Inferring Ocean Heat Uptake from Satellite Gravimetry and Altimetry

geodetic corrections

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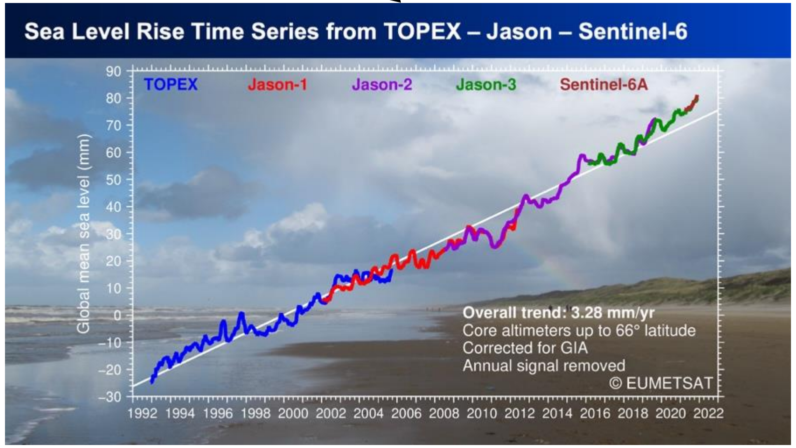

Sea Level Rise Time Series from TOPEX – Jason – Sentinel-6

Overall trend: 3.28 mm/yr
Core altimeters up to 66° latitude
Corrected for GIA
Annual signal removed
© EUMETSAT

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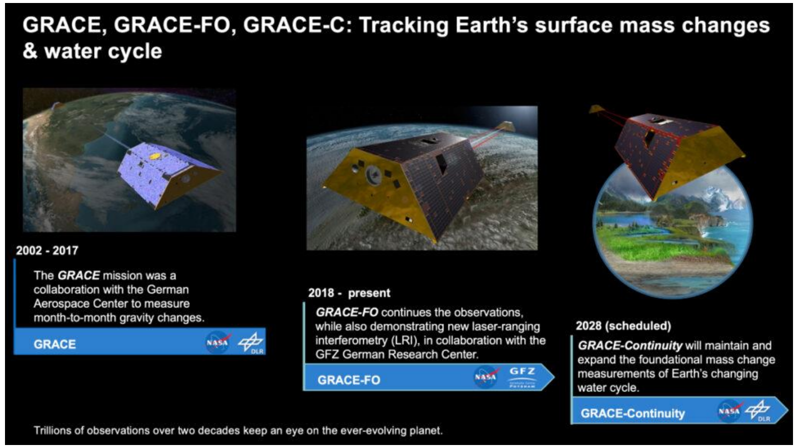


GRACE, GRACE-FO, GRACE-C: Tracking Earth's surface mass changes & water cycle

2002 - 2017

The ***GRACE*** mission was a collaboration with the German Aerospace Center to measure month-to-month gravity changes.

GRACE

2018 - present

GRACE-FO continues the observations, while also demonstrating new laser-ranging interferometry (LRI), in collaboration with the GFZ German Research Center.

GRACE-FO

2028 (scheduled)

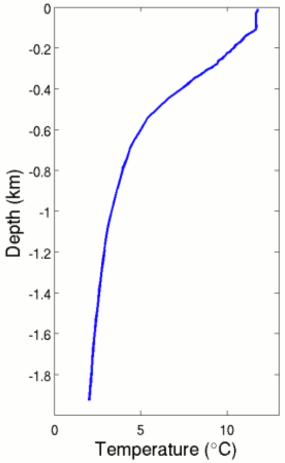
GRACE-Continuity will maintain and expand the foundational mass change measurements of Earth's changing water cycle.

GRACE-Continuity

Trillions of observations over two decades keep an eye on the ever-evolving planet.

) / α_{eff}

$\overset{?}{=} \sum$



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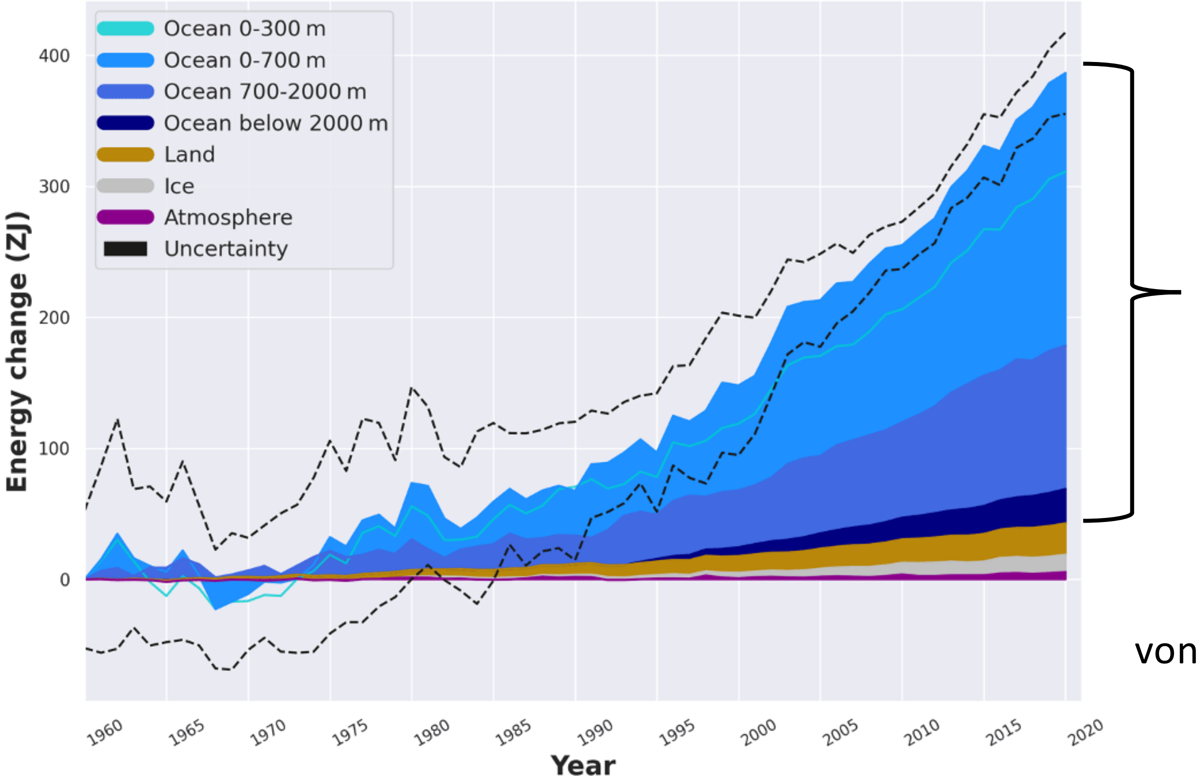
Why “ocean” heat uptake?



~90% of Earth’s energy uptake in recent years/decades has been in the ocean

von Schuckmann et al. 2023

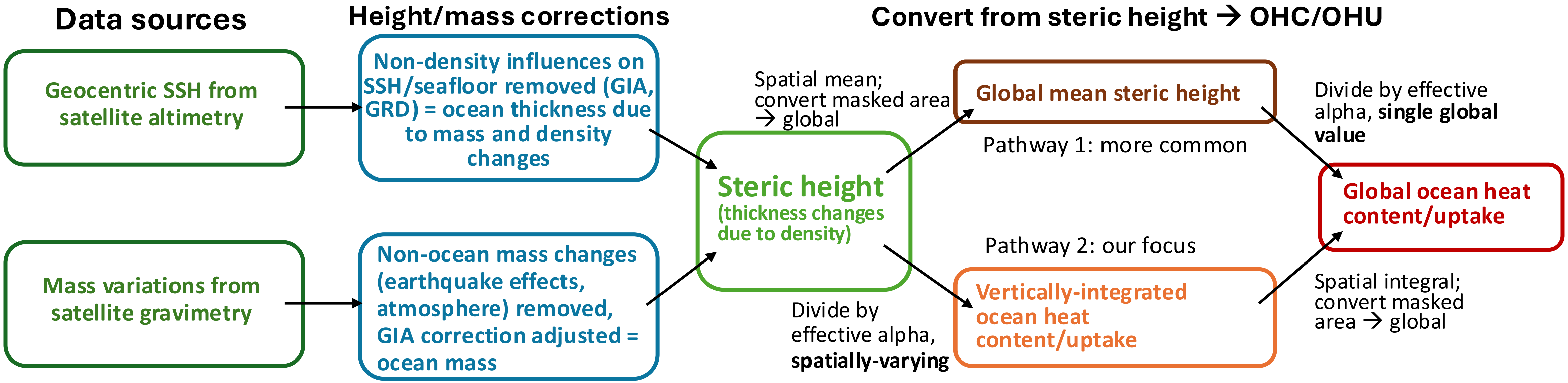
Why use satellites to observe (subsurface) ocean heat content?

- **Observations of ocean temperature/heat in-situ are inconsistent in spatiotemporal coverage, depending on the trajectories of individual floats or ships**
- **Nearly all in-situ observations (until quite recently) have been in the upper 2000 m, excluding ~half of the global ocean volume**

The geodetic approach to ocean heat content and uptake

Primary data sources

- “Geocentric” sea surface height from satellite altimetry, relative to sea floor
  - Satellites: TOPEX/Poseidon, Jason-1/2/3, Sentinel-6MF/-6B. **Data product: NASA-SSH v1 from PO.DAAC.**
- Mass variations from satellite gravimetry, relative to solid Earth & atmosphere gravity field
  - Satellites: GRACE, GRACE-Follow On. **Data product: Monthly mass grids, JPL RL06.3v04.**



Data sources

Height/mass corrections

Convert from steric height → OHC/OHU

Geocentric SSH from satellite altimetry

Non-density influences on SSH/seafloor removed (GIA, GRD) = ocean thickness due to mass and density changes

Mass variations from satellite gravimetry

Non-ocean mass changes (earthquake effects, atmosphere) removed, GIA correction adjusted = ocean mass

Steric height **(thickness changes due to density)**

Spatial mean; convert masked area → global

Global mean steric height

Pathway 1: more common

Divide by effective alpha, **single global value**

Divide by effective alpha, **spatially-varying**

Pathway 2: our focus

Vertically-integrated ocean heat content/uptake

Spatial integral; convert masked area → global

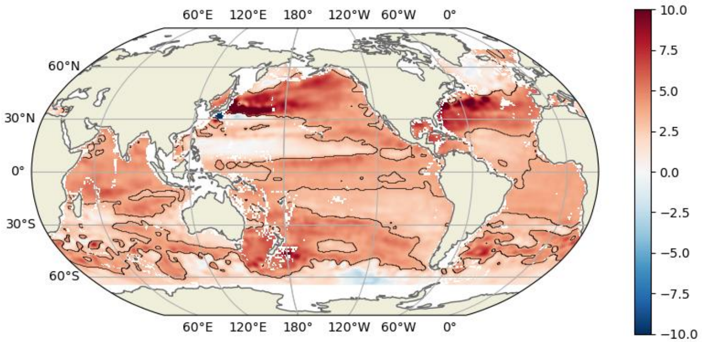
Global ocean heat content/uptake

Correcting altimetry to obtain steric height

(values shown indicate 2005-2024 trends)

NASA-SSH

“Global” mean: 3.469 mm yr^{-1}



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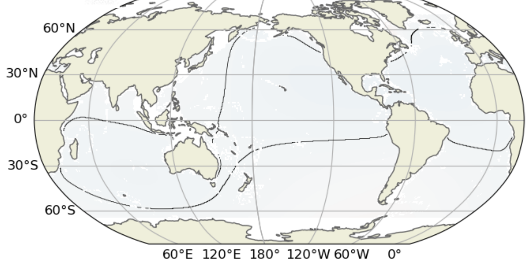
GIA (Caron et al. 2018)

“Global” mean: -0.295 mm yr^{-1}



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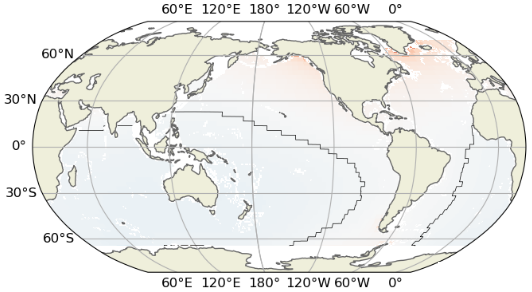
GRD at seafloor (G/GFO + pySLE)

“Global” mean: -0.228 mm yr^{-1}



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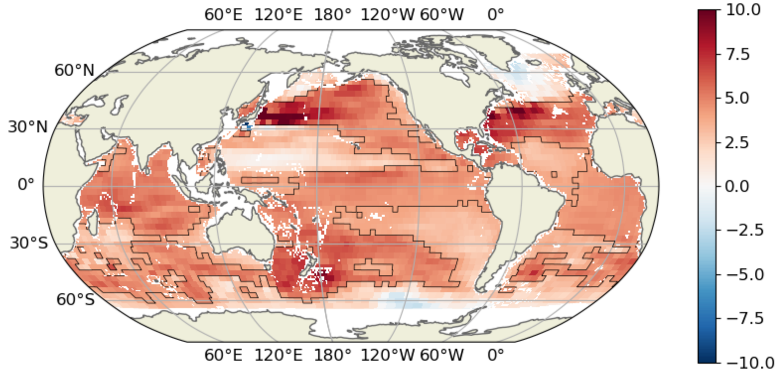
NASA-SSH corrected

“Global” mean: 3.992 mm yr^{-1}

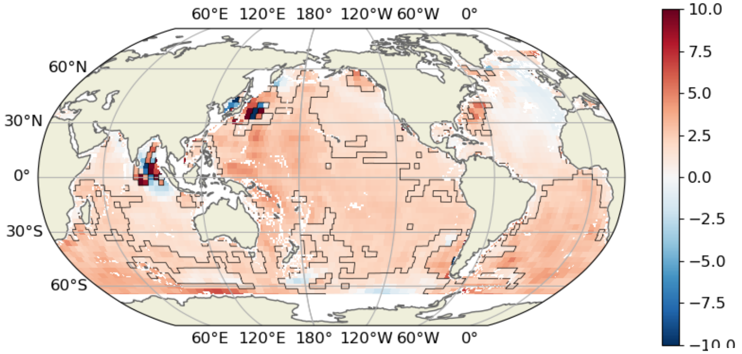


Correcting gravimetry to obtain steric height

(mass expressed as equivalent water height; values shown indicate 2005-2024 trends)

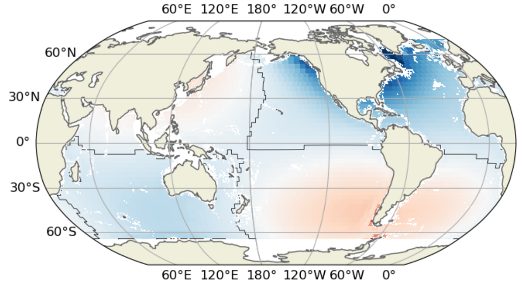
GRACE(-FO) JPL mascons

“Global” mean: 2.026 mm yr^{-1}



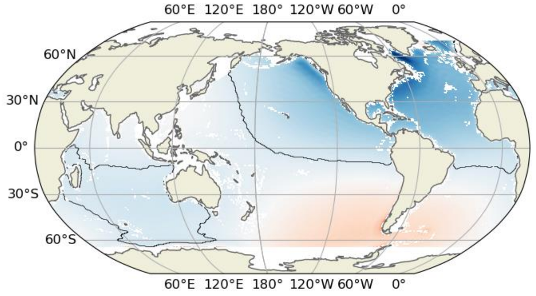
\+ **GIA** **(ICE6G-D; Peltier et al.)**

“Global” mean: -1.027 mm yr^{-1}



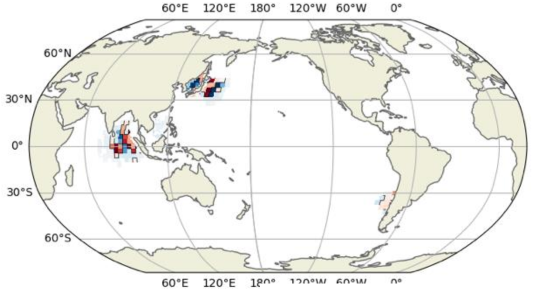
− **GIA** **(Caron et al. 2018)**

“Global” mean: -1.359 mm yr^{-1}



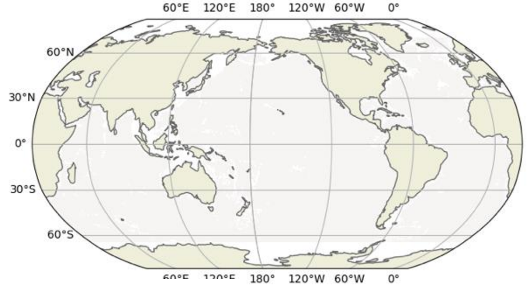
− **Earthquakes** **(Han et al. 2013)**

“Global” mean: 0.011 mm yr^{-1}



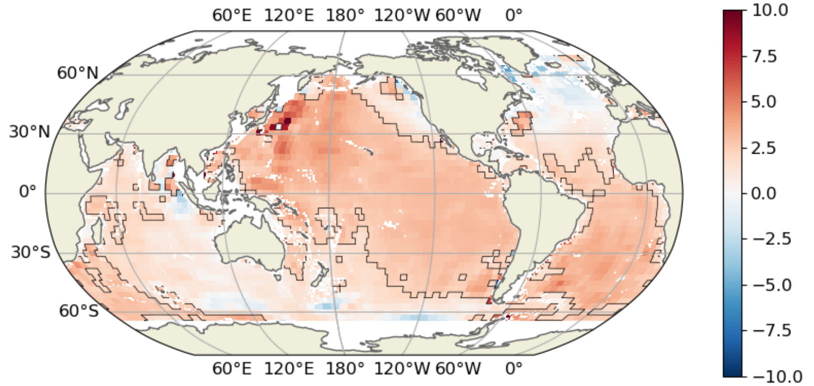
− **GAC (atmospheric mass)**

“Global” mean: 0.118 mm yr^{-1}



= **GRACE(-FO) JPL corrected**

“Global” mean: 2.166 mm yr^{-1}



From steric height to ocean heat content (OHC)

What is “effective” α?

- Satellites provide steric height variations, but that is not sufficient to determine OHC, proportional to the vertical integral of temperature anomaly $\int \Delta T dz$
- Instead we use an “effective” alpha, determined by linear regression of the steric height vs. vertical-mean temperature anomalies from in-situ data or models (e.g., ECCO)

$$\Delta h_{\text{steric}} \approx \int (\alpha \Delta T - \beta \Delta S)\, dz \approx \alpha_{\text{eff}} \int \Delta T\, dz$$

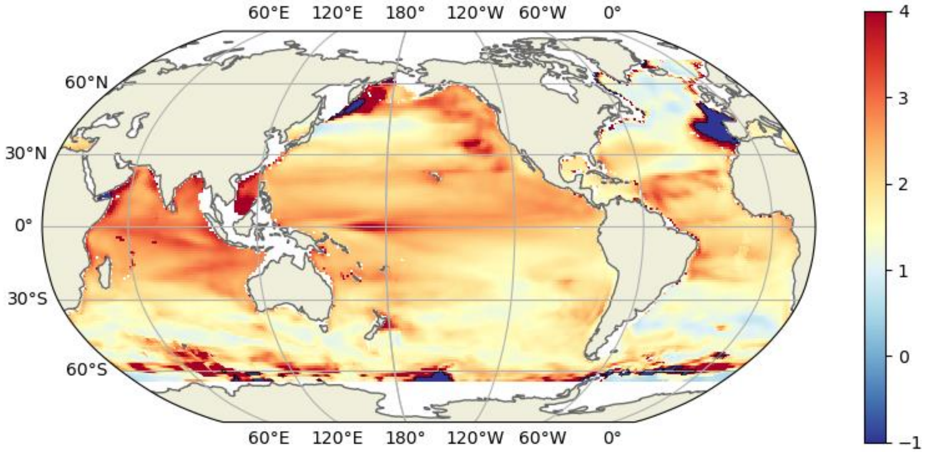
$$\alpha_{\text{eff}} = \frac{\overline{(\Delta h_{\text{steric}})^2}}{H \overline{\Delta h_{\text{steric}}[\Delta T]}}$$

Δ indicates anomaly (time mean and seasonal cycle removed)

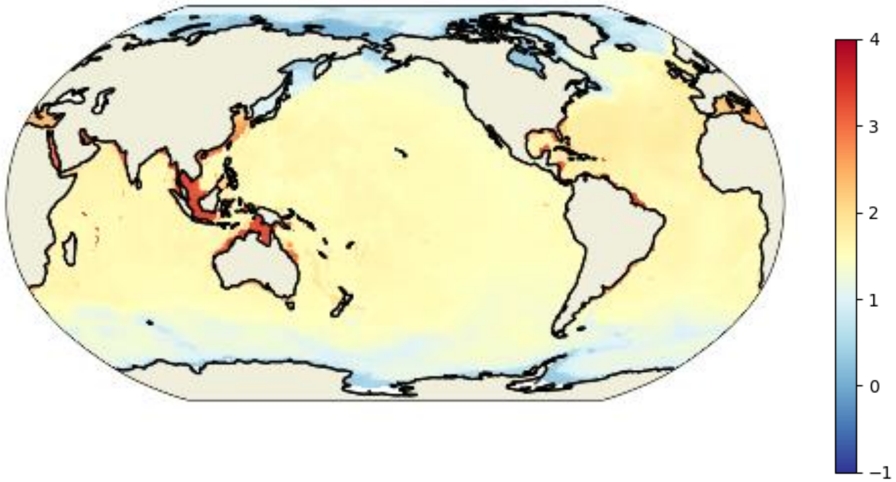
vertical mean ΔT

- α_{eff} can be a single value globally, or spatially-varying using steric height and vertical mean T at each location

Effective alpha [10^{-4} C^{-1}], as computed from steric height and temperature profiles in ECCO version 4 release 6



Compare with vertical mean “actual” alpha



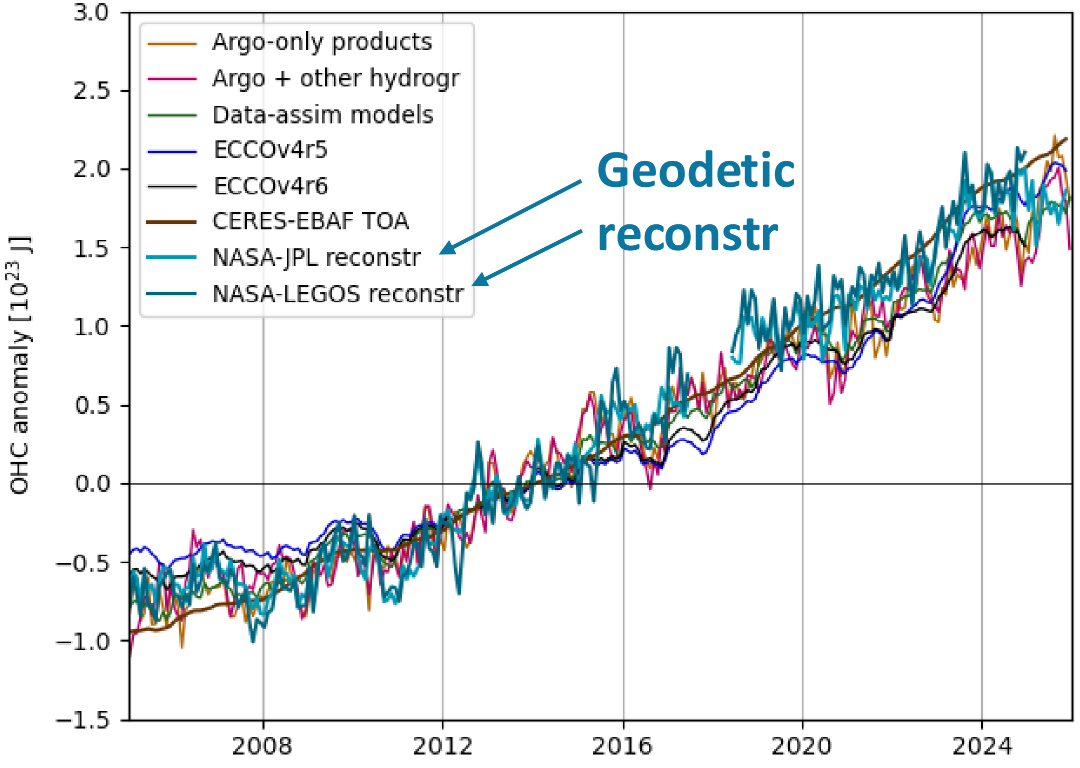
Geodetic OHC/OHU trends, compared to in-situ and TOA

$$\text{OHC} = \rho c_\rho \int \Delta T \, dz \approx \boxed{\rho c_\rho \Delta h_{\text{steric}} / \alpha_{\text{eff}}}$$

Geodetic

Global OHC time series

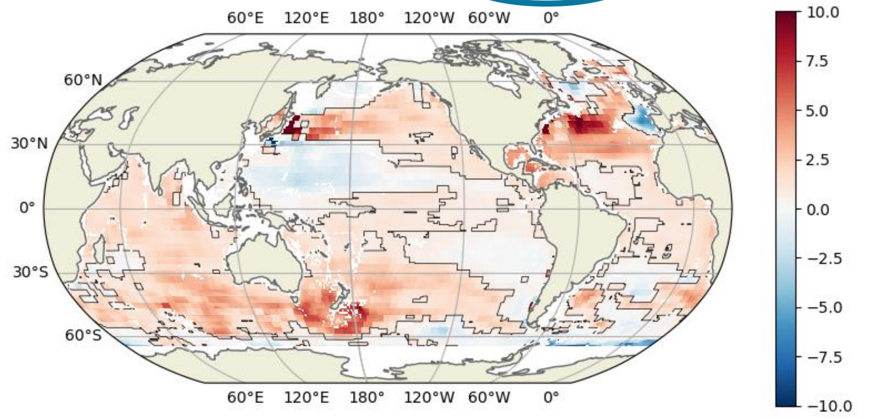
Global OHC from sat reconstr & other product ensembles,
adjusted from 0-2000 dbar, with 2006-2020 mean removed, no seasonal cycle



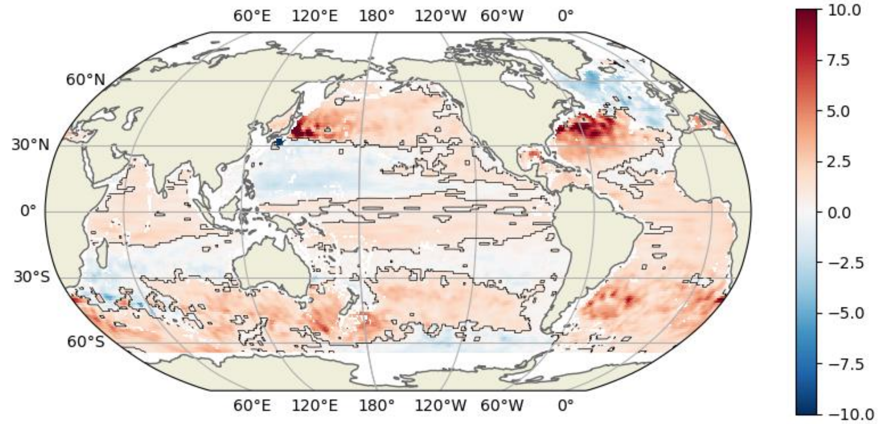
Geodetic reconstr

2005-2024 trends: sat reconstr vs. Argo

OHC 2005-2024 trend,
NASA-JPL sat reconstr, alpha_eff ECCOv4r6 [W m^{-2}]
Global mean (shown in contour): 0.863 W m^{-2}



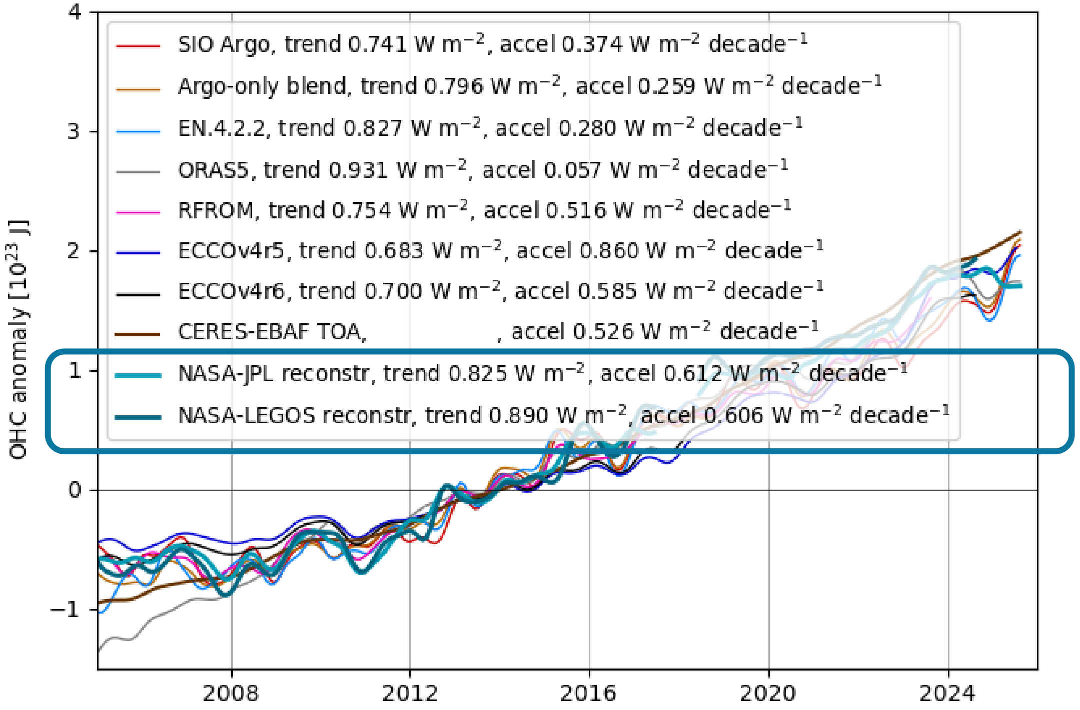
OHC 2005-2024 trend,
SIO_Argo [W m^{-2}]
Global mean (shown in contour): 0.741 W m^{-2}



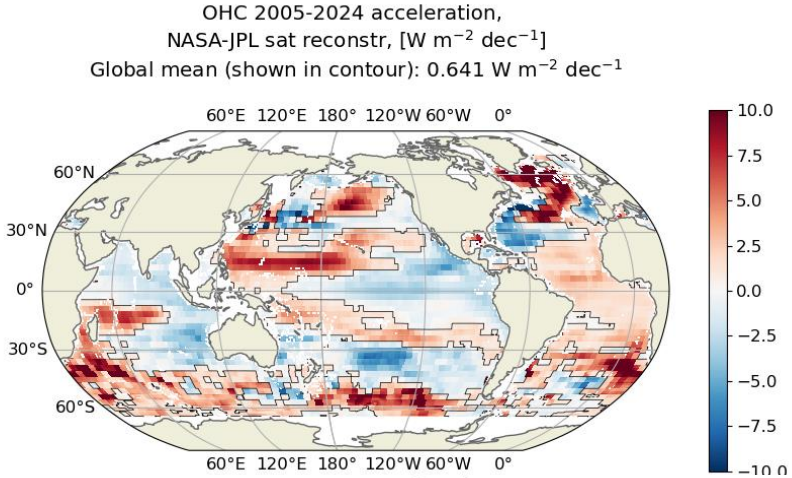
- Since Hakuba et al. (2024), as time series get longer (and the effect of the 2017-18 GRACE “gap” is diminished), satellite trend has gotten closer to observations…though still slightly higher
- **Regional differences in OHC trends, especially in high-lat N Atlantic, S Atlantic, subtropical S Indian**

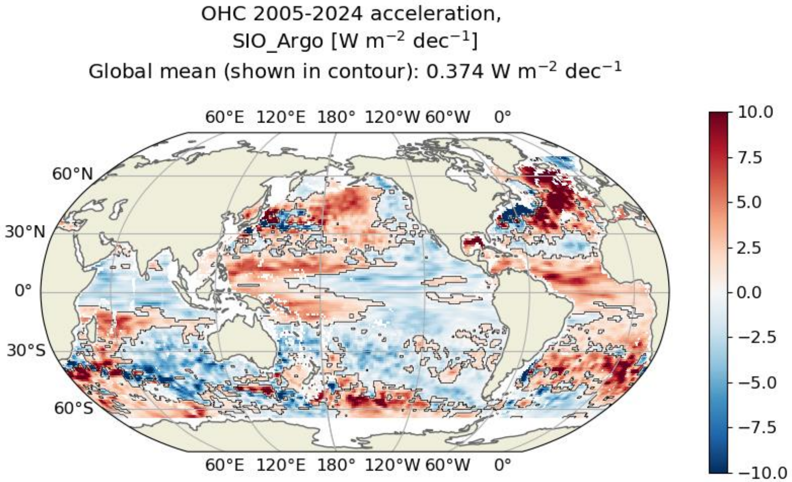
Geodetic OHC/OHU accelerations, compared to in-situ and TOA

OHC trend and acceleration, with 12-month low-passed time series



Geodetic reconstr


OHC 2005-2024 acceleration,
NASA-JPL sat reconstr, [W m^{-2} dec^{-1}]
Global mean (shown in contour): 0.641 W m^{-2} dec^{-1}

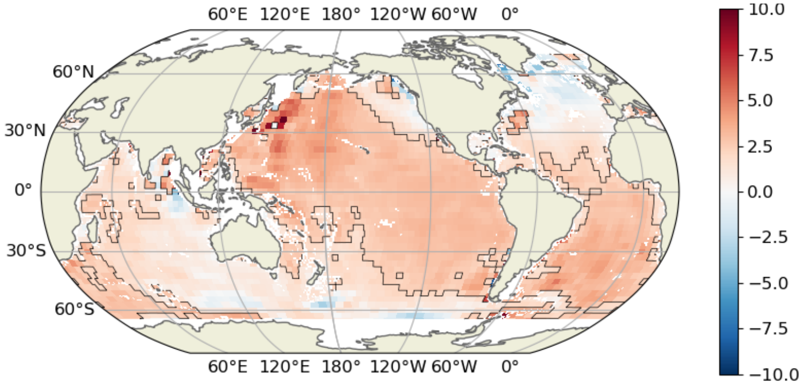

OHC 2005-2024 acceleration,
SIO_Argo [W m^{-2} dec^{-1}]
Global mean (shown in contour): 0.374 W m^{-2} dec^{-1}

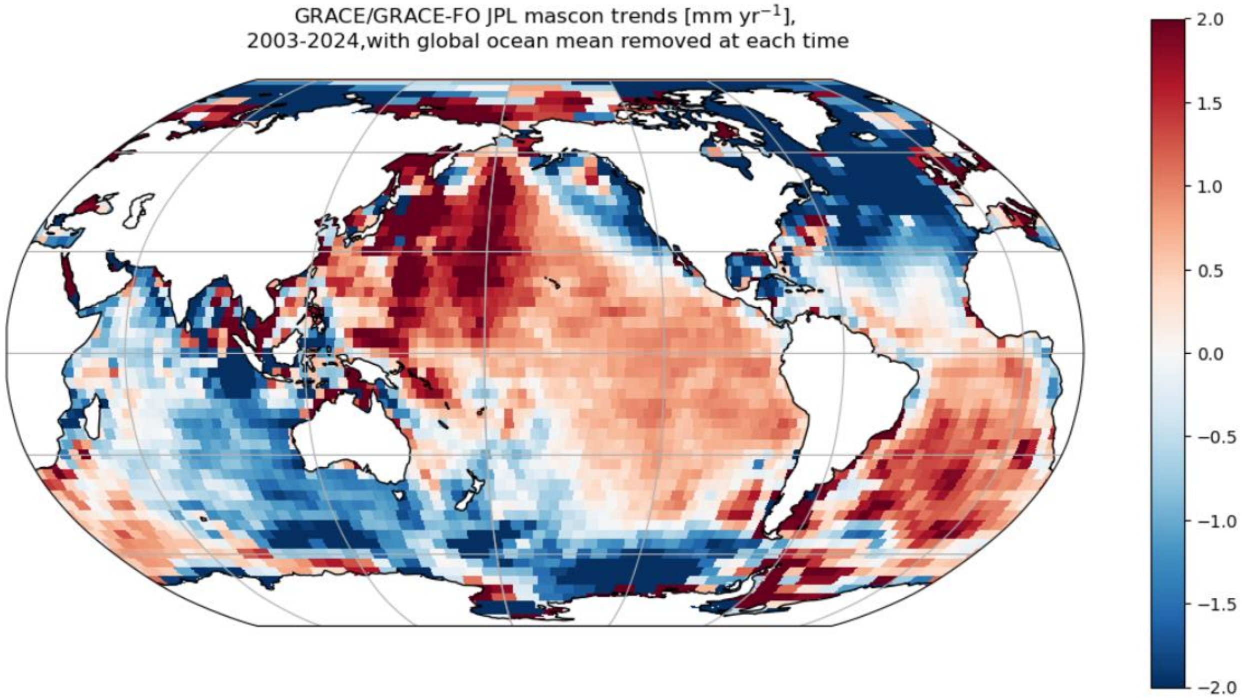
- Global geodetic OHC acceleration is comparable to or higher than TOA radiation estimates; Argo lower
- **But much agreement between geodetic and Argo in regional distribution of accelerations (more so than with trends)**

Sources of uncertainty in geodetic OHC: satellite corrections

GRACE(-FO) JPL corrected, 2005-2024 trend

"Global" mean: 2.166 mm yr^{-1}





- Spatial variations in GRACE/GRACE-FO trends have a large-scale (low-degree?) pattern that does not resemble known OBP patterns in models
- Is this an artifact of orbit determination? Geocenter modeling? Corrections for GIA or other solid Earth effects?

Sources of uncertainty in geodetic OHC: effective alpha

$$\Delta\mathrm{OHC} \propto \Delta h_{\mathrm{steric}}/\alpha_{\mathrm{eff}}$$

Effective alpha [10^{-4} C^{-1}], as computed from steric height and temperature profiles

Method

Tdenom

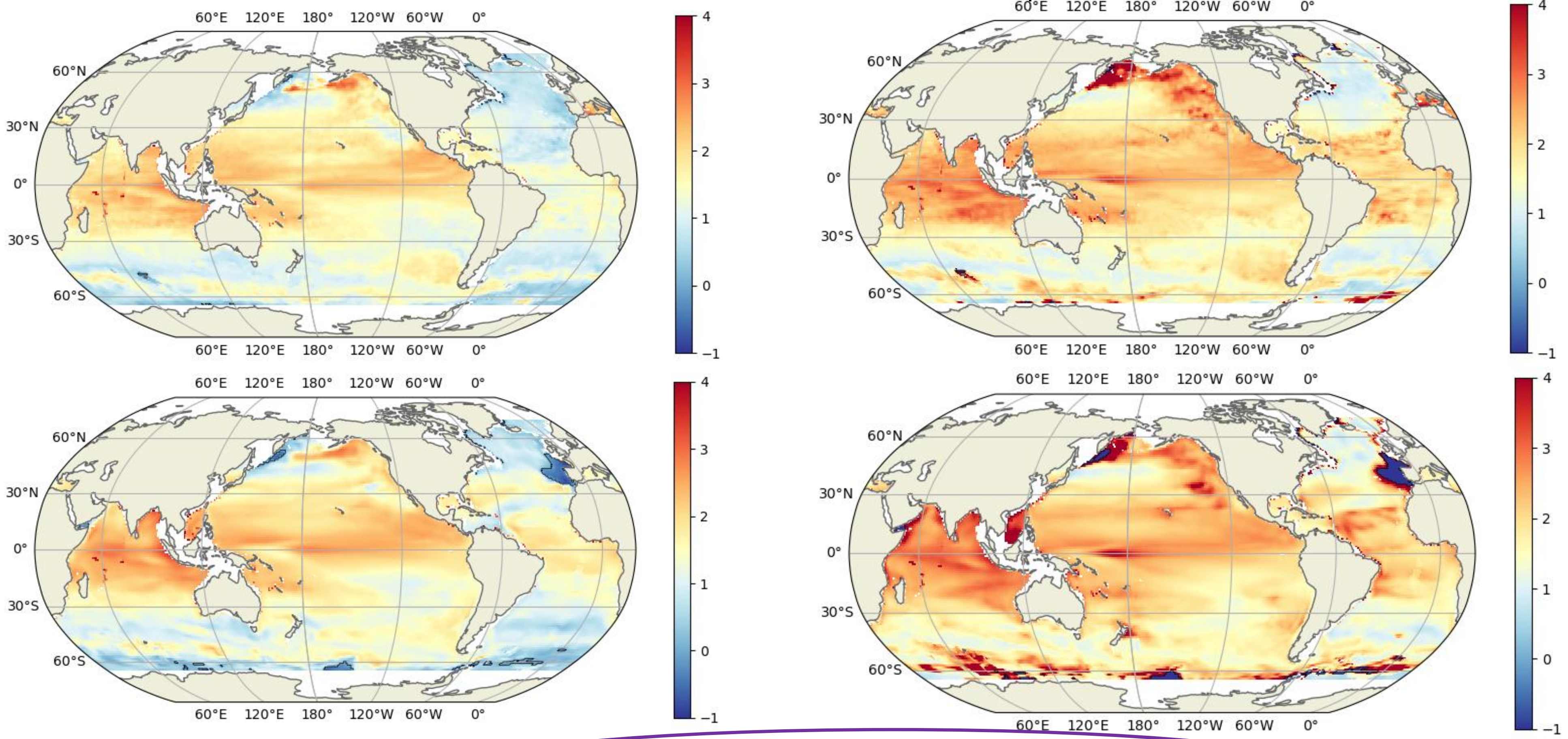
$$\alpha_{\mathrm{eff}} = \frac{\overline{\Delta h_{\mathrm{steric}}[\Delta T]}}{H\overline{[\Delta T]^2}}$$

SHAdenom-1

$$\alpha_{\mathrm{eff}} = \frac{\overline{(\Delta h_{\mathrm{steric}})^2}}{H\overline{\Delta h_{\mathrm{steric}}[\Delta T]}}$$

ocean depth

vertical mean ΔT



SIO Argo

ECCOv4r6

- Tdenom minimizes the **steric height** misfit, SHAdenom-1 minimizes the **temperature/OHC** misfit

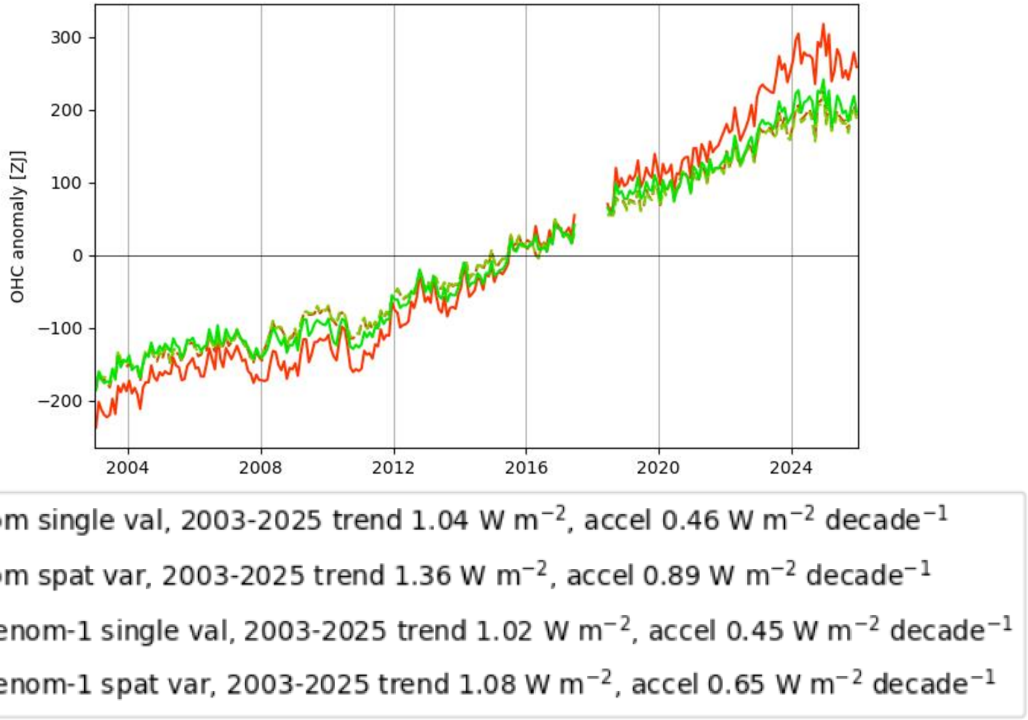
This is what we want

How effective alpha is computed matters

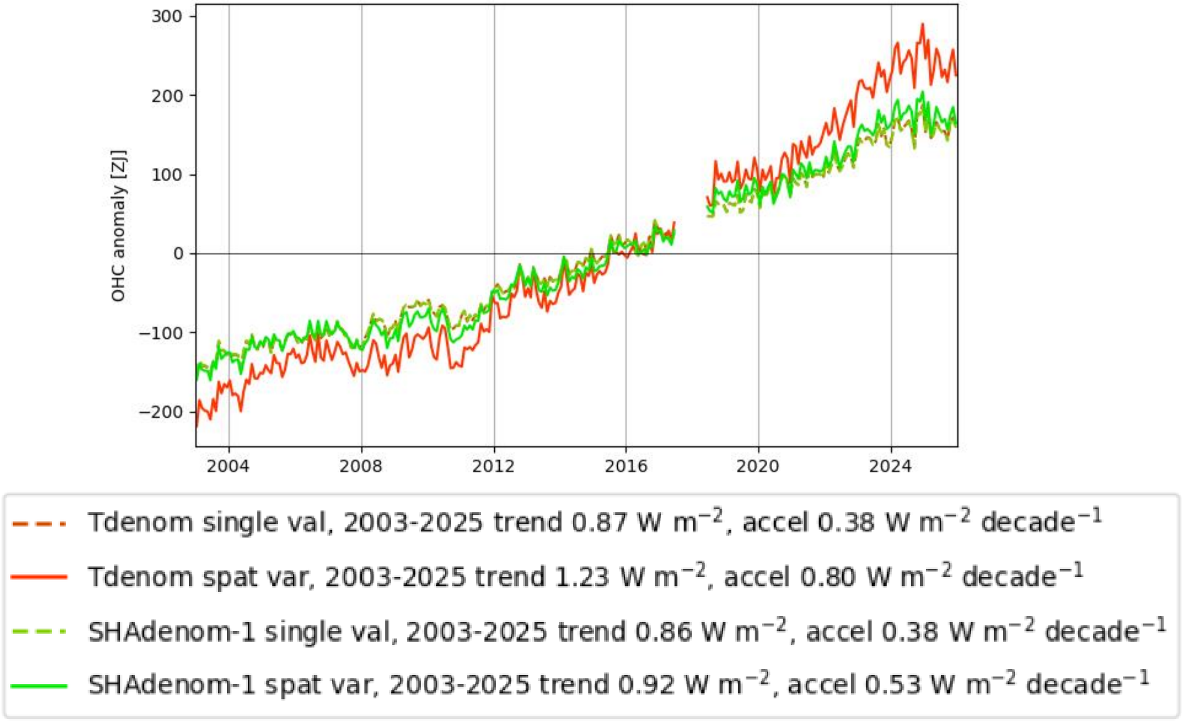
Consider effect of:

- **Method:** Putting temperature (Tdenom) vs. steric height (SHAdenom-1) in the denominator
- **Source:** Using a gridded Argo product (SIO Argo) vs. data-constrained model (ECCO) to define α_{eff}
- **Spatial distribution:** Using spatially-varying α_{eff} vs. single global α_{eff}

Global OHC reconstructions with SIO Argo α_{eff} source

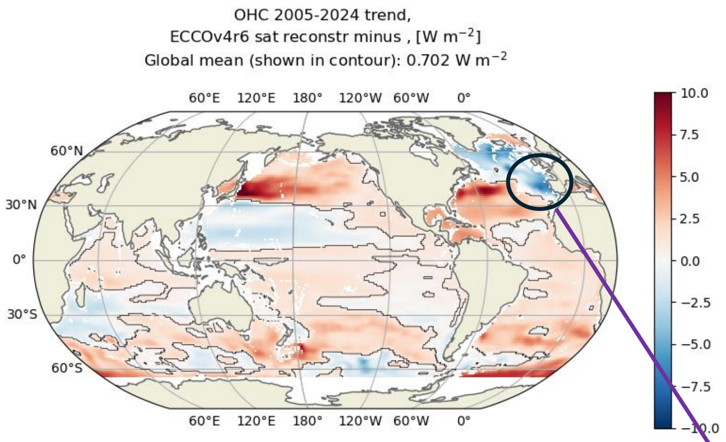


Global OHC reconstructions with ECCOv4r6 α_{eff} source

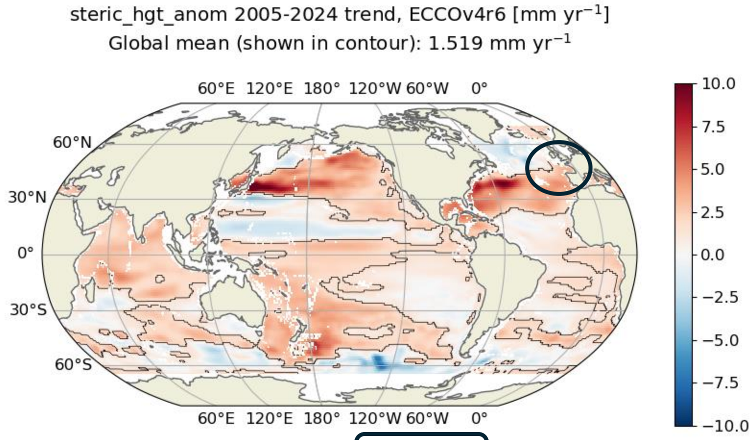


- Using SIO Argo gridded as source results in 10-20% larger trends/accelerations than using ECCO
- Method matters when allowing α_{eff} to spatially vary! Use **SHAdenom-1** to minimize OHC misfit
- **A spatially-varying α_{eff} allows for higher trends (5-10%) and especially accelerations (30-50%)!**

Where are regional reconstructions difficult? The case of the NE Atlantic



OHC 2005-2024 trend,
ECCOv4r6 sat reconstr minus , [W m^{-2}]
Global mean (shown in contour): 0.702 W m^{-2}

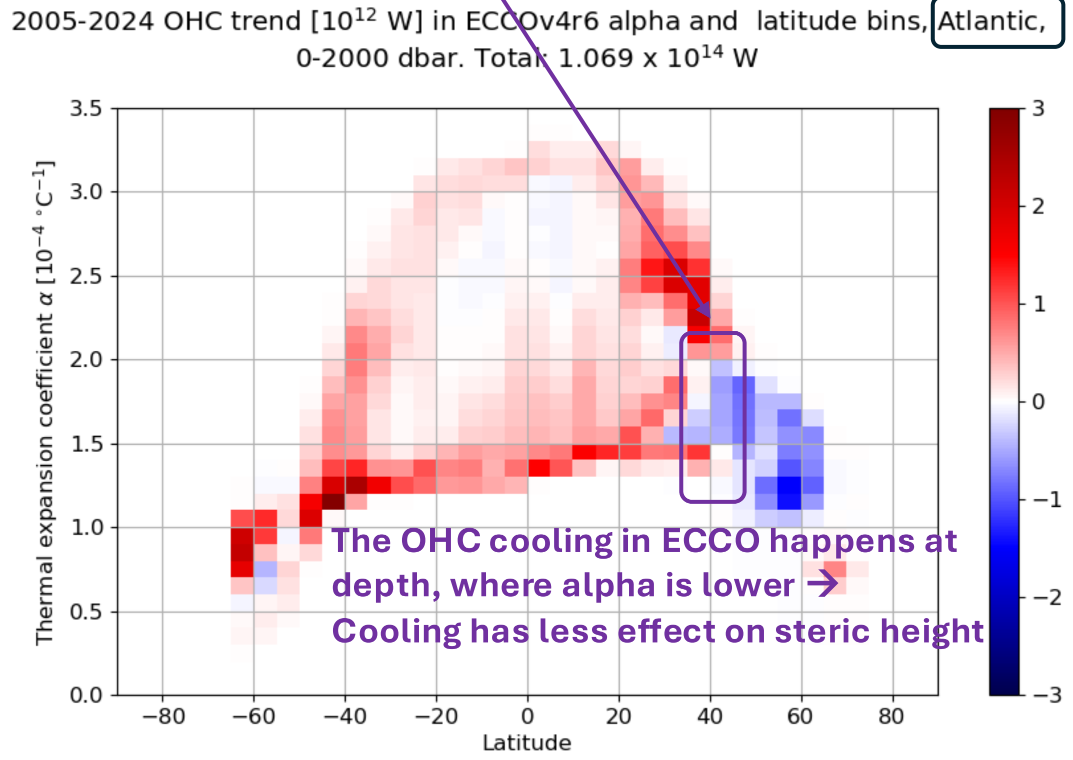


steric_hgt_anom 2005-2024 trend, ECCOv4r6 [mm yr^{-1}]
Global mean (shown in contour): 1.519 mm yr^{-1}

Neg OHC but pos steric height trend?

Higher alpha (generally warmer, shallower)

Lower alpha (generally colder, deeper)



2005-2024 OHC trend [10^{12} W] in ECCOv4r6 alpha and latitude bins, Atlantic, 0-2000 dbar. Total: 1.069 x 10^{14} W

The OHC cooling in ECCO happens at depth, where alpha is lower → Cooling has less effect on steric height

Where are regional reconstructions difficult? The case of the NE Atlantic

OHC 2005-2024 trend,
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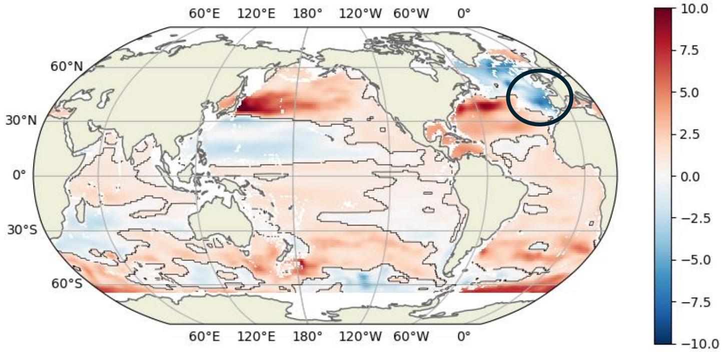

steric_hgt_anom 2005-2024 trend, ECCOv4r6 [mm yr^{-1}]
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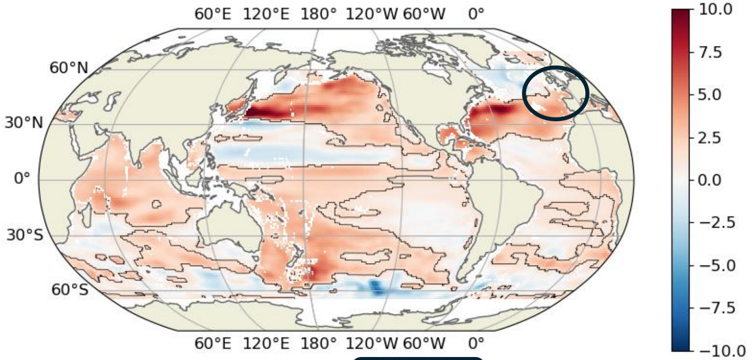
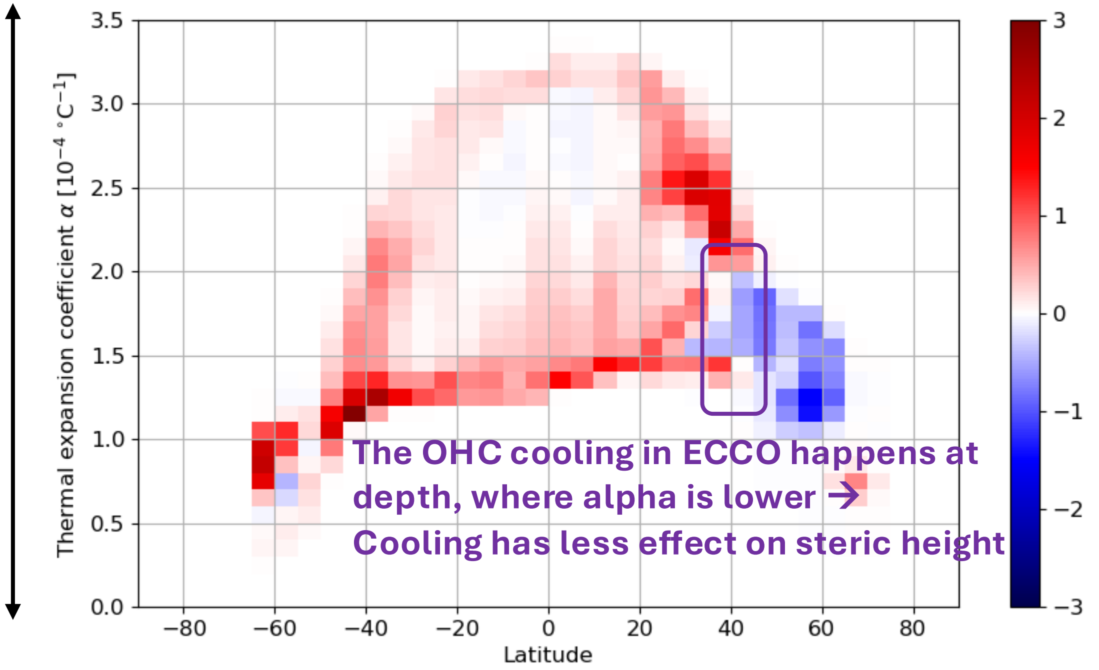


Neg OHC but pos steric height trend?

2005-2024 OHC trend [10^{12} W] in ECCOv4r6 alpha and latitude bins, Atlantic, 0-2000 dbar. Total: 1.069 x 10^{14} W

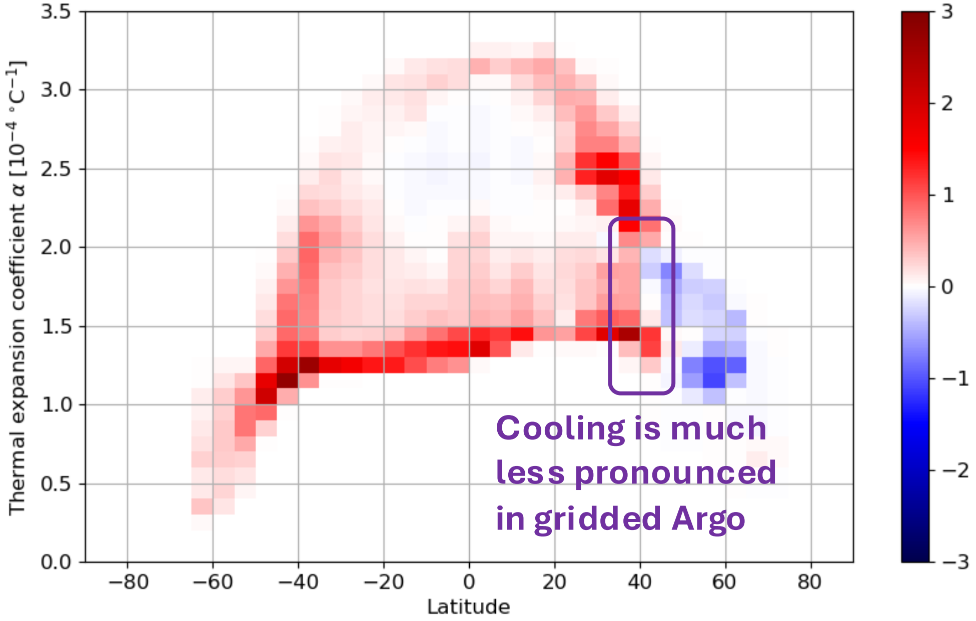
Higher alpha (generally warmer, shallower)



Lower alpha (generally colder, deeper)

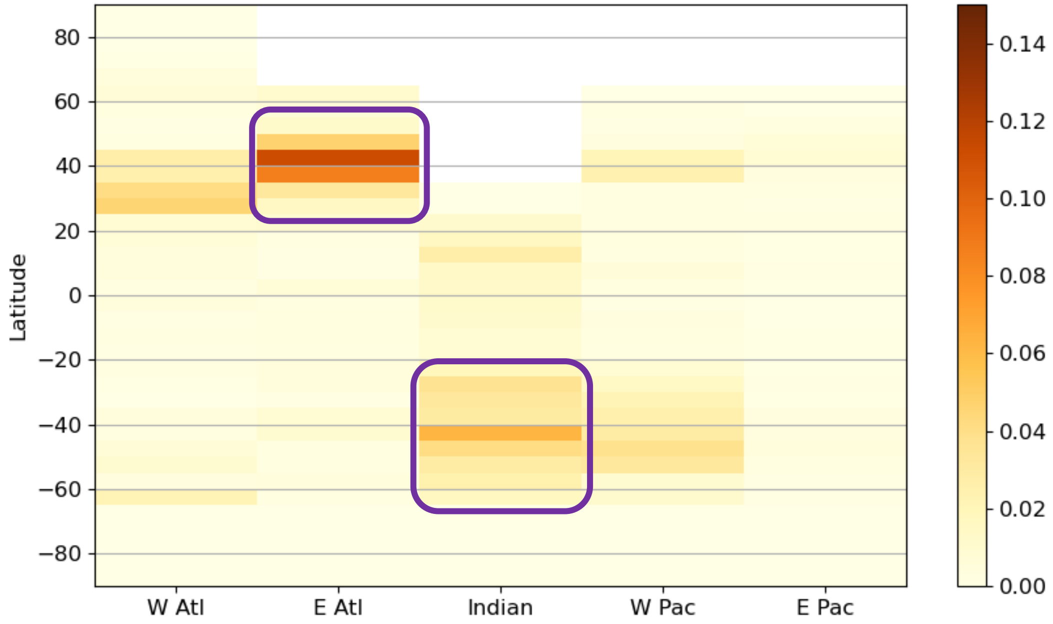
The OHC cooling in ECCO happens at depth, where alpha is lower → Cooling has less effect on steric height

2005-2024 OHC trend [10^{12} W] in RG_Argo alpha and latitude bins, Atlantic, 0-2000 dbar. Total: 1.207 x 10^{14} W

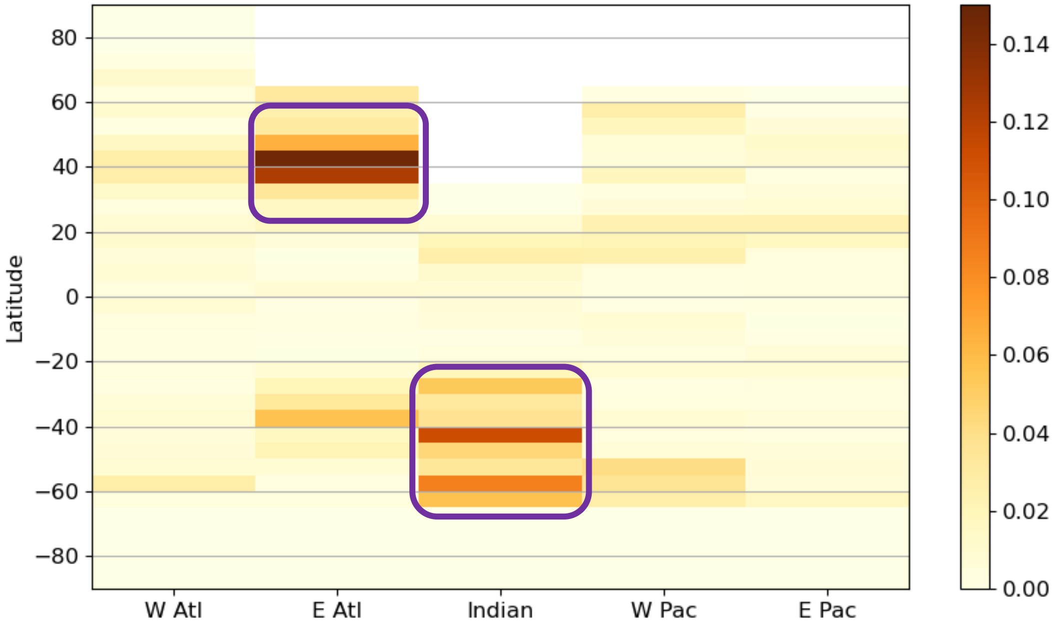


Cooling is much less pronounced in gridded Argo

“Uncertainty” in regional OHC trends and accelerations from geodetic (satellite) reconstructions, using α_{eff} from different sources



RMS difference across regional OHC **trends** using various α_{eff} sources, normalized by RMS diff of global trend



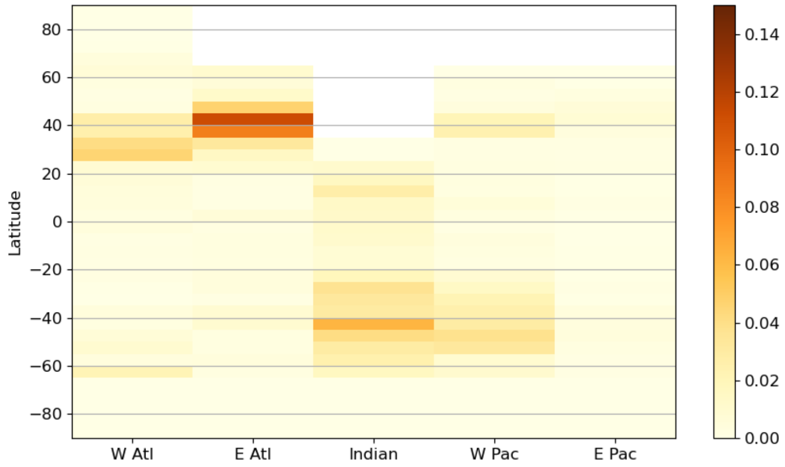
RMS difference across regional OHC **accelerations** using various α_{eff} sources, normalized by RMS diff of global acceleration

- Highest regional uncertainties in the NE Atlantic, likely due to a poor relationship between OHC and steric height there, as well as differences between Argo & ECCO
- South Indian Ocean (extending into that sector of Southern Ocean) also a source of substantial uncertainty

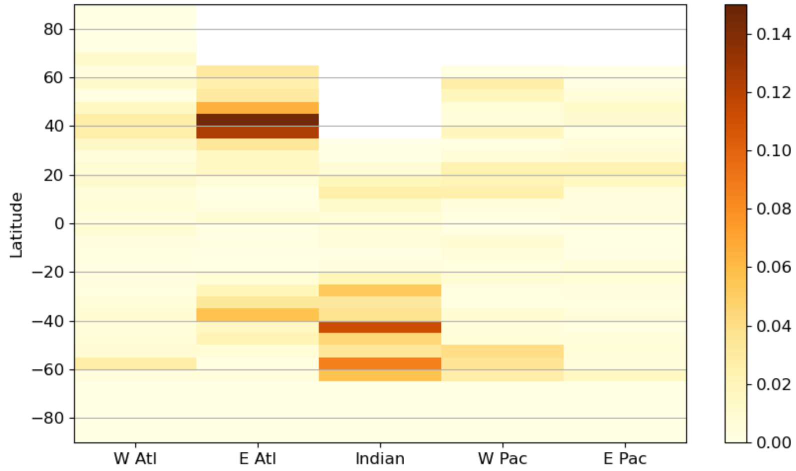
"Uncertainty" in regional OHC trends and accelerations from geodetic (satellite) reconstructions with various α_{eff} (vs. actual trends/accelerations using ECCOv4r6 α_{eff})

(Regional RMS diff/Global RMS diff)

OHC trends



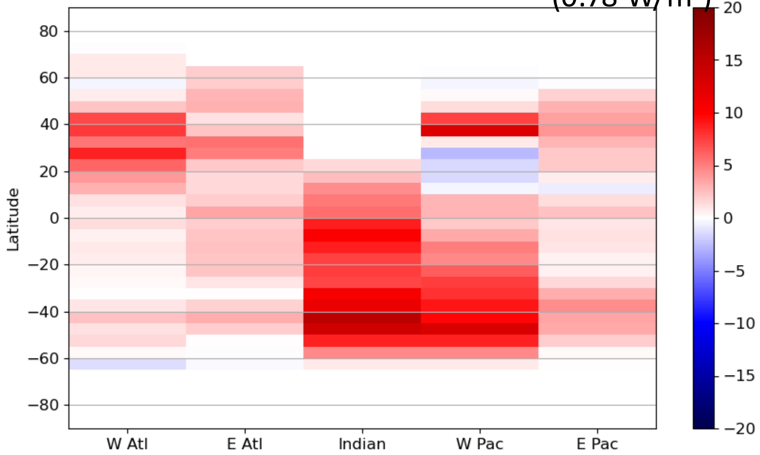
OHC accelerations



Values using ECCOv4r6 alpha_eff

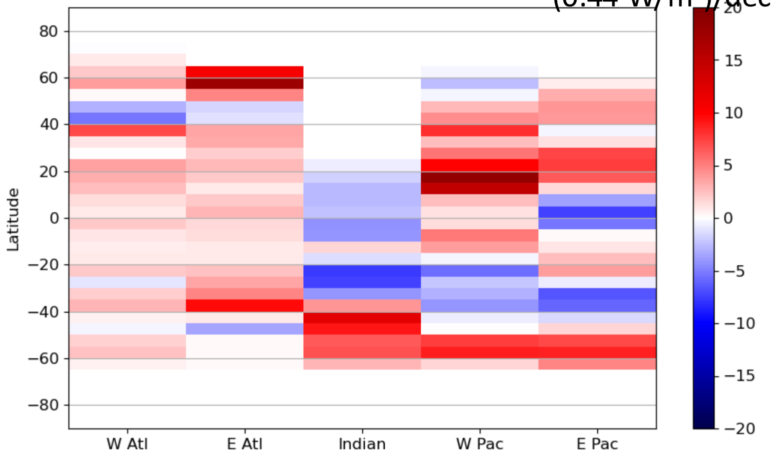
2003-2025 OHC trend [10^{12} W] in NASA-JPL OHC reconstr,
ECCOv4r6 SHAdenom-1 spat var alpha_eff, in regions.
Total: 3.966 x 10^{14} W

(0.78 W/m^2)



2003-2025 OHC accel [10^{12} W decade^{-1}] in NASA-JPL OHC reconstr,
ECCOv4r6 SHAdenom-1 spat var alpha_eff, in regions.
Total: 2.242 x 10^{14} W decade^{-1}

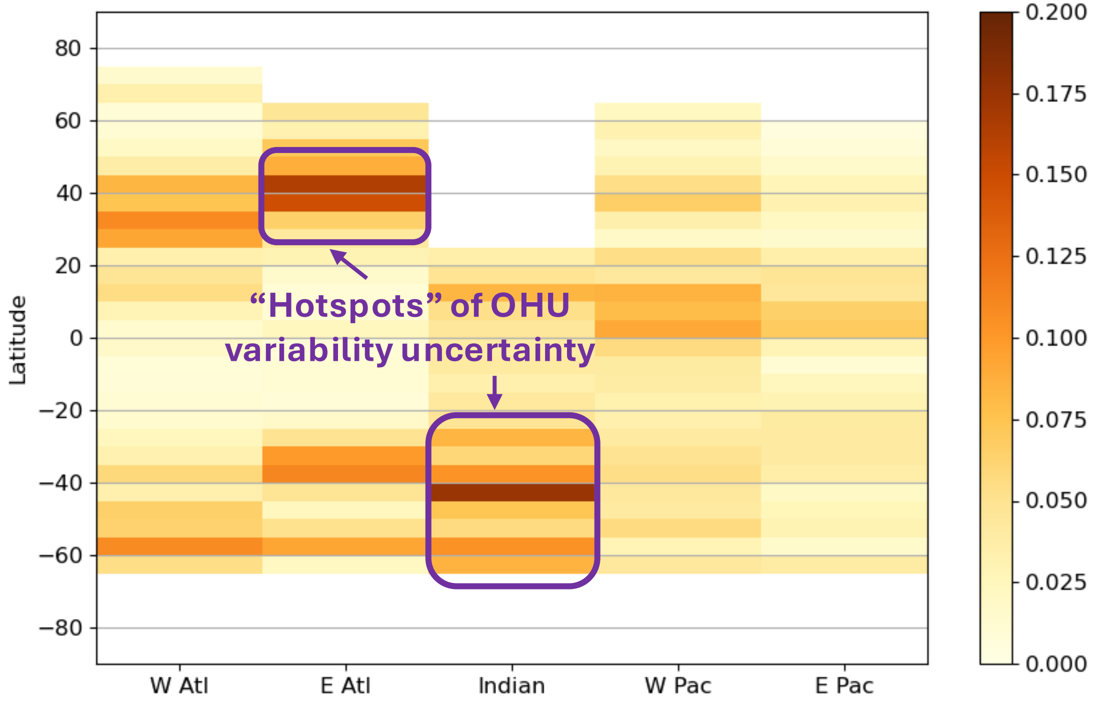
(0.44 W/m^2)/decade



- Regional **uncertainties** in trends/accelerations do not necessarily coincide with the largest **magnitudes** of trends/accelerations

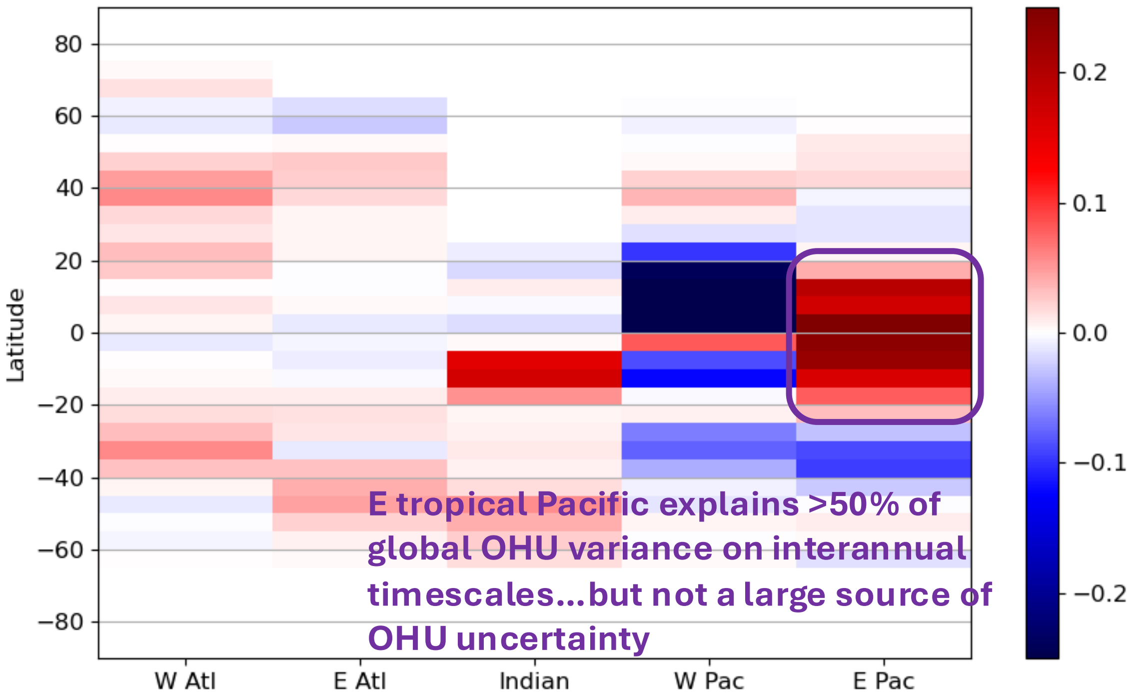
“Uncertainty” in regional interannual variability, from satellite reconstructions

Time mean **RMS diff of 2-year low-passed OHU** using various α_{eff}, normalized by global value



“Hotspots” of OHU variability uncertainty

Explained variance of global OHU (2-year low-passed) by regional OHU variability, using ECCOv4r6 α_{eff}



E tropical Pacific explains >50% of global OHU variance on interannual timescales…but not a large source of OHU uncertainty

- Again, NE Atlantic and South Indian Ocean are hotspots of uncertainty, though other areas emerge as well
- Notably, the largest regional contributor to global OHU interannual variability (tropical eastern Pacific, i.e., ENSO) has very low uncertainty (good agreement between Argo and ECCO)

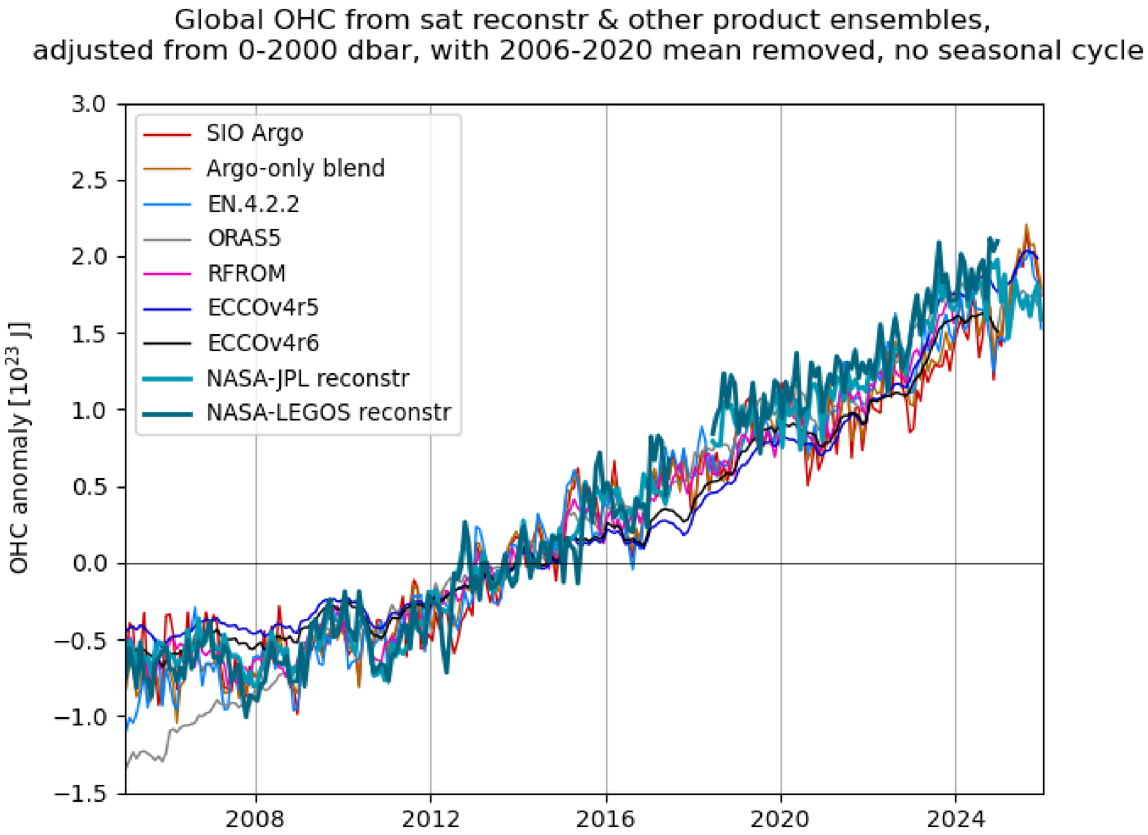
Key conclusions

- **Geodetic estimates of global OHC are closer to in-situ and TOA observations than even a few years ago, thanks to:**
  - Longer time series reducing the impact of the “gap”
  - Improved corrections (e.g. wet troposphere for altimetry, GIA modeling)

- **Global OHC acceleration (increase in OHU) from geodetic is similar to CERES**
  - Global accelerations are higher than in Argo, though regional patterns agree well

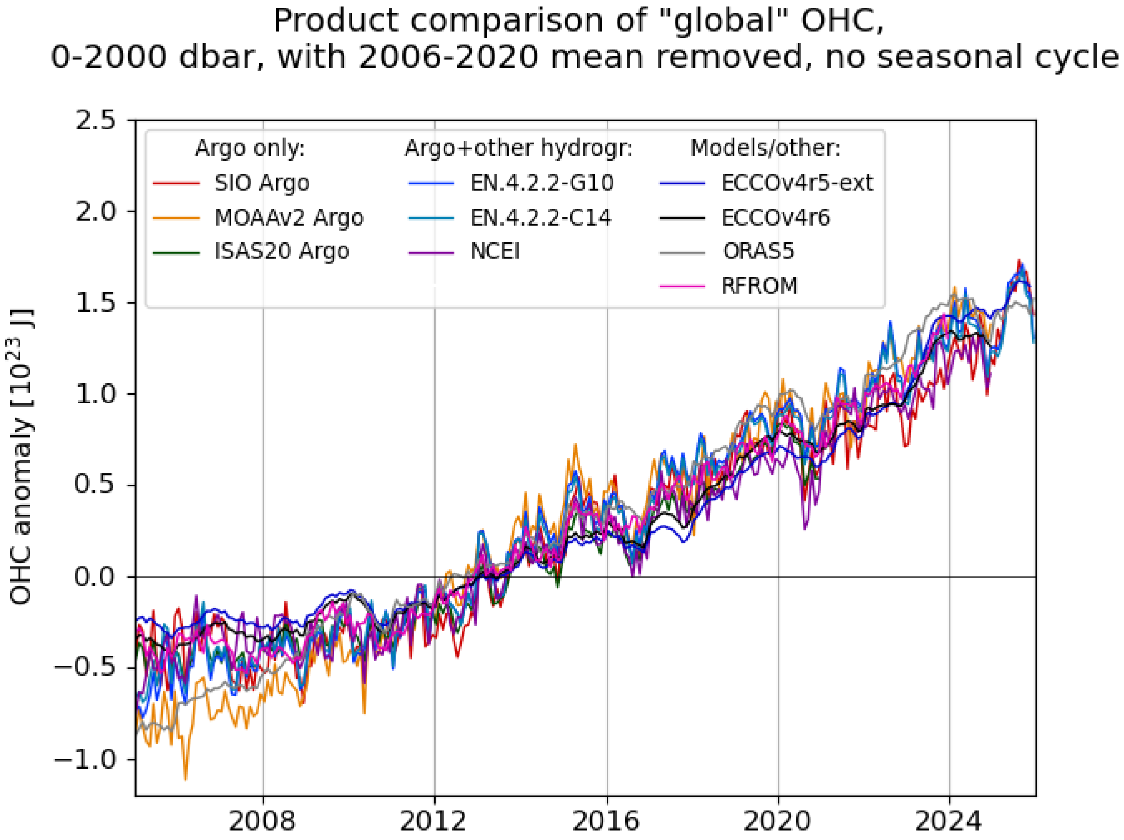
- **Remaining sources of uncertainty in geodetic approach**
  - **Corrections to input satellite data**, e.g. trends in gravimetry observations (GRACE/GRACE-FO)
  - **Computation of effective alpha** (how we get from steric height → ocean heat content), uncertainty from:
    - Differences in temperature/salinity trends and variability of **source datasets**; especially in their vertical/spatial structure
    - Regions where OHC and steric height **correlation is weak or negative** (e.g., NE Atlantic)

OHC reconstructions: more time series

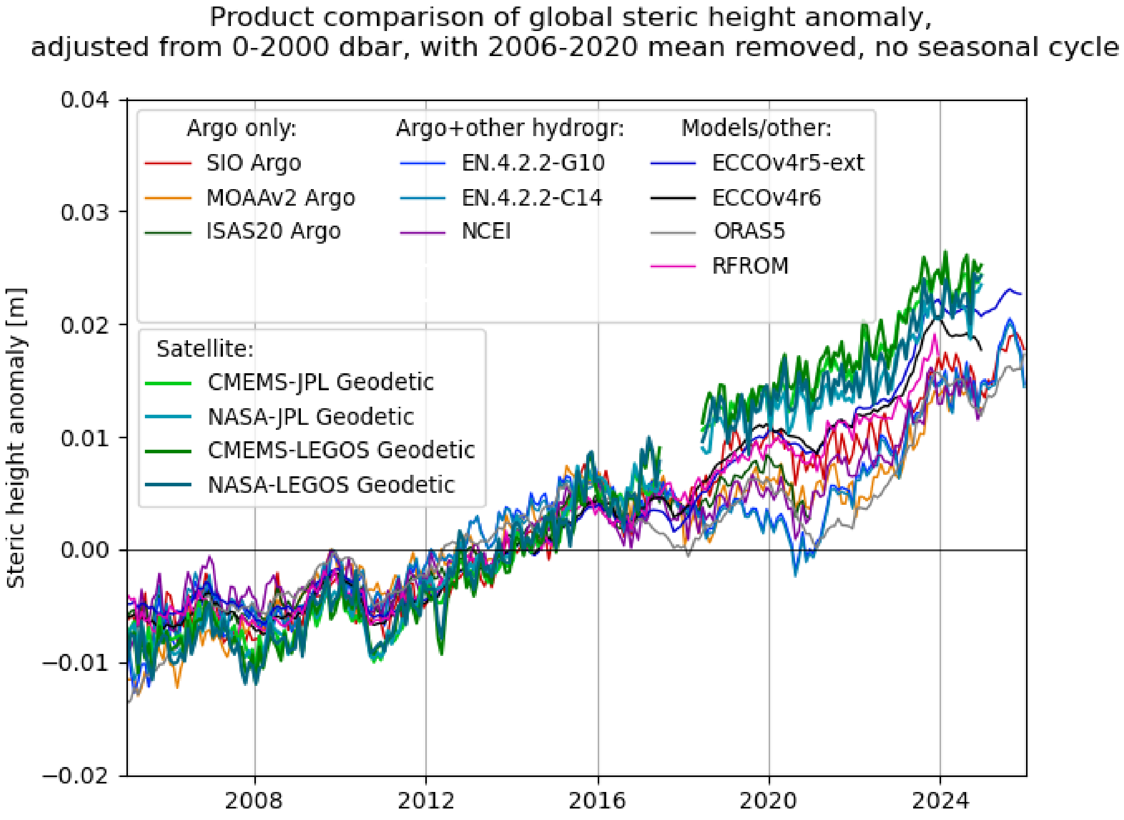


Global OHC from sat reconstr & other product ensembles,
adjusted from 0-2000 dbar, with 2006-2020 mean removed, no seasonal cycle

OHC and steric height: more data comparisons



Product comparison of "global" OHC, 0-2000 dbar, with 2006-2020 mean removed, no seasonal cycle



Product comparison of global steric height anomaly, adjusted from 0-2000 dbar, with 2006-2020 mean removed, no seasonal cycle