Department of Meteorology

University of Reading

EVIDENCE OF ACCELERATION IN ASPECTS OF THE GLOBAL ENERGY AND WATER CYCLES

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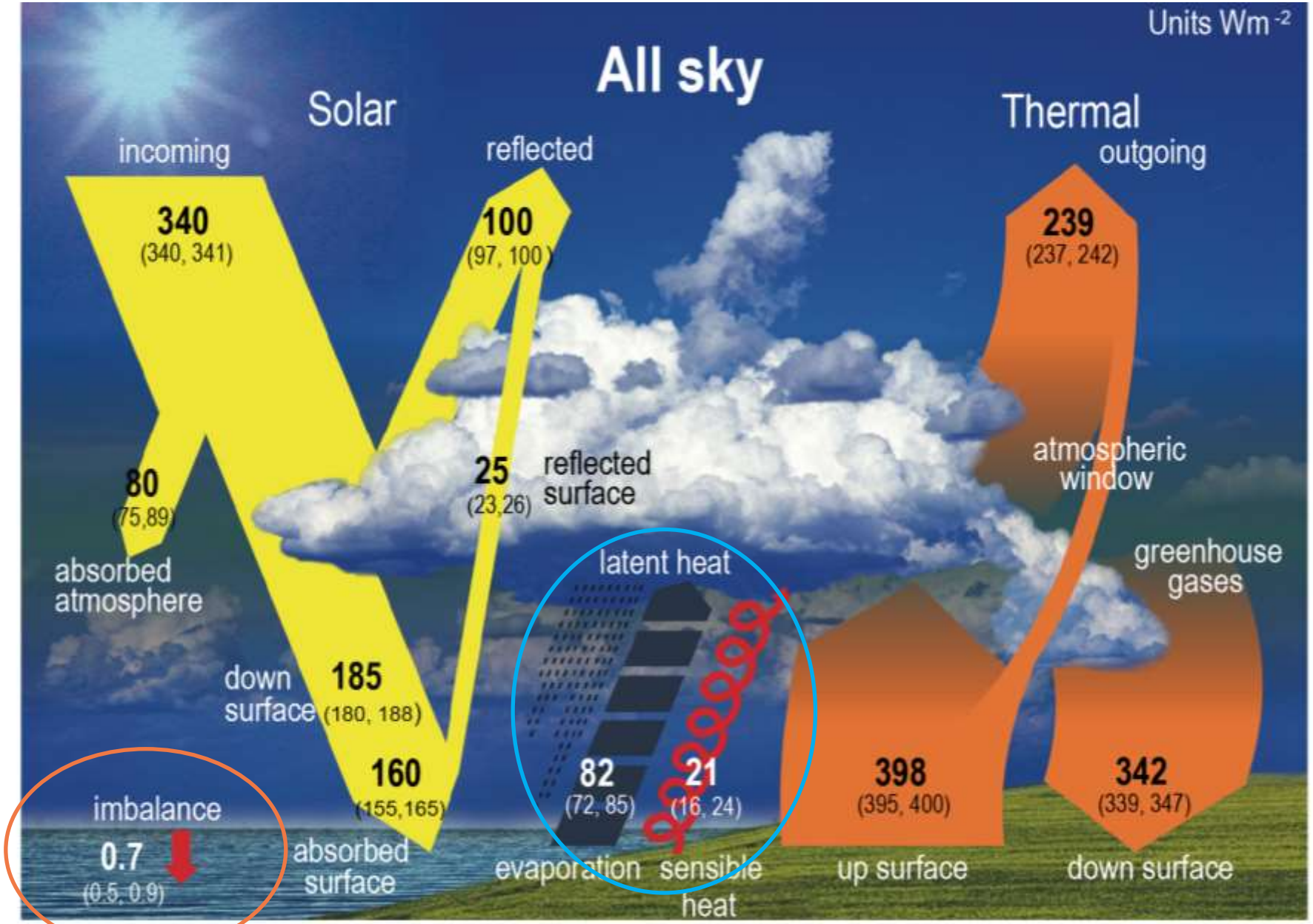
EARTH'S ENERGY BALANCE



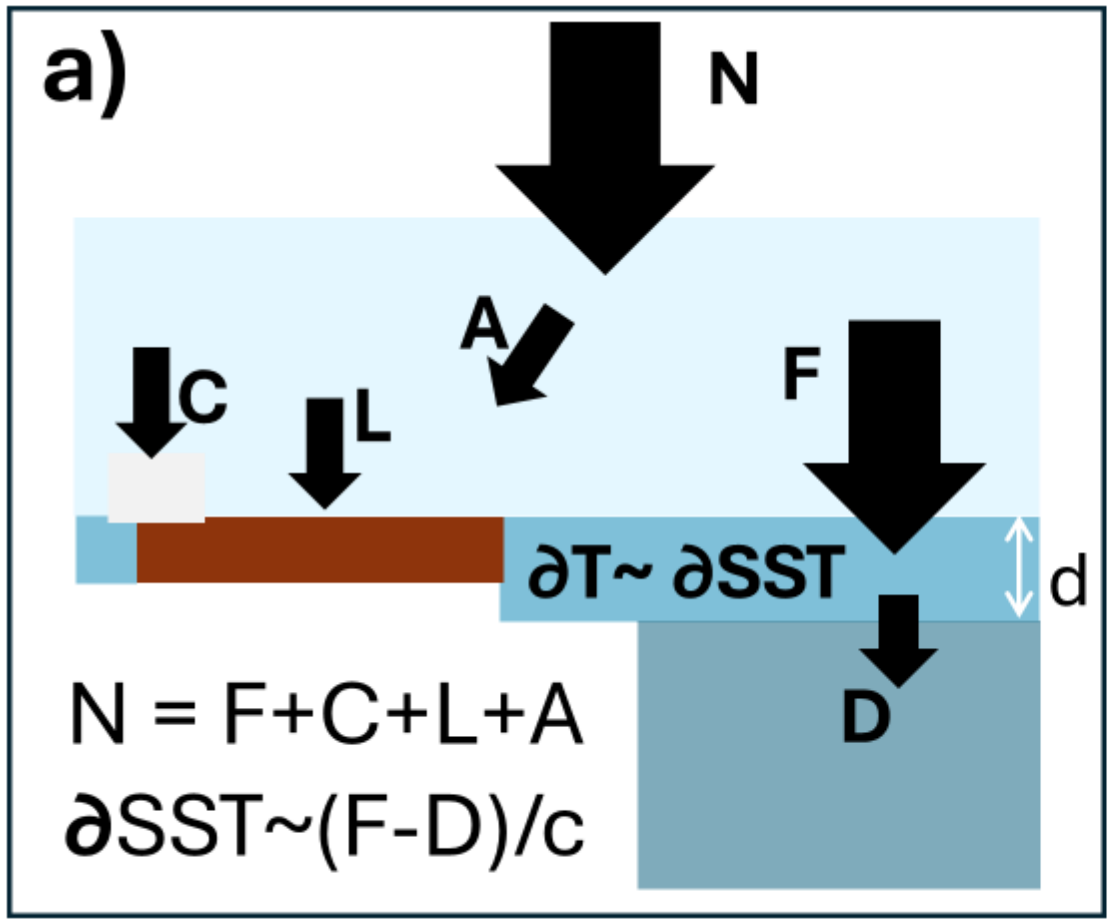
← Forster et al. (2021) IPCC WG1, Fig. 7.2

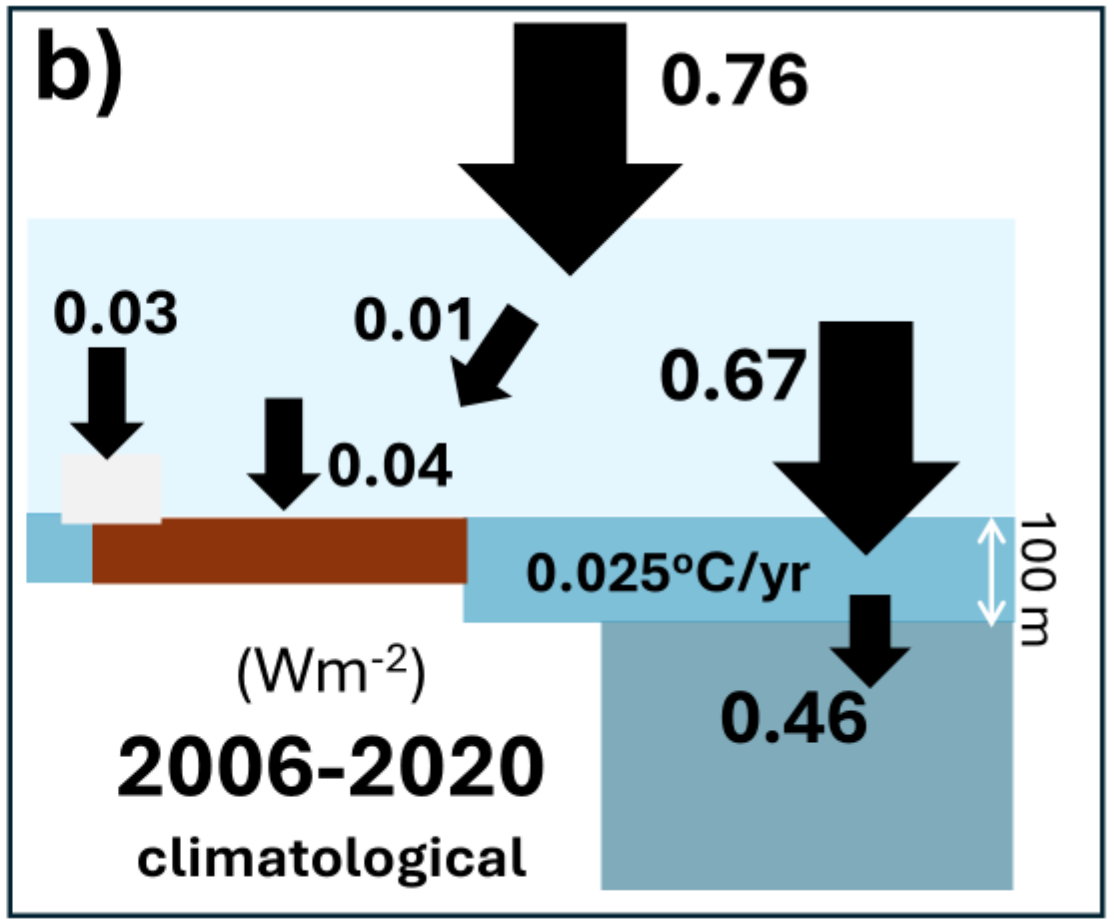
see also: Stephens et al. (2012) Nature Geosci.

Spot the imbalance…

Latest bottom up estimate 0.76 Wm^{-2} 2006-2020: von Shuckmann et al. (2023) ESSD

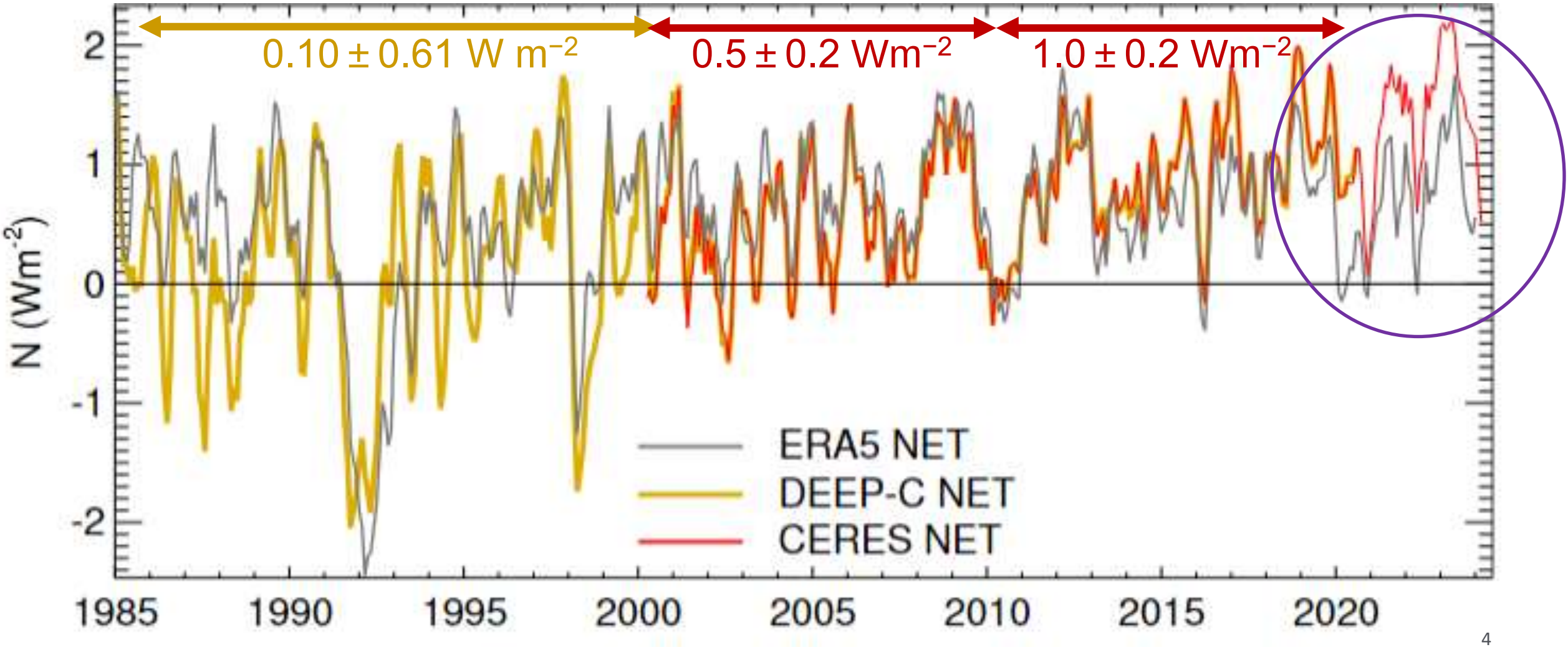
CLIMATOLOGICAL HEAT INVENTORY



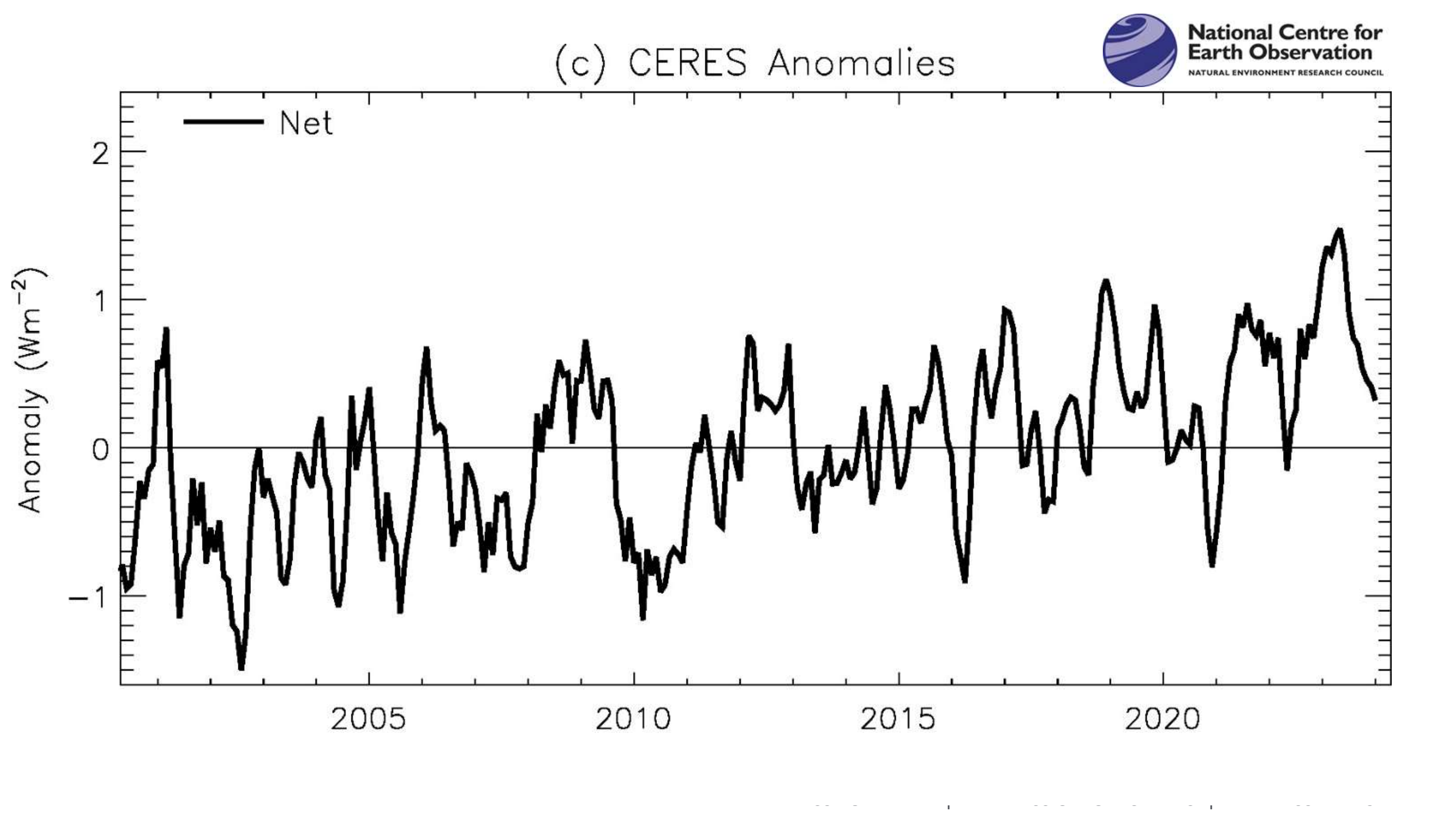


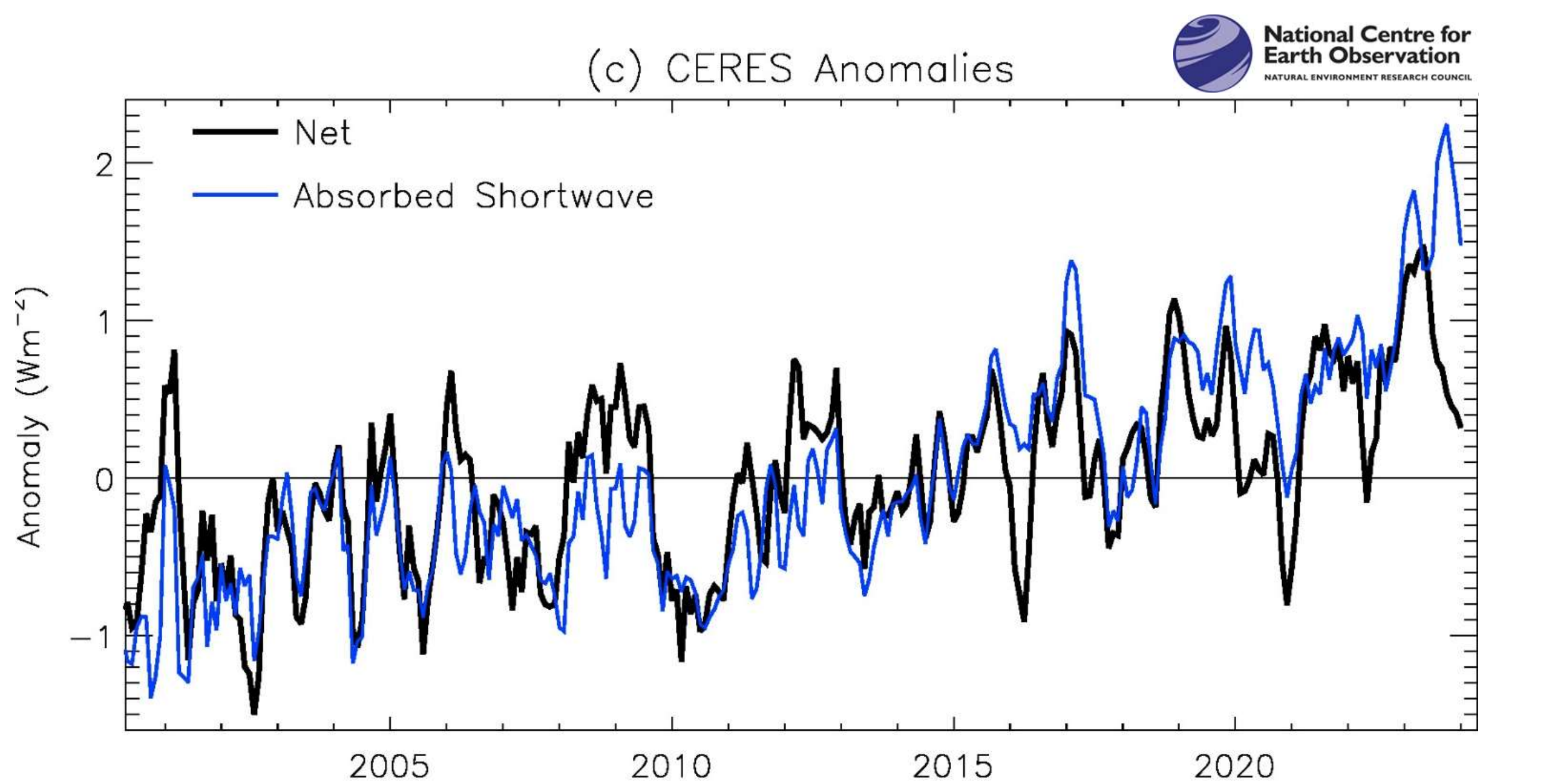
von Shuckmann et al. (2023) ESSD

INCREASING NET HEATING OF PLANET



based on Allan et al. (2014) GRL; Liu et al. (2020) Clim. Dyn.


(c) CERES Anomalies
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL
Net
Anomaly (Wm^{-2})
2
1
0
−1
2005
2010
2015
2020


(c) CERES Anomalies
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL
Net
Absorbed Shortwave
Anomaly (Wm⁻²)
2
1
0
−1
2005
2010
2015
2020

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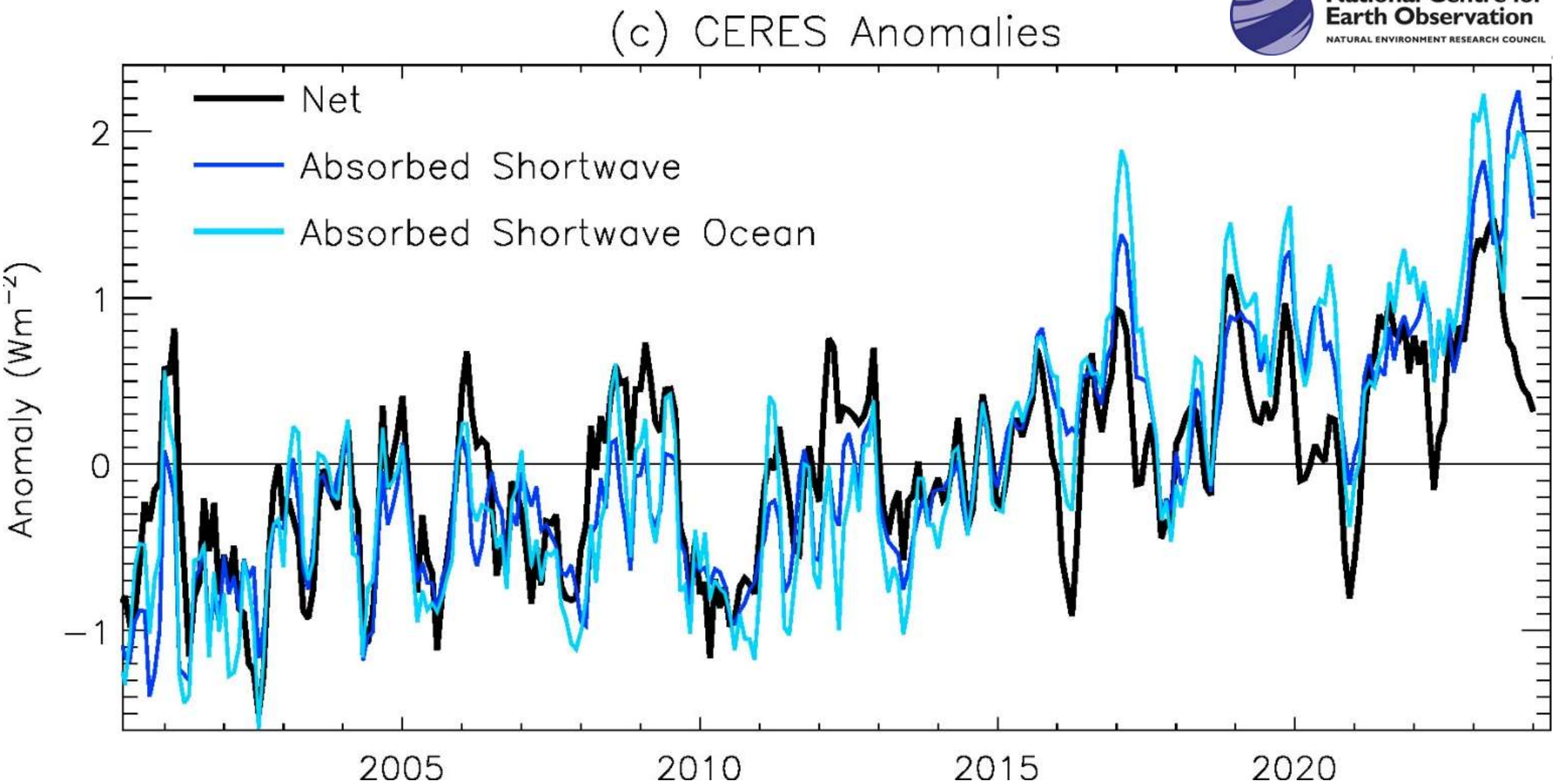

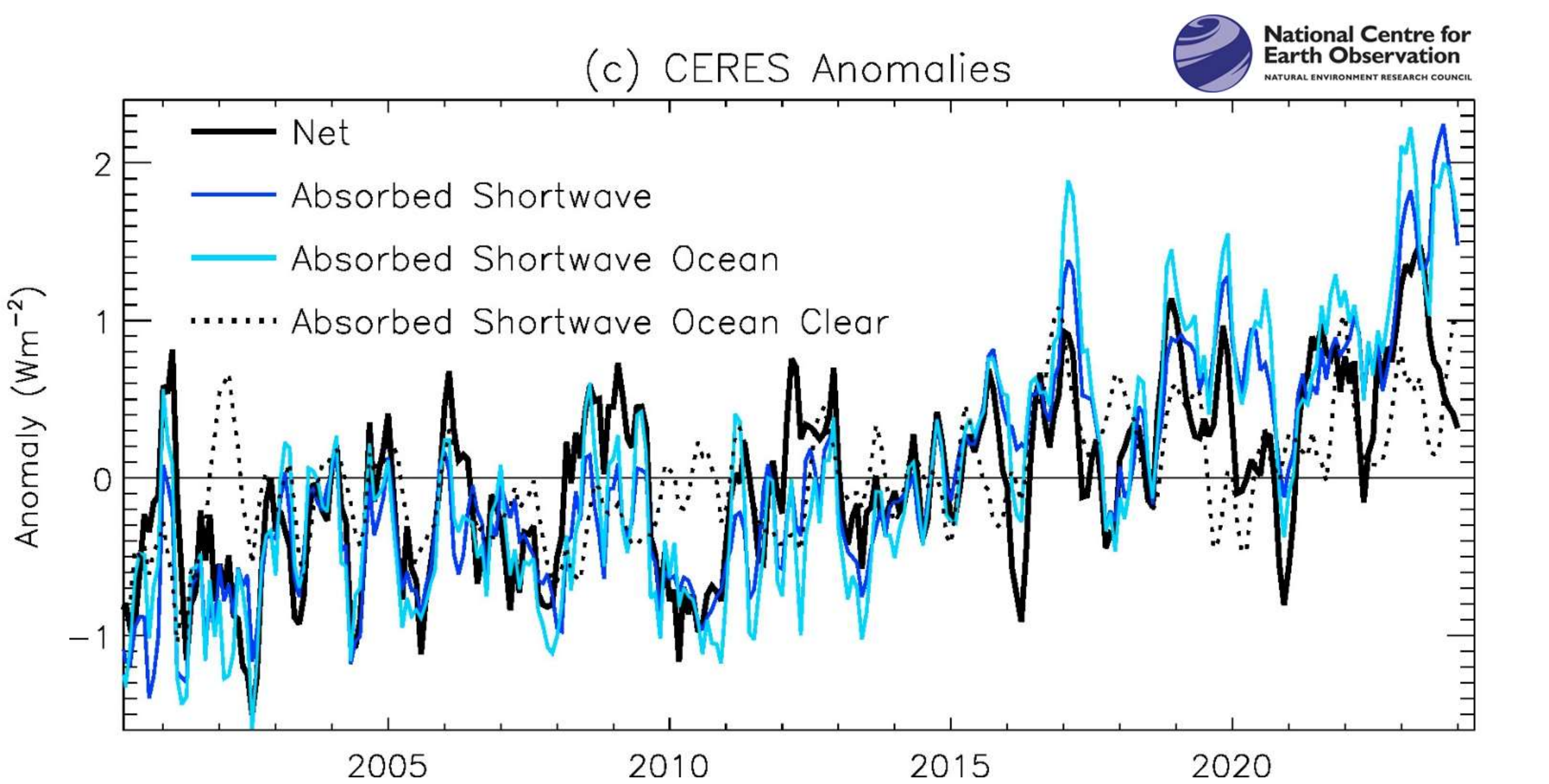
(c) CERES Anomalies
National Centre for Earth Observation
NATURAL ENVIRONMENT RESEARCH COUNCIL
Net
Absorbed Shortwave
Absorbed Shortwave Ocean
Absorbed Shortwave Ocean Clear
Anomaly (Wm^{-2})
2
1
0
−1
2005
2010
2015
2020

SPATIAL PATTERN OF IMBALANCE

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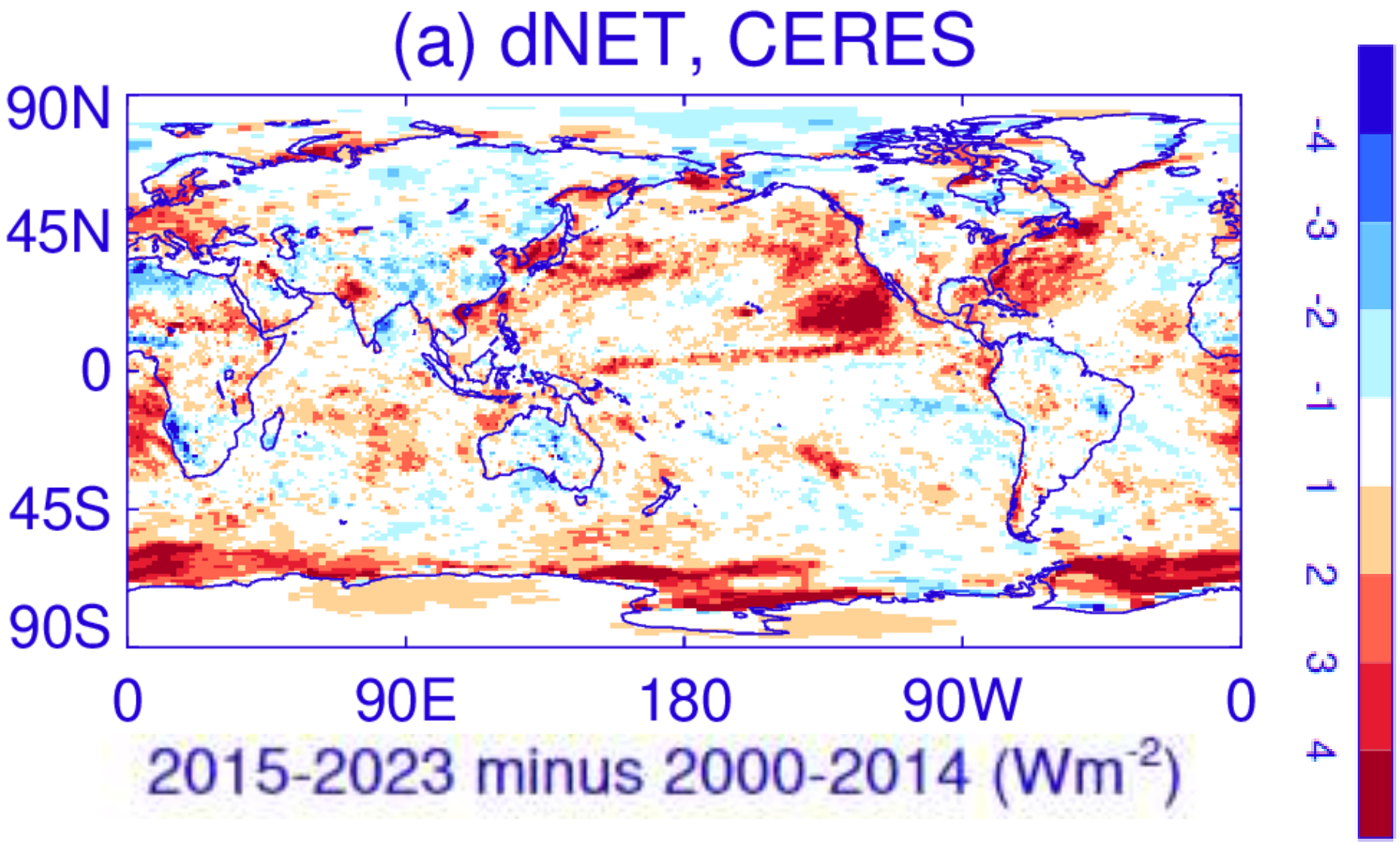

SPATIAL PATTERN OF IMBALANCE

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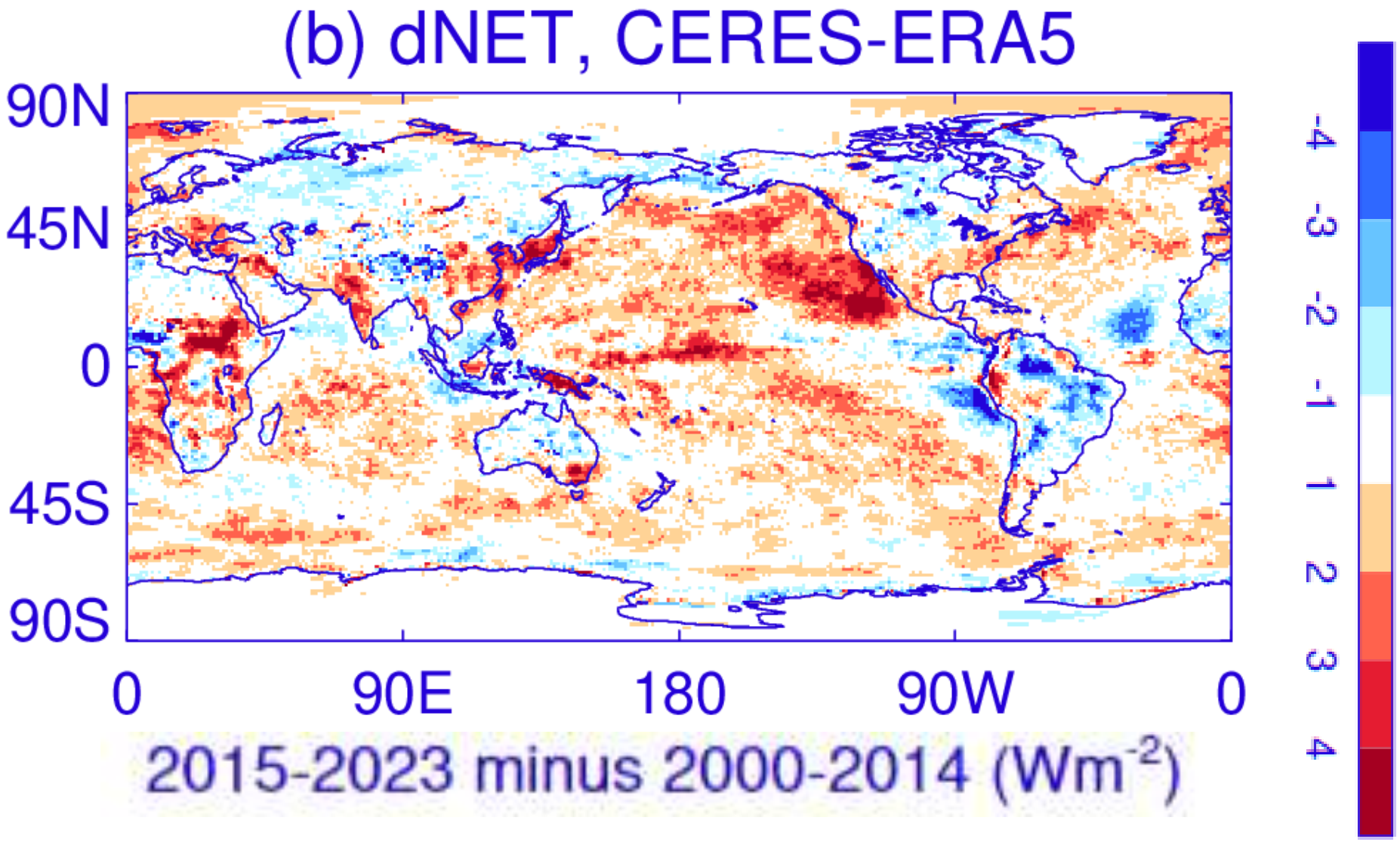
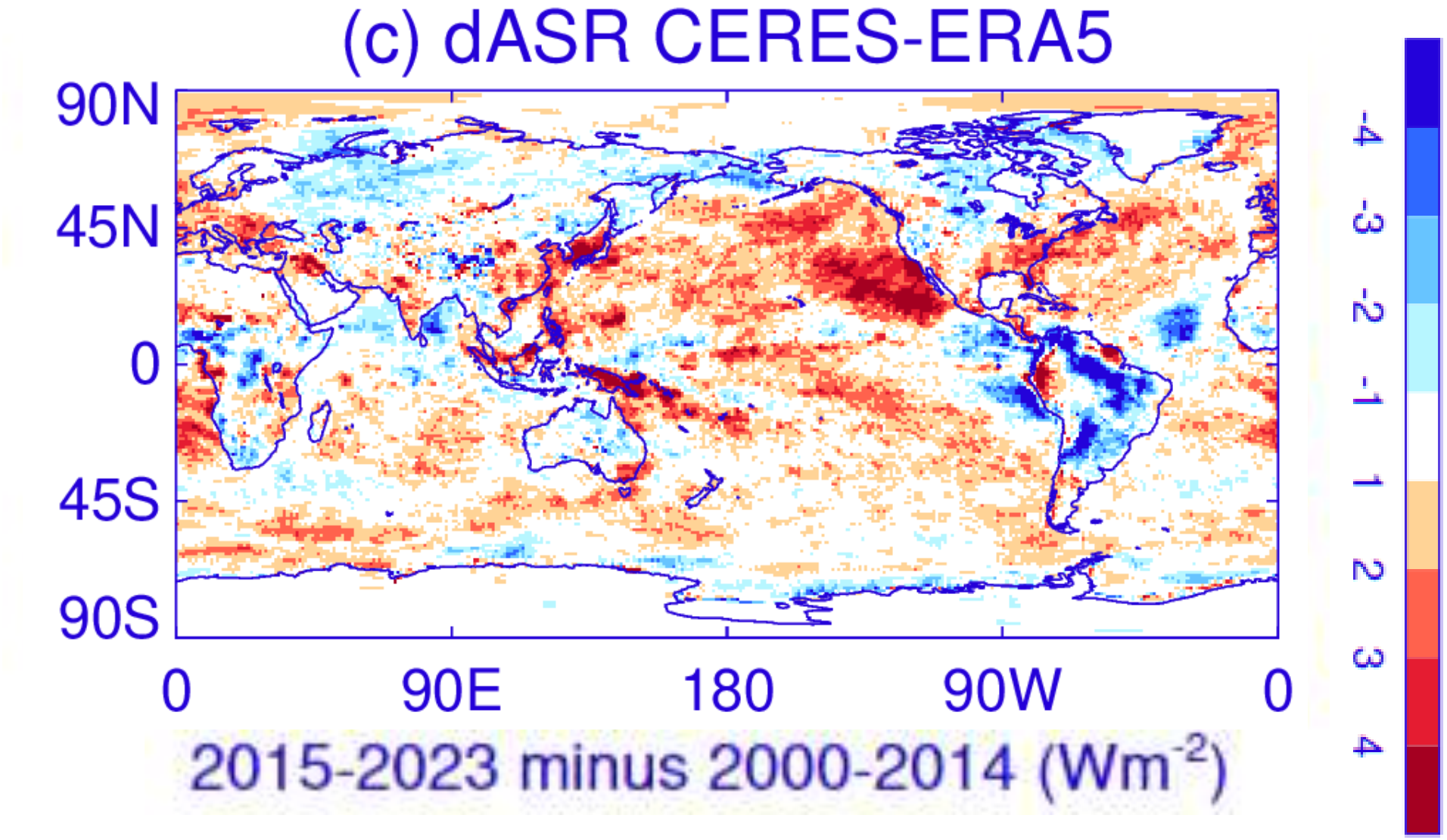
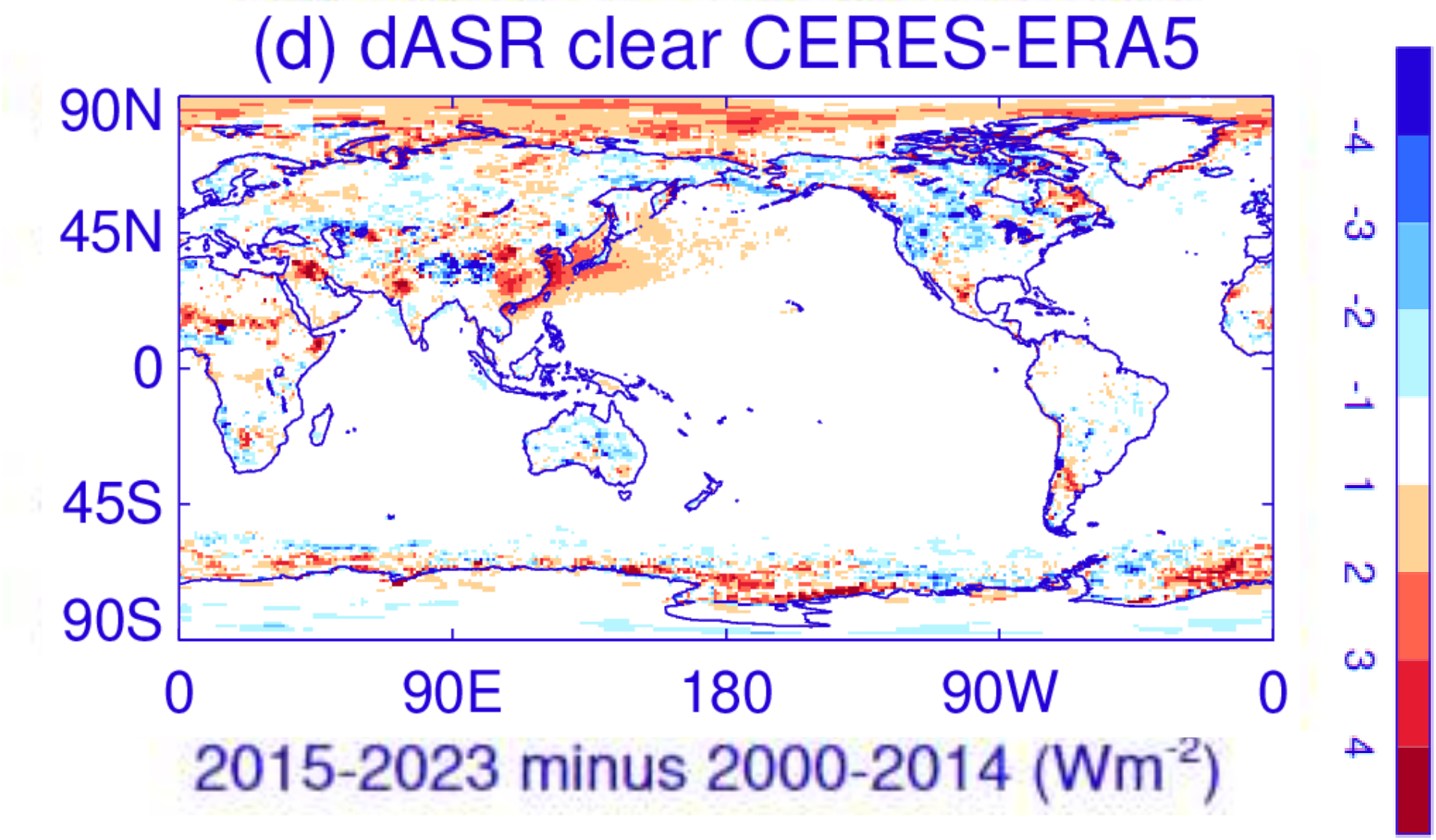
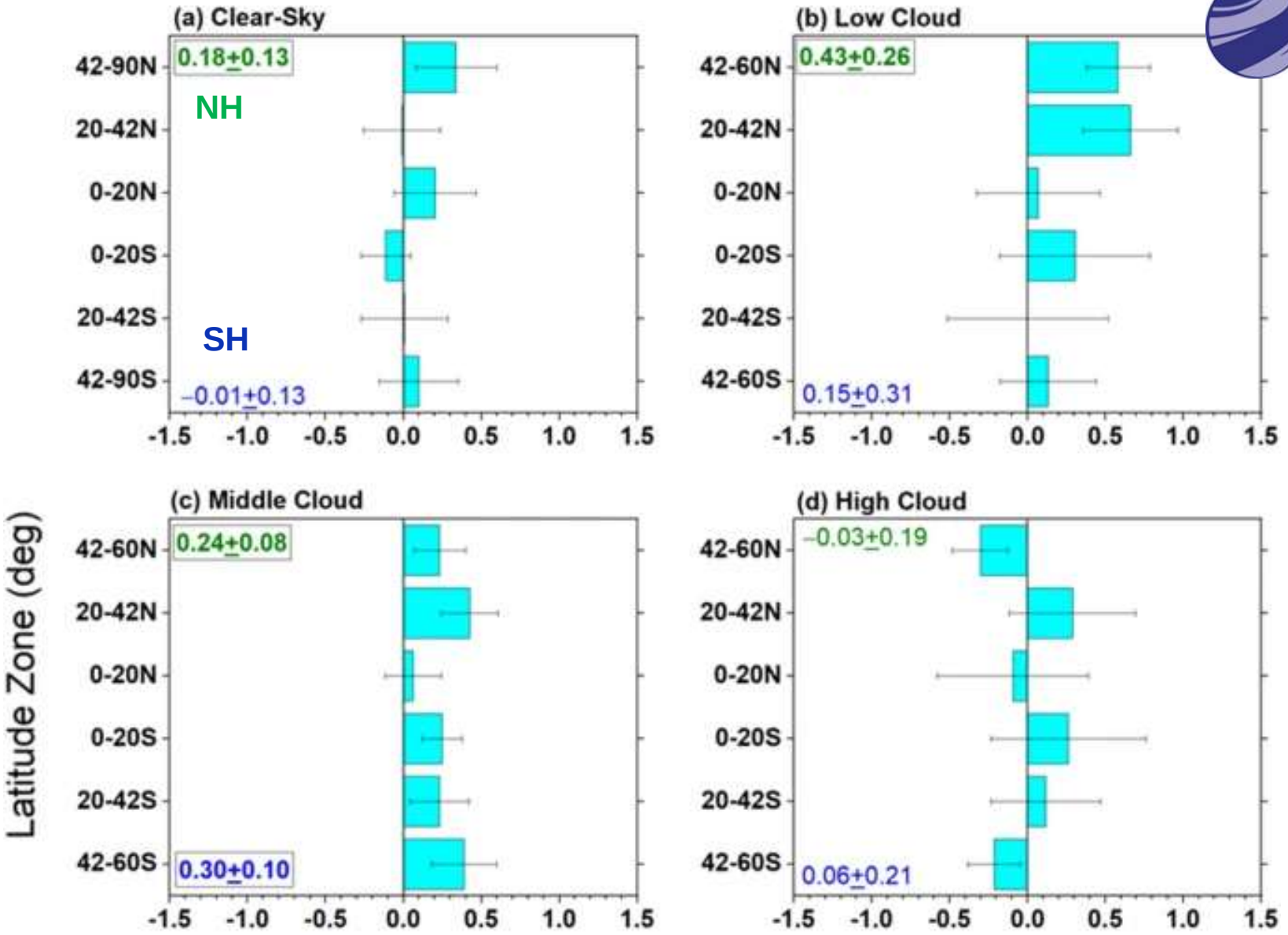


SPATIAL PATTERN OF IMBALANCE



SPATIAL PATTERN OF IMBALANCE





Trend 2002-2022

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ZONAL MEAN CONTRIBUTION OF CLOUD TYPE TO TREND IN ABSORBED SUNLIGHT

Loeb et al. (2024) Surv. Geophys

UNEXPECTED PATTERN OF GLOBAL WARMING

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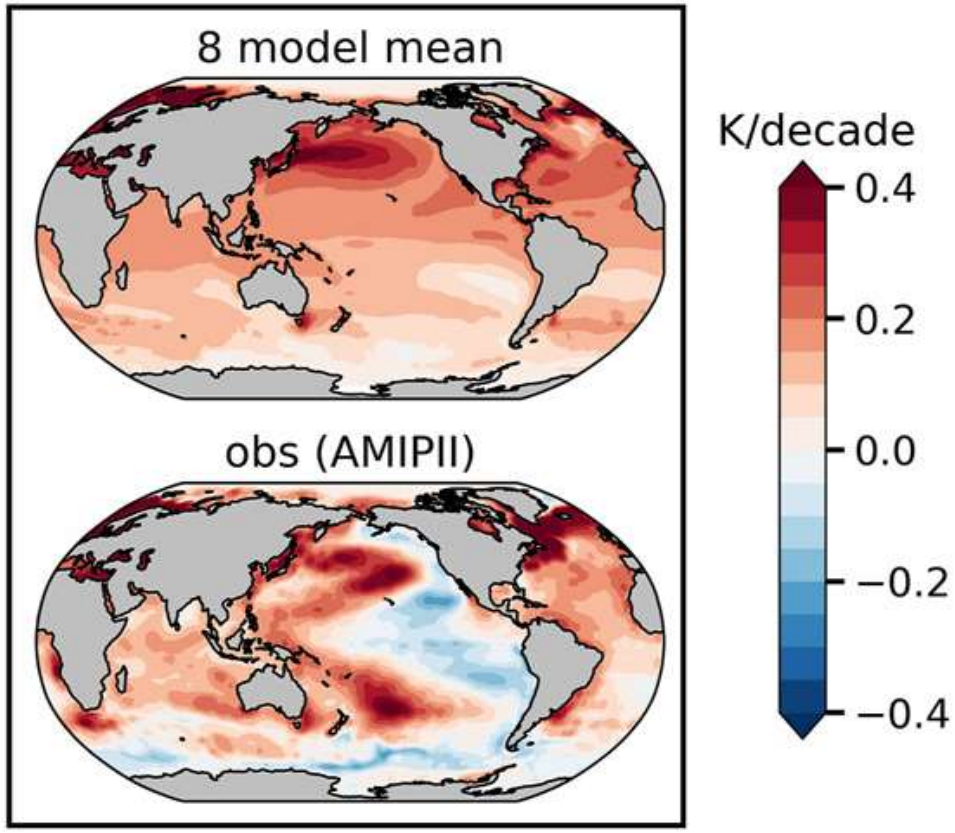
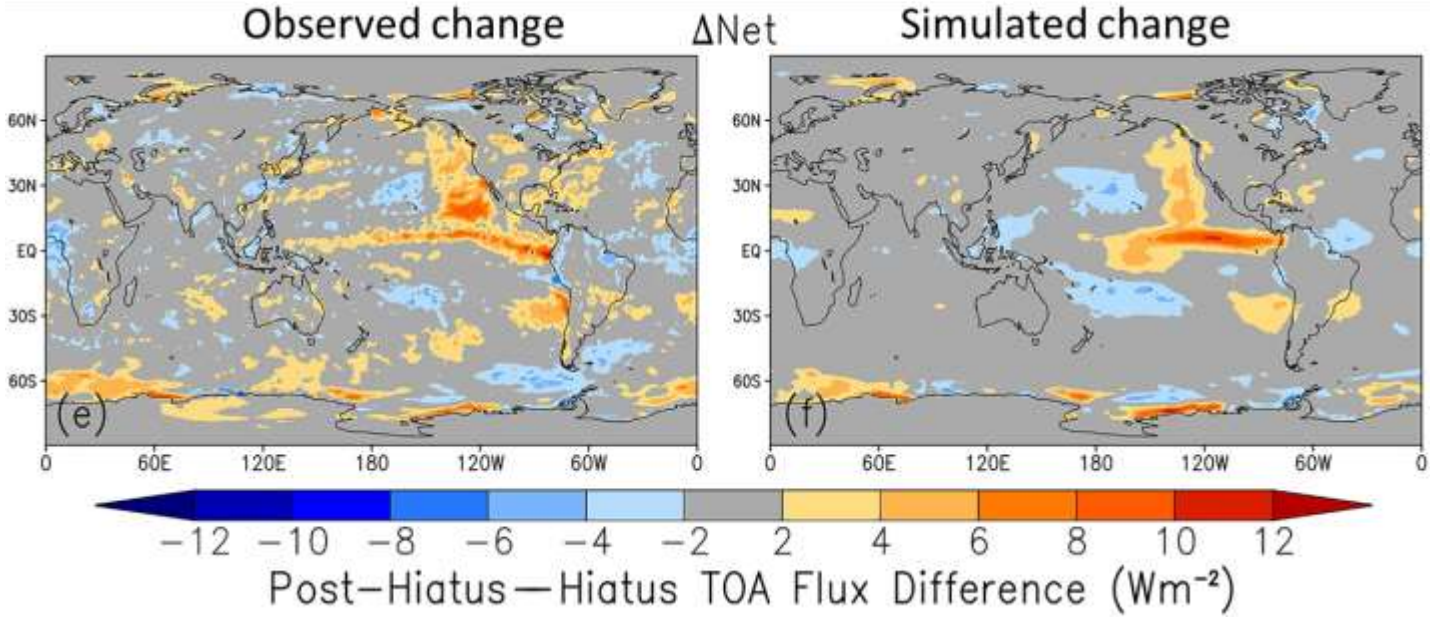


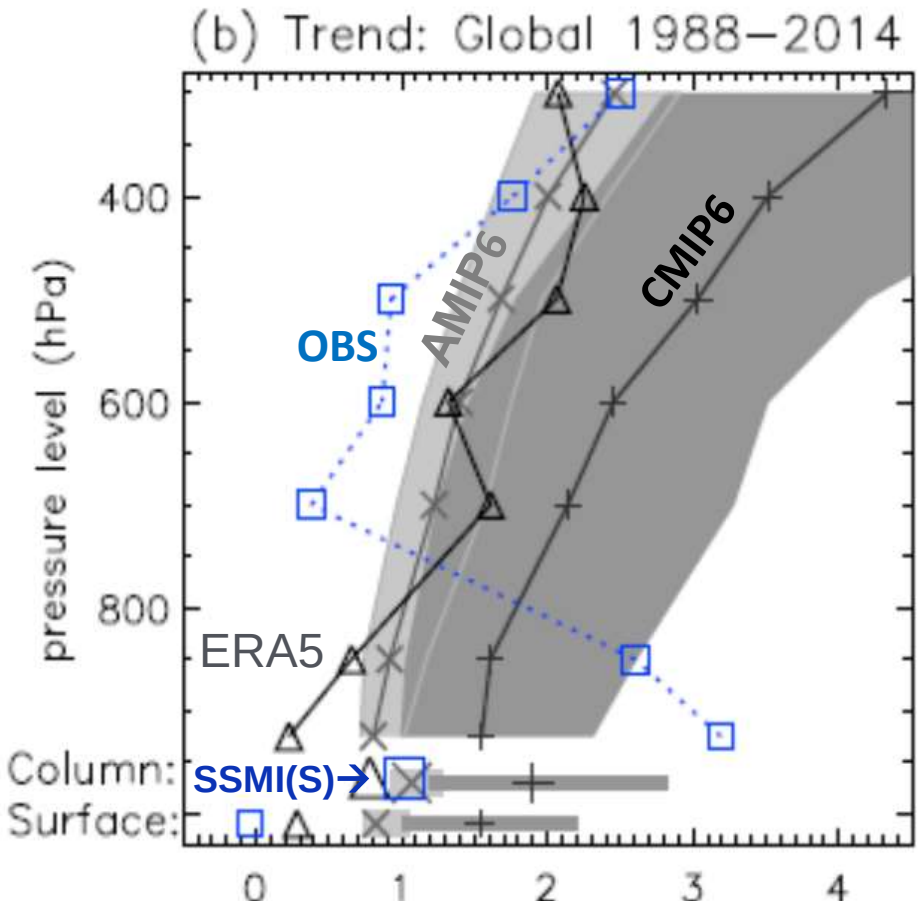
Pattern of observed warming (1979-2014) is unexpected!
Dong et al. (2021) GRL

This has weakened amplifying climate feedbacks relative to coupled models (Andrews et al. 2022 JGR)

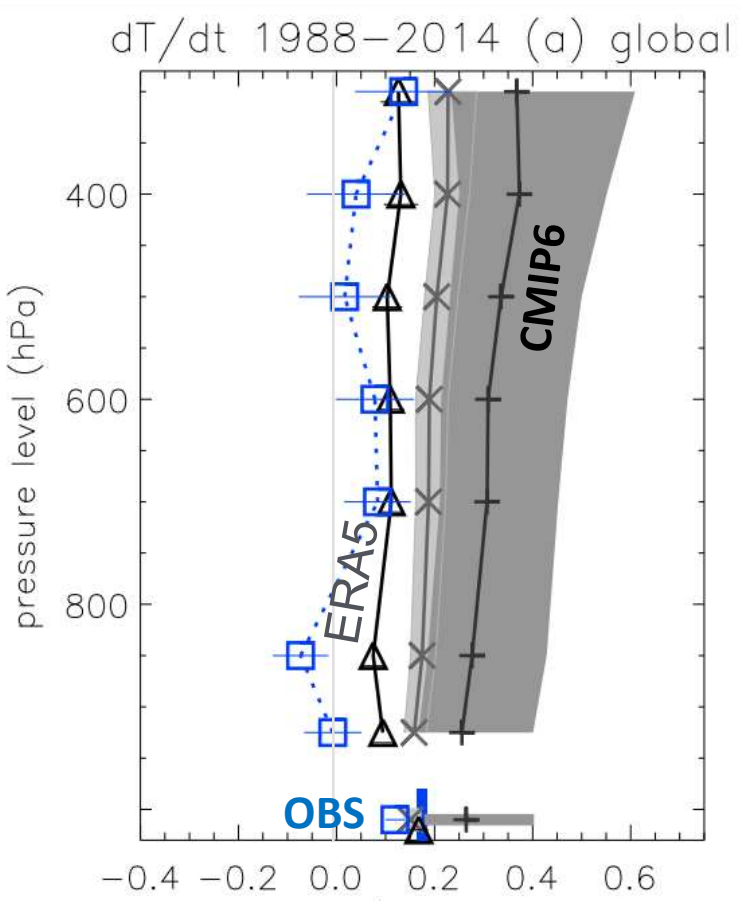
Temporary (?) reversal 2015/16? (Loeb et al. 2020 GRL)



STRONGER WARMING & MOISTENING IN MODELS



Water vapour trend (%/decade)

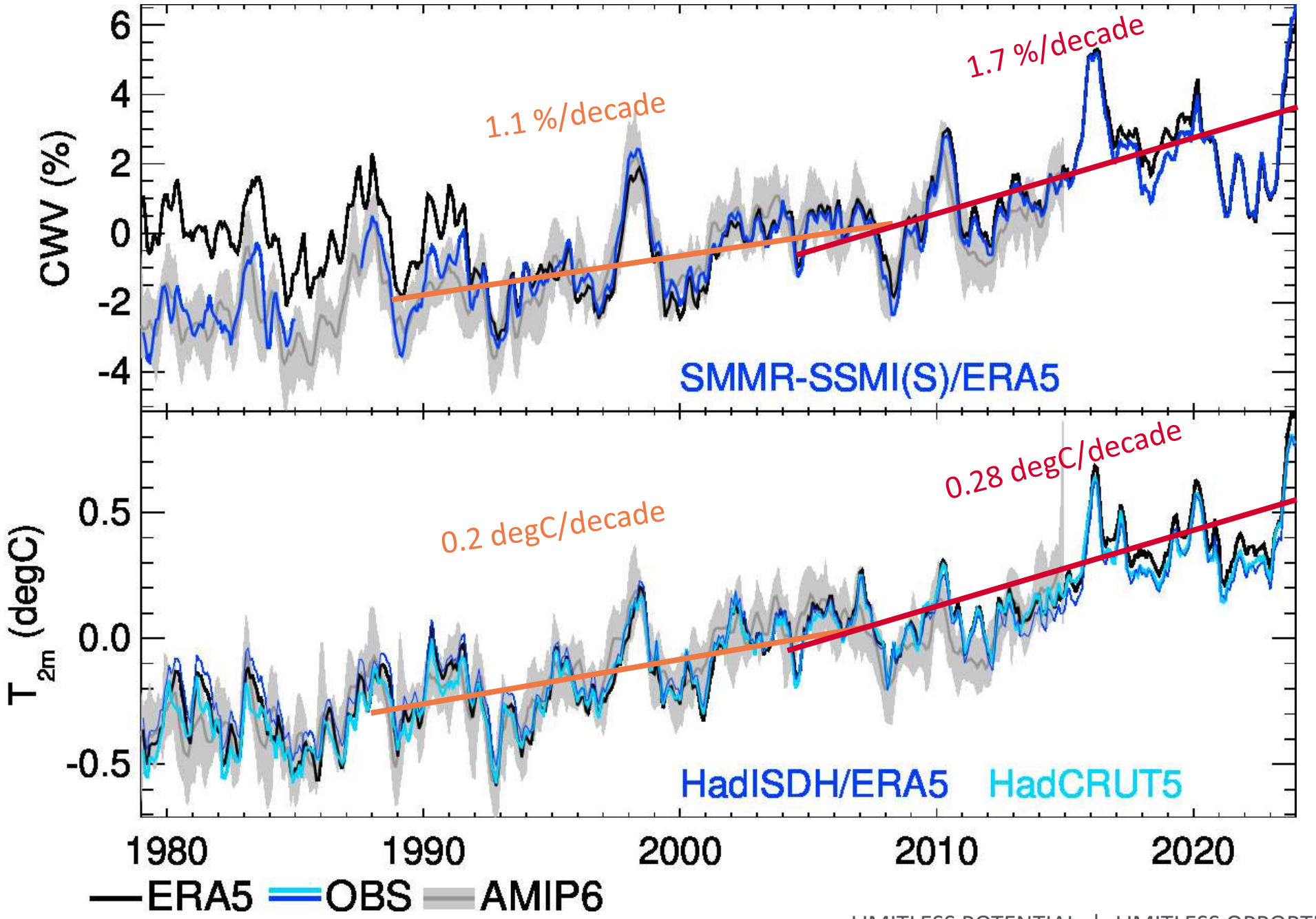


Temperature trend (K/decade)

CMIP6 overdo warming/moistening due to warming pattern (internal variability?)

Allan et al. 2022 JGR

HadISDH | HadCRUT5 | AIRS | AMIP | HIST | ERA5



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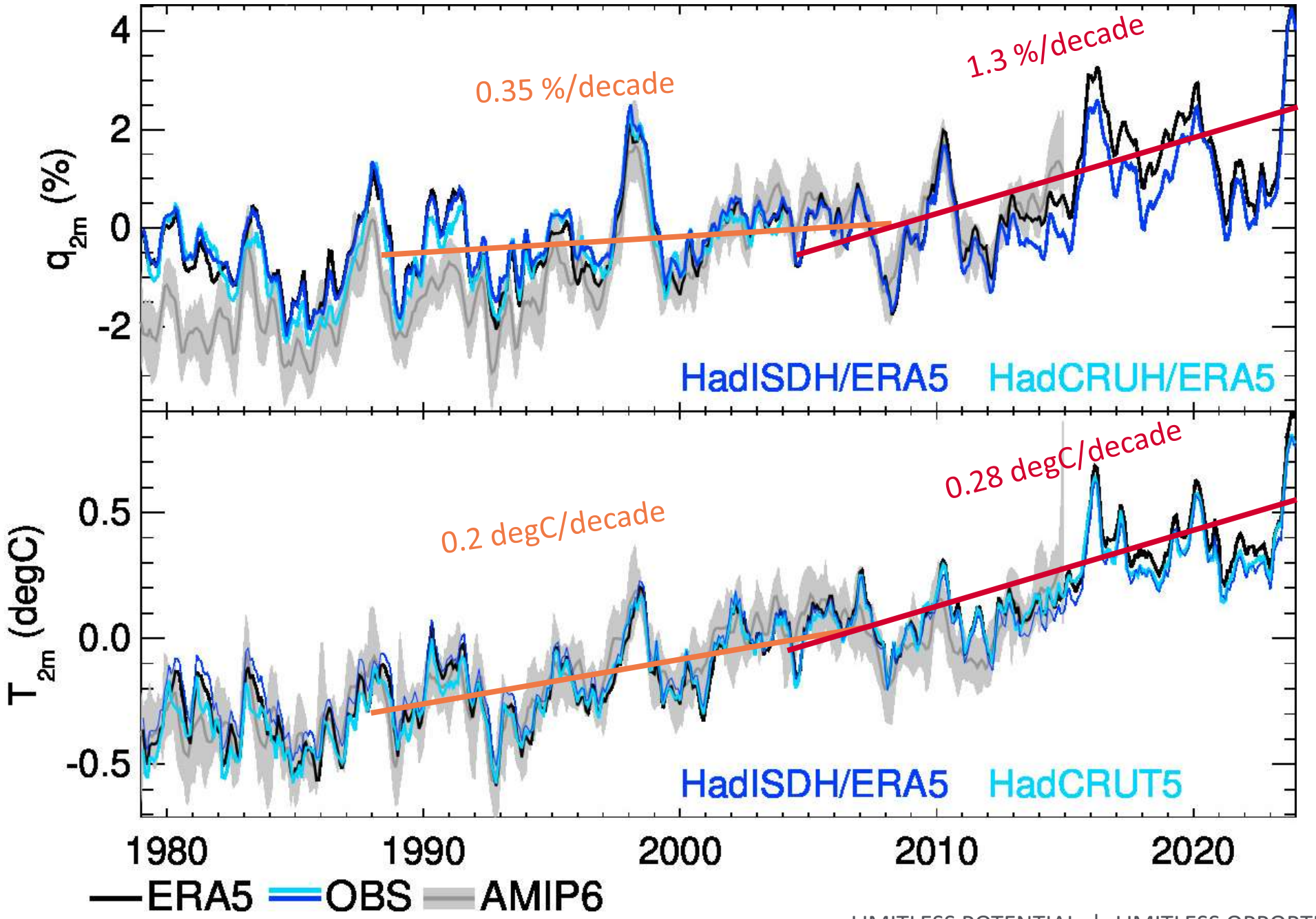
COLUMN WATER VAPOUR

Allan et al. (2022) JGR updated to 2023



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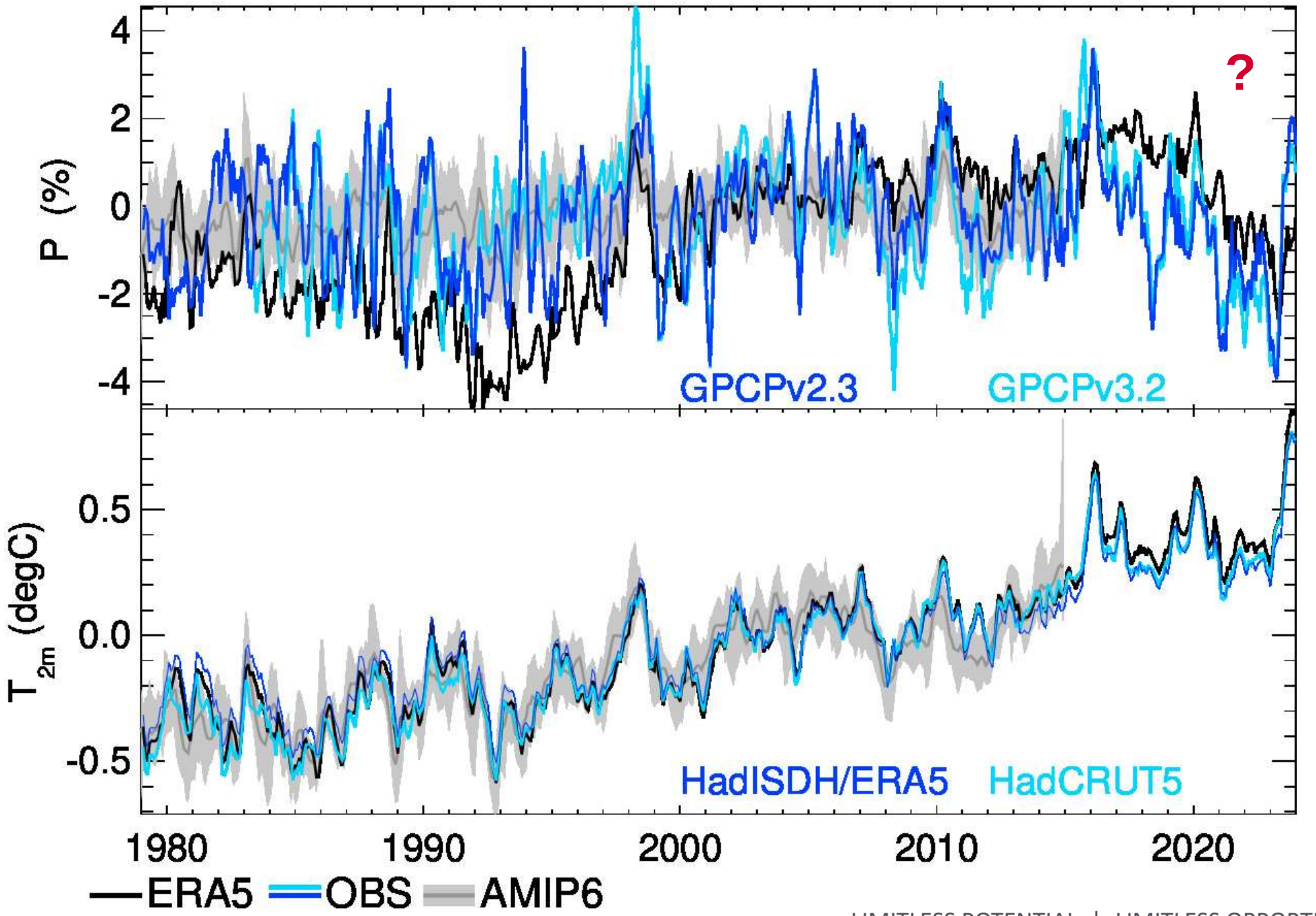
SURFACE WATER VAPOUR

Allan et al. (2022) JGR updated to 2023



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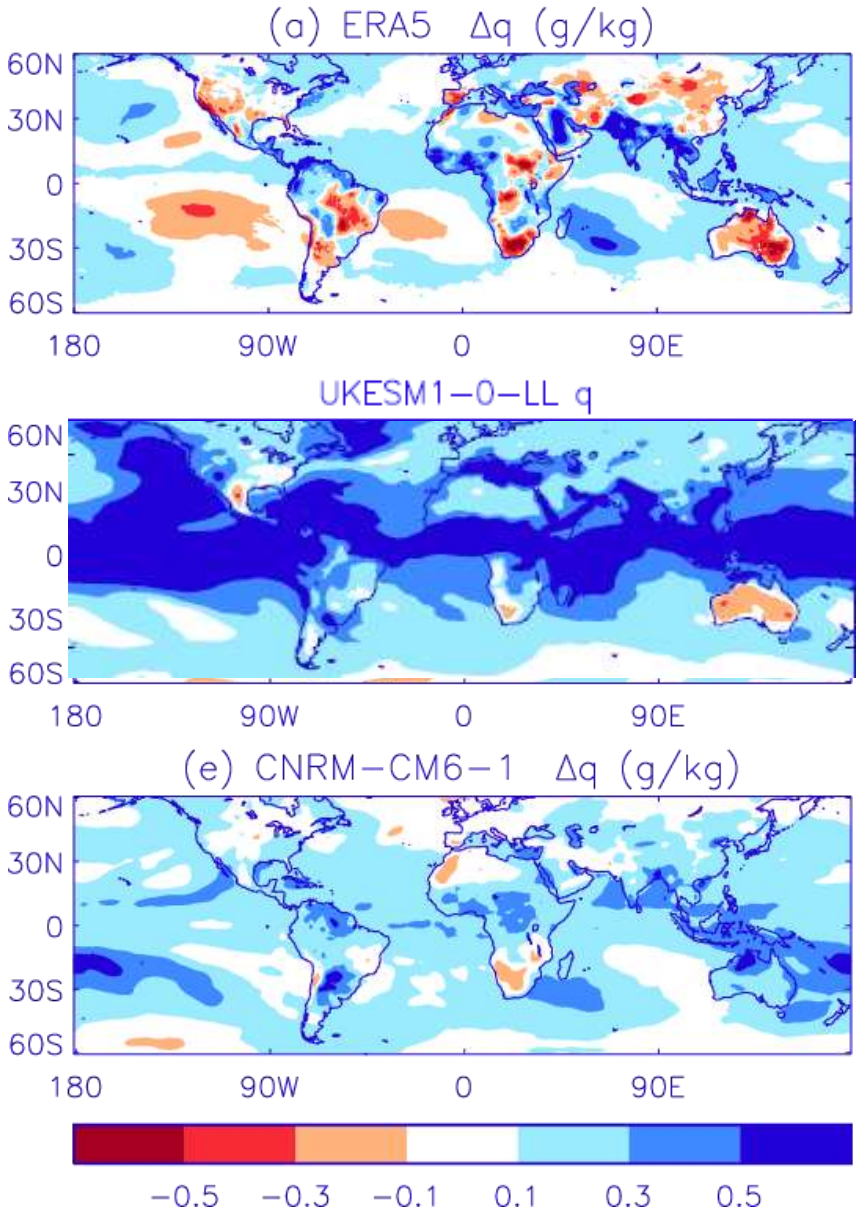
PRECIPITATION

see Allan et al. (2020) NYAS; Allan (2023) ERL

UNDERESTIMATION OF CONTINENTAL DRYING?



ERA5

Climate models

Declining Relative Humidity over land consistent with larger warming over land than sea e.g. O'Gorman & Byrne (2018) PNAS

Climate models overestimate water vapour increases since 1988, particularly over arid & semi-arid land regions

← *2004-2019 minus 1988-2003 water vapour changes* (Allan & Douville 2024 PNAS); see Simpson et al. (2024) PNAS; Dunn et al. 2017 ESD

DECLINING TERRESTRIAL WATER STORAGE

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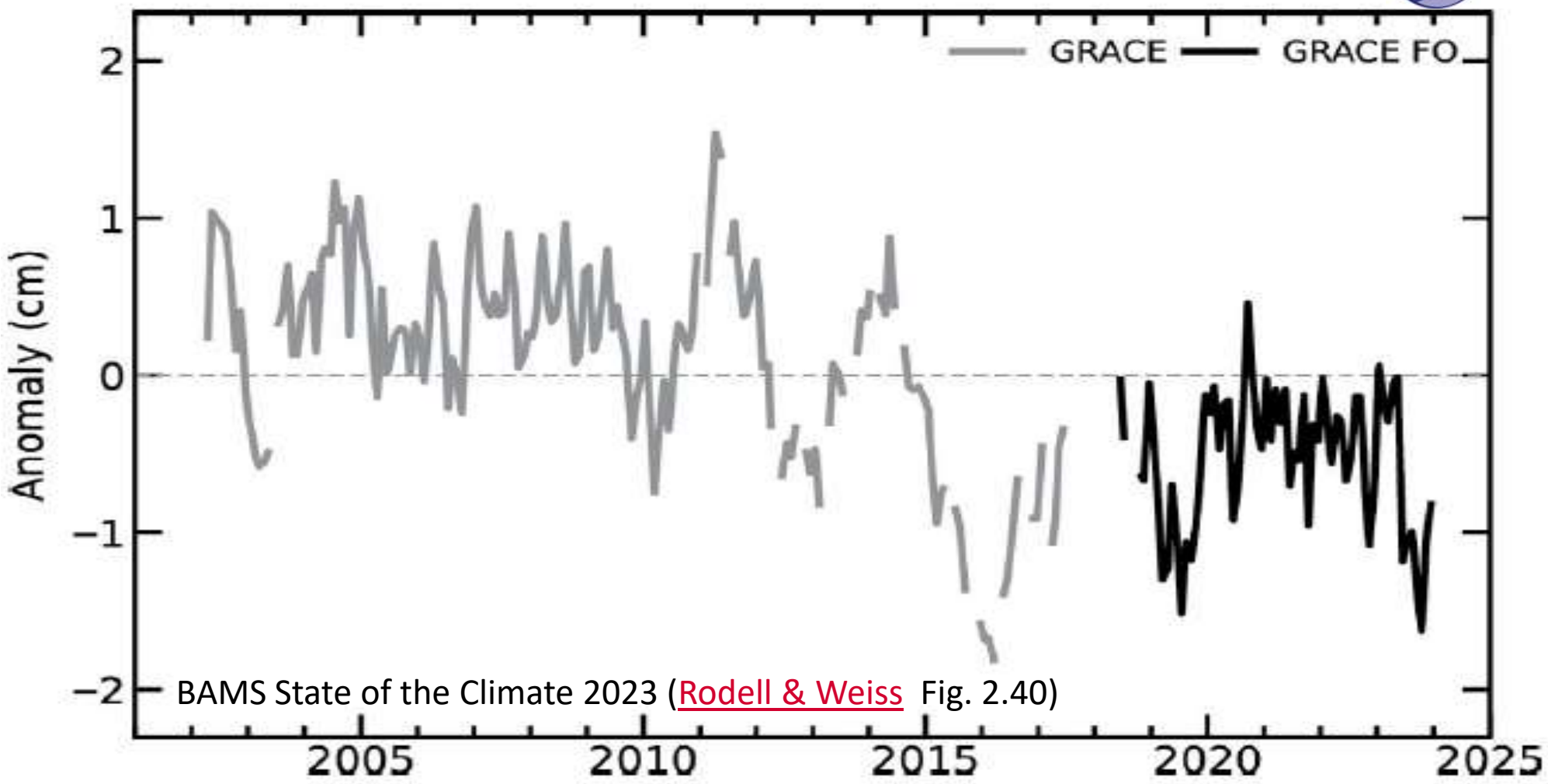

BAMS State of the Climate 2023 (Rodell & Weiss Fig. 2.40)

DECLINING TERRESTRIAL WATER STORAGE

(GRACE/GRACE-FO & COMBINED MODEL/OBS DATA)

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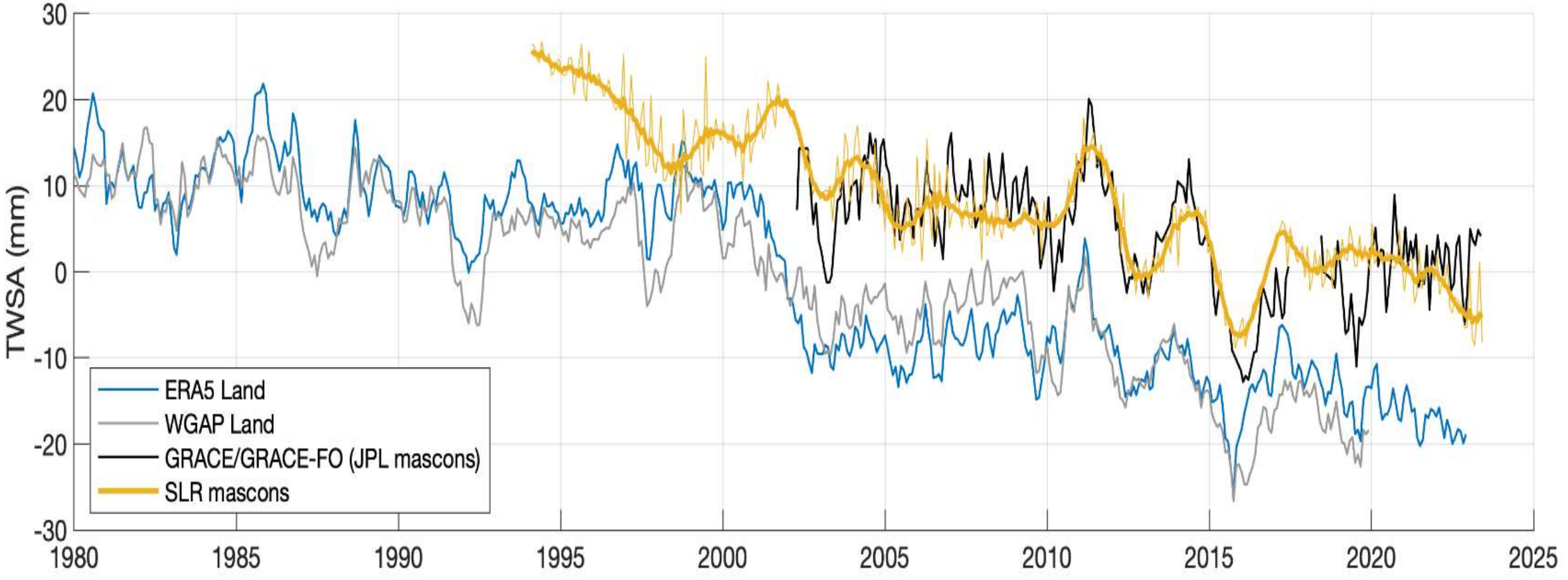

Rodell et al. (2024) Surv. Geophys.

DECLINING TERRESTRIAL WATER STORAGE (GRACE, GRACE-FO)

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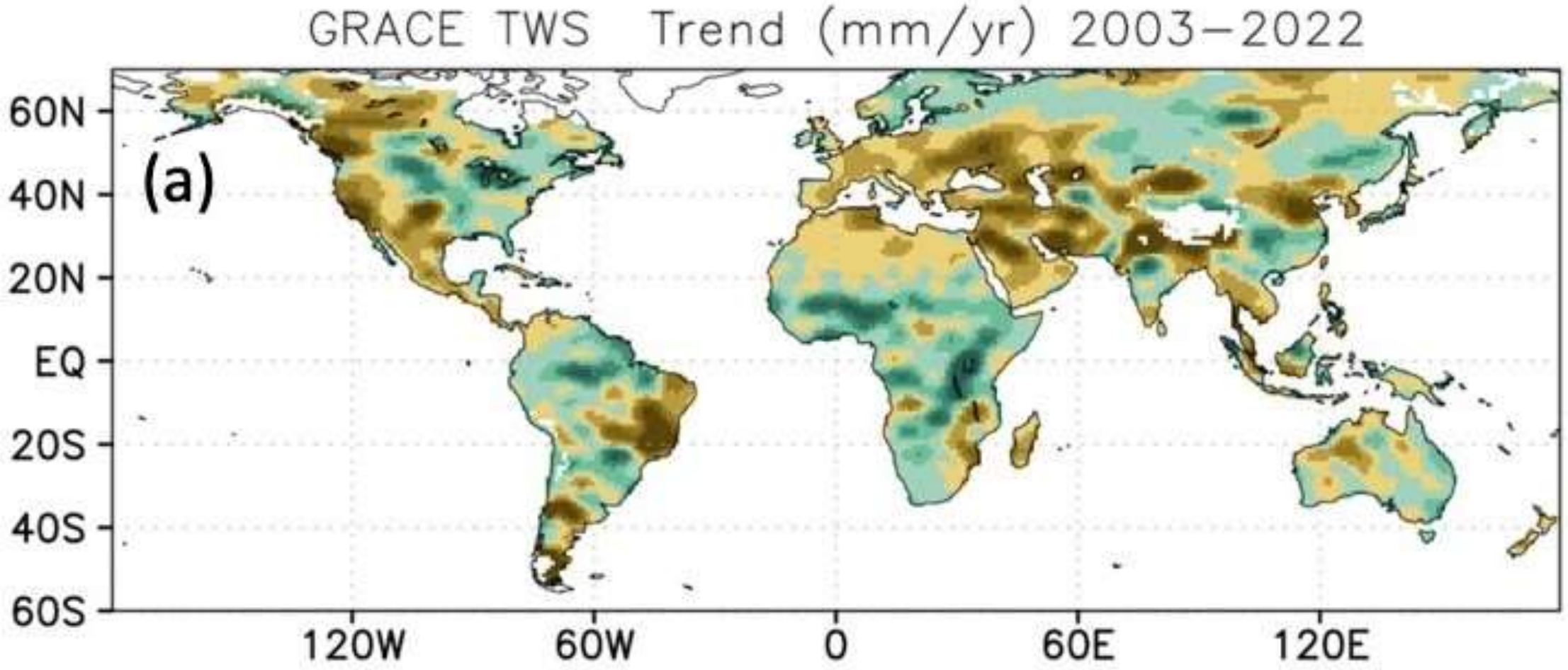

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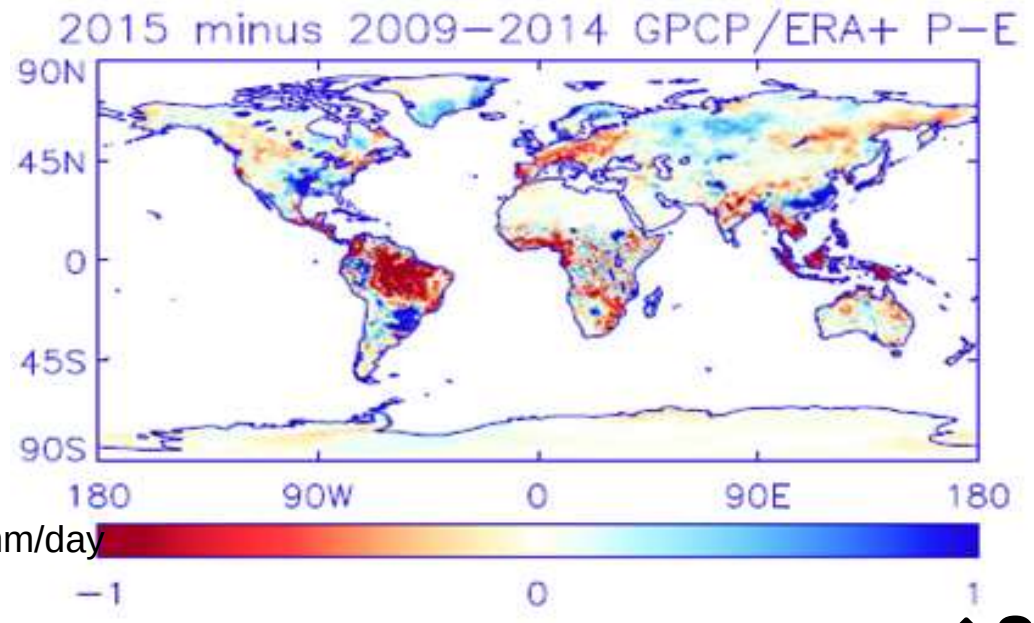
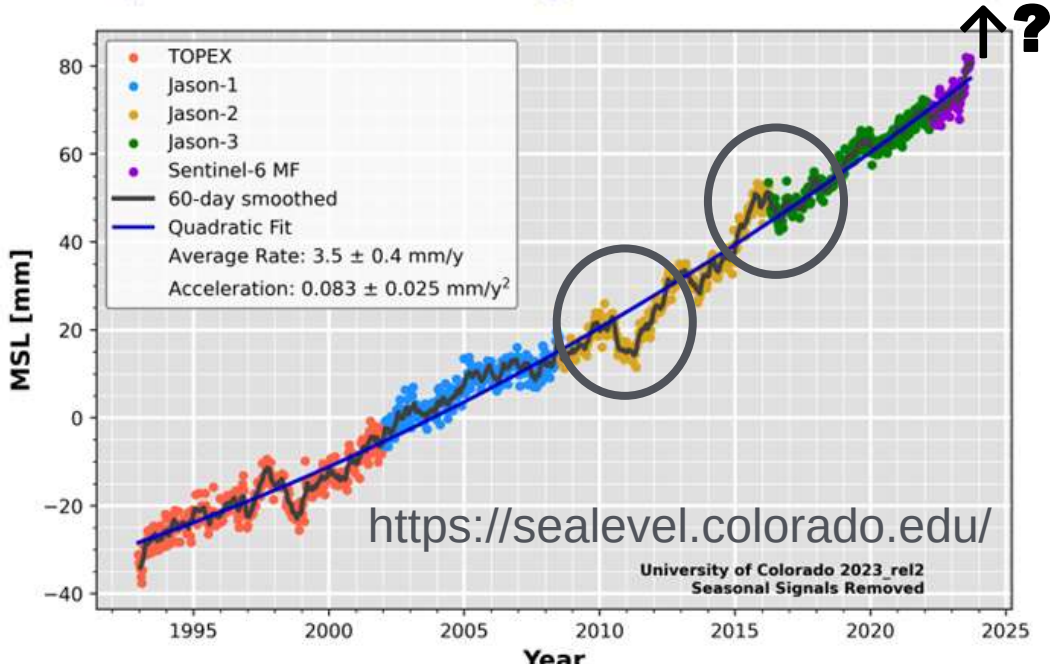
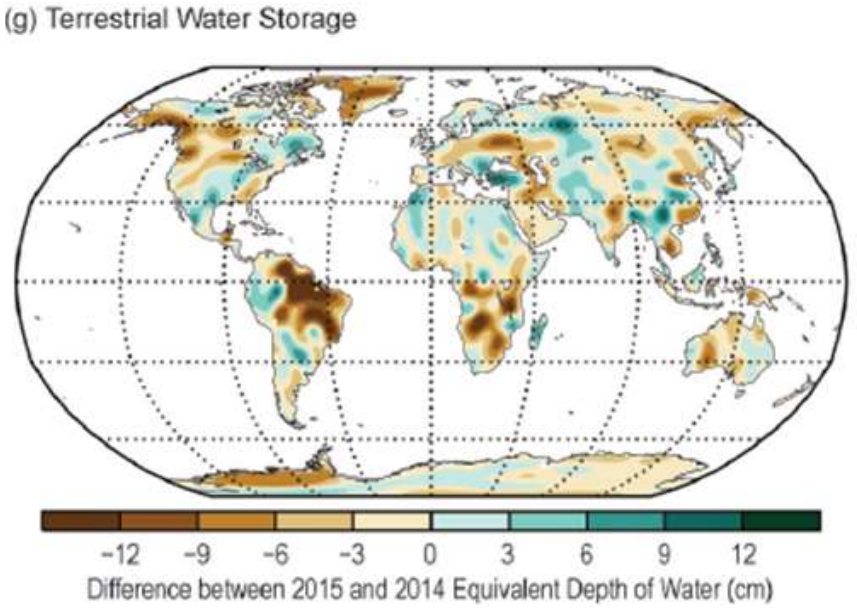
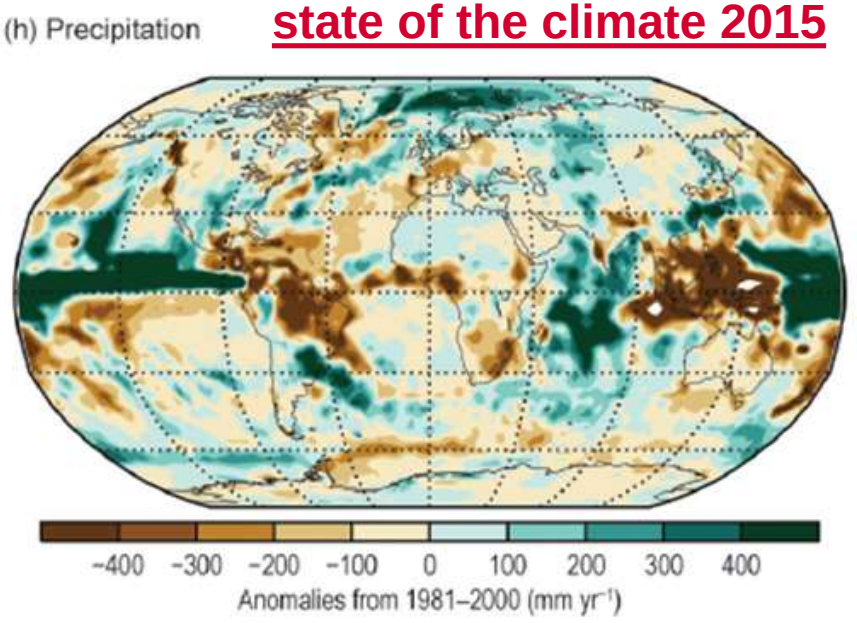




↑?





[state of the climate 2015]

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Chasing water through 2015/16 El Niño

2023/24?

[Boening et al. (2012) GRL: The 2011 La Niña so strong, the oceans fell]

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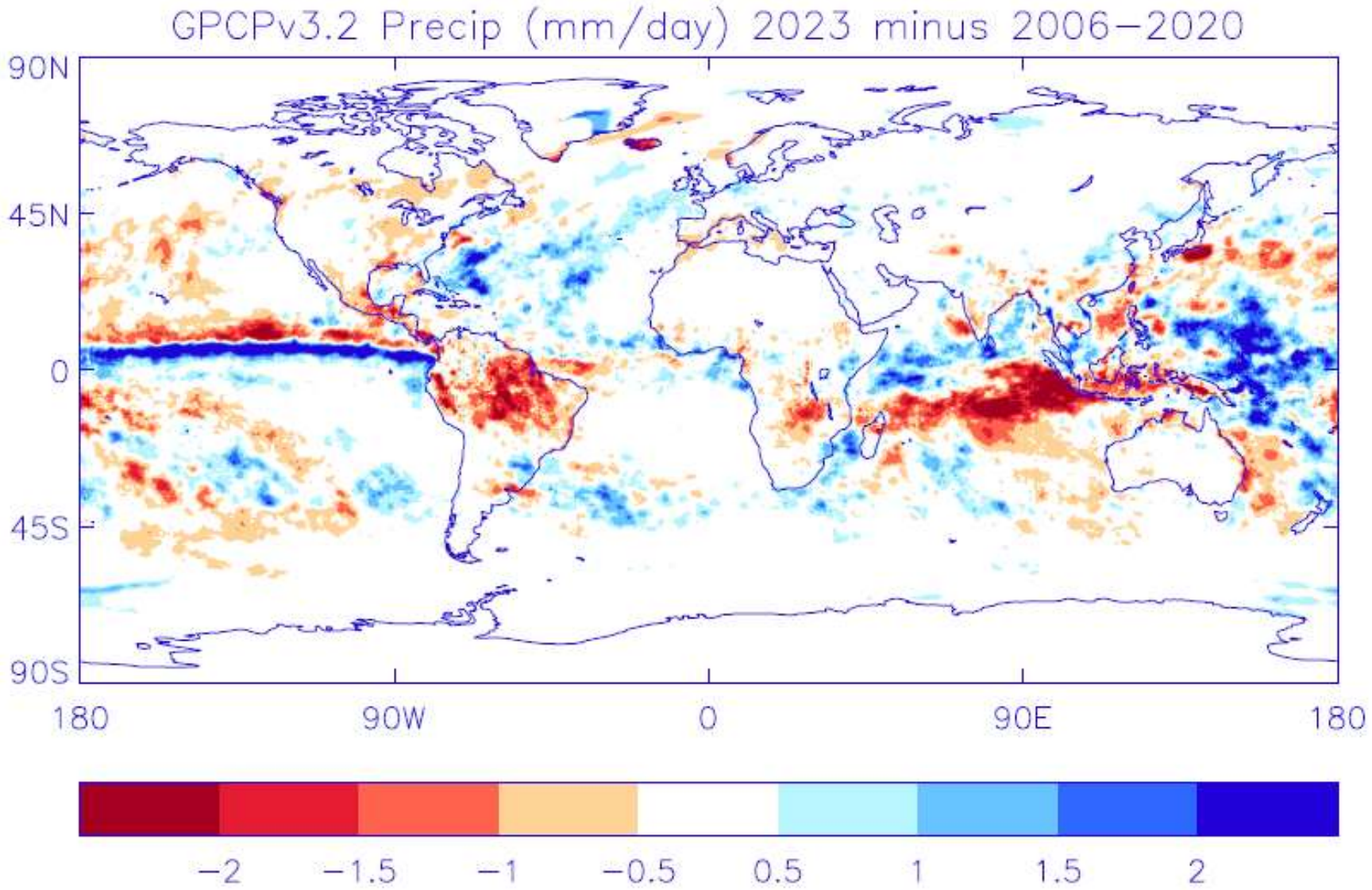
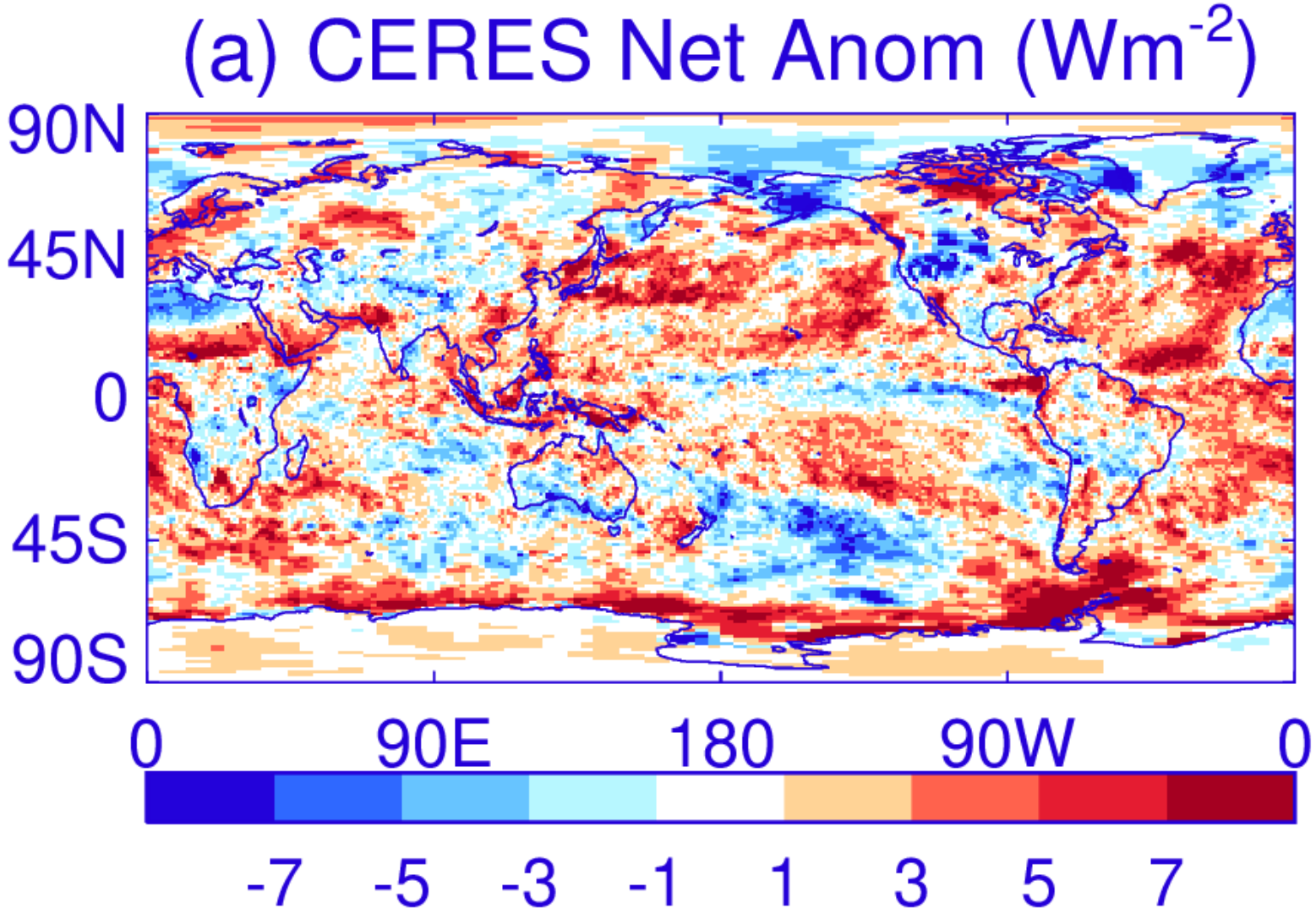


PRECIPITATION ANOMALY 2023

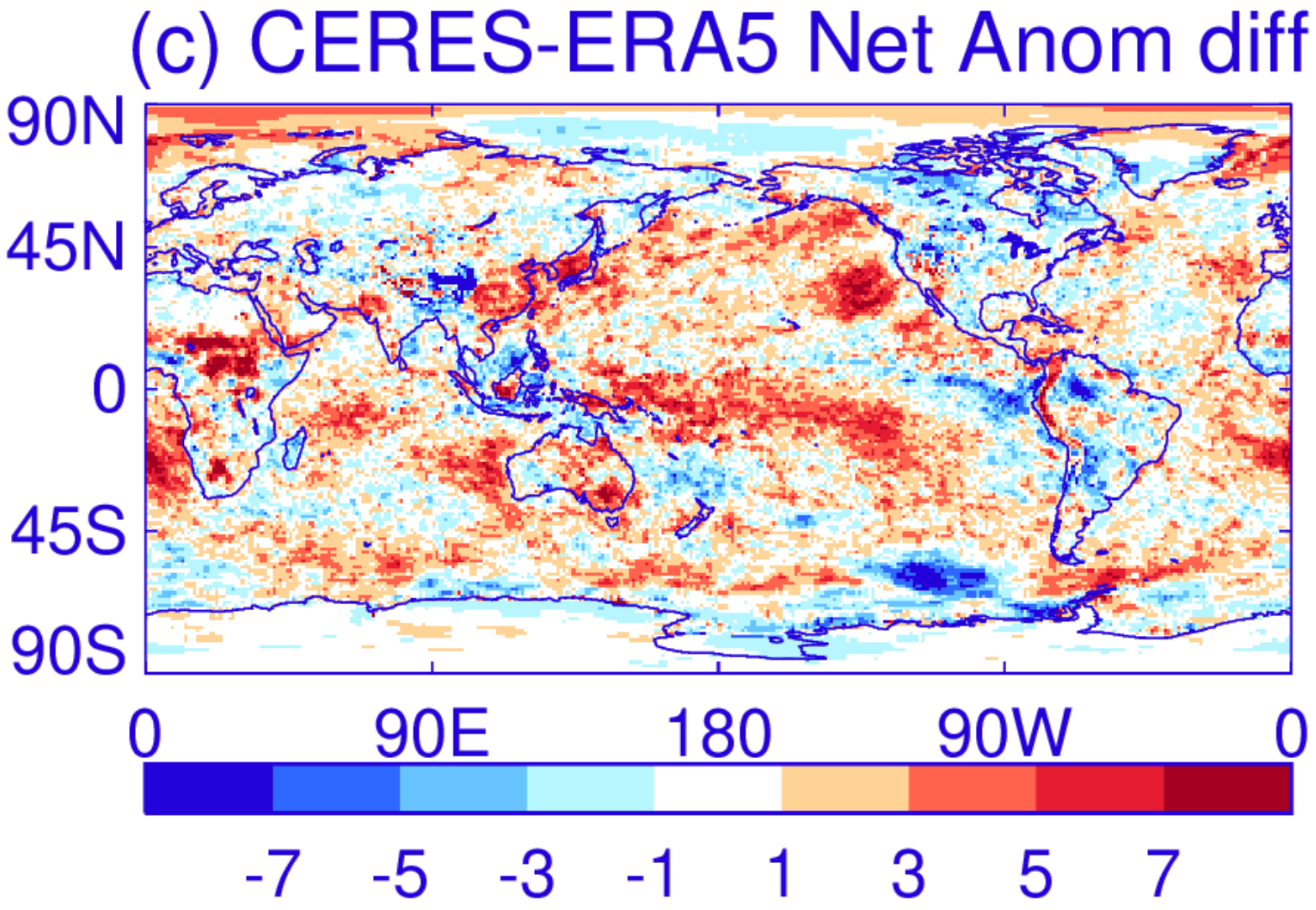
ENERGY IMBALANCE CHANGES 2022-23



CERES Net Imbalance Aug 2022-Jul 2023: **1.92 Wm^{-2}** (+1.09 Wm^{-2} larger than 2006-2020)

see also e.g. Hodnebrog et al. (2024) Comm. Earth Env.; Kuhlbrodt et al. (2024) BAMS

ENERGY IMBALANCE CHANGES 2022-23



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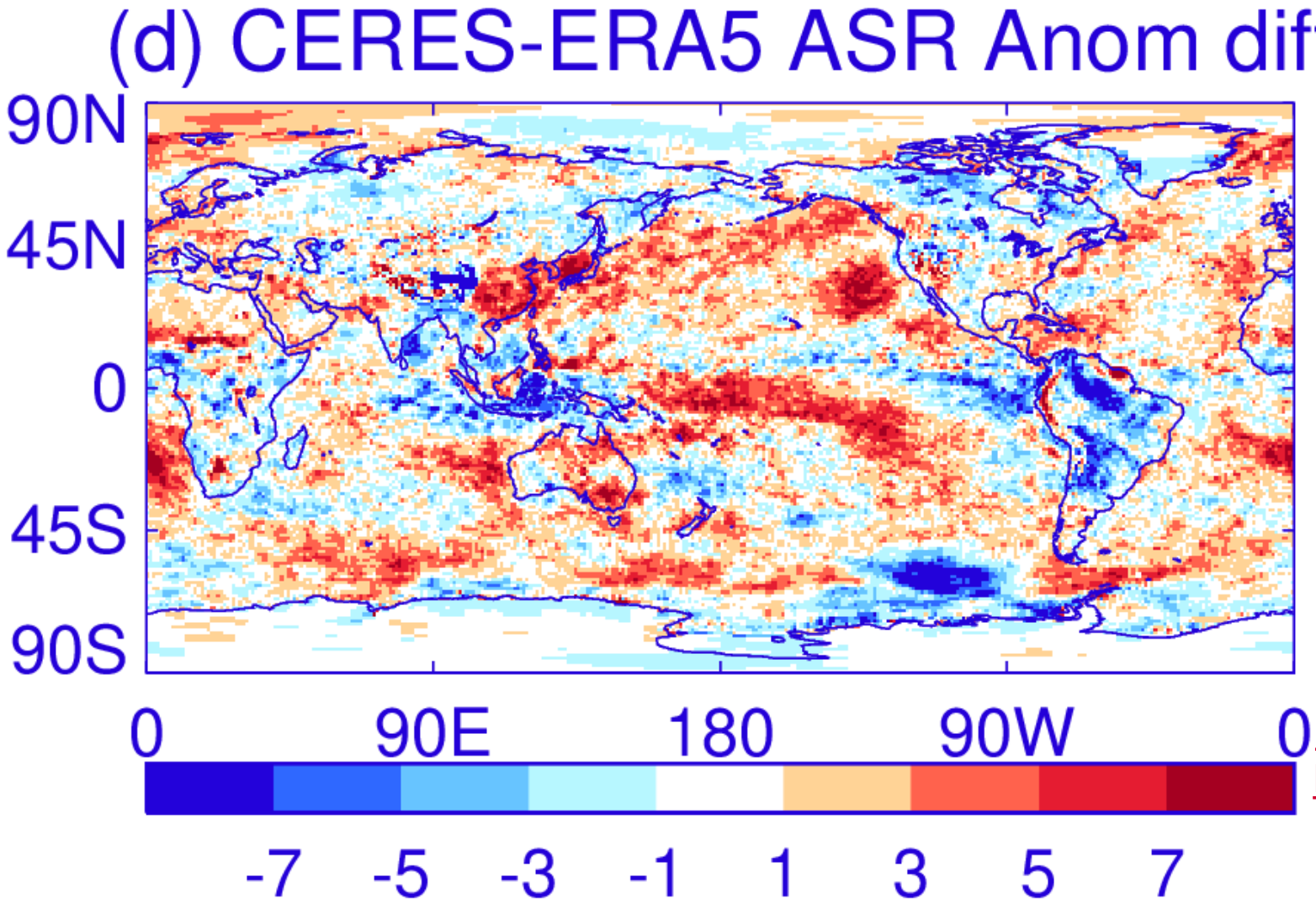
ENERGY IMBALANCE CHANGES 2022-23



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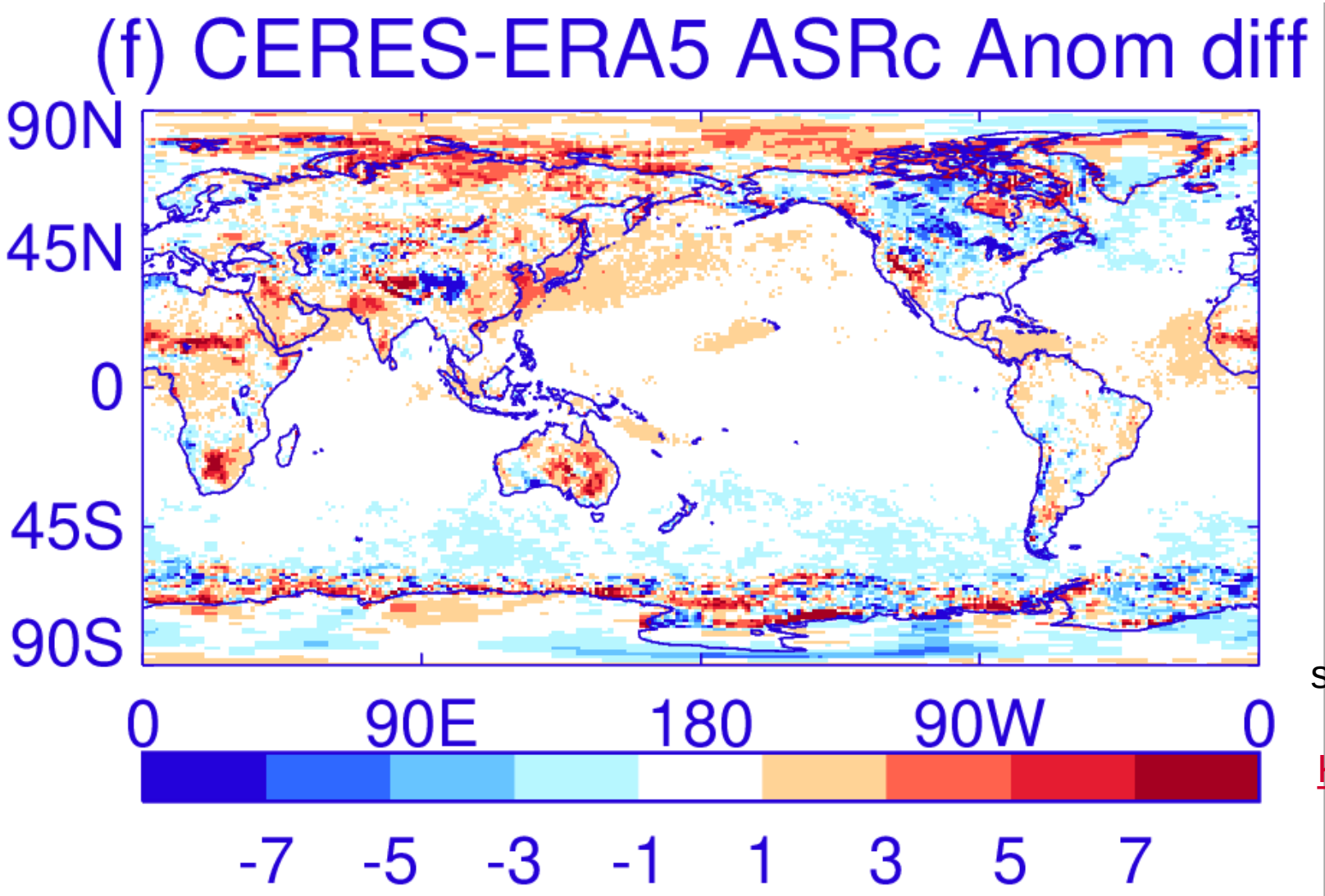
ENERGY IMBALANCE CHANGES 2022-23



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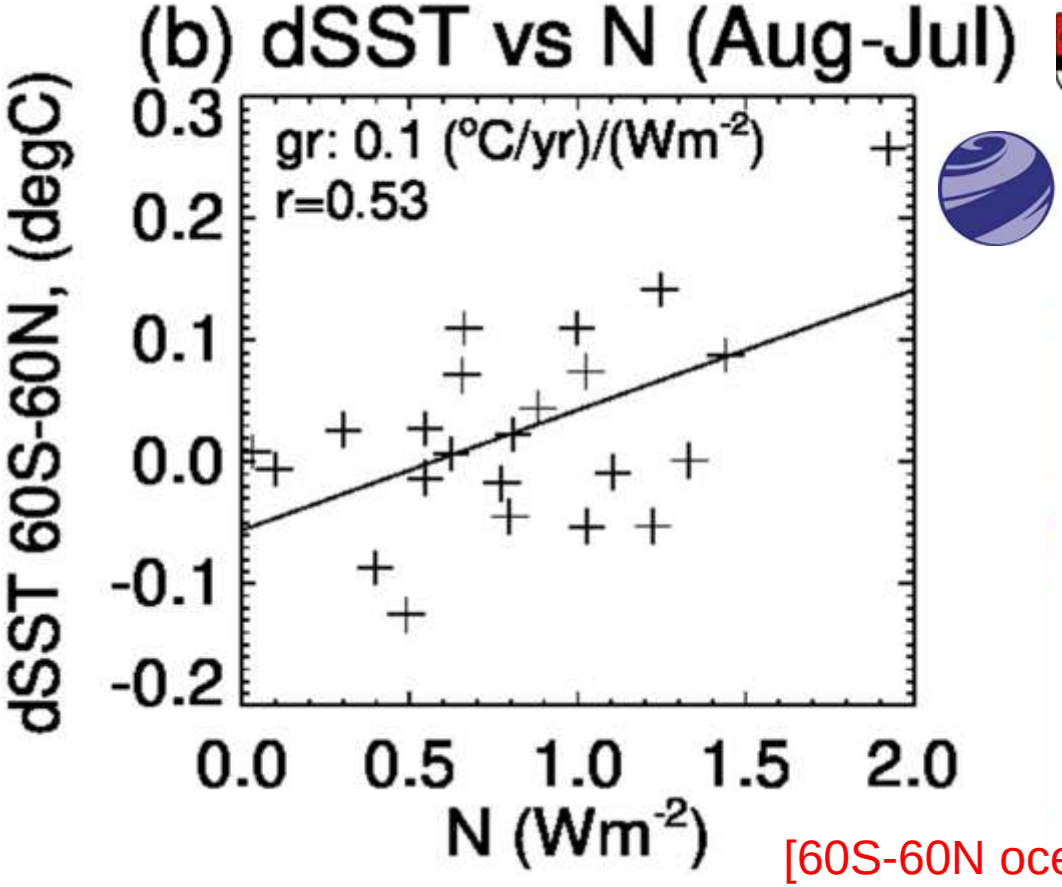
Domain	2006-2020 trend (Wm^{-2})
Atmosphere	0.014 ± 0.003 (ERA5: 0.017)
Land	0.039 ± 0.004
Cryosphere	0.028 ± 0.008
Total Ocean	**0.67 ± 0.3**
Total N	0.76 ± 0.2
CERES N	0.83 ± 0.18

von Shuckmann et al. (2023) ESSD

dSST/dt = 0.25 ºC/decade
(CCI, 60ºS-60ºN)



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[60S-60N ocean 63% of globe]

H ~ 0.63(dT/dt)dρc = 6.5x10^6 J/yr/m^2 = 0.21 Wm^{-2}

D = F – H = 0.67 – 0.21 = 0.46 Wm^{-2}

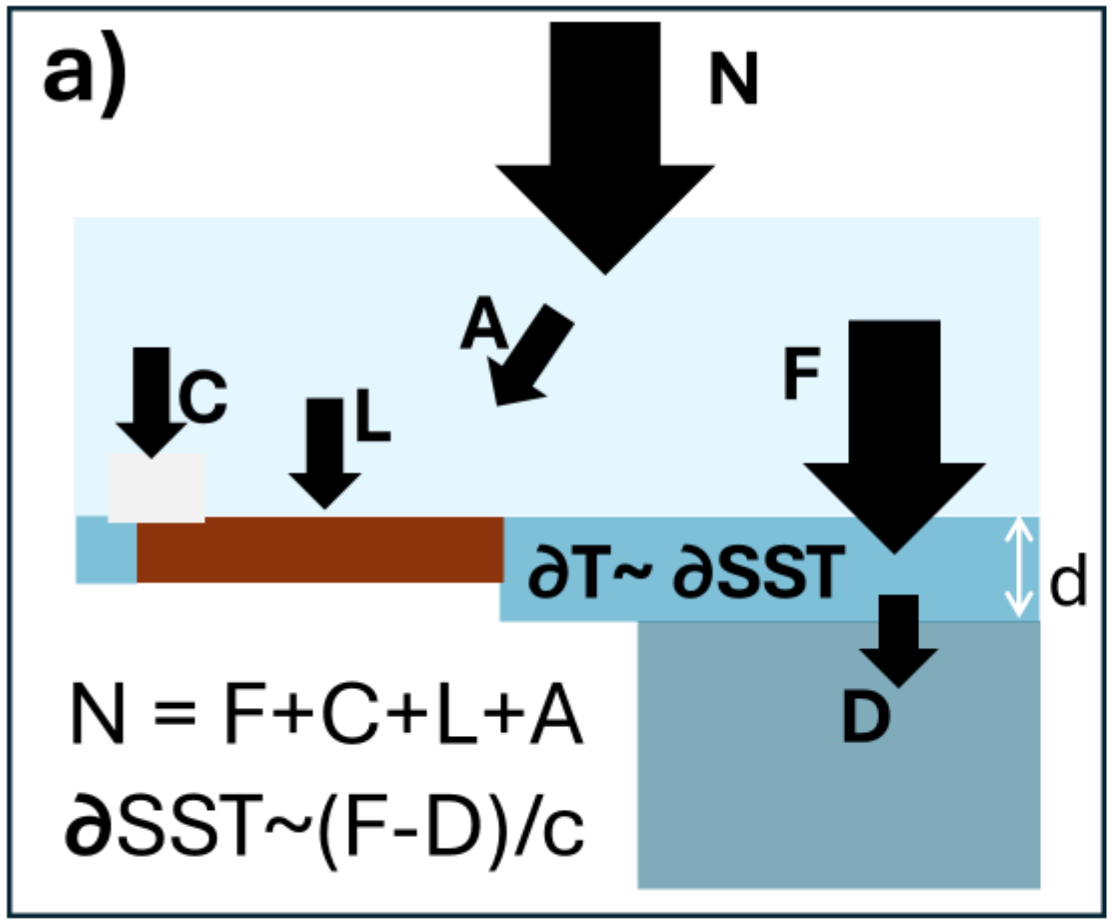
If N increases by 1 Wm^{-2} & D remains constant…

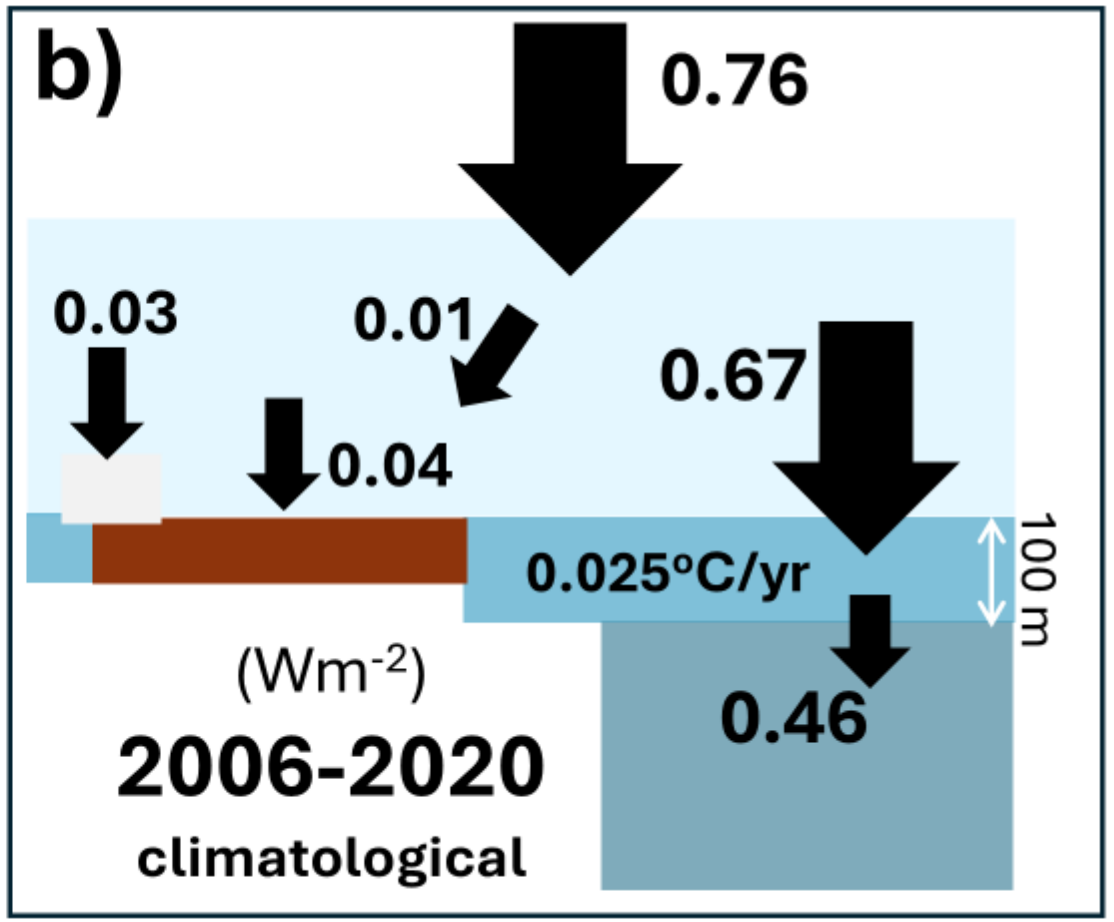
ΔH ~ ΔF ~ 0.89ΔN

Δ(dT/dt) ~ 0.89ΔN/0.63dρc = 0.11 ºC/yr

CLIMATOLOGICAL HEAT INVENTORY

Effective heating, k = (dSST/dt)/N = 0.33 ^{o}C/decade/(Wm^{-2})





Effective heating layer, d = F/ρc(dSST/dt)(A_o/A_g) ~ 300m

von Shuckmann et al. (2023) ESSD

2022 TO 2023 HEAT BUDGET?

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Domain	2006-2020 trend (Wm^{-2}) (Von Shuckmann 2023)	2022-2023 proportional heating (Wm^{-2})
Atmosphere	0.014 ± 0.003 (ERA5: 0.017)	0.034 (2%)
Land	0.039 ± 0.004	0.095 (5%)
Cryosphere	0.028 ± 0.008	0.068 (4%)
Total Ocean	0.67 ± 0.3	1.64
Total N	**0.76 ± 0.2**	**1.85**
CERES N	0.83 ± 0.18	1.92 (+1.1)

von Shuckmann et al. (2023) ESSD

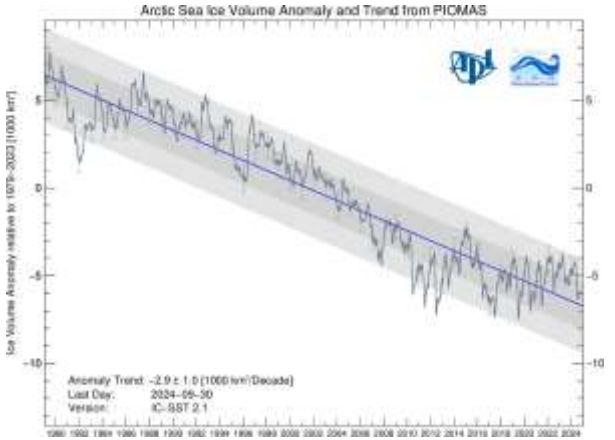
- Could assume same proportion as 2006-2020:
  - atmosphere heating (2%), ice melt (4%), land warming (5%)
  - 2022/23 ocean heating 1.6 Wm^{-2}
  - If flux to deeper layers fixed at D ~ 0.4 Wm^{-2}, mixed layer heating: H ~ 1.2 Wm^{-2}
  - Δ(dT/dt) ~ 1.2/0.63dpc ~ 0.15 $^{o}C/yr$
- Actual dSST = 0.25-0.27^{o}C
- Or 2023 minus 2022 rel. to 2006-2020 trends?

UPDATED ENERGY INVENTORY

- Changes 2023 minus 2022 relative to 2006-2020 trends
- ICE:
  - **Ice sheet changes** (GRACE): −170 Gt Greenland, +65 Gt Antarctic
    - 2006-2020 rate (−279 Gt/yr Greenland; −167 Gt/yr Antarctica)
    - Total about **300 Gt/yr less** than 2006-2020 trend
  - **Sea ice:**
    - Arctic (PIOMAS): −168 Gt (ice density 900 kg/m^3)

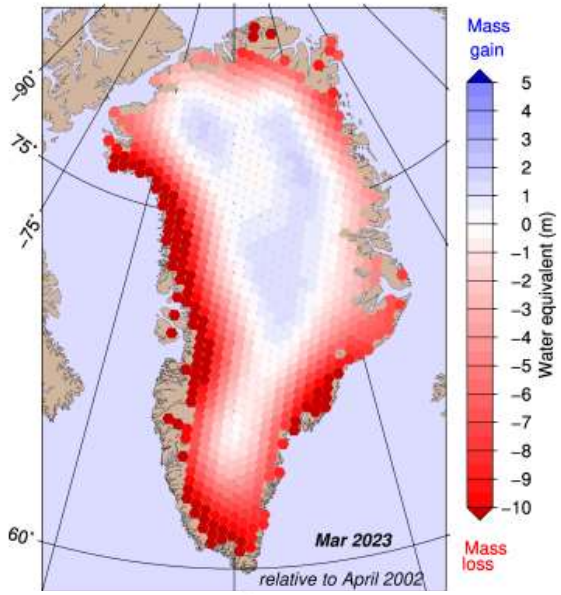
      >similar to 2006-2020 rate (−200 Gt/yr).
    - Antarctic ~1×10^6 km^2 less in 2023 than 2022

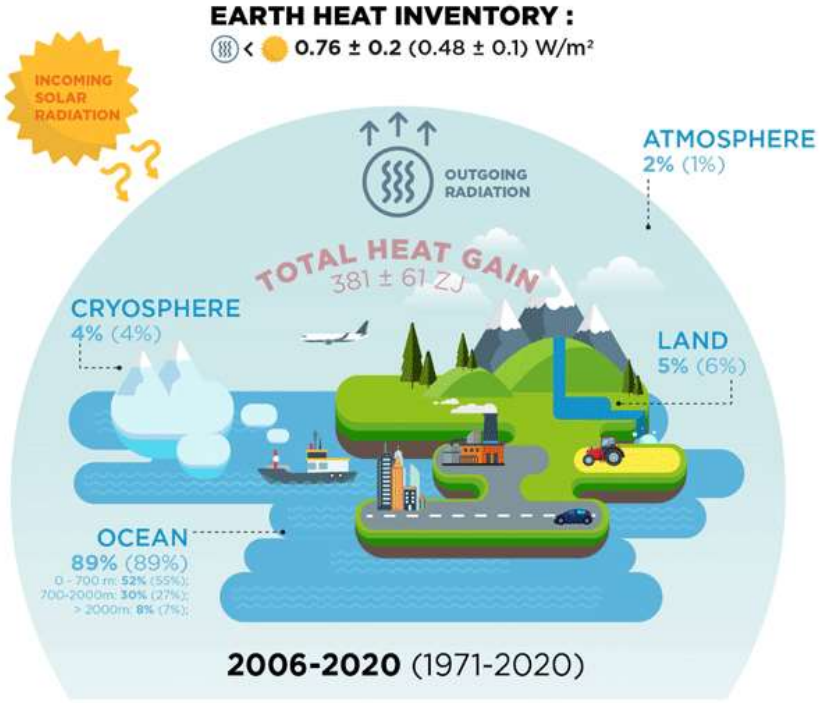
      >**~900 Gt loss** compared to little loss during 2006-2020 (if 1m thick)
  - **Total:** extra ~600 Gt/yr loss (900 Gt/yr sea ice minus 300 Gt/yr ice sheets)
    - Extra +0.012 Wm^{-2} heat used up melting ice



UPDATED ENERGY INVENTORY

- Changes 2023 minus 2022 relative to 2006-2020 trends
- **ICE:**
  - Extra +0.012 Wm^{-2} heat used up melting ice
  - 0.028 Wm^{-2} → <u>0.04 Wm^{-2}</u> (4% → 2%)
- **ATMOSPHERE:**
  - ERA5 atmos. heating 8.6× 2006-2020 rate (VITE) → <u>0.12 Wm^{-2}</u> (2% → 6%)
- **LAND:**
  - Land surface warmed ~10x 2006-2020 rate
  - If assume 5x heating rate (???) 0.039 Wm^{-2} → <u>0.2 Wm^{-2}</u> (5% → 11%)





UPDATED ENERGY INVENTORY

Domain	2006-2020 trend (Wm^{-2}) (Von Shuckmann 2023)	2022-2023 proportional heating (Wm^{-2})	2022-2023 estimated heating (Wm^{-2})
Atmosphere	0.014 ± 0.003 (ERA5: 0.017)	0.034	0.120 (ERA5: 0.146)
Land	0.039 ± 0.004	0.095	0.200
Cryosphere	0.028 ± 0.008	0.068	0.040
Total Ocean	0.67 ± 0.3	1.64	1.49
Total N	**0.76 ± 0.2**	**1.85**	**1.85**
CERES N	0.83 ± 0.18	1.92 (+1.1)	1.92

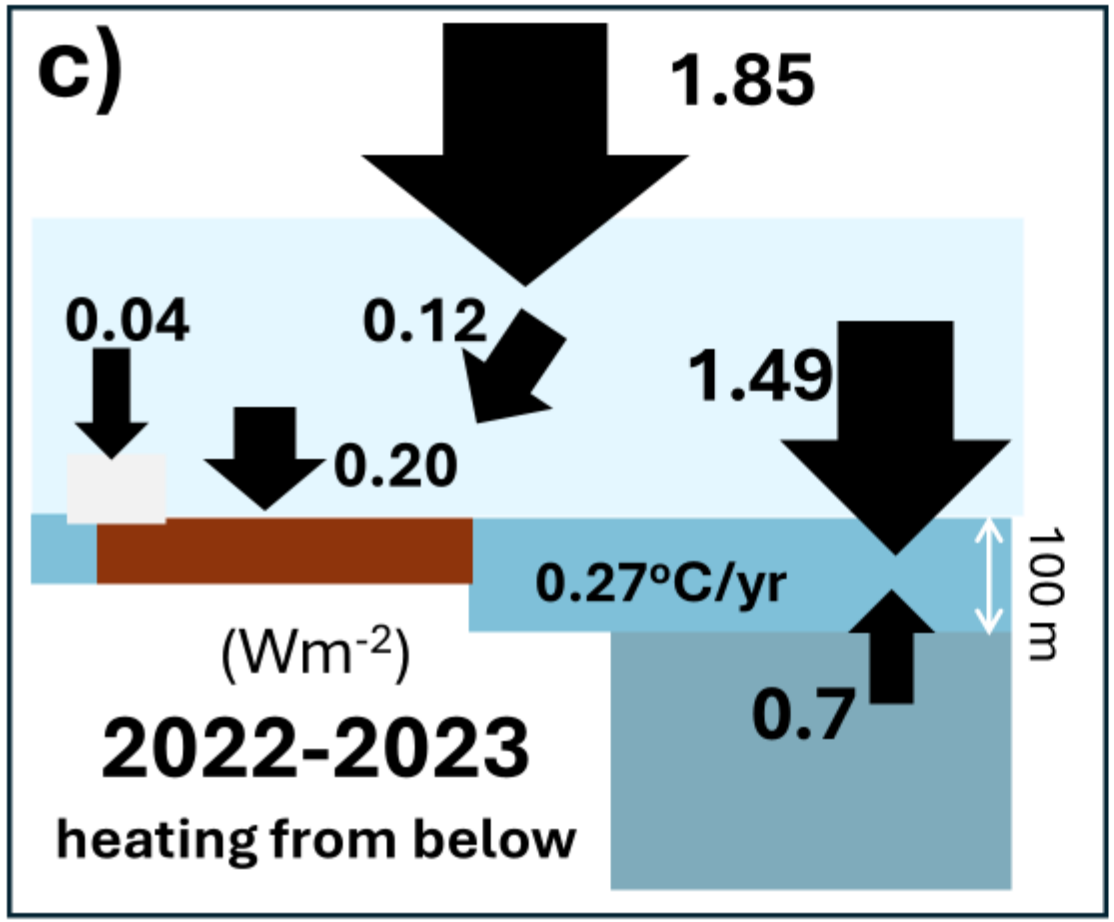
If 1.5 Wm^{-2} heating 100m mixed layer:

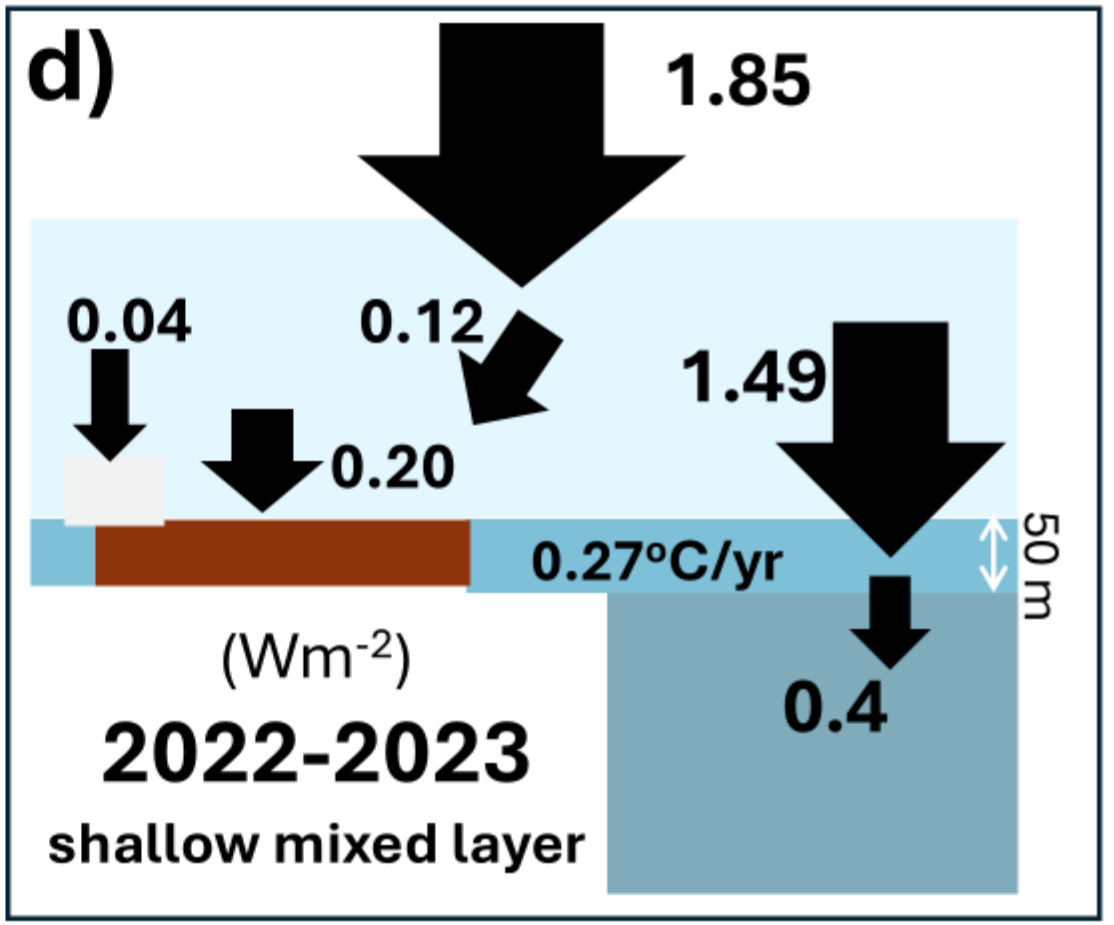
dSST = 1.5/0.63dpc = 0.18ºC

Or what depth would be warmed by 0.27ºC?
d = 1.5/0.63ρc.dSST
~ **70 m**)

But usually ~0.4 Wm^{-2} lost to deeper layers…

CAN ENERGY BALANCE EXPLAIN SURGE IN OCEAN WARMING 2022-23?





CONCLUSIONS

- Evidence of acceleration in energy and water cycle changes:
  - Surface warming, atmospheric water vapour increases, terrestrial water storage decline
  - Earth's energy imbalance growing
- What explains growing energy imbalance?
  - Dominated by reduced reflection of sunlight over cloudy ocean
  - Not captured by ERA5 reanalysis
  - Greenhouse gases (including methane surge), aerosol-cloud interactions, cloud-circulation adjustments, feedbacks to SST warming patterns, internal variability
- How were energy & water cycle involved in 2022-2023 surface warming surge?