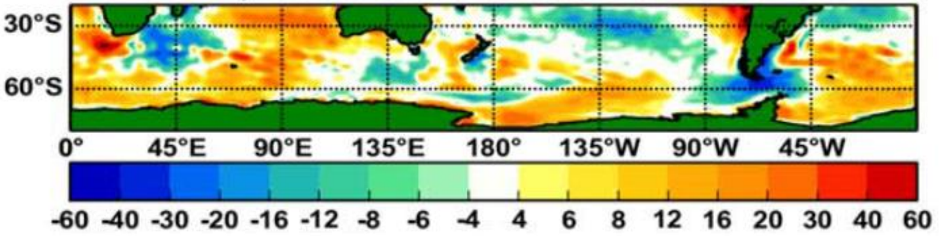
- Use surface flux product to trace causes of coupled SST biases to atmospheric model processes
- Biases in AMIP5 simulations of cloud linked to SST & zonal wind maximum latitude (ZWML) bias

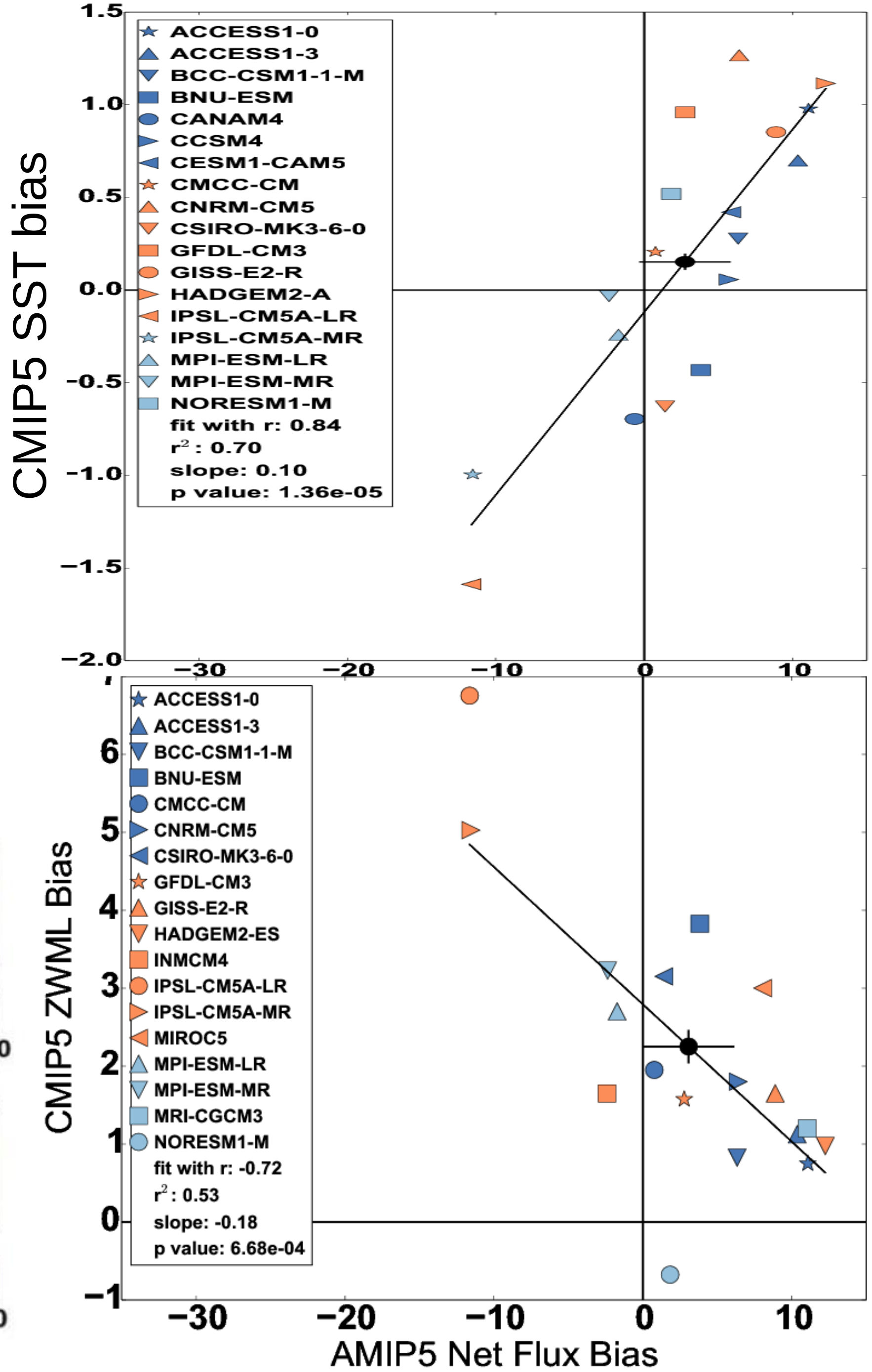
Hyder et al. (2018) *Nature Comms*

a) CMIP5 SST Mean Difference



c) AMIP5 Net Flux Mean Difference





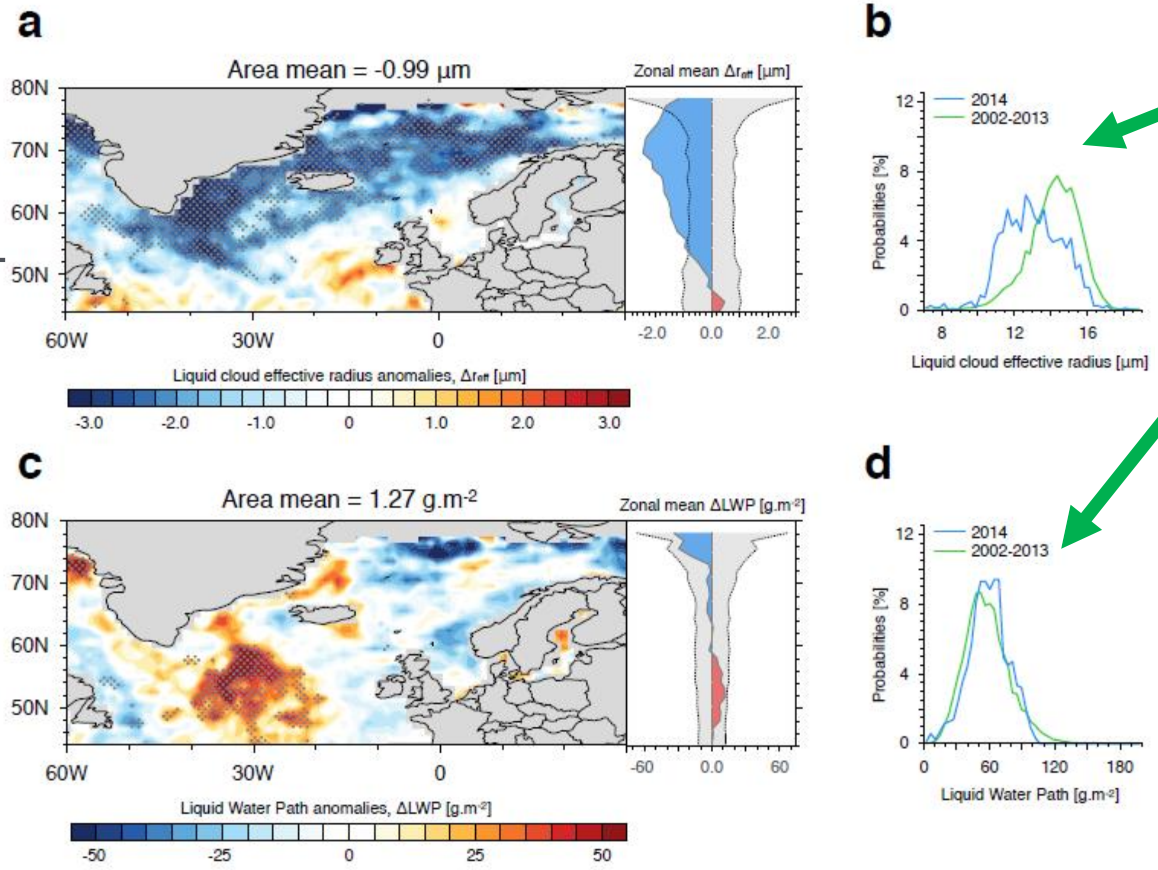
CLOUD-AEROSOL EFFECTS

- Indirect aerosol effects on cloud may have dominated inter-hemispheric climate shifts including Sahel drought in 1980s Chung & Soden (2017) Nature Geosci.

MODIS-Aqua Observations

Droplet size

Cloud water



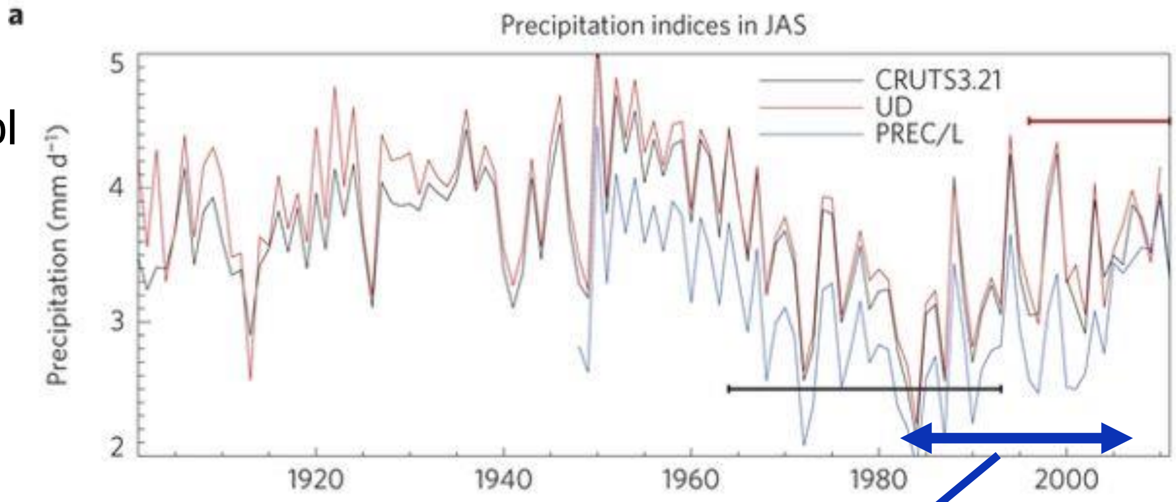
Malavelle et al. (2017) Nature

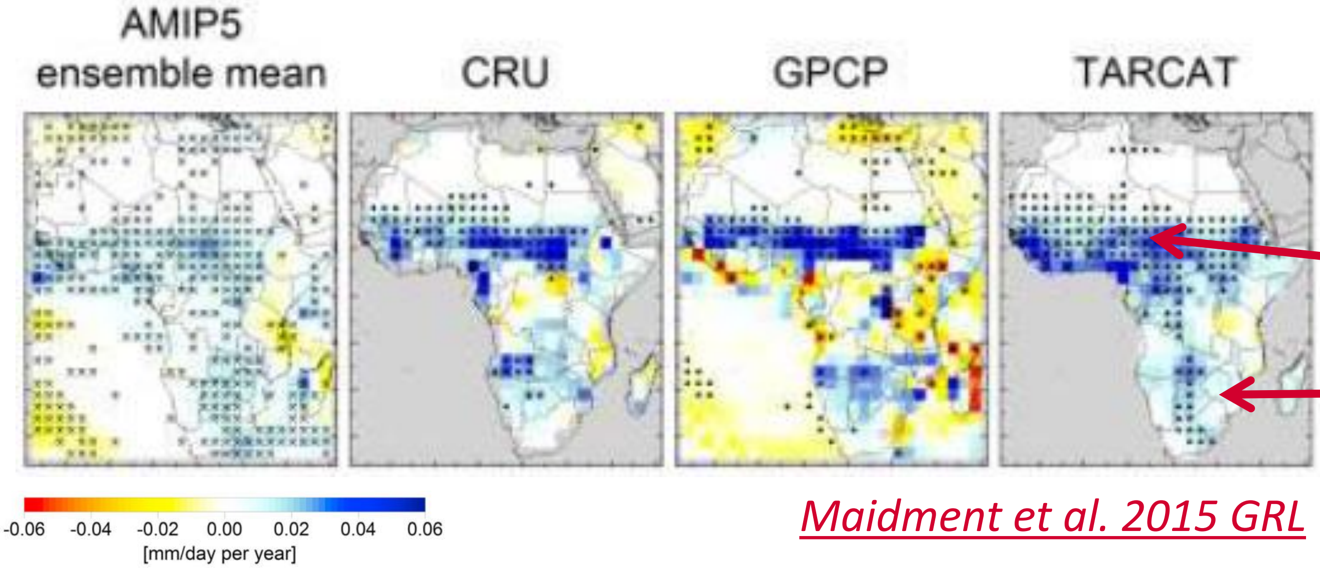
- Volcanic aerosol effect on cloud droplet size observable and consistent with simulations
- Further indirect effects in cloud water not detectable
- More complex sub-sampling may show effects for mid-latitude cyclones and marine stratocumulus

McCoy et al. (2018) ACPD, Rosenfeld et al. (2019) Science

SAHEL RAINFALL SENSITIVE TO REGIONAL ITCZ VARIABILITY

- Reduced Sahel rainfall 1950-1980s due to aerosol cooling (e.g. Hwang et al. (2013) GRL) may now be dominated by increases due to greenhouse gas heating (Dong & Sutton 2015 NatureCC →)





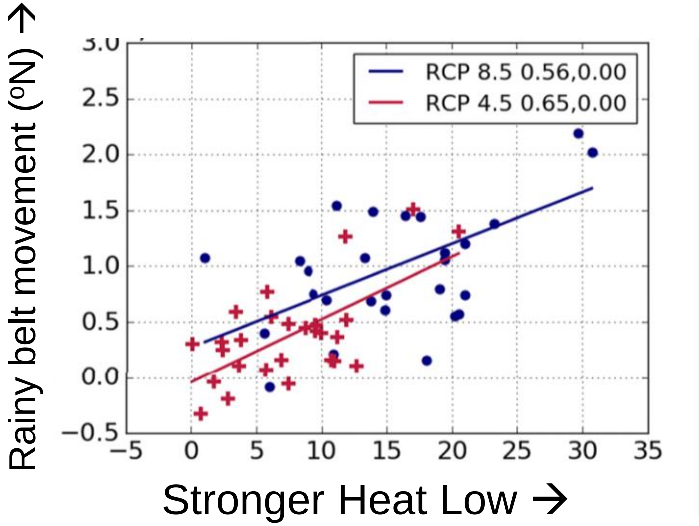
Radiative forcing?

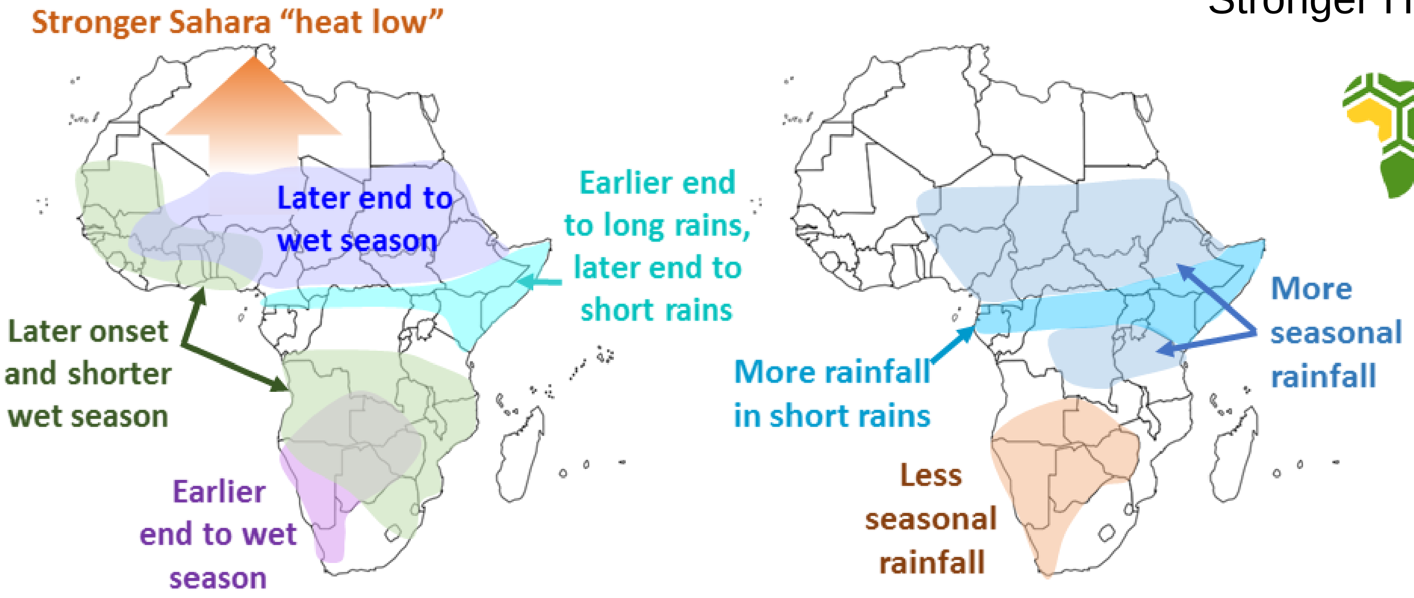
Internal variability?

Maidment et al. 2015 GRL

STRENGTHENING SAHARA HEAT LOW DELAYS WET SEASON

- Seasonal timing of wet season linked to impacts across Africa.
- New method to define wet season in satellite products/models (Dunning et al. 2016 JGR)
- Intensification of Sahara Heat Low drives later wet seasons in projections: Dunning et al. 2018 J. Clim




Stronger Sahara "heat low"

Later end to wet season

Earlier end to long rains, later end to short rains

Later onset and shorter wet season

Earlier end to wet season

More rainfall in short rains

More seasonal rainfall

Less seasonal rainfall

DACCIWA

BIASES IN SEASONAL RAINFALL SIMULATION HINDER PROJECTIONS

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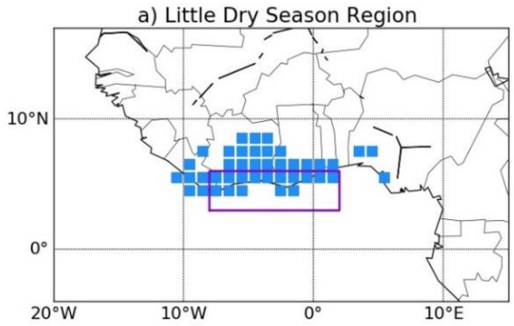
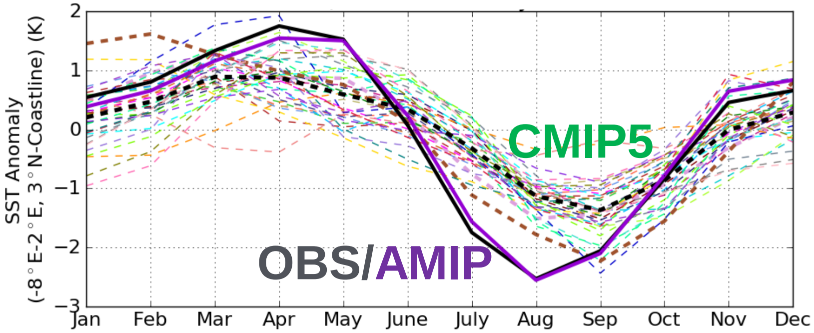
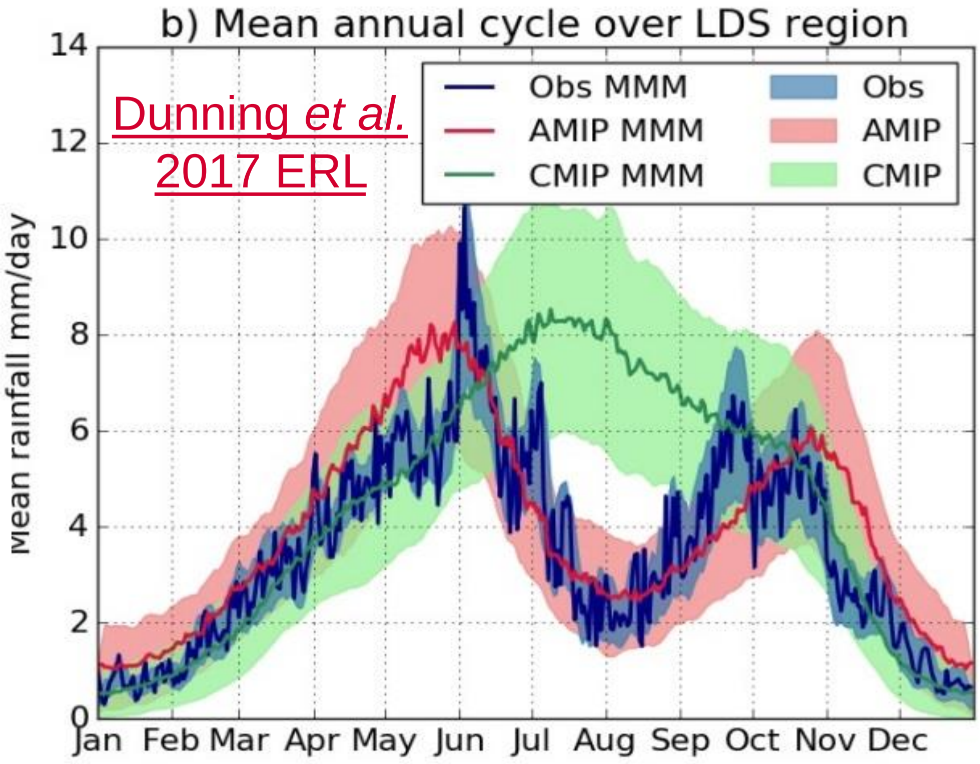


a) Little Dry Season Region



SST seasonal cycle



b) Mean annual cycle over LDS region

Dunning *et al.* 2017 ERL

Atmosphere-only simulations capture seasonal cycle, **coupled simulations** don't

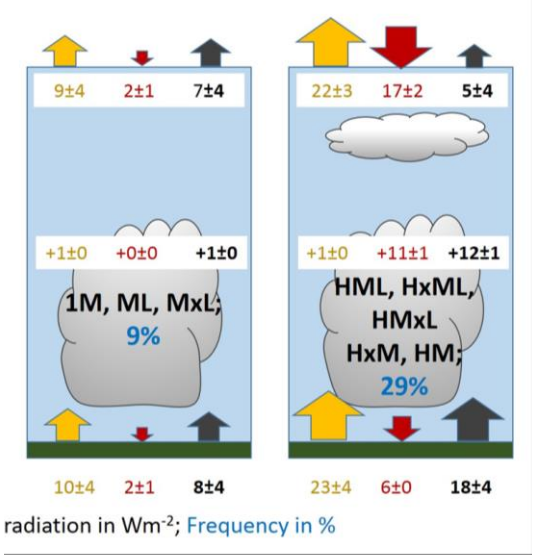
- Due to systematic biases in Gulf of Guinea sea surface temperature (SST) & deficient representation of SST/rainfall relationship (Wainwright et al. in prep)
- Are there links to Southern Ocean biases? (Hyder et al. in prep).

SYSTEMATIC BIASES IN CLOUD, RAINFALL & ENERGY BUDGET OVER WEST AFRICA

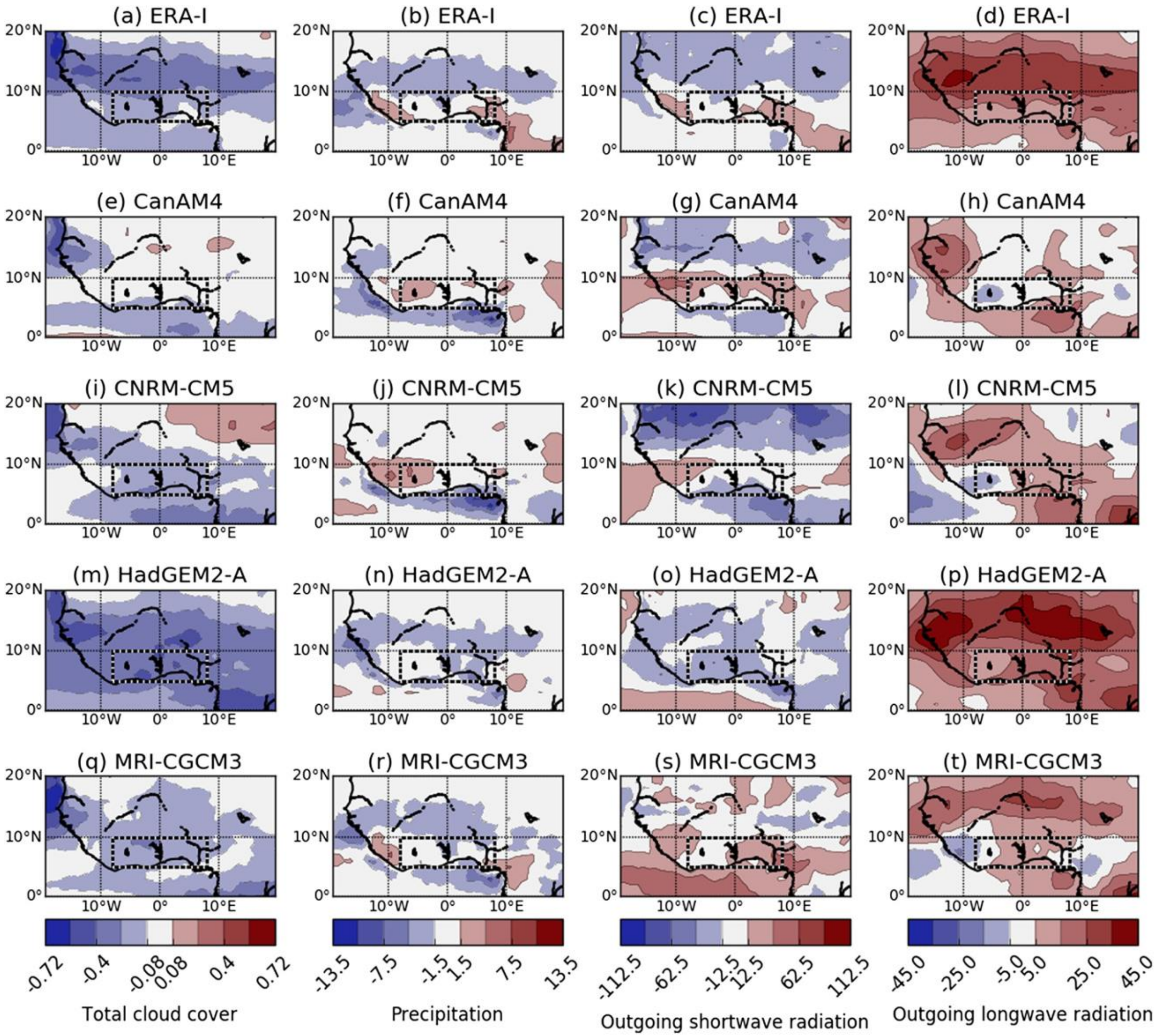
- Systematic biases in cloud/rainfall/radiation evident in CMIP5 simulations →

  Hill et al. 2016 JGR

- Cloud contributions to radiation budget Hill et al. 2018 J Clim:



radiation in Wm^{-2}; Frequency in %



CONCLUSIONS

- Water vapour increasing with warming climate as expected from thermodynamics
  - Abatement of near surface moistening over land since ~2000 remains
- Global precipitation barely increasing, expected from energy constraints
  - direct atmospheric heating from radiative forcings offsetting much of increase due to atmospheric warming that enhanced radiative cooling rate
- Imbalance in Earth’s energy budget driving climate change
  - Heating currently dominated by southern hemisphere
  - Imbalance in heating between hemispheres affecting precipitation patterns
- Systematic model biases related to hemispheric imbalance:
  - Aerosol indirect effects on cloud
  - Biases in cloud and SST in Southern Ocean & Africa/Atlantic region
  - Warming of climate and strengthening Sahara heat low expected to drive increases in rainfall and its intensity and later wet season over north Africa