ECCO-Darwin
Development/Science Update

Dustin Carroll, Dimitris Menemenlis, Raphaël Savelli, Clément Bertin, Hong Zhang, Stephanie Dutkiewicz, Jonathan Lauderdale, Ian Fenty, Kevin Bowman, Amanda Fay, Gaël Forget, Michelle Gierach, Chris Hill, Oliver Jahn, Peter Landschützer, Junjie Lui, Manfredi Manizza, Matt Mazloff, Galen McKinley, Charles Miller, Yoshihiro Nakayama, Christian Rödenbeck, David Schimel, Tom van der Stocken, Ariane Verdy, Daniel Whitt, Mike Wood, Hinne van der Zant, and many others…

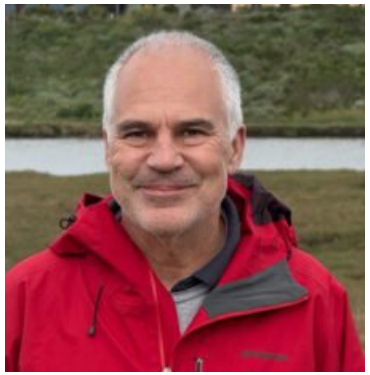
SJSU SAN JOSÉ STATE UNIVERSITY

ECCO Annual Meeting 2026

In memoriam: Jorge L. Sarmiento, 1946-2026

Team Updates

Dustin Carroll (SJSU)



Dimitris Menemenlis (SJSU)

Raphaël Savelli (SJSU)

Coming Soon!

Clément Bertin (SJSU/BAERI)

Sreelekha Jarugula (SJSU/BAERI)

Stephanie Lim (NPP, JPL)

Ioannis Tsakalakis (MC Fellow, SJSU)

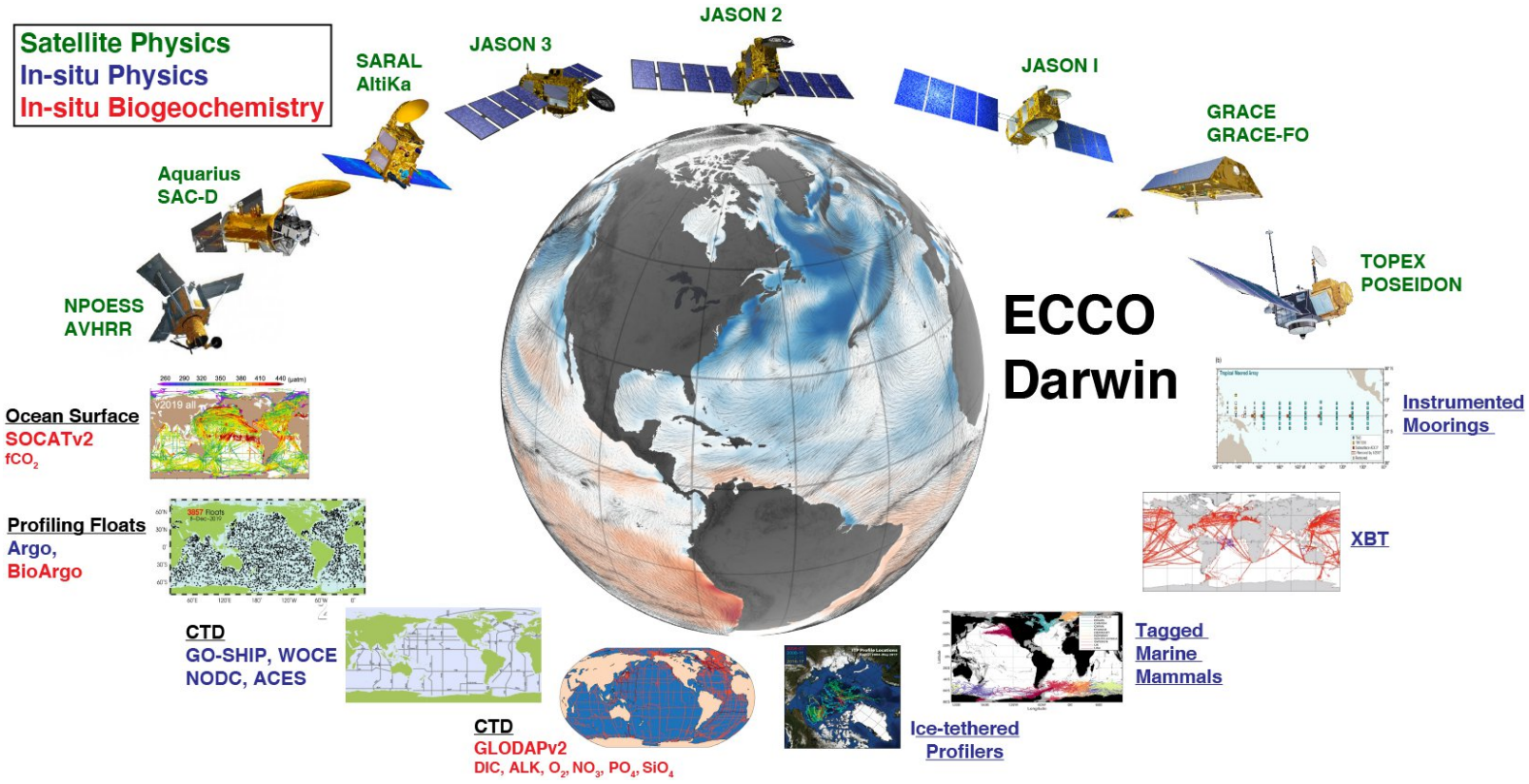
Flagship ECCO Carbon/BGC Products

ECCO Simulation	ECCO-Darwin	B-GOSE (Biogeochemical Global Ocean State Estimate)	B-SOSE (Biogeochemical Southern Ocean State Estimate)	TPOSE (Tropical Pacific Ocean State Estimate)	ASTE-BGC (Arctic Subpolar Gyre sTate Estimate)
Region of Interest	Global Ocean	Quasi Global Ocean (83°S–86°N)	Southern Ocean	Tropical Pacific Ocean	Arctic and Subpolar North Atlantic Ocean
Nominal Resolution	1 deg, 1/3 deg	1/6 deg	1/6 deg	1/6 deg	1/3 deg
Model Period	1992–2025	2013–2025	2013–2025	2010–2018	2002–2017
Biogeochemistry	Darwin	BLING	BLING	BLING	BLING
Reference	*Carroll et al. 2020, 2022, 2024*	*Mazloff et al. coming soon*	*Verdy and Mazloff, 2017*	*Verdy et al. 2017*	*Nguyen et al. 2021, 2023; Mosley et al. 2026, in revision*

+ downscaled simulations

ECCO-Darwin Overview

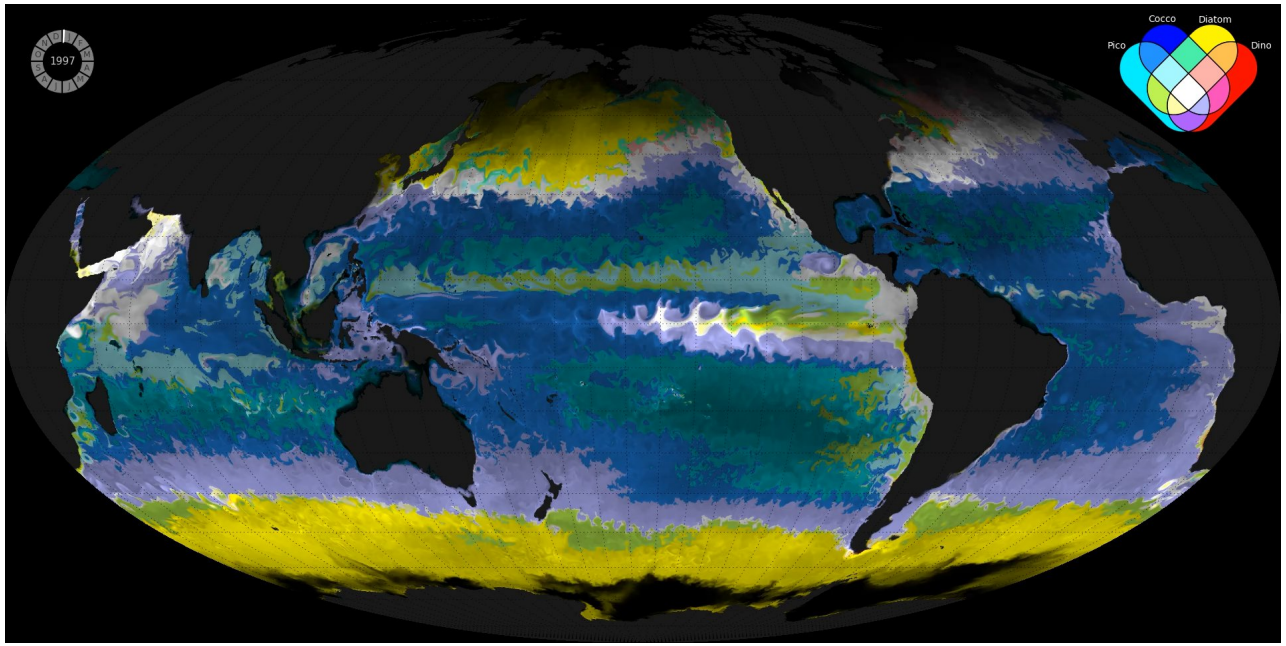
- ECCO-Darwin = global-ocean biogeochemistry model (1992 to 2025)
- Based on ECCO framework (physically consistent, property-conserving data assimilation, important for carbon budgets)
- Both LLC 90 V4r4/V4r5 and LLC 270 V5 alpha/V5r1 versions available
- MIT Darwin ecology model
- Physical (adjoint method) and biogeochemical (Green's Functions) optimization



All code and instructions available at:
https://github.com/MITgcm-contrib/ecco_darwin

Darwin Ecosystem Model

- Darwin is a versatile biogeochemical and ecosystem module (**pkg Darwin**)
- Cycling of C, N, P, Si, Fe, O_2, and alkalinity though inorganic and living/dead organic pools
- Can incorporate any number (up to ~4000) plankton functional types: phyto-, zoo-, mixo-, heterotrophic bacteria, other non-autotrophic prokaryotes, viruses
- Together with **radtrans pkg** simulates radiative transfer through water column — *direct link to NASA satellite ocean-color products*
- New NASA CCS project to investigate impact of ecosystem complexity on ocean carbon cycling



Darwin Ecological Provinces
Visualization Credit: Oliver Jahn, MIT

Darwin pkg code and documentation:
https://github.com/darwinproject/darwin3

ECCO-Darwin Recent Research Focus

- **Global-ocean studies on anthropogenic perturbations to ocean biogeochemistry, ecology, and carbon cycling**
- Improved representation of global and Arctic land-to-ocean fluxes of carbon and nutrients
- Including bottom-sediment processes in the open ocean and coastal zone
- Improving and expanding Darwin ecosystem + phytoplankton functional types
- High-resolution downscaled simulations for regional applications
- Marine Carbon Dioxide Removal (mCDR) simulations (alkalinity, iron, kelp)

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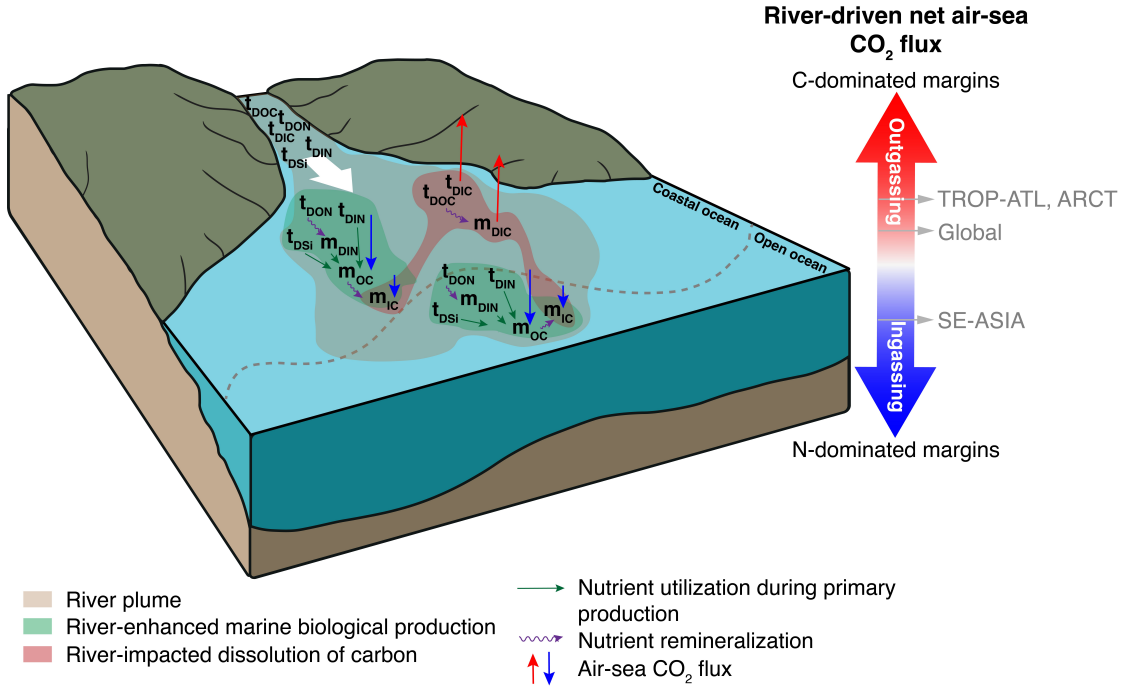
ECCO-Darwin Land-to-ocean Efforts

- **Implemented daily, point-source freshwater and carbon/nutrient discharge in LLC 90 and LLC 270 ECCO-Darwin simulations**
- Combine freshwater discharge from JRA55-do + Global NEWS 2 carbon/nutrient watershed model
- Results in biogeochemical discharge from 5,171 rivers worldwide
- Sensitivity experiments to assess role of freshwater, carbon, and nutrient discharge on ocean carbon cycling
- Now using discharge product in downscaled simulations

Implementing riverine biogeochemical inputs in ECCO-Darwin: a sensitivity analysis of terrestrial fluxes in a data-assimilative global ocean biogeochemistry model

Raphaël Savelli[1,2], Dustin Carroll[1,2], Dimitris Menemenlis[2], Jonathan M. Lauderdale[3,4], Clément Bertin[2], Stephanie Dutkiewicz[3,4], Manfredi Manizza[5,a], A. Anthony Bloom[2], Karel Castro-Morales[6], Charles E. Miller[2], Marc Simard[2], Kevin W. Bowman[2], and Hong Zhang[2]

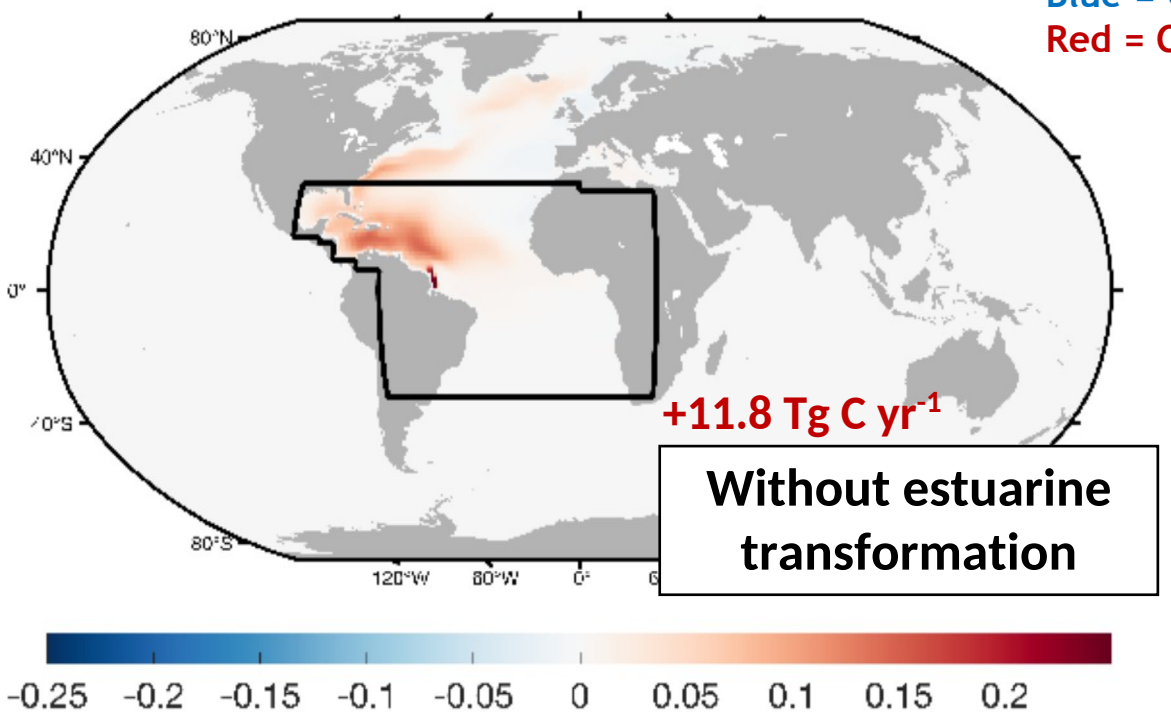


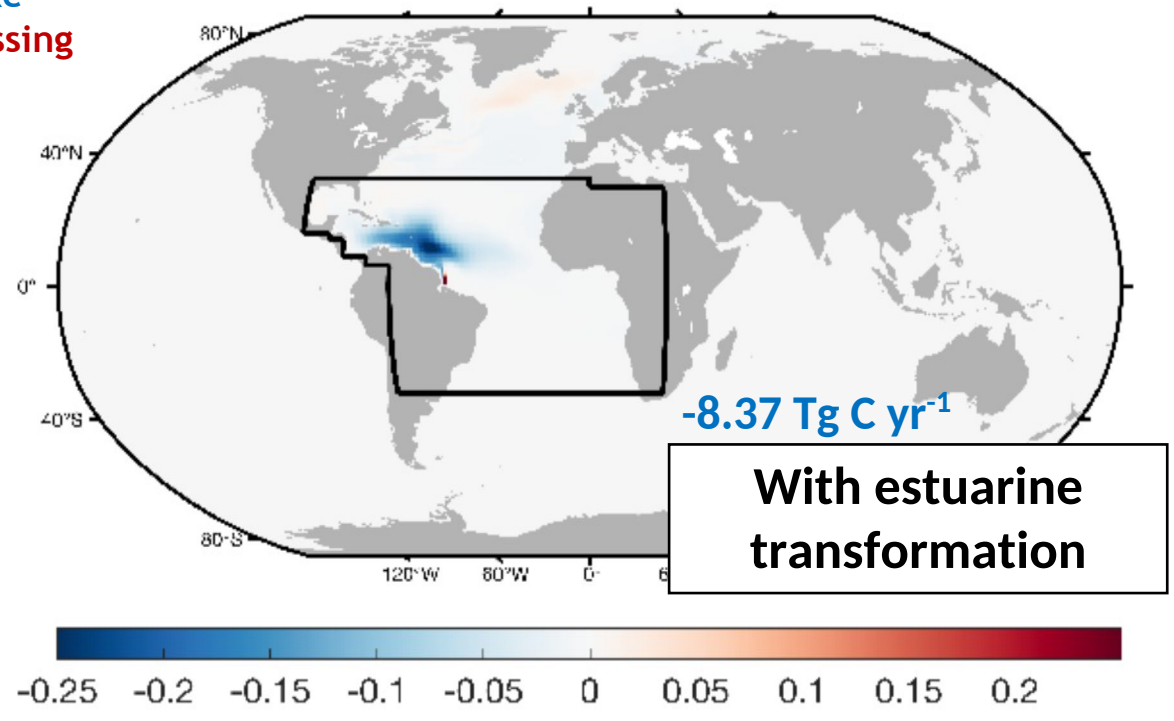
Savelli et al. 2025, GMD

Role of Estuarine Transformation on Air-sea CO_2 Fluxes Across the Amazon Delta Region

Savelli et al. *in prep. for submission to GRL*

Blue = CO_2 uptake
Red = CO_2 outgassing

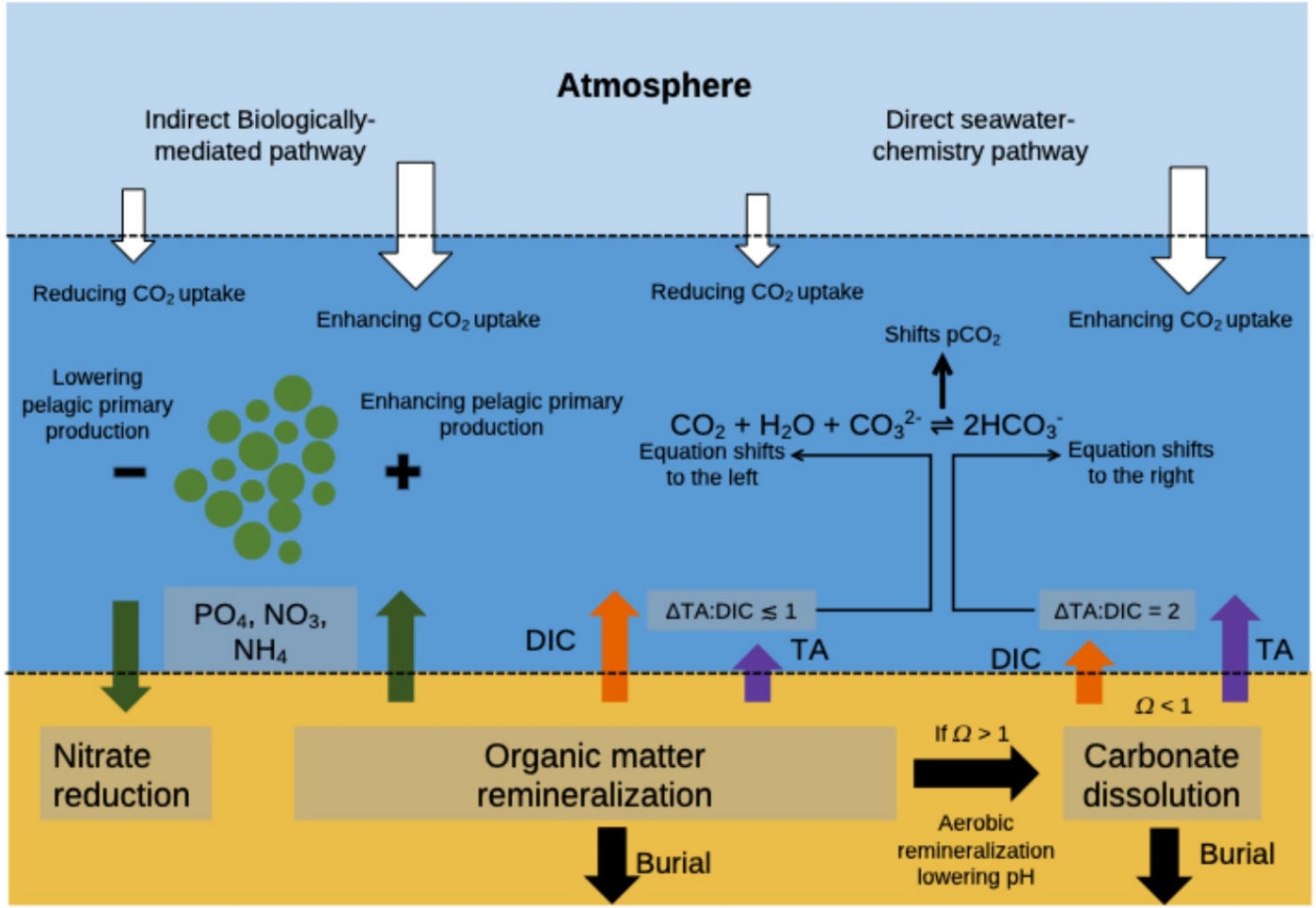




Simulated air-sea CO_2 flux driven by the Amazon River carbon and nutrients (mol C m^{-2} yr^{-1})

ECCO-Darwin Bottom-sediment Model

- Added a mechanistic sediment diagenesis model to ECCO-Darwin **(RADI)**
- First implemented in Sulpis et al. (2022, GMD) and updated in Van Der Zant et al. (2026, GMD)
- **Permits seawater-porewater exchange of carbon and nutrients**, with a large impact on coastal-ocean productivity, especially near rivermouths
- Investigating global-ocean anthropogenic perturbation to bottom-water dissolution and alkalinity



van der Zant et al. 2026, in prep.

ECCO-Darwin Downscaling

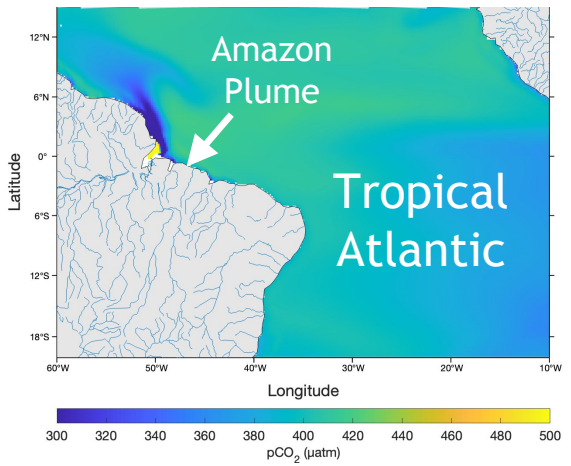
Available Downscaled Simulations:

- Beaufort Sea w/ BGC discharge
- California Current System
- Coastal West France
- Disko Bay w/ iceplume pkg
- East Antarctica w/ shelfice pkg
- East/West Greenland
- Gulf of Mexico w/ BGC discharge
- Gulf of Alaska
- Gulf of Guinea
- Mediterranean and Red Sea
- Tropical Atlantic w/ BGC discharge

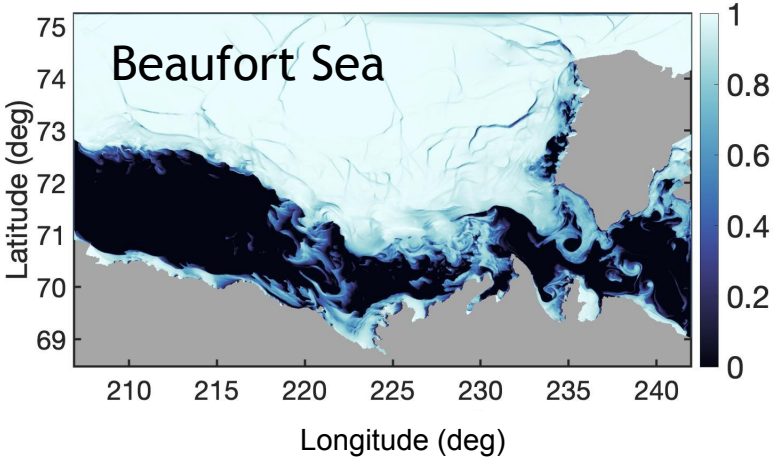
Added:

- Colored Dissolved Organic Matter (CDOM)
- Coastal sediment model (RADIv2)
- Arctic-Ocean-specific ecosystem

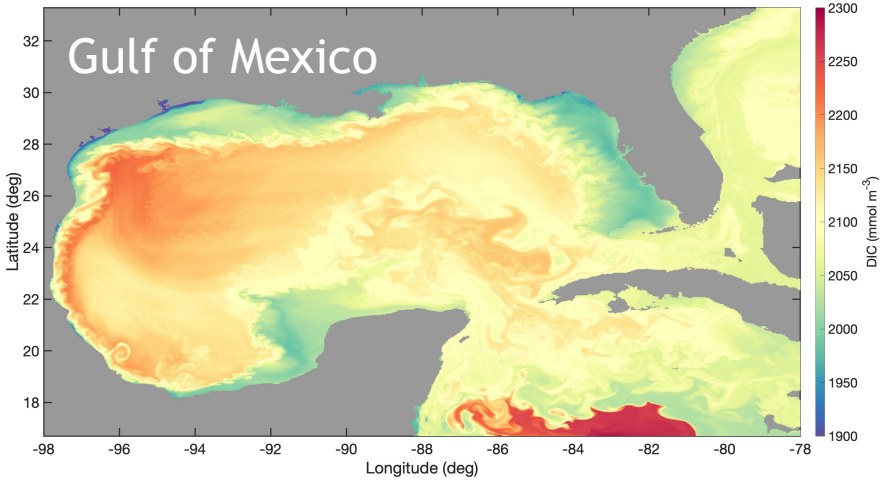
Surface-ocean pCO_2



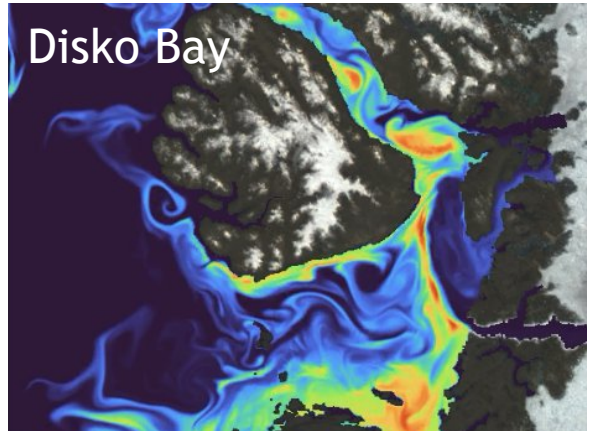
Sea-ice Cover



Surface-ocean DIC



Surface-ocean Chl



ECCO-Darwin Ocean-Glacier-Biology

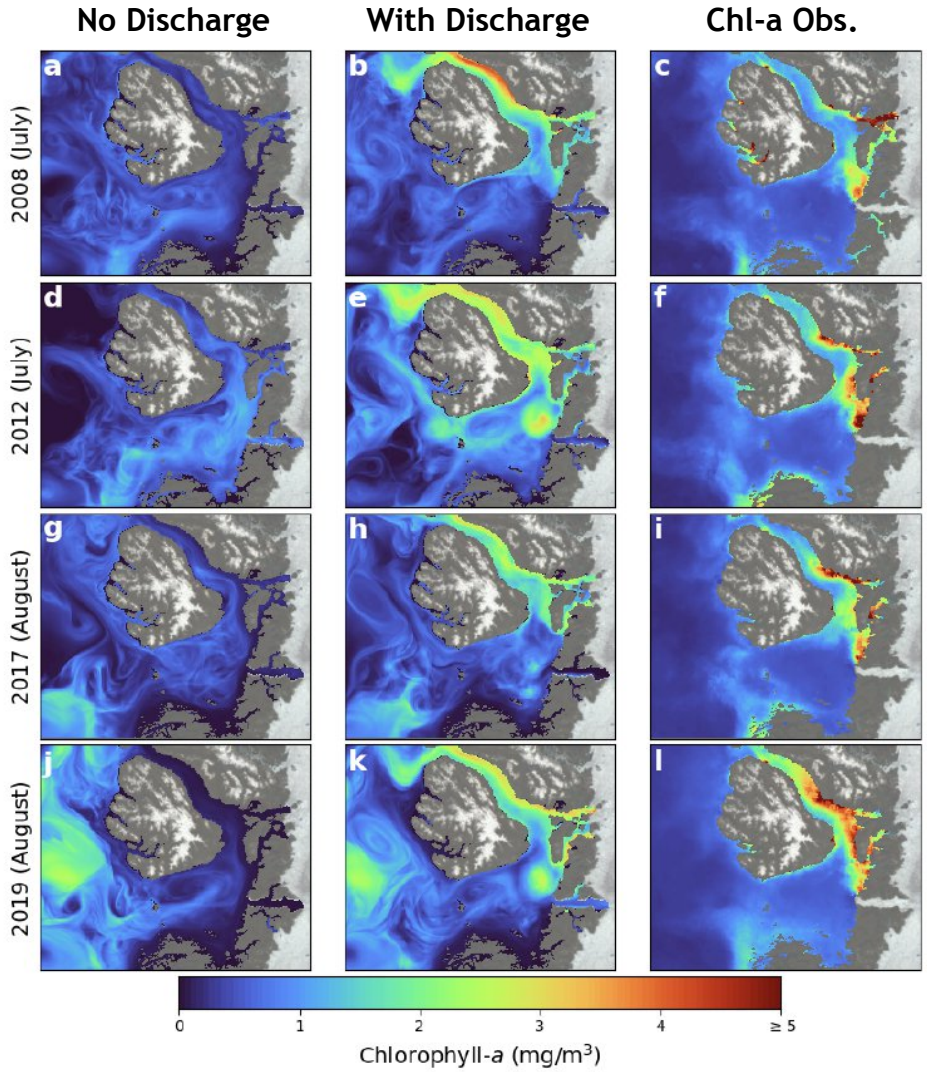
Article | Open access | Published: 05 August 2025

Increased melt from Greenland's most active glacier fuels enhanced coastal productivity

Michael Wood ✉, Dustin Carroll, Ian Fenty, Clément Bertin, Basil Darby, Stephanie Dutkiewicz, Mark Hopwood, Ala Khazendar, Lorenz Meire, Hilde Oliver, Tara Parker & Josh Willis

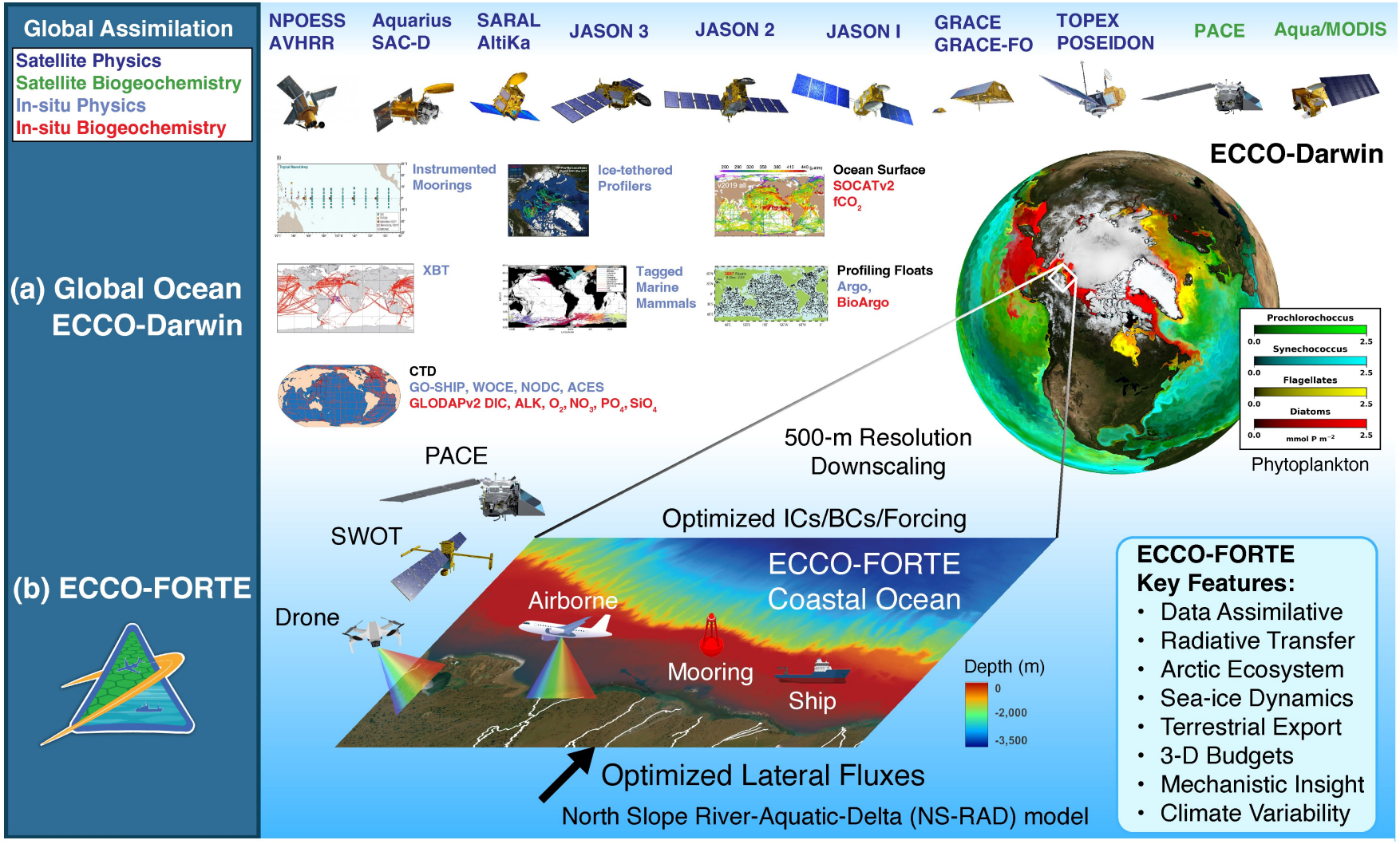
Communications Earth & Environment **6**, Article number: 626 (2025) | Cite this article

- Downscaled ECCO-Darwin simulation of Disko Bay, Greenland with **500-m horizontal grid spacing**
- Integration of **iceplume and Darwin pkg**
- Subglacial discharge plumes substantially **enhance coastal productivity** during summer
- Currently adding representation of ice mélange



Wood et al. (2025, Nature Communications: E&E)

“Delivering an ECCO-FORTE Data-Constrained Modeling Framework for Quantifying Land-to-Ocean Biogeochemical and Ecosystem Variability Across the North Slope”, PI Dustin Carroll



NASA EVS-4

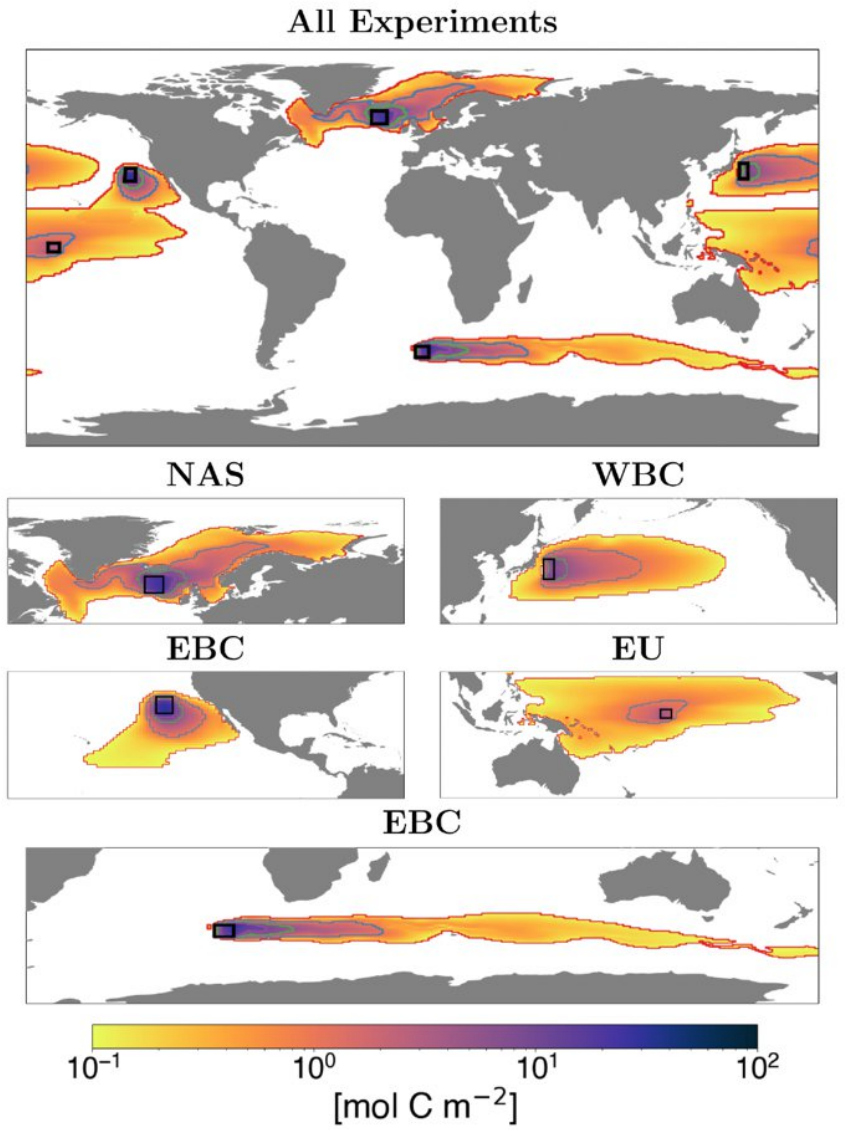
FORTE

Arctic Coastlines • Frontlines of Rapidly Transforming Ecosystems

Using ECCO-Darwin to support NASA field campaigns

ECCO-Darwin Marine Carbon Dioxide Removal (mCDR)

- We are using ECCO-Darwin to support **Marine Carbon Dioxide Removal (mCDR) efforts and NASA ES2A**
- Determine how these approaches could provide **gigaton-scale carbon sequestration**
- Developing model tools for testing various mCDR approaches, scalability, durability, **and impact on marine ecosystems**
- Now expanding work to include **Ocean Iron Fertilization (OIF)** with funding from Google and Ocean Vision, and working on mCDR uncertainty quantification paper
- ECCO-Darwin participating in **OAEMIP** led by Carbon to Sea



Suselj et al. (2025), *JAMES*

[LEFT] Time-integrated ECCO-Darwin CO_2 removal from Ocean Alkalinity Enhancement

Substantial inter-model variation in OAE efficiency between the CESM2/MARBL and ECCO-Darwin ocean biogeochemistry models

Michael Dominik Tyka ✉, Mengyang Zhou, Elizabeth Yankovsky, and Dustin Carroll

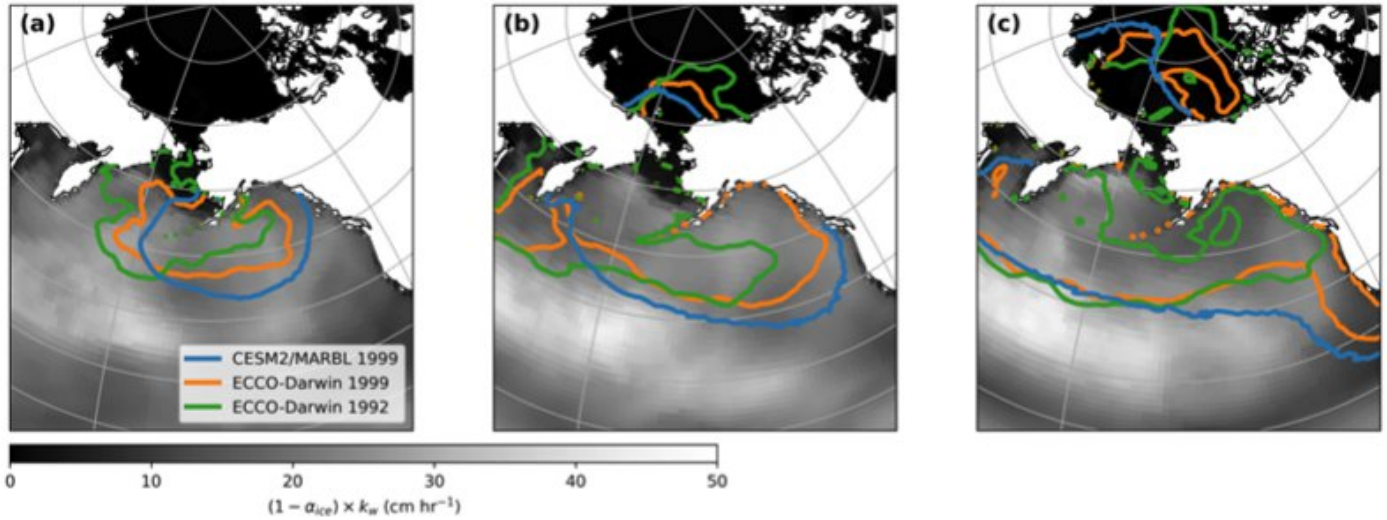


Figure 13. Three different plume outlines overlaid on the k parameter in greyscale from OceanSODA(Gregor and Gruber, 2021) after a) 12 b) 36 and c) 72 month after alkalinity release near Alaska.

Work led by Mike Tyka at

Google

Compared to CESM2, ECCO has more realistic representation of MLD, which is O(1) for mCDR

Tyka, M. D., Zhou, M., Yankovsky, E., & Carroll, D. (2026). Substantial inter-model variation in OAE efficiency between the CESM2/MARBL and ECCO-Darwin ocean biogeochemistry models. Biogeosciences, 1–35, *in press*.

Marine Carbon Dioxide Removal (mCDR)

ScienceAdvances

Current Issue First release papers Archive

HOME > SCIENCE ADVANCES > VOL. 11, NO. 25 > POTENTIAL OF CO_2 SEQUESTRATION THROUGH ACCELERATED WEATHERING OF LIMESTONE ON SHIPS

RESEARCH ARTICLE | OCEANOGRAPHY

Potential of CO_2 sequestration through accelerated weathering of limestone on ships

SIJIA DONG, WILLIAM M. BERELSON, PIERRE FORIN, MELISSA GUTIERREZ, DUSTIN CARROLL, DIMITRIS MENEMENLIS, ALBERT Y. KYI, AND JESS F. ADKINS Authors Info & Affiliations

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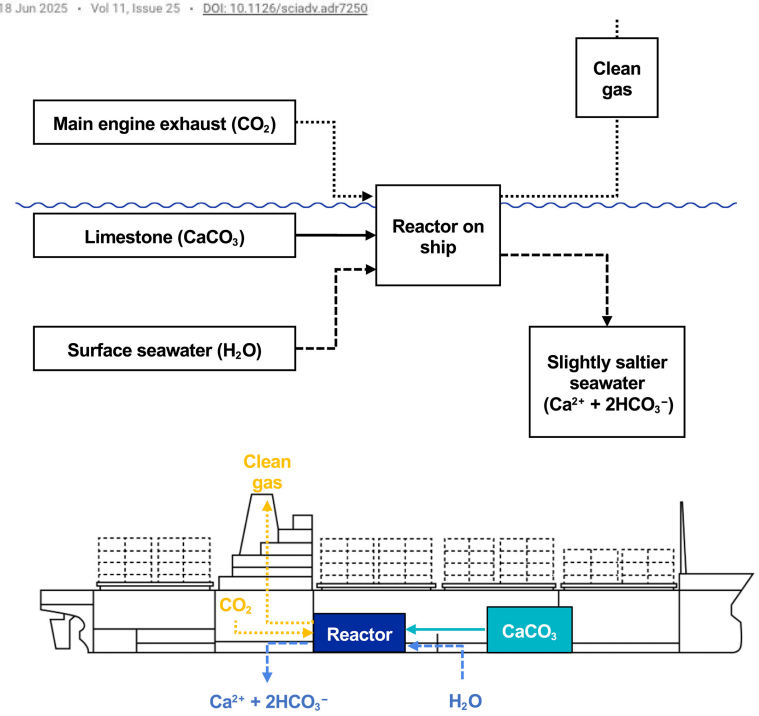
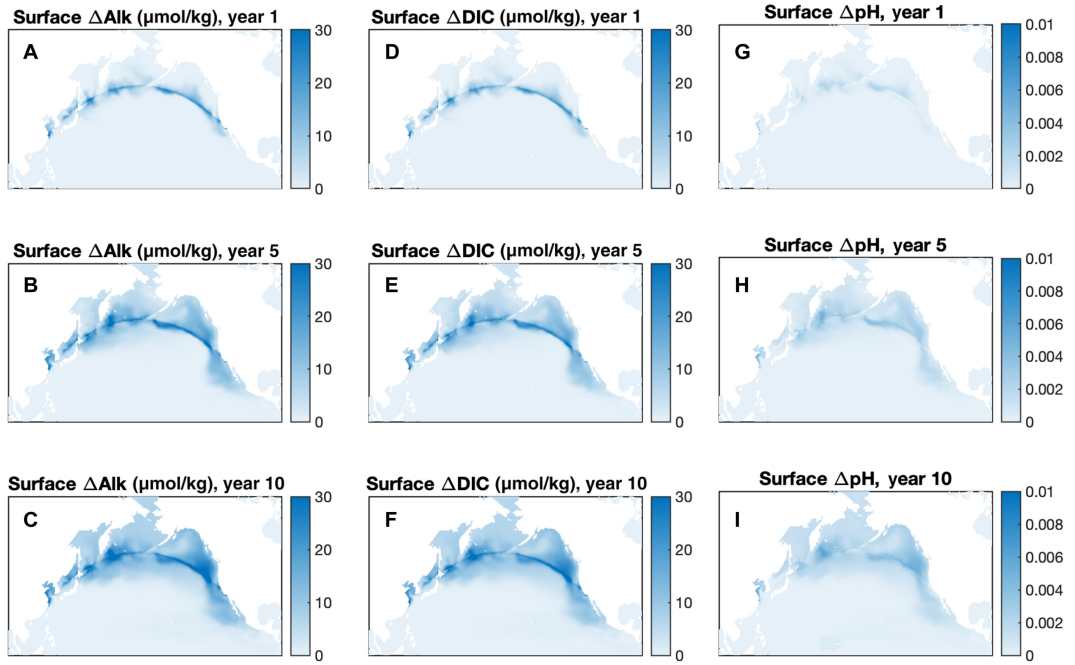


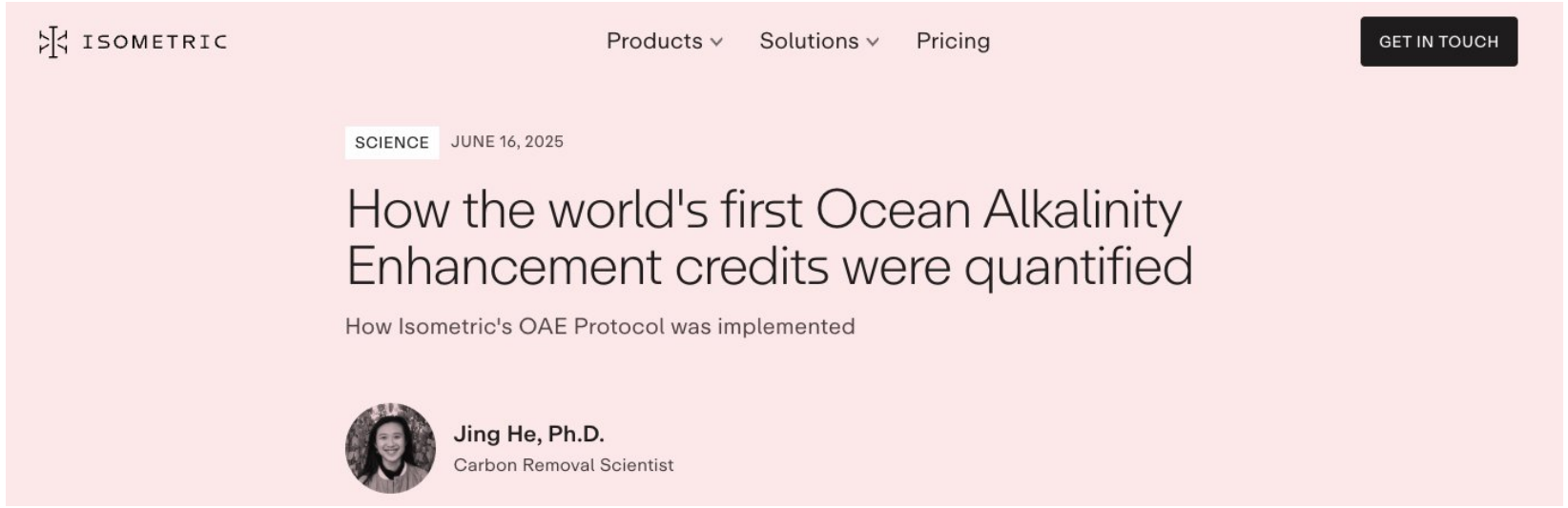
- **[LEFT]** Shipboard reactors using Accelerated Limestone Weathering (ALW) methods can reduce cargo ship CO_2 emissions by 50%
- **[BELOW]** ECCO-Darwin simulates impact on ocean carbon chemistry across a key shipping route in the Pacific Ocean



ECCO-Darwin Used to Quantify Ocean Carbon Credits

Planetary Technologies and Isometric **used ECCO-Darwin to model Ocean Alkalinity Enhancement (OAE) to support field trials and carbon credit quantification in Halifax, Canada**

PLANETARY



Global ECCO2 Darwin and DIC in "CMS I"

DIC model building blocks, forward and adjoint (cost air-sea CO2, K uncertainty quantification)

$$\frac{\partial C}{\partial t}_{DIC} = \text{Fluid Dynamics}_{DIC} + \text{Chemistry}_{DIC} + \text{Biology Source/ Sink}_{DIC}$$

ECCO2-Darwin model building blocks, forward and GF optimization (cost air-sea CO2, control initial C)

$$\frac{\partial C}{\partial t}_{E2D} = \text{Fluid Dynamics}_{E2D} + \text{Chemistry}_{E2D} + \text{Biology Source/ Sink}_{E2D}$$

Figure prepared by Chris Hill in 2014 for an unsuccessful proposal submitted to the CMS call

We can replace DIC pkg with BLING

Let's get it done!

ECCO-Darwin GitHub Repo

All code and instructions available at: https://github.com/MITgcm-contrib/ecco_darwin

- **1-D** water-column simulations (for testing new Darwin ecosystems)
- **3 deg**, based on verification/tutorial_global_oce_biogeo
- **1 deg**, based on LLC 90 ECCOV4r4 and V4r5
- **1/3 deg**, based on LLC 270 V5 alpha and V5r1, with time extension back to 1985
- **Regional** cut-outs (based on LLC 270 and higher resolution)
- **Detailed instructions for downscaling** based on diagnostics_vec pkg
- **Legacy** simulations (including CS 510 solutions)
- **Platform-independent instructions** for compilating/integrating
- **Example analysis scripts** in MATLAB/Python

Published ECCO-Darwin model output (ECCO Data Portal):
https://data.nas.nasa.gov/ecco/

ECCO-Darwin time extension to near-present (ECCO Drive):
https://ecco.jpl.nasa.gov/drive/files/ECCO2/LLC270/ECCO-Darwin_extension

Thank you!

Email: dustin.carroll@sjsu.edu