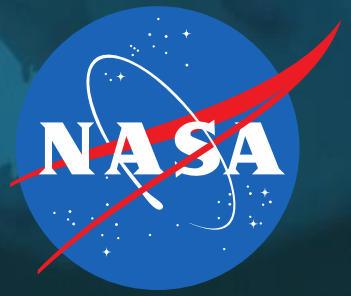
ECCO-Darwin Development Update

Dustin Carroll, Dimitris Menemenlis, Stephanie Dutkiewicz, Jonathan Lauderdale, Jess Adkins, Kevin Bowman, Holger Brix, Ian Fenty, Gaël Forget, Mick Follows, Michelle Gierach, Chris Hill, Oliver Jahn, Peter Landschützer, Junjie Lui, Manfredi Manizza, Matt Mazloff, Charles Miller, Yoshihiro Nakayama, John Naviaux, Christian Rödenbeck, David Schimel, Tom Van der Stocken, Ariane Verdy, Daniel Whitt, Hong Zhang, and many others…

SJSU SAN JOSÉ STATE UNIVERSITY



ECCO Annual Meeting 2024

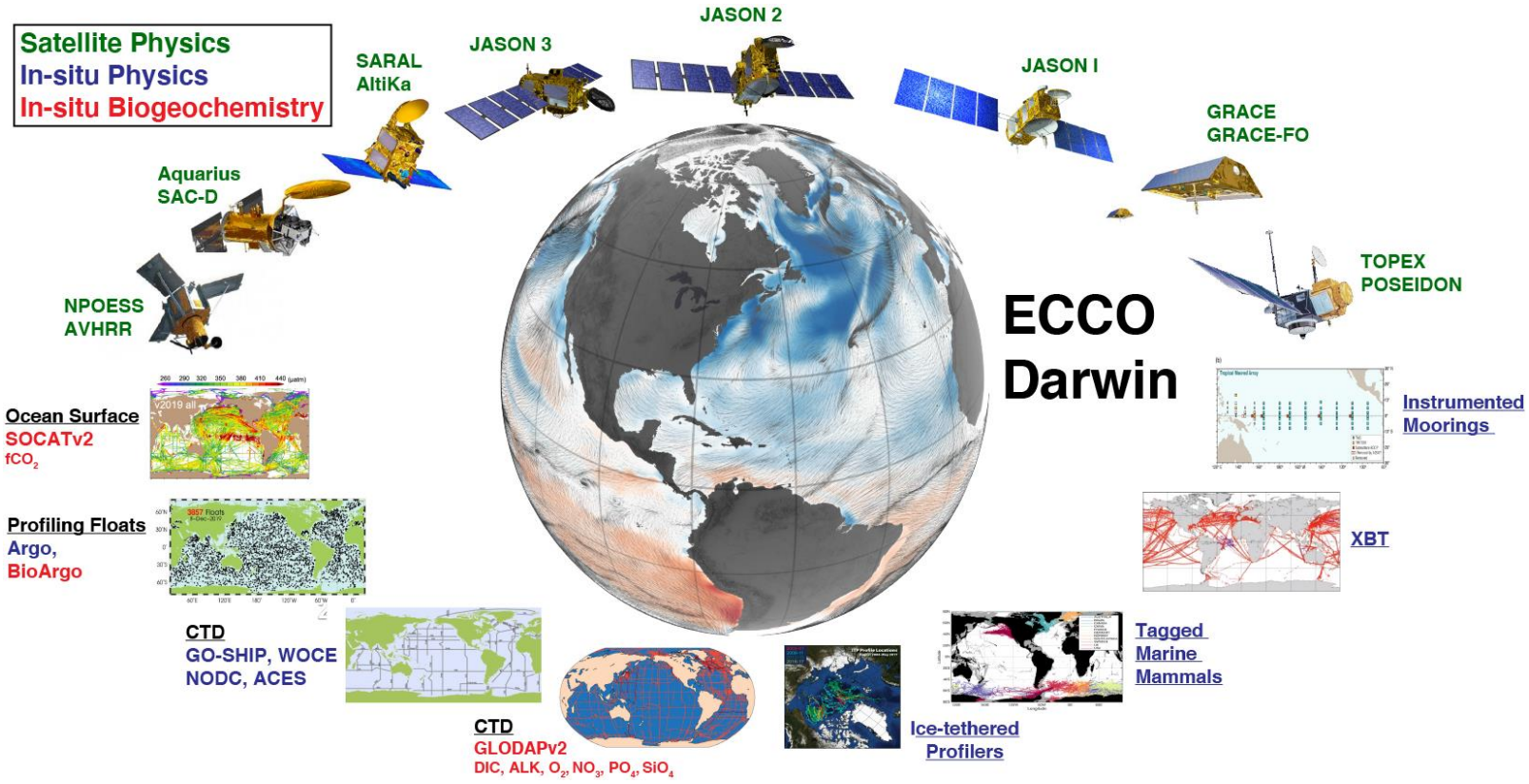
Flagship ECCO Carbon/BGC Products

ECCO Simulation	**ECCO-Darwin**	**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	Southern Ocean	Tropical Pacific Ocean	Arctic and Subpolar North Atlantic Ocean
Nominal Resolution	1 deg, 1/3 deg	1/6 deg	1/6 deg	1/3 deg
Model Period	1992–2023	2013–2021	2010–2018	2002–2017
Biogeochemistry	Darwin	BLING	BLING	BLING
Reference	*Carroll et al. 2020, 2022, 2024*	*Verdy and Mazloff, 2017*	*Verdy et al. 2017*	*Nguyen et al. 2021, 2023*

+ downscaled simulations (see talks by Clément Bertin and Mike Wood)…

ECCO-Darwin Overview

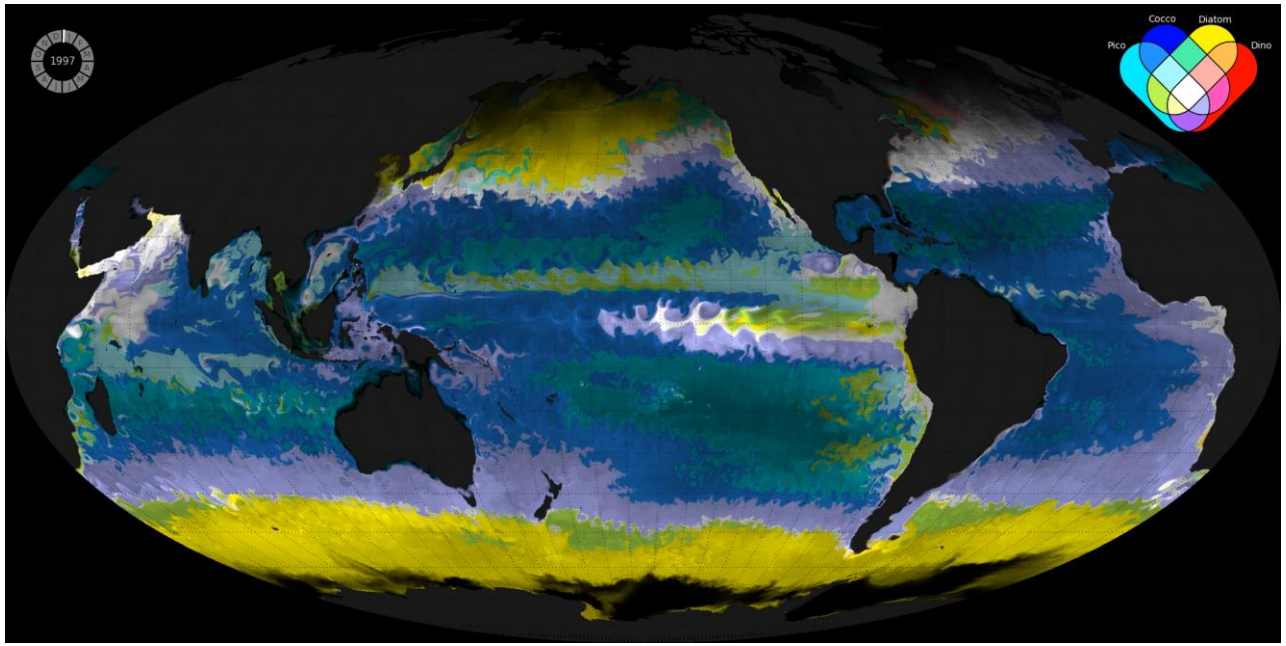
- **ECCO-Darwin** = ocean biogeochemistry state estimate (1992–2023)
- Based on ECCO framework (physically consistent, property-conserving data assimilation, important for carbon budgets)
- Both LLC 90 V4r4/V4r5 and LLC 270 versions now available
- MIT Darwin ecology model
- Physical (adjoint method) 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 **pkg/radtrans** simulates radiative transfer through water column — *direct link to NASA satellite ocean-color products*
- Currently expanding global-ocean ECCO-Darwin ecosystem to have 6 phyto- and 4 zoo-plankton functional types + radiative transfer



Darwin Ecological Provinces
Visualization Credit: Oliver Jahn, MIT

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

Ongoing ECCO-Darwin Projects

Model Development

Global Carbon Cycling

Regional Studies

Marine Ecosystems

Land-to-ocean

Ocean carbon sink variability: Internal vs. forced mechanisms
PI: G. McKinley

Using the ECCO-Darwin data-assimilative global-ocean biogeochemistry model to quantify the drivers and uncertainty of ocean carbon sources and sinks
PI: D. Menemenlis

NASA Carbon Monitoring System Flux (CMS-Flux) in support of the global stocktake
PI: K. Bowman

Ecosystem engineers: The role of diel vertical migrators in redistributing marine biogeochemical properties
PI: M.M. Wilhelmus

ECCO: Connecting NASA ocean, cryosphere, and biogeochemistry observations to support national climate policy
PI: I. Fenty

Impacts of changing sea-ice regimes on Arctic Ocean biology
PI: C. Miller

Elucidating the role of the ocean circulation in changing North Atlantic Ocean nutrients and biological productivity
PI: D. Whitt

Exploring AMOC controls on the North Atlantic carbon sink using novel inverse and data-constrained models (EXPLANATIONS)
PI: N. Mackay

Closing the carbon cycle loop: quantifying land-to-sea carbon fluxes
PI: D. Carroll

A land to sea paradigm: impact of spatially and temporally varying nutrient and freshwater fluxes on coastal carbon dynamics in the northern Gulf of Mexico
PI: M. Gierach

Estimating the past, present, and future response of marine primary productivity to Greenland ice sheet melt
PI: M. Wood

- **Carbon Cycling:** Wu et al., 2021; Carroll et al. 2020, 2022, **2024; Byrne et al. 2022; Suplis et al. 2022; Schimel and Carroll, 2024; Yasunaka et al. 2023; DeVries et al. 2023; Hauck et at. 2023; Mackay et al. 2024; Sun et al., *in revision*; Suselj et al., *in review;* Savelli et al., *in prep.***
- **Nutrient Cycling:** Follett et al. 2021; Gupta et al. 2022
- **Plankton Ecosystem Dynamics and Diversity:** Juranek et al. 2020; Dutkiewicz et al. 2020, 2021, 2024; Zúñiga et al. 2021; Tsakalakis et al. 2021; Wu et al. 2021; Treguer et al. 2021; Follett et al. 2022; Archibald et al. 2022; Manizza et al. 2019, **2023**; **Mattei et al., *in prep.***
- **Methylmercury in Marine Systems:** Wu et al. 2020, 2021; Zheng et al. 2021
- **Statistical Analyses and Province Definitions:** Sonnewald et al. 2021; Hyun et al. 2022; **Jonsson et al. 2023; McGinty et al., 2023**
- **Links to Satellite Products:** Dutkiewicz et al. 2018; **Jonsson et al. 2023; Serra-Pompeii et al. 2023; Madani et al., *in prep.***
- **Genomics:** Mieller et al. 2022; **Raut et al., *in prep.***
- **Global Bacteria/Archaeal Community Structure:** Zakem et al. 2020; **Zakem et al., *submitted***
- **Inclusion of Cell-level Macromolecules** Inomura et al. 2022; **Sharoni et al., *in prep.***
- **Land-to-ocean: Bertin et al. 2023; Bertin et al., *in review;* Savelli et al., *in prep.*; Castro Morales et al., *in prep*; Le Fouest et al. *in prep.***

Recent manuscripts
(**blue = since last ECCO Annual Meeting**)
associated with a combination of ECCO physics **(rows)** and Darwin ecosystem complexity **(columns)**

P = phyto Z = zoo	2P + Macro Molecules	2P + 2Z + Many Non-auto Prokaryotes	5P + 2Z	15P + 16Z	35P + 16Z w/ Radiative Transfer	350P + 16Z w/ Radiative Transfer	31P + 16Z + 3B w/ Radiative Transfer
ECCO-GODAE	Inomura et al. 2022; **Sharoni et al., *in prep.***	Zakem et al. 2020; **Zakem et al., *submitted***		Tsakalakis et al. 2022; Wu et al. 2021b	Juranek et al. 2020; Wu et al., 2020; Dutkiewicz et al. 2021; Meiler et al. 2022	Dutkiewicz et al. 2020	Follett et al. 2022; Archibald et al. 2022; **Serra-Pompeii et al. 2023; Dutkiewicz et al. 2024; Mattei et al., *in prep.***
LLC 90 ECCO/ ECCO-Darwin			**Suselj et al., *in review;* Savelli et al., *in prep.***		Sonnewald et al. 2020; Follett et al. 2021; Wu et al. 2021a; Zhang et al. 2021; Hyun et al. 2022; **Jonsson et al. 2023**		
LLC 270 ECCO-Darwin			Carroll et al. 2020, 2022, **2024;** Zúñiga et al. 2021 Sulpis et al. 2021; **Carroll and Schimel, 2024; Yasunaka et al. 2023; DeVries et al. 2023; Hauck et at. 2023; Mackay et al. 2024; Sun et al., *in revision;* Madani et al. *in prep.***				
CS 510 ECCO2-Darwin			Manizza et al. 2019, **2022**		Kuhn et al. 2019; Gupta et al. 2022; Treguer et al. 2021; **Raut et al., *in prep.***		
LLC 4320					Wilson et al. 2019		
Regional ECCO-Darwin			**Bertin et al. 2023; Bertin et al. *in review;* Castro Morales et al. *in prep;* Le Fouest et al. *in prep.***				

ECCO-Darwin Model-data "Evaluation" Framework

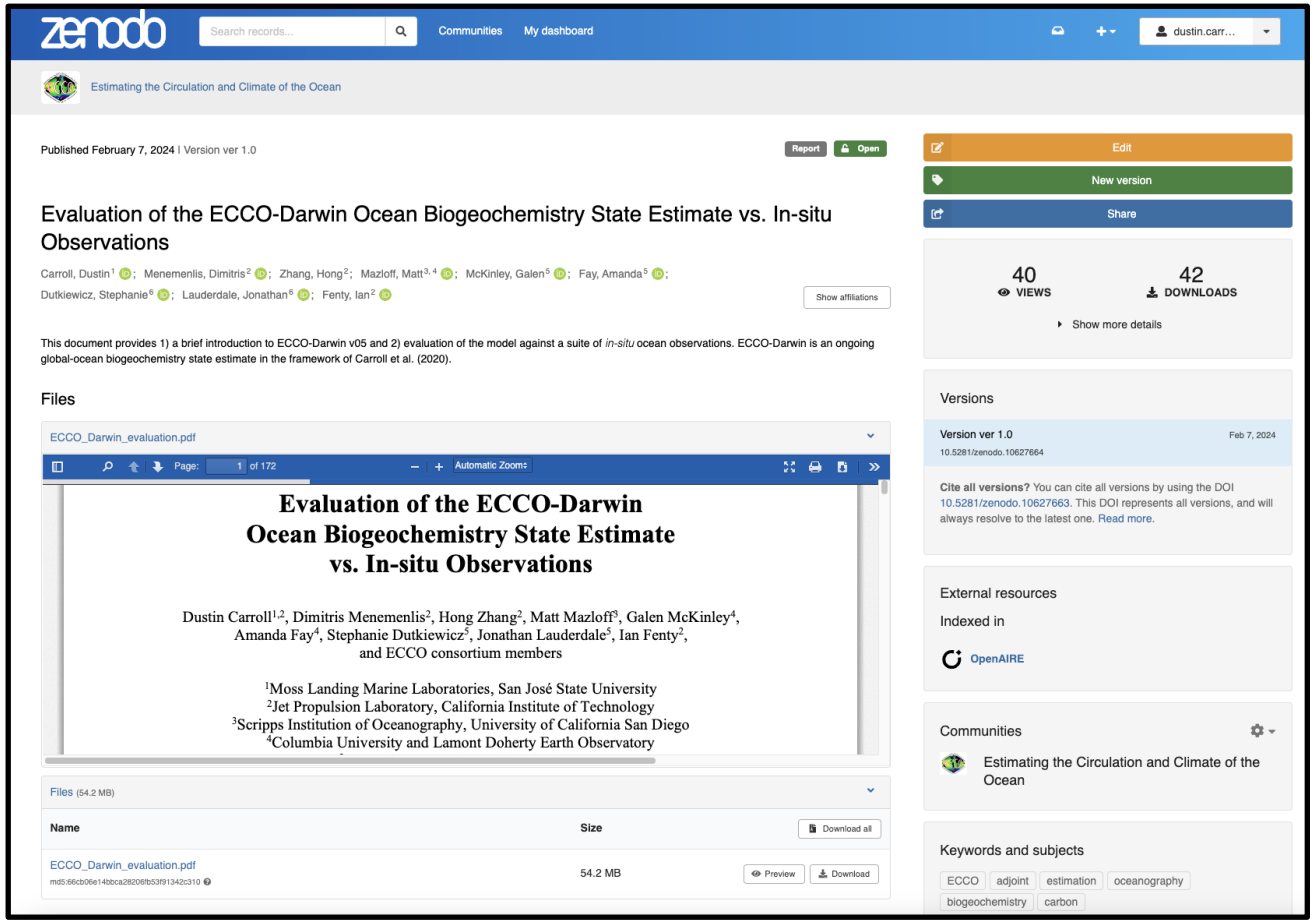
- **Comprehensive framework + white paper** for providing full transparency of model vs. in-situ observations for each ECCO-Darwin release

- Model evaluation against all available SOCAT, GLODAP, and BGC-Argo observations

- 9 pages of high-level model description/text

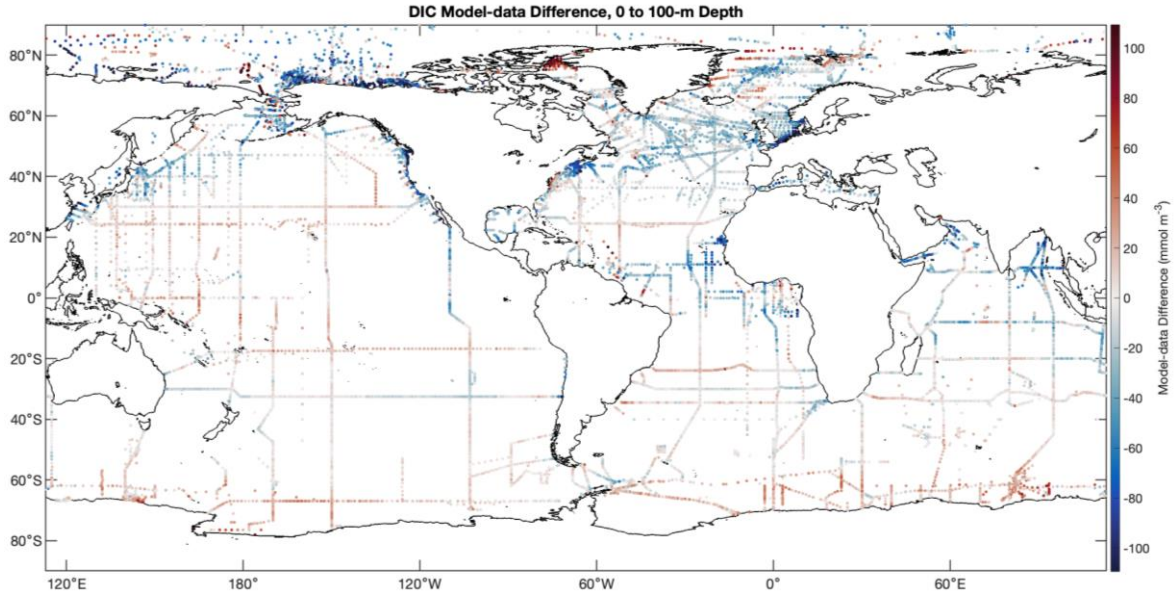
135 evaluation figures:

- Analysis in global ocean + 22 distinct biomes
- Time-mean fields (surface ocean and various depth ranges)
- Model-data scatterplots w/ statistics
- Vertical profiles
- Seasonal climatology
- Monthly and annual-mean time series of all model-data pairs over simulation period

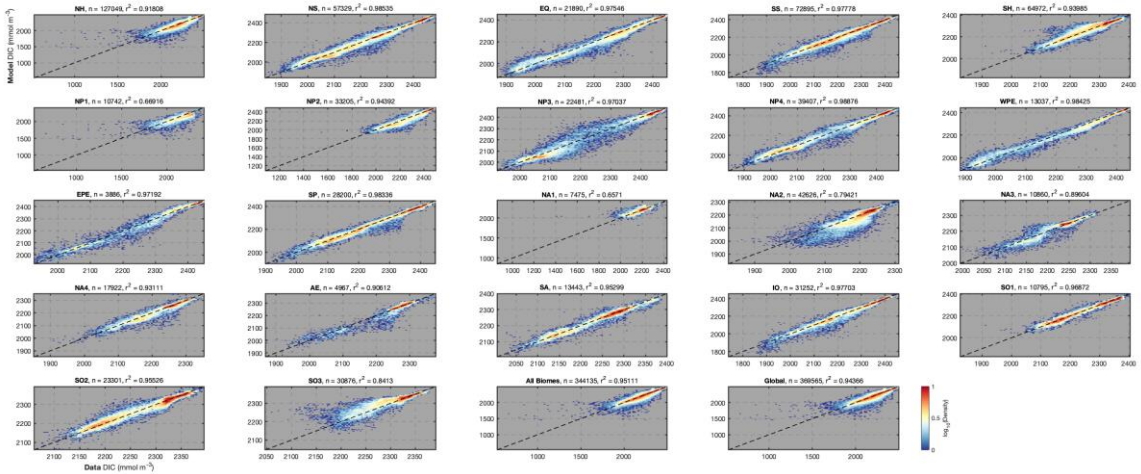


https://zenodo.org/records/10627664

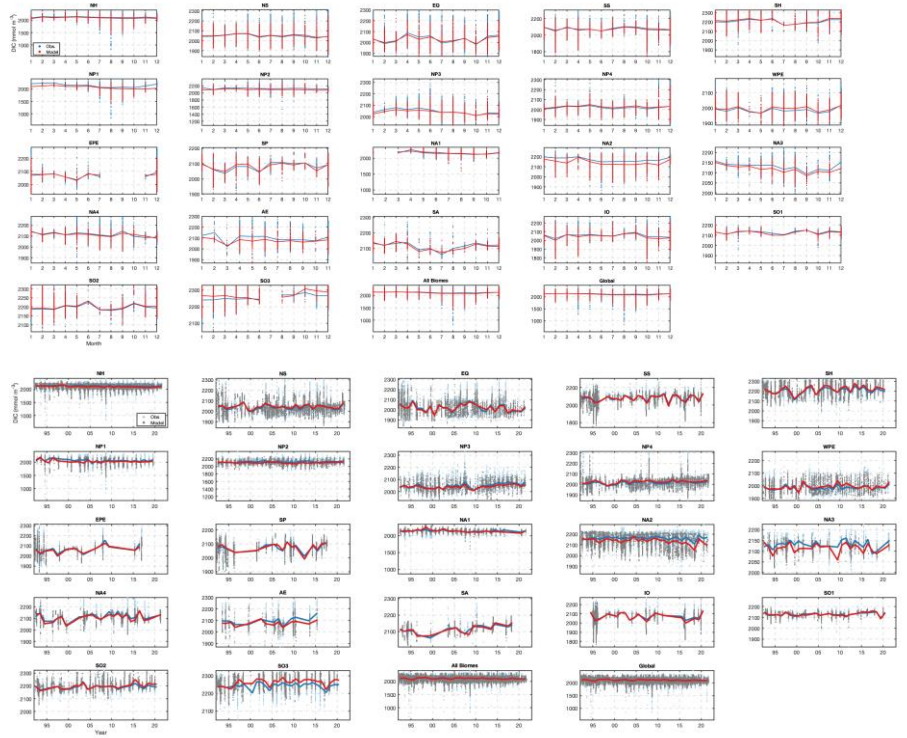
Climatological Fields



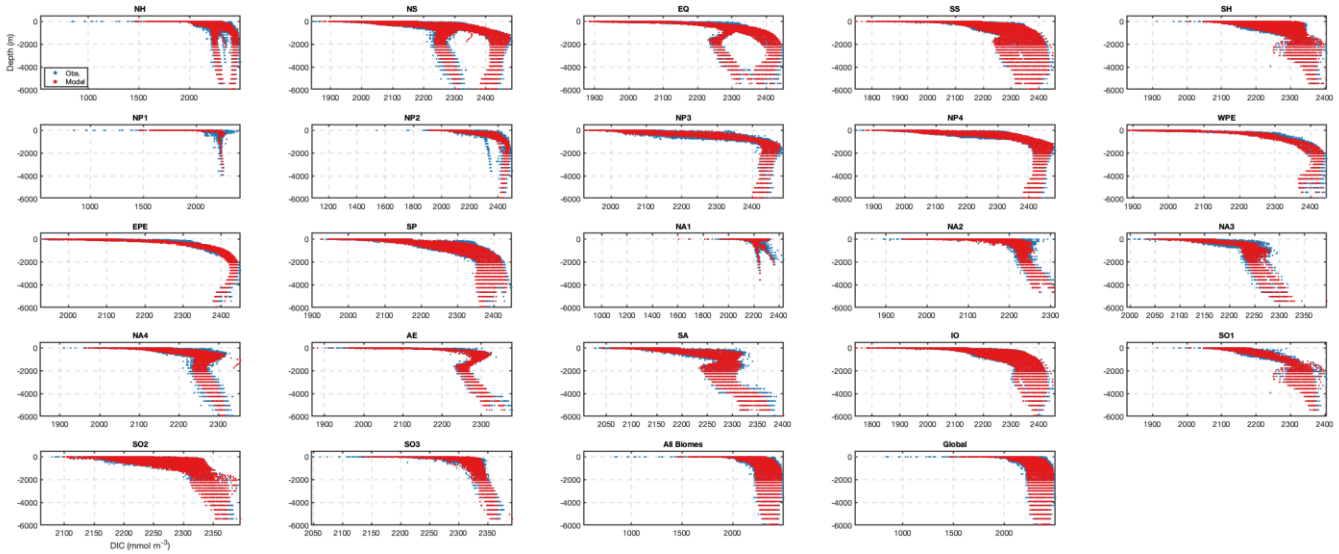
Model-data Scatterplots



Seasonal and Interannual Time Series

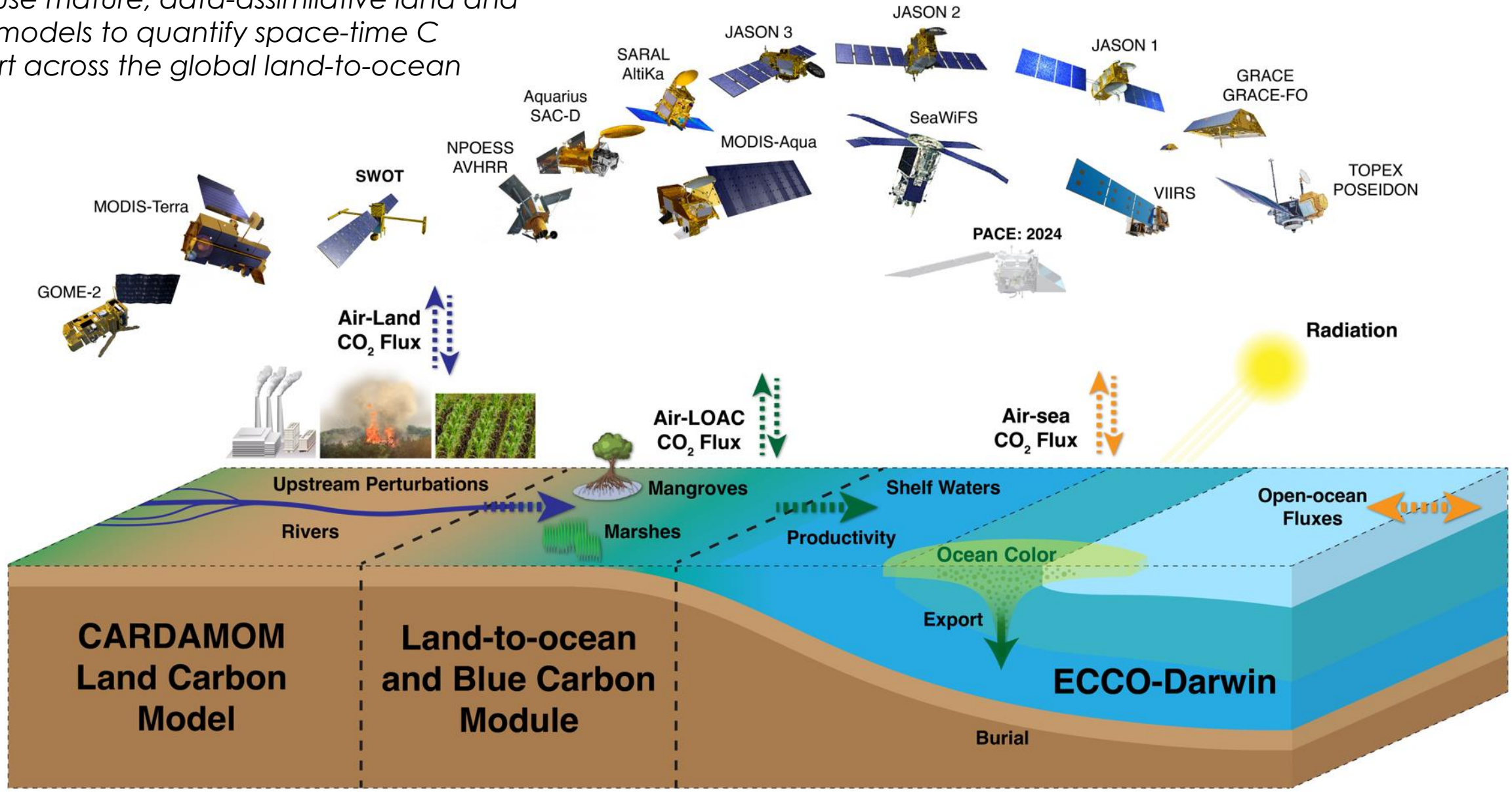


Vertical Profiles



Land-to-ocean ECCO-Darwin Vision:

Goal: *Fuse mature, data-assimilative land and ocean models to quantify space-time C transport across the global land-to-ocean system*



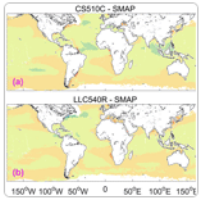
NASA Carbon Monitoring Systems (CMS) PI: D. Carroll

ECCO-Darwin Land-to-ocean Efforts

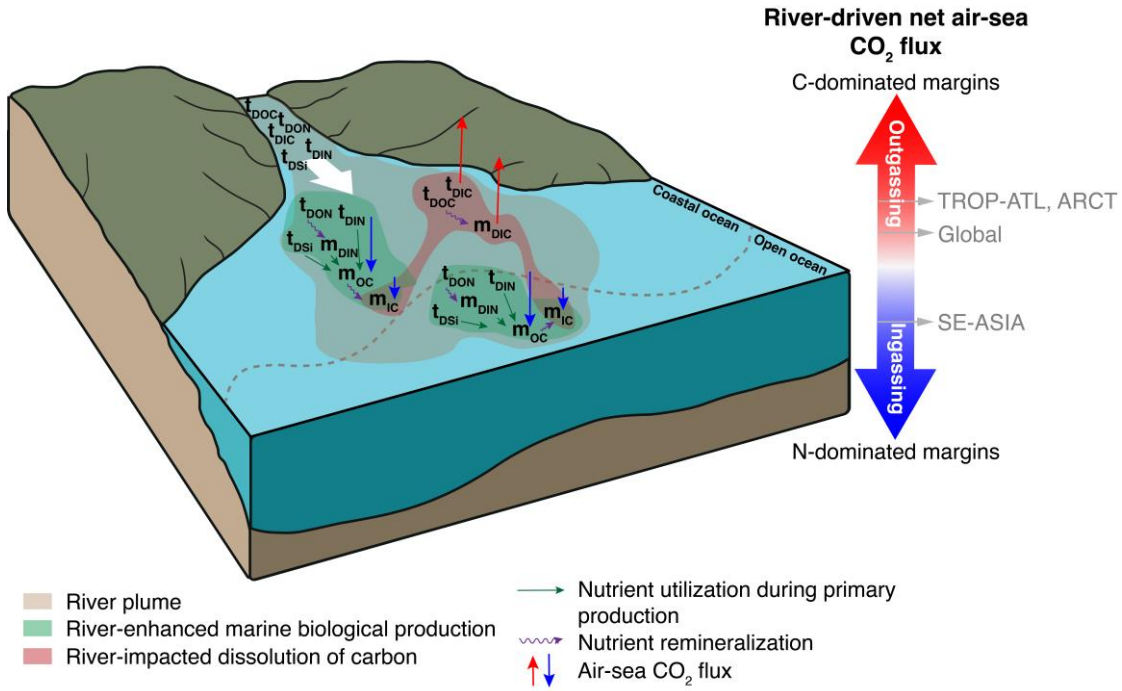
- Building on results from Feng et al. 2021, which showed that using daily point-source discharge improves model fit to SMAP observations
- **Implemented daily, point-source freshwater and carbon/nutrient discharge in LLC 90 and LLC 270 ECCO-Darwin simulations**
- Combine freshwater discharge from JRA55-do and Global NEWS 2 watershed model
- Results in BGC discharge from 5,171 rivers worldwide
- Sensitivity experiments to assess role of freshwater, carbon, and nutrient discharge on ocean carbon cycling (See talk by Raphaël Savelli)
- Using this discharge product in downscaled simulations

Development and technical paper | 01 Apr 2021

Improved representation of river runoff in Estimating the Circulation and Climate of the Ocean Version 4 (ECCOv4) simulations: implementation, evaluation, and impacts to coastal plume regions



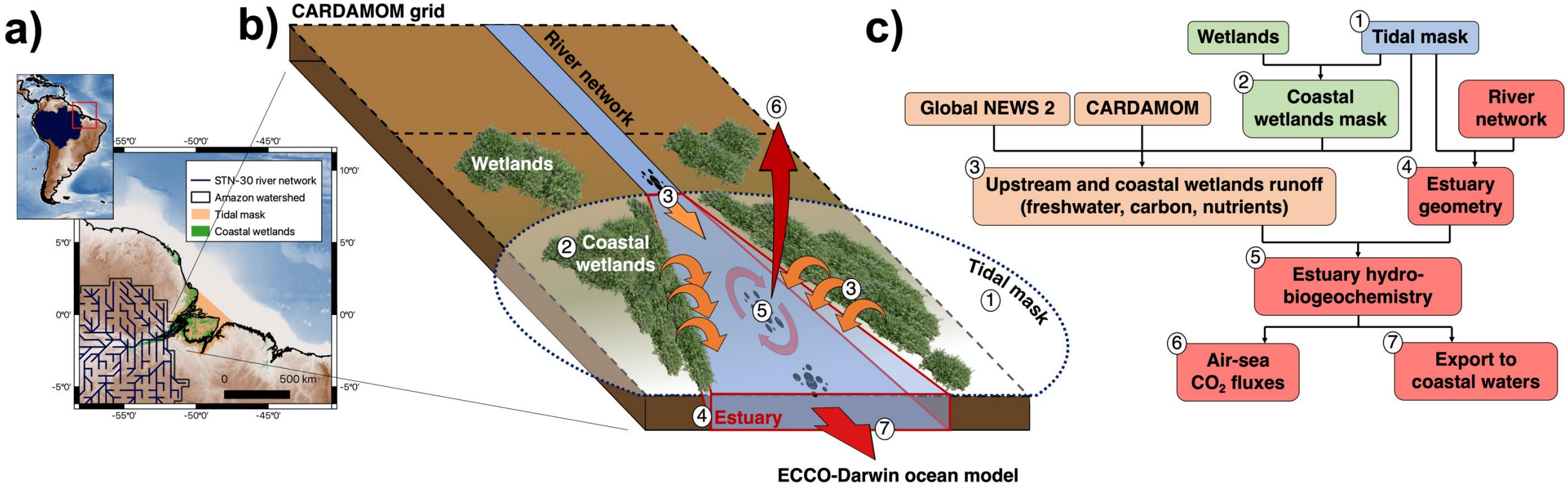
Yang Feng, Dimitris Menemenlis, Huijie Xue, Hong Zhang, Dustin Carroll, Yan Du, and Hui Wu



Savelli et al. *in prep.*

Land-Ocean-Aquatic-Continuum (LOAC) Module

- Developing a **LOAC Module** to link CARDAMOM land and ECCO-Darwin ocean
- Spatially-explicit C runoff from blue carbon ecosystems will be computed with CARDAMOM and an estuarine hydro-biogeochemistry model



ECCO-Darwin Downscaling

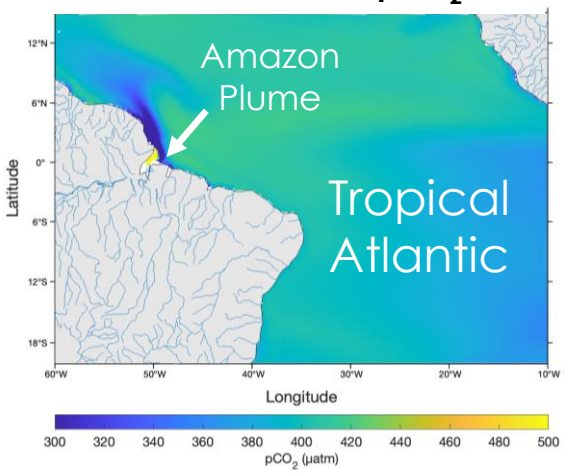
Available Downscaled Simulations:

- Beaufort Sea w/ BGC discharge (see talk by Clément Bertin)
- California Current System
- Coastal West France
- Disko Bay w/ iceplume (see talk by Mike Wood)
- East Antarctica (Totten Ice Shelf)
- East/West Greenland
- Gulf of Mexico w/ BGC discharge
- Gulf of Alaska
- Gulf of Guinea
- Mediterranean and Black Sea
- Tropical Atlantic w/ BGC discharge

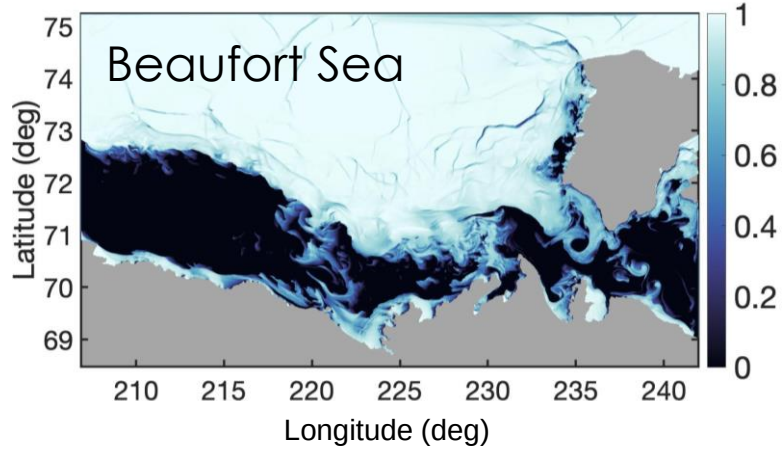
Currently Adding:

- Colored Dissolved Organic Matter (CDOM)
- Coastal sediment model (RADIv2)
- Improved representation of under-ice light

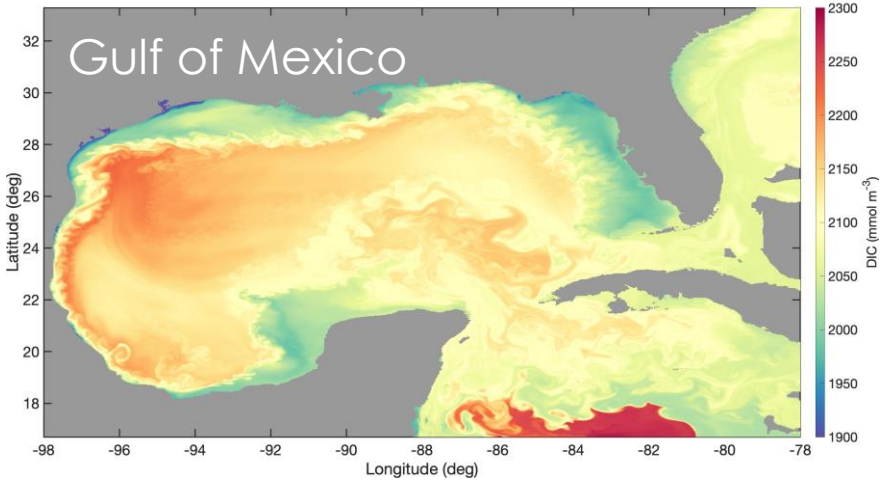
Surface-ocean pCO_2



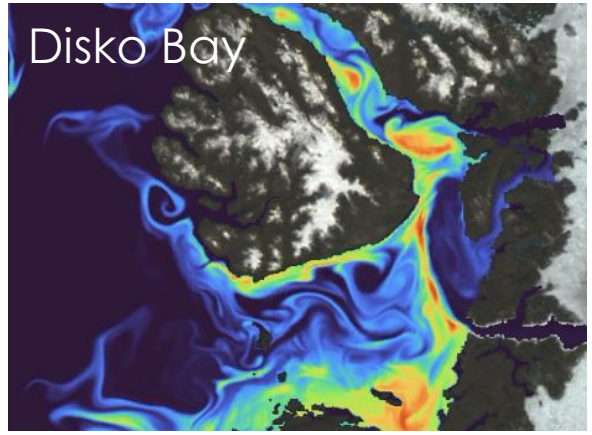
Sea-ice Cover



Surface-ocean DIC

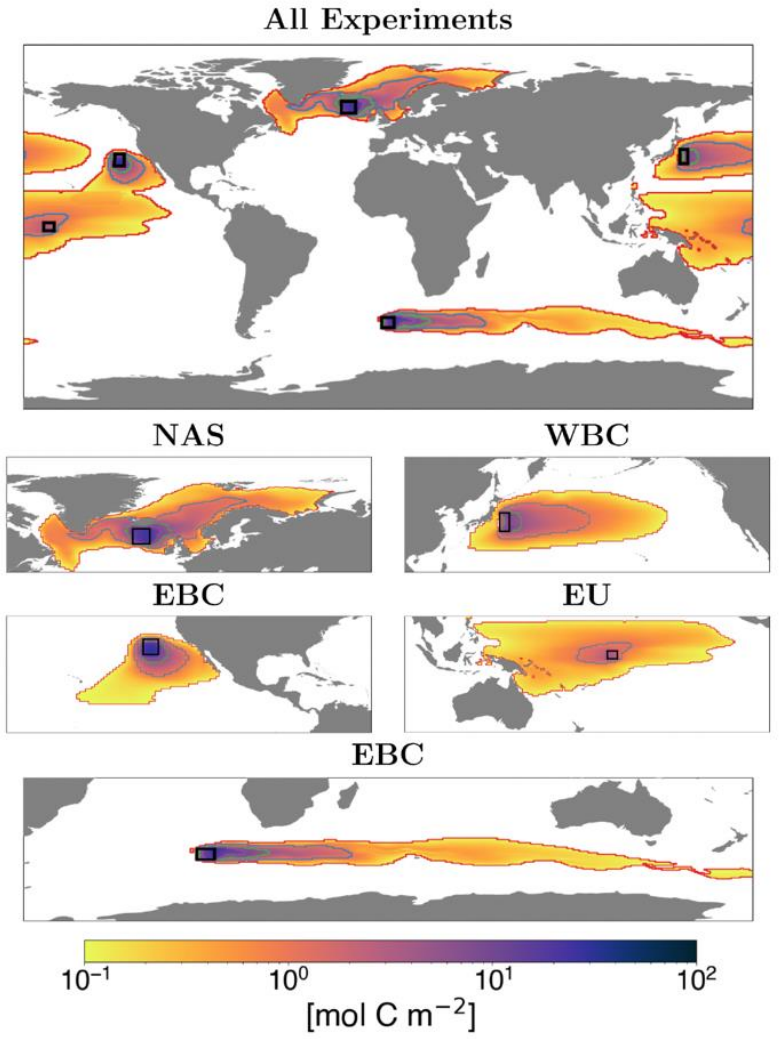


Surface-ocean Chl



Marine Carbon Dioxide Removal (mCDR)

- Using ECCO-Darwin to simulate **marine carbon dioxide removal (mCDR)**
- Currently focused on ocean alkalinity enhancement (OAE), biomass sinking, and coastal kelp afforestation
- ECCO-Darwin is a powerful tool for testing various mCDR approaches, scalability, durability, and impact on marine ecosystems
- Connects ECCO w/ NASA Earth Science to Action



Suselj et al. *in review, AGU: Earth's Future*

Ocean alkalinity enhancement at 5 open-ocean regions

Use ECCO-Darwin budgets to quantify carbon sequestration potential

ECCO-Darwin mCDR proposal submitted to NASA CMS 2024

[LEFT] Time-integrated CO_2 removal from ocean alkalinity enhancement

Pre-print available at: https://zenodo.org/records/10632054

ECCO-Darwin Industry Stakeholders

- IPCC's 6th Assessment Report emphasizes that atmospheric CO_2 removal on the gigaton scale will be necessary to reach net-zero emissions (IPCC, 2022)
- White House Office of Science and Technology Policy (OSTP) has established a new Fast-Track Action Committee on Marine Carbon Dioxide Removal (MCDR–FTAC)
- Goal is to develop a comprehensive Federal mCDR research program
- Private companies and non-profit organizations are interested in using ECCO-Darwin for **mCDR quantification**

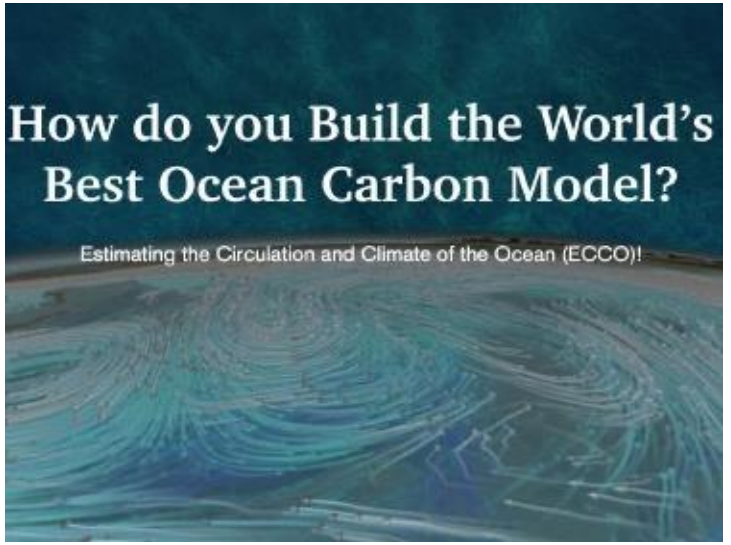
How can ECCO better address societally-relevant issues?

https://assets.science.nasa.gov/content/dam/science/esd/earth-science-division/earth-science-to-action/ES2A_2-Page_web.pdf

Google Worthy PRONOE RUNNING TIDE ISOMETRIC CLIMATE FOUNDATION

Communicating ECCO-Darwin Results

- We use **ECCO-Darwin ArcGIS StoryMaps** to communicate science results to a broader audience and stakeholders
- Especially important for BGC and stakeholder community!
- Use blend of visuals and informative text to introduce topics and describe key paper results
- Embed interactive model-data visualization (NetCDF), movies, and figures
- Special thank you to Annette deCharon!



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

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, with time extension back to 1985
- Regional cut-outs (based on LLC 270 and higher resolution)
- Legacy simulations (including CS 510 solutions)
- Platform-independent instructions for compilating/integrating
- Example analysis scripts in MATLAB/Python

ECCO-Darwin output now available at U.S. Greenhouse Gas (GHG) Center

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

ECCO-Darwin output at **U.S. Greenhouse Gas (GHG) Center:**
https://earth.gov/ghgcenter/data-catalog/eccodarwin-co2flux-monthgrid-v5

Thank you!