

The Ocean and Earth's Energy Imbalance in a Changing Climate

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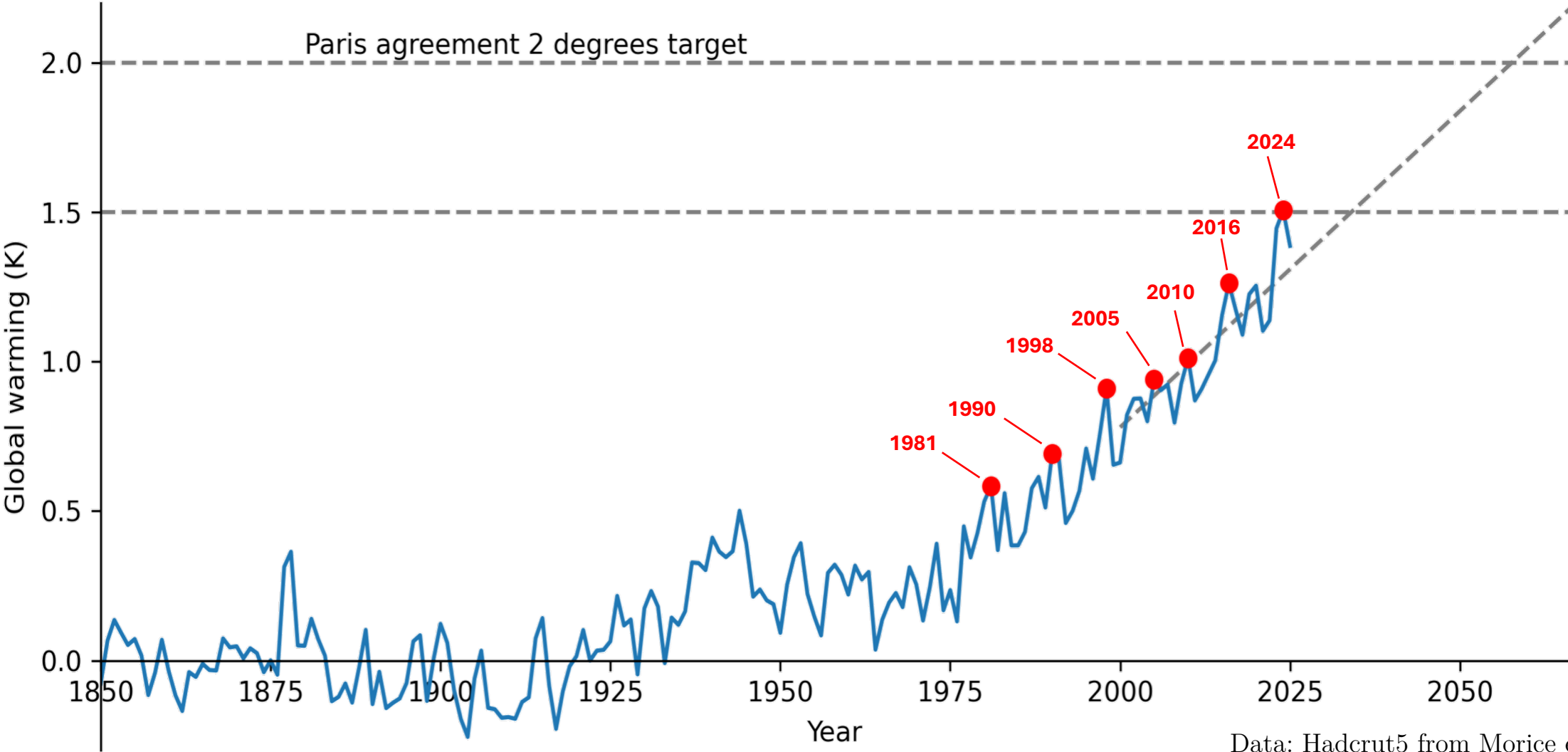
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S.Fourest, R.Roca, T.Fiolleau, A.Blazquez, T.Duvignacq and many others...



Earth is warming...

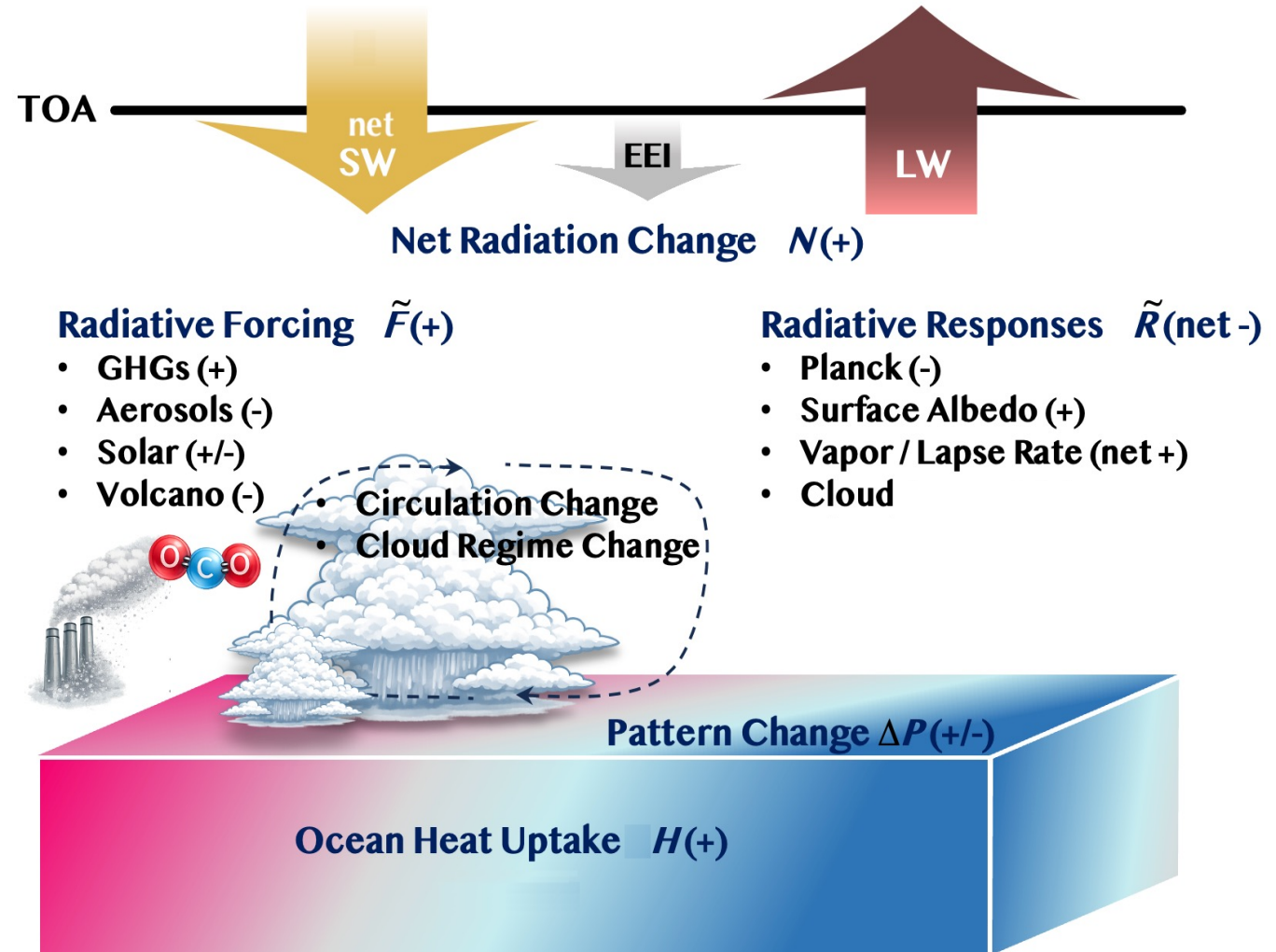


Data: Hadcrut5 from Morice et al. 2021

... because GHG emissions disrupt the radiation balance

Anthropogenic GHG emissions:

- **disrupted** the radiative balance at the top of the atmosphere
- **triggered** climate feedbacks
- **yielded** current Earth Energy Imbalance (EEI)

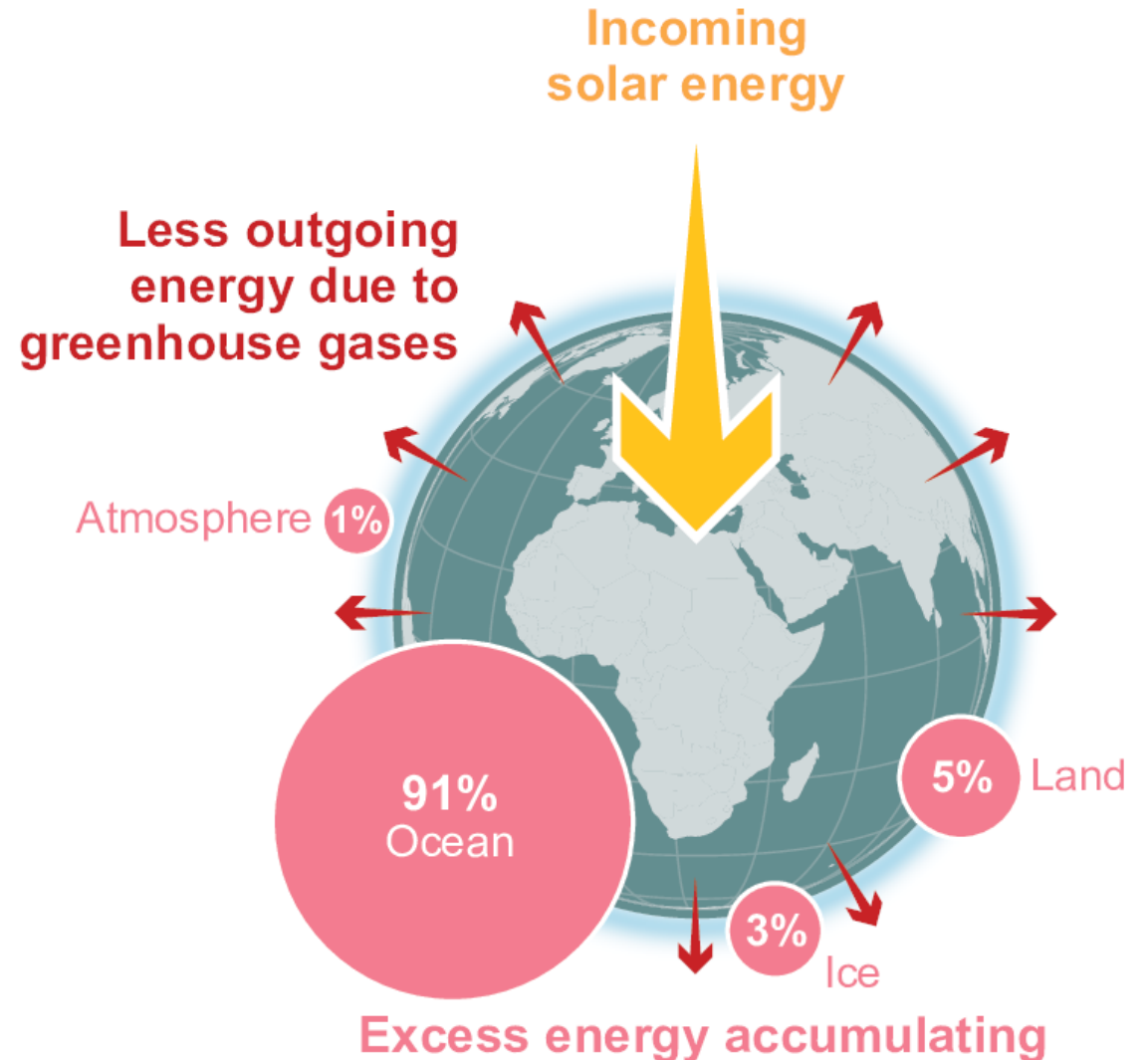


The climate system stores the excess energy

Anthropogenic GHG emissions:

- **disrupted** the radiative balance at the top of the atmosphere
- **triggered** climate feedbacks
- **yielded** current Earth Energy Imbalance (EEI)

➔ Because of EEI, energy is stored in the climate system, causing global warming



... and this energy storage has severe consequences

➤ Surface temperature rise

➤ Ice melt

➤ Sea level rise, acceleration

➤ More frequent extreme weather

Heat waves become more common and hotter

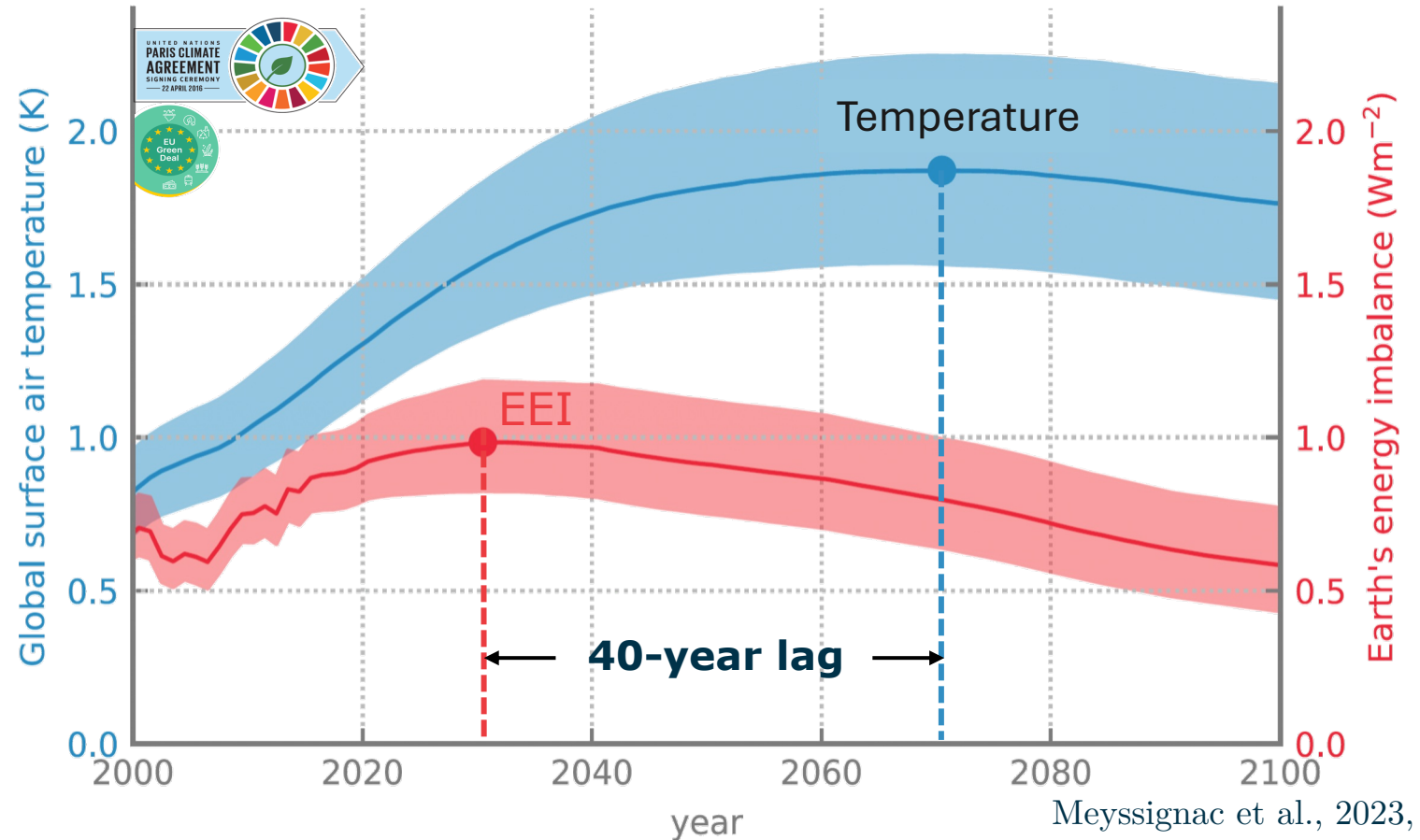
More intense droughts

Heavy rainfall and flooding increase



EEI is a metrics of the warming that is still to come

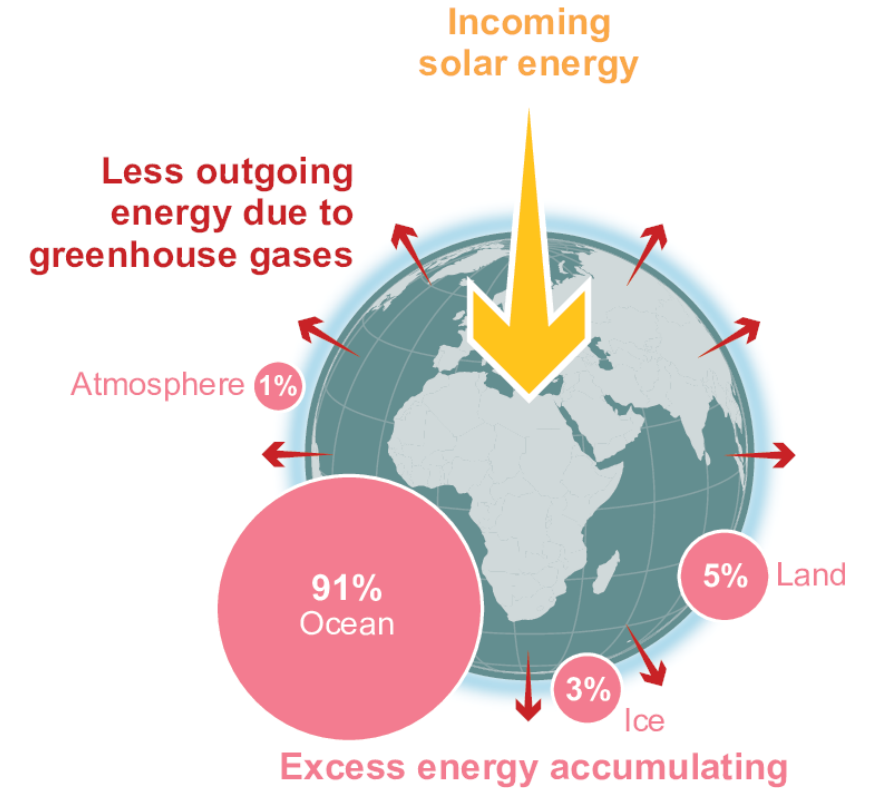
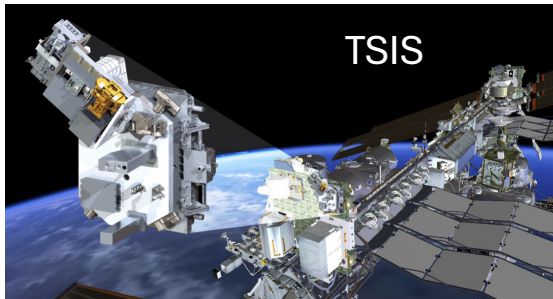
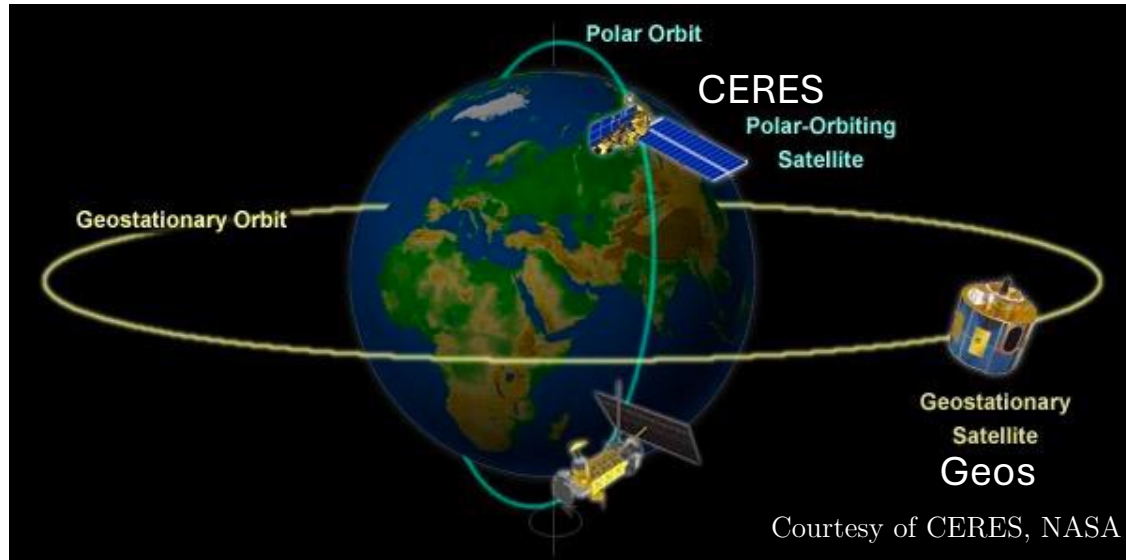
- In the future **EEI will reduce towards zero** as GHG concentration stabilize
- **EEI responds to mitigation decades** before the temperature, providing an early detection of mitigation policy efficacy



Meyssignac et al., 2023,
10.1038/s41558-023-01735-z.
With IPCC AR6 data, 2021, Chapter 7

How do we estimate the Earth energy imbalance?

Top of the Atmosphere radiation budget



From IPCC AR6

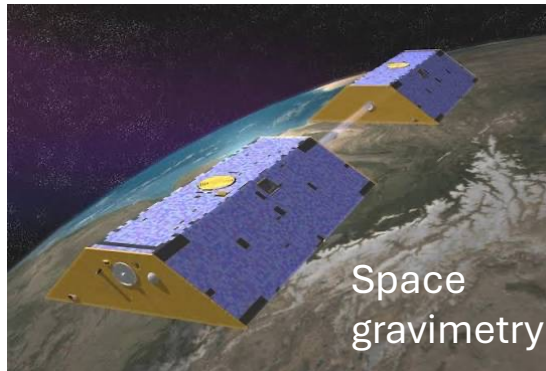


TOA radiation budget : High precision, High stability

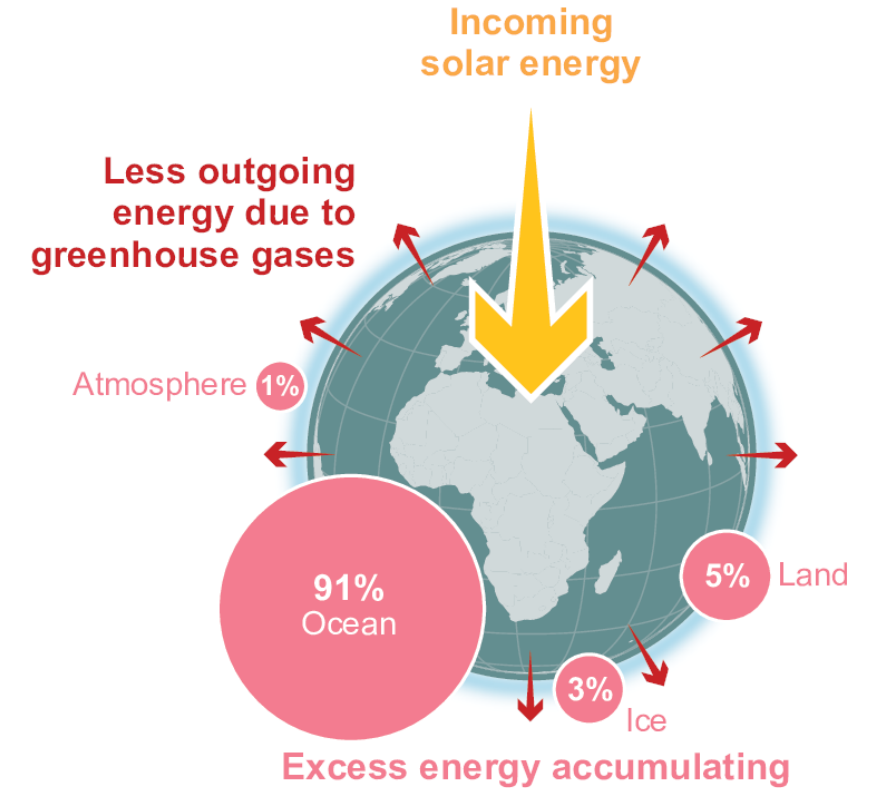
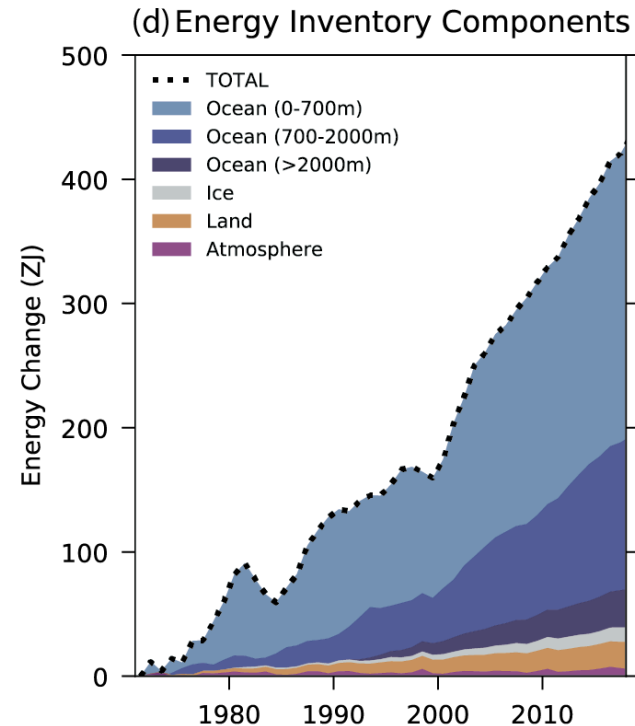
How do we estimate the Earth energy imbalance?

Planetary energy inventory

- Combination of *in situ* Argo network of profiling floats with ocean satellite altimetry space gravimetry, to estimate the ocean heat uptake (OHU)



Argo floats



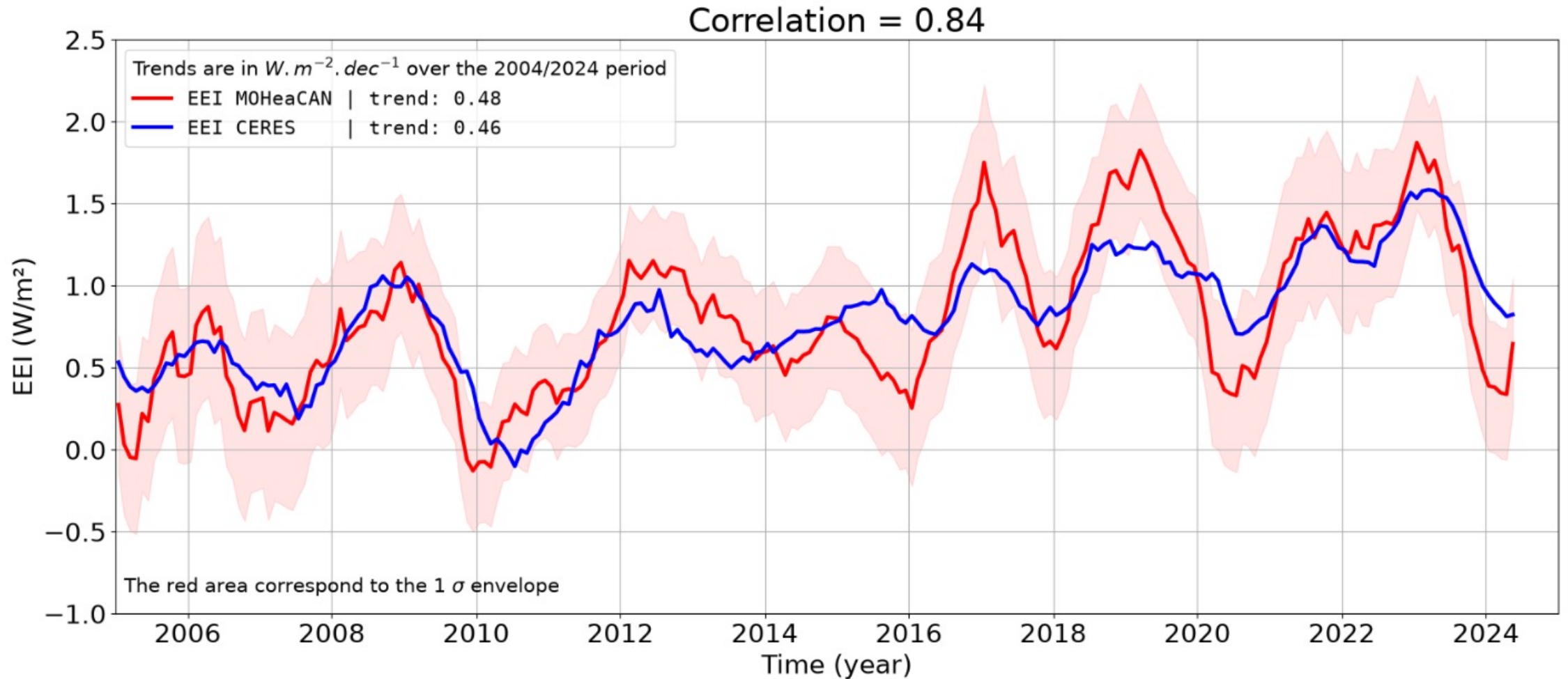
From IPCC AR6



planetary energy inventory (mostly Ocean Heat Uptake) : High Accuracy

How do we estimate the Earth energy imbalance?

Planetary energy inventory and Earth energy imbalance

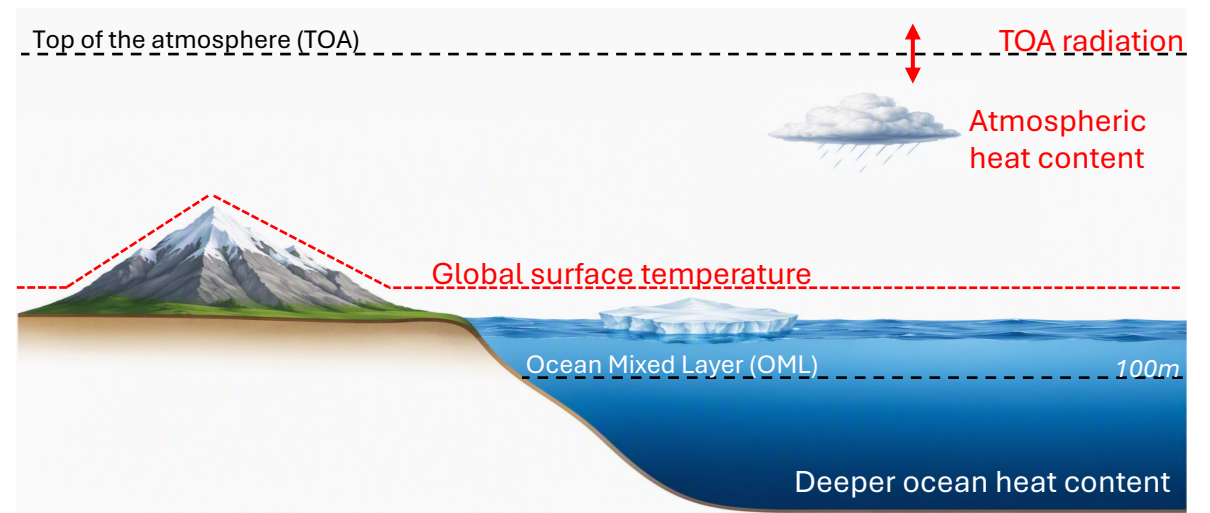


From Fourest et al. accepted

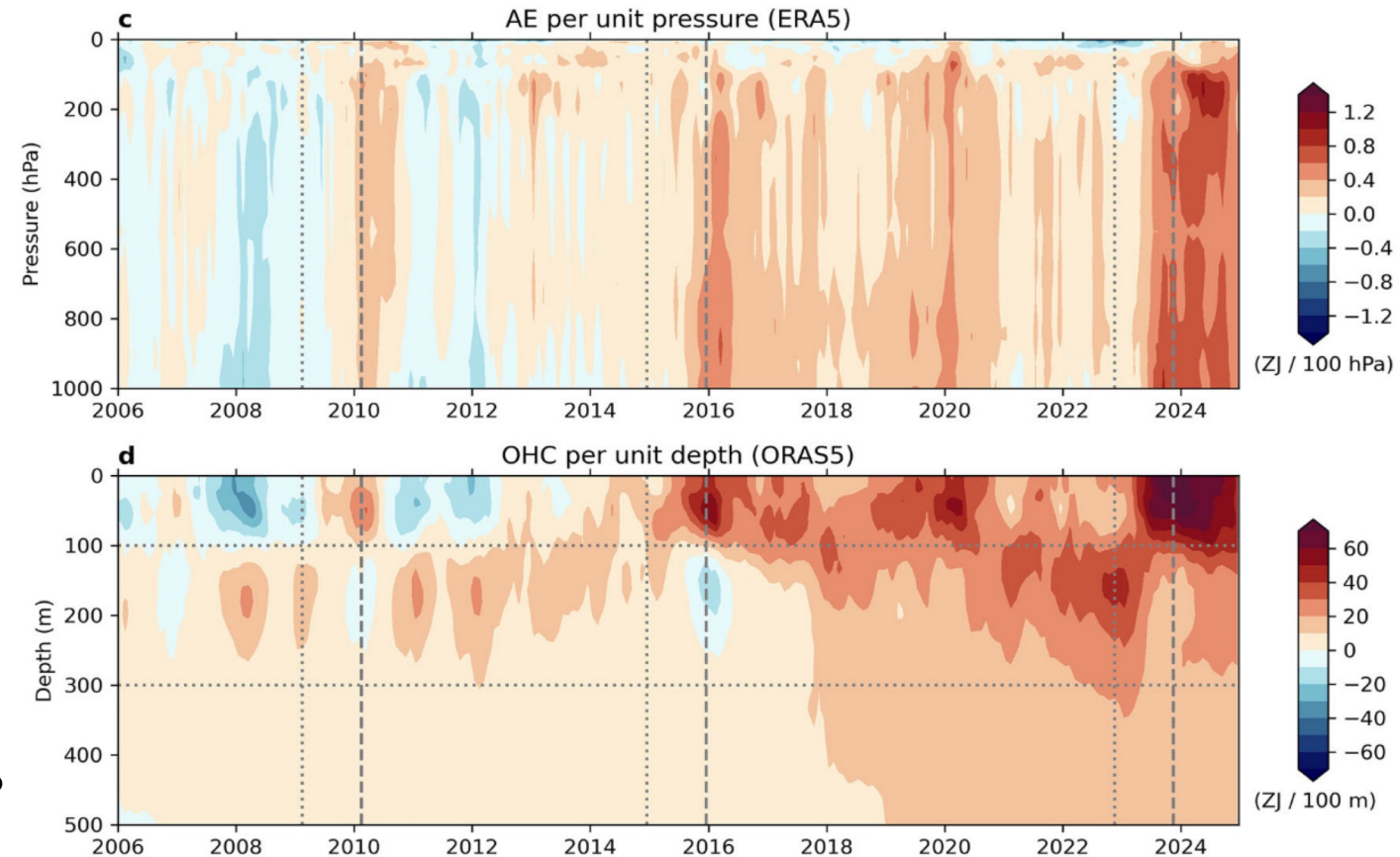


TOA Earth radiation budget **at risk!!!** No continuity ensured after Libera in 2032
Ocean heat content estimates **at risk!!!** Futur US contribution to Argo is unsure

From Hedemann et al. 2017



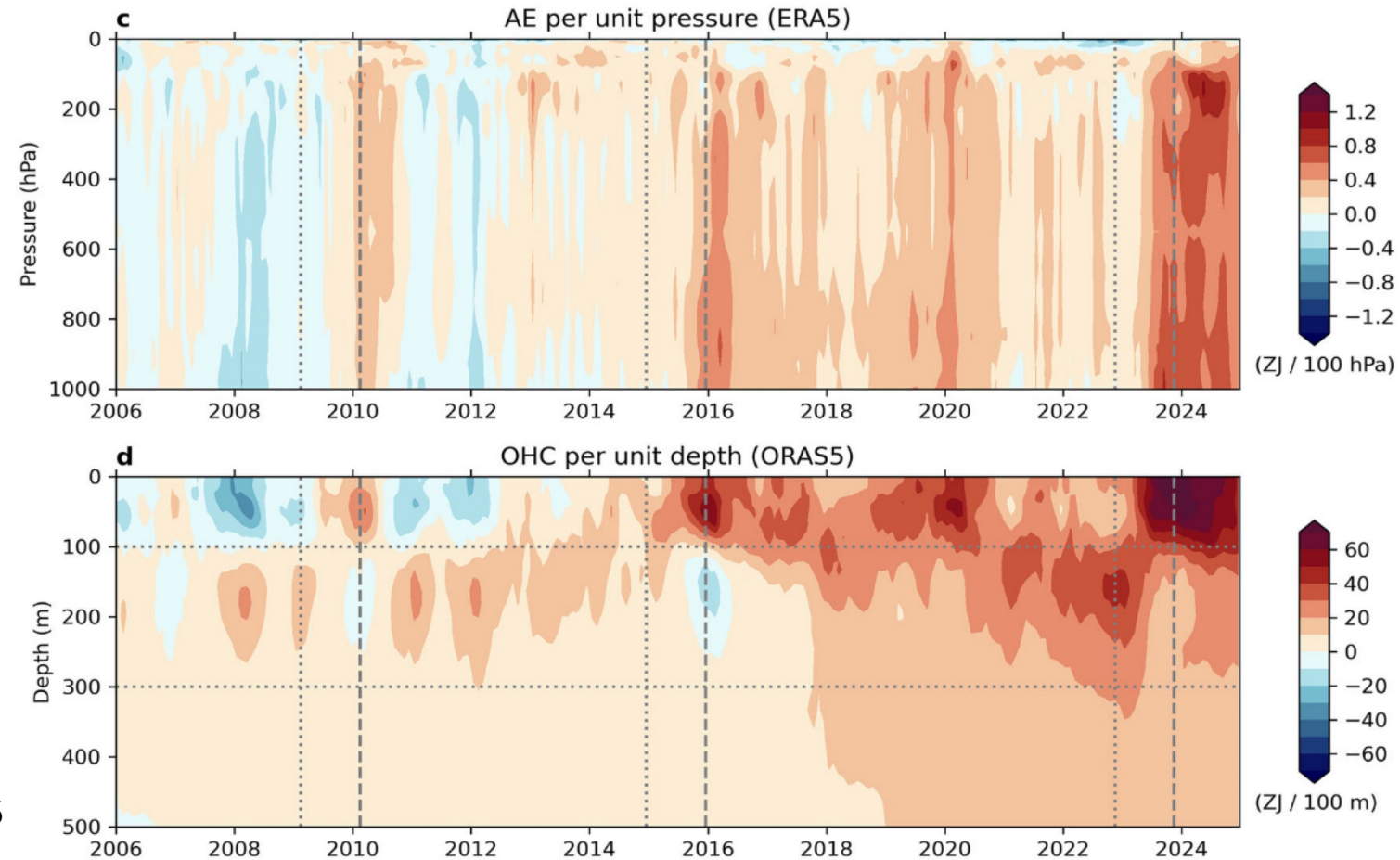
The Earth energy imbalance and the ocean heat uptake determine the Global Mean Surface Temperature variability



From Meyssignac et al. in prep

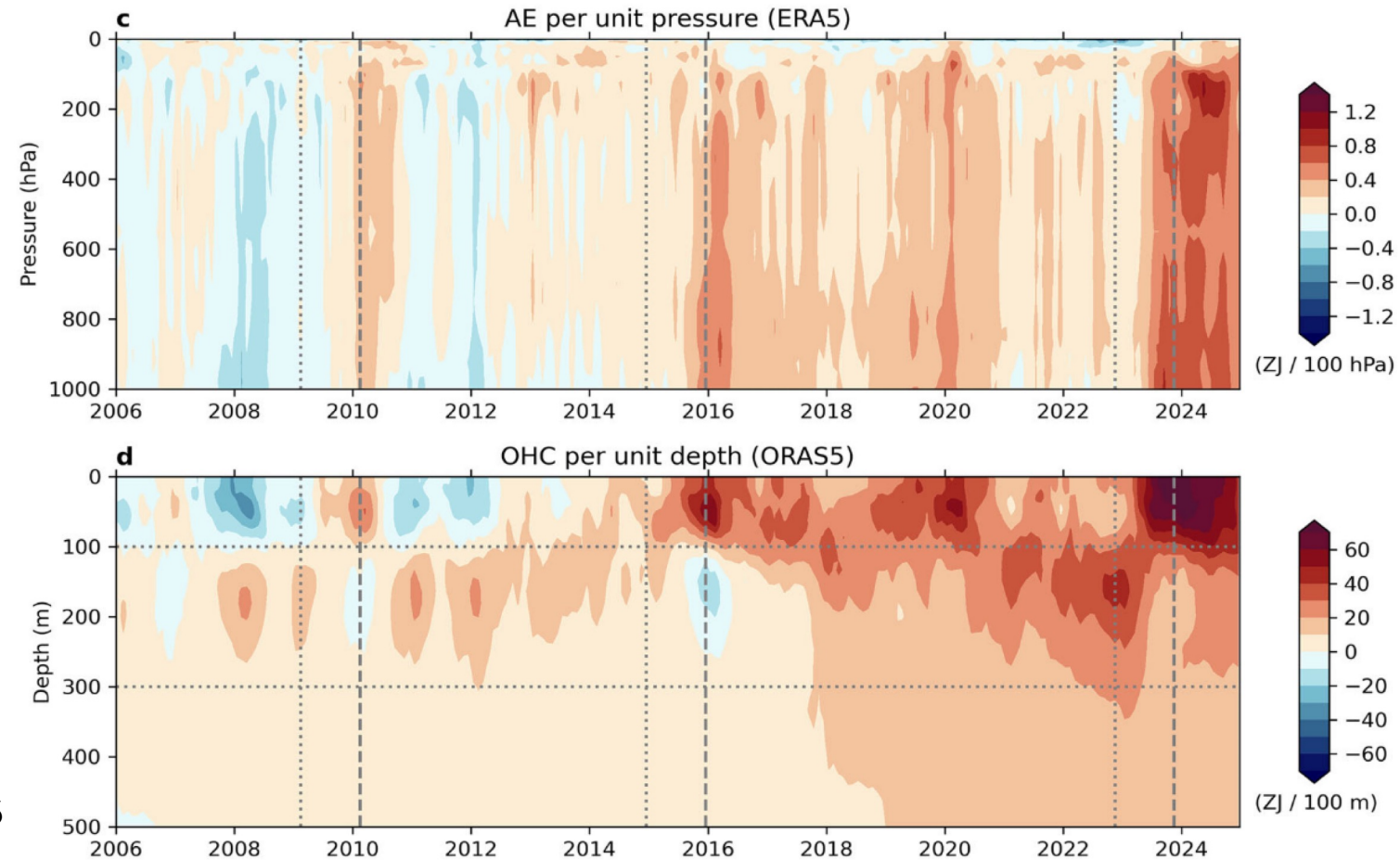
The ocean absorbs 90%
of the excess energy
slowing down the rate
of surface warming

From Minobe et al. 2025



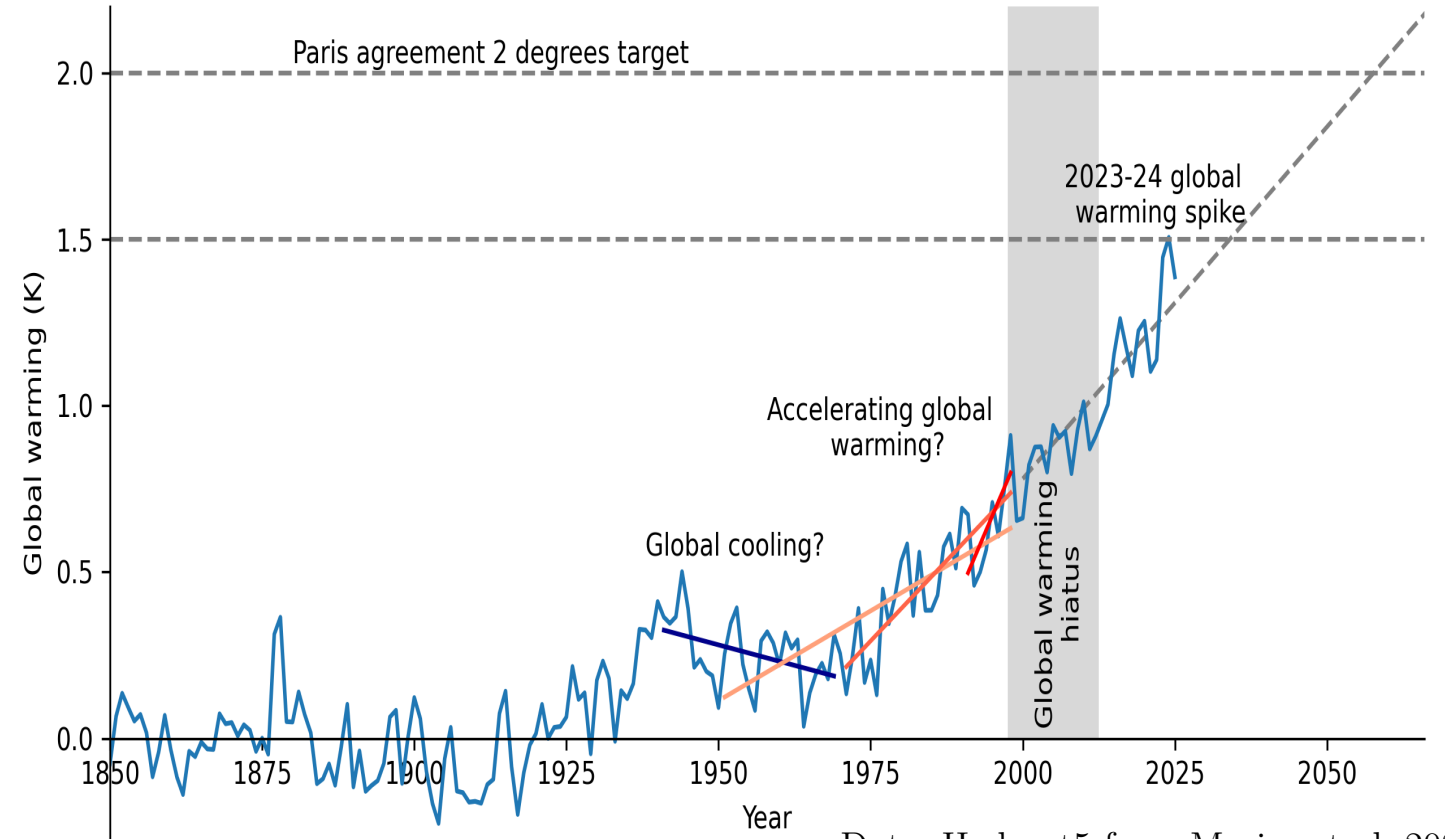
During ENSO events ,
the ocean releases
stored heat
pushing GMST to
records

From Minobe et al. 2025



EEI and Ocean vertical heat redistribution drives also GMST decadal variability

$\pm 0.1 \text{ W.m}^{-2}$ in EEI or OHU can explain decadal variability in GMST like hiatus



Data: Hadcrut5 from Morice et al. 2021

Ocean sea surface temperature pattern modulates the strength of radiative feedbacks and the effective climate sensitivity.

Climate sensitivity
is not constant!

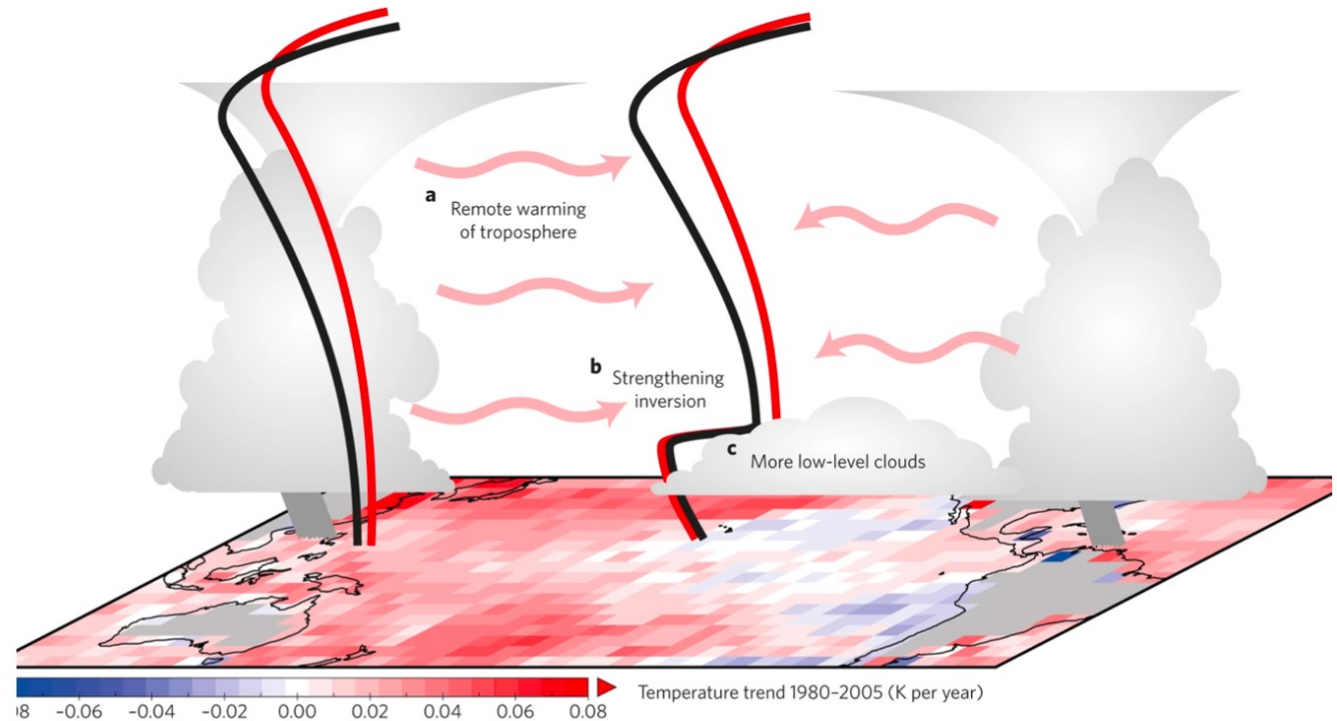
Surface warming patterns
change in time



Climate feedbacks'
intensity
evolve



Climate sensitivity
varies



From IPCC AR6

Ocean sea surface temperature pattern modulates the strength of radiative feedbacks, the effective climate sensitivity.

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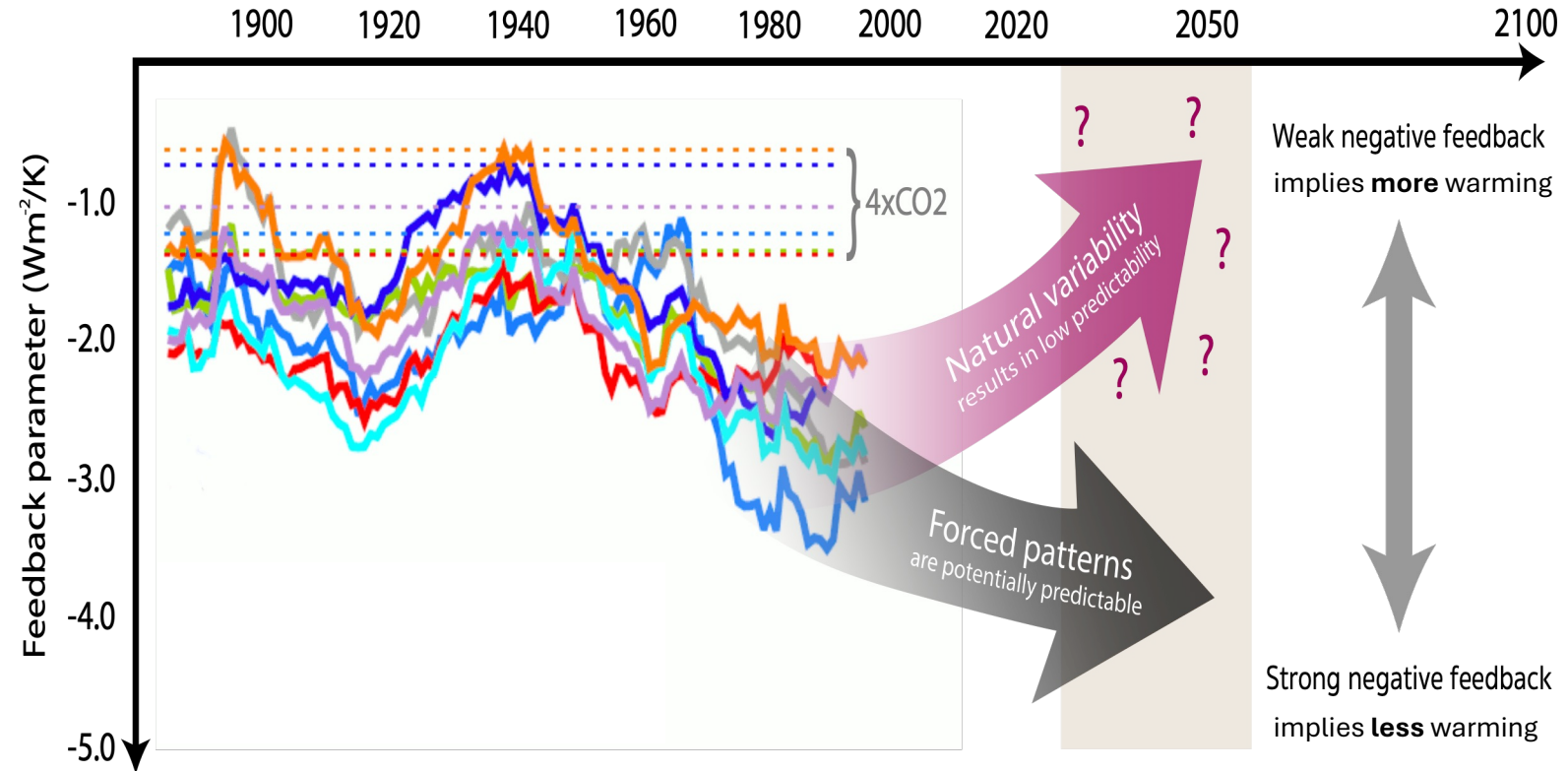
Surface warming patterns
change in time



Climate feedbacks'
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Adapted from Andrews et al. 2018

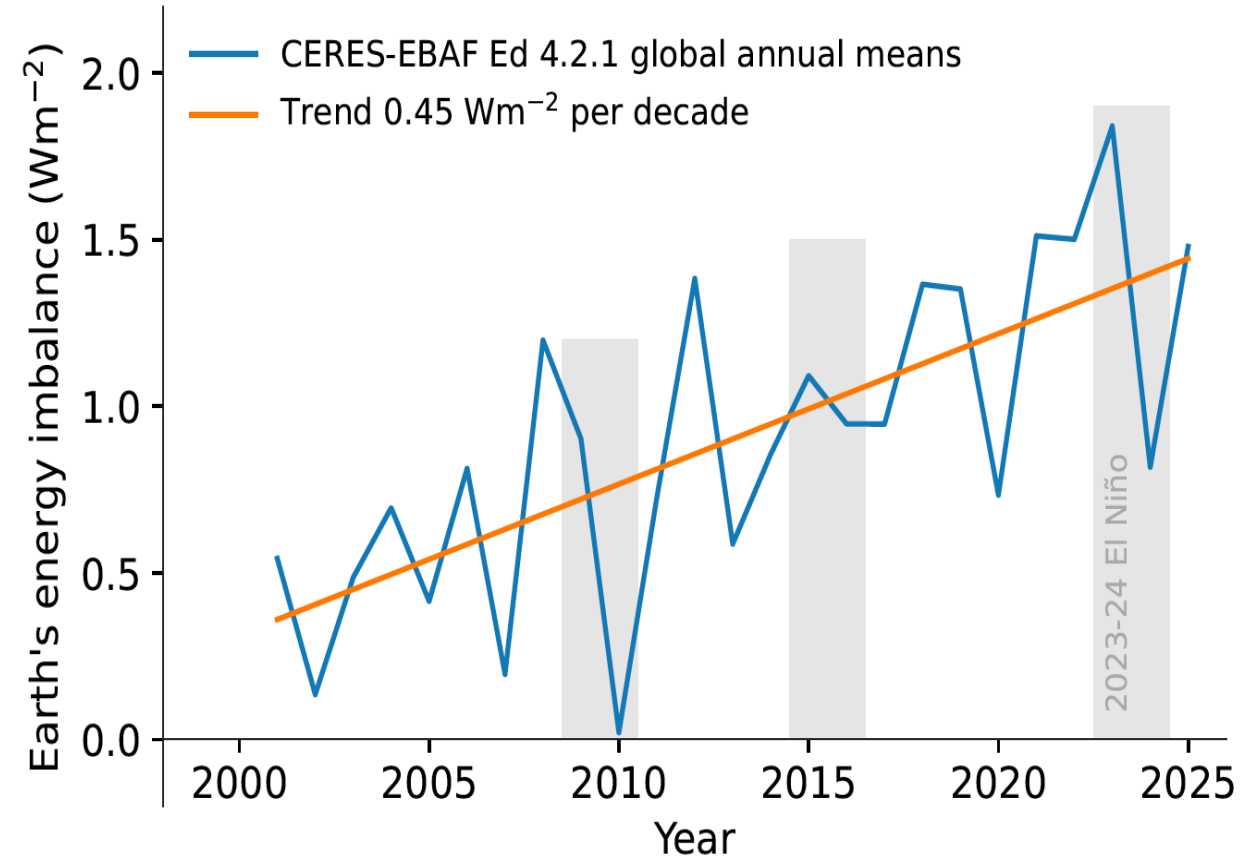
Today EEI and OHC are growing unexpectedly rapidly!

Independent lines of evidence suggest **EEI has doubled since 2000 ...** implying climate now **warms twice as fast as in 2000.**

**Why has EEI doubled?
We don't know!**

Three possible explanations:

- a) There are systematic errors in the observing system, trend in EEI is smaller
- b) Climate Sensitivity is much higher than expected
- c) Internal variability is much higher than expected



From Mauritsen et al. 2025

The ocean and the Earth energy imbalance: next frontier

- **EEI is the fundamental variable of climate change:** it determines whether Earth is gaining or losing heat and how much warming is still to come.
- **The ocean is Earth's main heat reservoir.** Monitoring ocean heat uptake and EEI is therefore essential and both observing systems are today at risk.
- **It is not only how much heat Earth gains, but where the heat goes.** The vertical distribution of ocean heat is critical for understanding and predicting global temperature changes and climate extremes.
- **Ocean surface temperature patterns influence climate sensitivity** and the response of the climate system.
- **Of high concern is the trend in EEI and ocean heat uptake:** global warming is accelerating faster than expected and we don't understand the root cause of it.
- We need to combine **in-situ observations, satellites, high-resolution models and physical understanding** of the Ocean-Atm coupled system (including aerosols and clouds) to resolve these questions