Department of Meteorology

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RECONSTRUCTION OF GLOBAL ENERGY BUDGET 1985 – PRESENT

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MULTI-DECADAL EARTH'S RADIATION BUDGET RECORD

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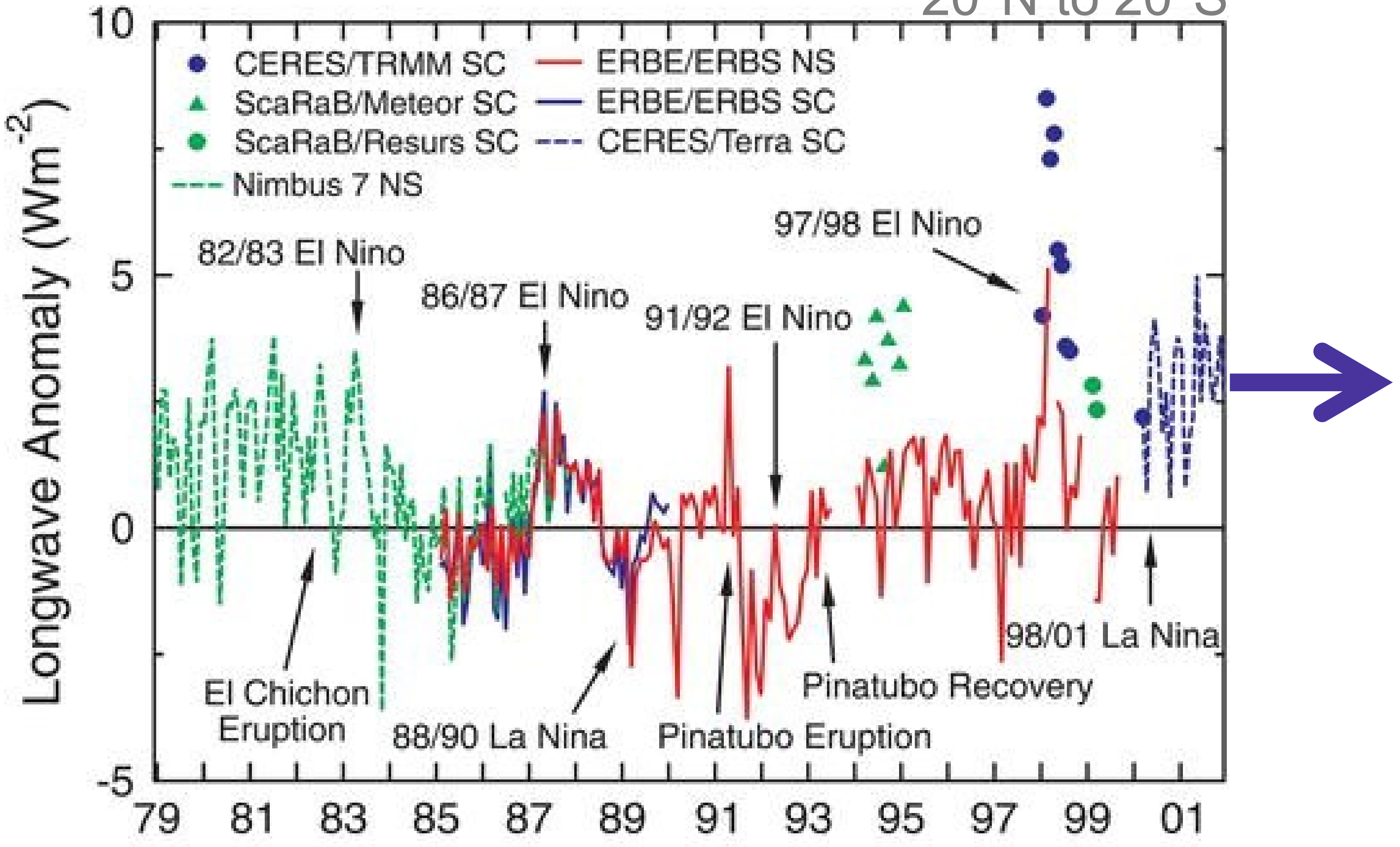
- Diagnose global climate forcing and feedback response
- Evaluate regional radiative processes related to climate
- Understand drivers of variability and trends
- Homogeneity and calibration issues
- Consistency with heat content/sea level e.g. Loeb et al. (2012) Nat. Geosci; Allison et al. (2020) ERC;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

20°N to 20°S

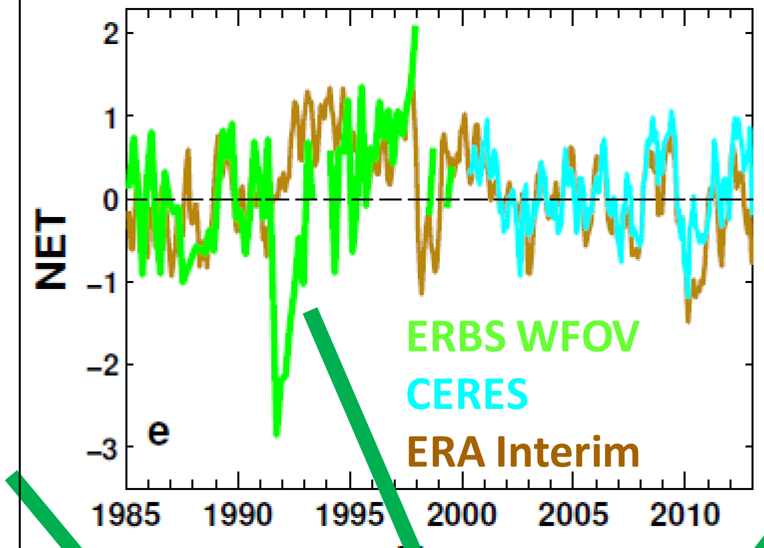


Wong et al. (2006) J Clim; Wielicki et al. (2002) Science

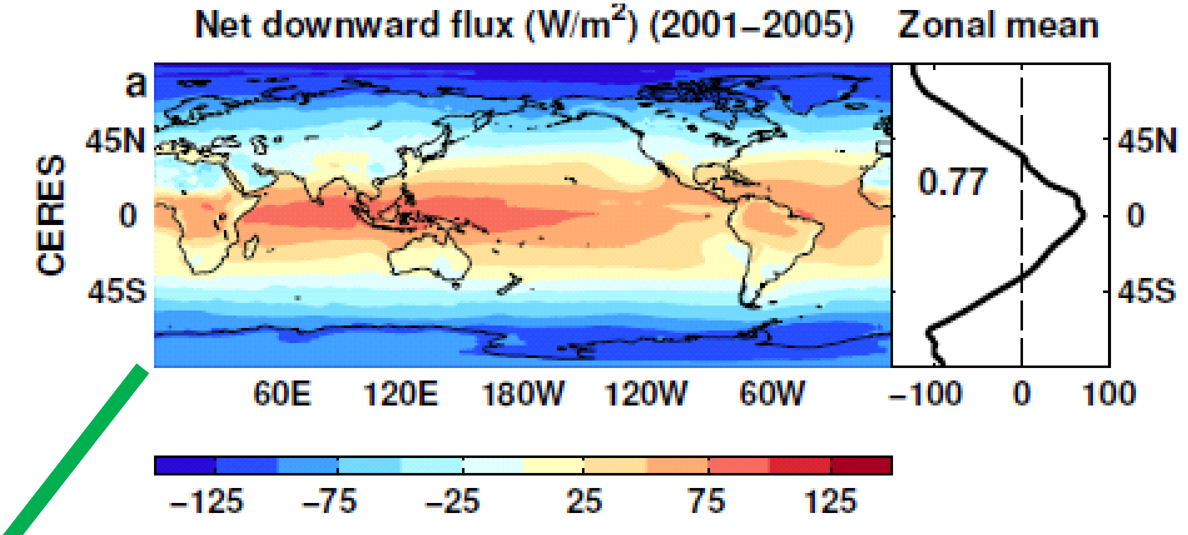
RECONSTRUCTING GLOBAL TOP OF ATMOSPHERE RADIATIVE FLUXES PRIOR TO 2000 (PART OF "DEEP-C" PROJECT)

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

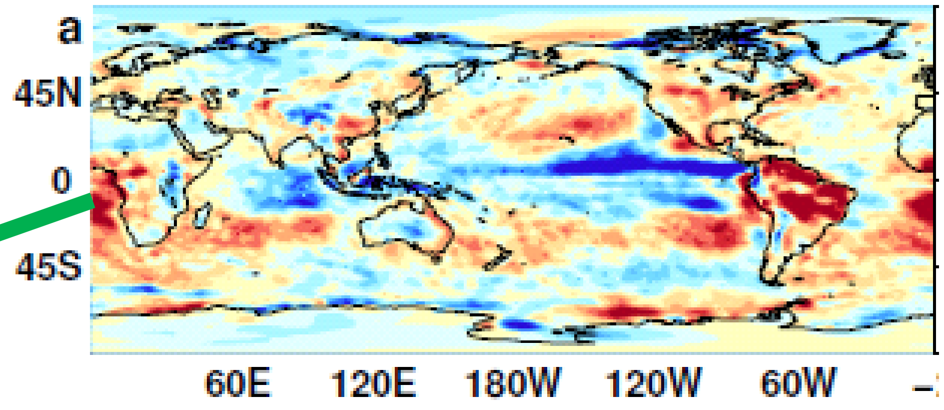
ERBS/CERES variability



CERES monthly climatology



ERA Interim spatial anomalies



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

[Allan et al. (2014) GRL]

AMIP6 CONSTRAINT ON GAPS IN RECORD

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- Standard deviation of multi-model mean net difference:
  - 0.12 Wm^{-2} at 1999 gap
  - 0.51 Wm^{-2} at 1993 gap
- Less well constrained by models at 1993 gap due to Pinatubo aerosol
- Could we assume no change in WFOV calibration at 1993 gap?
- Future constraint could use large ensembles to better account for internal climate variability
- Other data/nudged models?

AMIP6 Model	1999 gap			1993 gap		
	Before	After	Difference (After minus Before)	Before	After	Difference (After minus Before)
BCC-CSM2-MR	2.18	2.25	**0.07**	0.75	1.94	**1.20**
CESM2	3.38	3.60	**0.22**	3.66	3.38	**-0.28**
CNRM-CM6-1	0.54	0.65	**0.11**	-0.05	0.27	**0.32**
EC-Earth3-Veg	-0.19	0.12	**0.31**	-1.31	-0.32	**0.99**
FGOALS-f3-L	-0.89	-0.73	**0.17**	-1.68	-0.92	**0.76**
HadGEM3-GC31-LL	0.39	0.45	**0.06**	-1.01	0.14	**1.14**
IPSL-CM6A-LR	2.38	2.64	**0.26**	1.32	2.14	**0.82**
MIROC6	0.21	0.34	**0.13**	-0.74	0.02	**0.76**
MRI-ESM2-0	2.09	2.54	**0.44**	1.11	2.02	**0.90**
SAM0-UNICON	2.36	2.61	**0.25**	2.54	2.41	**-0.13**
Multi-model mean	1.25	1.45	**0.20**	0.46	1.11	**0.65**

NEW ESTIMATES OF SURFACE ENERGY FLUX

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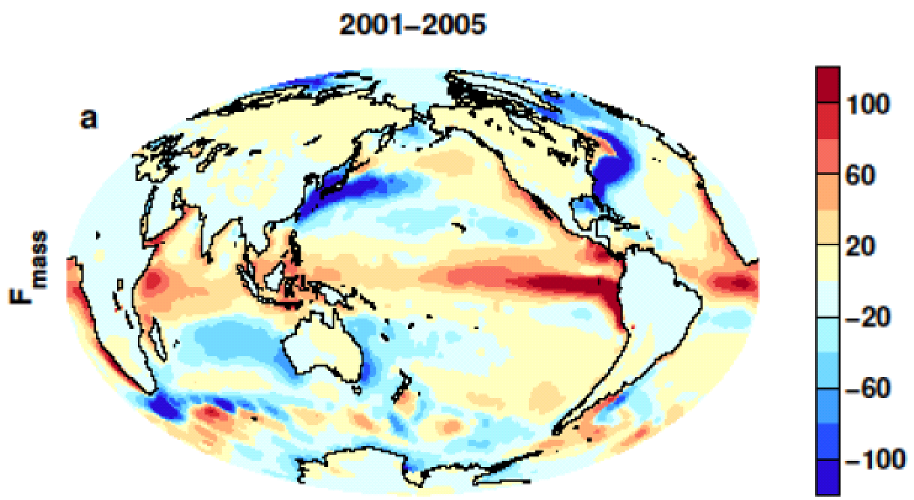
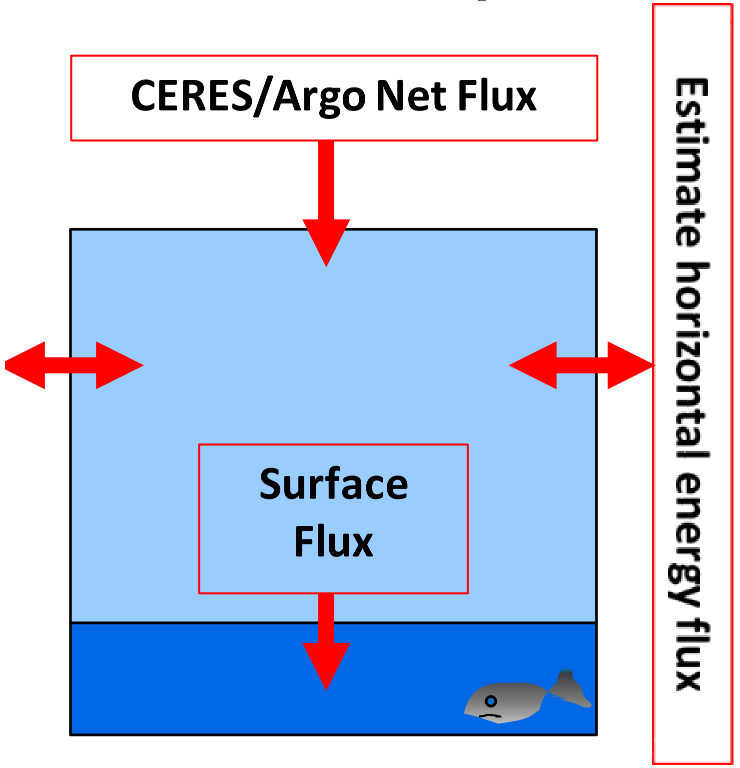
$$F_{SFC} = F_{TOA} - \frac{\partial TE}{\partial t} - \nabla \cdot \frac{1}{g}\int_0^1 V(Lq + C_pT + \varphi_s + k)\frac{\partial p}{\partial \eta}d\eta$$



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

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



- Unrealistic regional anomalies over land compared to temperature change
- Correction applied based on combined modelling and observations
- Improvements to AMIP adjustments, land correction and account for enthalpy

Liu et al. (2020) Clim. Dyn.

CURRENT ENERGY BUDGET CHANGES

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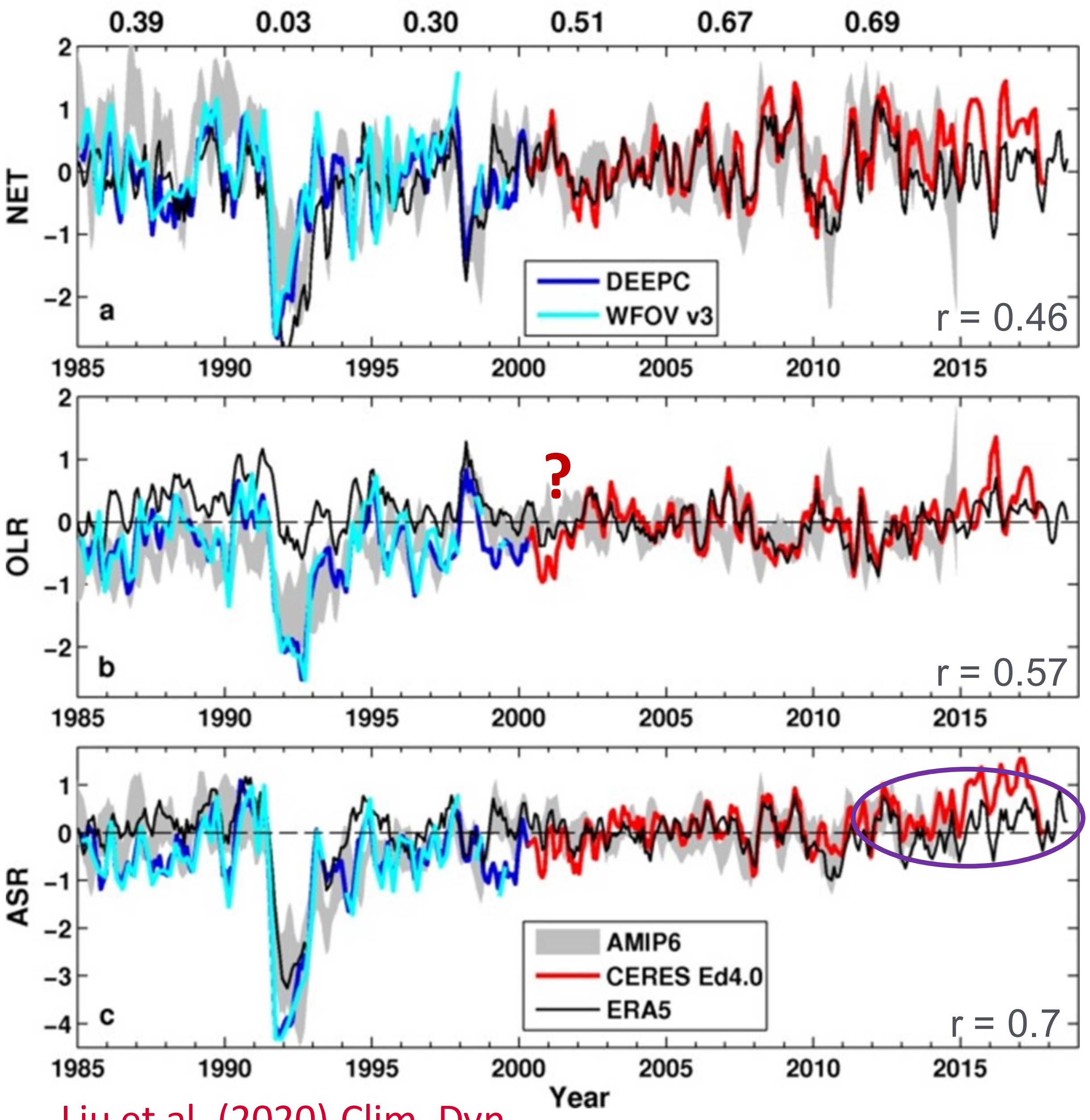


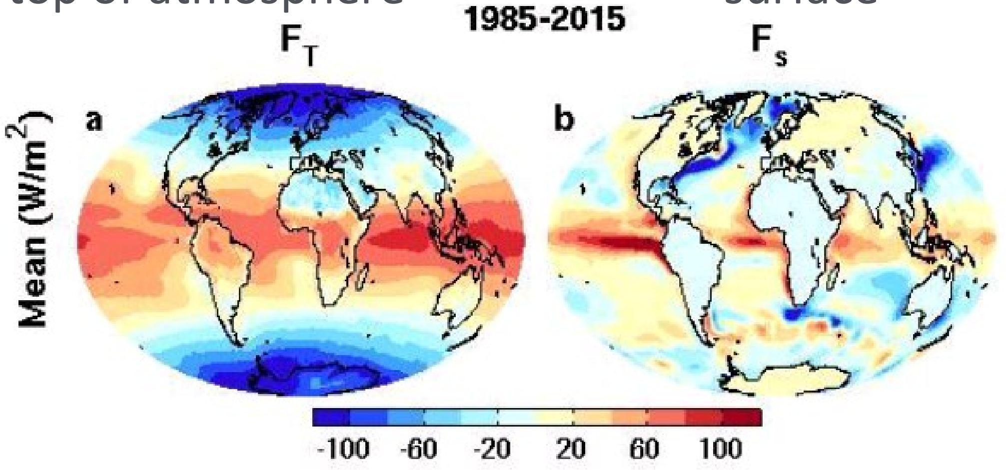
Liu et al. (2020) Clim. Dyn.

- Preliminary comparison with AMIP6 and ERA5
- Net imbalance: 1985–1999 to 2000–2016
  - 0.10 ± 0.61 W m^{-2} to 0.62 ± 0.1 W m^{-2}
  - ± 0.1 W m^{-2} Argo uncertainty + homogeneity
- 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?

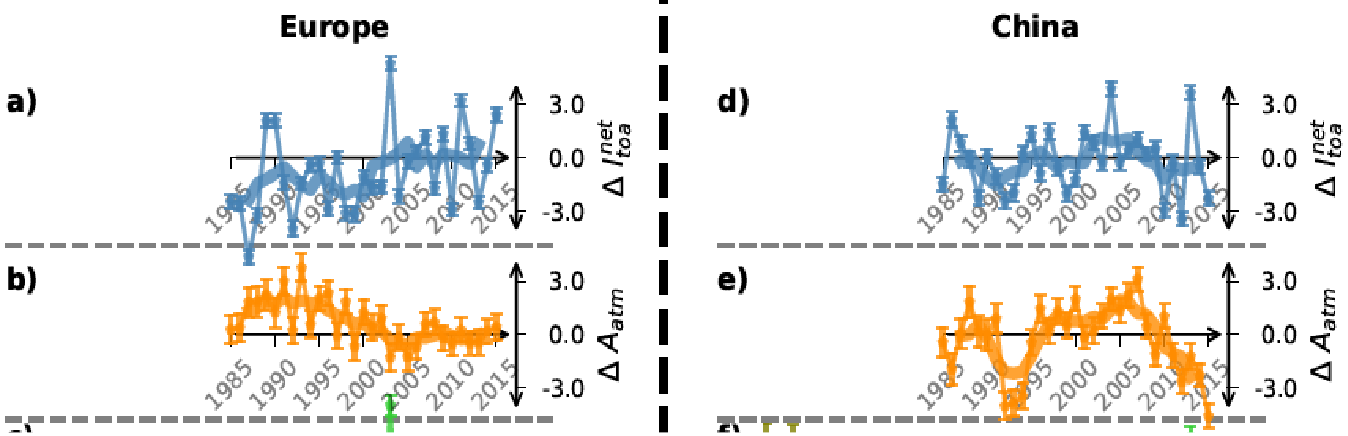
FURTHER APPLICATIONS

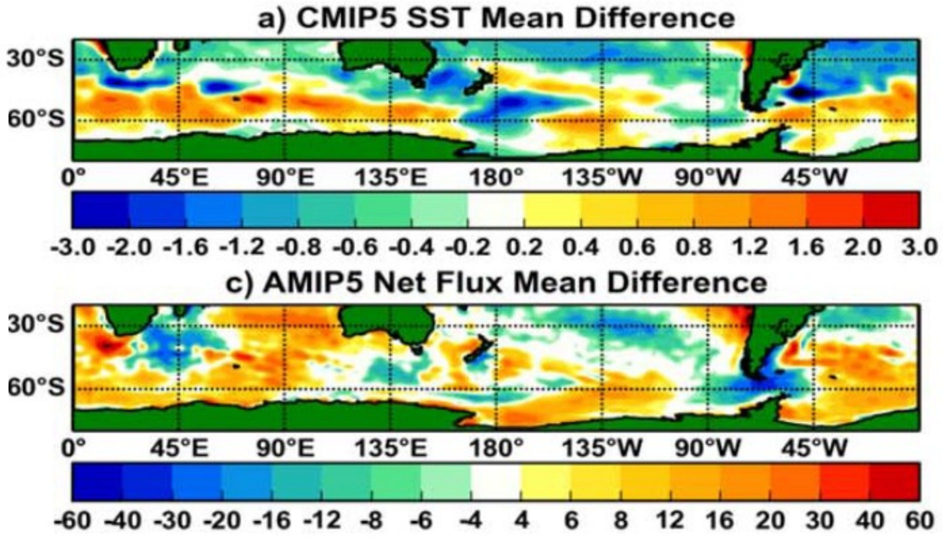
- Earth system heating
  e.g. Allison et al. (2020) ERC; Cheng et al. 2017 Sci. Adv.
- Evaluation of models, reanalyses, satellite products
  e.g. Williams et al. (2018) *JAMES*; Wittenberg et al. (2018) *JAMES* ; Roberts et al. (2018) *GMD*; Sus et al. (2018), …
- Evaluation of cloud biases & feedbacks:
  Hyder et al. (2018) *Nature Comms*; Loeb et al. 2020 GRL
- North Atlantic Heat transports:
  Brydon et al. (2020) J. Clim; Menary et al. (2020) GRL
- Volcanic radiative responses: Schmidt et al. (2018) JGR
- Aerosol / energy budget: Schwarz et al. (2020) Nature Geosci.

top of atmosphere   surface

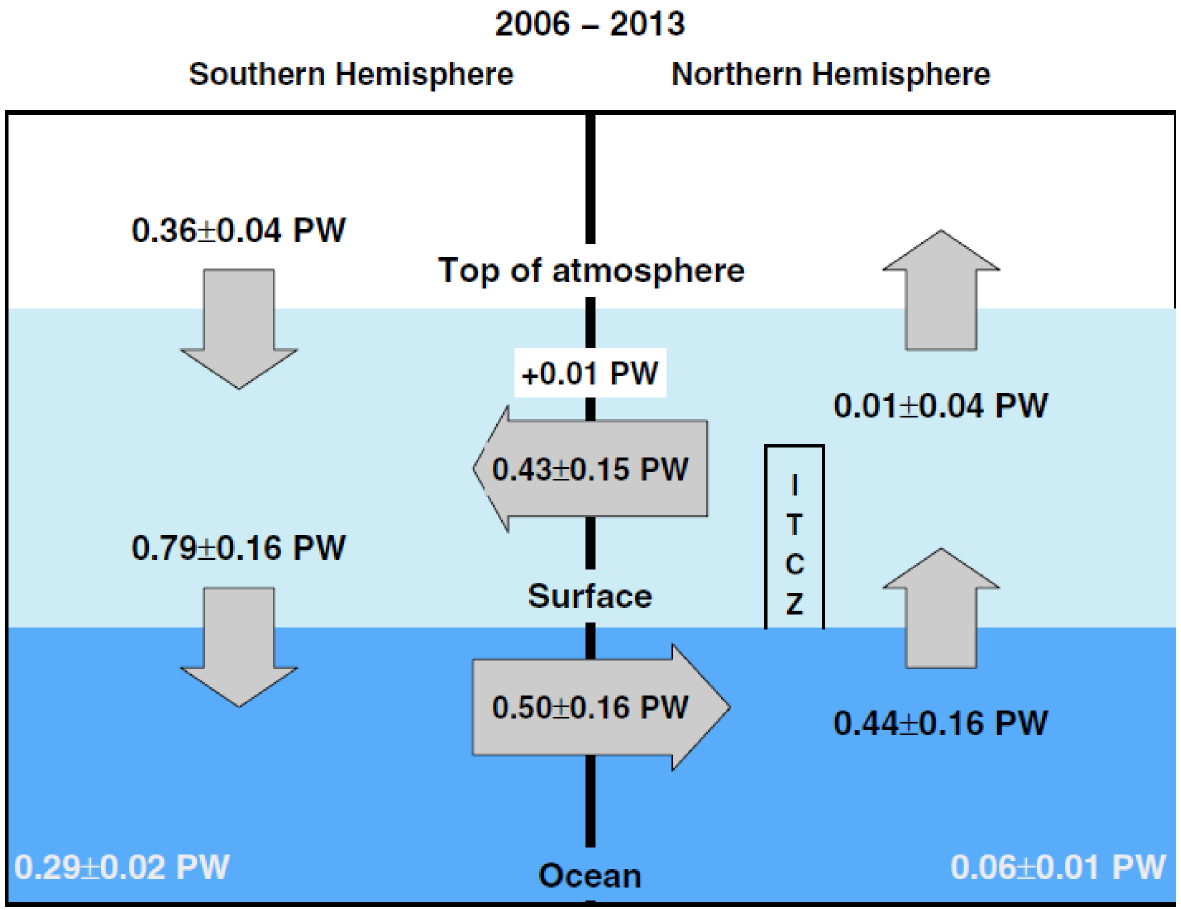


Data: doi.org/10.17864/1947.111





HEMISPHERIC ASYMMETRY IN EARTH'S ENERGY BUDGET



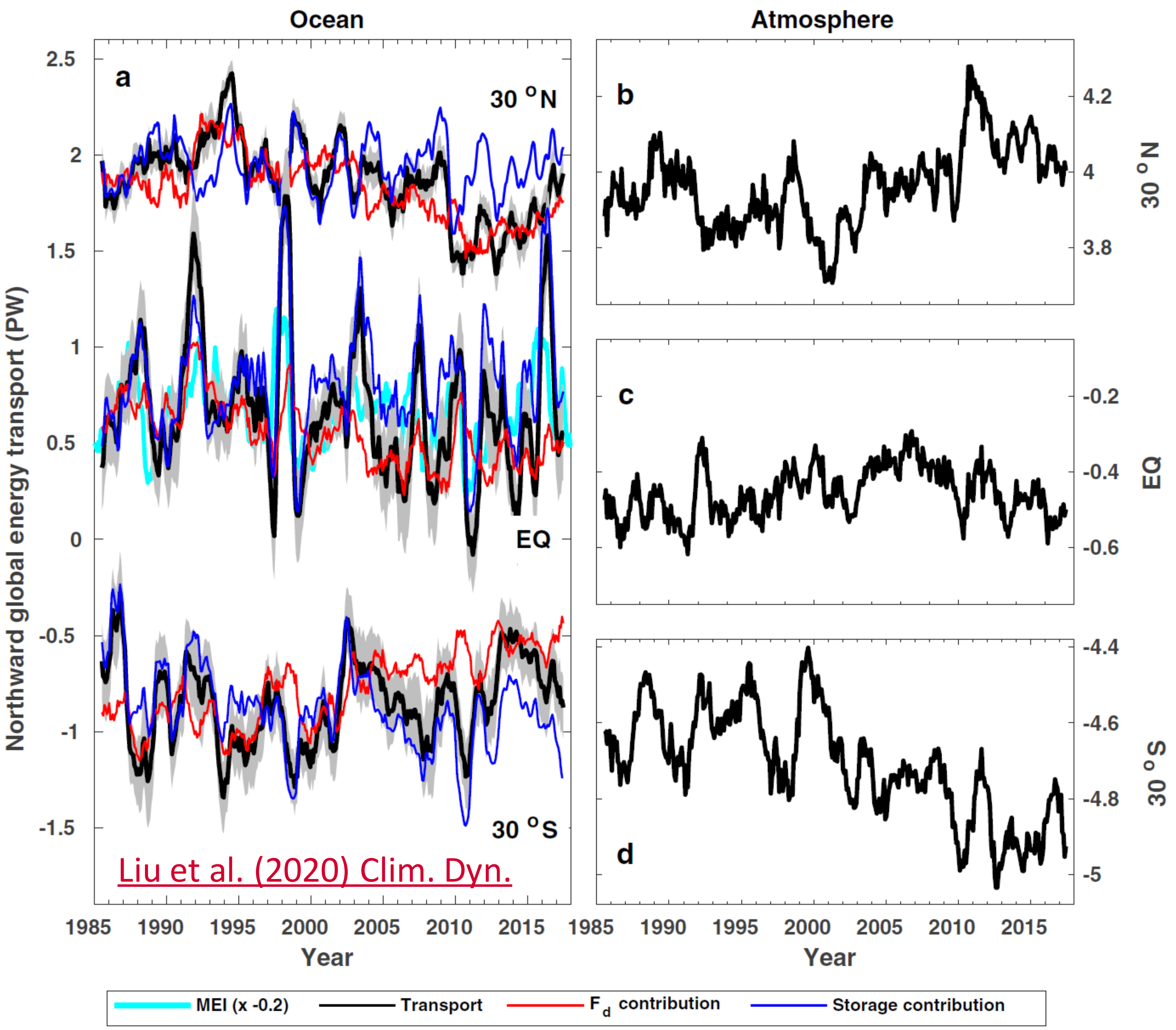
Liu et al. (2020) Clim. Dyn.

- 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, Desbruyeres et al. (2016) GRL or ORAS4 reanalysis)

Careful with days per month & enthalpy transfers!



Liu et al. (2020) Clim. Dyn.

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?

INFERRED OCEAN ENERGY TRANSPORTS@26N

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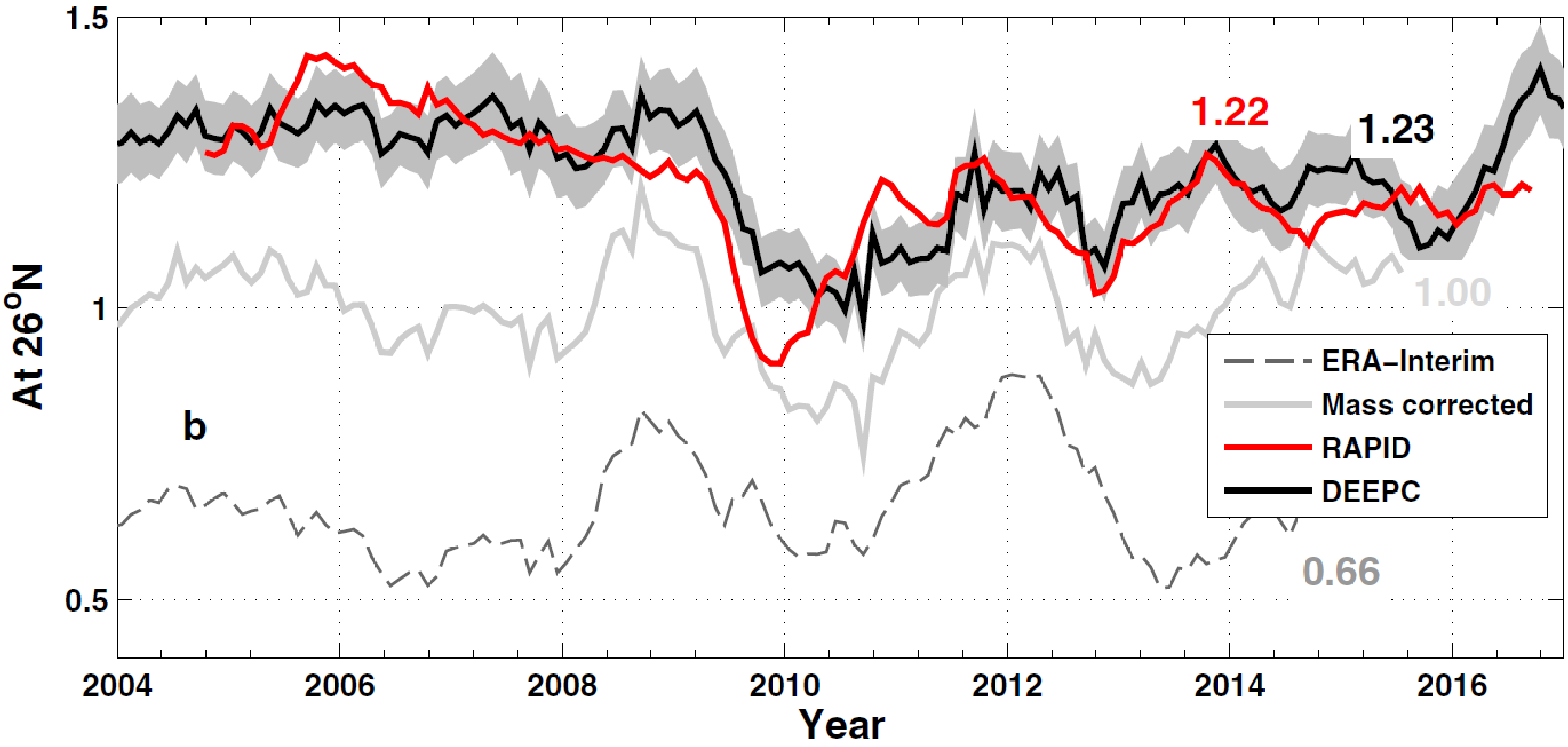

Liu et al. (2020) Clim. Dyn. after Trenberth & Fasullo, 2017 GRL

RECENT UPDATES TO DEEP-C DATASET (V5)

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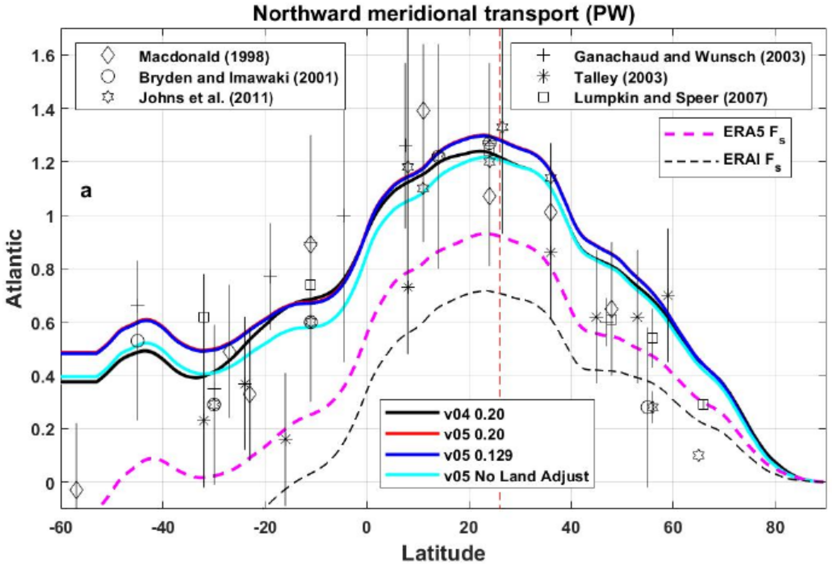
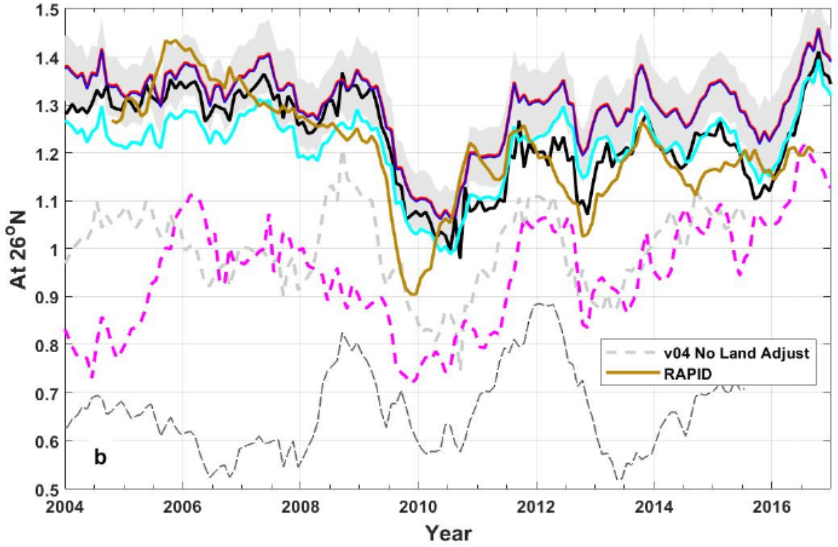


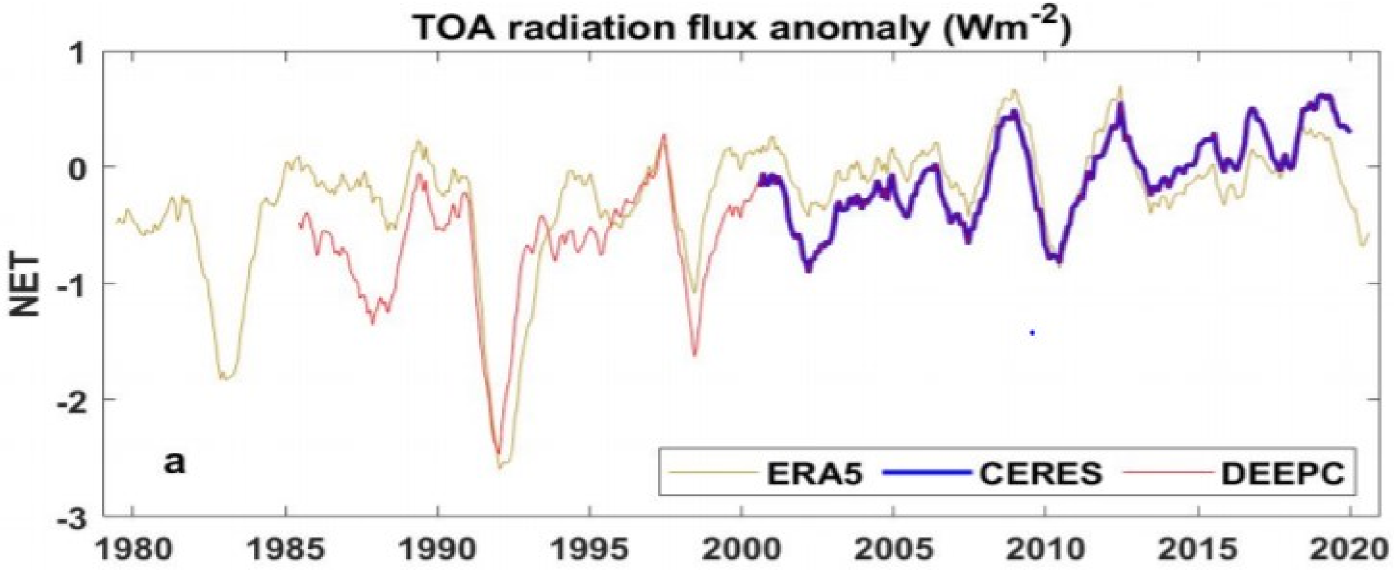


Update to Liu et al. (2020)

- Update of TOA radiation dataset to 2020, CERES v4.1 (v5)
- Update to ERA5; account for enthalpy in surface flux estimates
- Updated land heat flux Cuesta-Valero et al. 2021

← ocean heat transports (left)

- Continued wider use of dataset (Met Office, ETH, etc)
- Major science questions: how is energy budget driving and responding to climate change & influencing global water cycle e.g., Allan et al. (2020) NYAS, →IPCC



SUMMARY

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- Variability in Earth's energy budget & hemispheric flows important climate diagnostic
- Gaps in record present major issue in assessing changes in energy budget crucial in understanding radiative forcing, heating of the system and feedback response
- Ensuring stability of record (including calibration) vital
- AMIP simulations a physically self consistent method to constrain gaps in energy budget record
  - CMIP6 radiative forcing estimates & observed sea surface temperature offer robust constraint
  - structural uncertainty across models & ensemble members accounting for internal variability
  - …but records then not model independent
- Longer records also help modellers interested in long climatology/earlier periods e.g IPCC use 1995-2014 as "present day"; 1985-present or 1979-present also commonly used
- Comparison to independent ocean heat content & sea level rise records good consistency check
- Combining satellite radiation budget data with reanalyses provides powerful method to estimate surface energy budget that is independent of surface energy budget calculations/measurements