Inferring Ocean Heat Uptake from Satellite Gravimetry and Altimetry

Andrew Delman (UCLA-JIFRESSE), Maria Hakuba (JPL), Ian Fenty (JPL)
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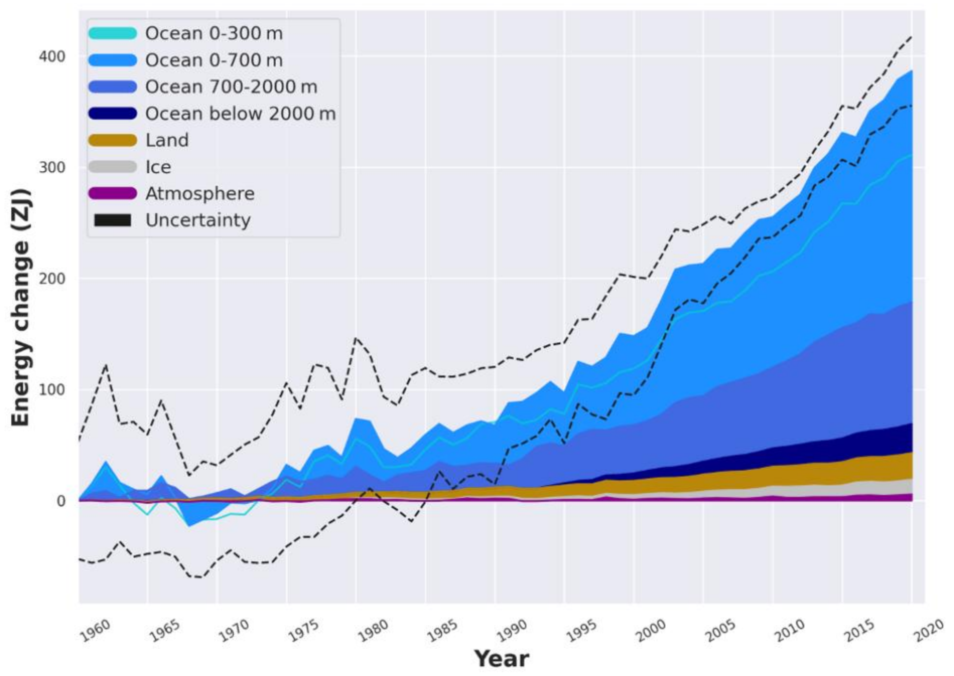
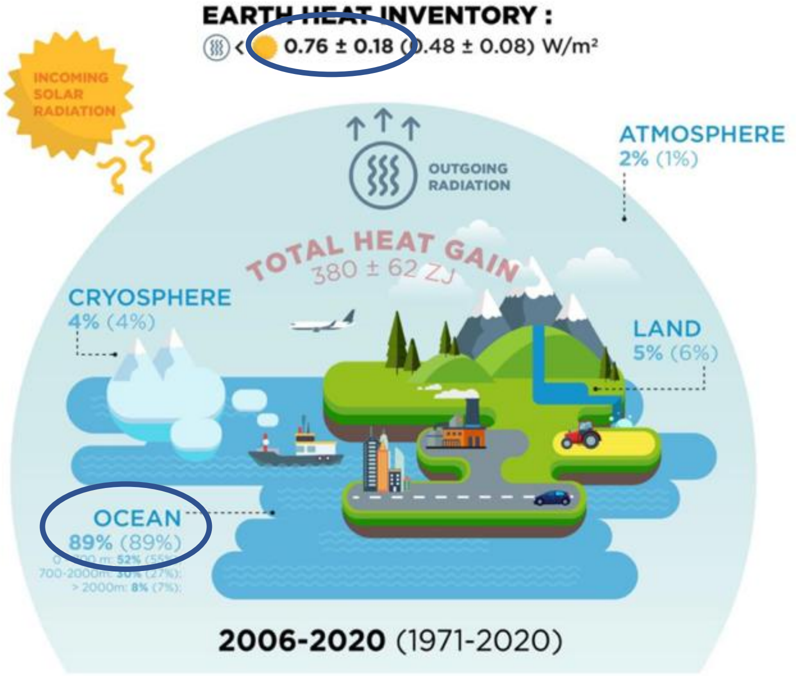
Why is ocean heat content/uptake important?

- The Earth's energy imbalance (EEI) is the key quantity for assessing changes of heat in the Earth system and its components
  - von Schuckmann et al. 2023 estimated EEI for 2006-2020 period at **0.76 ± 0.18 W/m²**
- Of the net heat uptake into the Earth system in recent years (through top of atmosphere), ~90% has entered and been retained in the ocean (e.g., Trenberth et al. 2016; von Schuckmann et al. 2023)





von Schuckmann et al. 2023

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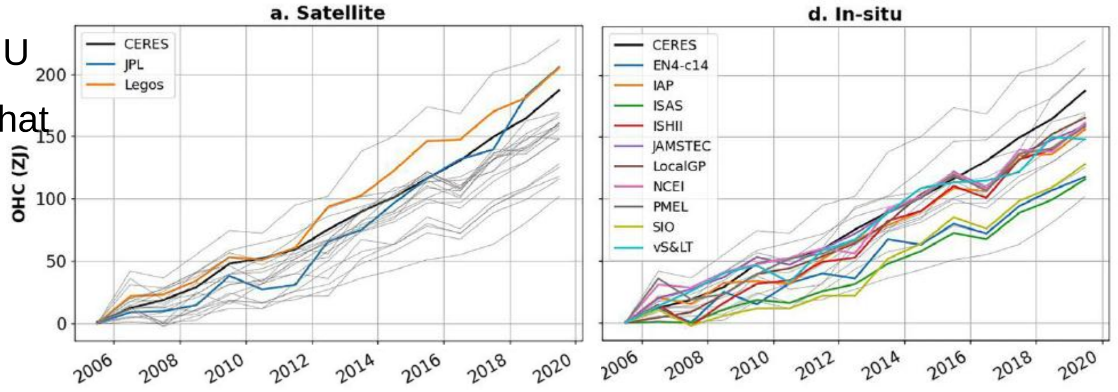
What are we trying to do?

- Estimate **global and regional** ocean heat content (OHC) and its rate of change (ocean heat uptake/OHU) from steric height
- Steric height is the part of sea level change not associated with ocean mass change
- This can be observed by satellites (sea level is observed by altimeters, ocean mass change by GRACE/GRACE-FO)

Previous work on satellite (geodetic) ocean heat content/uptake

- Hakuba et al. (2021; 2024) used geodetic steric height to estimate OHC/OHU
- The geodetic OHC approach yields OHU trends and interannual variability that are closer to top-of-atmosphere observations (CERES), compared to reanalysis and in-situ data product estimates



Hakuba et al. 2024

Open question: What is causing these differences in OHC/OHU trends and variability?

- In-situ data coverage limitations?
- The method used to deduce geodetic OHC from steric height? How is this affected if we account for regional variations in the ocean state?

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The ocean's thermal expansion efficiency

- Ocean steric height changes due to density changes – the temperature contribution to density (ρ) is often approximated in a tangent linear sense as the **thermal expansion efficiency (α)**…the fraction a water parcel expands per degree °C increase

$$\Delta h_{\text{steric}} \approx \int \alpha \Delta T \, dz \qquad \text{where} \quad \alpha(T,S,p) = \frac{\rho \, \partial(1/\rho)}{\partial T}$$

- **To get from $\Delta h_{\text{steric}} \rightarrow \Delta T$ (steric height → OHC/OHU), we need to quantify the ocean's "effective" thermal expansion efficiency**
- The expansion efficiency α is well-defined for a water parcel of fixed temp/salinity/pressure…

  but we need the "effective" α for a vertical (or global) region

$$\Delta h_{\text{steric}} \approx \int \alpha \Delta T \, dz \approx \alpha_{\text{eff}} \langle \Delta T \rangle H$$

Even if vertical profile of α is known, many solutions for ΔT

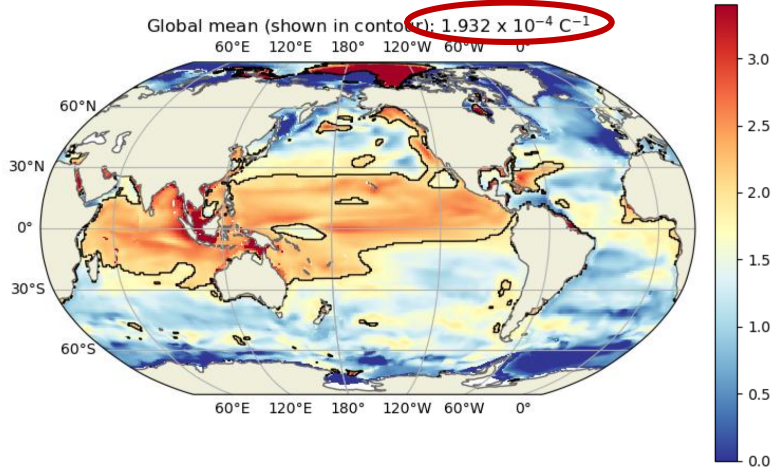
What we need

End goal

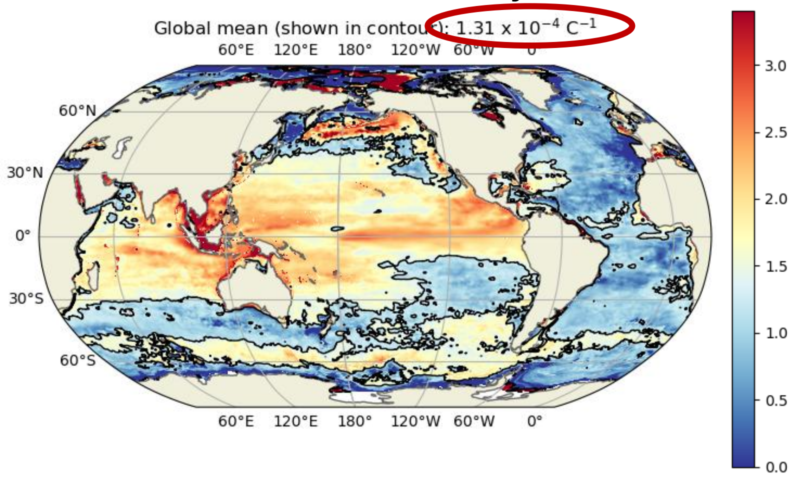
We know this

Effective α_{eff} computed by linear regression from

NASA ECCO state estimate (v4r4)



ECMWF ORAS5 reanalysis



Global mean α_{eff} values can vary by >40% among products!

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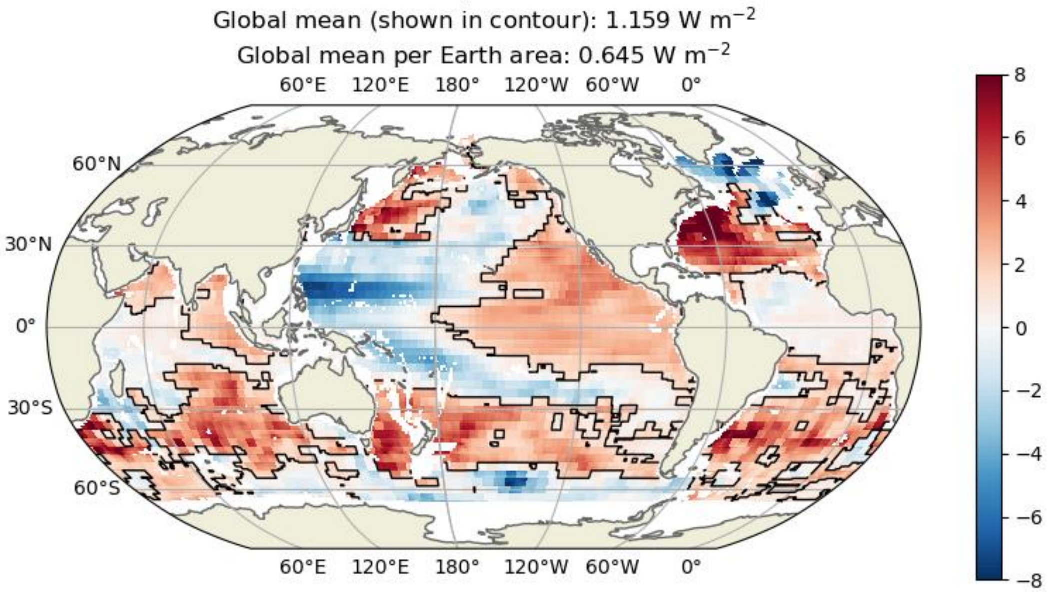
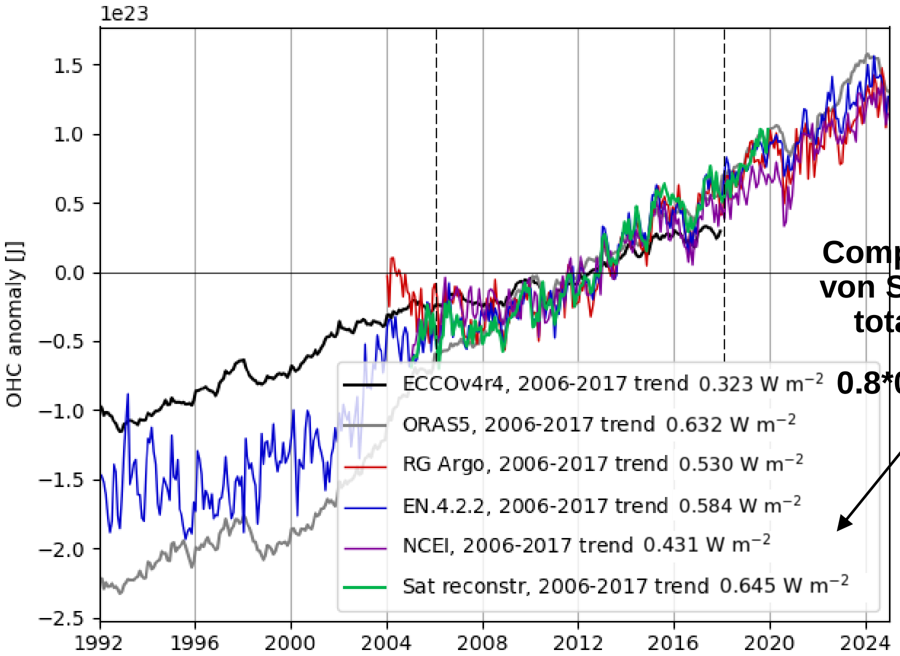
Using effective α (α_{eff}) to reconstruct ocean heat content

- Using ensemble (product) averages to compute $\boldsymbol{\alpha_{eff}}$ for each location (rather than one global value), the geodetic (satellite) OHC reconstruction corresponds quite well with existing hydrographic- and reanalysis-based global OHC time series

2006-2017 0-2000 m OHC trend (OHU), based on reconstruction from satellite steric height (altimetry – GRACE)



Global 0-2000 m OHC time series comparison, satellite reconstruction vs. other products



Compare with ~80% of von Schuckmann et al. total EEI estimate:

0.8*0.76 = 0.61 W m^{-2}

Takeaways

- Satellite-based steric height can be used to reconstruct OHC trend **and** higher-frequency variability, though we need greater confidence about effective α
- Frameworks for quantifying α_{eff} and its uncertainty are currently being studied
- Plan to submit manuscript by end of 2025
- **GEWEX-EEI workshop, June 1-5, 2026 in Pasadena:** https://climatesciences.jpl.nasa.gov/events/20260601-workshop/index.html

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Supplemental details

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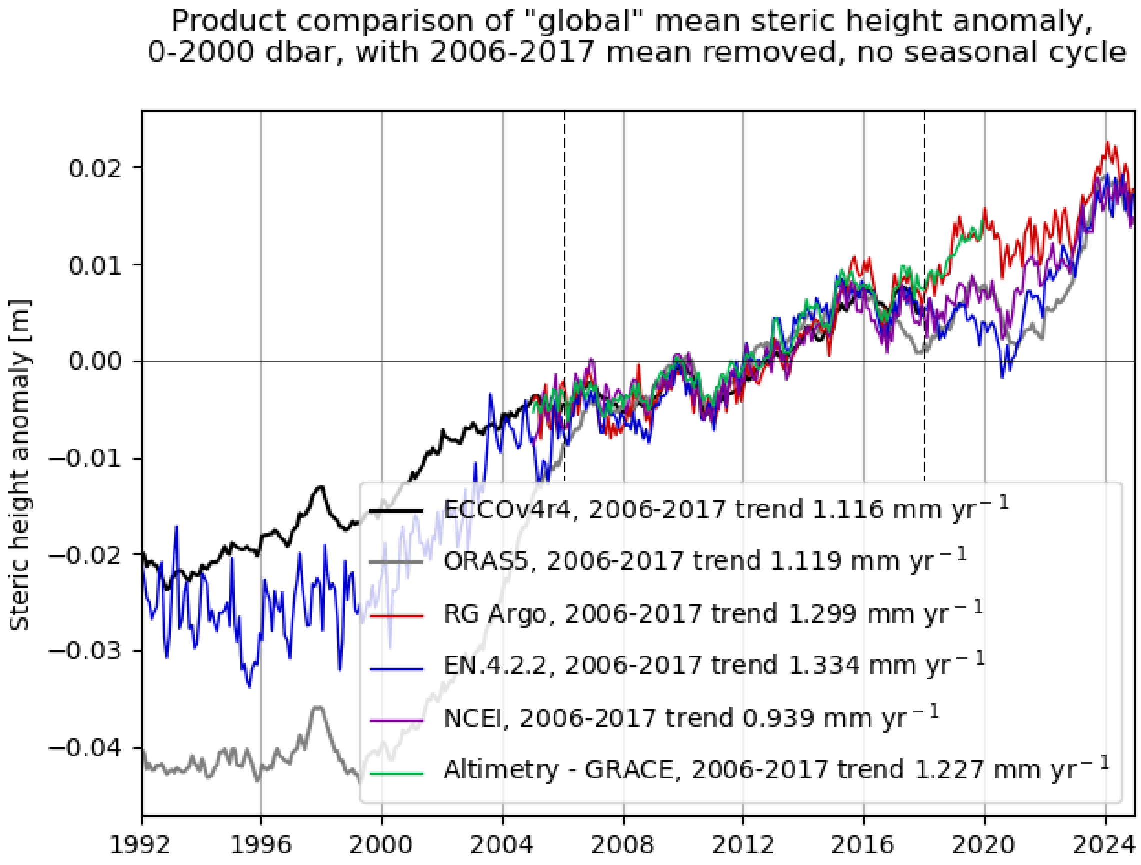
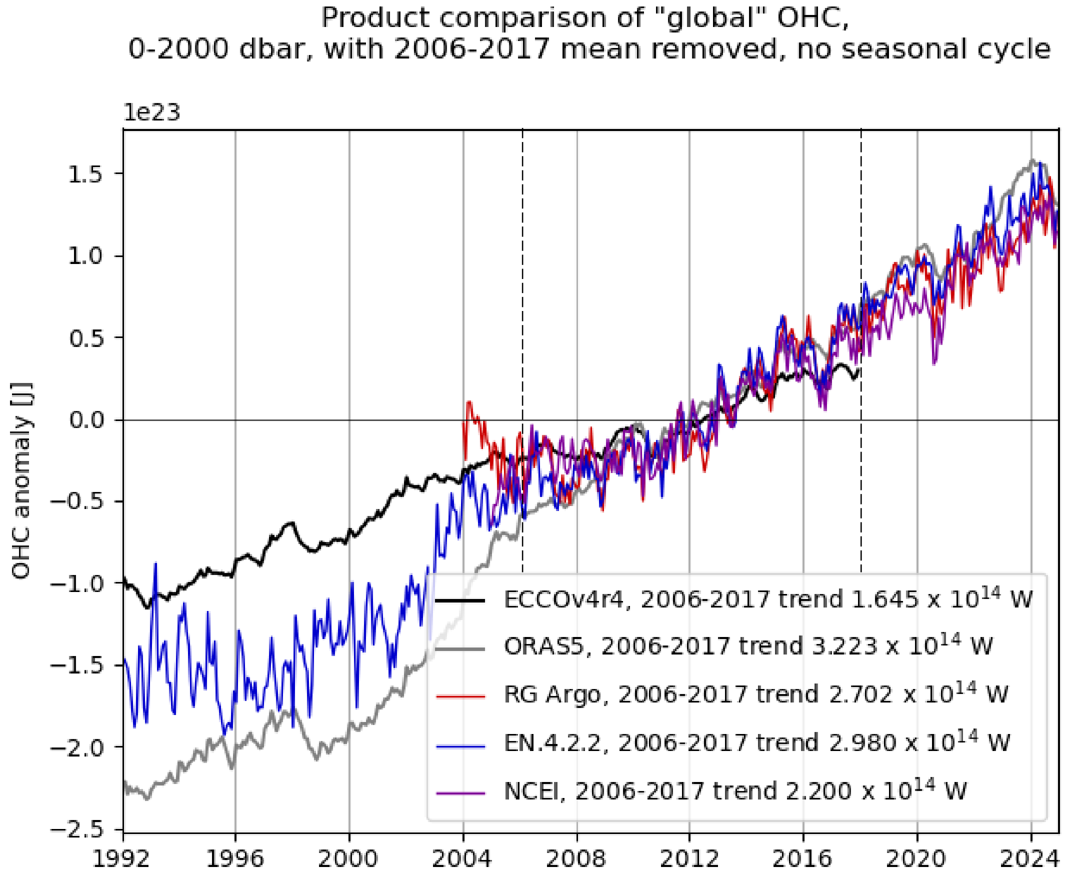
Global mean steric height and OHC

- Steric height: good agreement across state estimate/reanalysis and hydrographic-derived products during 2006-2017 period
    - Substantial differences before (pre-Argo) and after (2017-2019 divergence)
- Ocean heat content/uptake: 2006-2017 trends vary by a factor of 2!





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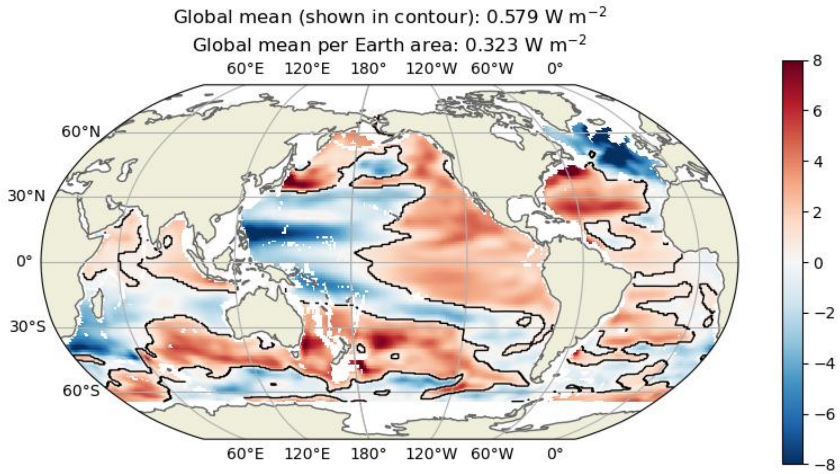
Ocean heat content trends: 2006-2017

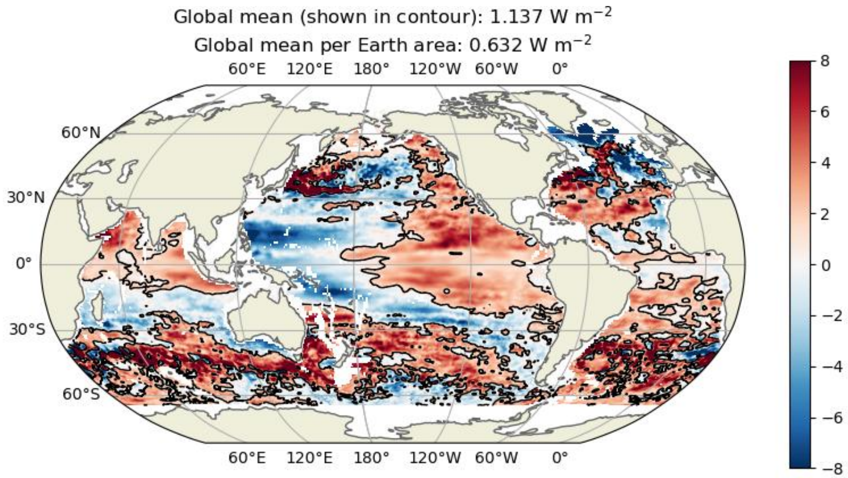
- Computed 0-2000 m depth only, with a mask that excludes the polar regions and marginal seas where Argo data are not available
- Overall agreement in regional distribution across products
- Differences in heat uptake in the South Atlantic & Agulhas Return Current help explain differences in global means

Data-assimilating models:

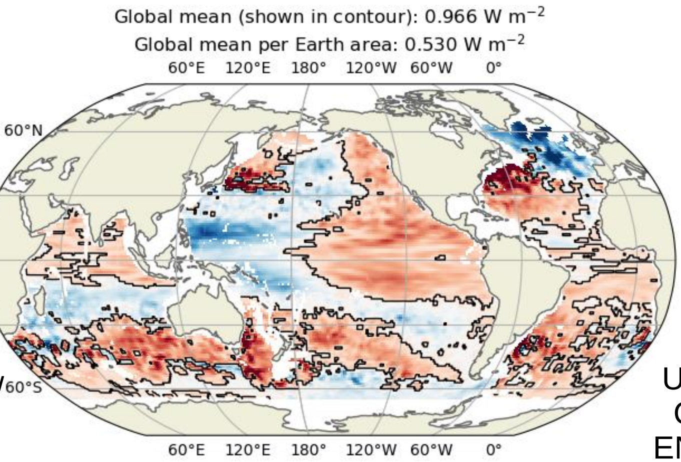
NASA
ECCOv4r4
state estimate



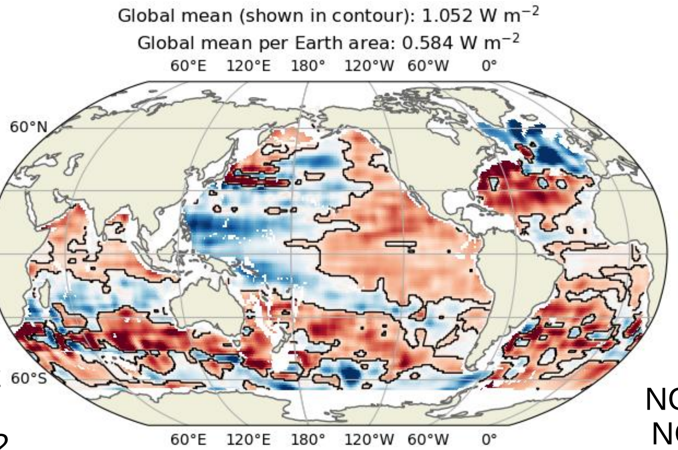
ECMWF
ORAS5
ocean
reanalysis



Gridded hydrographic products:



SIO
Roemmich/
Gilson
Argo



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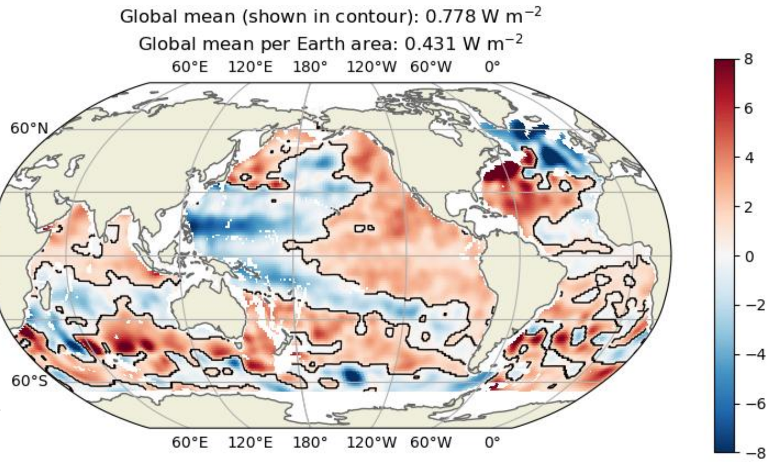
EN.4.2.2



NOAA
NCEI

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Ocean’s thermal expansion efficiency (α) – more details

- Ocean steric height changes due to density changes – the temperature contribution to density (ρ) is often approximated in a tangent linear sense as the **thermal expansion efficiency (α)**…the fraction a water parcel expands per degree °C increase

$$\rho = \rho(T, S, p)$$

Density depends on temp, salinity, pressure

$$\alpha(T, S, p) = \frac{\rho \, \partial(1/\rho)}{\partial T}$$

Definition of thermal expansion efficiency (alpha)

$$\Delta h_{\text{steric}} = \int \rho \, \Delta\left(\frac{1}{\rho}\right) dz \approx \int \alpha \Delta T \, dz \approx \alpha_{\text{eff}} \langle \Delta T \rangle H$$

Steric height change in terms of temp change and “effective” alpha

Effective α_{eff} computed by linear regression (0-2000 m depth only, excluding marginal seas) from:

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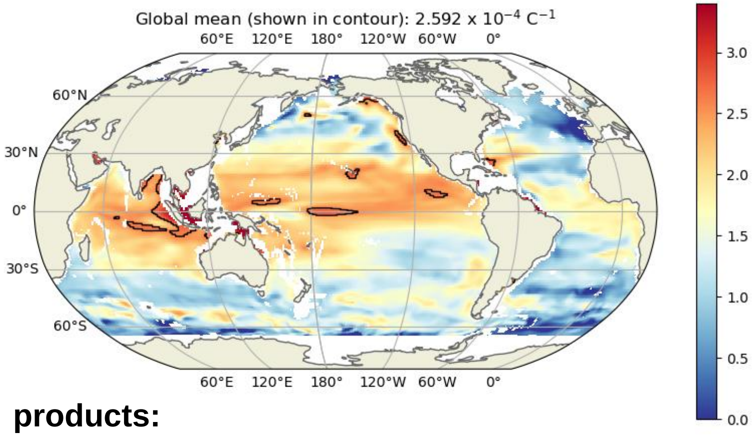
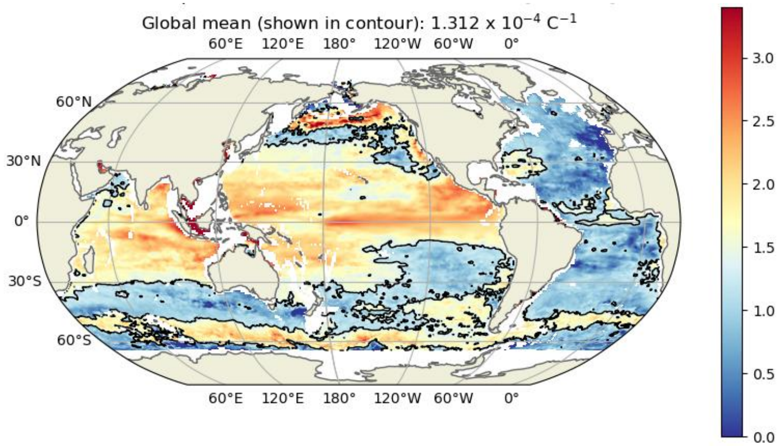


ECMWF ORAS5 ocean reanalysis



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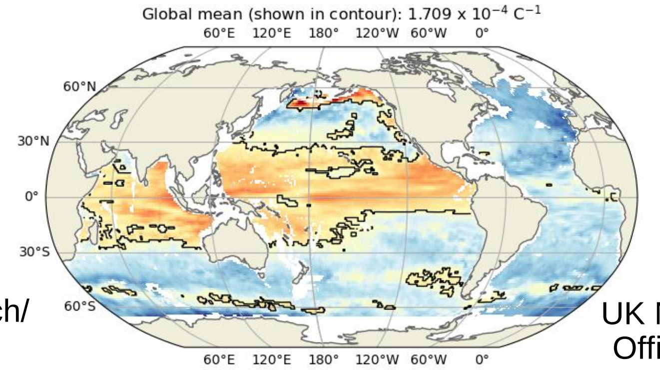
SIO Roemmich/ Gilson Argo



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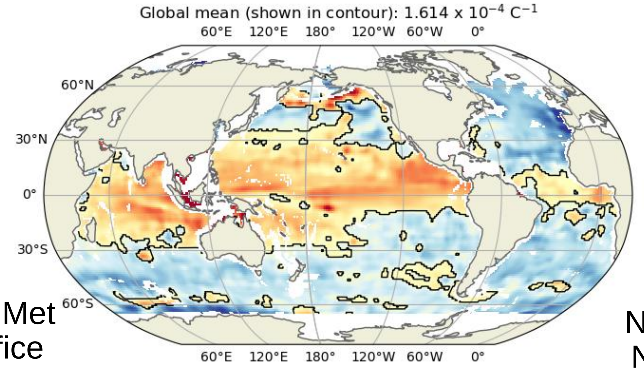

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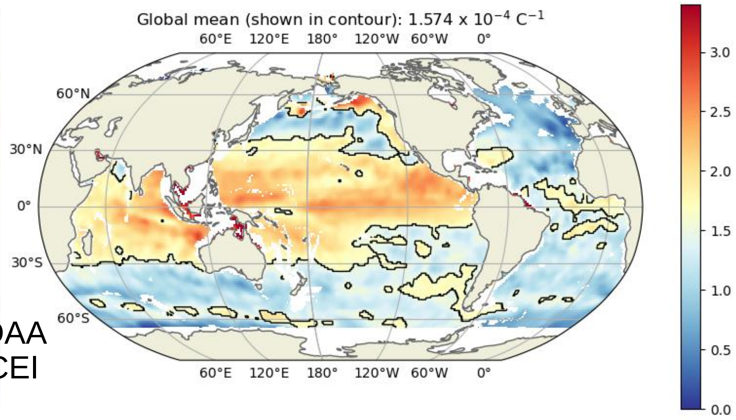

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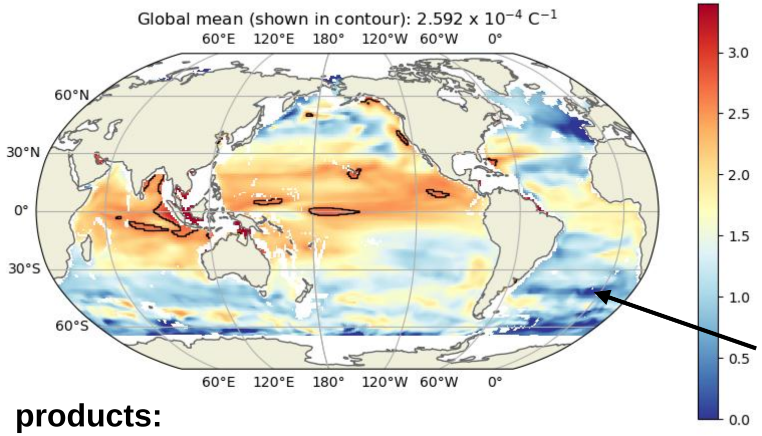

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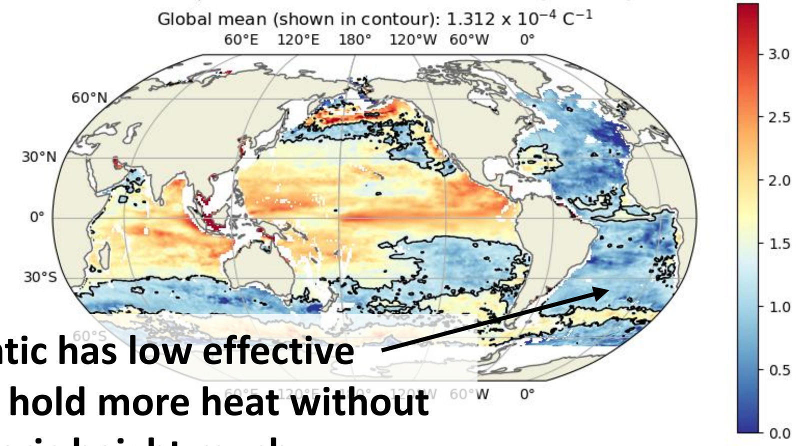
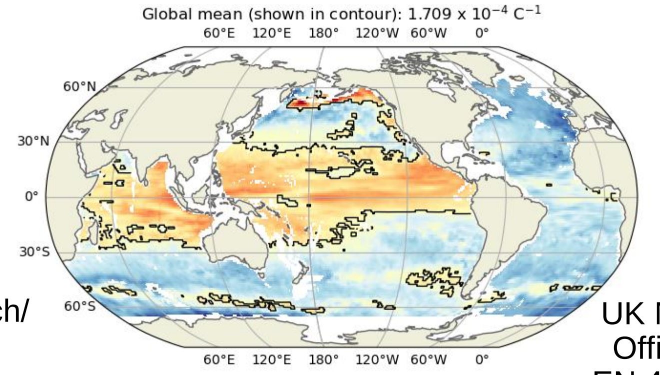
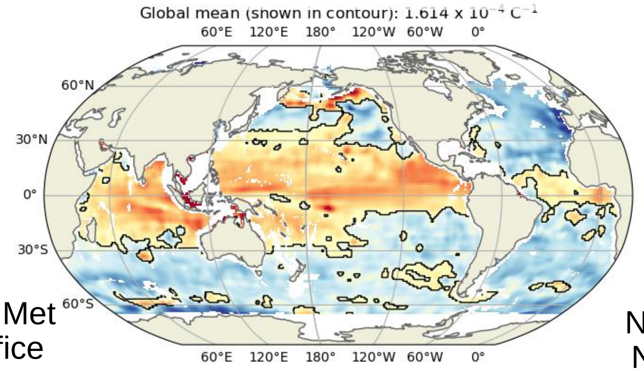


South Atlantic has low effective alpha – can hold more heat without changing steric height much

Gridded hydrographic data products:



SIO Roemmich/ Gilson Argo



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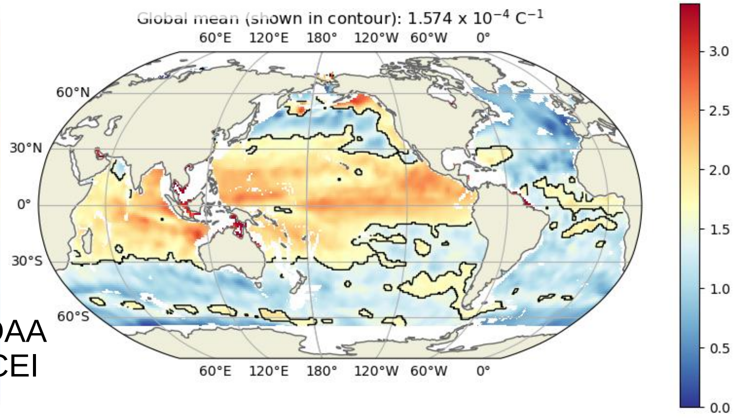

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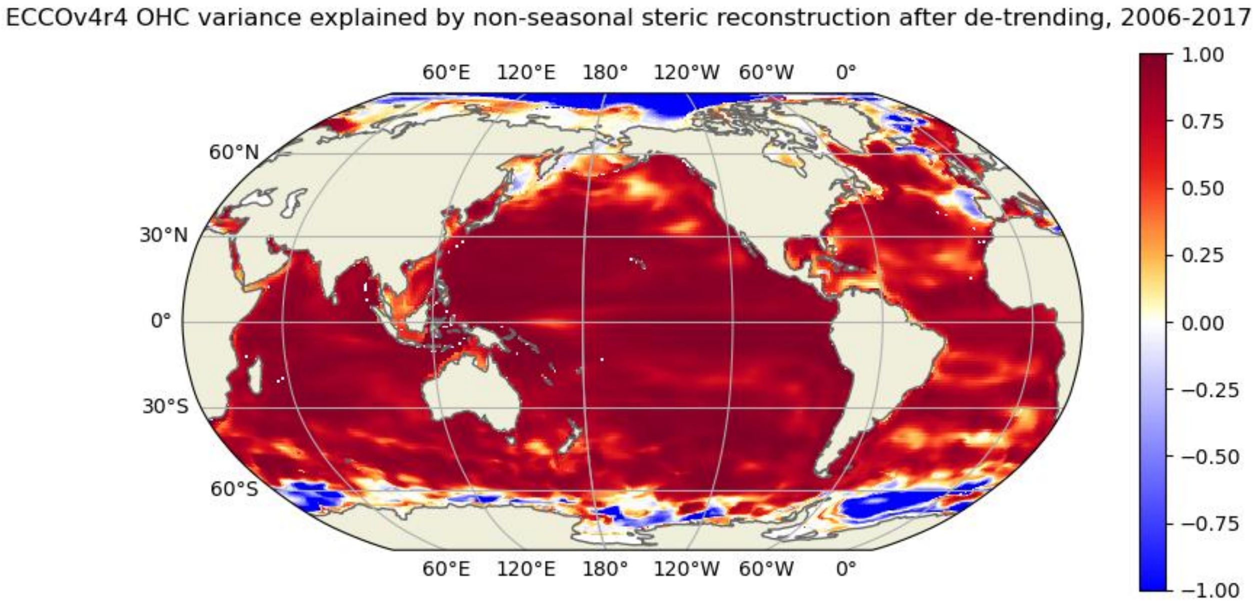
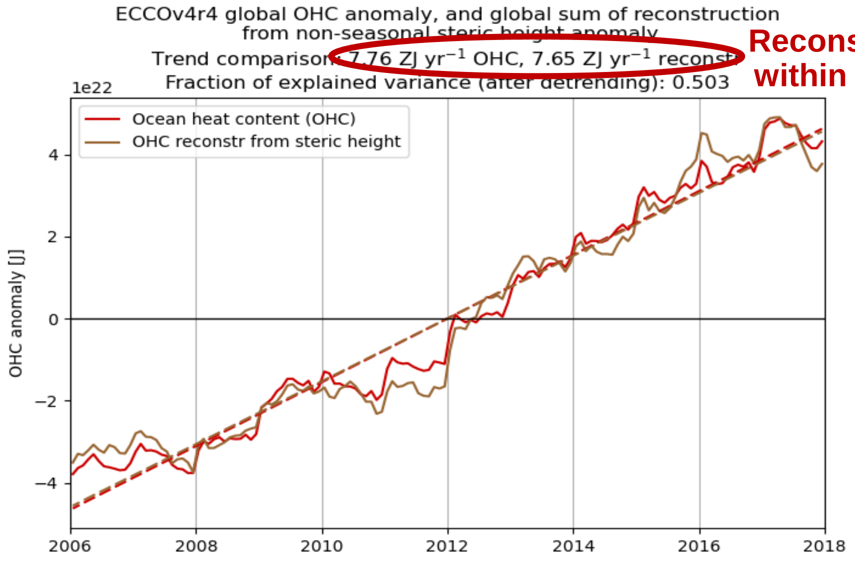
Using effective α (α_{eff}) to reconstruct ocean heat content

- Reconstructions of ECCO global OHC using ECCO-derived expansion efficiencies and steric height can quantify trend to within 2%
  - Also explains >80% of detrended interannual variance at most locations, though only ~50% globally
  - Thermal expansion explains most of the trend and variance – salinity is not a major influence on steric height outside of polar regions)
  - This test assumes that we can quantify α_{eff} confidently (does not account for differences between products)





Reconstruction trend within 2% of original