

Estimating ocean warming: challenges and best practices for robust evaluation.

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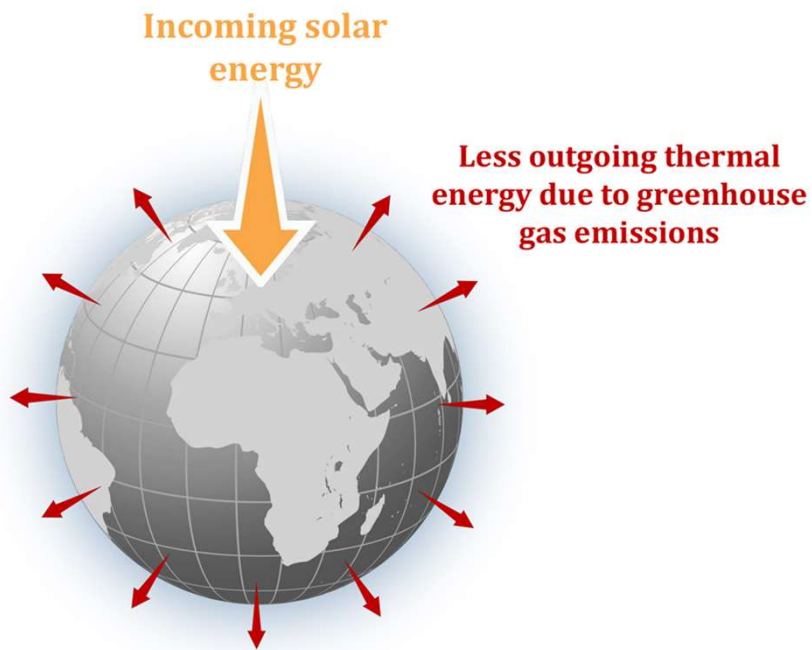


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• Understanding ocean warming

Positive energy imbalance at
the top of the atmosphere



Adapted from IPCC AR6, 2021

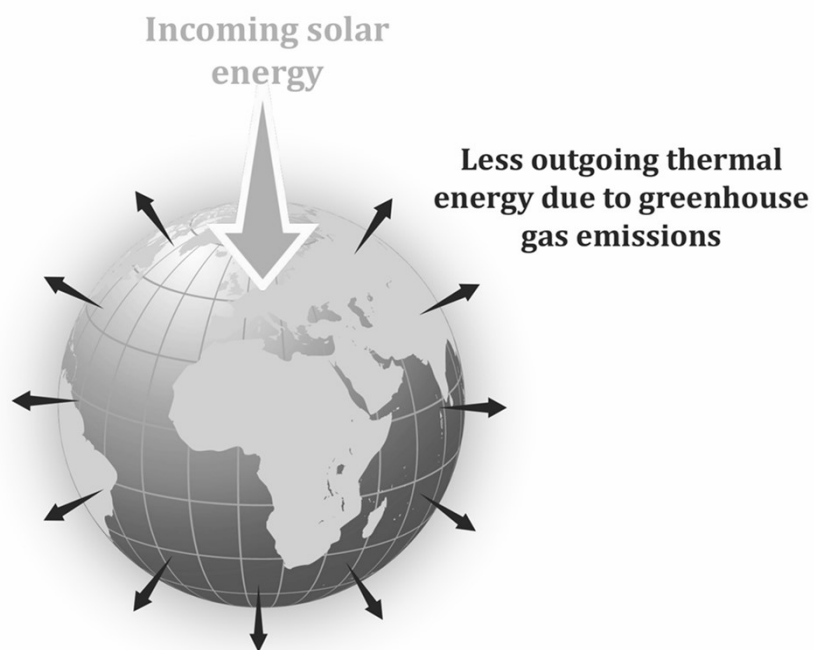


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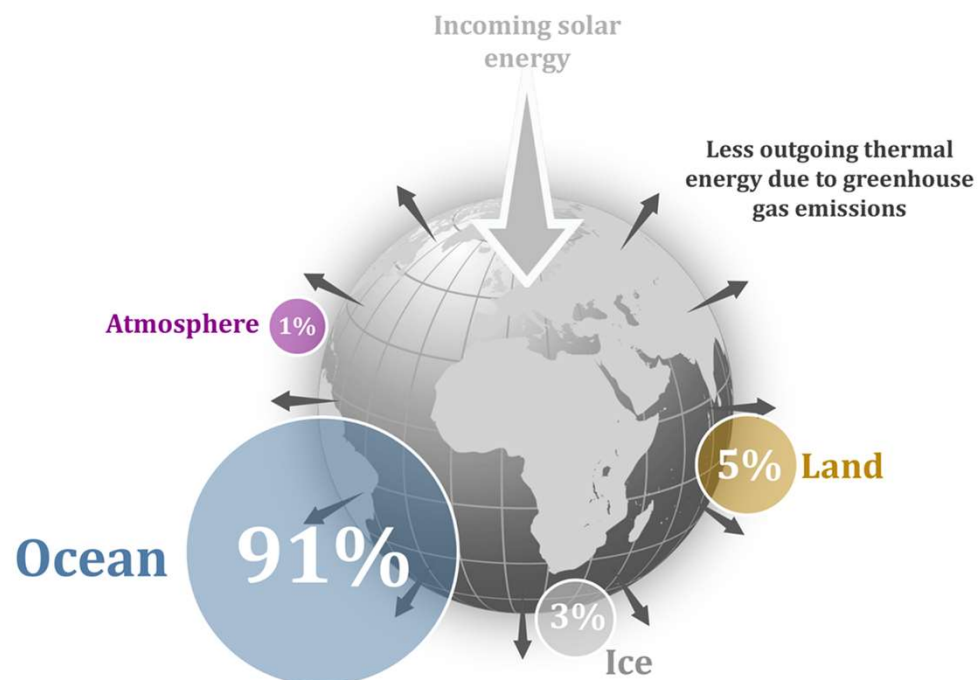
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• Understanding ocean warming

Positive energy imbalance at
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Accumulation of excess energy throughout
the different components of the Earth system



Adapted from IPCC AR6, 2021

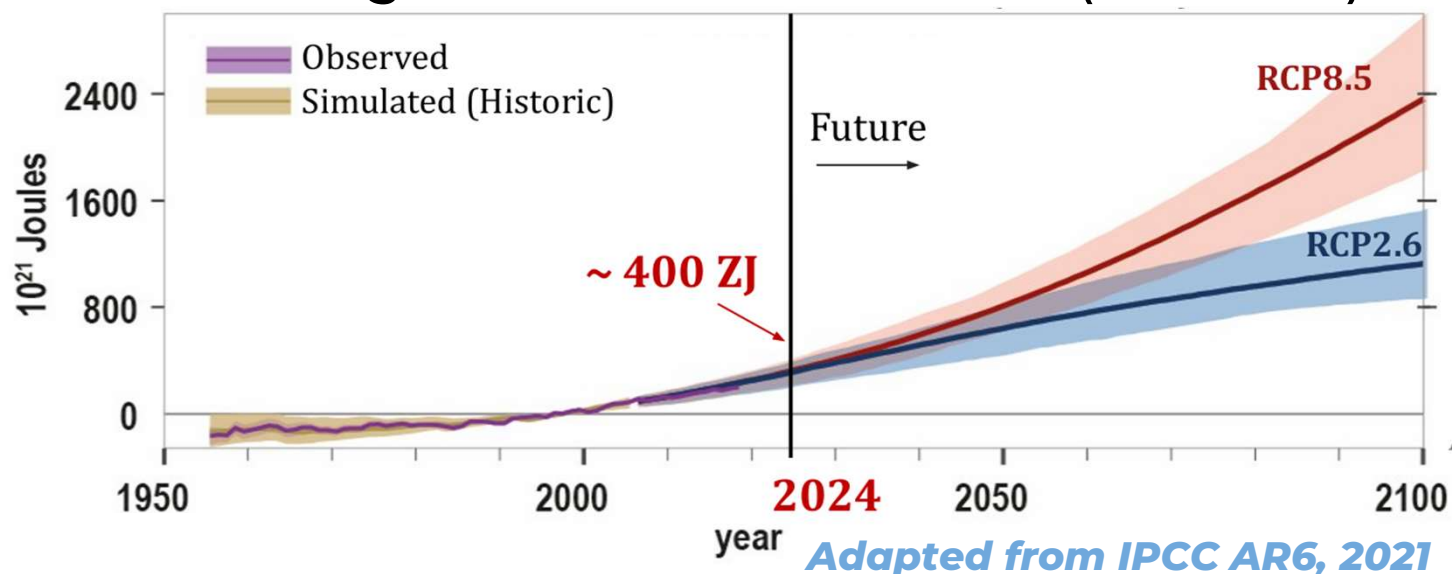


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- **Ocean Heat Content: a key climate indicator**

Change in Ocean heat content (0-2000m)



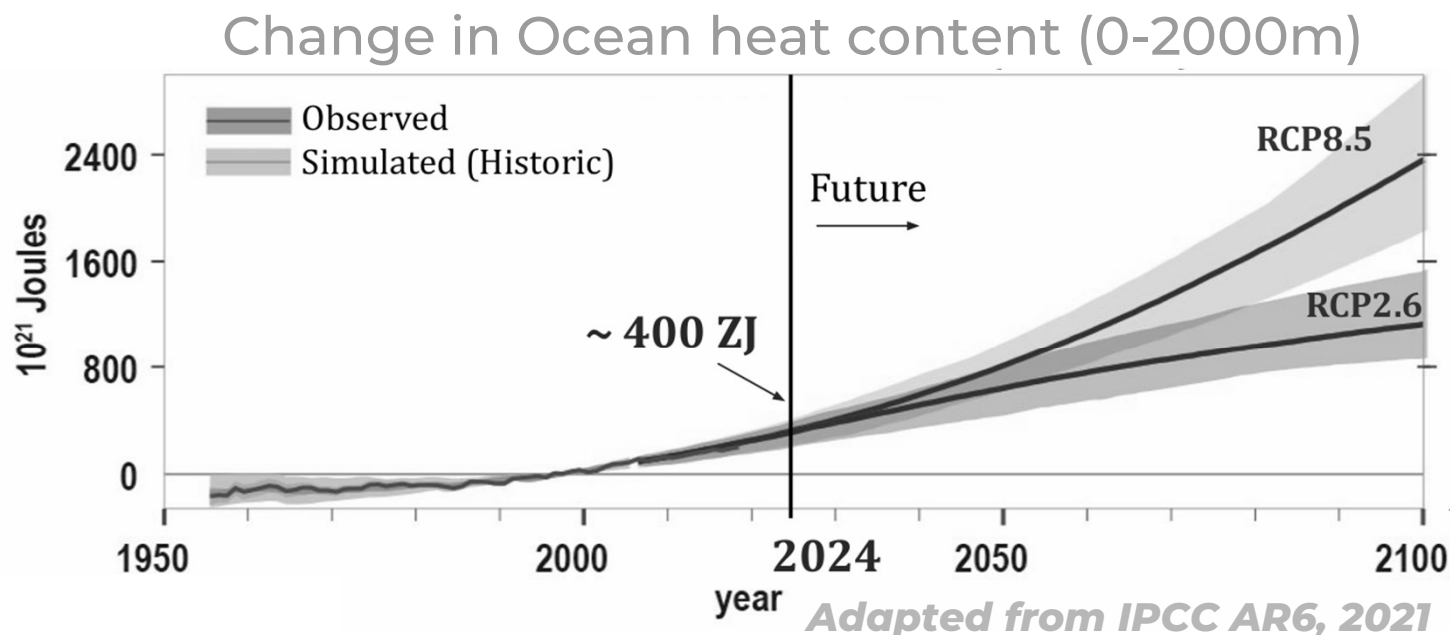
Deep ocean warming is **irreversible** and **committed** for many years



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- **Ocean Heat Content: a key climate indicator**



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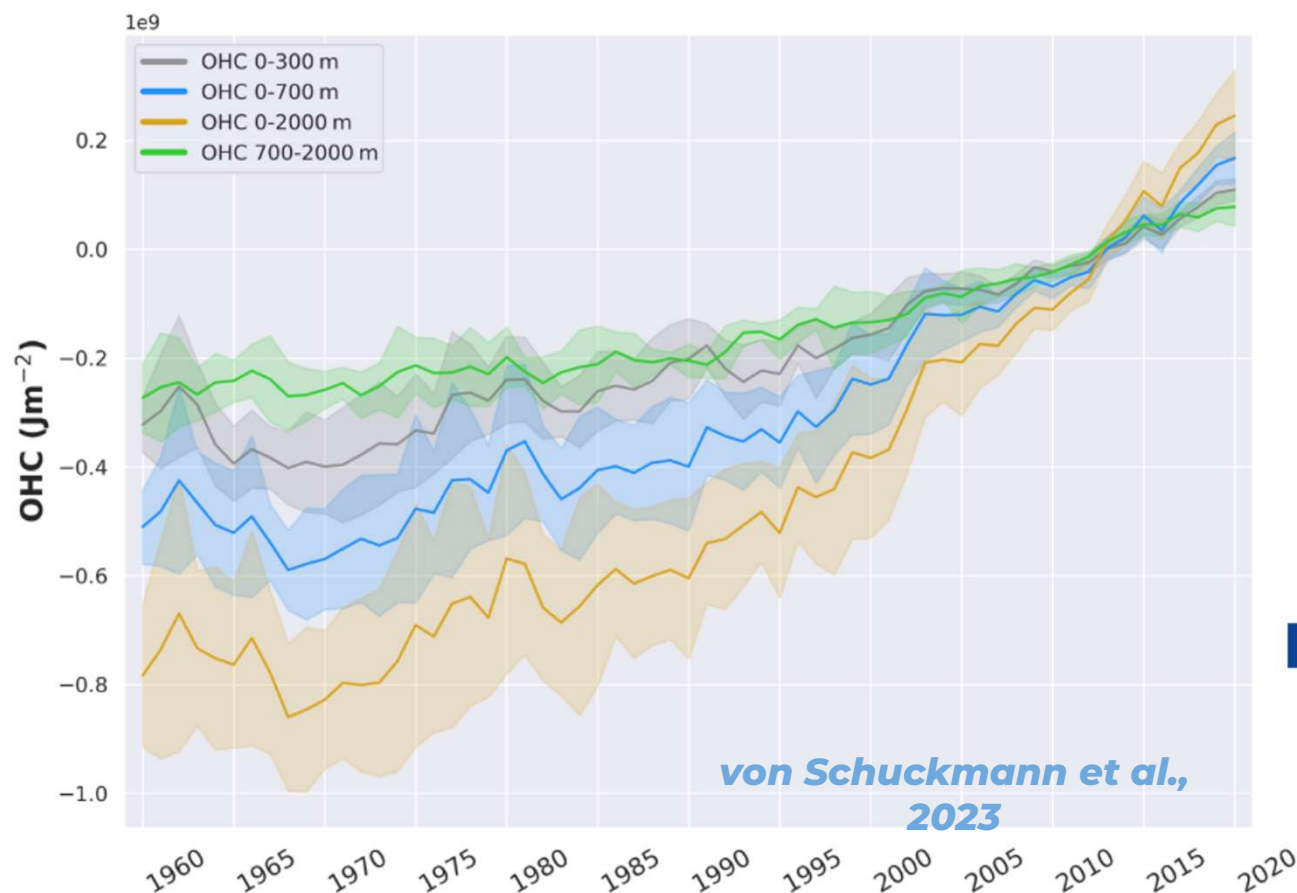
OHC is a crucial indicator for assessing past, present, and future climate changes.



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• A coordinated effort to estimate OHC



A key indicator supporting **international climate monitoring programs**, including Copernicus, WMO, and GCOS.



WORLD
METEOROLOGICAL
ORGANIZATION

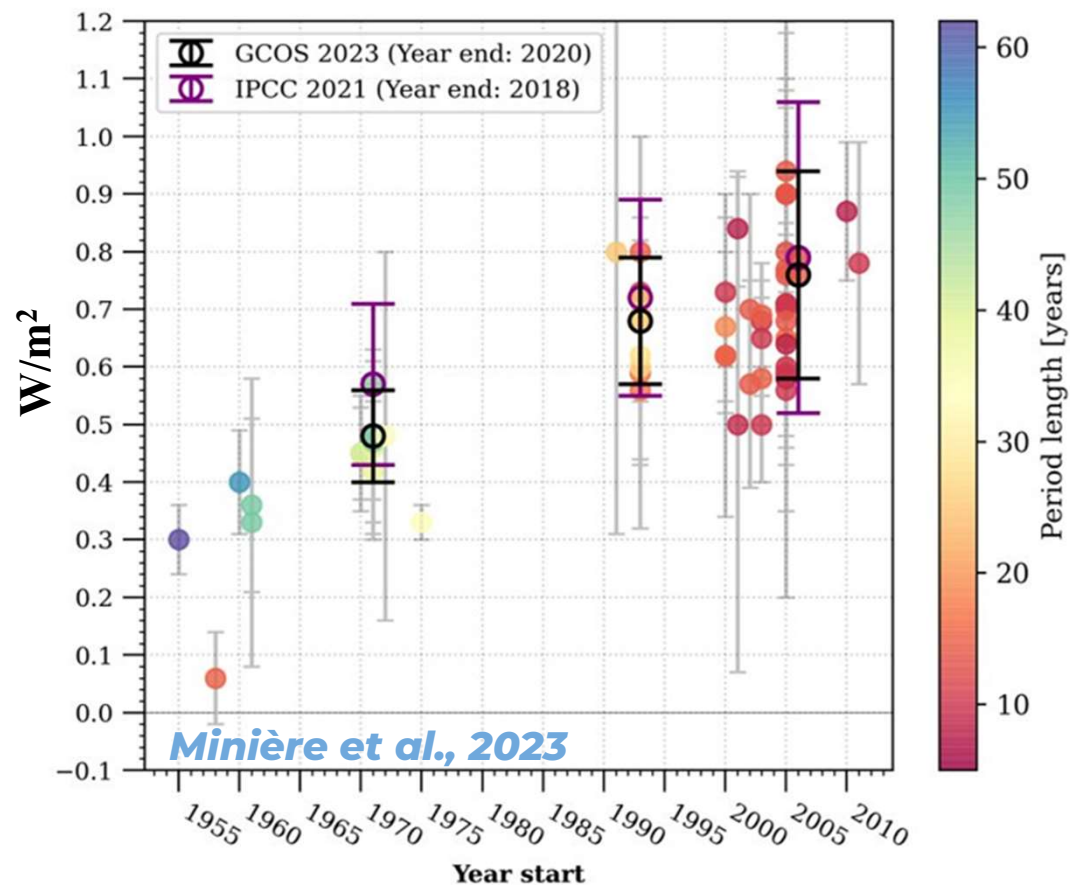


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• At which rate ocean is warming?

Global warming rates in literature

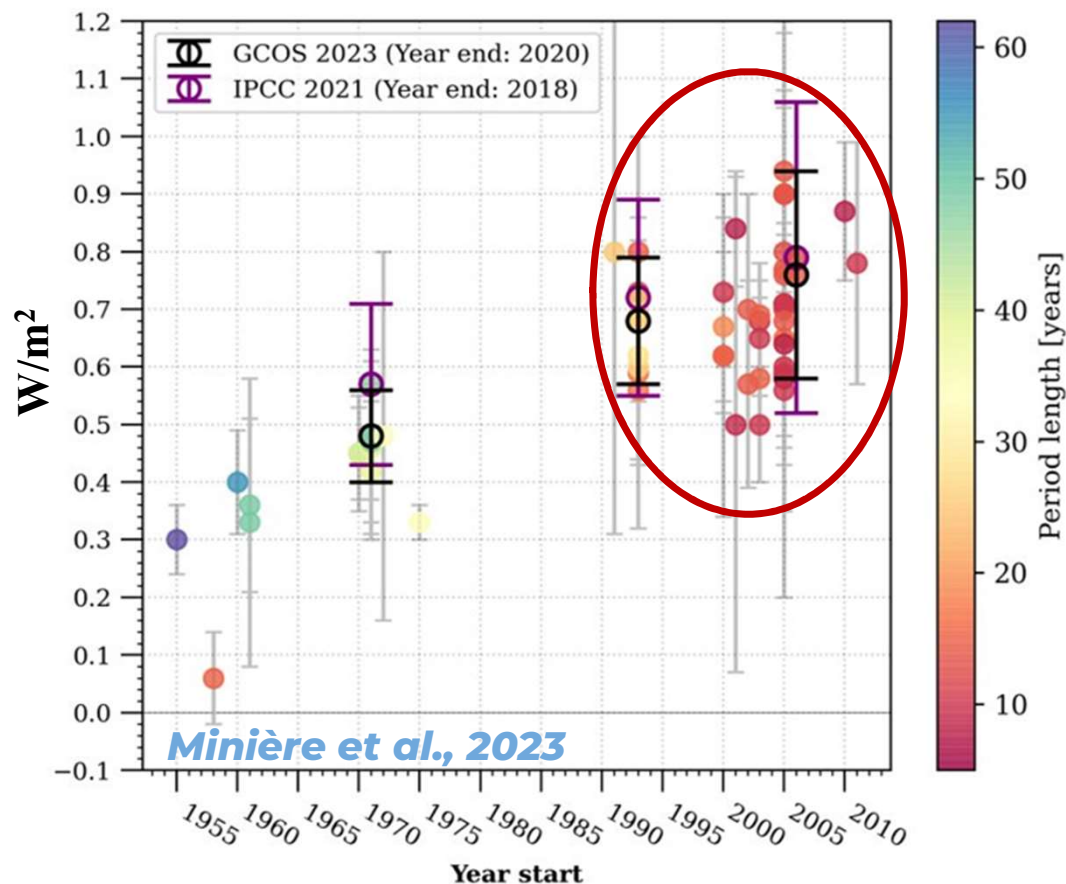


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Global warming rates in literature



2005-present:

**~ 0.5 to 1
W/m²**

Large spread among
estimates

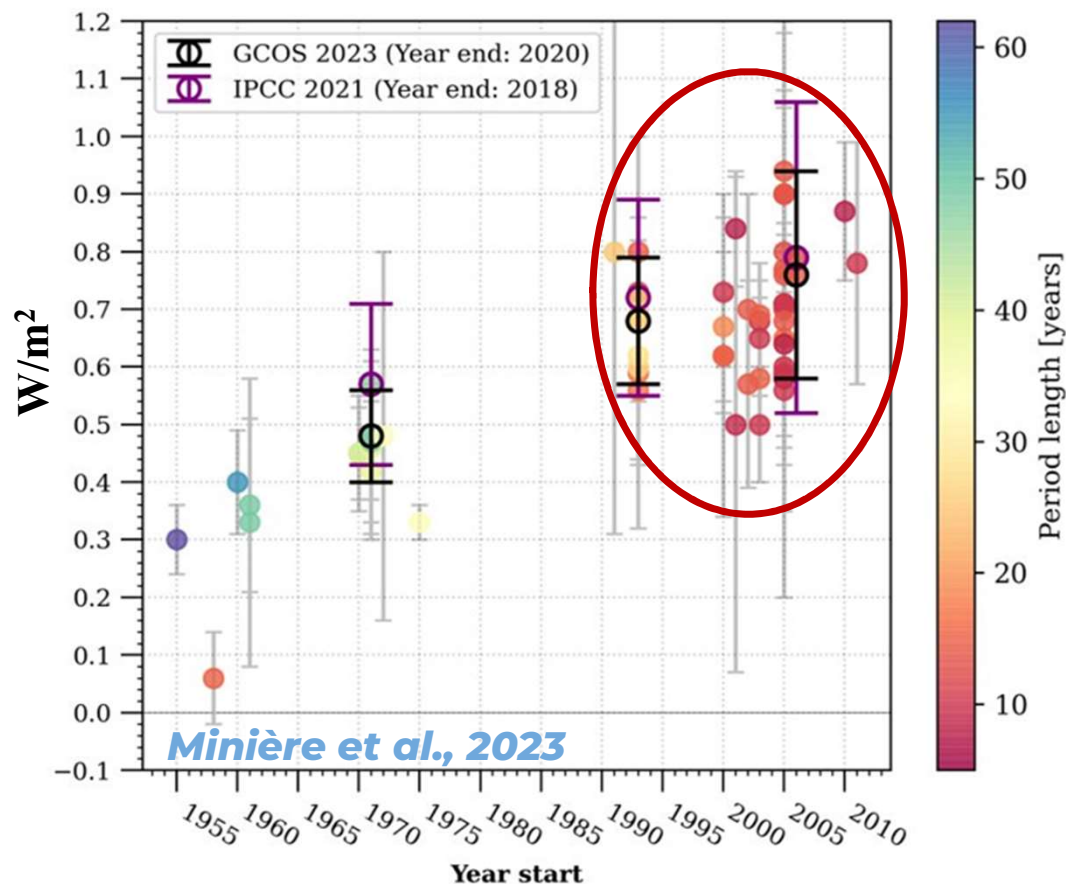


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Why such discrepancies ?

Today, no established "**best practices**" in the literature for estimating ocean warming rates

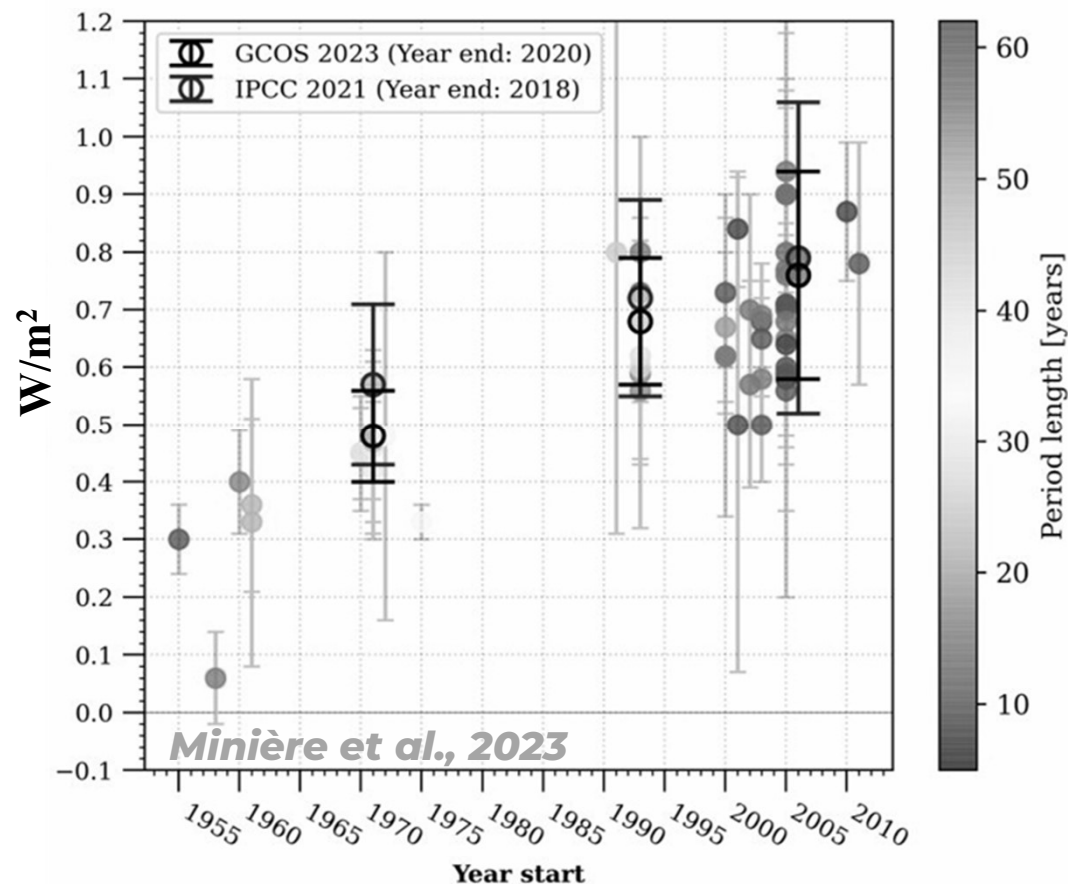


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How to ensure a robust comparison between different estimates of ocean warming rate?



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- **How to estimate OHC indicator ?**

Ocean Heat Content (Joules)

$$OHC = \iiint_{xyz} \rho C_p T \, dx dy dz$$



- **How to estimate OHC indicator ?**

Ocean Heat Content (Joules)

$$OHC = \iiint_{xyz} \rho C_p T dx dy dz$$

Diagram illustrating the components of the Ocean Heat Content (OHC) equation:

- ρ : sea water density (kg.m^{-3})
- C_p : heat capacity of sea water ($\text{J.kg}^{-1}.\text{°C}^{-1}$)
- T : sea water temperature (°C)
- $dx dy dz$: ocean volume (m^3)

- **How to estimate OHC indicator ?**

Ocean Heat Content (Joules)

$$OHC = \iiint_{xyz} \rho C_p T \, dx dy dz$$

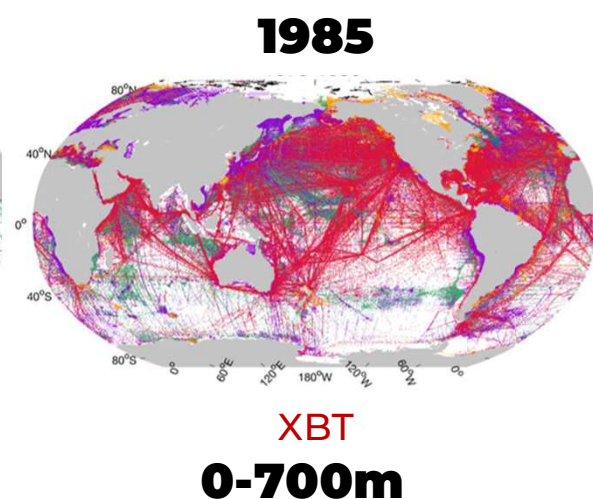
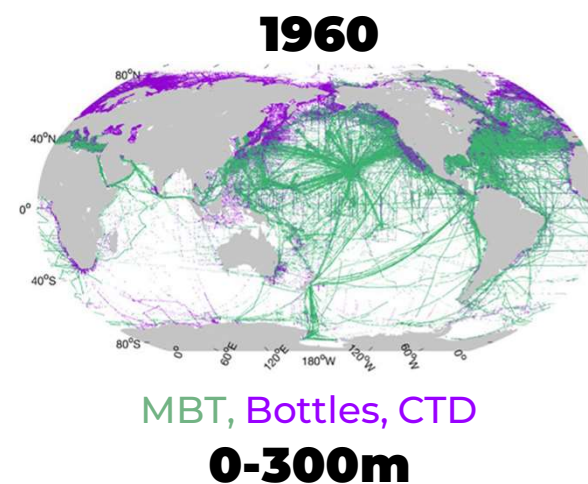
A 'simple' temperature-volume integral but hiding complex observational challenges...



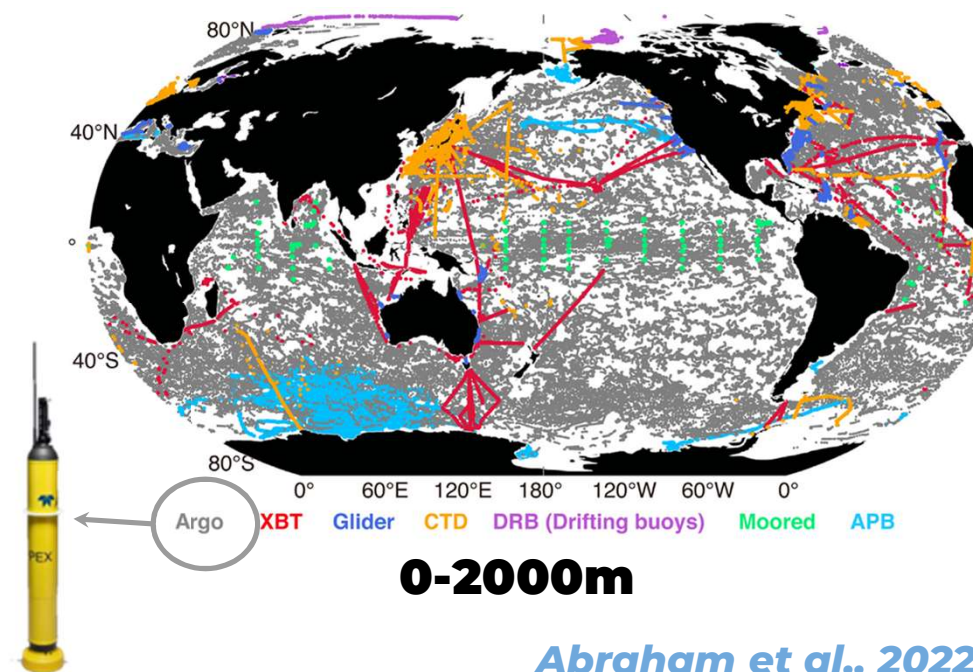
• How do we measure sea water temperature ?

The evolving subsurface temperature observing system

2005-present: Golden era

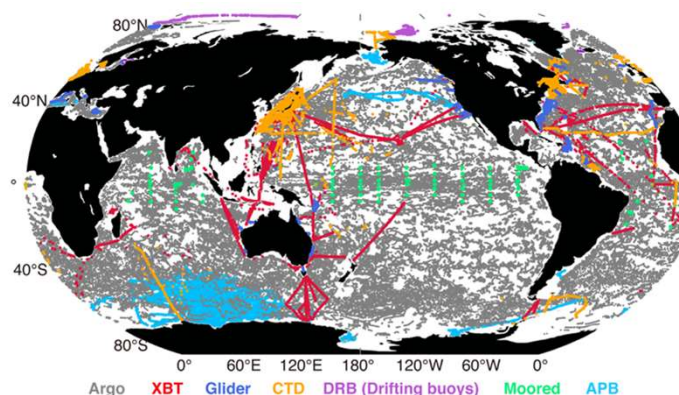


Zhang et al., 2024

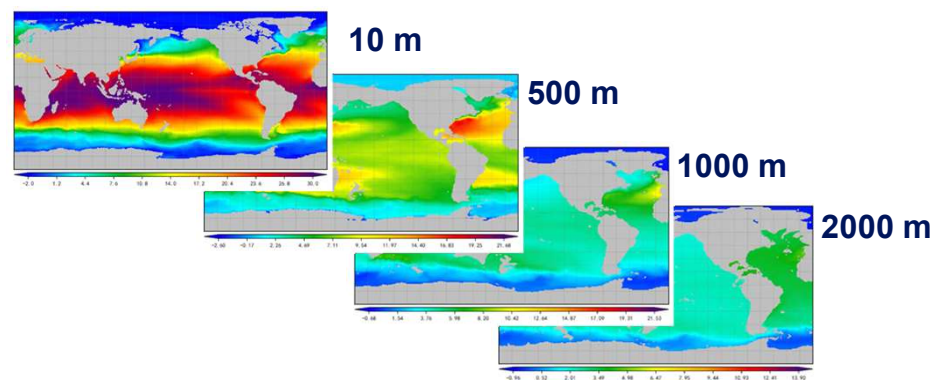


• How do we build subsurface temperature product ?

Irregular T° profiles (raw data)



3D gridded T° product (processed data)



Methodological choices

- Instrumental bias correction (XBT/MBT)
- Gap filling
- Mapping
- Selection of instrument type (Argo, Nansen bottle, XBT/MBT, CTD, etc)
- Quality control
- Climatology choice (first guess)

**Large amount
of T° products**

Boyer et al., 2016 ; Savita et al., 2022



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OHC indicator estimation

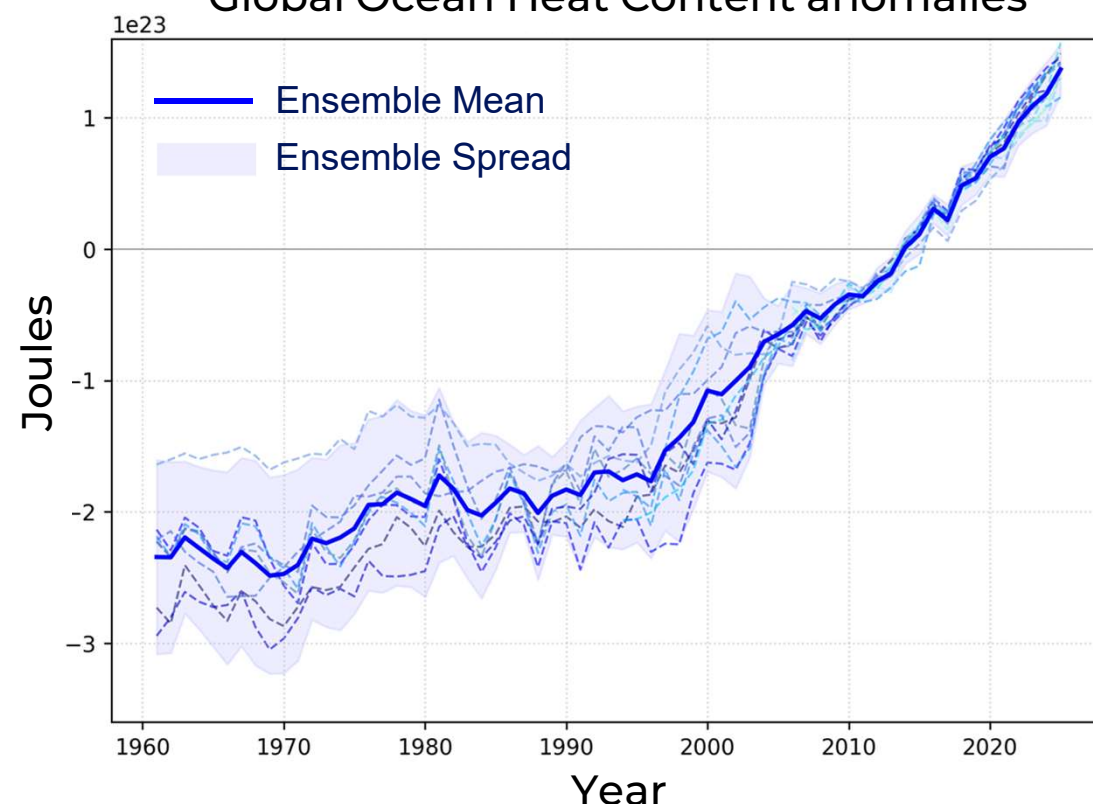
Ensemble approach

List of 3D gridded products of temperature

- IAP, Cheng et al. (2017)
- EN.4.2.2.L09, Good et al. (2013), Levitus et al. (2009)
- EN.4.2.2.G10, Good et al. (2013), Gouretski and Reseghetti (2010)
- EN.4.2.2.C13, Good et al. (2013), Cowley et al. (2013)
- EN.4.2.2.C14, Good et al. (2013), Cheng et al. (2014)
- JMA/MRI, Ishii et al. (2017)
- NOAA/NCEI, Levitus et al. (2012)
- RFROM, Johnson and Lyman (2023)
- CORA5.2, Cabanes et al. (2013)
- ARMOR3D, Guinehut et al. (2012)
- MOAA GPV, Hosoda et al. (2008)
- SIO, Roemmich and Gilson (2009)
- BOA-Argo, Li et al. (2017)
- GDCSM, Zhang et al. (2022)

0-
2000m

Global Ocean Heat Content anomalies



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OHC indicator estimation

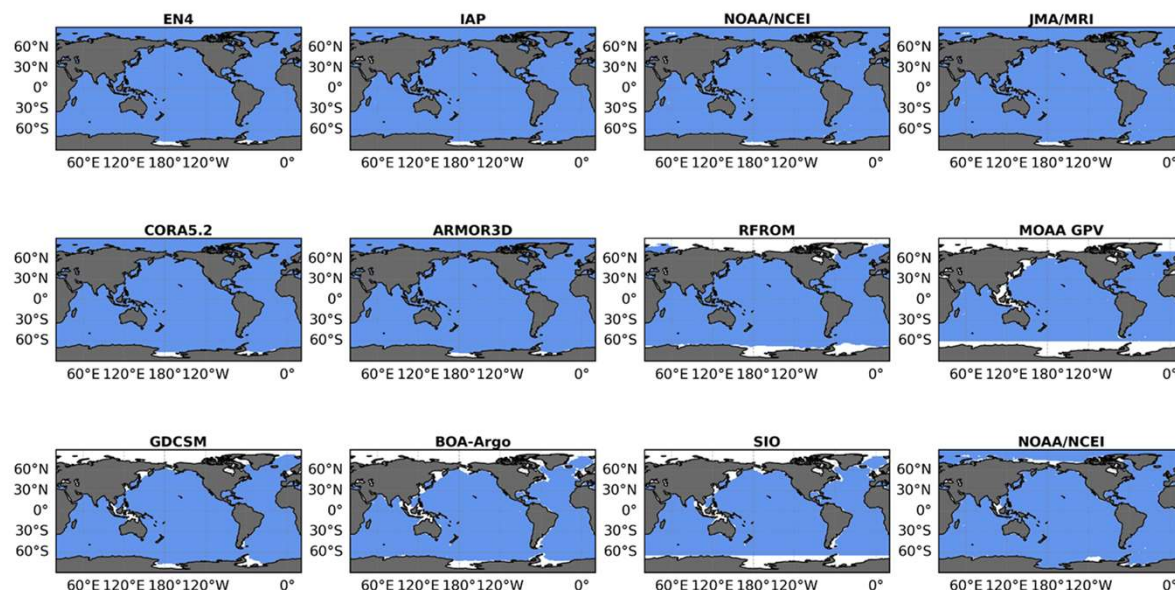
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0-
2000m

→ Different ocean domain from one product to another



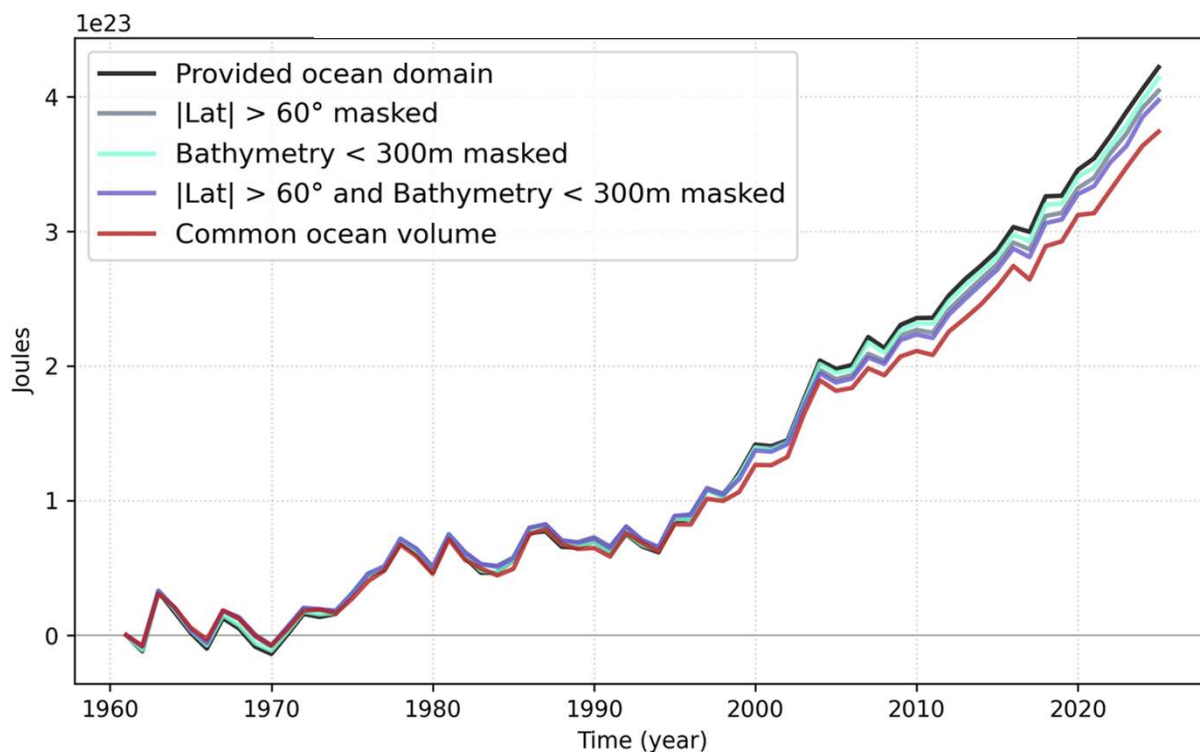
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• OHC indicator estimation

Sensitivity test on ocean domain

Global OHC estimated from IAP temperature product



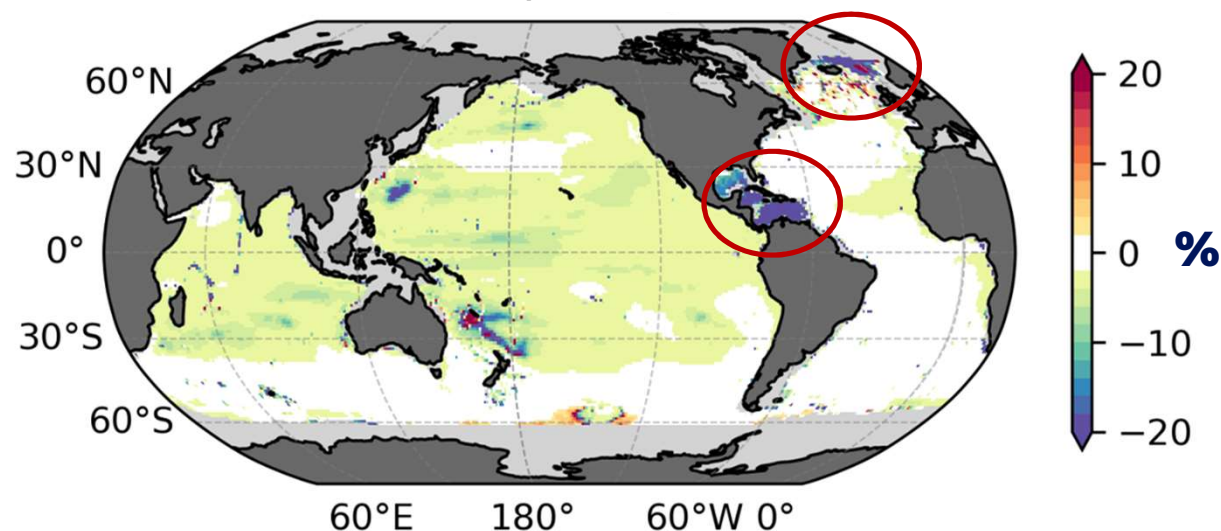
Sensitivity of the GOHC trend to the choice of ocean domain: **up to 12%**

↓
Impact of taking a coherent volume at regional scale?

• OHC indicator estimation

Sensitivity test on ocean domain

Relative changes in OHC trends (Common ocean volume vs. Original ocean volume) based on IAP product



Local OHC trends
reduced by more than
20%

↓
Recommendation: Exclude these regions from global OHC estimation (Caribbean sea, Indonesian archipelago, $|\text{Latitudes}| > 60^\circ$, $\text{Bathy} < 300\text{m}$)

• Recommendation paper

How to ensure a robust comparison between different estimates of ocean warming rate?

$$OHC = \iiint_{xyz} \rho C_p T dx dy dz$$

Annotations for the equation:

- OHC : Tendency, uncertainty ?
- ρ : ρ value?
- C_p : C_p value?
- T : T° product?
- $dx dy dz$: Ocean domain?

- OHC in **reanalyses**?
- OHC in **CMIP6**?
- **Deep** ocean warming (> 2000m)?
- **Indirect** OHC estimates (satellite)?

Paper (in prep.)

The best practices for OHC indicator estimation,
Minière A., Speich S., von Schuckmann K. et al., 2025

• Take-Home messages



- Ocean Heat Content (OHC) is a **crucial indicator** for understanding past, present, and future climate changes.
- Its assessment is **challenging** and requires a robust and consistent methodology, ensuring careful data processing at every stage.
- Using an **ensemble approach** helps ensure a reliable comparison across different OHC estimates, accounting for differences in products and methodologies.
- A **coordinated international** effort is essential to establish clear **guidelines** for a reliable OHC indicator, addressing critical aspects such as ocean domain selection, product characteristics (in situ, reanalysis, models, satellite), and uncertainty assessment.

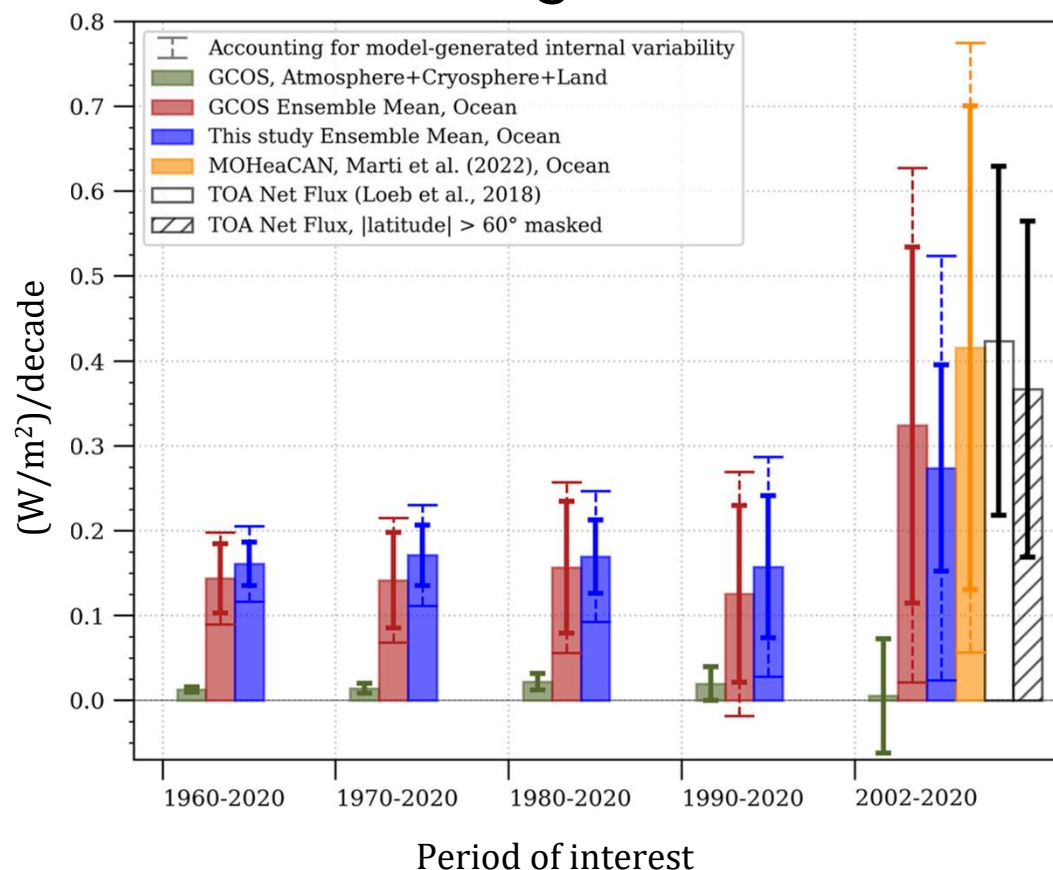


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- **Not only is the ocean warming, but this warming is accelerating**

Global warming acceleration rates



When estimated consistently and robustly, the OHC indicator is of crucial importance to address the question of **warming acceleration**.

Minière et al., 2023



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Thank you!

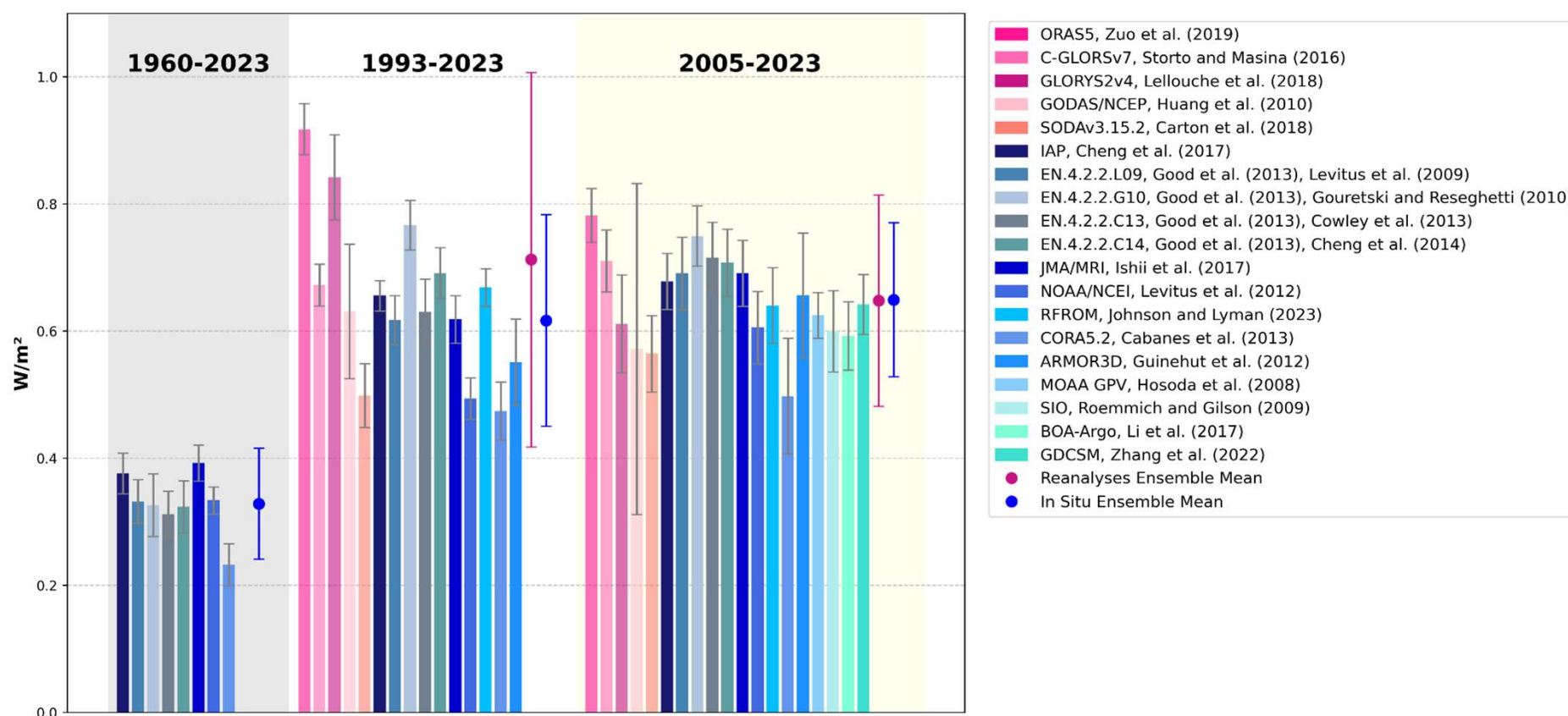


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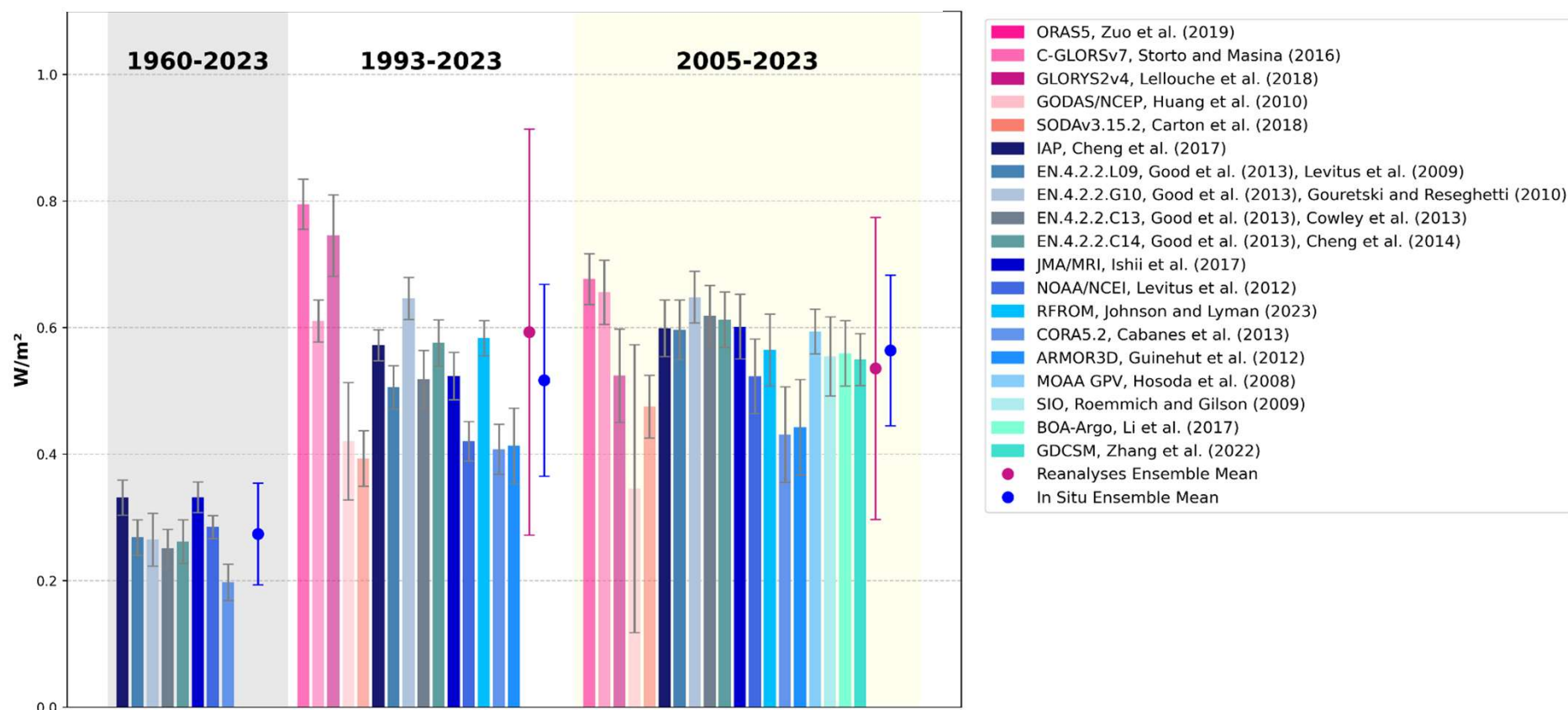
• Ocean warming rates in reanalysis

0-2000m, original volume



• Ocean warming rates in reanalysis

0-2000m, coherent volume

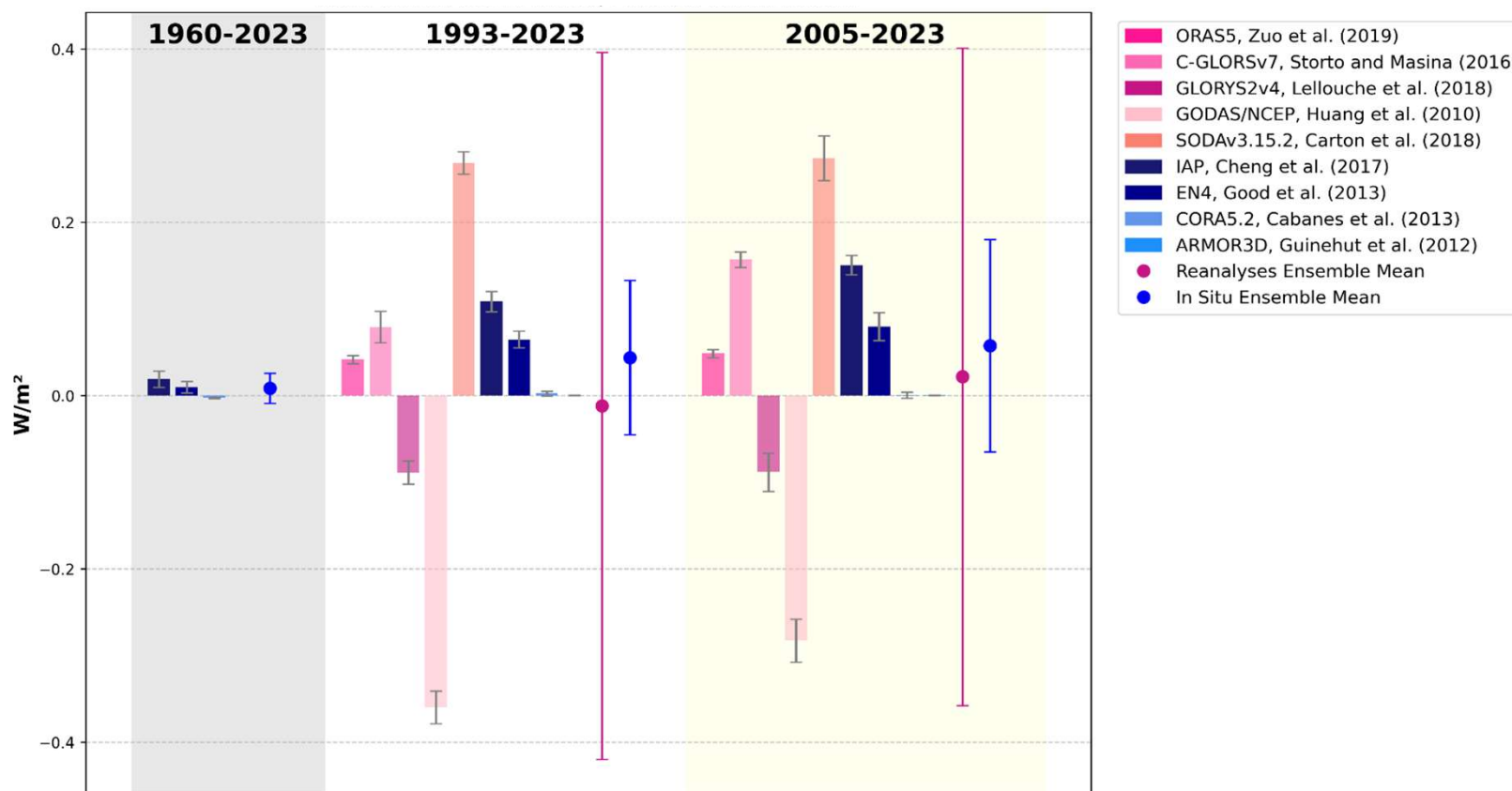


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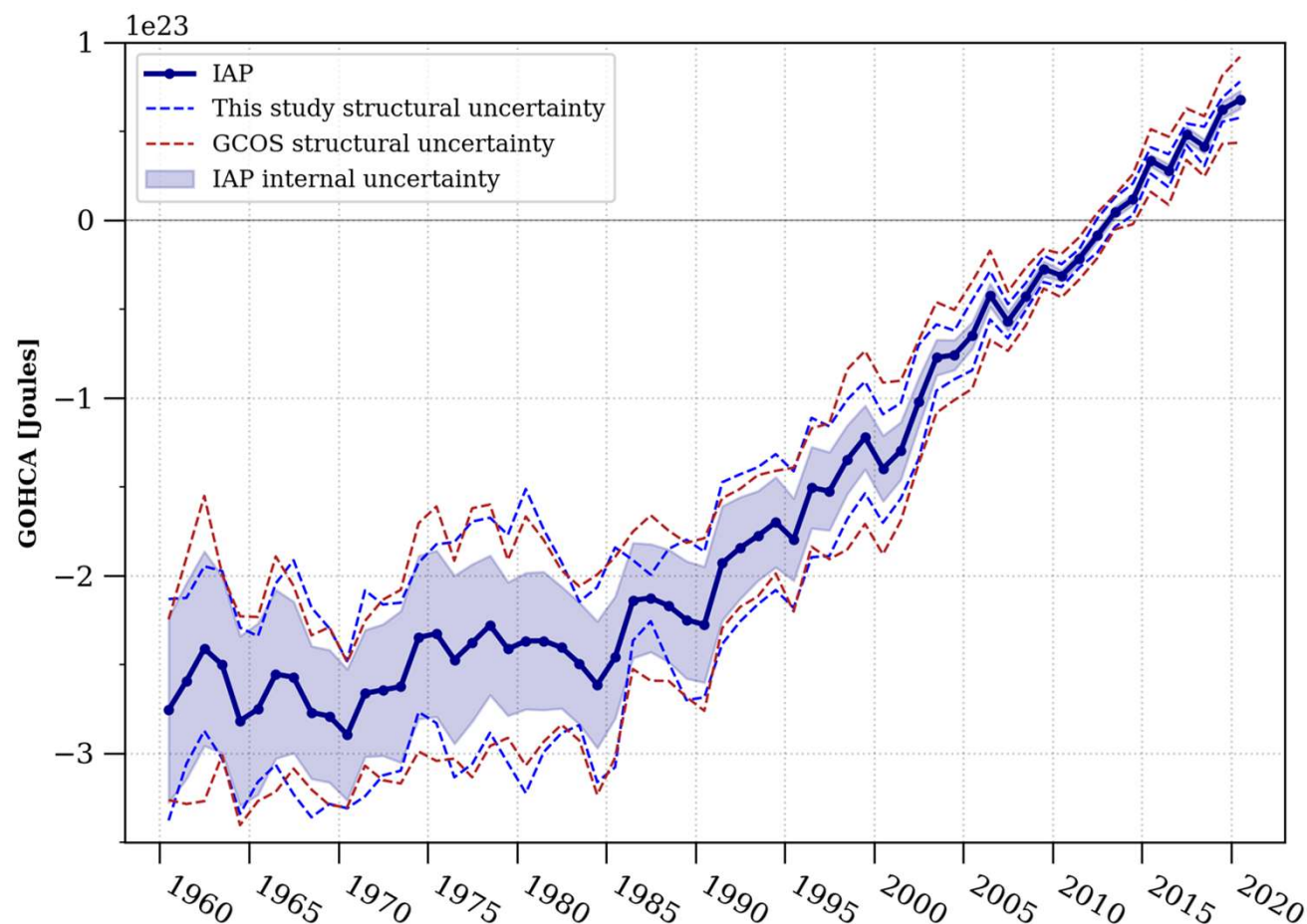
• Deep ocean warming

2000-6000m, original volume



• OHC processing

Ensemble spread vs product uncertainty



—●— GOHCA (IAP, Cheng et al., 2017)

— IAP product uncertainty,
Cheng et al. (2017)

Ensemble Spread

..... This study
..... GCOS, von Schuckmann et al. (2023)



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