Department of Meteorology

University of Reading

RECONCILING HEAT INVENTORY OF 2023/2024 WITH GLOBAL WARMTH

Richard P. Allan r.p.allan@reading.ac.uk @rpallanuk

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National Centre for Earth Observation
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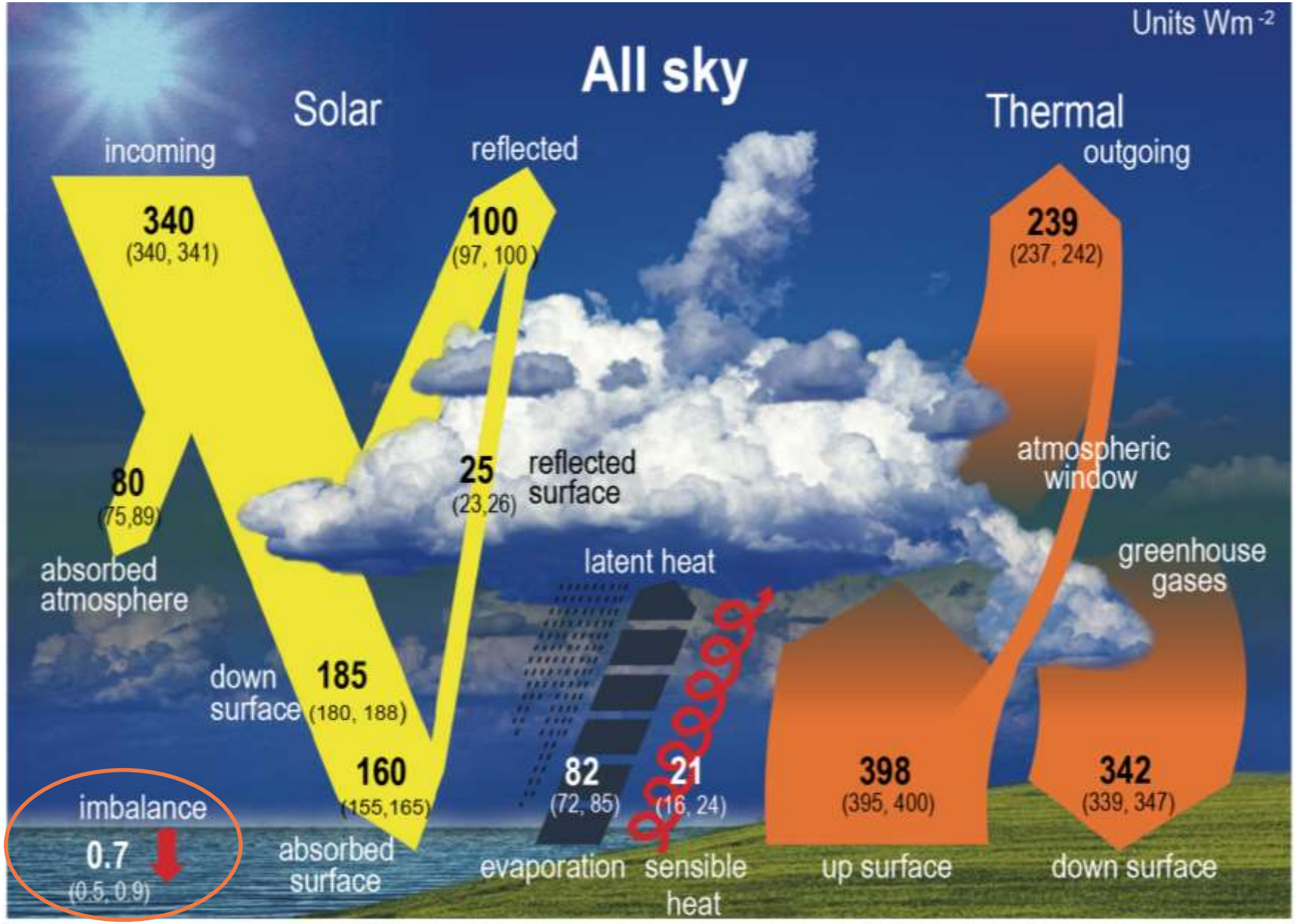
EARTH'S ENERGY BALANCE



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

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

Spot the imbalance…

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

INCREASING NET HEATING OF PLANET

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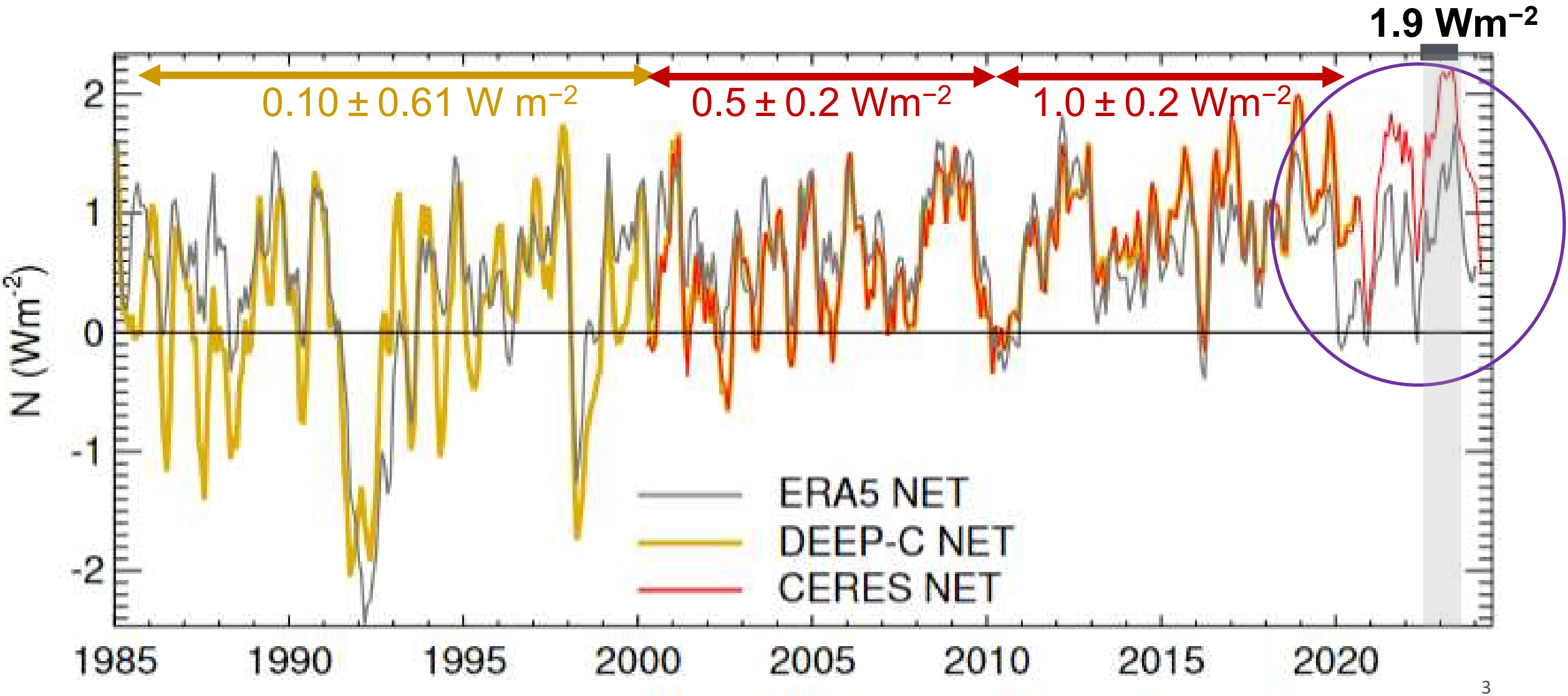
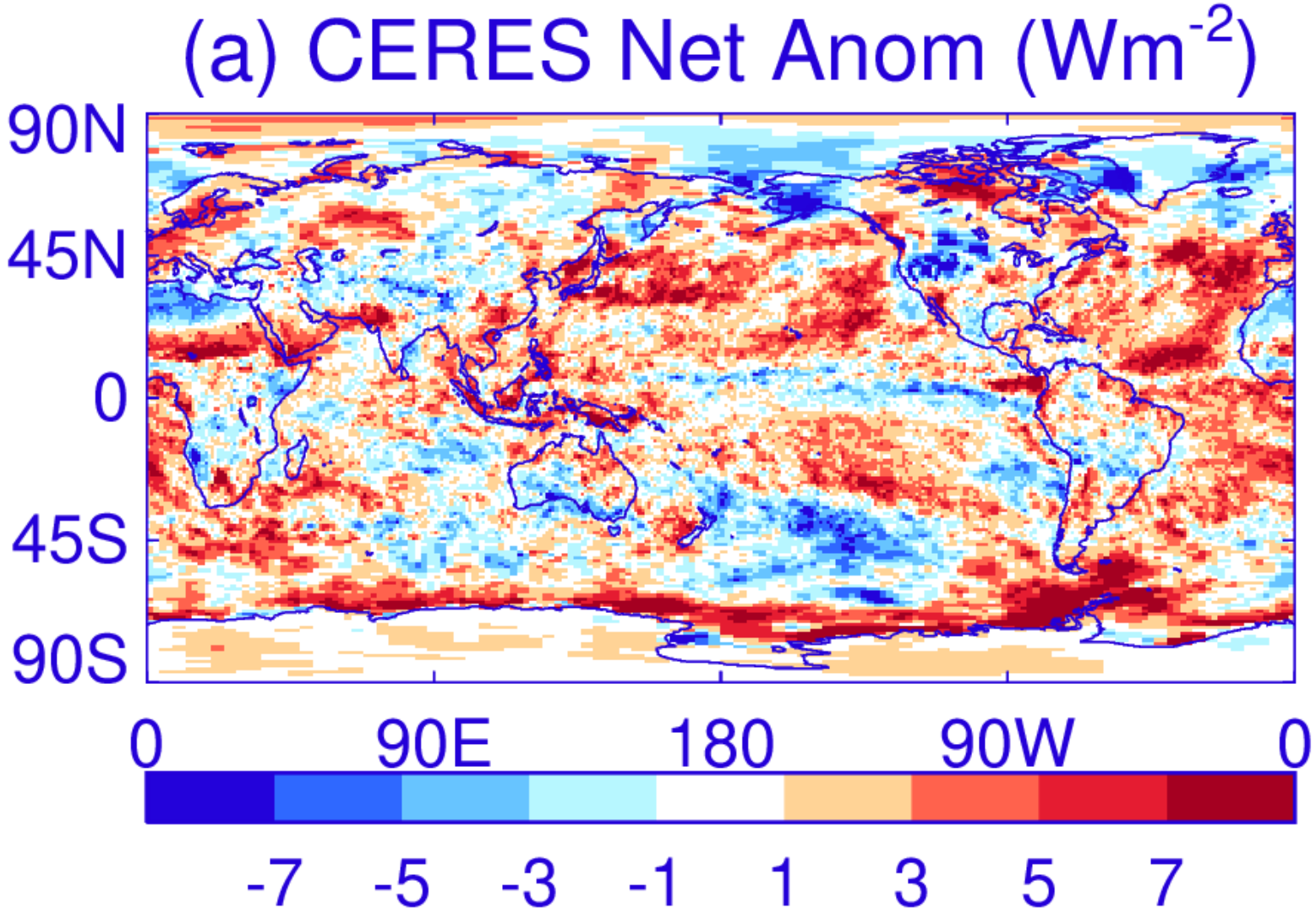


based on Allan et al. (2014) GRL; Liu et al. (2020) Clim. Dyn.; Allan & Merchant (2025) ERL

ENERGY IMBALANCE CHANGES 2022-23

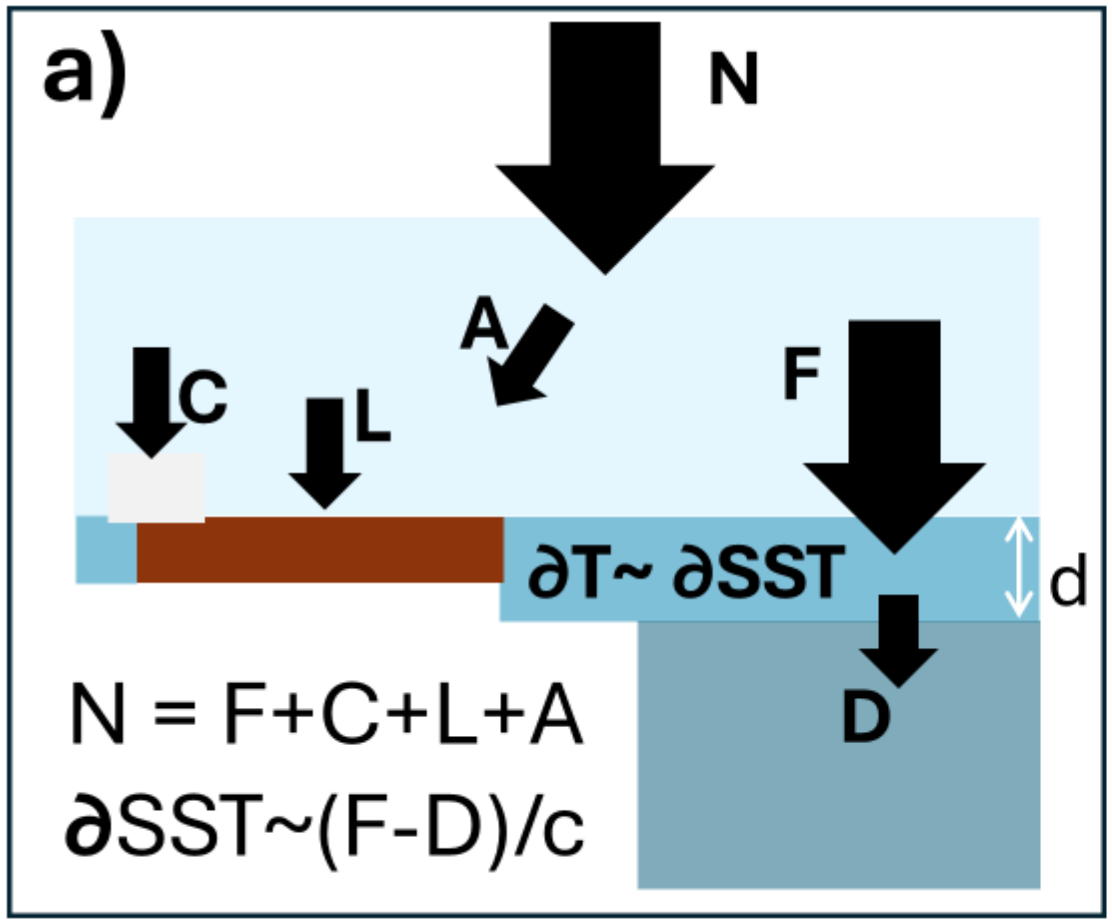


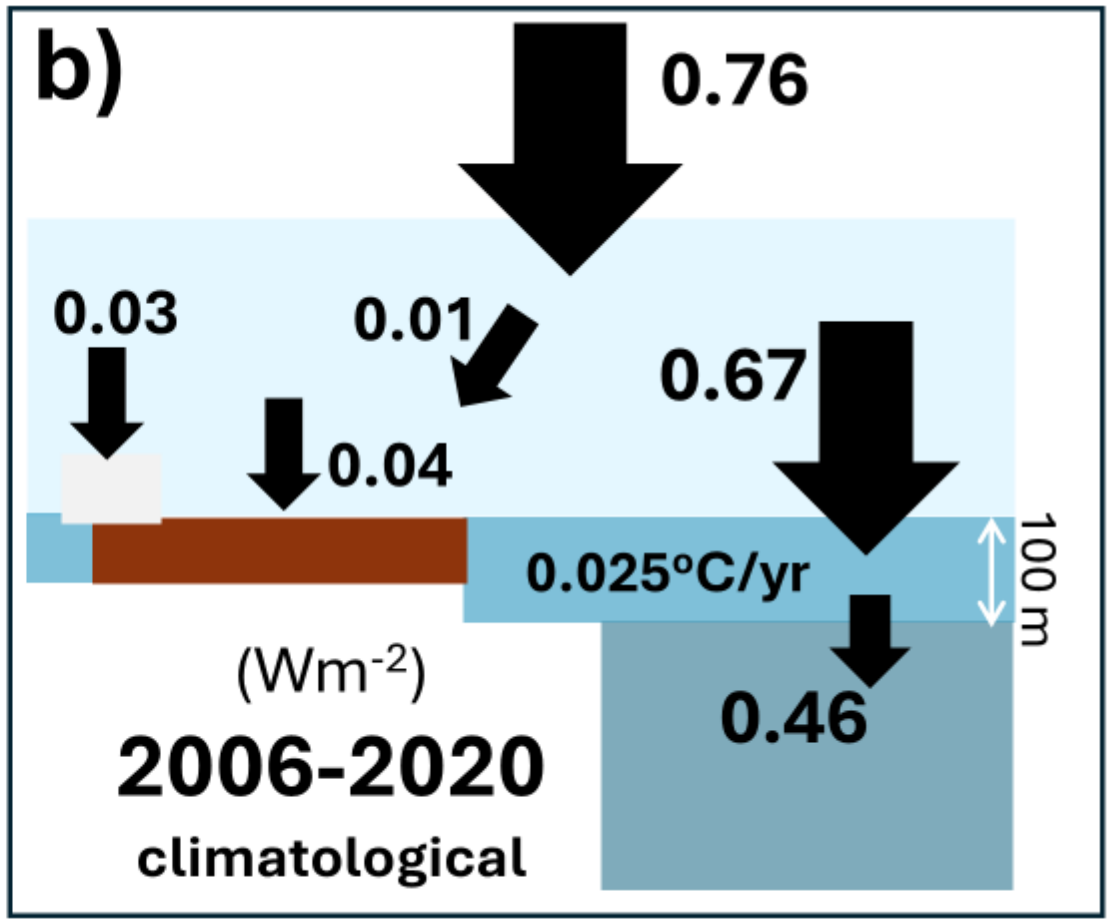
CERES Net Imbalance Aug 2022-Jul 2023: **1.92 Wm^{-2}** (+1.09 Wm^{-2} larger than 2006-2020)

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

CLIMATOLOGICAL HEAT INVENTORY

Effective heating, k = (dSST/dt)/N = 0.033 ^{o}C/decade/(Wm^{-2})

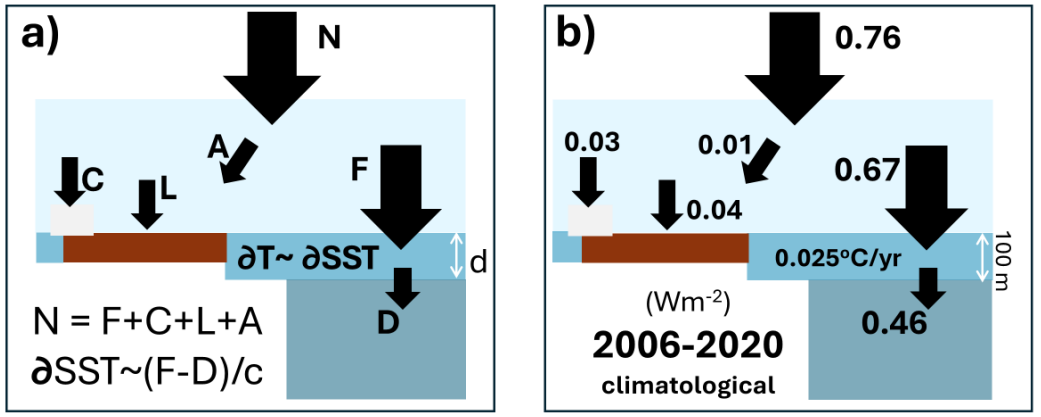




Effective heating layer, d = F/ρc(dSST/dt)(A_o/A_g) ~ 300m

von Shuckmann et al. (2023) ESSD

2006-2020



- N = 0.76 Wm^{-2}
- **dSST/dt** = 0.25°C/decade (60°S-60°N, ESA CCI)
- Effective heating, k = (dSST/dt)/N = 0.025/0.76 = 0.033 (°C/yr)/(Wm^{-2})
- 89% of net energy imbalance heats the ocean (**F** = 0.67 Wm^{-2})

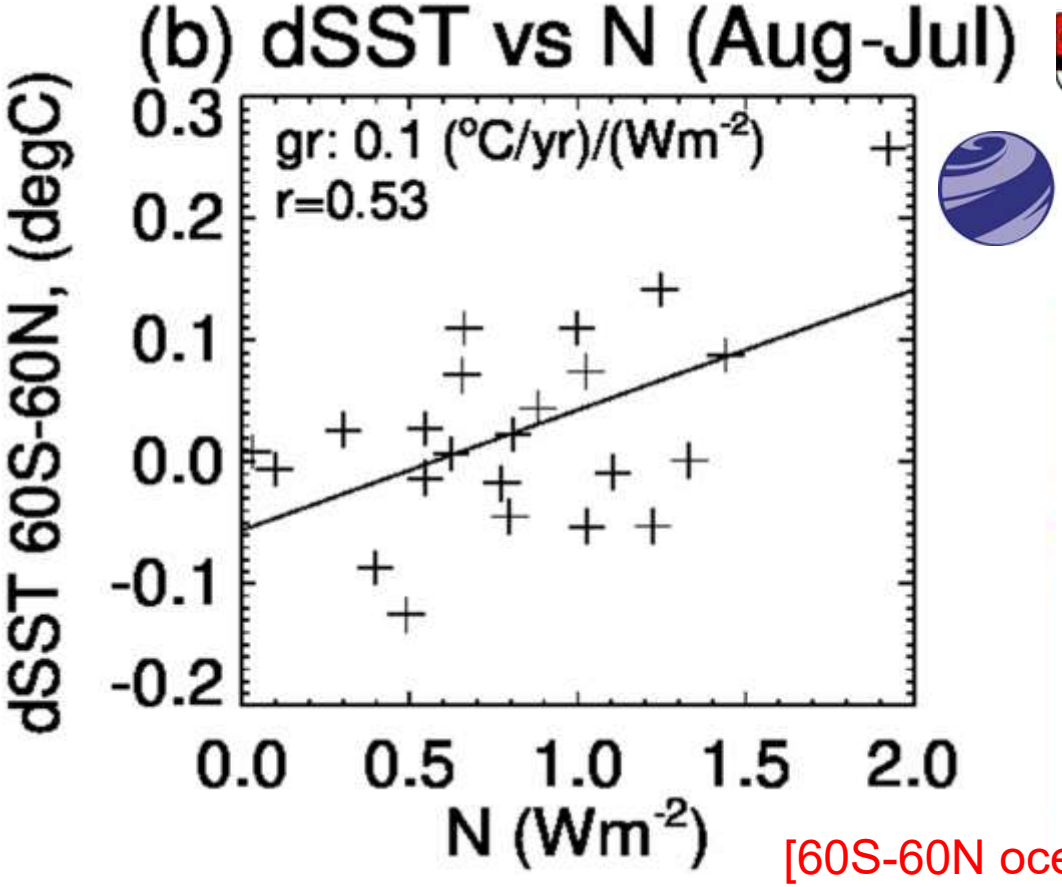
What 'effective' layer of ocean is being heated?

- Ocean heat capacity, **c** = 4003 J/kg/K; Ocean water density, **ρ** = 1027 kg/m^3 .
d = F/ρc(dSST/dt) (times s/decade, divide ocean/global Area, A_o/A_g)
~ (0.67/(1027×4003×0.25×0.63)) × 86400×365×10 ~ 300 m

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 (F)	**0.67 ± 0.3**
Total N	0.76 ± 0.2
sub-100m ocean D	~0.46 ?
CERES N	0.83 ± 0.18

von Shuckmann et al. (2023) ESSD

dSST/dt = 0.25 °C/decade
(CCI, 60°S-60°N)



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

$H \sim 0.63(dT/dt)d\rho c = 6.5 \times 10^6$ 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…

$\Delta H \sim \Delta F \sim 0.89\Delta N$

$\Delta(dT/dt) \sim 0.89\Delta N/0.63 d\rho c = 0.11$ °C/yr

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)

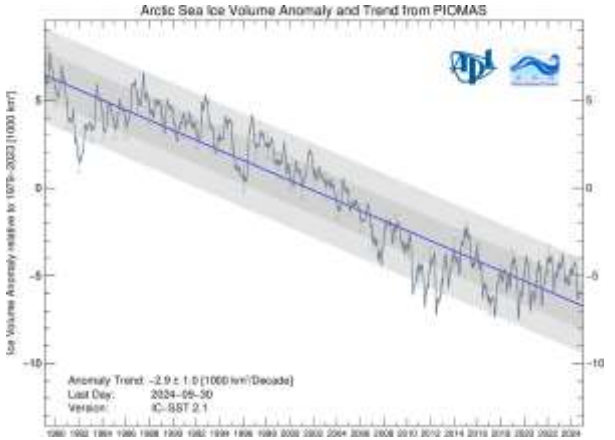
von Shuckmann et al. (2023) ESSD

- 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}
  - $\Delta(dT/dt) \sim 1.2/0.63$dpc $\sim 0.15\ ^oC/yr$
- Actual dSST = 0.25-0.27^{o}C

c = 4003 J/kg/K; ρ = 1027 kg/m^3; d ~ 100m
60S-60N ocean area 63% of globe

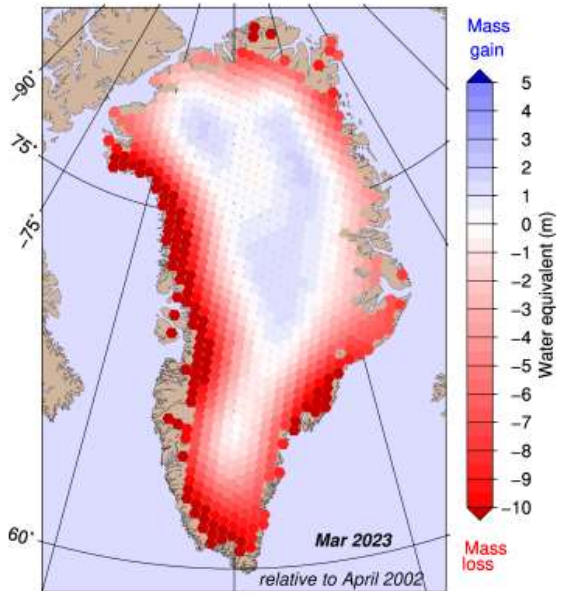
UPDATED ENERGY INVENTORY

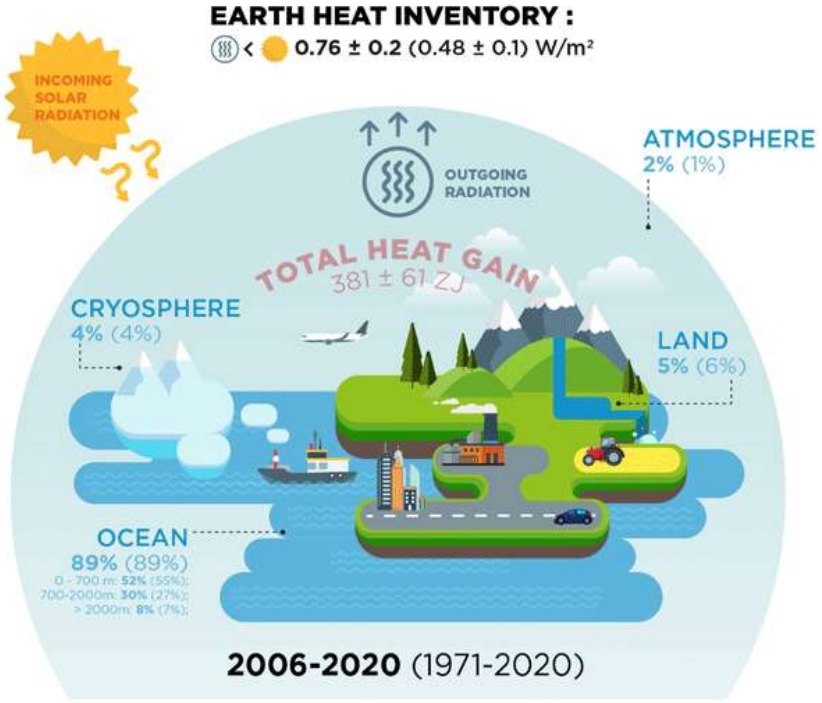
- Changes 2023 minus 2022 relative to 2006-2020 trends
- ICE:
  - **Ice sheet changes** (GRACE): −170 Gt Greenland, +65 Gt Antarctic
    - 2006-2020 rate (−279 Gt/yr Greenland; −167 Gt/yr Antarctica)
    - Total ~ **300 Gt/yr less melting** than 2006-2020 trend
  - **Sea ice:**
    - Arctic (PIOMAS): −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** (if 1m thick) compared to little loss during 2006-2020
      > **Total:** extra ~600 Gt/yr loss (900 Gt/yr sea ice − 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} → 0.04 Wm^{-2} (4% → 2%)
- **ATMOSPHERE:**
  - ERA5 atmos. heating 8.6× 2006-2020 rate (VITE) → 0.12 Wm^{-2} (2% → 6%)
- **LAND:**
  - Land surface warmed ~10x 2006-2020 rate
  - If assume 5x heating rate (???) 0.039 Wm^{-2} → 0.2 Wm^{-2} (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

Allan & Merchant (2025) ERL

c = 4003 J/kg/K; ρ = 1027 kg/m^3; d ~ 100m
60S-60N ocean area 63% of globe

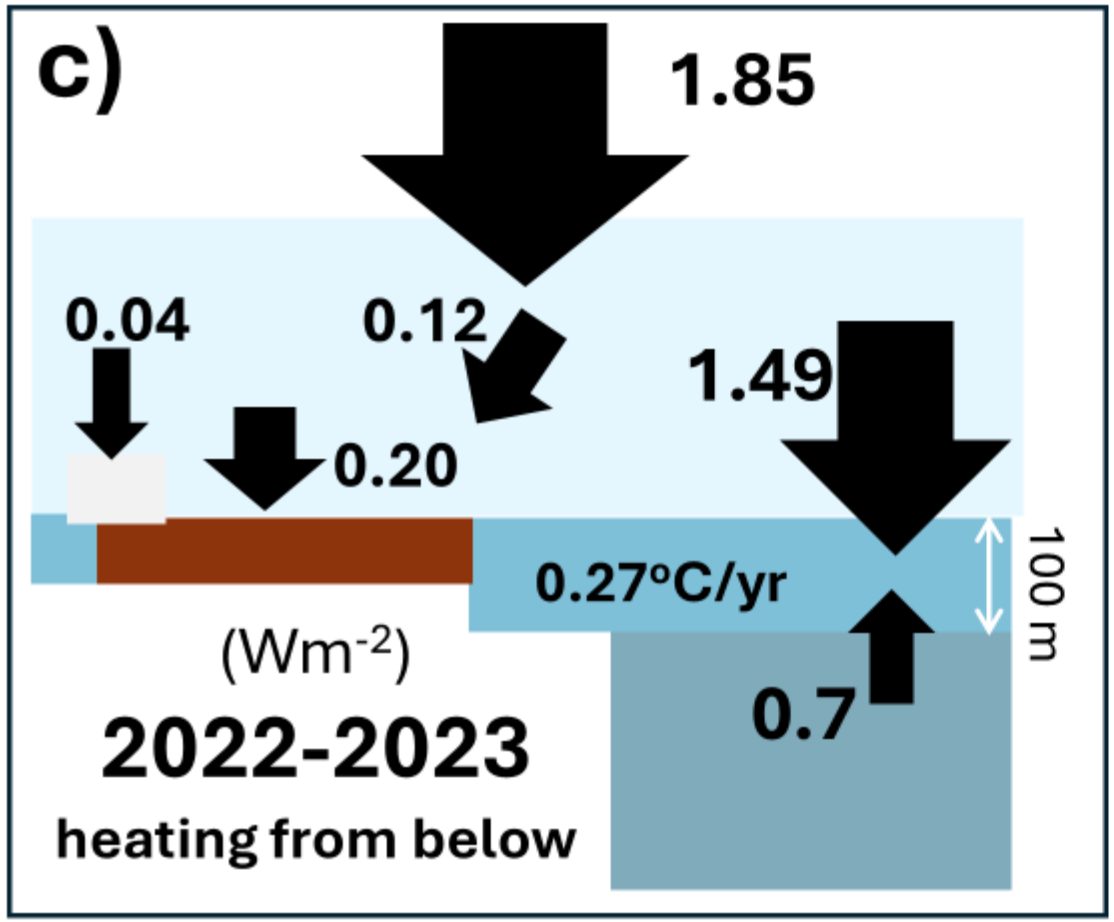
If 1.5 Wm^{-2} heating 100m mixed layer:

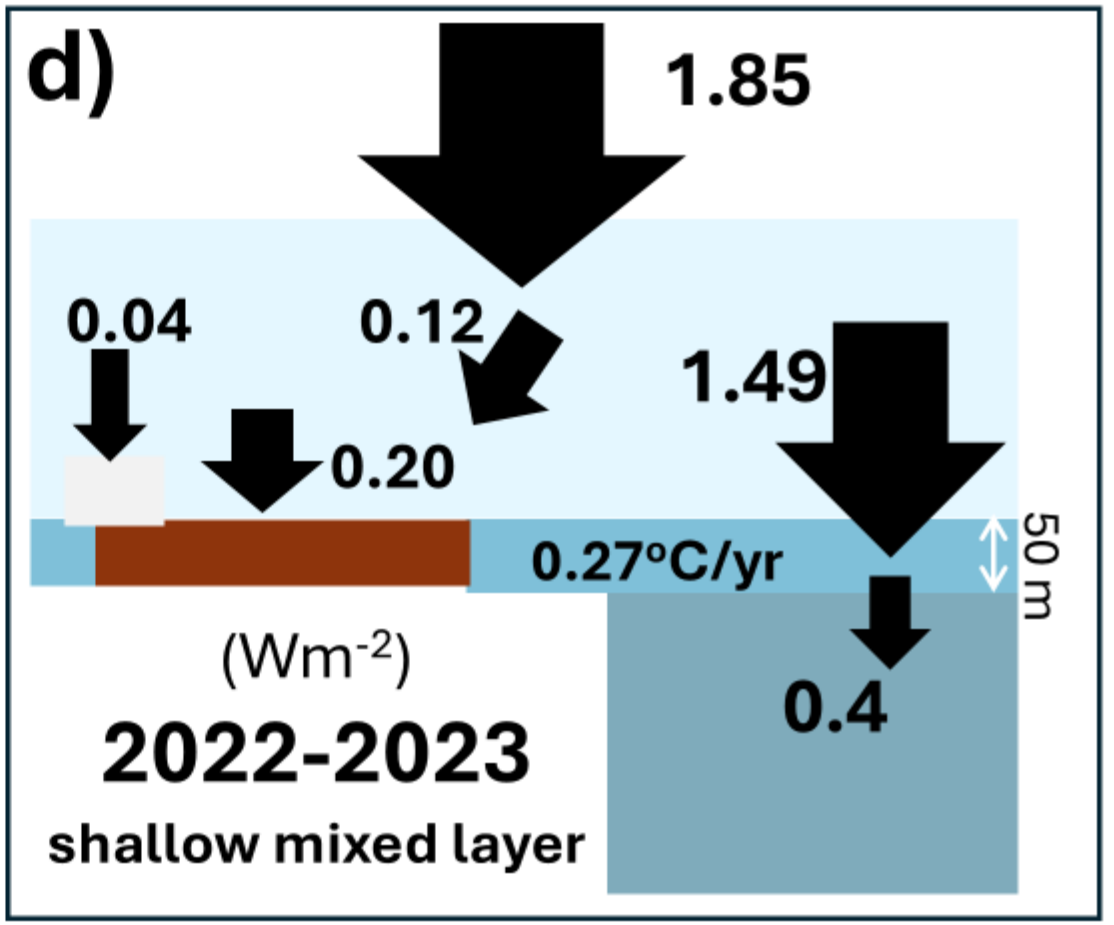
dSST = 1.5/0.63dpc = 0.18°C

Or what depth would be warmed by 0.27°C?
d = 1.5/0.63pc.dSST
~ 70 m)

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

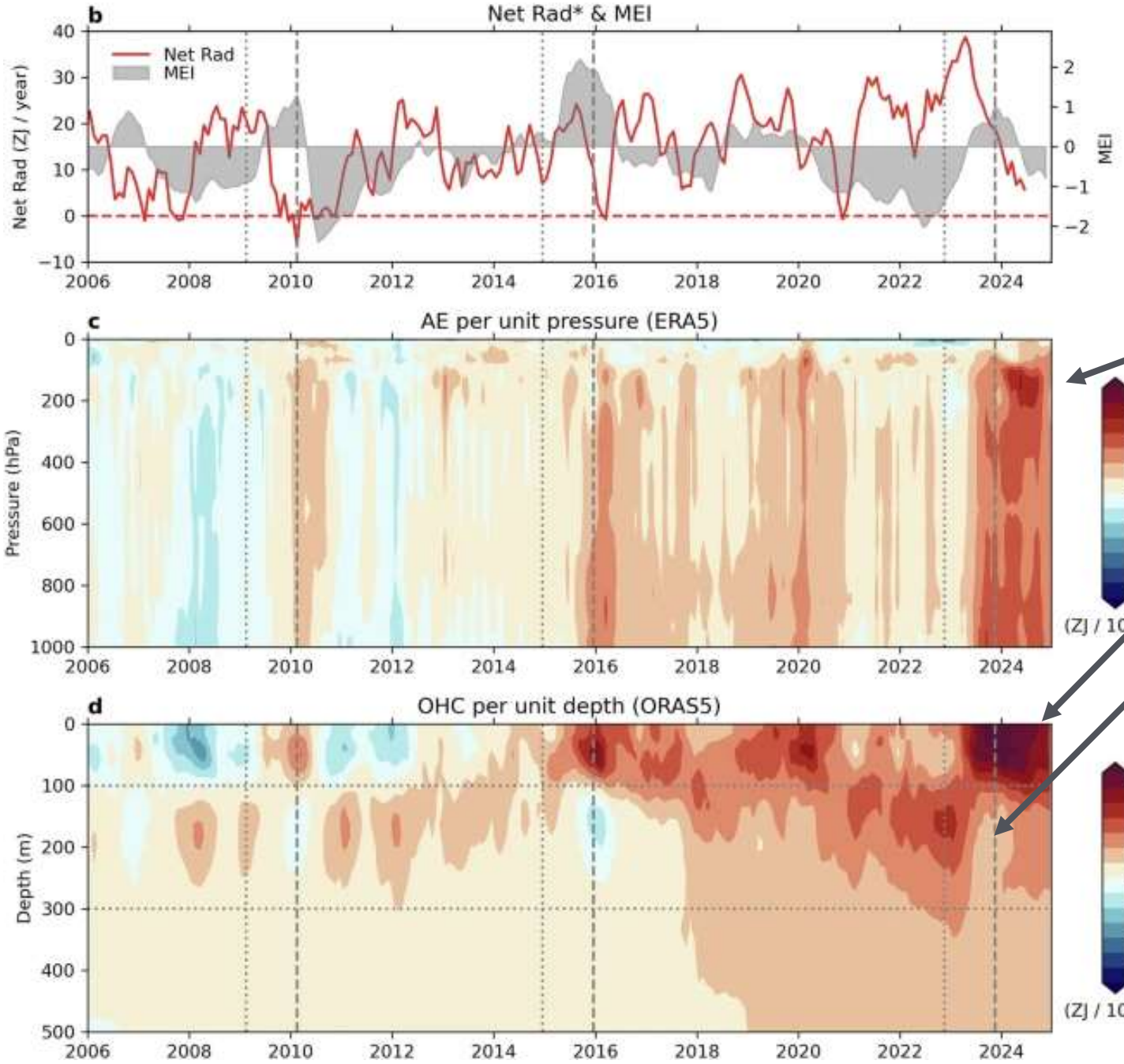
RECONCILING ENERGY BALANCE WITH SURGE IN OCEAN WARMING 2022-23?





Allan & Merchant (2025) ERL

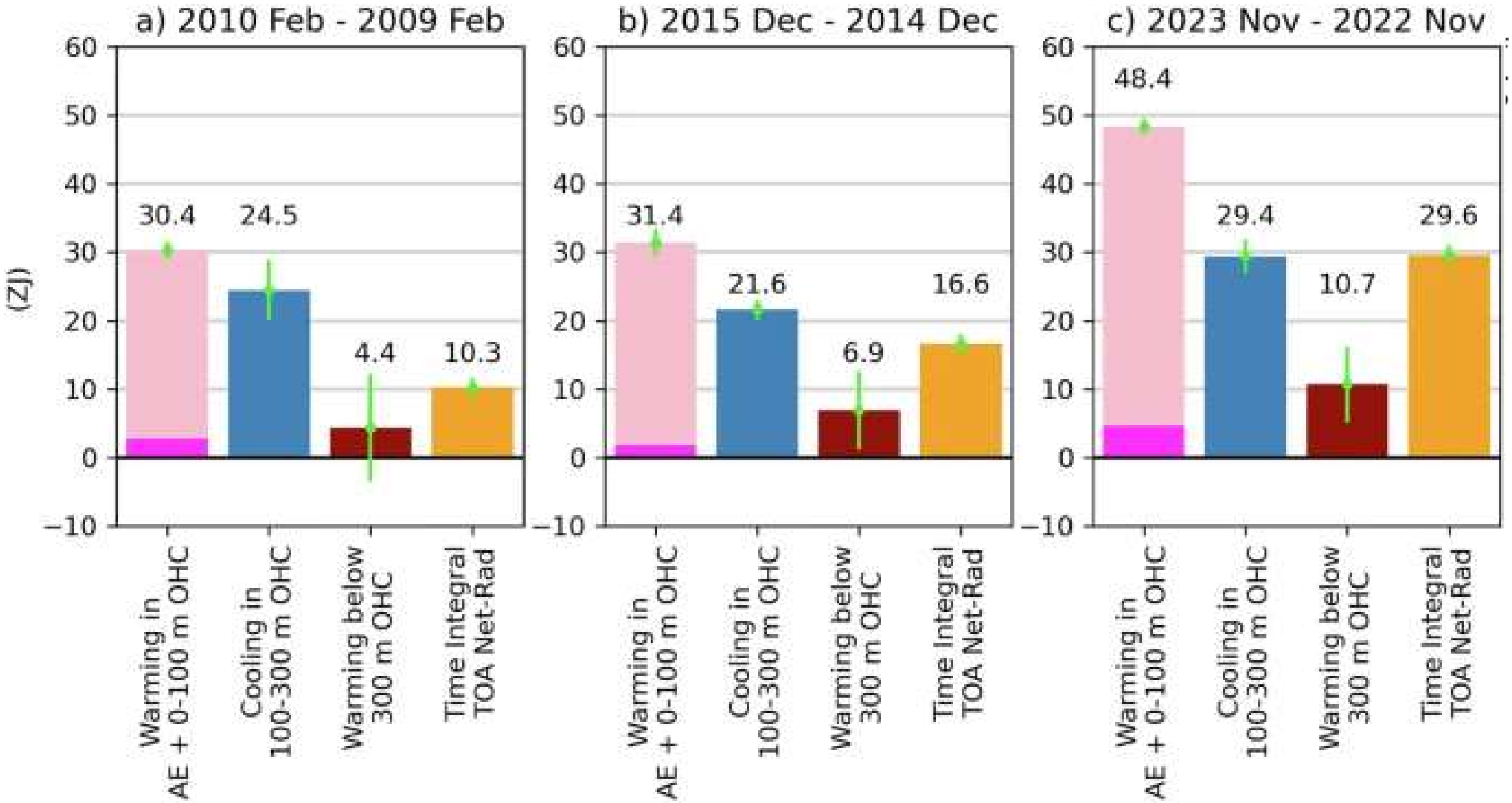
OCEAN COOLING?



Remarkable atmospheric and upper ocean heating

But 100-300m cooling (consistent with El Nino; Allison et al. 2020 ERC)

Minobe et al. (2025) npj Clim. Atmos. Sci.

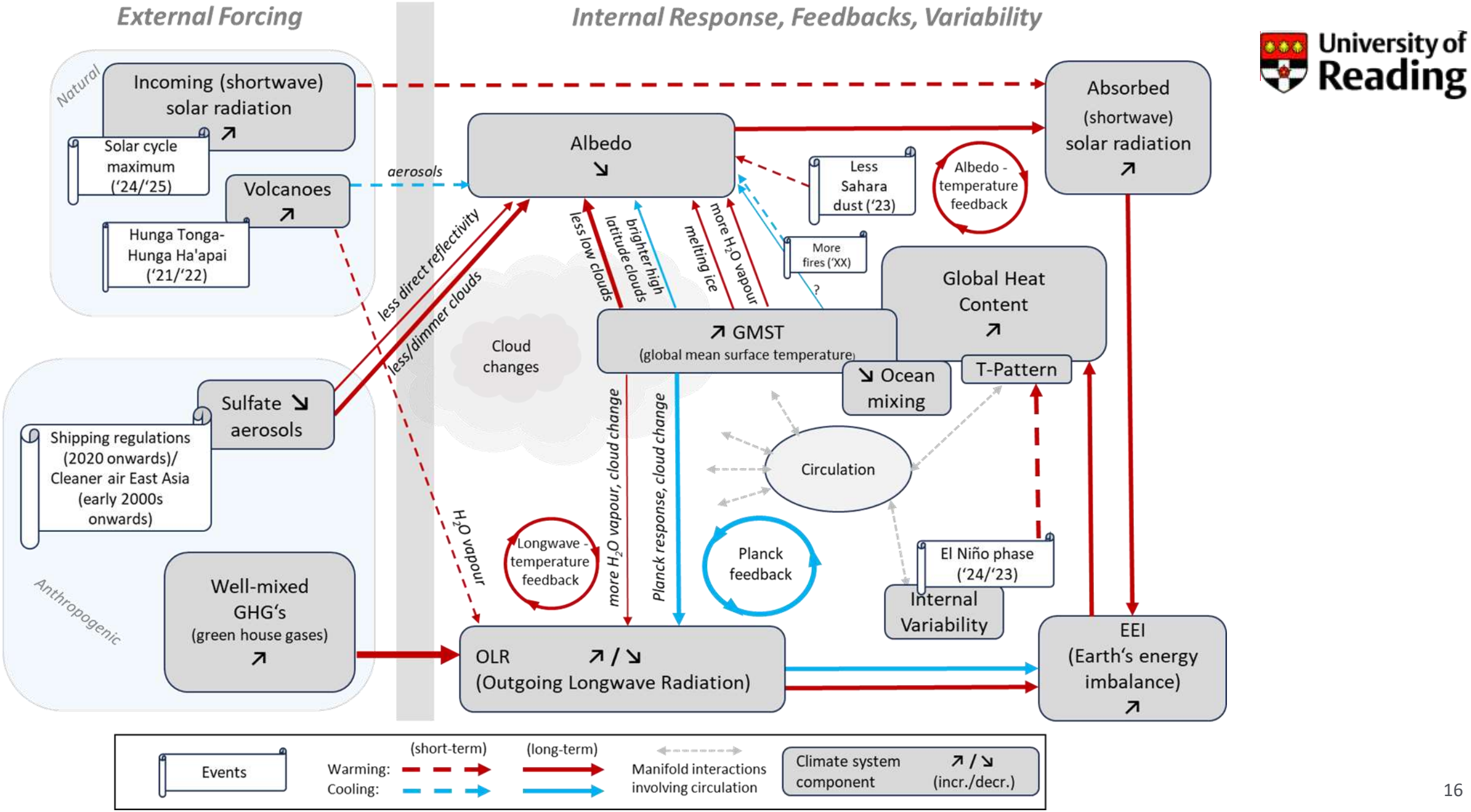


Minobe et al. (2025) npj Clim. Atmos. Sci.

Sub 100m ocean flux = 10.7 – 29.4 ZJ = -18.7 ZJ = -5.9×10^{14} W = **-1.2 Wm^{-2}** global?

CONCLUSIONS

- Record warmth in 2023-2024, close to or above 1.5°C warmer than pre-industrial
  - Ocean surface warming of 0.27°C from 2022 to 2023
- Earth's energy imbalance reached record levels in the satellite era
  - ~2 Wm^{-2} August 2022-July 2023
- About 15-20% heated the atmosphere, land and to a lesser extend melted and heated ice (larger than the climatological proportion of ~10%)
- If 1.5 Wm^{-2} heated the ocean and 0.4 Wm^{-2} went below mixed layer (~100m) as implied from climatology, this would only warm ocean surface by ~0.18°C
- Can only reconcile observed warming and heating if:
  (1) Heating concentrated on shallower ocean mixed layer (e.g. England et al. 2025 Nature)
  (2) Heating from above combined with reversal of downward heat flux to deeper ocean
- What explains growing energy imbalance? Allan & Merchant (2025) ERL; Minobe et al. (2025) npj Clim. Atmos. Sci. ;Loeb et al. (2024) Surv. Geophys.; Goessling et al. (2024) Science; Hansen et al. (2025) Environment: SPSD; Hodnebrog et al. (2024) Comm. Earth Env.; Kuhlbrodt et al. (2024) BAMS


External Forcing
Internal Response, Feedbacks, Variability
Natural
Incoming (shortwave) solar radiation
Solar cycle maximum ('24/'25)
Volcanoes
Hunga Tonga-Hunga Ha'apai ('21/'22)
aerosols
Albedo
Absorbed (shortwave) solar radiation
Less Sahara dust ('23)
Albedo - temperature feedback
More fires ('XX)
?
less direct reflectivity
less/dimmer clouds
less low clouds
brighter high latitude clouds
melting ice
more H2O vapour
Global Heat Content
GMST (global mean surface temperature)
Cloud changes
Ocean mixing
T-Pattern
Sulfate aerosols
Shipping regulations (2020 onwards)/ Cleaner air East Asia (early 2000s onwards)
Anthropogenic
more H2O vapour, cloud change
Planck response, cloud change
Circulation
H2O vapour
Longwave - temperature feedback
Planck feedback
El Niño phase ('24/'23)
Internal Variability
Well-mixed GHG's (green house gases)
OLR (Outgoing Longwave Radiation)
EEI (Earth's energy imbalance)
Events
(short-term)
(long-term)
Warming:
Cooling:
Manifold interactions involving circulation
Climate system component
(incr./decr.)