Department of Meteorology

University of Reading

PHYSICALLY CONSISTENT MONITORING OF GLOBAL ENERGY AND WATER CYCLE

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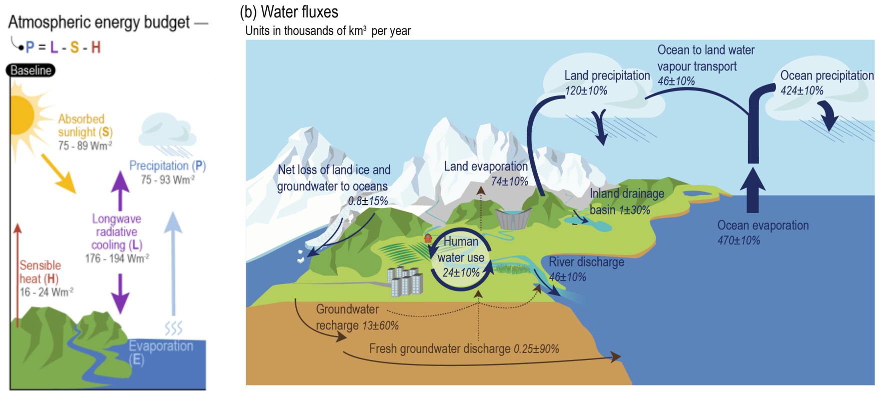

INTRODUCTION

- Challenges in understanding energy and water cycle responses to a warming world are conceptual as well as technological
- Observing and monitoring changes are important for advancing understanding of processes, trajectory of climate change & observing systems
- But almost no observing systems have stability to detect global climate change
- Observations must be taken in context of physical framework to be useful
- Physical linkages between global energy & water cycles a powerful constraint **(e.g. Tristan L'Ecuyer, Remy Roca, Keith Haines talks)**
- But regional to local climate change, extremes and plausible high impact possibilities should be a central motivation

GLOBAL WATER & ENERGY BUDGETS

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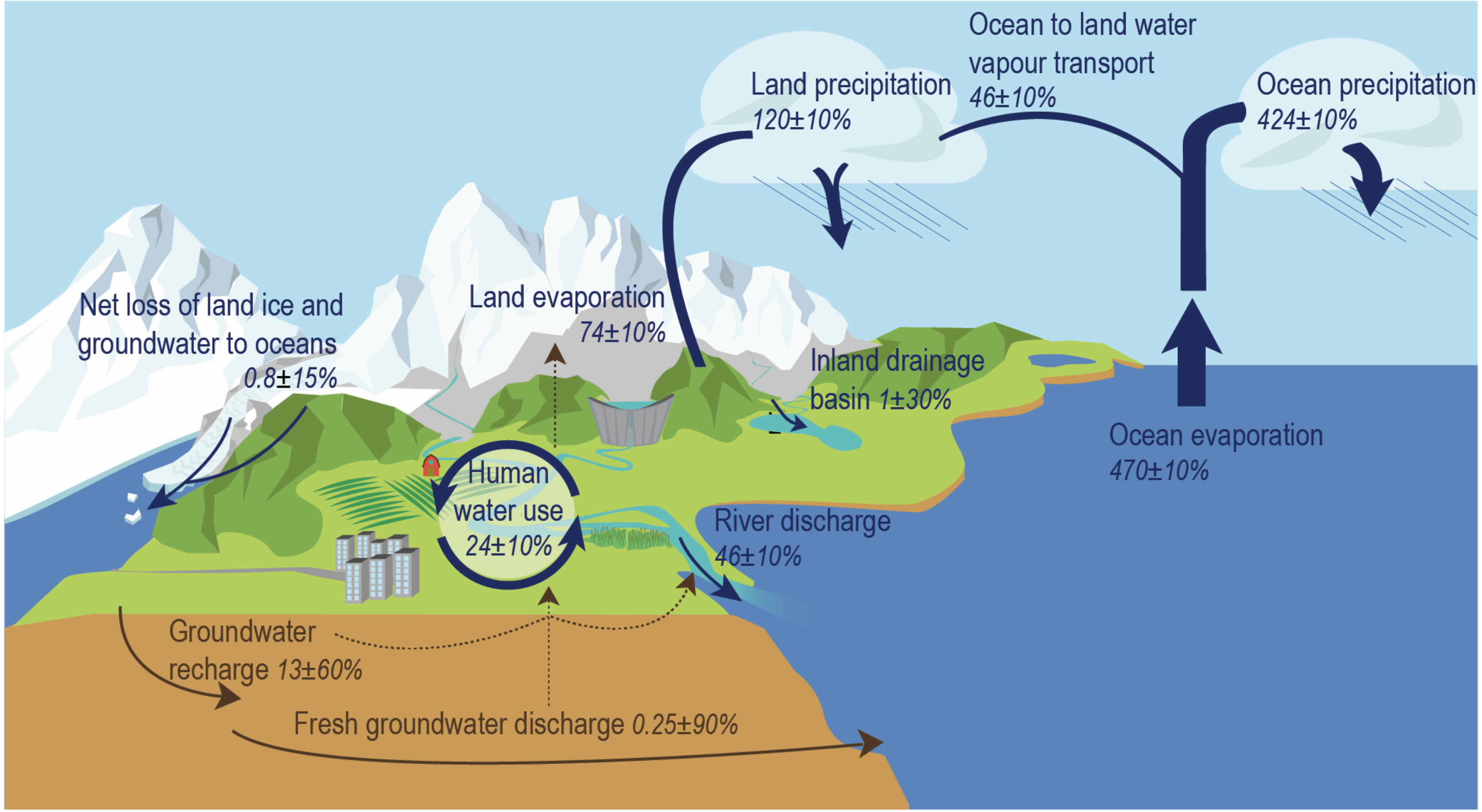
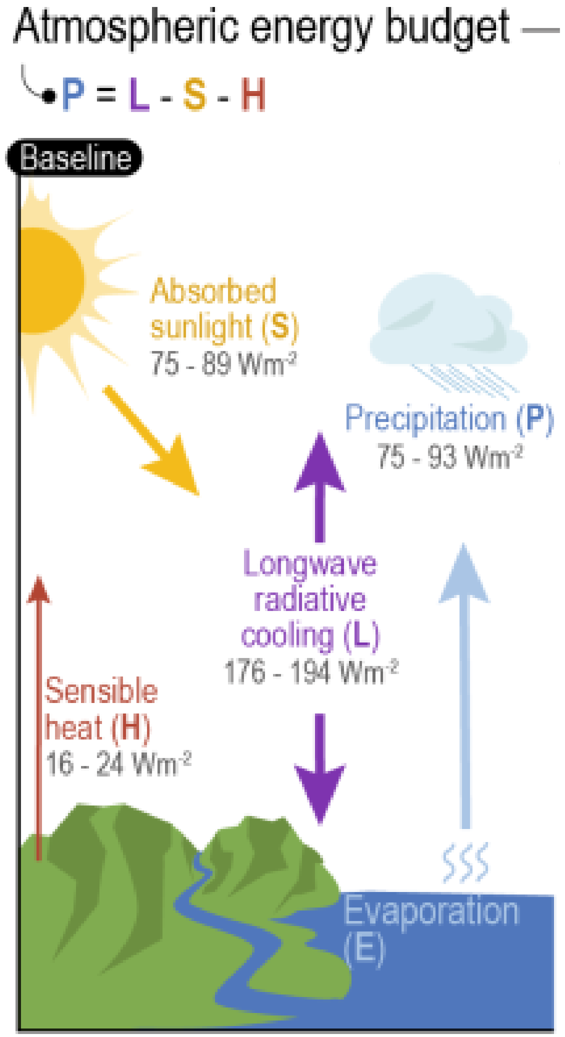
(b) Water fluxes

Units in thousands of km³ per year





Douville et al. (2021) IPCC, Ch 8 (Fig. 8.1b; Fig. 8.3a); Allan et al. (2020) NYAS

GLOBAL CONSTRAINTS, LOCAL NEED

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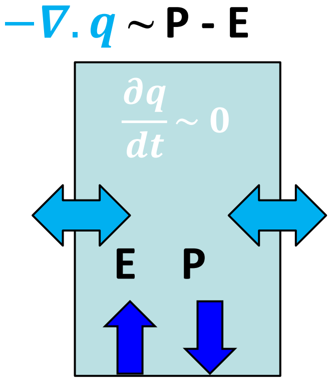
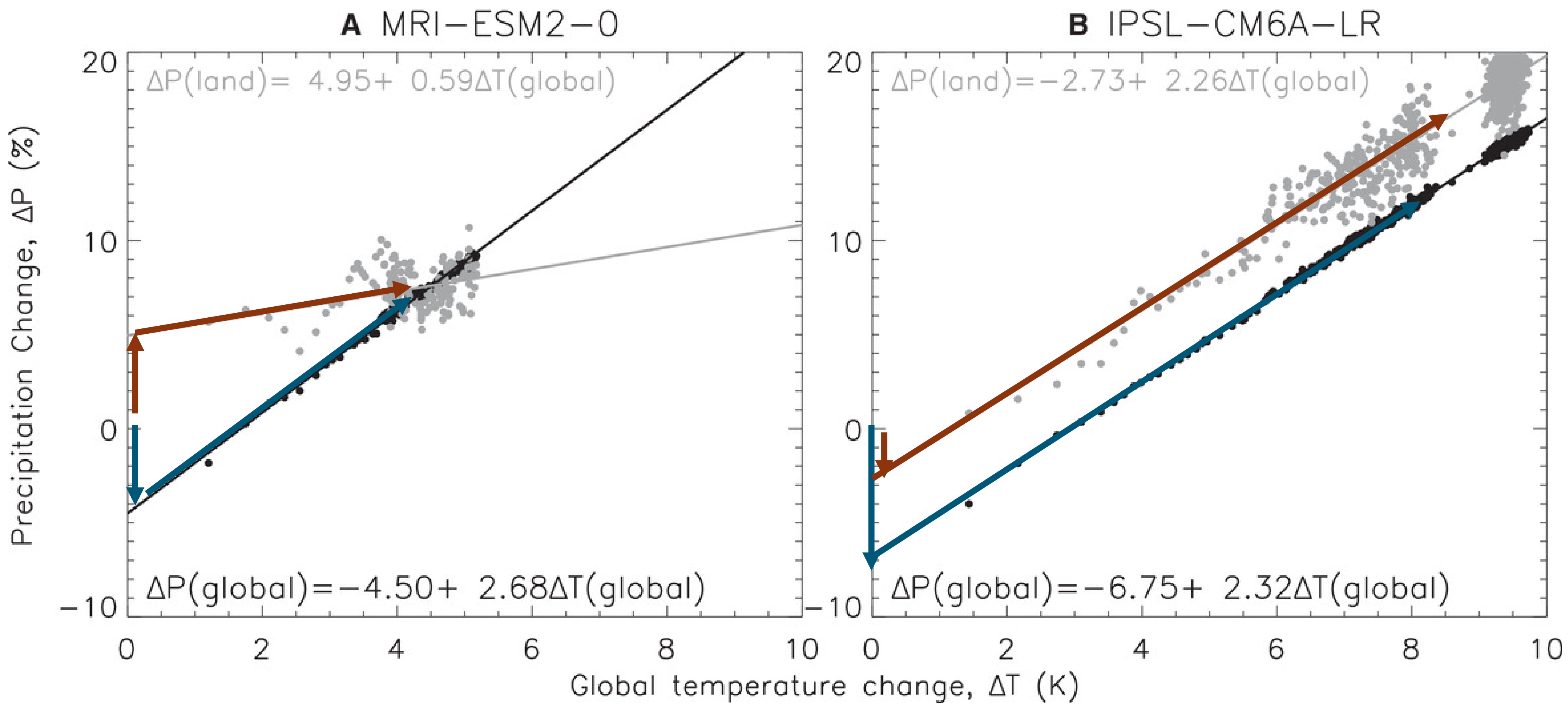
- $N = \Delta F + Y\Delta T$
  - Feedbacks involving water cycle components determine climate response to GHGs (water vapour, clouds including role of warming pattern)
- $dP = \eta\Delta T - \Sigma f_F.\Delta F$ $(-\Delta SH)$
  - Global precipitation increases with warming but this is muted by rapid adjustments to heating of atmosphere relative to the surface
- $\Delta\boldsymbol{\nabla}.\boldsymbol{q} \sim 7\%/\boldsymbol{K}$
  - But regional water cycle dominated by thermodynamics and dynamics
  - Amplification of water cycle modulated by shifts in circulation
- e.g. Trenberth & Stephens et al. et al.



FAST & SLOW GLOBAL PRECIPITATION RESPONSES TO 4XCO$_2$



Allan et al. (2020) NYAS

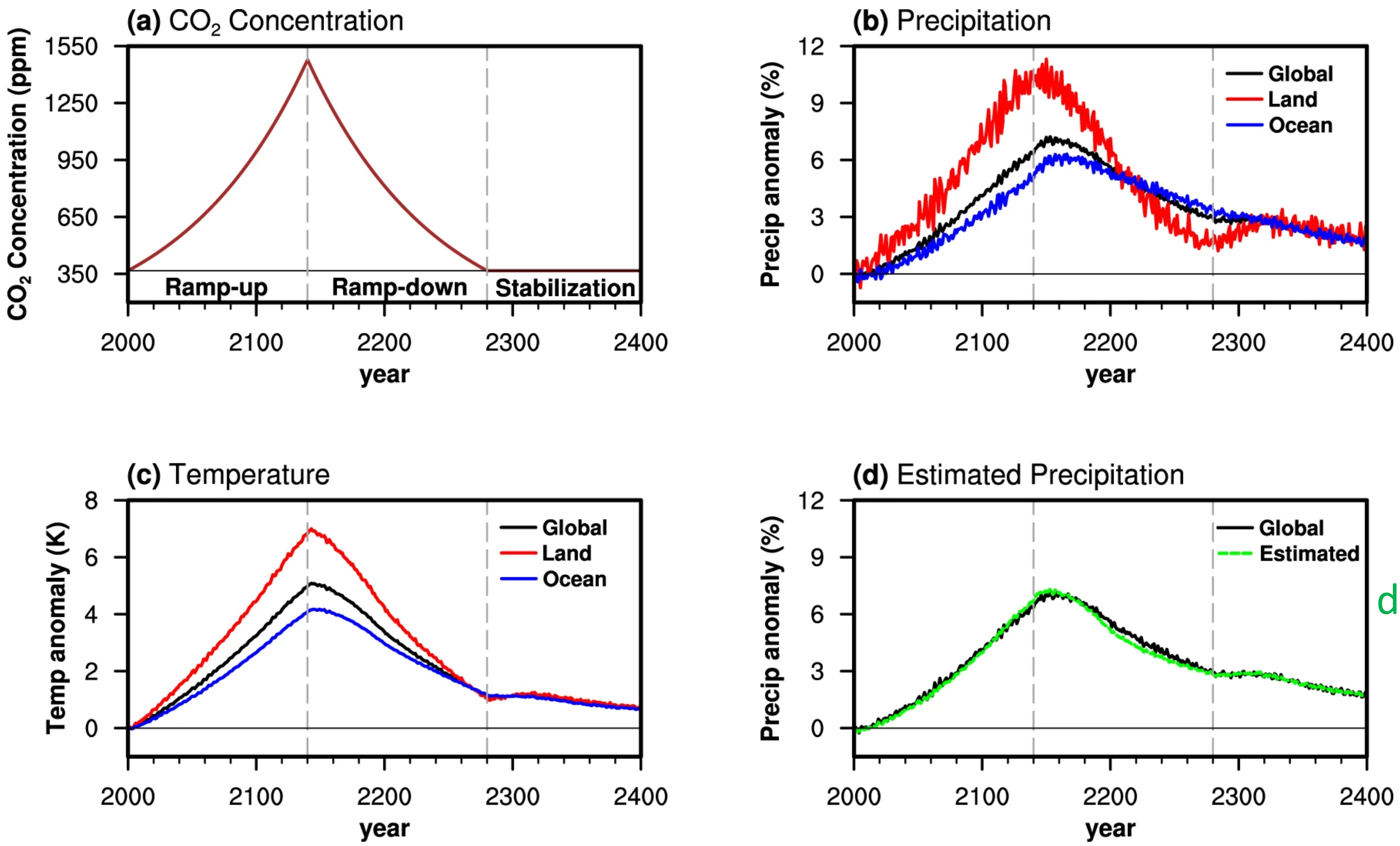
Global: rapid decline, consistent slow increase with warming (2-3%/^{o}C)

Land: model-dependent rapid response & suppressed(?) increase per ^{o}C warming

e.g. **Andrews et al. (2009) J Climate**; **Samset et al. (2018) Clim. Atmos. Sci.**:

WHAT WILL A POST NET ZERO WORLD LOOK LIKE?

e.g. see King et al. (2022) Nature Climate Change

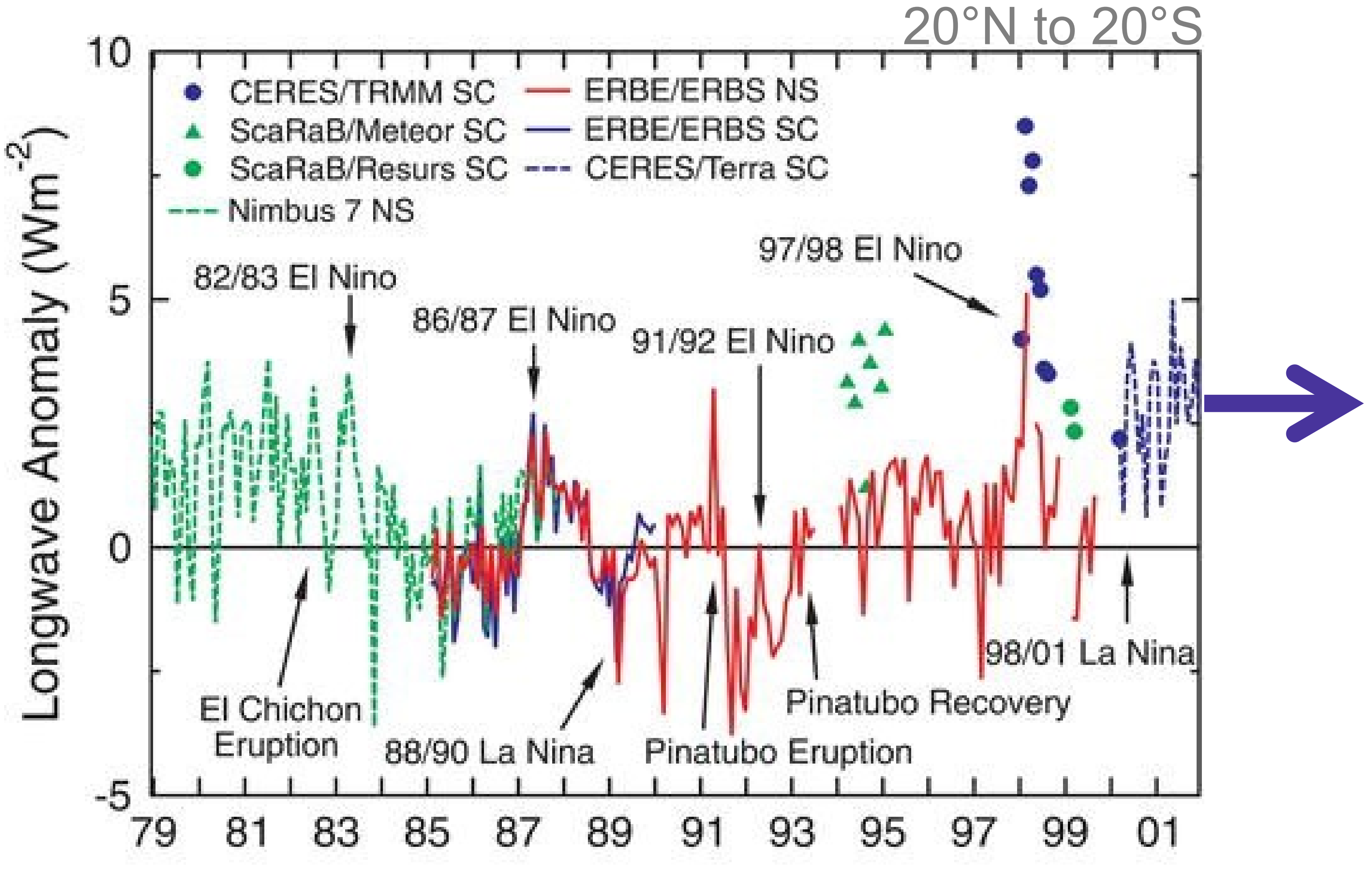


$dP = \eta\Delta T - \Sigma f_F.\Delta F$

Yeh et al. (2021) npj Clim Atmos Sci

MULTI-DECADAL EARTH RADIATION BUDGET RECORD

- Diagnose global climate forcing and feedback response
- Evaluate regional radiative processes related to climate
- Understand drivers of variability and trends
- Homogeneity, sampling & calibration issues
- Consistency with heat content/sea level e.g. Loeb et al. (2012) Nat. Geosci; Allison et al. (2020) ERC; Cheng et al. 2017 Sci. Adv.



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

RECONSTRUCTING ENERGY BUDGET BEFORE 2000

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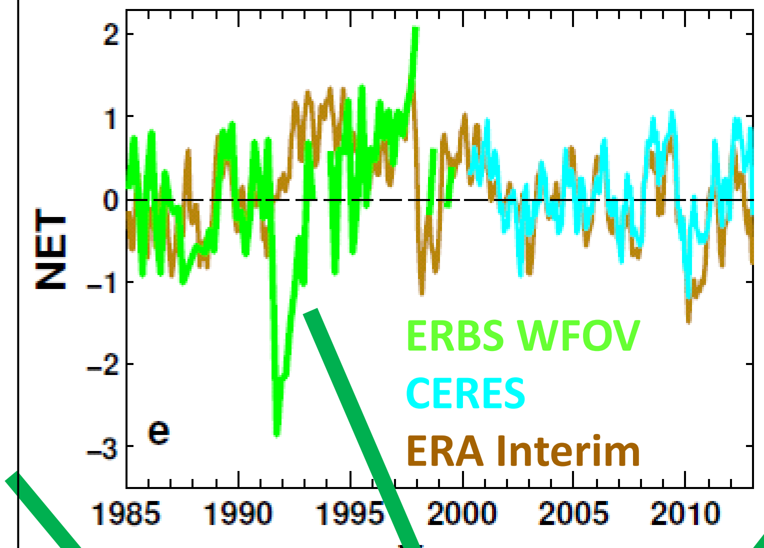
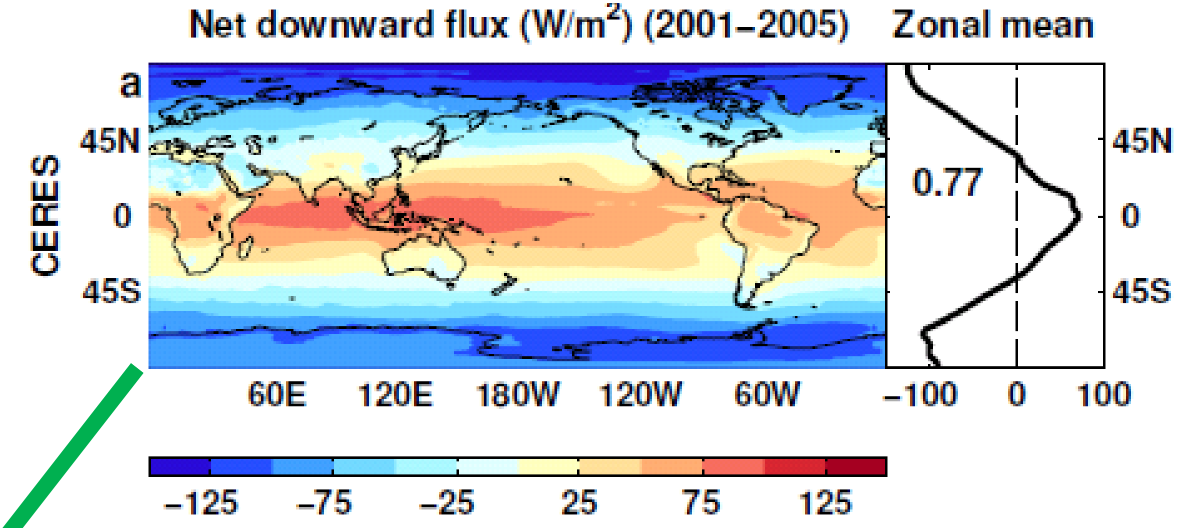
Part of DEEP-C project

Breaks in WFOV and WFOV/CERES records constrained by AMIP simulations; reanalyses for monthly interpolation

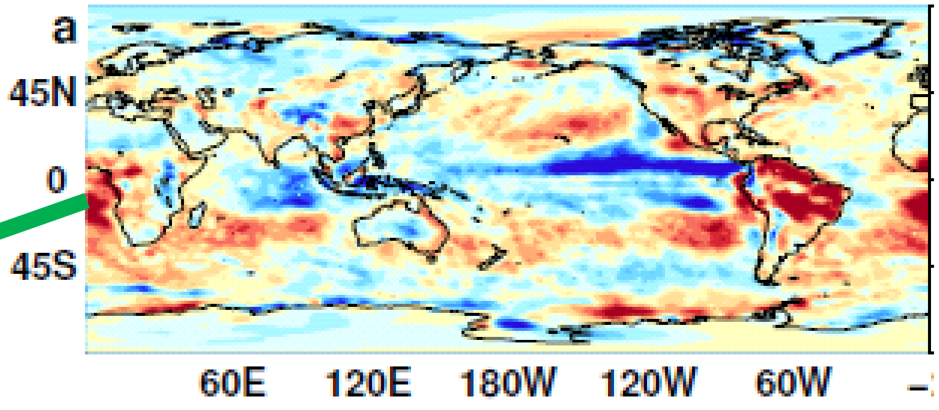
ERBS/CERES variability



CERES monthly climatology



ERA reanalyses spatial anomalies



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

[Allan et al. (2014) GRL]

ESTIMATES OF SURFACE ENERGY FLUX

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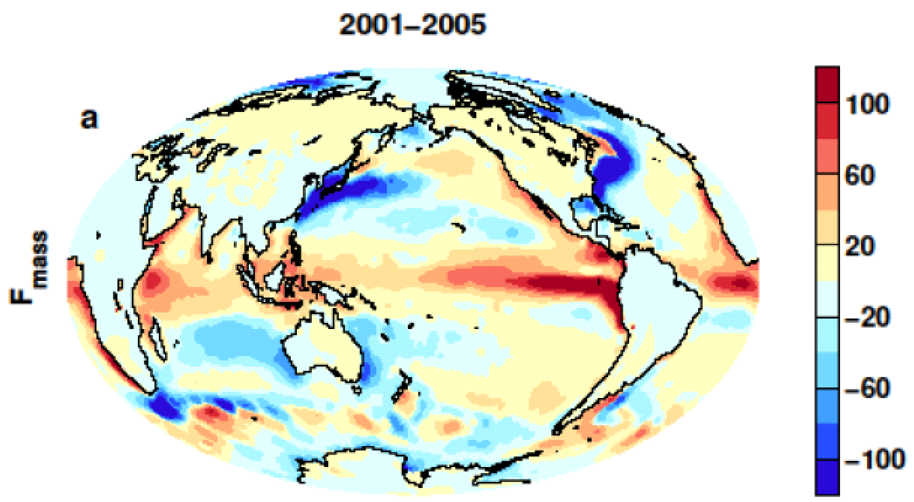
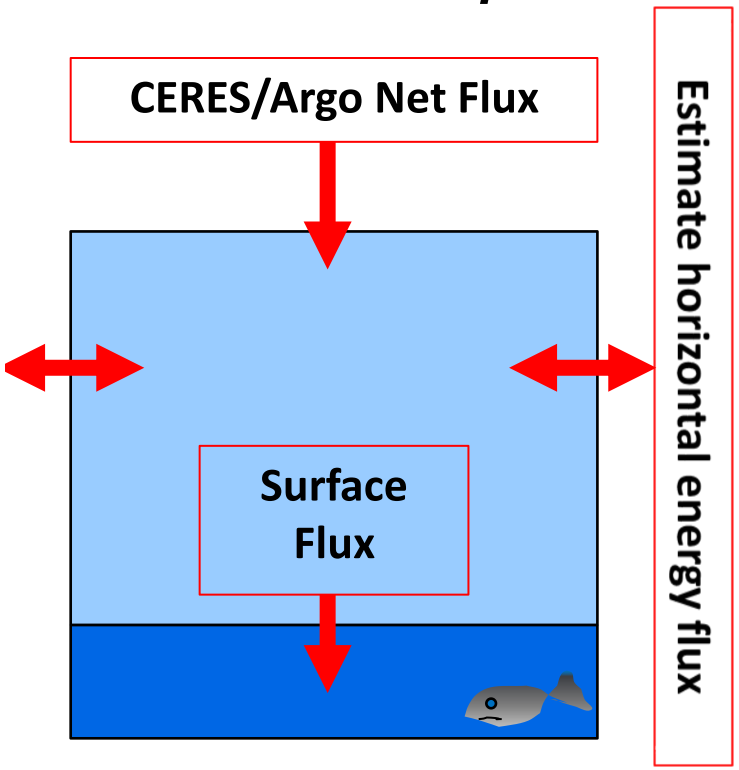
$$F_{SFC} = F_{TOA} - \frac{\partial TE}{\partial t} - \nabla \cdot \frac{1}{g}\int_0^1 V(Lq + C_pT + \varphi_s + k)\frac{\partial p}{\partial \eta}d\eta$$



Net surface downward energy flux (Wm^{-2})



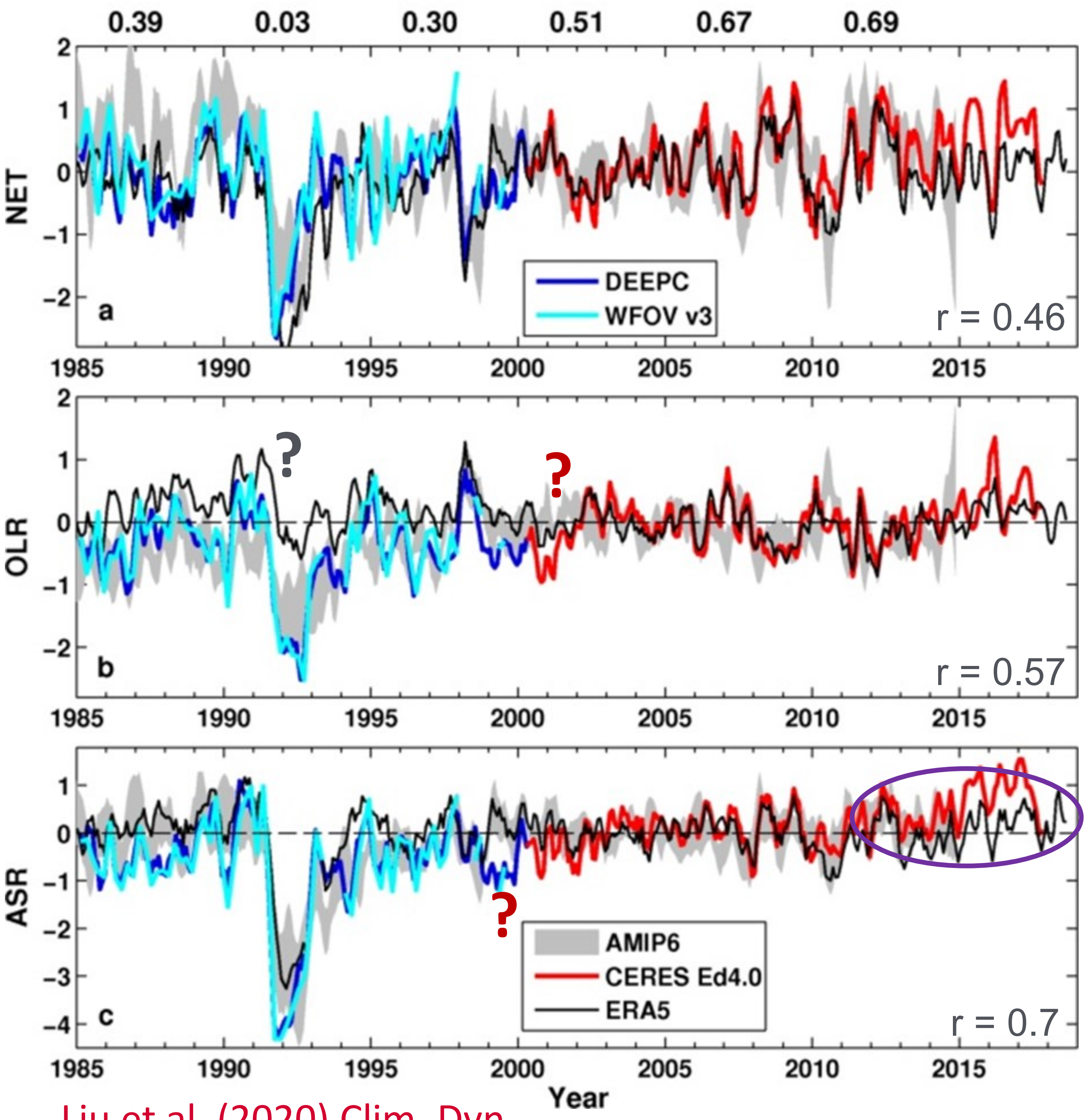
Liu et al. (2017) JGR; Liu et al. (2015) JGR

Improved formulations, see: Trenberth & Fasullo (2018) J. Clim.; Mayer et al. (2022) J.Clim; Lauritzen et al. (2022) JAMES

- Unrealistic regional anomalies over land compared to temperature change
- Correction applied based on combined modelling and observations e.g. Cuesta-Valero et al. 2021
- Improvements to AMIP adjustments, land correction and account for enthalpy

Michael Mayer talk

CURRENT ENERGY BUDGET CHANGES



Liu et al. (2020) Clim. Dyn.

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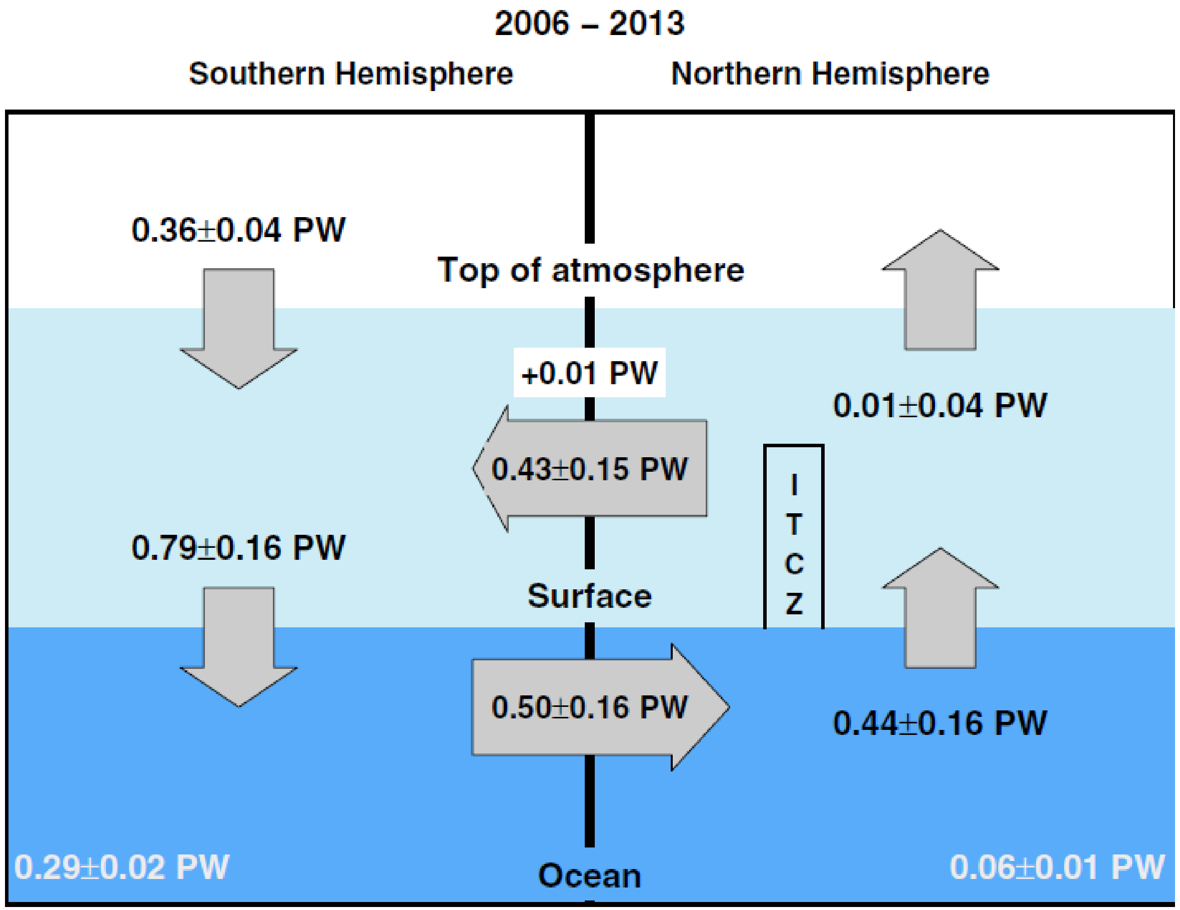
- Large uncertainty in pre-CERES EEI remains
  - Update to using AMIP6 adjustments increases change from ~0.3 Wm^{-2} (Liu et al. 2017) to ~0.5 Wm^{-2} (Liu et al. 2020) & uncertainty range
- Consistent with ocean heat content changes (Cheng et al. 2017 Sci. Adv.), lower than Resplandy et al. (2019) Sci. Rep. Who have larger range following correction (0.3-1.3 Wm^{-2})
- ERA5 does not capture observed ASR increase after warming slowdown (e.g. Loeb et al. 2018)
  - ↑Heating 2015/16
  - Cloud plus aerosol? Calibration drift?

Norman Loeb's talk

HEMISPHERIC ASYMMETRY IN EARTH'S ENERGY BUDGET



Liu et al. (2020) Clim. Dyn. after Loeb et al. (2015) Clim. Dyn

- Mean position of the tropical rainy belt in northern hemisphere determined by northward energy transport by ocean & inter-hemispheric energy budget: Frierson et al. (2013) Nature Geosci

← Inferred 2006-2013 cross equatorial energy flux (updated from Liu et al. 2017 & using ocean heating from Roemmich et al. (2015) Nature Clim, Desbruyeres et al. (2016) GRL or ORAS4) *Careful with days per month & enthalpy transfers!*

See: Stephens et al. (2022) Proc. Roy. Soc.; Diamond et al. (2022) Commun. Earth Environ. Yukimoto et al. (2022) GRL on aerosol/cloud/ cryosphere effects, model biases & changes. Past peak aerosol: Quaas et al. (2022) ACP

INFERRED OCEAN ENERGY TRANSPORTS@26N

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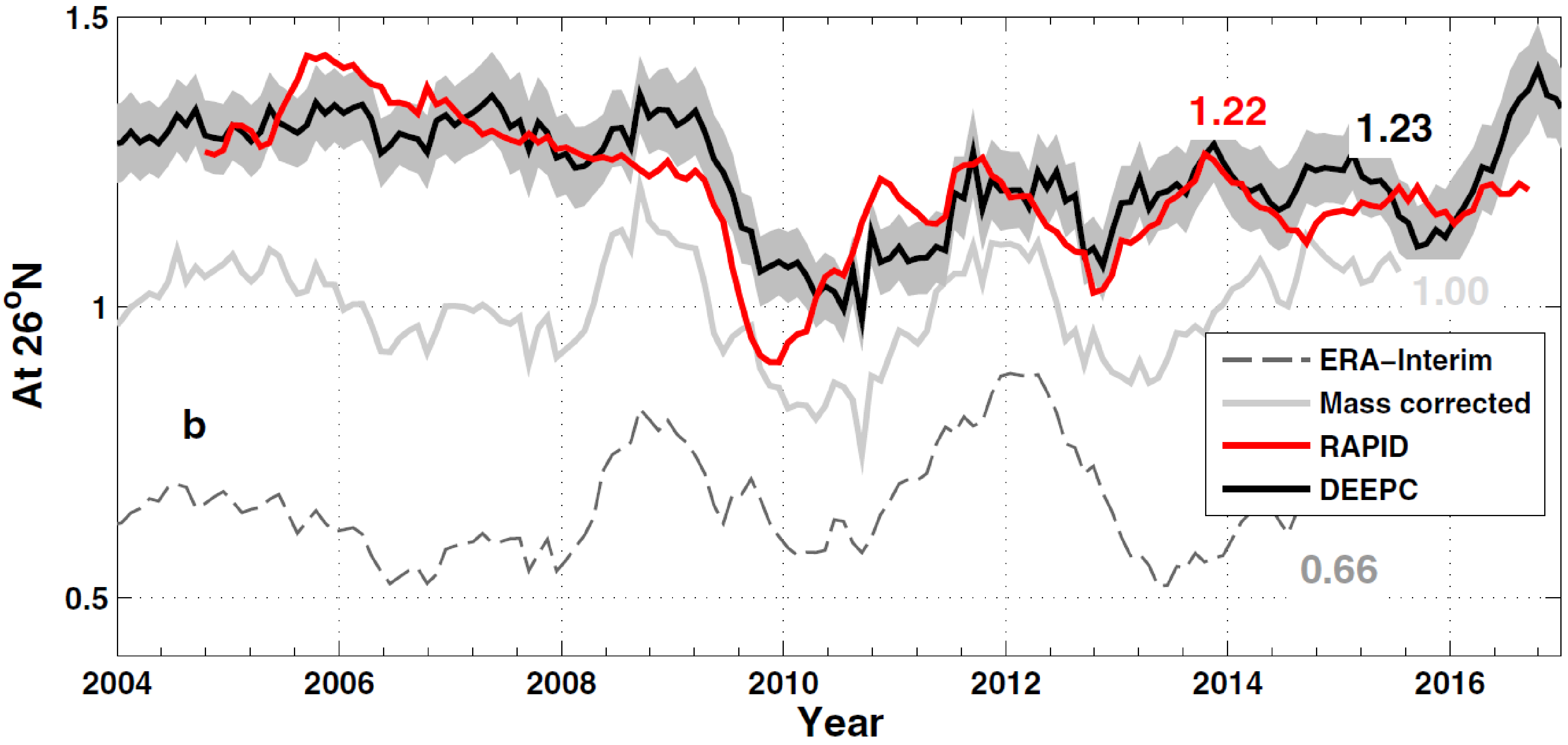
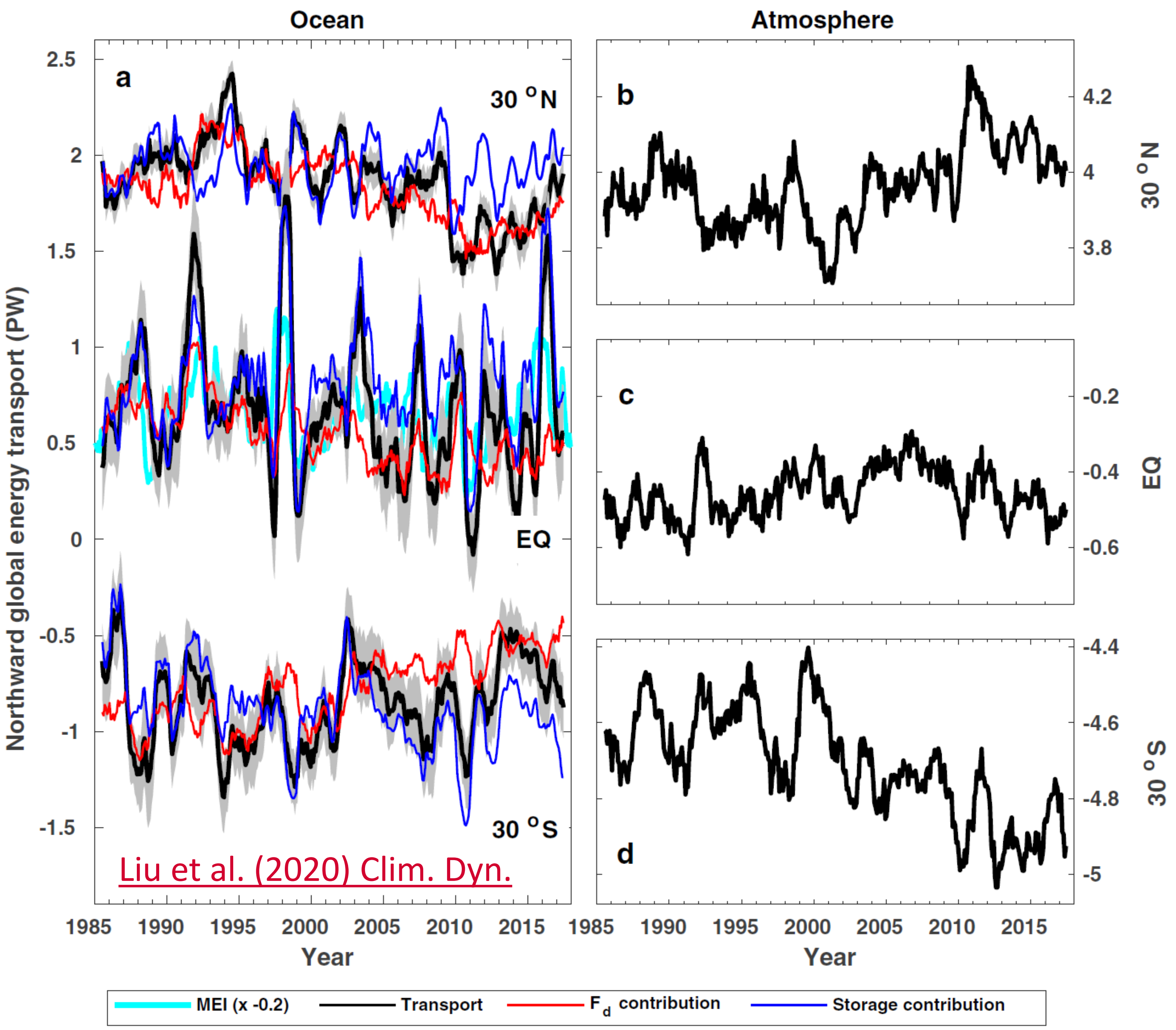


Liu et al. (2020) Clim. Dyn. after Trenberth & Fasullo, 2017 GRL



Liu et al. (2020) Clim. Dyn.

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INFERRED MERIDIONAL ENERGY TRANSPORTS

- How is atmosphere and ocean circulation responding to and modifying energy imbalances?
- Ocean poleward heat transport at 30°N:

− 0.22 PW/decade (1995–2011)

- Atmospheric poleward heat transport increase inferred from CERES period?

PLANETARY HEATING SINCE THE 1980S FROM MULTIPLE INDEPENDENT DATASETS

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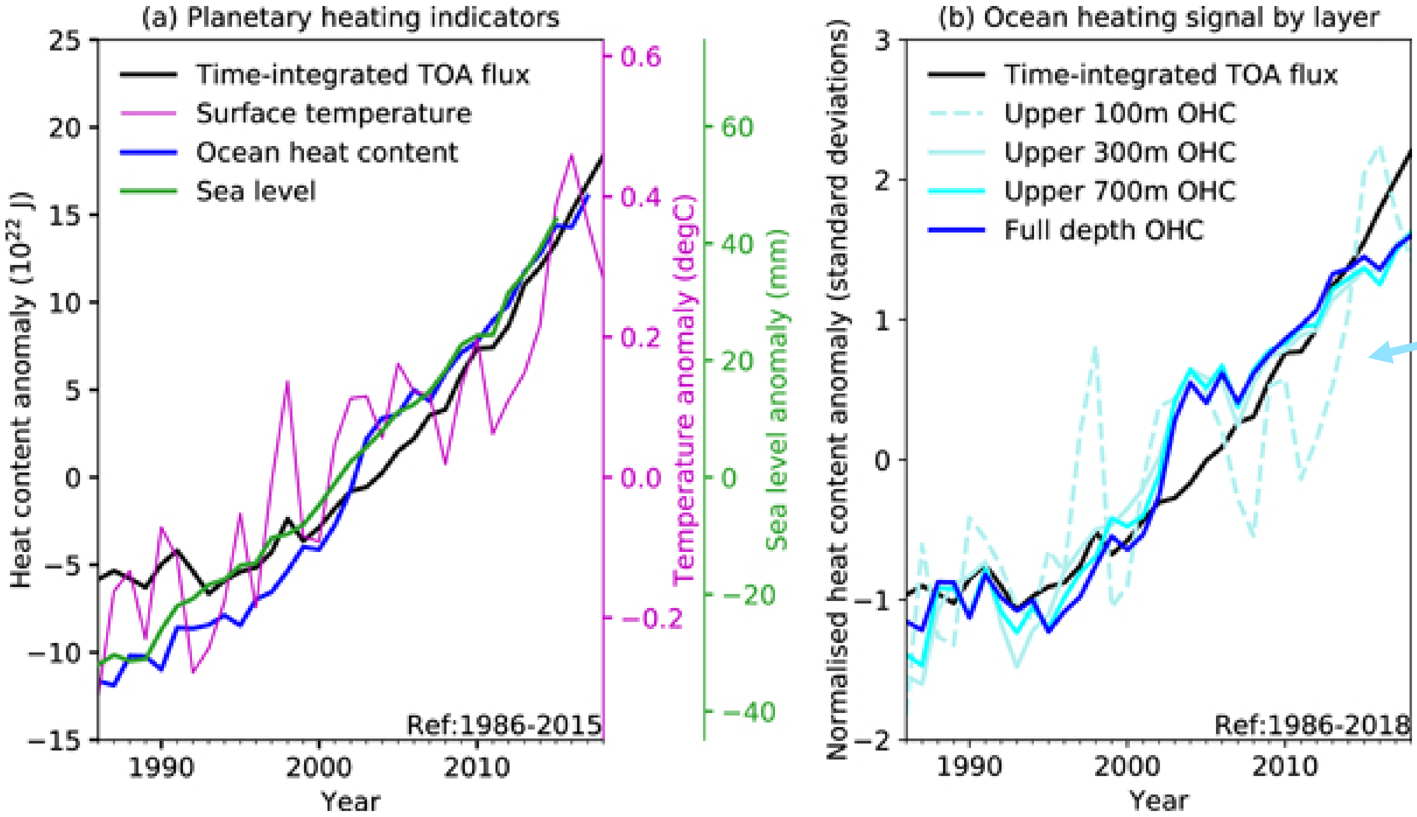


Allison et al. (2020) ERC doi:10.1088/2515-7620/abbb39

See also Cheng et al. 2017 Sci. Adv.

Heating:

- 1985-1999: **0.10 ± 0.61 W m^{-2}**
- 2000–2016 **0.62 ± 0.1 W m^{-2}**

Liu et al. 2020 Clim. Dyn

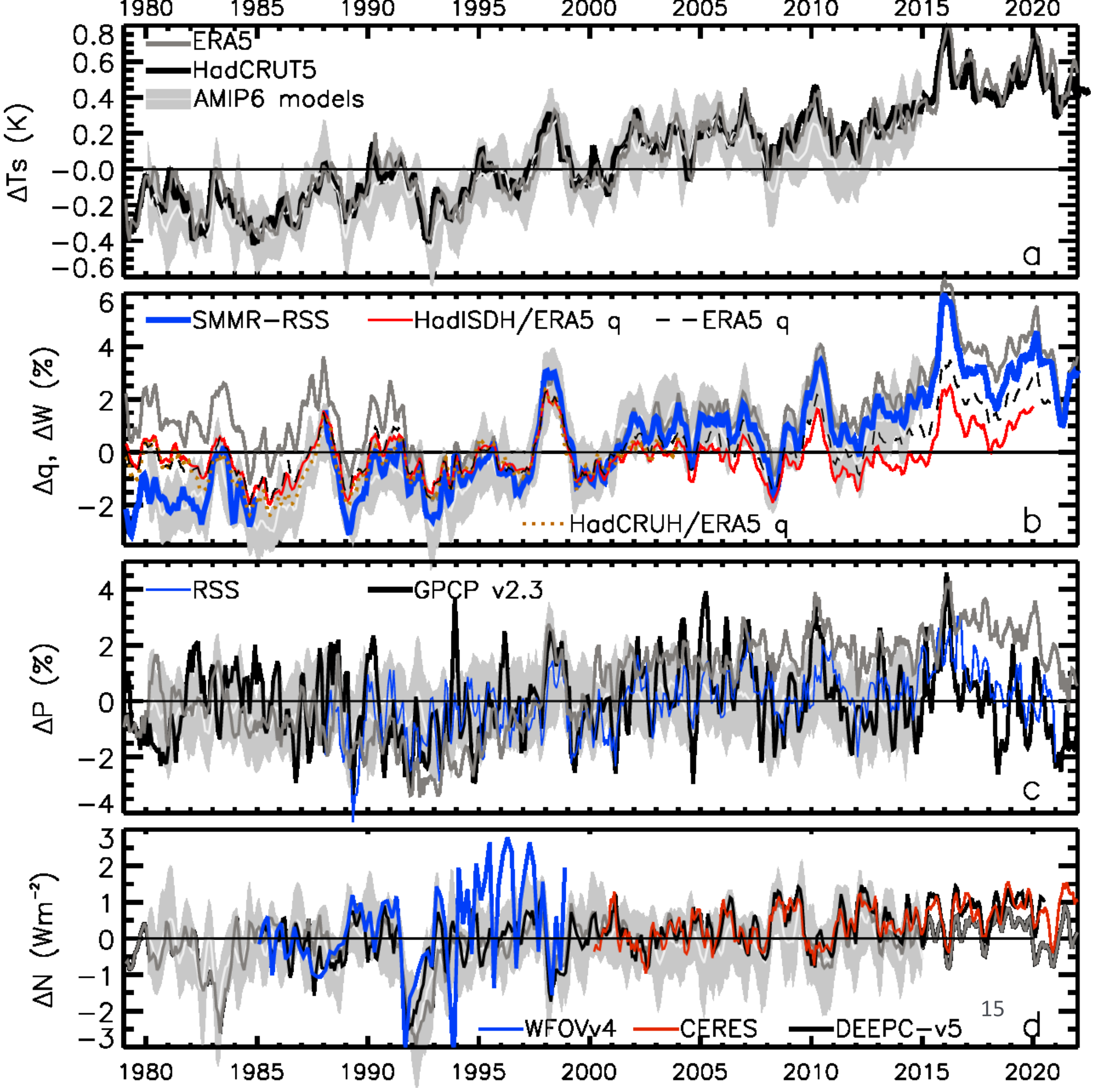
- Surface temperature determined by upper mixed layer ocean heat e.g. Allan (2018) Nature Clim.

Next section on OHC (Boyer/ Lyman/Johnson/Barnoud)

Can we measure acceleration of climate change? (Norman Loeb talk; von Shuckmann et al. (2022) ESSD submitted)

CURRENT ENERGY & WATER CYCLE CHANGES

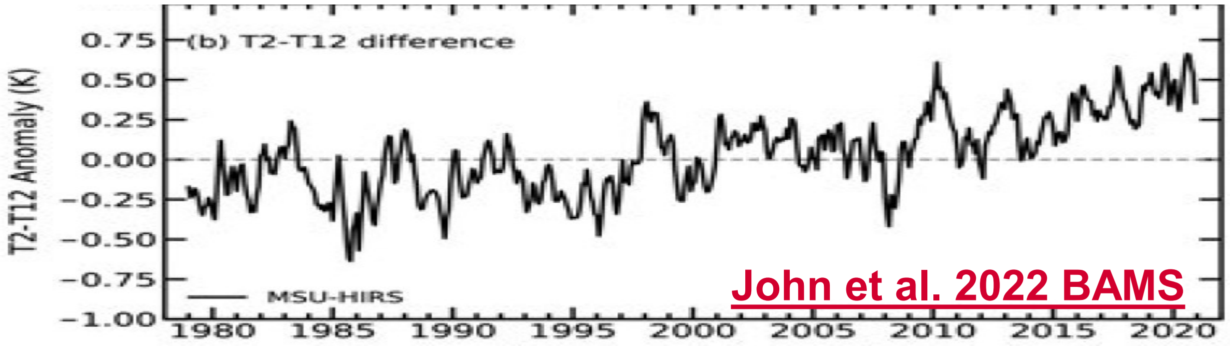
- Step-climate change?
- Water vapour obeys (for microwave/AMIP)
- ERA5 realistic net energy & moisture after 1980s, chaotic global precipitation & P-E
- Increasing CERES net energy, not in ERA5



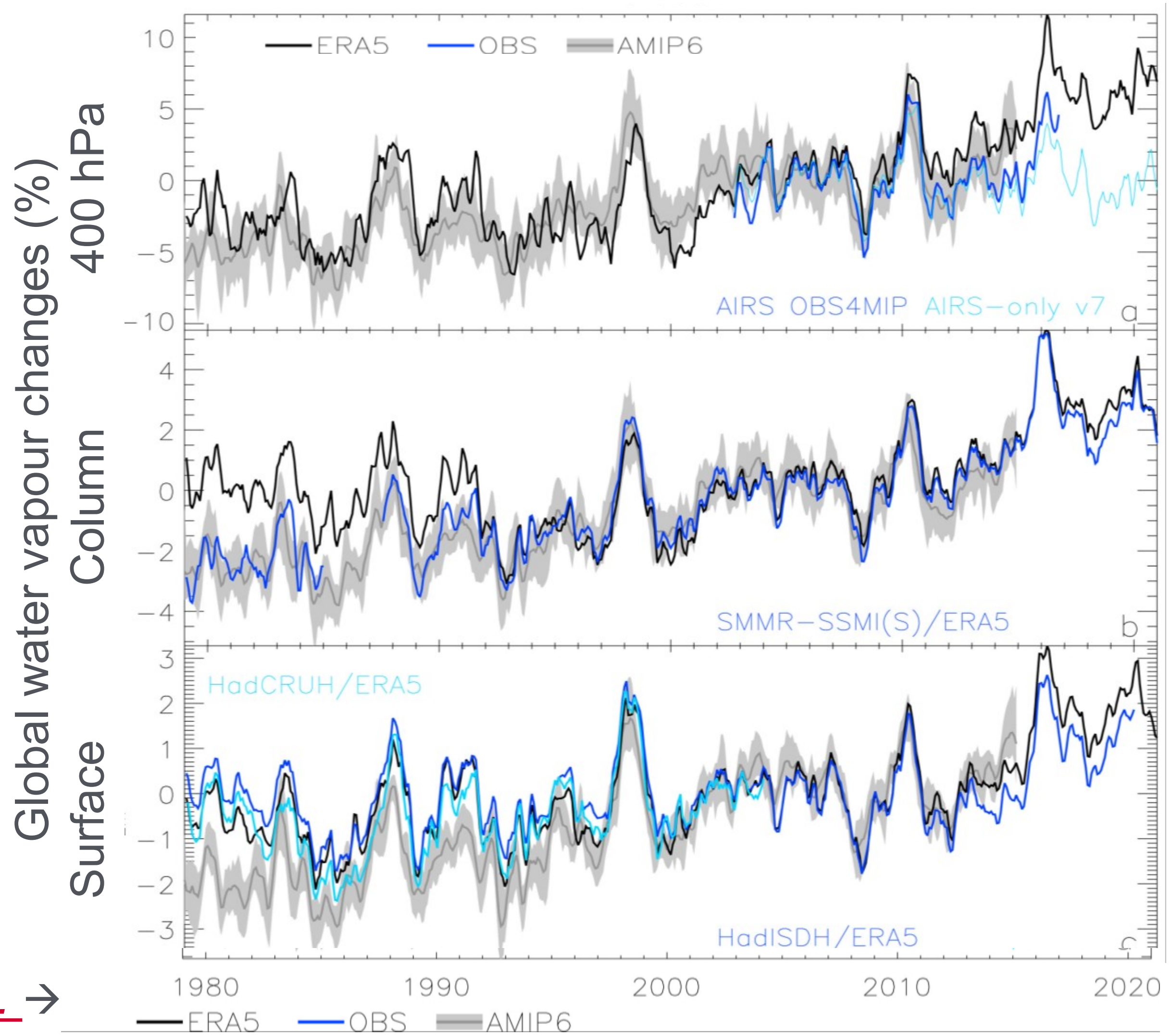
WATER VAPOUR CHANGES

See Helen Brogniez's talk!

- Total water vapour increasing about 1% per decade in observations and simulations → increased SW abs/LW↓ **(e.g. Seiji Kato, Martin Wild talks?)**
- Robust increase in water vapour with surface temperature on interannual time-scales
  - ~5%/^{o}C near surface up to ~15%/^{o}C at 300 hPa
  - Larger increases in upper troposphere an expected consequence of thermodynamics
- Spurious trends in some datasets? ERA5 decreases before 1990s over ocean; HadISDH surface observations; AIRS satellite observations
  - CMIP6 simulations overestimate warming & moistening (Pattern effect?/**Tim Andrews talk**)
  - Powerful additional observational constraint on climate change e.g. Douville et al. submitted



John et al. 2022 BAMS



Allan et al. (2022) J. Geophys. Res. →

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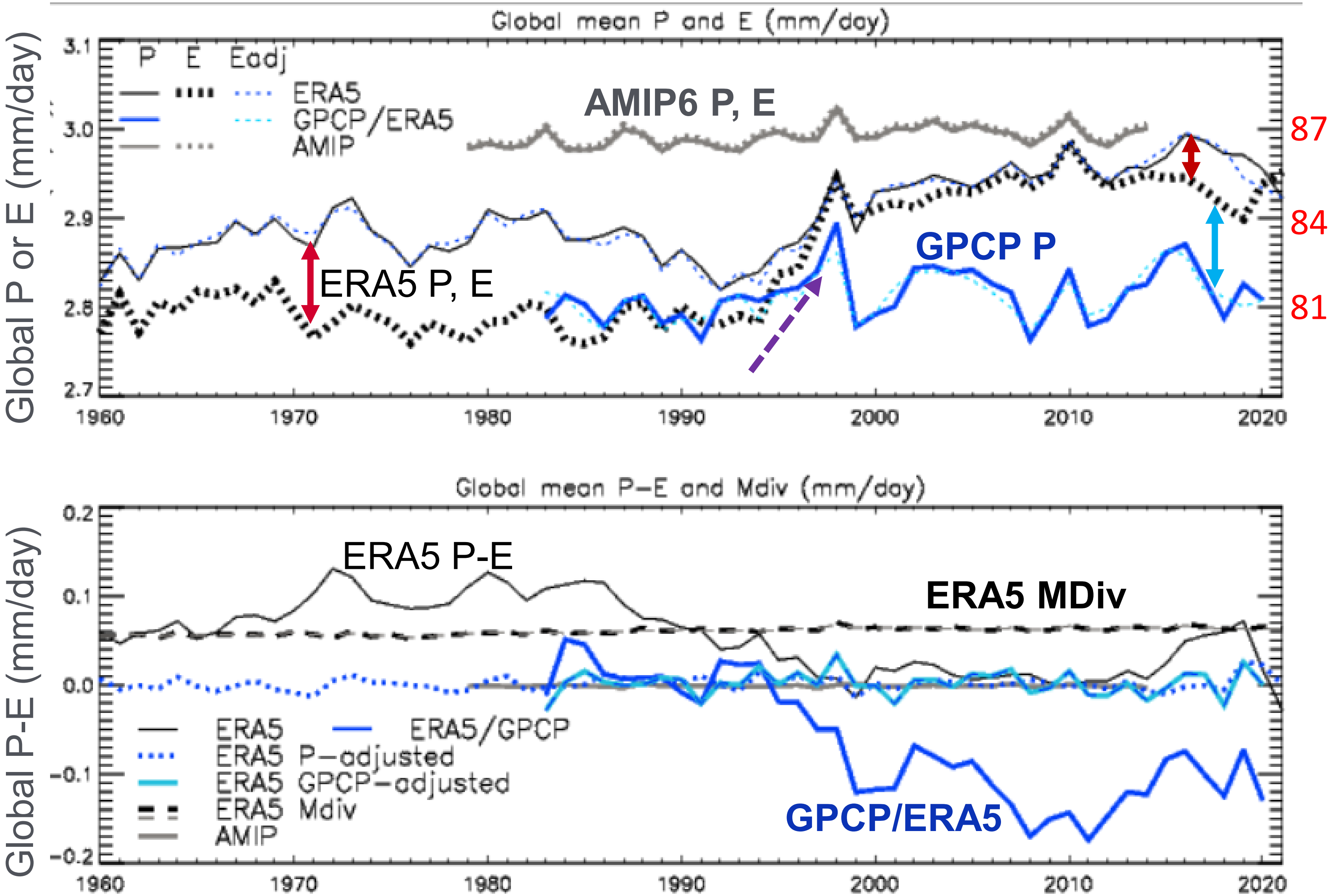
GLOBAL PRECIPITATION MINUS EVAPORATION



- ERA5:
  - P-E > 0 before 1990s (also late 2010s)
  - Large increase in E in 1990s
  - Moisture divergence as proxy for P-E quite stable (but positive)
- ERA5 E close to GPCP P in 1980s, larger after
- **AMIP6 P-E ~ 0**
- P: AMIP6 > ERA5 > GPCP

OUTSTANDING QUESTIONS

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- Where is climate monitoring relevant?
  - processes/diagnostics/early warning….?
- How can long term stability/continuity in observational records be ensured/prioritised?
  - Assume long-term records wrong unless good corroborating evidence?
  - How are gaps best dealt with?
- Can reanalyses be constructed to close energy/water cycles? (see Mike Bosilovic talk)
- What is best way to combine models/reanalyses/observations (model-data fusion)
- How can global constraints be made relevant to local impacts?
- Is model discrepancy in pattern effect (e.g. England et al. 2014 Nature Climate; Seager et al. 2019 Nature Clim.; Wills et al. 2022 GRL; **Tim Andrews talk**) evident in energy budget/water cycle responses
- Toward consistent energy/water/sea level budgets; toward net zero world