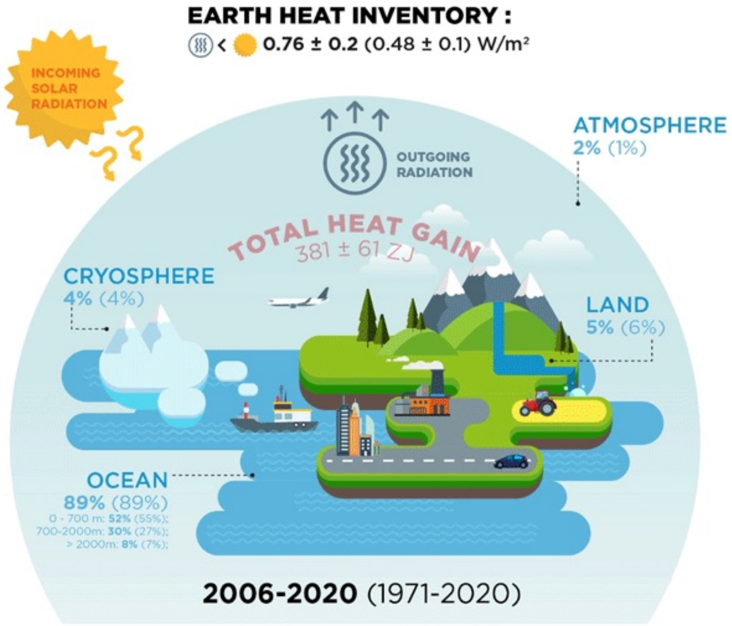
ECCO's perspective on Earth's energy imbalance

ECCO Meeting 2026

29 May 2026, Austin, TX



von Schuckmann et al. 2023

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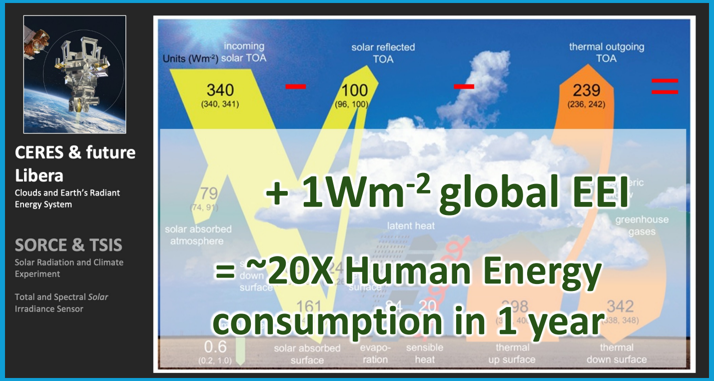
[3]Planet, Haarlem, The Netherlands

Estimating the Circulation and Climate of the Ocean

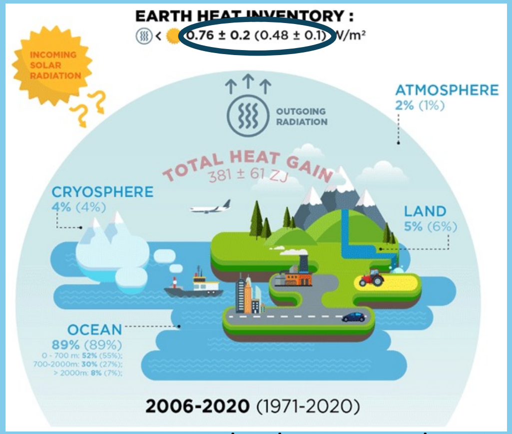
What is Earth’s energy imbalance?

1



Earth’s energy imbalance (EEI), observed at the top-of-the atmosphere, is highly uncertain due to radiometric inaccuracy.

2



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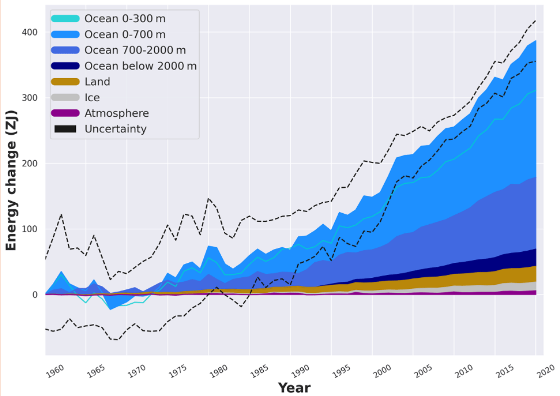
EEI can be constrained by **heat inventory analysis** (of ocean, land, cryosphere, atmosphere).

3



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~90% of the energy imbalance is absorbed by the ocean, so EEI estimates largely hinge on **ocean heat uptake.**

How do we assess ocean heat content and uptake?

Data types	Argo (only)	Argo + XBTs + misc.	Reanalyses	Satellite (geodetic)	State estimate
Example data products	• SIO (Roemmich/ Gilson) • JAMSTEC (MOAAv2) • LOPS (ISAS-series)	• UK Met Office (EN4) • NCEI • RFROM (machine learning)	• ECMWF (ORAS5) • Copernicus (GLORYS12)	• Steric height from altimetry (reference series) minus GRACE-series	• ECCO (v4r5 and v4r6 most recent)
Pros	• Consistent in-situ observing platform	• Includes more in-situ data, longer time series	• “Some” physical constraints (but weak)	• More complete, consistent spatial coverage	• **Strong physical constraints help with data inhomogeneities**
Cons	• Top 2000 m only for most of the record • Instrument biases (e.g. salinity drift) • **Unphysical artifacts from gridding**	• Heavily weighted to Argo recently • XBTs also have biases (fall rate) • **Unphysical artifacts from gridding**	• **Not very good at handling inhomogeneities in data (e.g. beginning of Argo)**	• **SSH and mass need to be corrected (for GIA, GRD, other effects)** • **Need to assume vertical structure (effective alpha)**	• May be “conservative” in estimating changes/variability of ocean state

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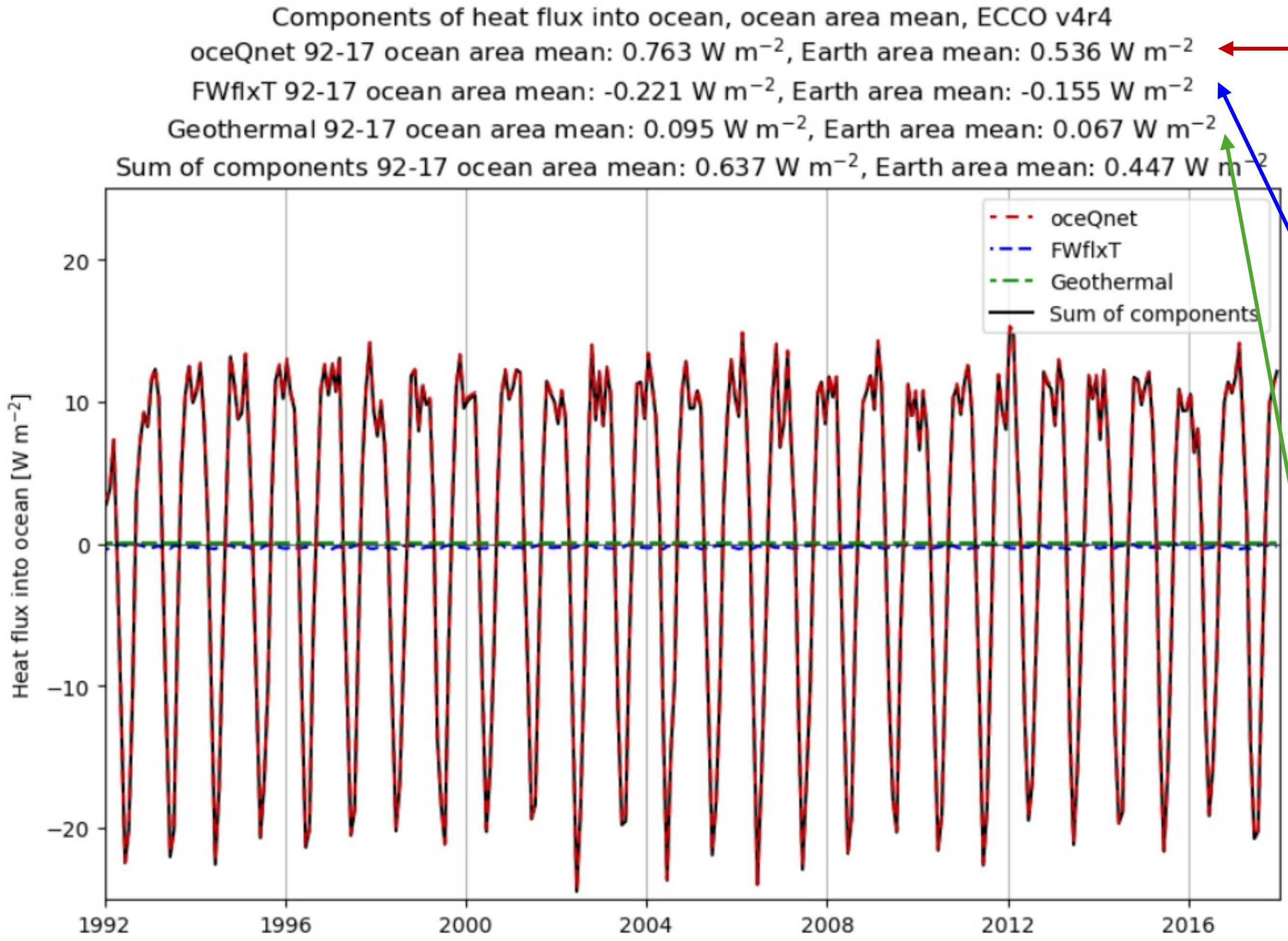
- **In-situ observations are direct, but inhomogeneous in coverage and subject to biases**
- **Satellite observations have better spatial coverage, but need to be corrected to obtain steric height, which is still not temperature/OHC**
- **ECCO can be a valuable tool to resolve data inhomogeneities, and understand the relationship between steric height and temperature/OHC**

Let’s look at what ECCO tells us about…

- **The ocean’s heat budget**
- **OHC trends, acceleration, variability compared to other data products**
- **How to infer ocean heat content/uptake from steric height (supporting the satellite-based method of inferring OHC)**
- **Plus brief plug for some Python-based ECCO tools at the end!**

Ocean’s heat budget (in ECCOv4r4)

For more info (and a Jupyter notebook to do this yourself), check out this tutorial!



Components of heat flux into ocean, ocean area mean, ECCO v4r4
oceQnet 92-17 ocean area mean: 0.763 W m^{-2}, Earth area mean: 0.536 W m^{-2}
FWflxT 92-17 ocean area mean: -0.221 W m^{-2}, Earth area mean: -0.155 W m^{-2}
Geothermal 92-17 ocean area mean: 0.095 W m^{-2}, Earth area mean: 0.067 W m^{-2}
Sum of components 92-17 ocean area mean: 0.637 W m^{-2}, Earth area mean: 0.447 W m^{-2}

- oceQnet includes all heat fluxes (radiative, latent, sensible) through the ocean surface – that do not involve a mass flux
    - This is the only heat flux into/out of the ocean in most models
- FWflxT is the heat flux associated with the surface freshwater mass flux: on average, water added to the ocean (from precip/runoff) is cooler than water evaporated
    - NOT the same as latent flux!
    - Reduces ocean heat uptake by ~25% in ECCOv4r4; net transfer of heat to atmosphere
- Geothermal flux (spatially-varying but no change in time)
    - Increases ocean heat, ~10-15% of total ocean heat uptake

Ocean's heat budget (in ECCOv4r4)

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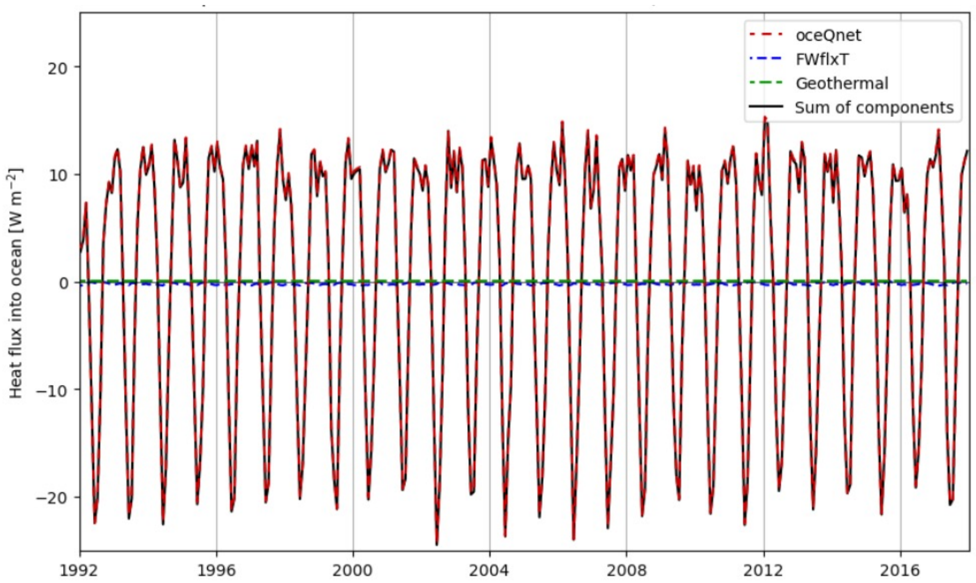
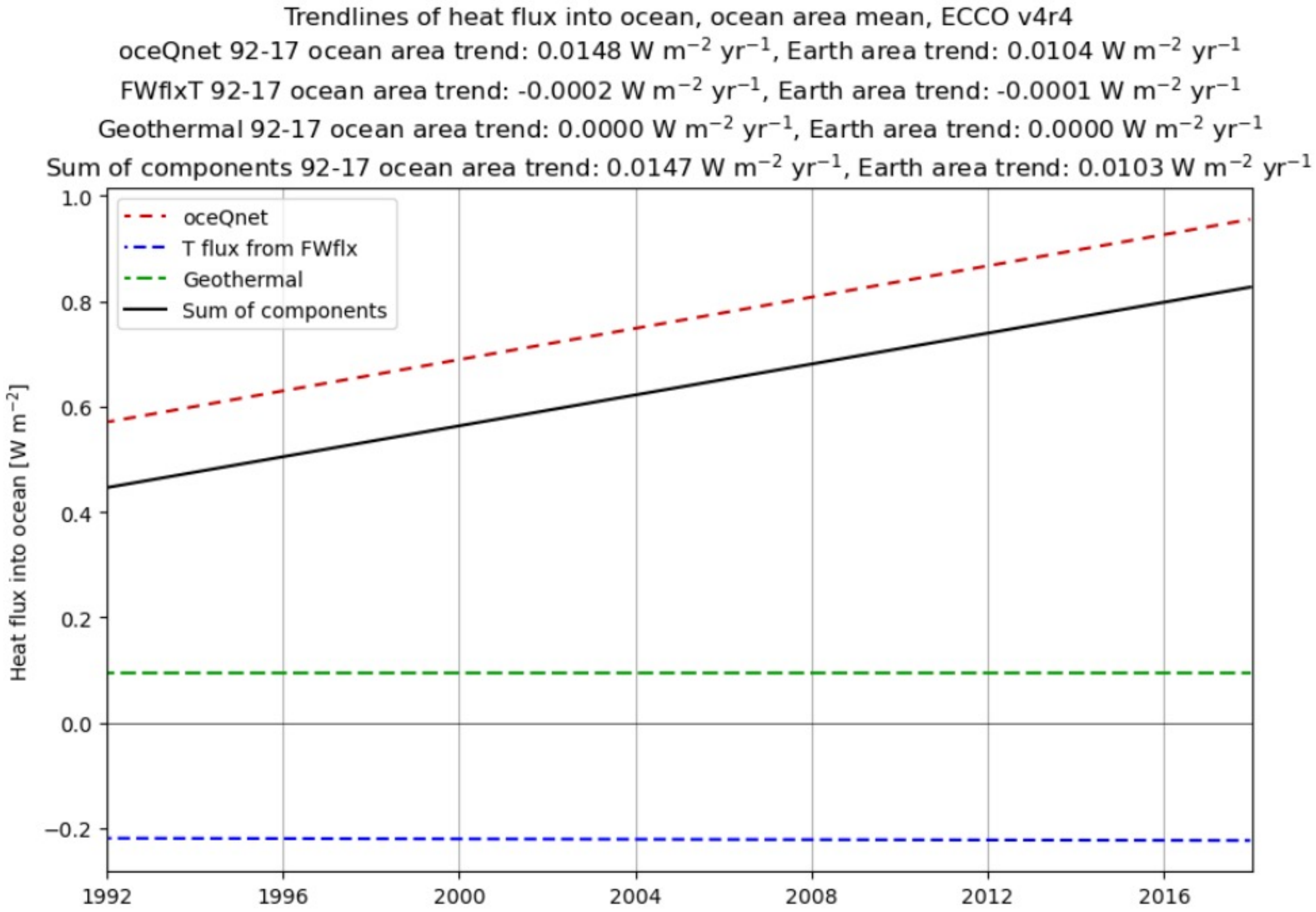
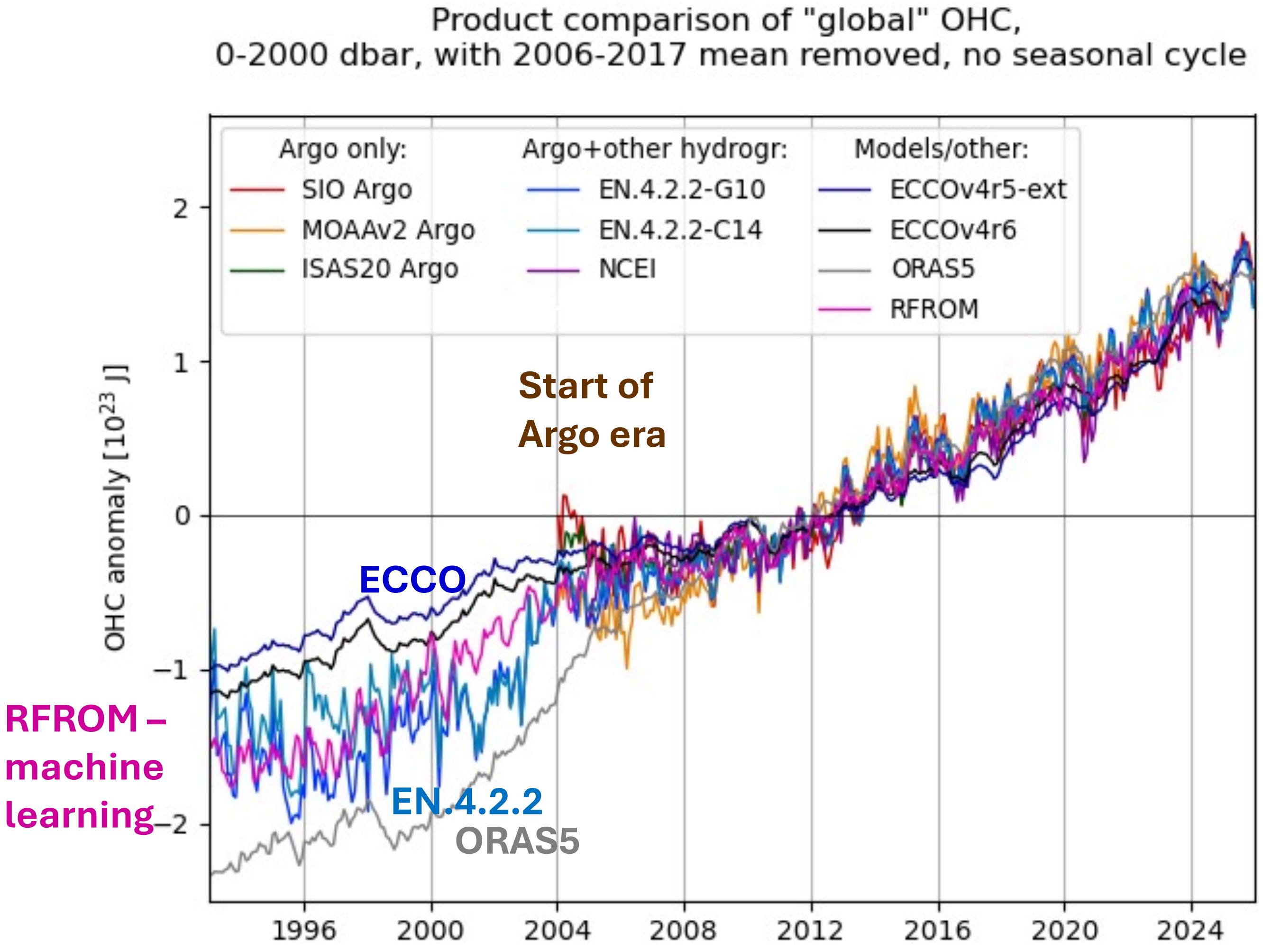




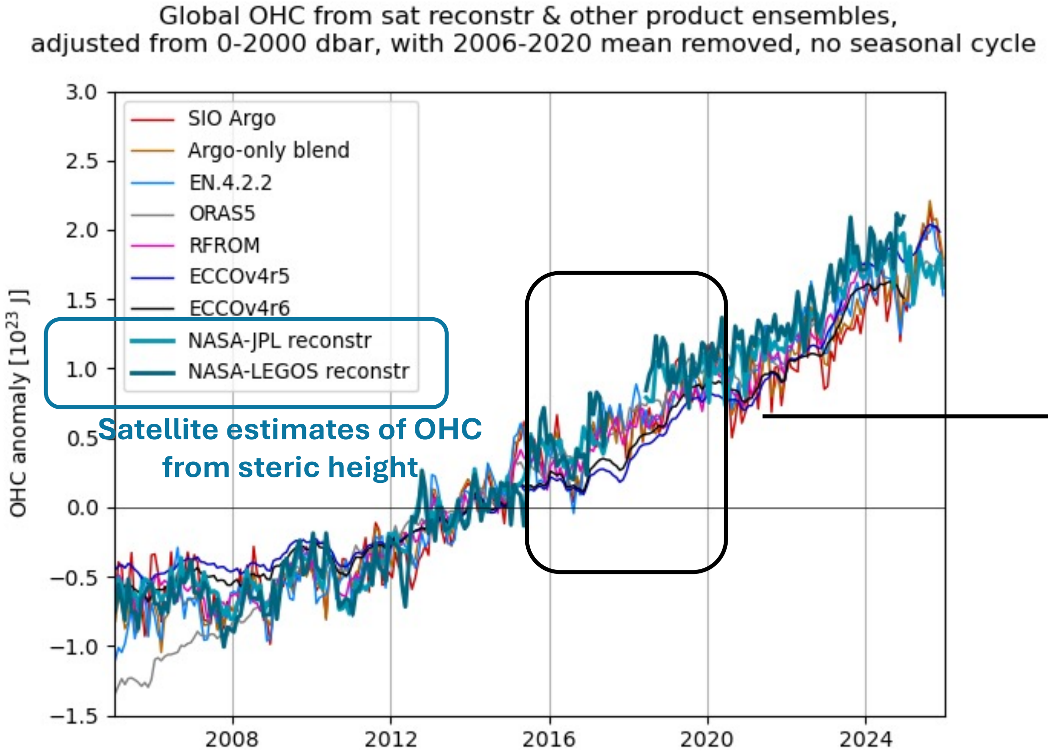
- Only oceQnet contributes meaningfully to the trend in ocean heat uptake (i.e., the ocean heat content acceleration), at least according to ECCOv4r4

Global ocean heat content: ECCO in context

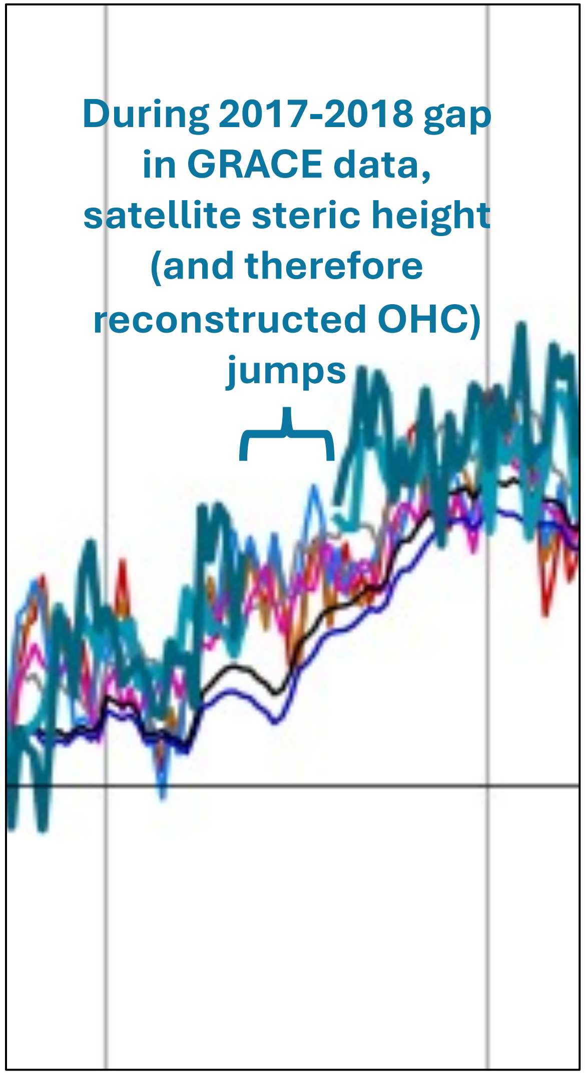


- Before the mid-2000s (start of Argo period), available OHC estimates are widely divergent!
- ECCO avoids an OHC “jump” that many other products have as Argo floats start to be deployed

Global ocean heat content: “The kink”

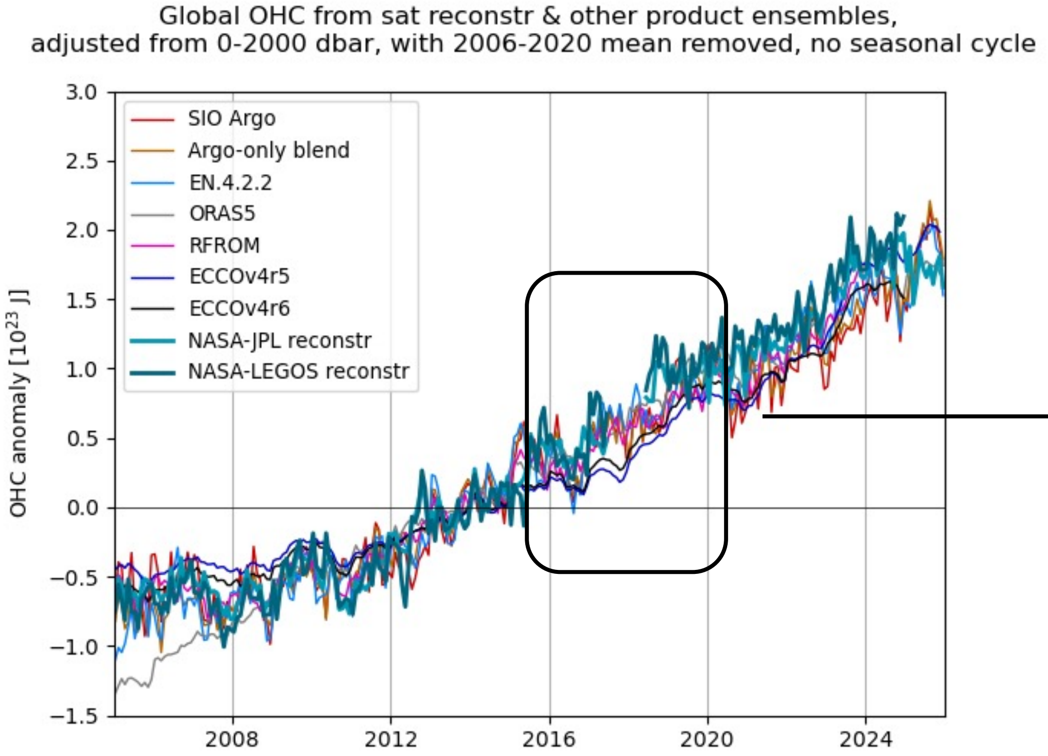


Satellite estimates of OHC from steric height

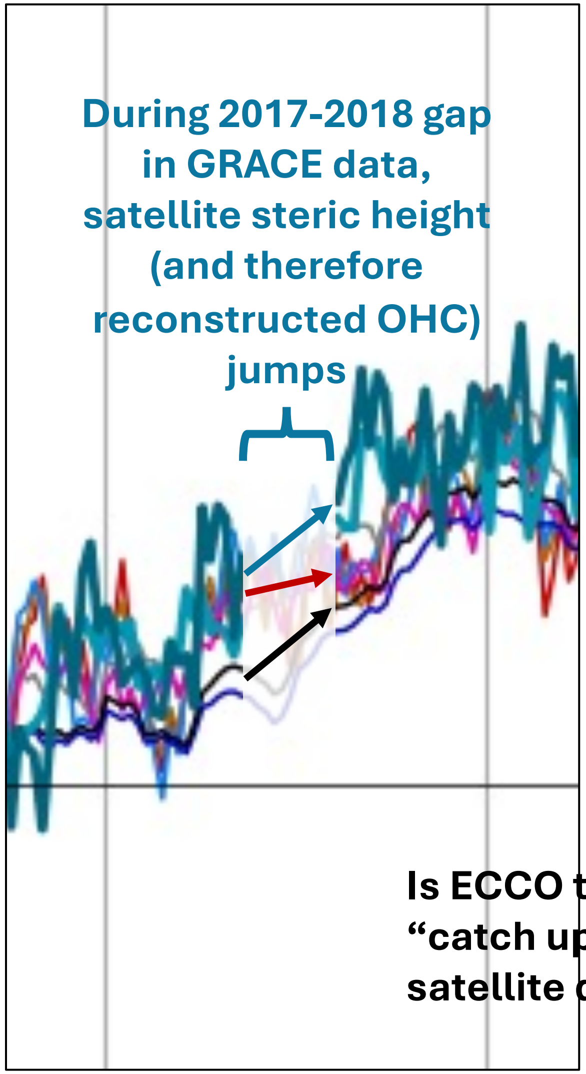


During 2017-2018 gap in GRACE data, satellite steric height (and therefore reconstructed OHC) jumps

Global ocean heat content: “The kink”



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



During 2017-2018 gap in GRACE data, satellite steric height (and therefore reconstructed OHC) jumps

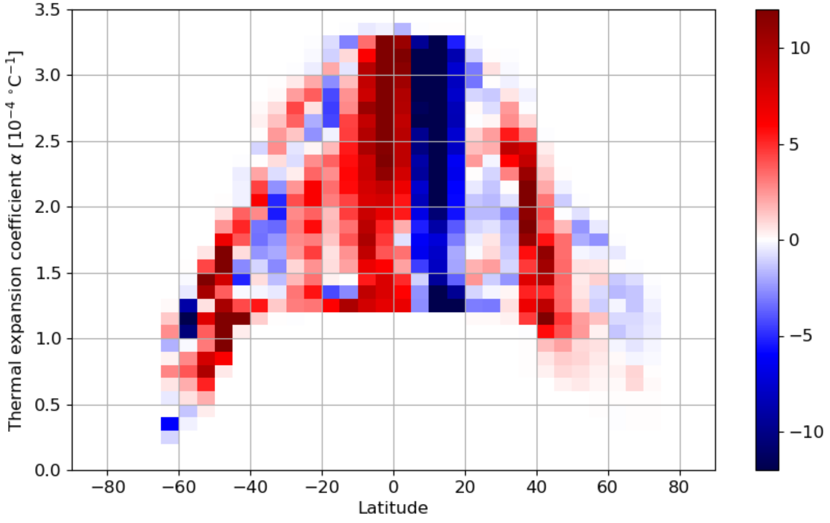
Argo/in-situ OHC does not rise substantially until end of 2018 (El Niño)

Is ECCO trying to “catch up” to satellite data?

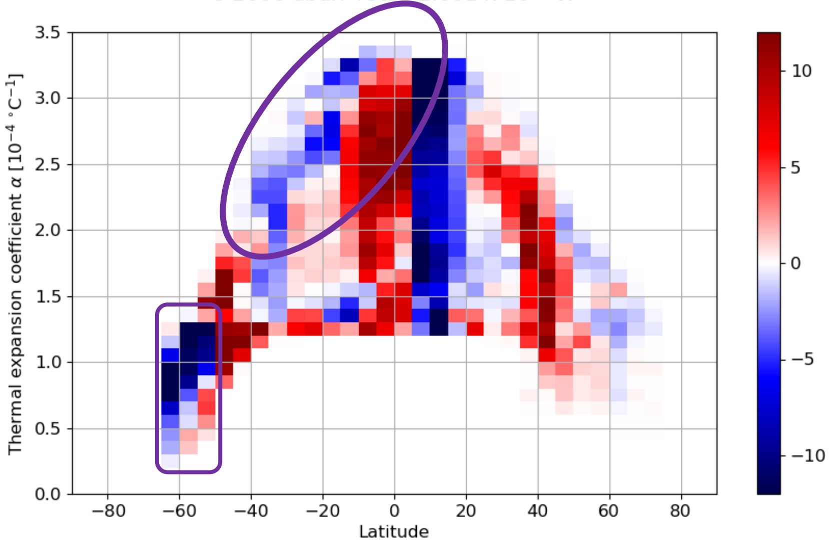
Global ocean heat content: “The kink”

Higher alpha
(generally
warmer,
shallower)

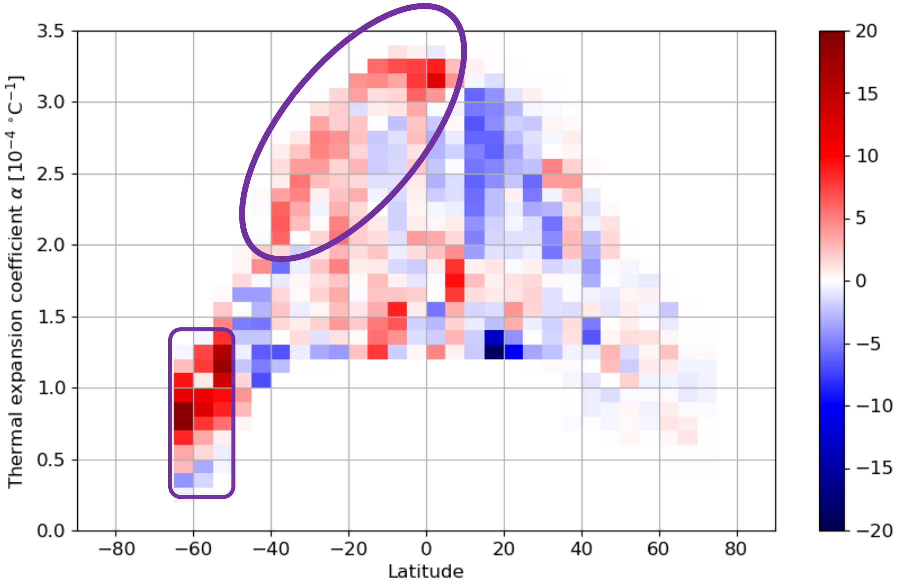
Lower alpha
(generally
colder,
deeper)



2017-2018 OHC trend [10^{12} W] in ECCOv4r6 alpha and latitude bins, global, 0-2000 dbar. Total: 5.063 x 10^{14} W



2017-2018 OHC trend [10^{12} W] in RG_Argo alpha and latitude bins, global, 0-2000 dbar. Total: 2.601 x 10^{14} W

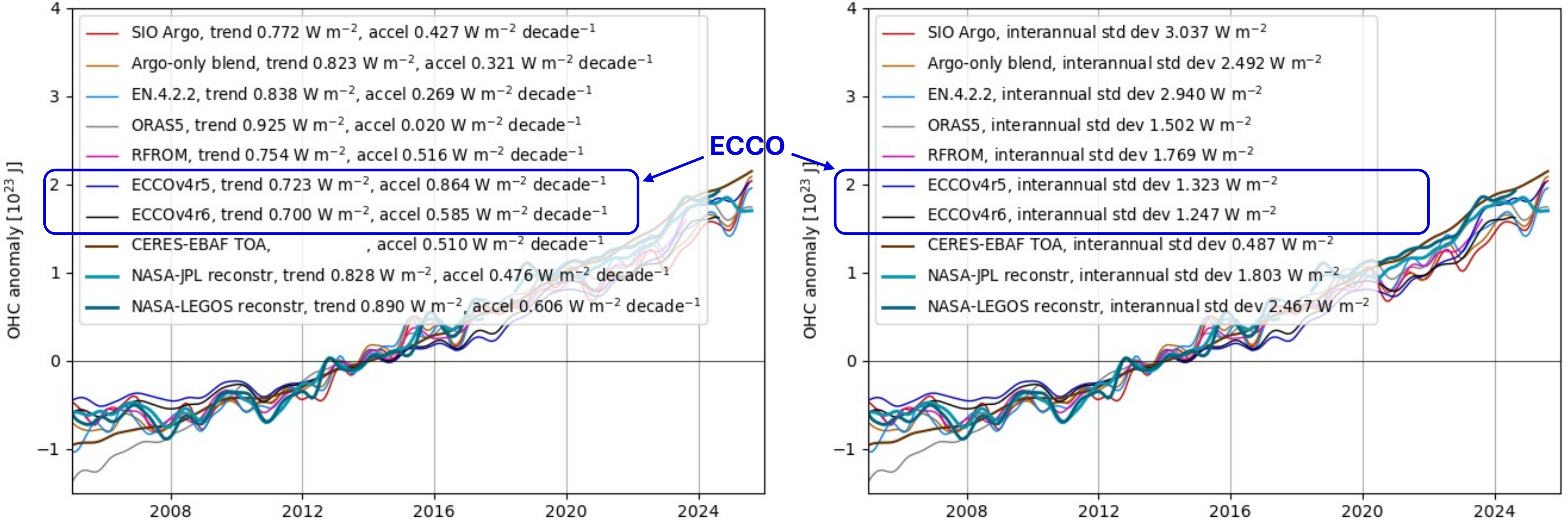


2017-2018 global OHC trend anomaly [10^{12} W], ECCOv4r6_minus_RG_Argo, in alpha and latitude bins, 0-2000 dbar. Total: 2.462 x 10^{14} W

Argo cooling in Southern Ocean (and Southern Hemisphere near-surface) is largely absent in ECCO

Global ocean heat content: ECCO in context

Global OHC, low-passed for periods > 12 months, no seasonal cycle



Trend and acceleration (2005-2024)

Interannual variability (2005-2024)

- Recent ECCO releases have OHC trends **close to (slightly lower than)** other observations and models
- ECCO accelerations **higher** than in-situ observation-based products, though **closer** to satellite and machine learning products
- Interannual variability in ECCO is **lower** than most other products

What if we need to get OHC from steric height (the satellite approach)?

What is "effective" α?

- Satellites provide steric height variations, but that is not sufficient to determine OHC, i.e., the vertical integral of temperature $\int \Delta T dz$
- 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)

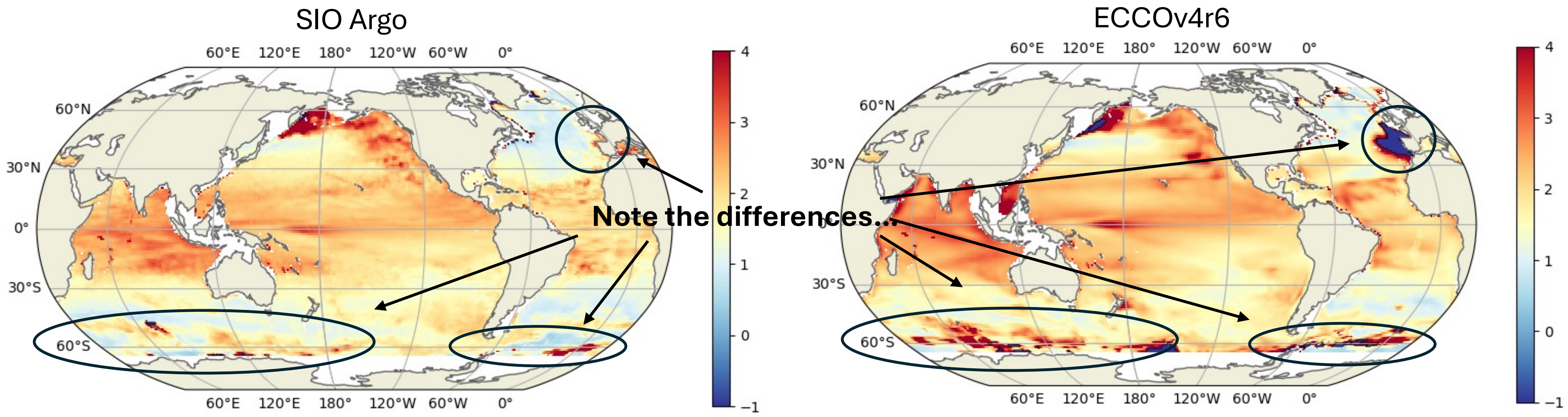
$$\Delta h_{\text{steric}} \approx \int (\alpha \Delta T - \beta \Delta S)\, dz \approx \alpha_{\text{eff}} \int \Delta T\, dz$$

Δ indicates anomaly (time mean and seasonal cycle removed)

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

vertical mean ΔT

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



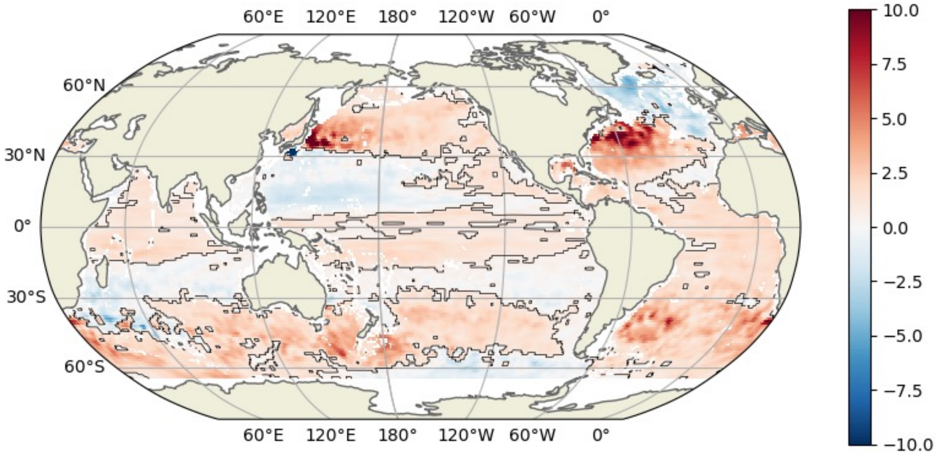
SIO Argo

ECCOv4r6

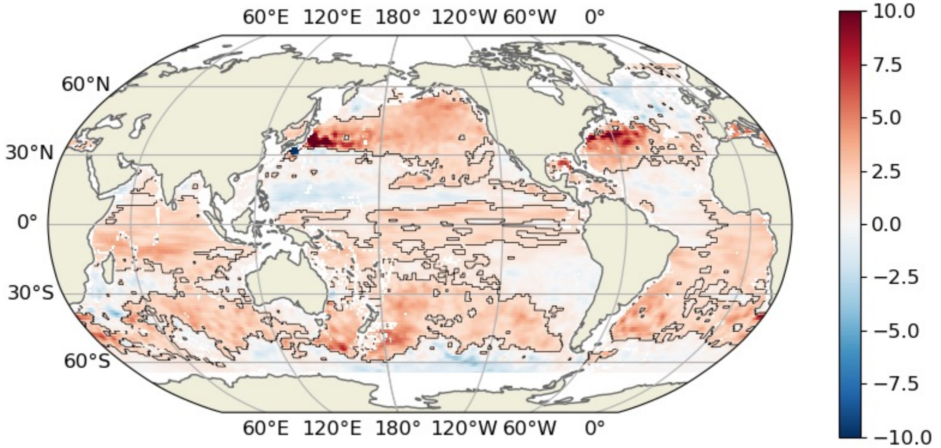
Note the differences...

Why the differences in effective alpha, SIO Argo vs. ECCOv4r6?

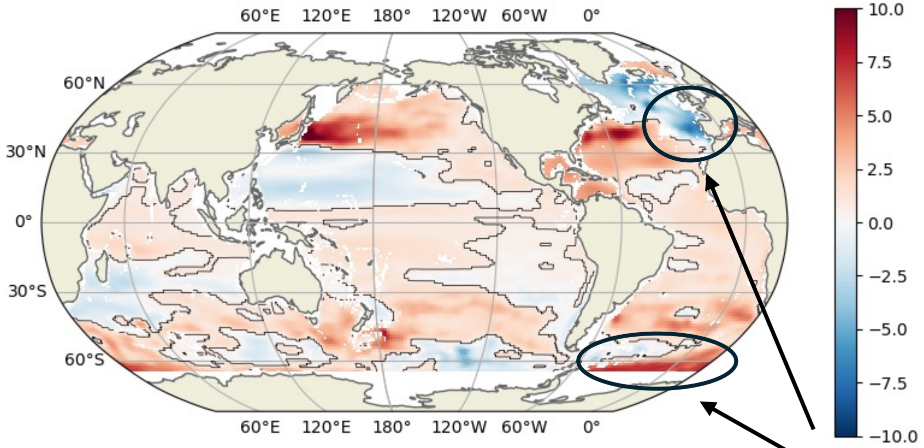
OHC 2005-2024 trend,
SIO_Argo [W m^{-2}]
Global mean (shown in contour): 0.741 W m^{-2}



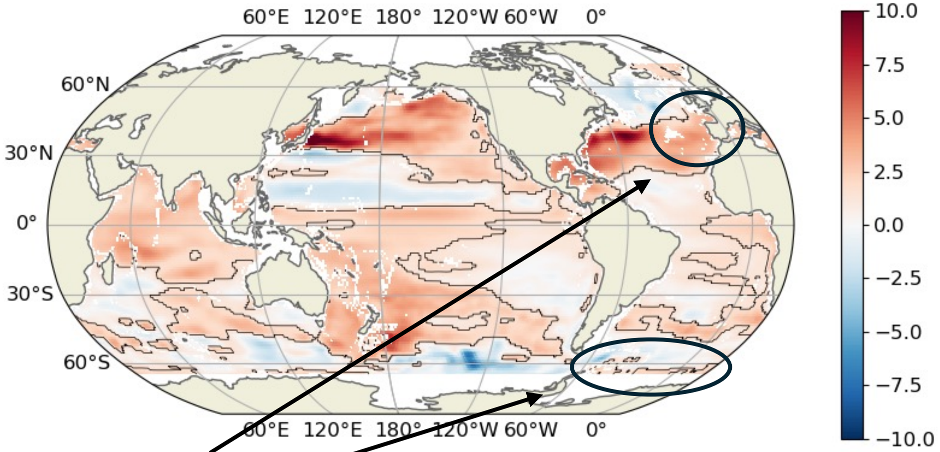
steric_hgt_anom 2005-2024 trend, SIO_Argo [mm yr^{-1}]
Global mean (shown in contour): 1.364 mm yr^{-1}



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

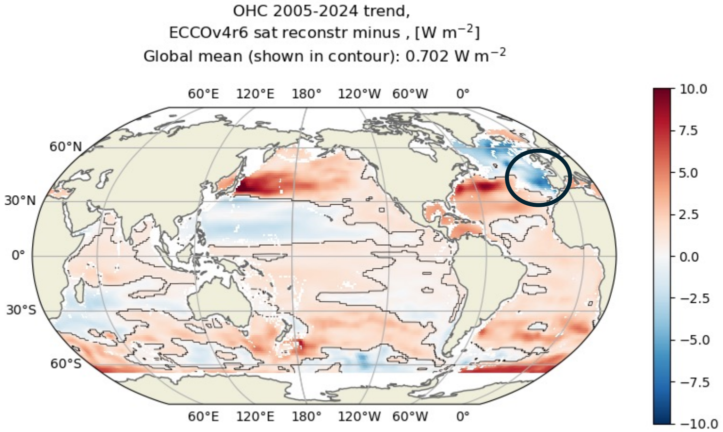


steric_hgt_anom 2005-2024 trend, ECCOv4r6 [mm yr^{-1}]
Global mean (shown in contour): 1.519 mm yr^{-1}



The ECCO OHC and steric height trends diverge in some areas…

Why the differences in effective alpha, SIO Argo vs. ECCOv4r6?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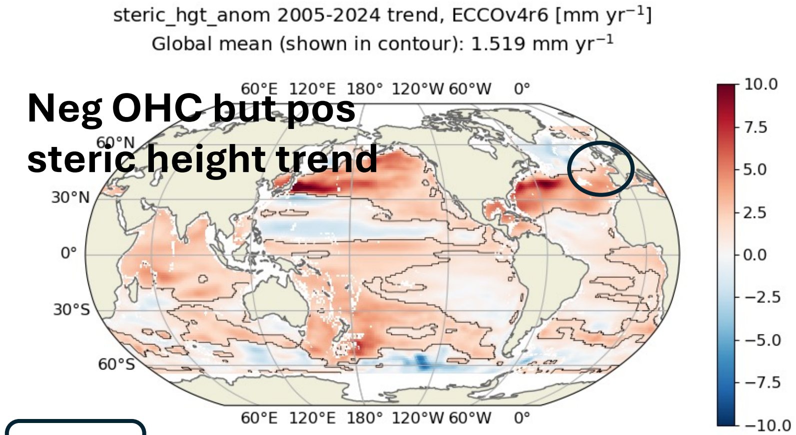
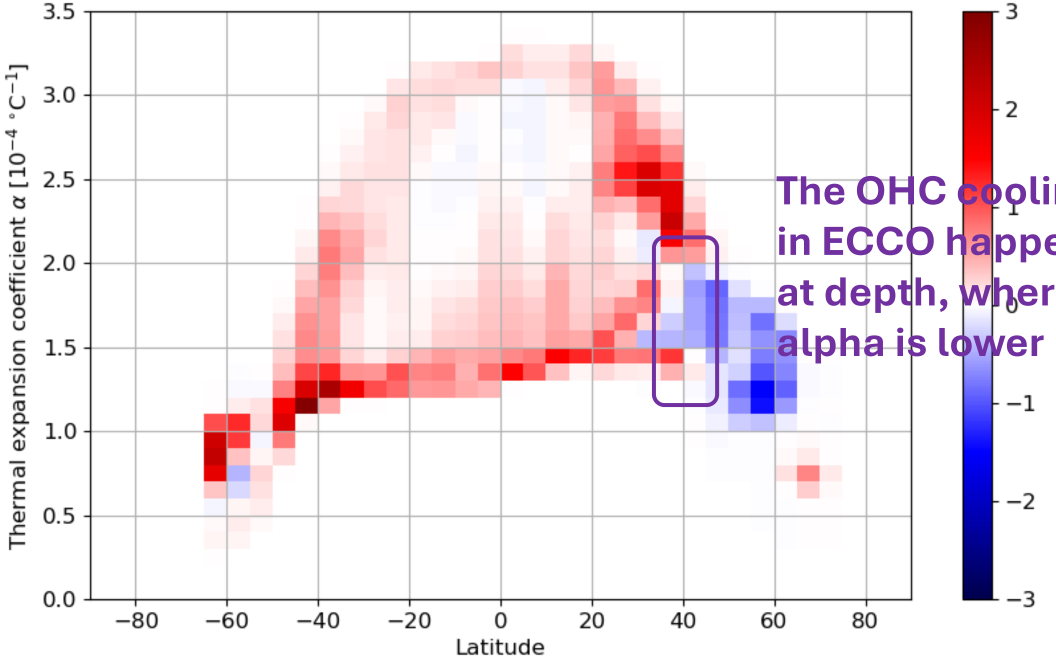

steric_hgt_anom 2005-2024 trend, ECCOv4r6 [mm yr^{-1}]
Global mean (shown in contour): 1.519 mm yr^{-1}

Neg OHC but pos steric height trend

Higher alpha (generally warmer, shallower)

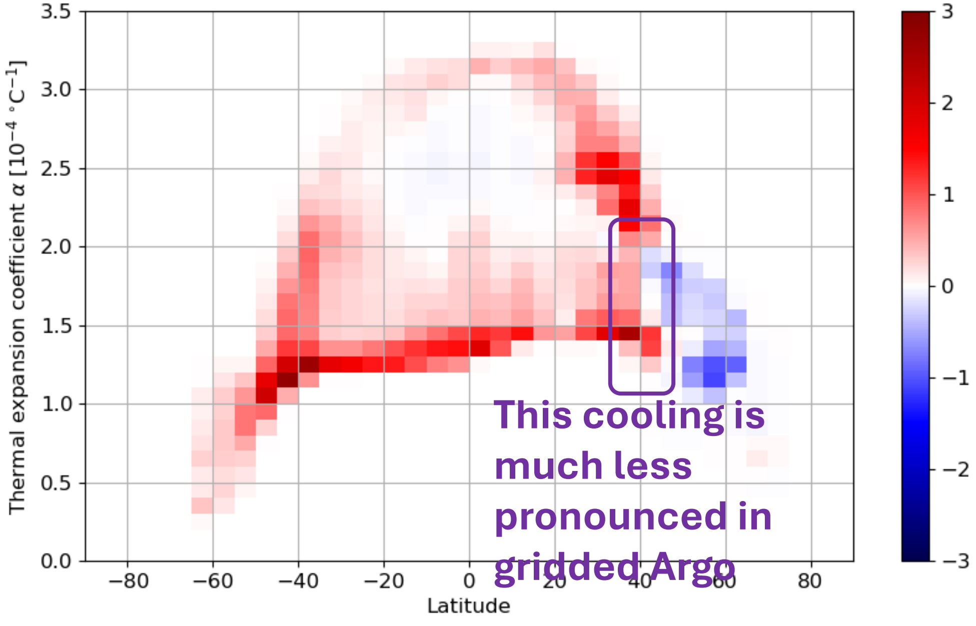
Lower alpha (generally colder, deeper)

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

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



This cooling is much less pronounced in gridded Argo

A few takeaways

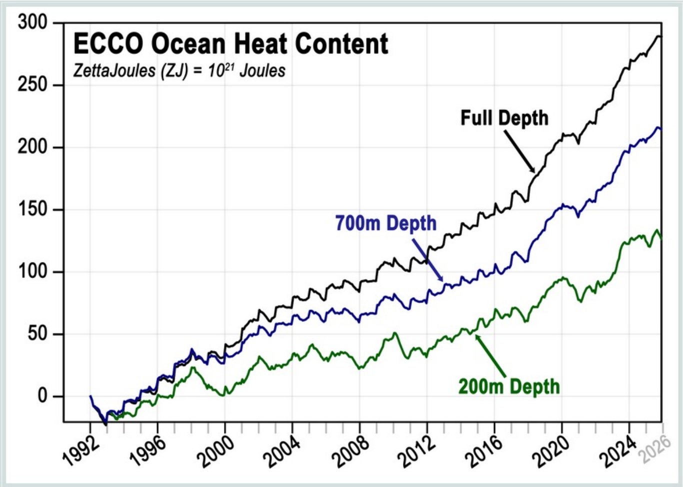
- ECCO provides a uniquely valuable perspective on the evolution of ocean heat content since the 1990s – assessing ocean heat content was one key reason for ECCO's development!

- ECCO includes the thermal impact of surface freshwater (mass) fluxes as well as geothermal fluxes, which are often neglected in ocean models

- ECCO's physical consistency and stability also make it a useful tool in the definition of the thermal expansion coefficient "effective alpha"
  - Though substantial differences with gridded Argo and other data sources still merit further study

- For more information (and StoryMaps!),
- it is worth checking out this page:

https://ecco-group.org/ohc.htm

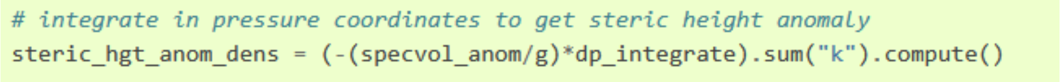


Quick update: ECCO v4 Python Tutorial

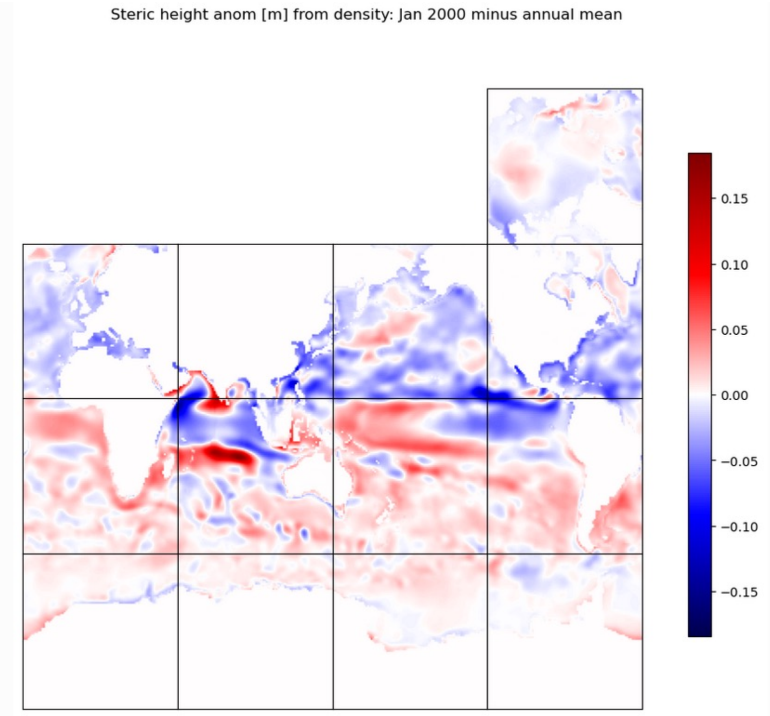
- https://ecco-v4-python-tutorial.readthedocs.io

- **Jupyter notebook tutorials, showing how to compute budgets, derivatives, and other ocean state quantities of interest with Python code**

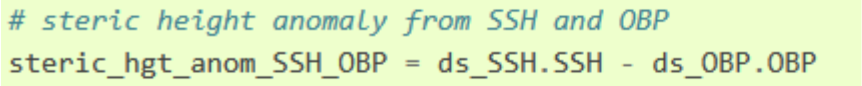
- **Some new tutorials posted recently – steric height from SSH – OBP, gradient and curl in ECCO, volume budget extension to close sea level budget**



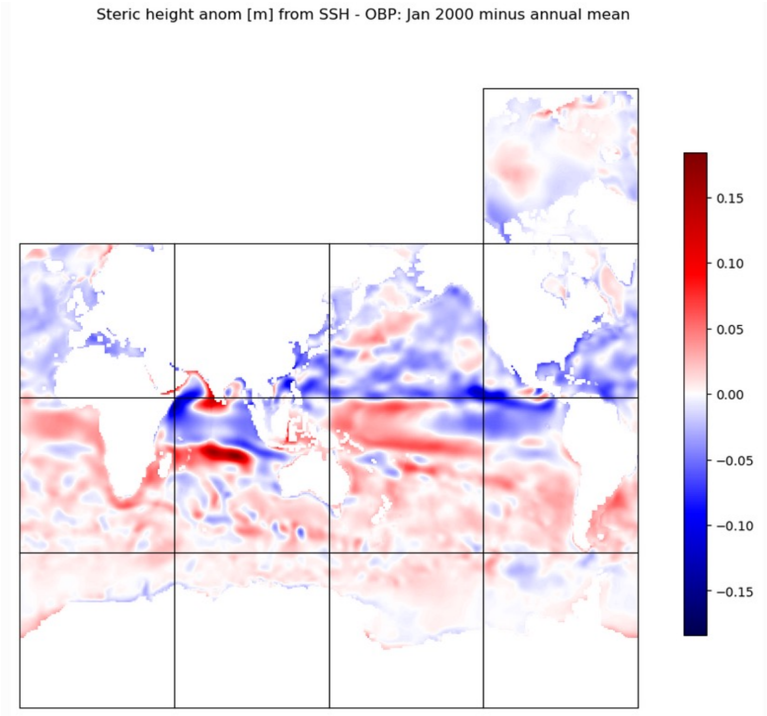
```
# integrate in pressure coordinates to get steric height anomaly
steric_hgt_anom_dens = (-(specvol_anom/g)*dp_integrate).sum("k").compute()
```



Steric height anom [m] from density: Jan 2000 minus annual mean



```
# steric height anomaly from SSH and OBP
steric_hgt_anom_SSH_OBP = ds_SSH.SSH - ds_OBP.OBP
```



Steric height anom [m] from SSH - OBP: Jan 2000 minus annual mean

Quick update: *ecco access* Python package

- https://ecco-access.readthedocs.io ← **Documentation/tutorials here!**

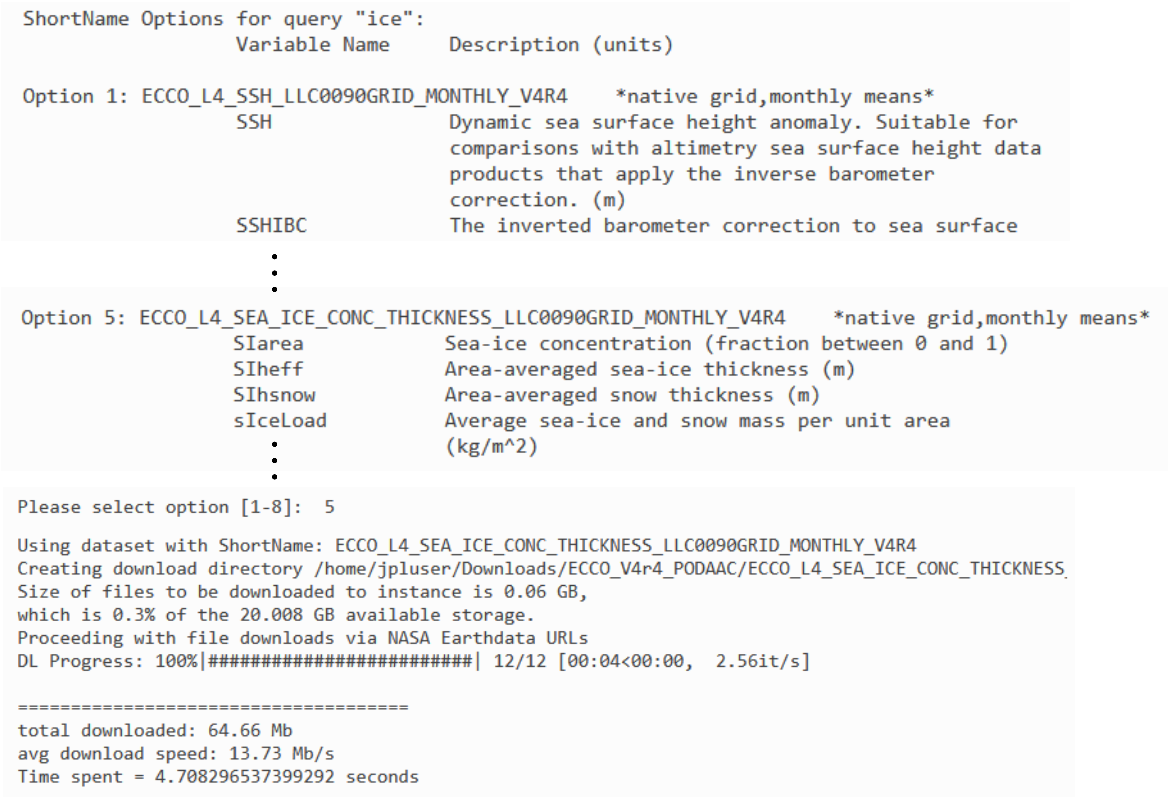
- ***ecco_access*** **utilities (earlier part of the ecco_v4_py package) are now a standalone package: install using conda or pip!** `conda install ecco_access` `pip install ecco-access`

- **Query ECCO variables and download associated datasets from NASA Earthdata; subset in time and space; also can direct access ECCO output on AWS Cloud**

```python
import ecco_access as ea

# identify user's home directory
user_home_dir = expanduser('~')

# query variable lists for "ice" and open the selected result as an xarray dataset
ds_seaice_conc = ea.ecco_podaac_to_xrdataset('ice',grid='native',time_res='monthly',\
                                              StartDate='2007-01',EndDate='2007-12',\
                                              mode='download_ifspace',\
                                              download_root_dir=\
                                                join(user_home_dir,'Downloads','ECCO_V4r4_PODAAC'),
                                              max_avail_frac=0.5)
```



```
ShortName Options for query "ice":
                 Variable Name     Description (units)

Option 1: ECCO_L4_SSH_LLC0090GRID_MONTHLY_V4R4    *native grid,monthly means*
                 SSH               Dynamic sea surface height anomaly. Suitable for
                                   comparisons with altimetry sea surface height data
                                   products that apply the inverse barometer
                                   correction. (m)
                 SSHIBC            The inverted barometer correction to sea surface
                    ⋮

Option 5: ECCO_L4_SEA_ICE_CONC_THICKNESS_LLC0090GRID_MONTHLY_V4R4    *native grid,monthly means*
                 SIarea            Sea-ice concentration (fraction between 0 and 1)
                 SIheff            Area-averaged sea-ice thickness (m)
                 SIhsnow           Area-averaged snow thickness (m)
                 sIceLoad          Average sea-ice and snow mass per unit area
                    ⋮              (kg/m^2)

Please select option [1-8]:  5

Using dataset with ShortName: ECCO_L4_SEA_ICE_CONC_THICKNESS_LLC0090GRID_MONTHLY_V4R4
Creating download directory /home/jpluser/Downloads/ECCO_V4r4_PODAAC/ECCO_L4_SEA_ICE_CONC_THICKNESS_
Size of files to be downloaded to instance is 0.06 GB,
which is 0.3% of the 20.008 GB available storage.
Proceeding with file downloads via NASA Earthdata URLs
DL Progress: 100%|########################| 12/12 [00:04<00:00,  2.56it/s]

=====================================
total downloaded: 64.66 Mb
avg download speed: 13.73 Mb/s
Time spent = 4.708296537399292 seconds
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