The Estimating the Circulation and Climate of the Ocean (ECCO) Central Estimate

A Multi-decadal, Coupled Ocean Reanalysis

Ian Fenty

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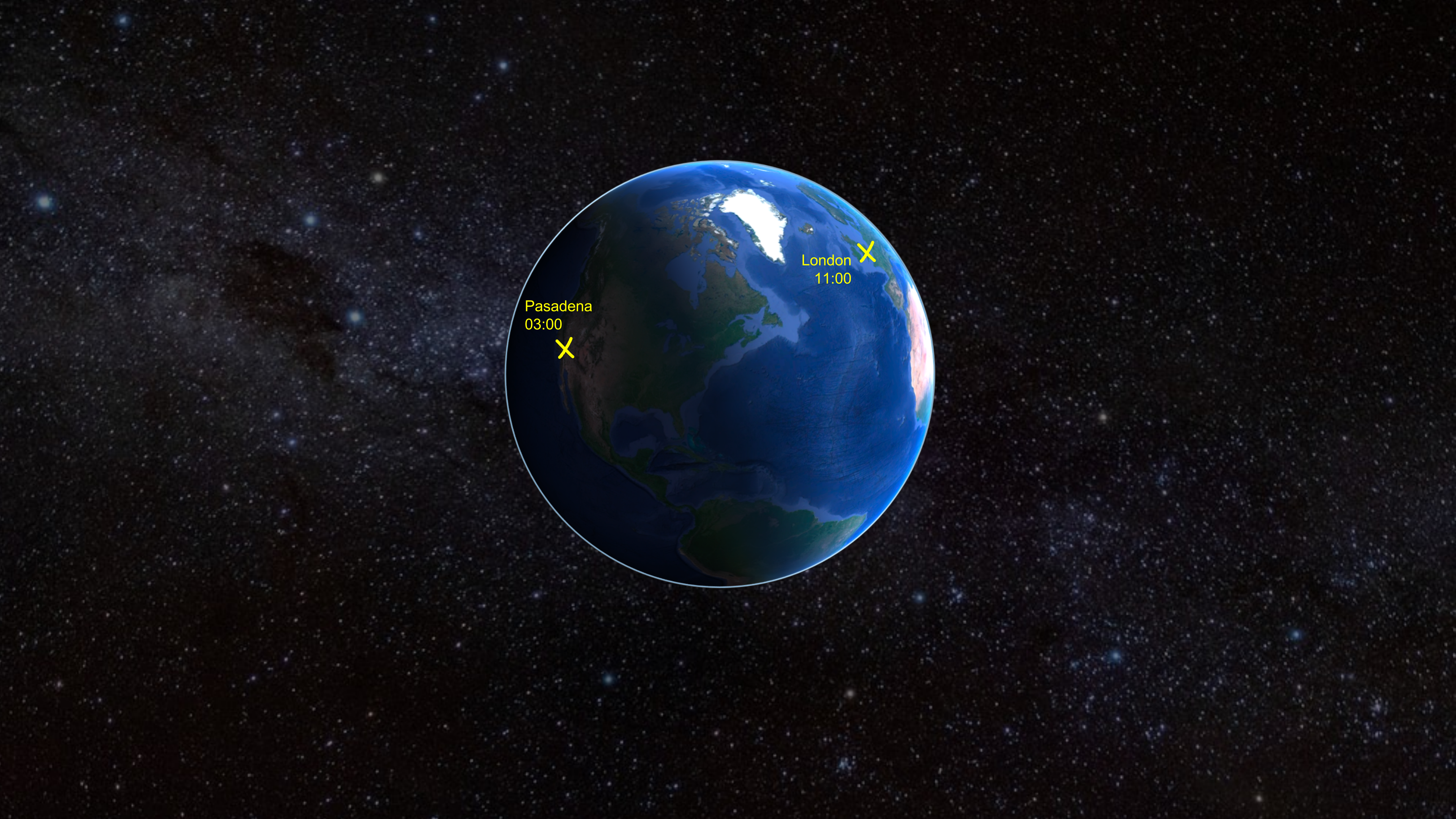

Pasadena
03:00
London
11:00

- **ECCO description**
- Recent developments
- Next steps
- Community resource

Estimating the Circulation and Climate of the Ocean (ECCO)

Heritage and Support

- Initiated in 1999 to synthesize hydrographic data from the World Ocean Circulation Experiment (WOCE) and satellite sea surface height measurements into a complete and coherent description of the ocean.
- Support from NASA’s **Physical Oceanography, Modeling Analysis and Prediction** (MAP), and **Cryosphere Programs**

Main Branches

1) *State Estimates:* assimilation system providing complete, physically-consistent, multi-decadal reconstructions of the full-depth, time-evolving global ocean and sea-ice state (e.g. ocean reanalysis).
2) *High-Resolution Simulations:* pushing frontiers of global ocean numerical modelling to resolve fine-scale ocean dynamics [e.g., submeso-scale permitting global 2km resolution model to support SWOT mission]

Selected Community Use and Outcomes

- Over 1300 publications: 100+ in 2020
- Cloud-based data distribution with NASA’s PO.DAAC
- AGU Fall Meeting & Ocean Sciences Town Halls & Workshops
- Summer schools (first in 2019, next 2023)
- Open source libraries & tutorials

ECCO state estimates "continuously assimilate" data over the entire multi-decadal time-trajectory using the adjoint method (4DVAR)

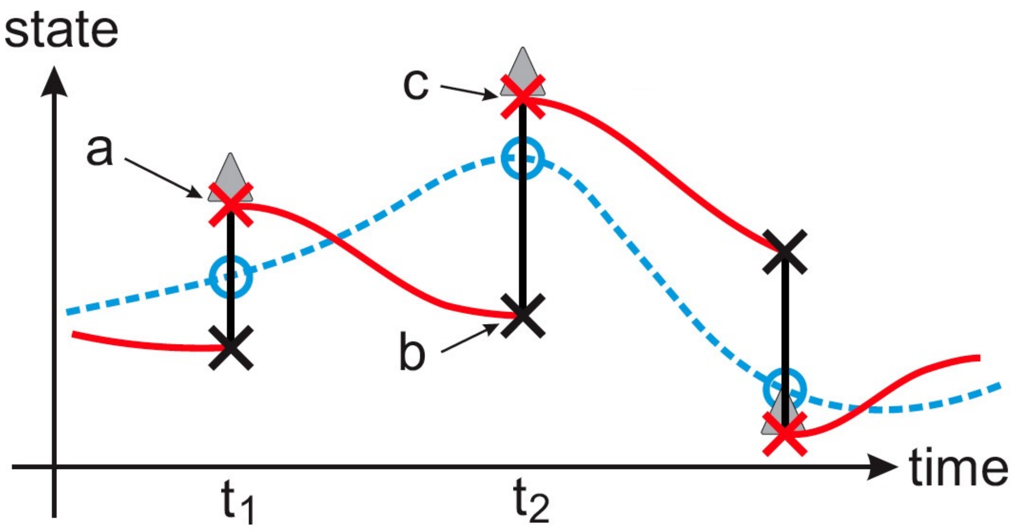
Two general approaches for ocean reanalysis*

Sequential Assimilation: "filtering"

- **Goal**: best possible fit to data, forecast initialization
- **Approach**: adjust the forecasted model state as new data become available
- **conservation laws are not necessarily respected →** time-trajectories may be unphysical
- ***dynamical consistency and property conservation across the analysis step is NOT required***

Continuous Assimilation: "ocean state estimation"

- **Goal**: understand the dynamical evolution of the ocean from past to present
- **Approach**: find optimal trajectory of free-running model that yields best fit to observations over entire simulation window
- **conservation laws are implicitly respected →** time-trajectories are physically-consistent
- ***dynamic consistency and property conservation is required for studying mechanisms of ocean variability on climate timescales***



x : observation (data)
— : sequential assimilation time-trajectory
x : forecast at observation time
--- : state estimate time-trajectory
o : state estimate at observation time

Wunsch and Heimbach (Physica D 2007)
Forget et al. (Geosci. Model Dev. 2015)
Stammer et al. (Annu. Rev. 2016)
Heimbach et al. (Front. Mar. Sci. 2019)
**Moore et al., (Front. Mar. Sci. 2019)*

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ECCO Version 4: a global, multidecadal ocean and sea-ice reanalysis

Numerical model: Massachusetts Institute of Technology general circulation model (**MITgcm**) coupled ocean, sea-ice, ice-shelf model

Adjoint: automatically-derived (Giering et al., 2015)

Horizontal resolution: Ver. 4: 1-deg., Ver. 5 (next): 1/3-deg

Vertical levels: 50 unequally-spaced

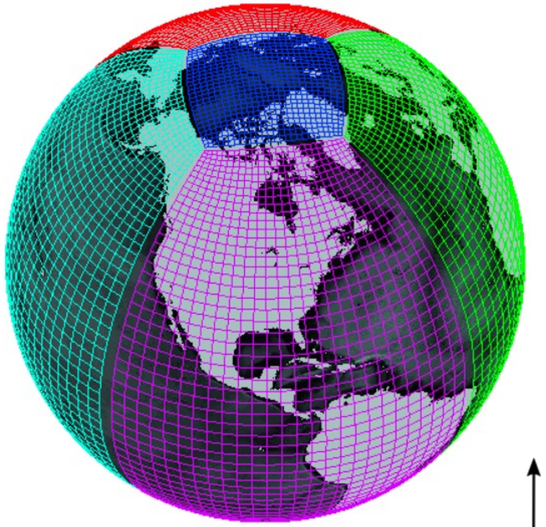
Time window: 1992-2019

First-guess atmospheric state: MERRA-2 from NASA's GMAO (Gelaro et al., 2017).

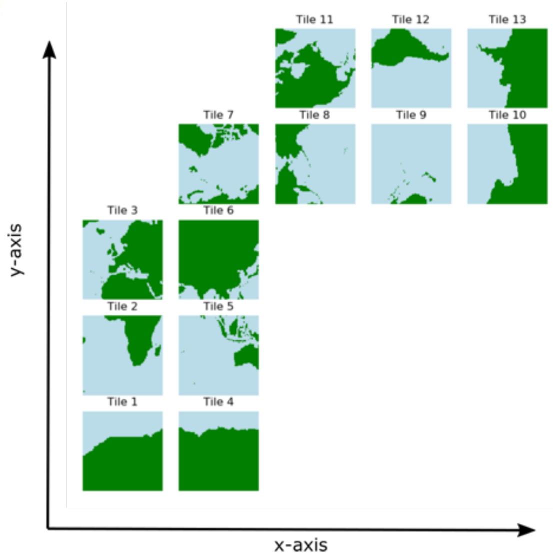
Assimilation notes:

1. model-data misfit cost terms and atmospheric control parameters split: (i) anomalies w.r.t. mean (ii) mean. *Different weights for anomaly and mean cost terms*
2. Space & time proximate *in-situ* data down-weighted to approximate covariance
3. *in-situ* data representation error associated with unresolved dynamics derived from global 2km model

"lat-lon-cap 90"



13 tiles of 90x90x50



Giering, R., et al. (2005). https://doi.org/10.1016/j.future.2004.11.003
Gelaro, R., et al. (2017). https://doi.org/10.1175/jcli-d-16-0758.1

ECCO Version 4: fields provided to the community

Ocean and sea-ice

- T, S^*, $\vec{u}$, η, ρ, Φ
- sea-ice and snow h and c
- 3D fluxes of ocean volume, heat, salt, and momentum
- 2D fluxes of sea-ice and snow volume

Atmosphere & Radiative Fluxes

- Surface T, q, $|u|$, $\vec{\tau}$, and downwelling short and long-wave radiative fluxes
- Air–sea ice–ocean fluxes of heat, moisture, energy, and momentum (bulk formulae)

Subgrid-scale mixing parameters

- 3D GM κ and Redi κ
- 3D vertical diffusivity

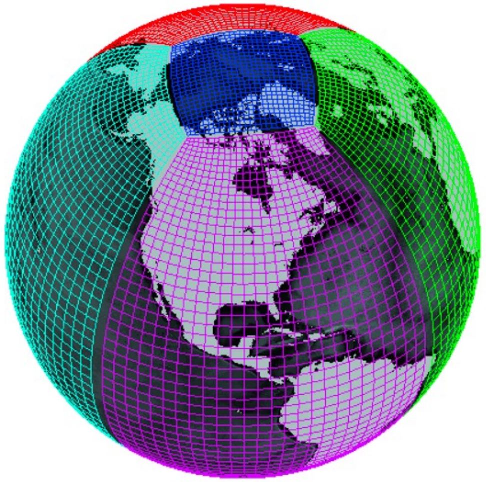
red : model control parameters

**Initial T and S are model control parameters*

Fields are provided on two grids

0.5° lat-lon

"lat-lon-cap 90"



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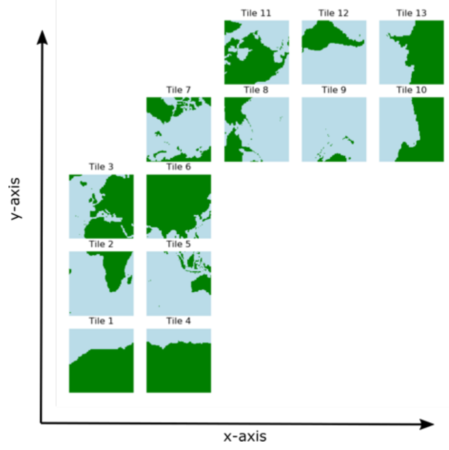
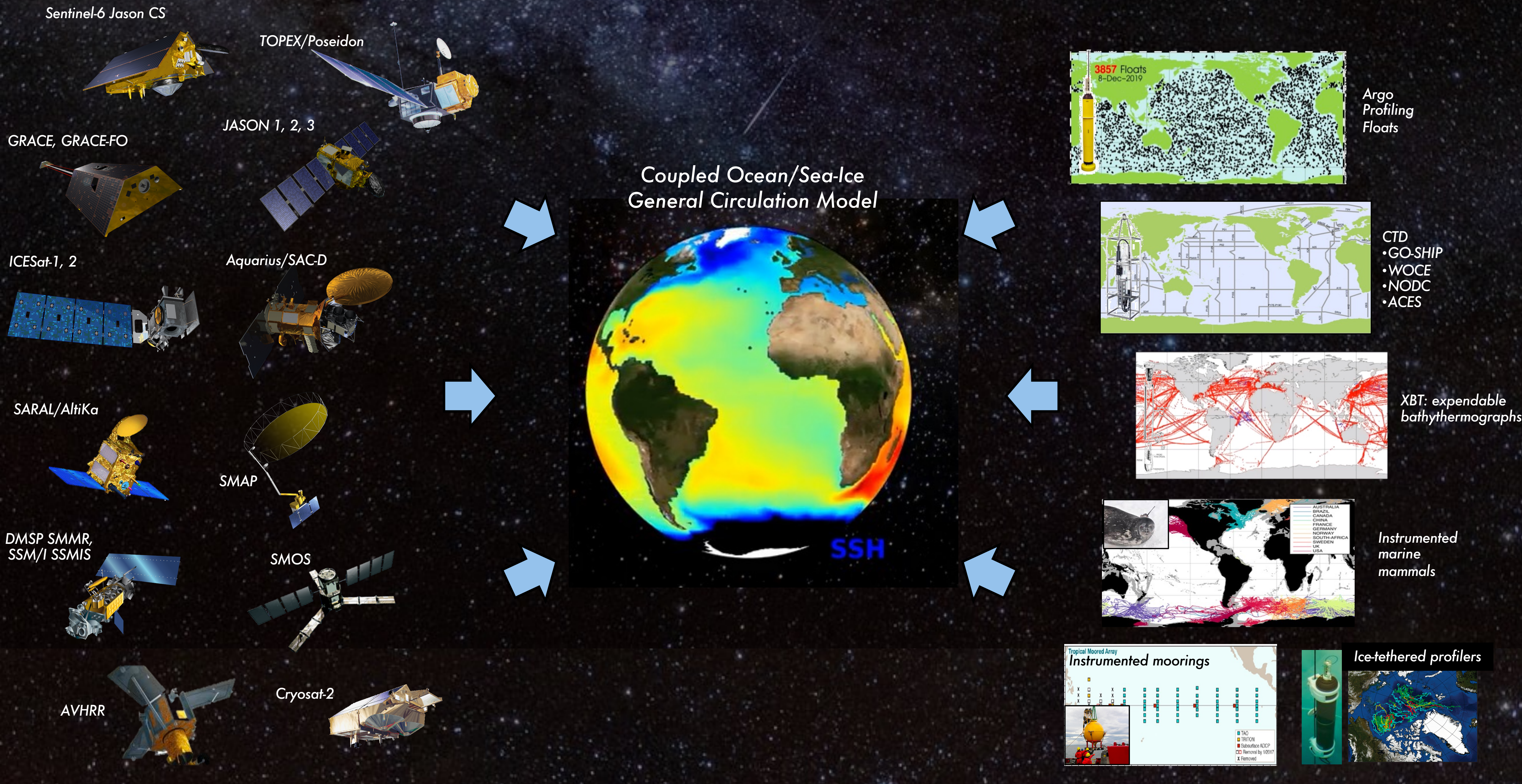
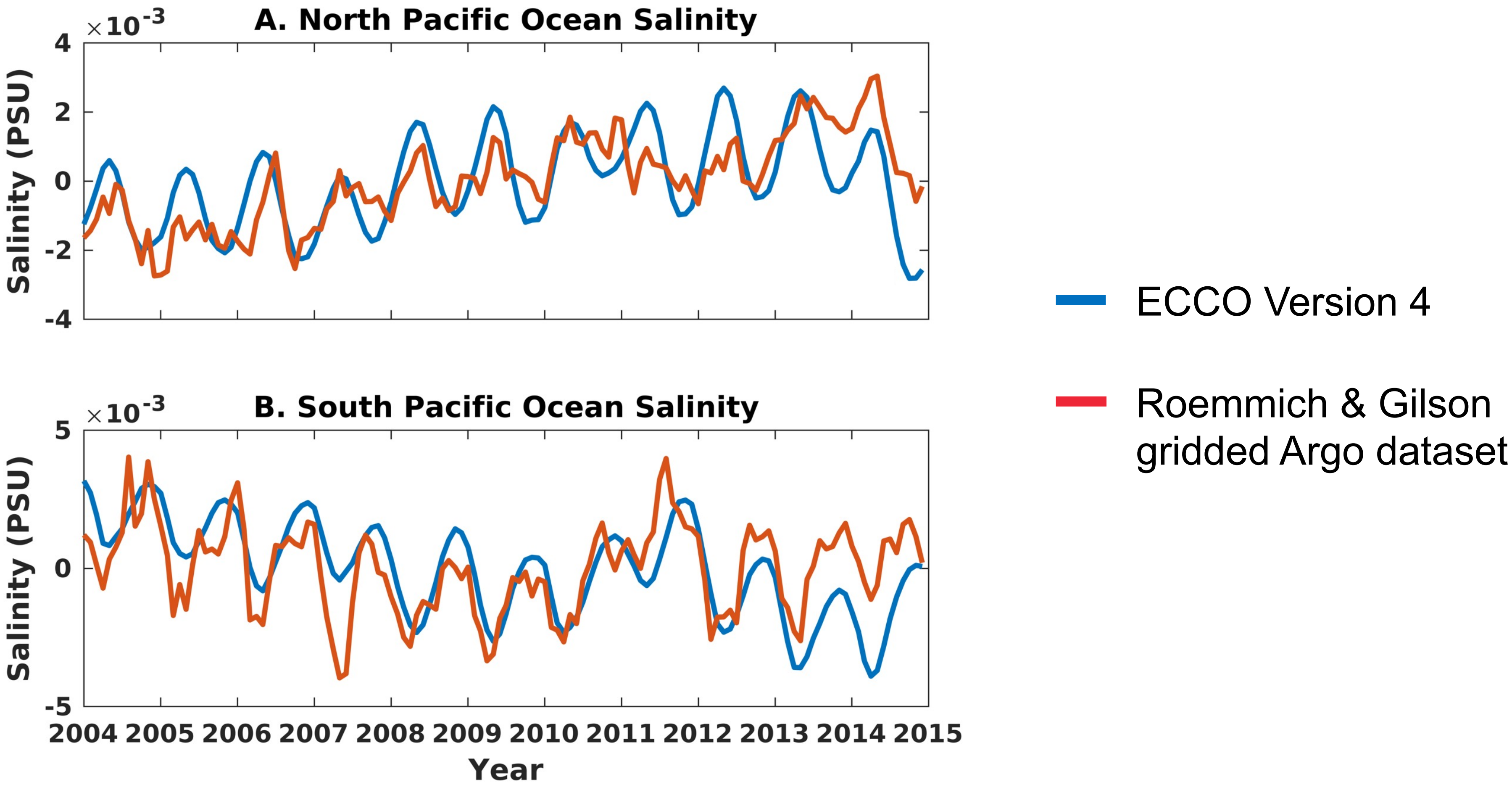


ECCO Version 4 data constraints



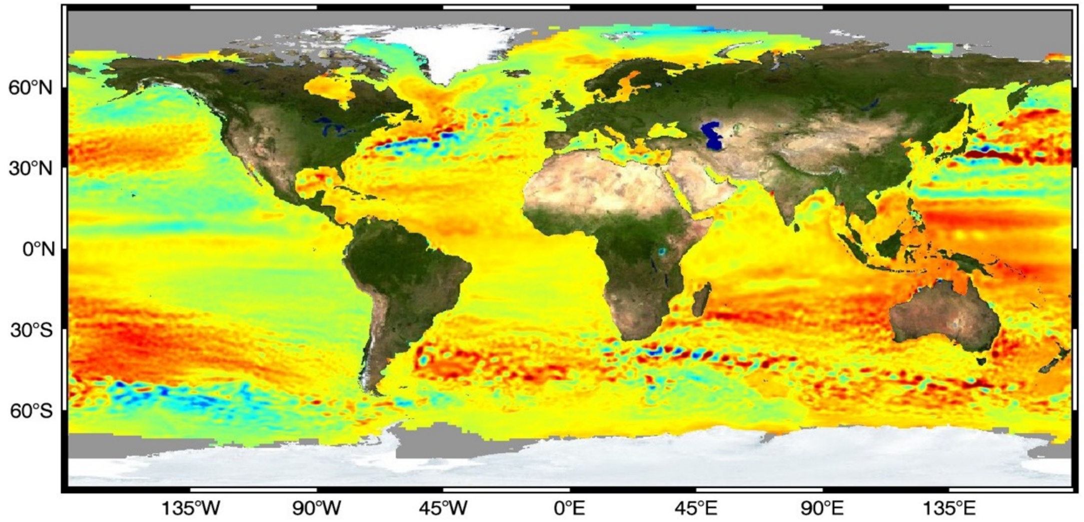
Basin-Scale 0-2000m Ocean Salinity: ECCO V4 vs. Argo Hydrography Product



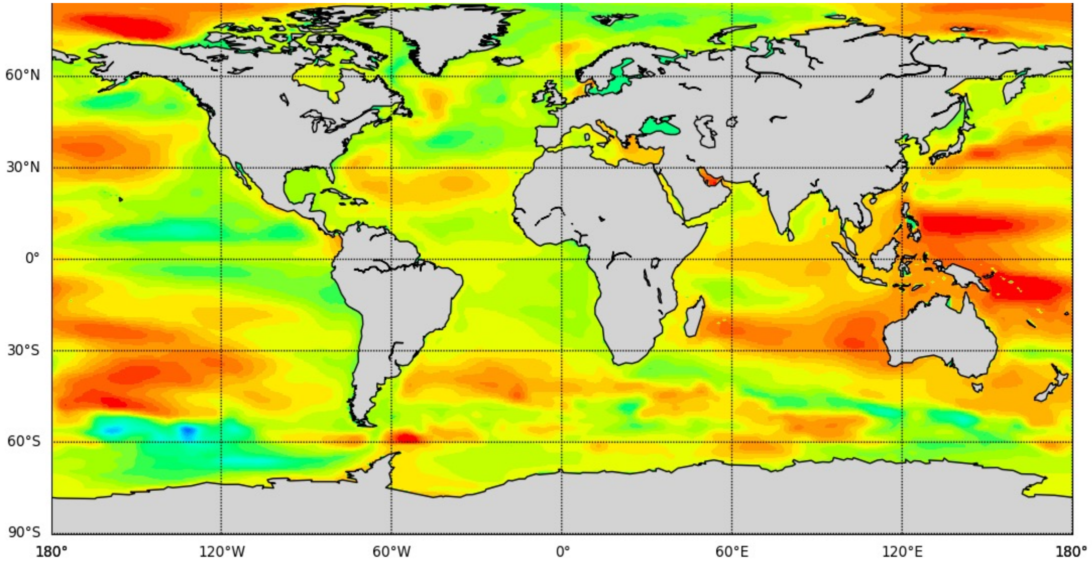
Courtesy of Chris Piecuch, WHOI

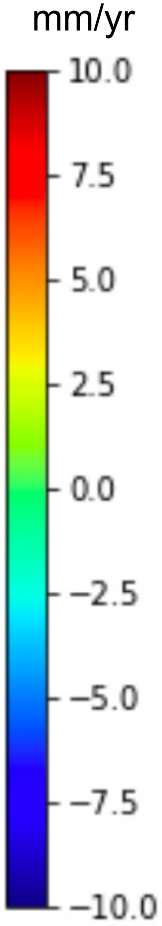
Global Mean Sea Level Trend: ECCO V4 vs. Multi-mission Satellite Product

Multi-mission satellite altimeter product



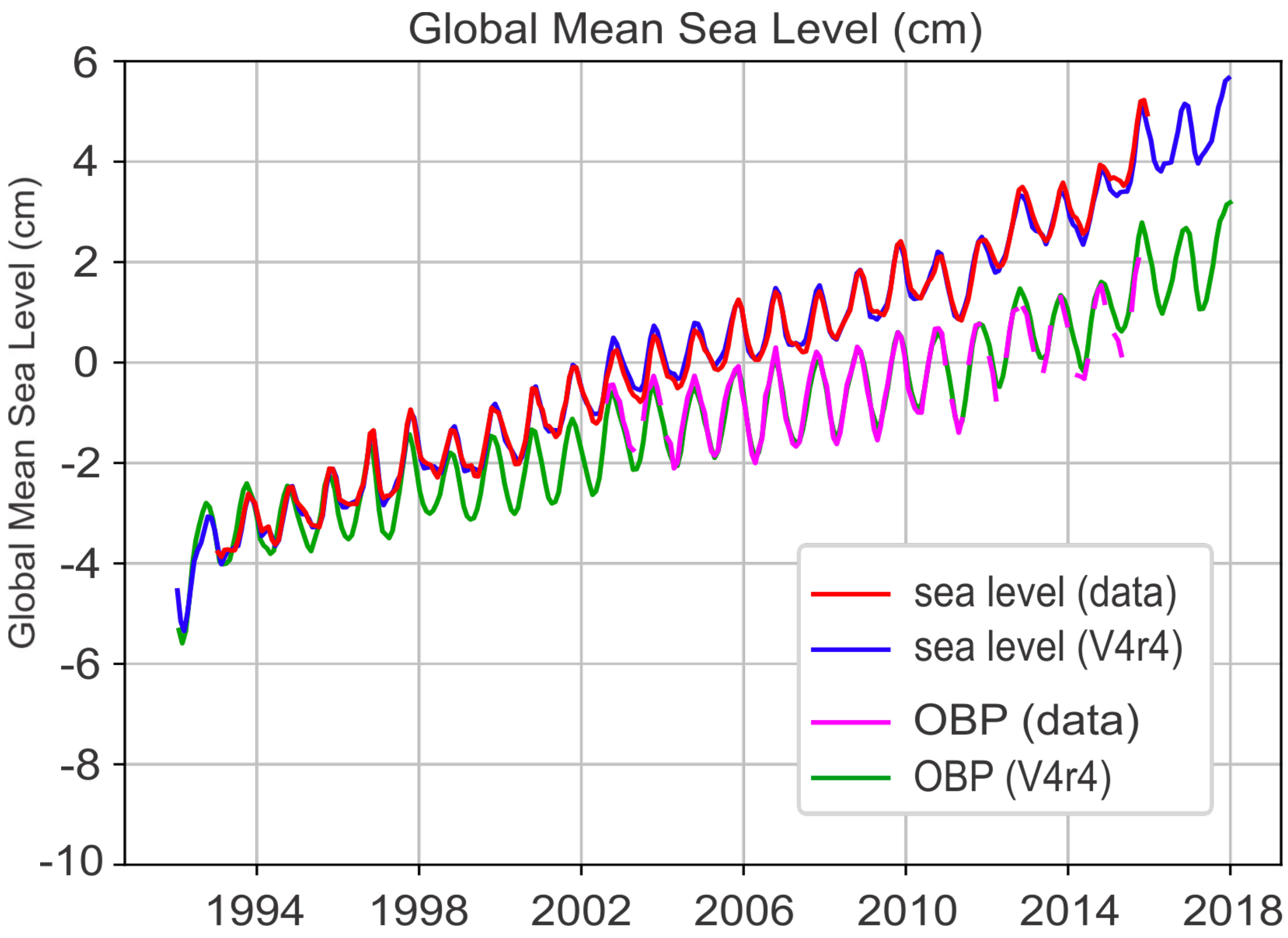
ECCO V4



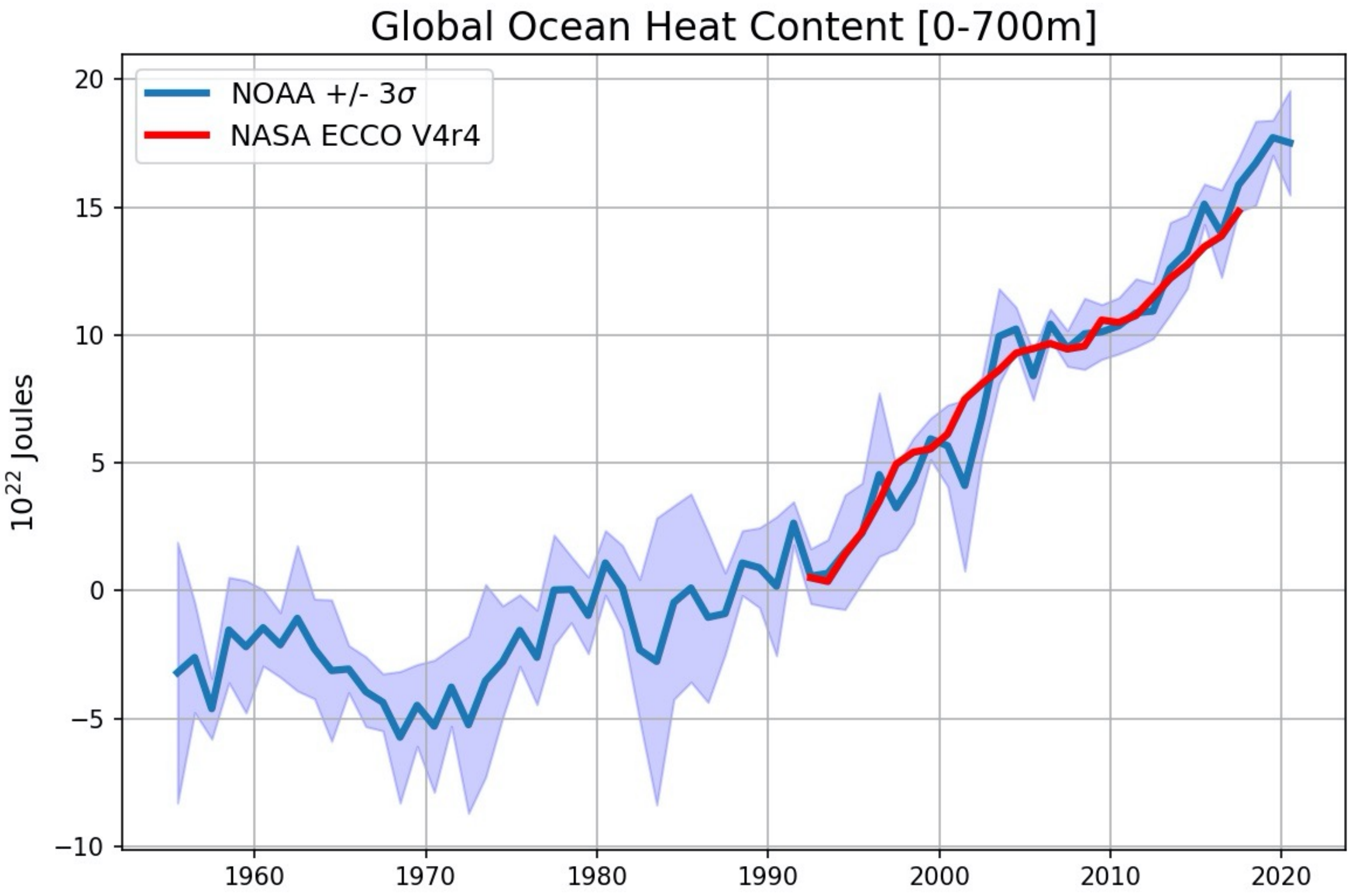


1992-2018

Global Mean Sea Level and Ocean Bottom Pressure Trends: ECCO V4 vs. multi-mission satellite product and GRACE



Upper Ocean Heat Content: ECCO V4 vs. NOAA OHC product



Constraining the state estimate to Antarctic ice-shelf basal melt data

ECCO V4 now includes a data-constrained thermodynamic Antarctic ice-shelf model

“3 equation” ocean/ice melt model

(1) linearized version of the seawater freezing point

$$T_B = \underbrace{aS_B}_{\text{S dependence}} + b + \underbrace{cp_B}_{\text{P dependence}}$$

+S → -T_b
+P → -T_b

(2) Heat conservation

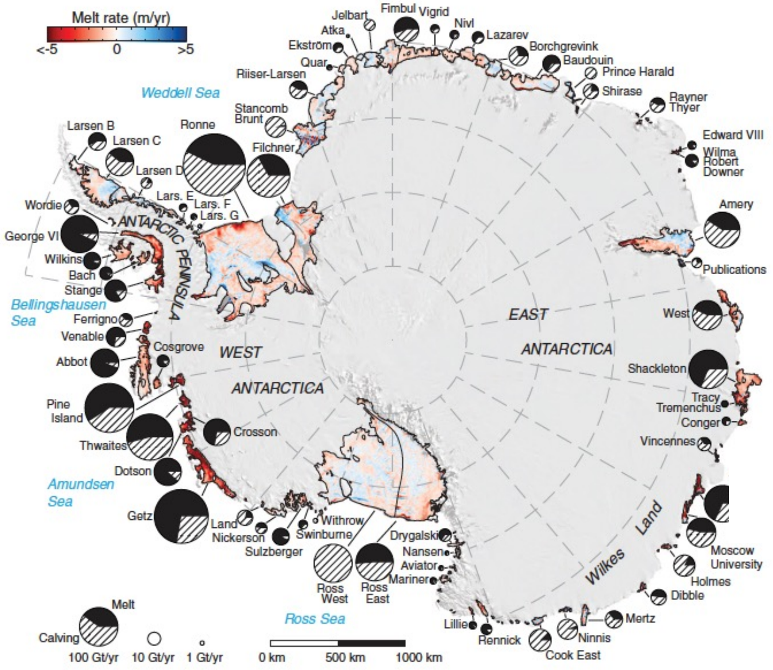
$$\underbrace{C_{pW}\rho_w\gamma_T(T - T_B)}_{\text{Turbulent heat flux from 'far field' to boundary layer}} + \underbrace{\rho_I C_{pI}\kappa\frac{(T_{ice} - T_B)}{h}}_{\text{Conductive heat flux from boundary layer into ice}} = \underbrace{-L_f q}_{\text{Latent heat flux to melt ice}}$$

(3) Salt conservation

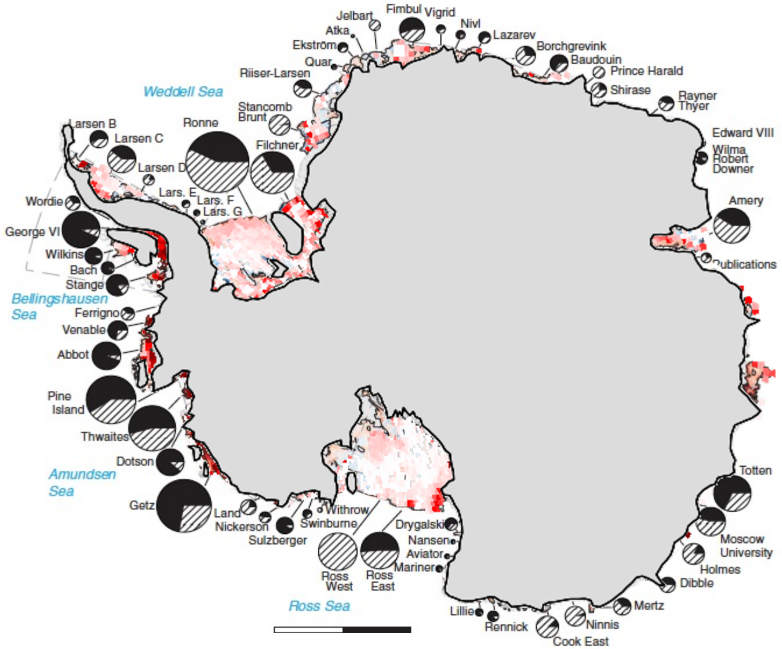
$$\underbrace{\rho_w\gamma_S(S - S_B)}_{\text{Turbulent salt flux from 'far field' to boundary layer}} = \underbrace{-q(S_B - S_{ice})}_{\text{Freshwater flux from melting ice}}$$

Time-mean basal melt rate

Observations

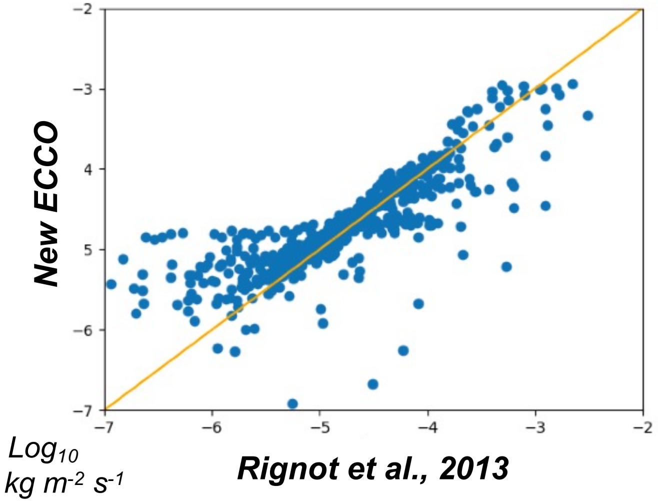


New ECCO estimate



Time-mean basal melt rate

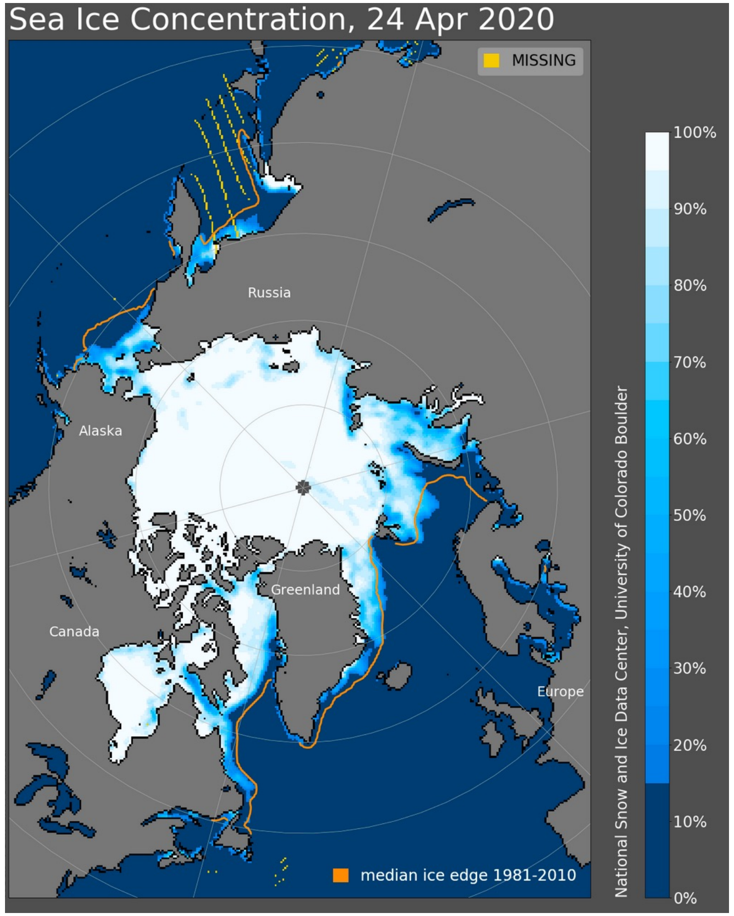
Observations vs. New ECCO



Constraining the state estimate to satellite sea-ice concentration data

ECCO V4 now includes an adjointable thermodynamic sea-ice model

- Previous ECCO V4 ocean state estimates included a dynamic/thermodynamic sea-ice model whose adjoint was unstable.
- We incorporated an new adjointable thermodynamic sea-ice model and added daily sea-ice concentration data constraints.
- Experiments demonstrate substantial and rapid reduction of model-data misfit using the new sea-ice model and data constraints



Arctic sea ice concentration. Credit: NSIDC

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New Cryosphere Datasets in ECCO

Sea-Ice

Current: Sea-ice concentrations from Passive Microwave Radiometers (*e.g.,* SSMR, SSMI/S)

Next : sea-ice & snow freeboard and thickness

1. *ICESat Arctic Sea Ice Freeboard and Thickness, V1*
2. *CryoSat-2 Level-4 Sea Ice Elevation, Freeboard, and Thickness, V1*
3. *ATLAS/ICESat-2 L3A Sea Ice Freeboard, V3*
4. *Antarctic sea ice cover from ICESat-2 and CryoSat-2: freeboard, snow depth, and ice thickness (e.g., Kacimi and Kwok)*
5. *SMOS thin ice thickness*

Ice-Sheet

Current: Time-mean basal melt (Rignot, 2013)

Next Up: time-variable basal melt

1. *ITS_LIVE V1, NASA MEaSUREs, Gardner et al., (2021, in prep)*

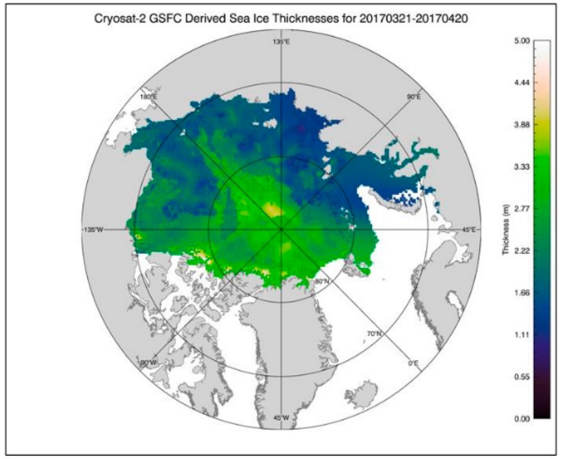
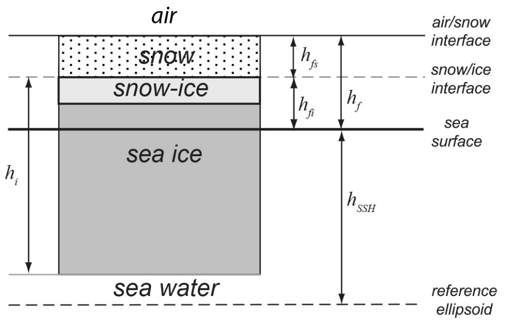
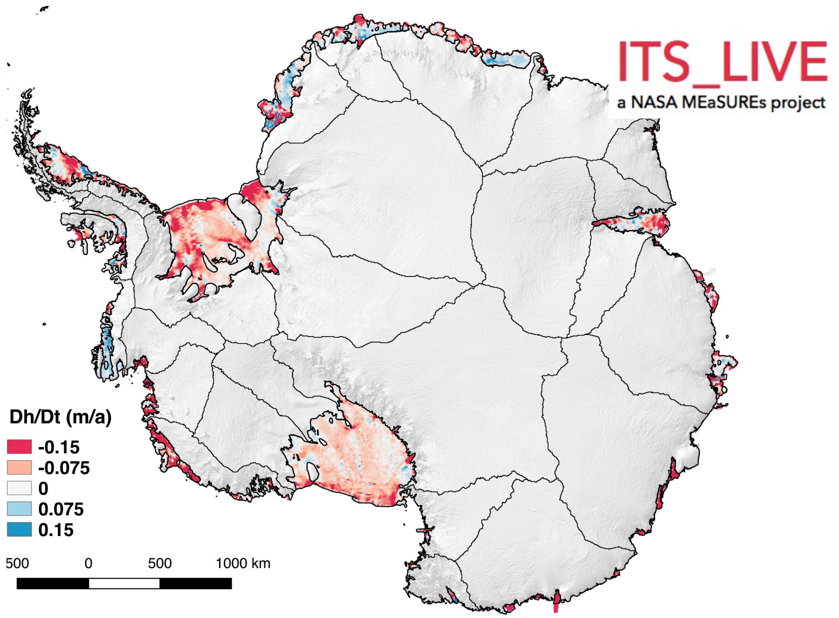


Figure 2. Sea Ice Thickness Plot RDEFT4_20170420_thickness_plot.png





ECCO-Darwin Ocean Biogeochemistry Estimation

Led by Dimitris Menemenlis (JPL) and Dustin Carroll (MLML)

A new global ocean biogeochemistry estimate that is fit to *in-situ* observations (Fig. 1) and interpolation-based estimates of air-sea CO_2 fluxes (Fig. 2) using Green's functions approach to infer unknown biological and chemical rate coefficients. Permits attribution of spatio-temporal CO_2 flux variability.

To be included in next ECCO "Central Estimate"

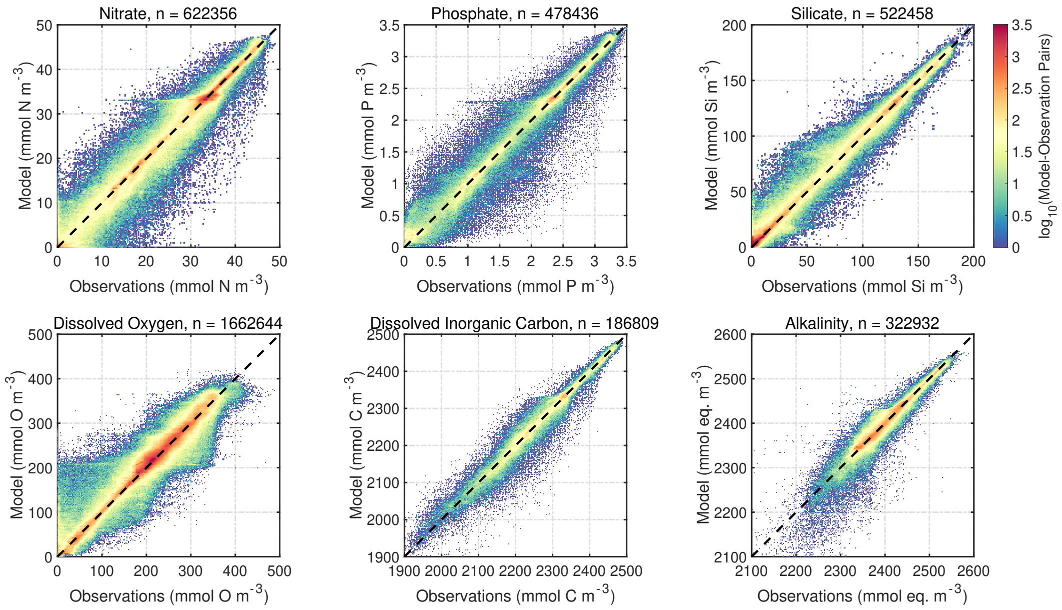


Fig. 1: Comparison with in-situ data

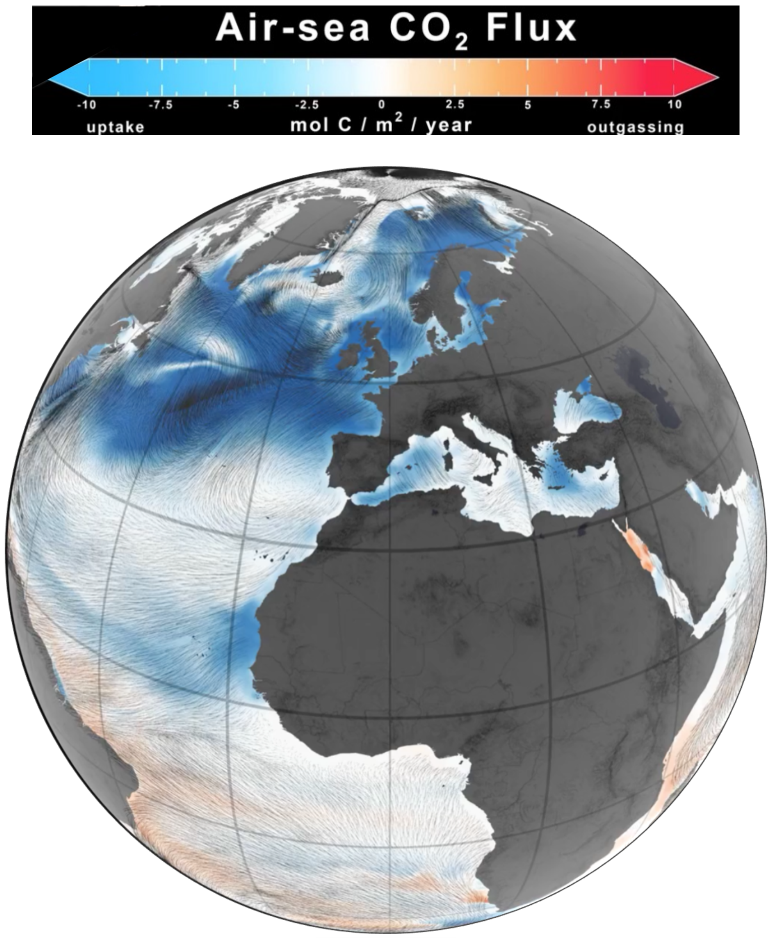


Fig. 2: ECCO-Darwin air-sea CO_2 fluxes

Carroll, D., et al. (2020) doi:10.1029/2019ms001888

Multi-scale Approach for Eddy-Resolving State Estimation

- Adjoint method feasible for models to ~1/3 degree
- Wall clock times for gradient computation
  - 1 degree: ~5 days
  - 1/3 degree ~15 days
- Nonlinear instabilities can dominate gradients when mesoscale dynamics

Multi-scale sequence:

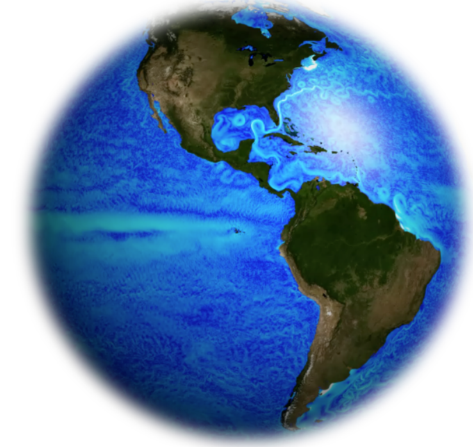
1. calculate model-data differences on high-resolution model associated with model control parameters, x_n,
2. calculate approximate gradient of J_{4D} with respect to x_n using adjoint of coarser model
3. update control parameters (x_{n+1})
4. GOTO(1)

Compute misfits with high-res (HR) model

$$\mathbf{x}_k = M_k(\mathbf{x}_{k-1}). \quad \textit{state propagation}$$

$$J_{4D}(\mathbf{x}_0) = \sum_{k=0}^{L} \underbrace{\|\mathbf{y}_k - H_k(\mathbf{x}_k)\|}_{\text{HR model-data}}{}^2_{\mathbf{R}_k^{-1}} + \|\mathbf{x}_0 - \mathbf{x}_0^b\|^2_{\mathbf{B}_0^{-1}}$$

Cost function



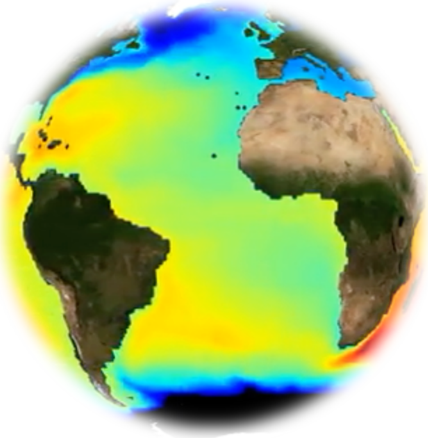
high-res forward model

Compute approximate gradient of J using adjoint of low-res model forced with HR model-data misfits

$$\tilde{\mathbf{x}}_k = \mathbf{M}_k^T \tilde{\mathbf{x}}_{k+1} + \mathbf{H}_k^T \mathbf{R}_k^{-1} \underbrace{(\mathbf{y}_k - H_k(\mathbf{x}_k))}_{\text{HR model-data}} \quad \text{for } k = L, \ldots, 0.$$

approx gradient of J_{4D}

adjoint of low-res model



low-res adjoint model

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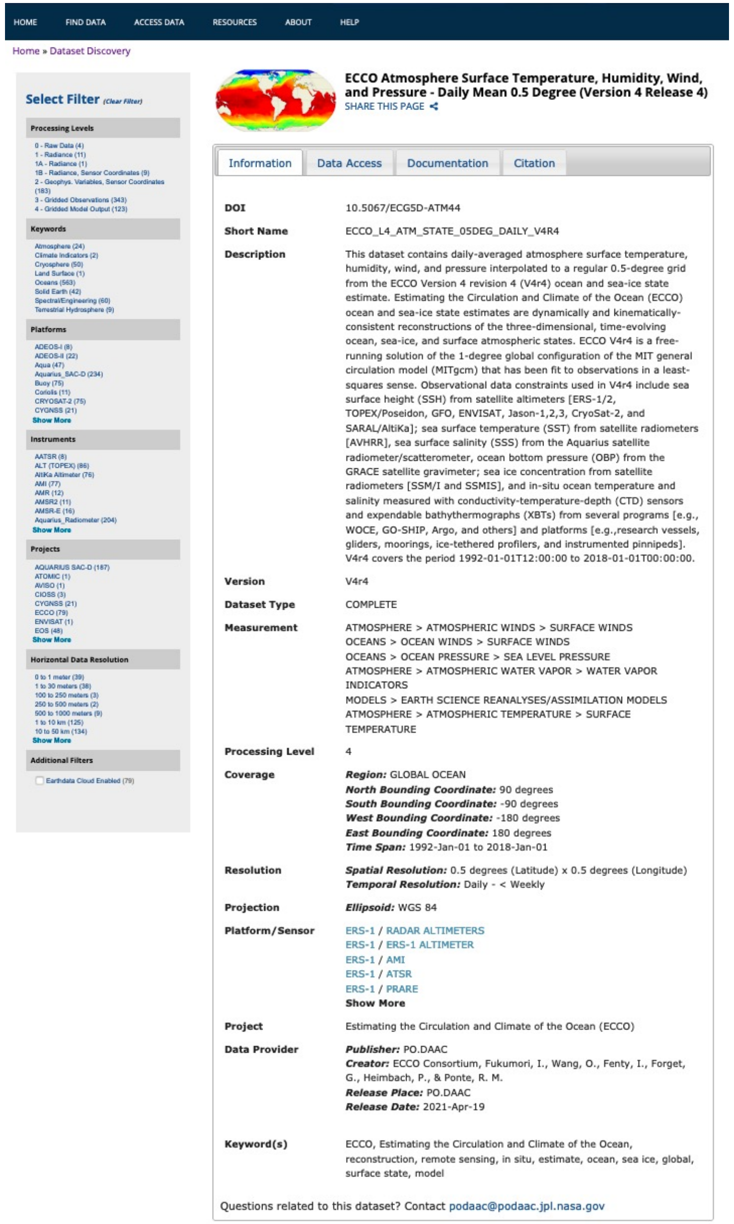
ECCO V4 data distribution via NASA PO.DAAC

Tuesday, April 27, 2021
The PO.DAAC is pleased to announce the public release of the ECCO Version 4 Release 4 (V4r4) ocean and sea-ice state estimates.

The ECCO V4r4 datasets provide global coverage over the period from 1992 to 2018 at daily, monthly, and snapshot (instantaneous) time intervals. This release consists of 79 datasets represented on the ECCO “Lat-Lon-Cap” 90 (LLC90) native model grid and a 0.5 degree latitude-longitude interpolated grid (05DEG), and a 1-D global time series. The nominal spatial resolution of the LLC90 datasets is 1 degree latitude-by-longitude, as referenced at the Equator, with finer grid resolutions at higher latitudes due to the grid projection



ECCO V4 Python Tutorial

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

ECCO Version 4 Python Tutorial

latest

Search docs

Welcome to the ECCO Version 4 Tutorial

This website contains a set of tutorials about how to use the ECCO Central Production Version 4 (ECCO v4) global ocean and sea-ice state estimate. The tutorials were written in Python and make use of the ecco_v4_py Python library, a library written specifically for loading, plotting, and analyzing ECCO v4 state estimate fields.

Additional Resources

The ECCO v4 state estimate is the output of a free-running simulation of a global ca. 1-degree configuration of the MITgcm. Prior to public release, the model output files model are assembled into NetCDF files. If you would like to work directly with the flat binary "MDS" files provided by the model then take a look at the xmitgcm Python package. The xgcm Python package provides tools for operating on model output fields loaded with xmitgcm. If you wish to analyze the MITgcm model output using Matlab then we strongly recommend the extensive set of tools provided by the gcmfaces toolbox.

The ecco_v4_py package used in this tutorial was inspired by both the xmitgcm package and gcmfaces toolbox.

Getting Started

- The ECCO Ocean and Sea-Ice State Estimate
- ECCO v4 state estimate ocean, sea-ice, and atmosphere fields
- Python and Python Packages
- How to get the ECCO v4 State Estimate
- Tutorial Overview

ECCO V4 Python Package

https://github.com/ECCO-GROUP/ECCOv4-py

An open-source resource to facilitate analysis of ECCO V4

Subroutines for calculating:

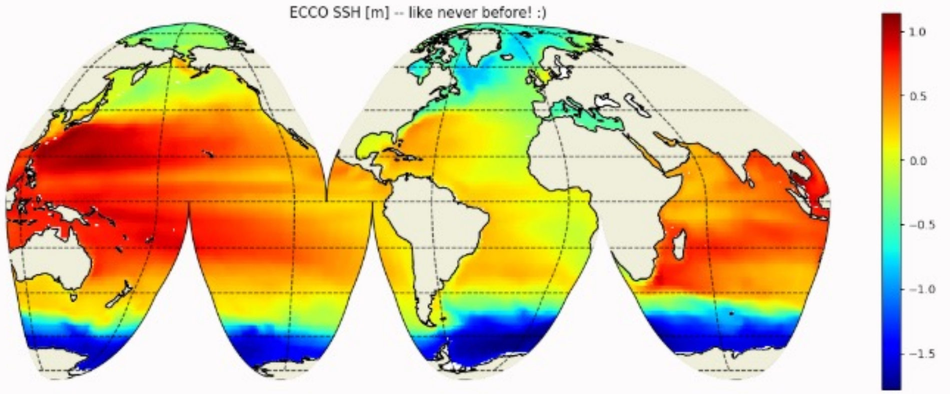
- Global mean sea level, ocean heat content, ocean volume
- Global and regional heat, salt, and volume budgets
- Heat, salt, and volume transports across arbitrary sections
- Meridional overturning circulation streamfunction

```
[27]: plt.figure(figsize=(16,6), dpi=90)

      tmp_plt = ecco_ds.SSH.isel(time=1)
      tmp_plt = tmp_plt.where(ecco_ds.hFacC.isel(k=0) !=0)

      ecco.plot_proj_to_latlon_grid(ecco_ds.XC, ecco_ds.YC, \
                                    tmp_plt, \
                                    user_lon_0=-66,\
                                    projection_type='InterruptedGoodeHomolosine',\
                                    plot_type = 'pcolormesh', \
                                    show_colorbar=True,
                                    dx=1, dy=1);

      plt.title('ECCO SSH [m] -- like never before! :)');
```



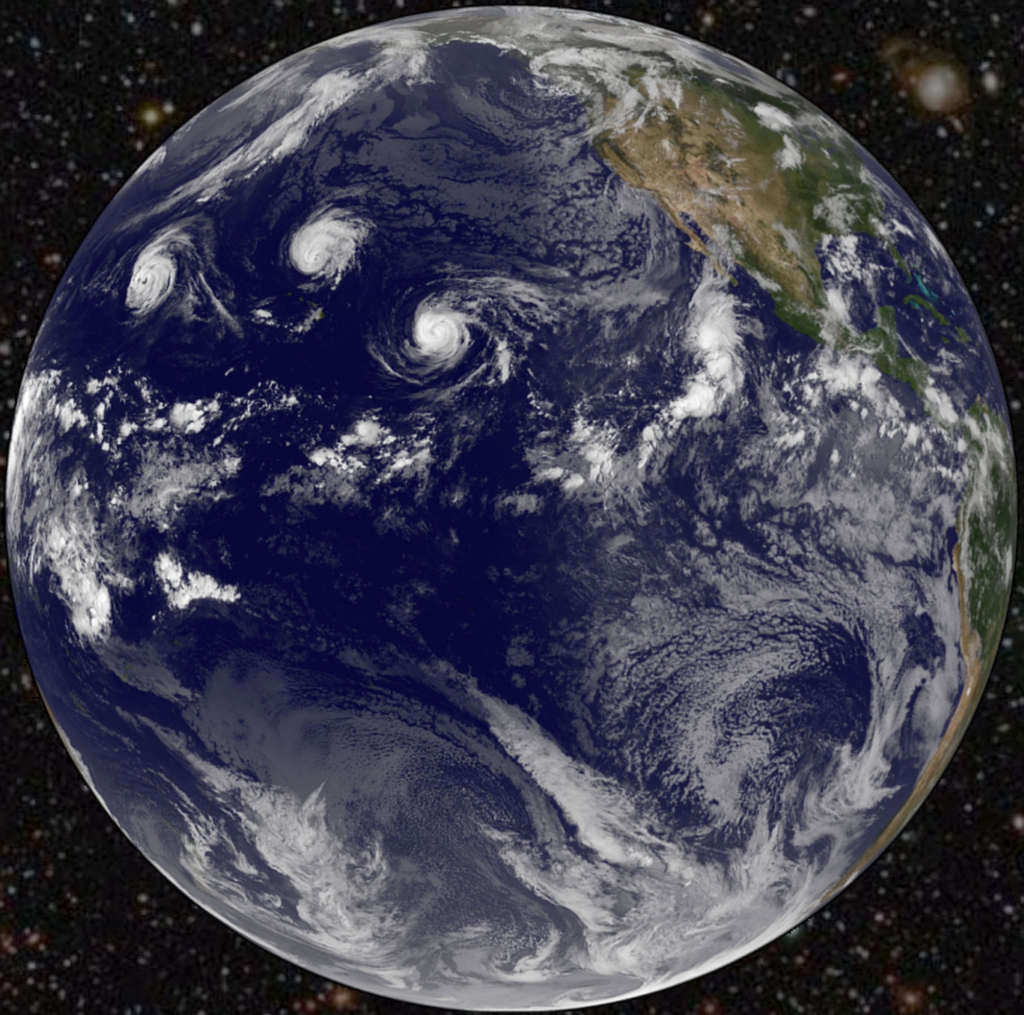
Facing Big Data Challenges

ECCO Data Distribution // Data Volumes

ECCO v**4** llc90	**0.25 Tb**	1 deg, 50 levels
ECCO v**5** llc270	**3 Tb**	1/3 deg, 50 levels
ECCO v**6** llc1080	**80 Tb**	1/12 deg, 90 levels

- How can we efficiently distribute ECCO products to researchers?
- How can we facilitate the scientific analysis of ECCO products?
- Should we leverage new cloud-based tools for big-data analysis?

www.ecco-group.org



"How inappropriate to call this planet Earth, when it is quite clearly Ocean."

Arthur C. Clarke

https://eoimages.gsfc.nasa.gov/images/imagerecords/86000/86532/

The Estimating the Circulation and Climate of the Ocean (ECCO) "Central Estimate"
a Multi-decadal, Coupled Ocean Reanalysis

Abstract:

The Estimating the Circulation and Climate of the Ocean (ECCO) Consortium has been producing dynamically and kinematically-consistent global ocean state estimates for nearly two decades. Our current focus is Version 4 of the "Central Estimate", a data-constrained global, 1-degree, coupled ocean, sea-ice, and thermodynamic ice-sheet model that spans the period 1992-present. The coupled ocean model is made consistent with a diverse and heterogeneous set of ocean, sea-ice, and ice-sheet data in a least-squares sense by iteratively adjusting a set of control parameters using the gradient of an uncertainty-weighted model-data misfit cost function. The gradient of the cost function is provided by the automatically-derived adjoint of the model (MITgcm).

By construction, ECCO state estimates perfectly satisfy the laws of physics and thermodynamics encoded in the numerical model and therefore conserve heat, salt, volume, and momentum. Our philosophy of strict adherence to these conservation principles ensures that ECCO reanalyses are useful for investigating the causal origins of observed ocean climate variability. However, because of the enormous scale of the nonlinear optimization problem, strictly obeying conservation laws involves a trade-off with goodness-of-fit; on the whole, ECCO reanalyses are unlikely to reproduce observations as well as ocean reanalyses that allow incremental adjustments to their state vectors through time.

Here we summarize our efforts to date with a focus on addressing recent challenges associated with (i) coupling to the sea-ice and thermodynamic ice-sheet models, (ii) adding novel data constraints such as ocean bottom pressure from GRACE and GRACE-FO, and (iii) increasing the spatial resolution of the state estimation system to achieve eddy-resolving scales.

ECCO V4 observational data constraints

Variable	Observations
Sea surface height	ERS-1/2 (1992-2001), TOPEX/Poseidon (1993-2005), GFO (2001-2007), ENVISAT (2002-2012), Jason-1 (2002-2008), Jason-2 (2008-2017), CryoSat-2 (2011-2017), SARAL/AltiKa (2013-2017), Jason-3 (2016-2017),
***in situ* temperature**	Argo (1995-2017), CTDs (1992-2017), XBTs (1992-2017), marine mammals (APB 2004-2017), gliders (2003-2017), Ice-Tethered Profilers (ITP, 2004-2017), moorings (1992-2017)
***in situ* salinity**	CTDs (1992-2017), moorings (1992-2017), Argo floats (1997-2017), gliders (2003-2017), marine mammals (APB 2004-2017), ITP (2004-2017),
Sea surface temp.	AVHRR (1992-2017)
Sea surface salinity	Aquarius (2011-2015), SMOS (2010-2017), SMAP(2015-2017)
Sea-ice concentration	SSM/I (1992-2009), SSMIS (2006-2017)
Ocean bottom pressure	GRACE (2002-2016)
T and S climatology	World Ocean Atlas 2015
Mean dynamic Topography	DTU17 (1992-2015)

Coupled GEOS/ECCO Modeling and Estimation

Led by Dimitris Menemenlis

Both GEOS and ECCO have been run, separately, at groundbreaking resolutions, providing valuable scientific and practical insights (Fig. 1). We are developing a fully-coupled atmosphere-ocean-ice simulation, where all three fluids are integrated globally with km-scale horizontal grid spacing (Figs. 2 & 3).

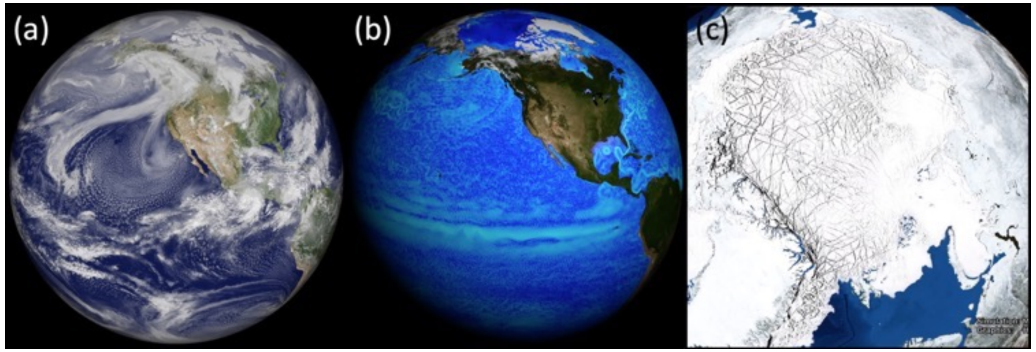


Fig. 1: Cloud-resolving GEOS (a) and submesoscale (b) and sea-ice-lead (c) admitting ECCO simulations.

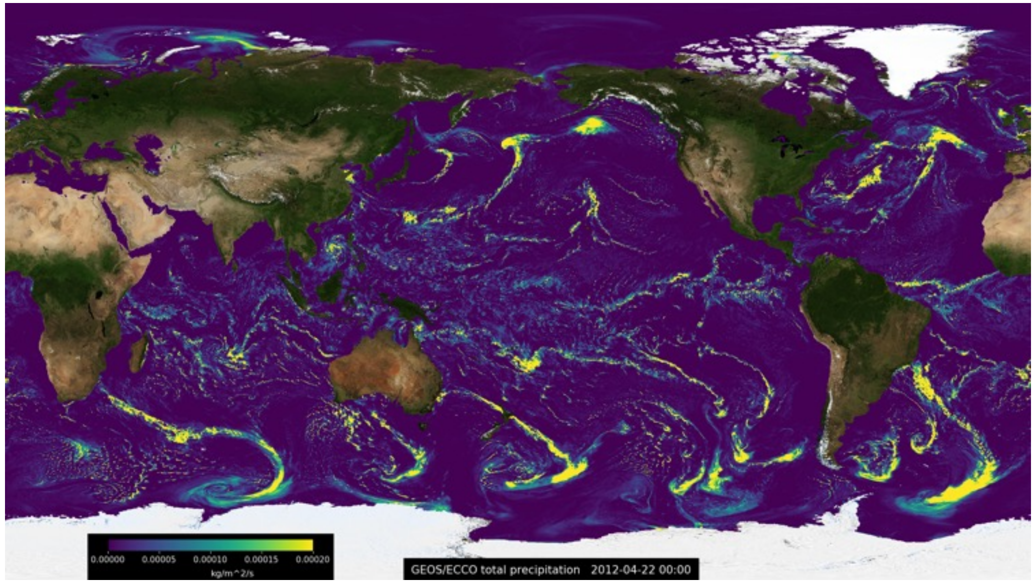


Fig. 2: Precipitation in GEOS/ECCO simulation with 2-6-km grid spacing.

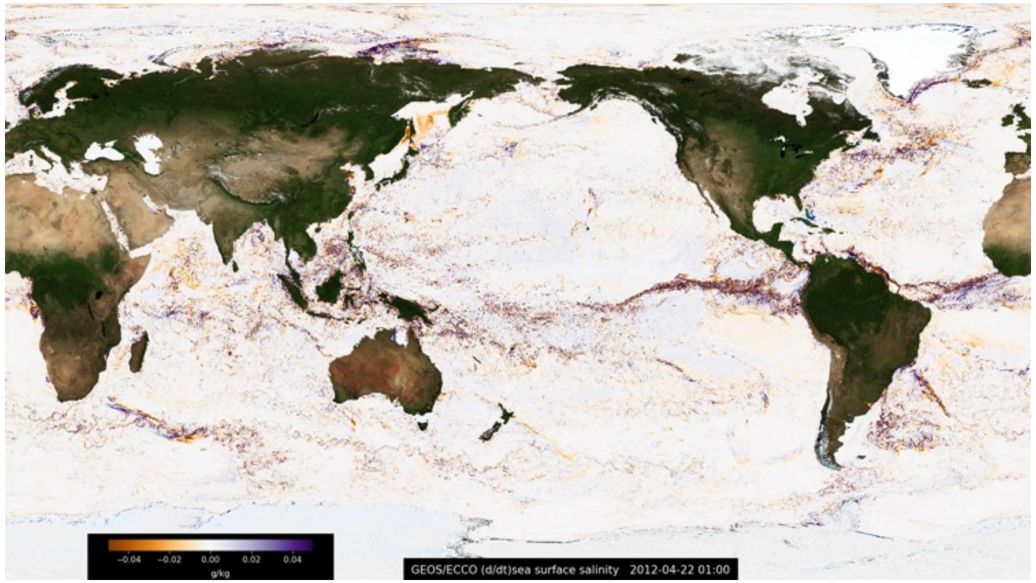


Fig. 3: Sea surface salinity tendency in same GEOS/ECCO simulation