Ocean Carbon and Biogeochemistry: A "Killer App" for ECCO

Dustin Carroll, Dimitris Menemenlis, Stephanie Dutkiewicz,
Jonathan M. Lauderdale, Jess F. Adkins, Kevin W. Bowman, Holger Brix,
Ian Fenty, Michelle M. Gierach, Chris Hill, Oliver Jahn,
Peter Landschützer, Junjie Lui, Manfredi Manizza, Matt R. Mazloff,
Charles E. Miller, John Naviaux, Christian Rödenbeck, David S. Schimel,
Ariane Verdy, Tom Van der Stocken, Daniel B. Whitt, Hong Zhang,
and many others…

Moss Landing Marine Laboratories

SJSU SAN JOSÉ STATE UNIVERSITY

NASA

ECCO Annual Meeting 2023

What is a "Killer App"?

- In marketing terminology, a **"killer app"** is any software that is so necessary or desirable that it proves the core value of some larger technology.

- For example, consumers would buy the more expensive hardware just to run that application. A killer app can substantially **increase sales** of the platform on which it runs.

"One mark of a good computer is the appearance of a piece of software specifically written for that machine that does something that, for a while at least, can only be done on that machine." Steven Levy (Wired Magazine), 1985

What is a “Killer App”?

“One mark of a good ocean state estimate is the appearance of applications specifically written for that solution that does something that, for a while at least, can only be done with that solution.”

What is a "Killer App"?

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Carbon

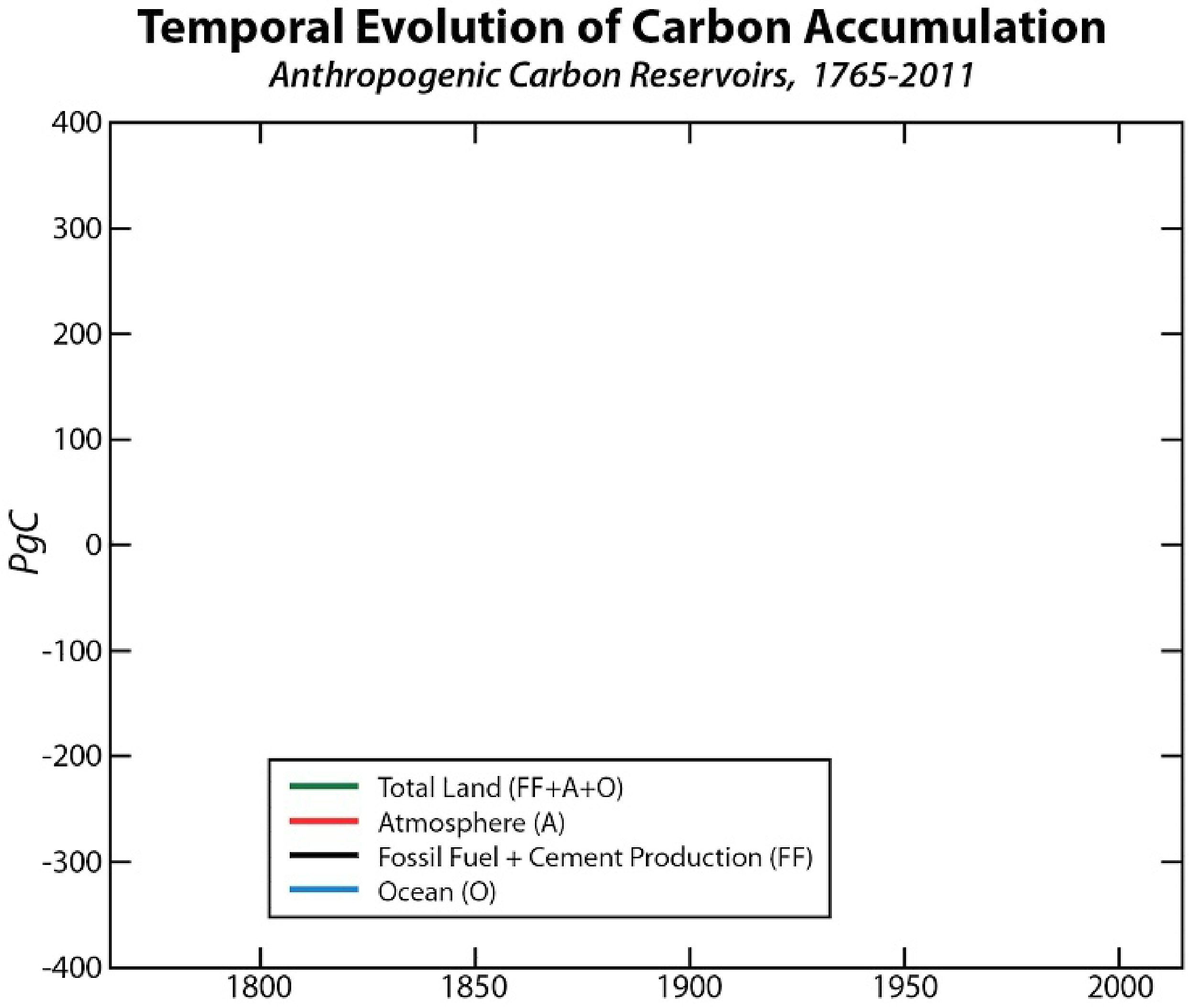
Biogeochemistry

Estimating the Circulation and Climate of the Ocean

ECCO

National Aeronautics and Space Administration

Our Market: Earth's Carbon Cycle



Khatiwala et al. *Nature* (2009); *Biogeoscience* (2013)

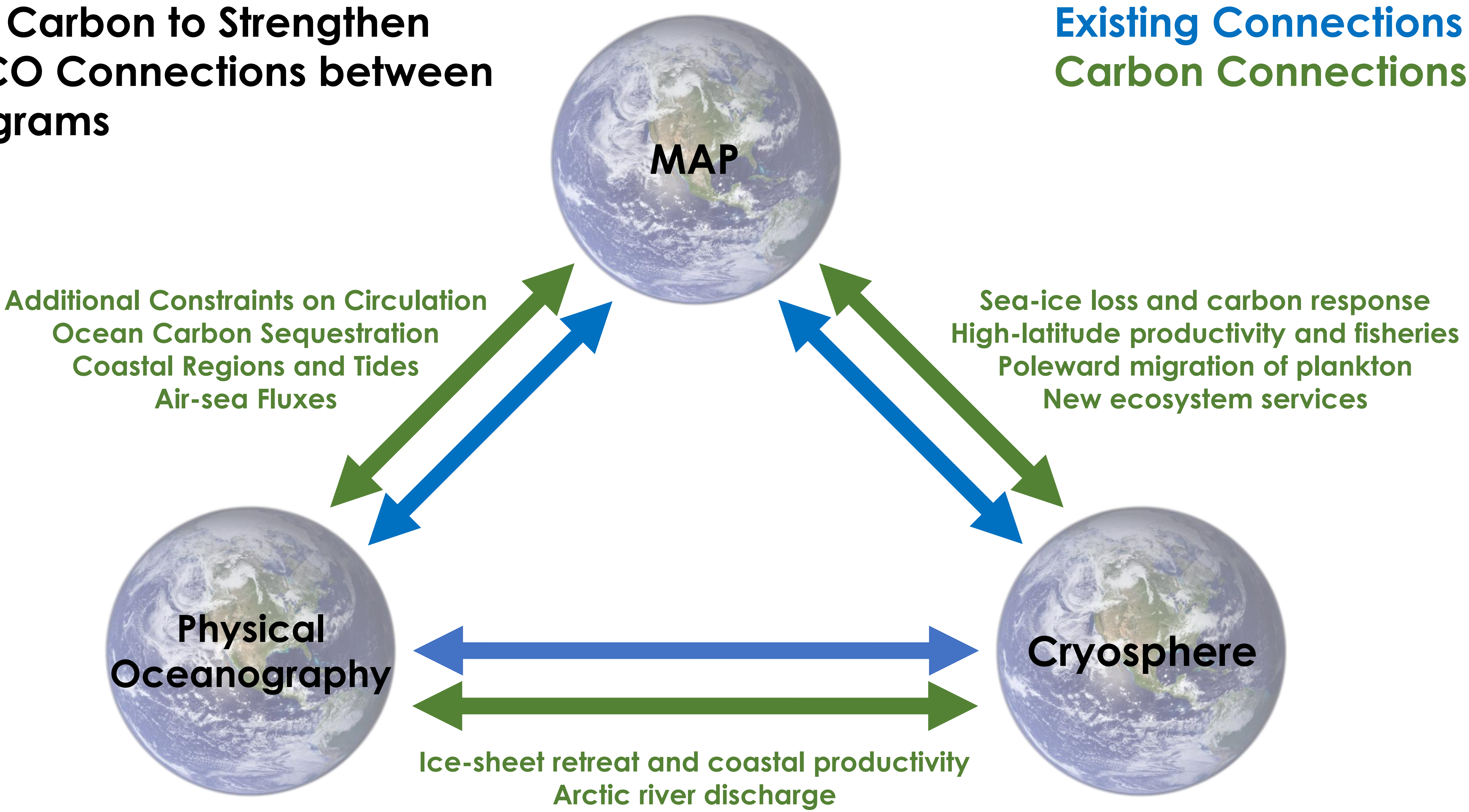
- Anthropogenic emissions adversely affect the socio-economic stability of human society and global marine-terrestrial ecosystems.
- The ocean has absorbed **~40% of CO_2** emissions since the beginning of the industrial era.
- **There has never been a greater need for delivering timely, policy-relevant science on the magnitude and evolution of the human-impacted global carbon cycle.**

Goal: Use ECCO framework to address this problem

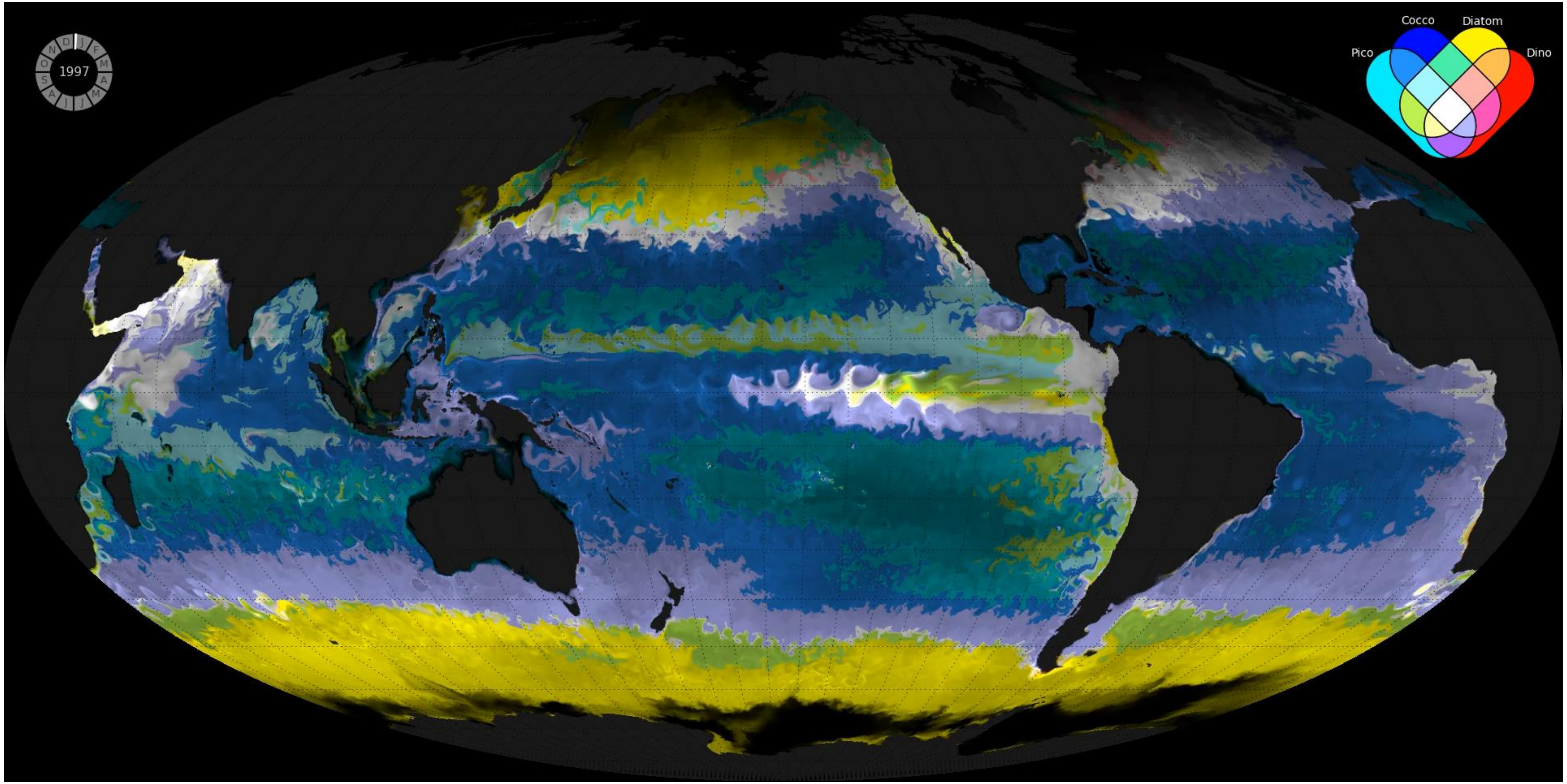
Why is Carbon a "Killer App" for ECCO?

- Our existing user base and open-source tools (community and transparency)
- Data-assimilation technology + solutions spanning multiple decades
- Property conservation and budgets (key for ocean carbon studies)
- Realism of *Darwin* and *BLING* biogeochemistry packages
- Diversity of ECCO products (ECCOV4r4 to LLC 4320)
- Our "ecosystem" of outreach materials (ECCO/MITgcm website, ArcGIS StoryMaps, NASA Scientific Visualization Studio products)

Use Carbon to Strengthen ECCO Connections between Programs



Asset: Darwin Ecosystem Model



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	1/3 deg	1/6 deg	1/6 deg	1/3 deg
Model Period	1992–2022	2013–2021	2010–2018	2002–2017
Biogeochemistry	Darwin	BLING	BLING	BLING
Reference	*Carroll et al. 2020, 2022*	*Verdy and Mazloff, 2017*	*Verdy et al. 2017*	*Nguyen et al. 2021*

Plus downscaled simulations…

Recent Darwin Ocean Ecology Studies That Use ECCO Products (Since 2019):

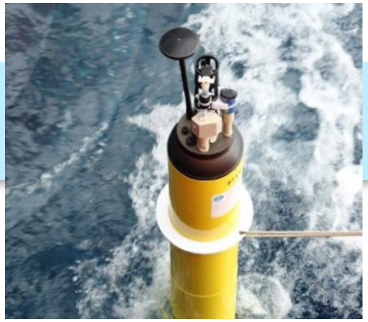
- **Carbon Cycling:** (Carroll et al. 2020, 2022)
- **Nutrient Cycling:** (Gupta et al. 2022; Follett et al. 2021)
- **Plankton Ecosystem Dynamics and Diversity:** (Juranek et al. 2020; Dutkiewicz et al. 2020, 2021, *in prep;* Tsakalakis et al. 2021; Wu et al. 2021; Treguer et al. 2021; Follett et al. 2022; Archibald et al. 2022; Manizza et al. 2019, 2022, *in revision*)
- **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; Jonsonn et al. *submitted*)
- **Links to Satellite Products:** (Dutkiewicz et al. 2018; Jonnson et al. *in review;* Serra-Pompeii et al. *in review*)
- **Links to Genomic Data:** (Mieller et al. 2022; Raut et al. *in prep.*)
- **First Applications of Global Bacteria/Archaeal Community Structure:** (Zakem et al. 2020) and **Inclusion of Cell-level Macromolecules** (Inomura et al. 2022)

	2P + Macro Molecules	2P + 2Z + 6 Non-auto Prokaryotes	5P + 2Z	15P + 16Z	35P + 16Z w/ RT	350P + 16Z w/ RT	31P + 16Z + 3B w/ RT
ECCO-GODAE (1deg)	Inomura et al. 2022	Zakem et al. 2020		Tsakalakis et al. 2022; Wu et al. 2021b	Juranek et al. 2020; Dutkiewicz et al. 2021; Meiler et al.2022; Wu et al., 2020	Dutkiewicz et al. 2020	Follett et al. 2022; Archibald et al. 2022; Serra-Pompeii et al. *in review;* Dutkiewicz et al. *in prep.*
LLC 90 ECCOV4 (1 deg)					Sonnewald et al. 2020; Follett et al. 2021; Hyun et al. 2022; Jonson et al. *in review;* Wu et al. 2021a; Zhang et al. 2021		
LLC 270 ECCO-Darwin (1/3 deg)			Carroll et al. 2020; Carroll et al. 2022				
CS 510 (~18km)			Manizza et al. 2019, 2022 *in revision*		Kuhn et al. 2019; Gupta et al. 2022; Treguer et al. 2021		Raut et al. *in prep.*
LLC 4320 (~2km)					Wilson et al. 2019		

Recent manuscripts (since 2019) associated with a combination of ECCO physics ***(rows)*** *and levels of ecosystem complexity* ***(columns)***

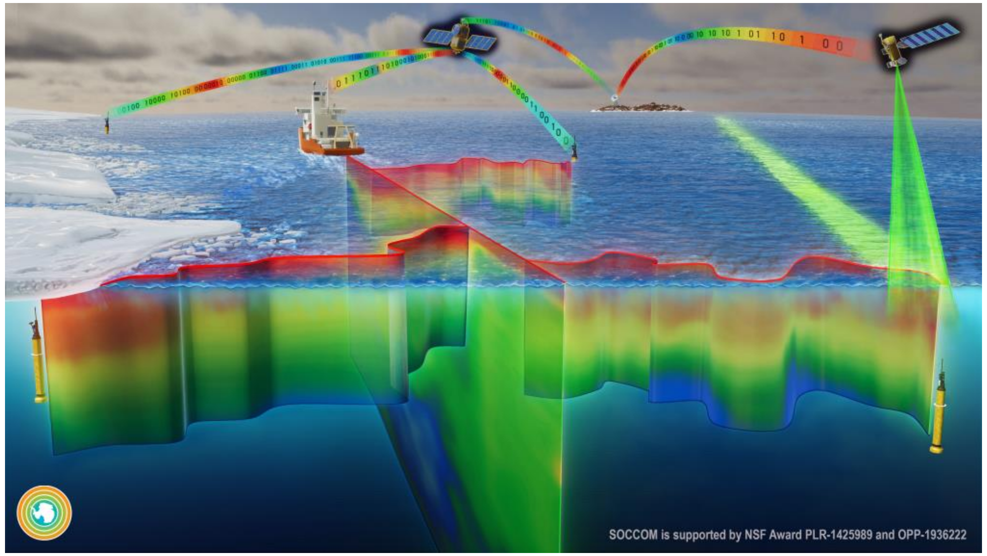
Lightning Round: Showcase of Ongoing ECCO-related Carbon and Biogeochemistry Efforts

SOCCOM



Southern Ocean Acidification Revealed by BGC-Argo

Matt Mazloff (UCSD/Scripps), Ariane Verdy, Sarah Gille, Ken Johnson, Bruce Cornuelle

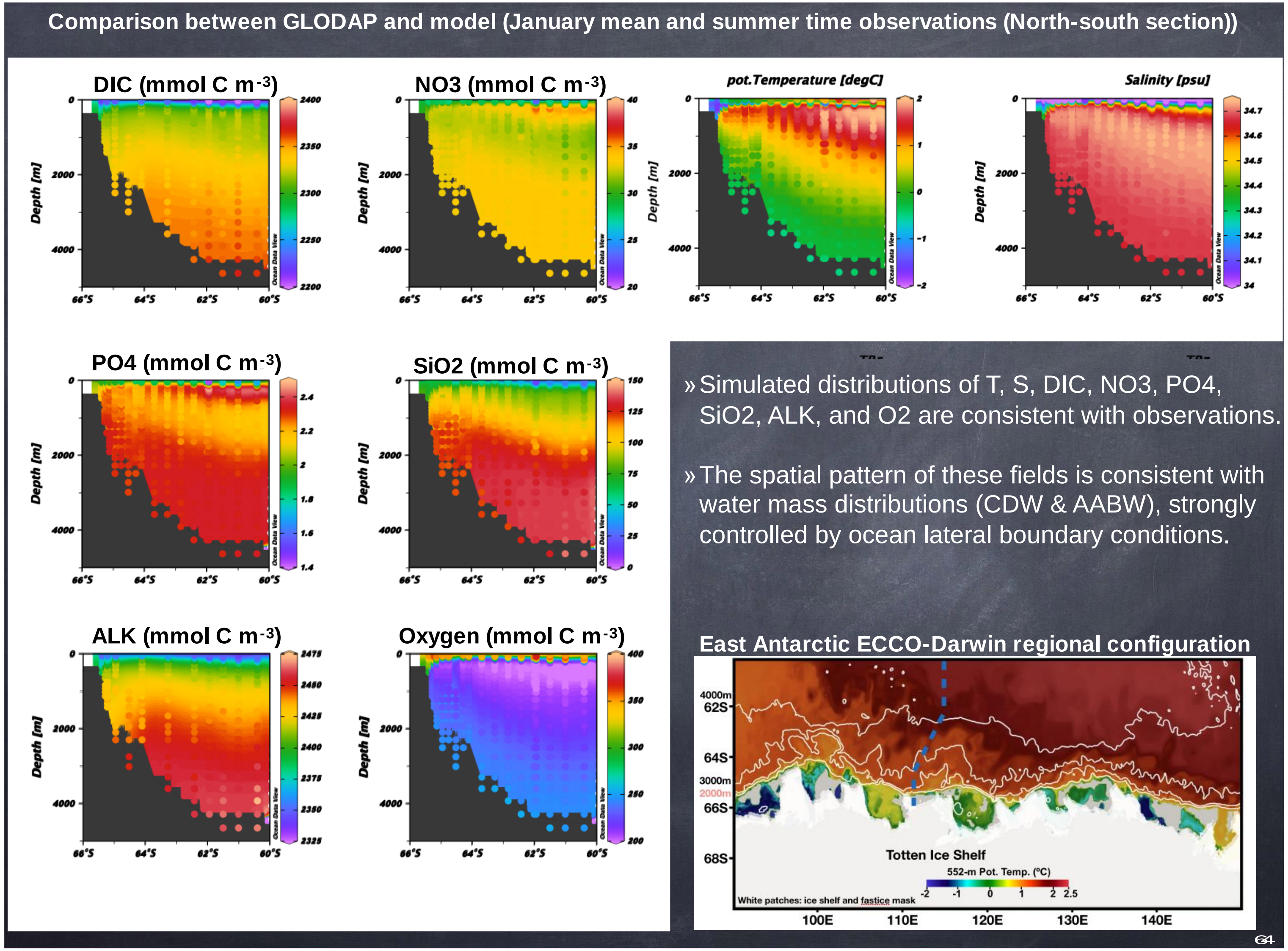


Key Points:

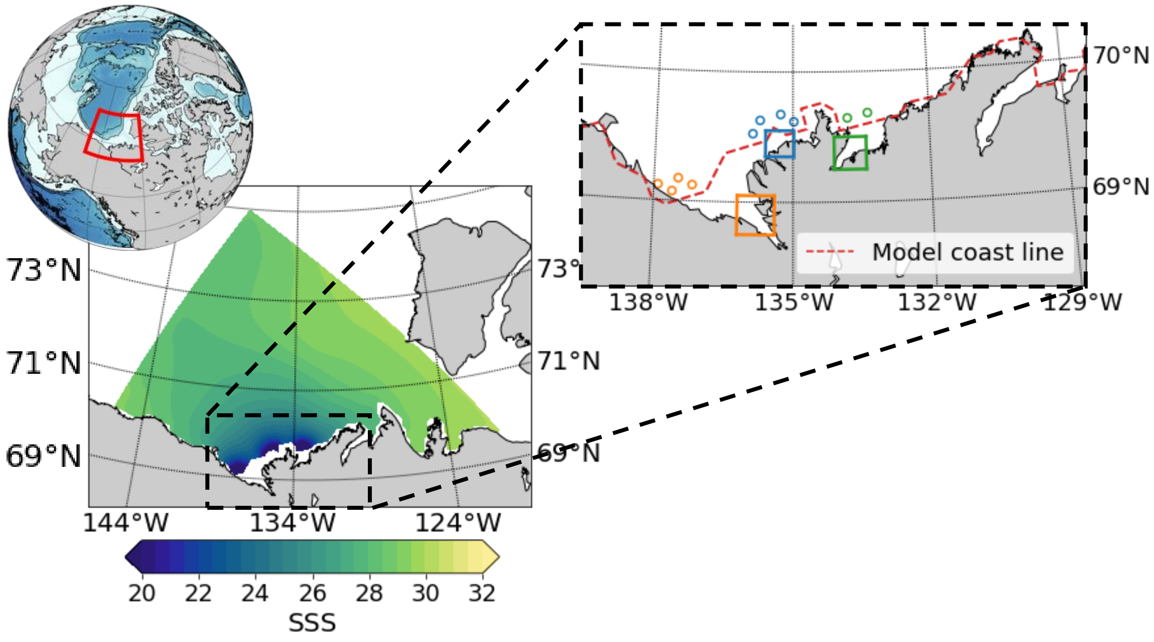
- BGC-Argo pH obs enable constructing a 2014–2020 Southern Ocean pH baseline map
- Comparison to ship obs reveals a pH decrease above 1500 m of up to 0.02 per decade
- This trend is widespread with magnitudes reflecting the overturning circulation.
- Mapped climatology available at http://sose.ucsd.edu/
- Manuscript in review at JGR Oceans

Yoshihiro Nakayama (Hokkaido University): *Optimization and evaluation of a high-resolution, regional, East-Antarctic ocean biogeochemistry model with novel in-situ physical and biogeochemical observations*

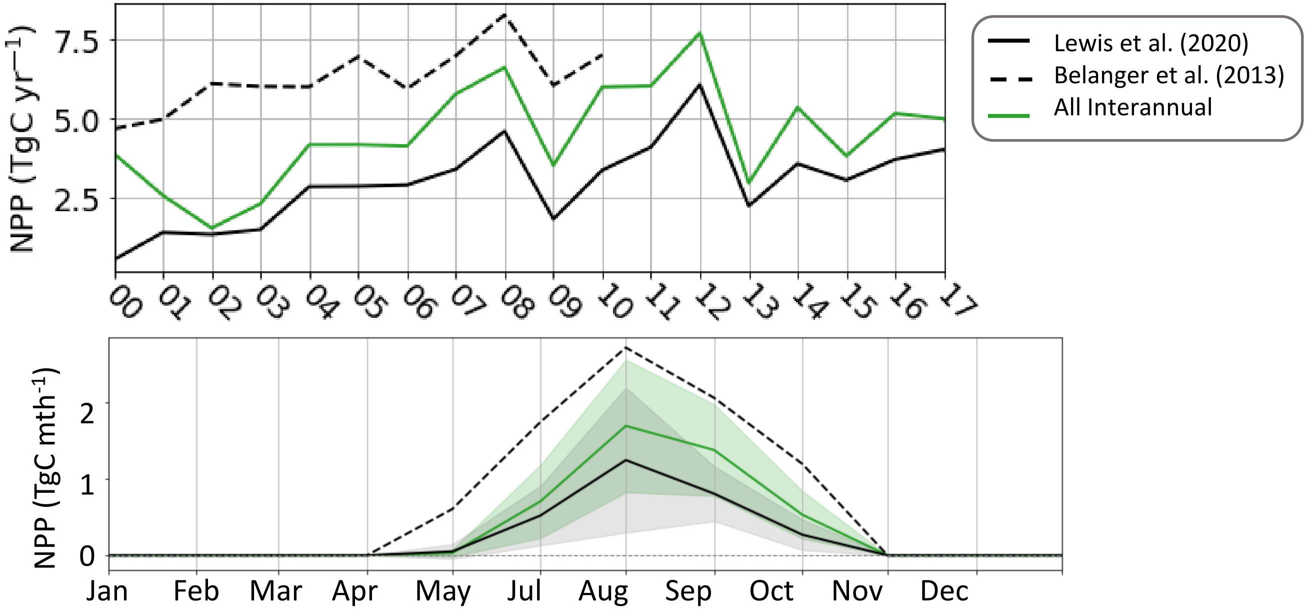
- Regional ECCO-Darwin simulation of East Antarctica with melting ice shelves
- Horizontal grid spacing of ~3-4 km with 50 vertical levels.
- Model period: 1992–2016
- Bathymetry based on ETOPO with recent updates of more accurate bathymetry for the continental shelf offshore of Totten Ice Shelf.
- Atmospheric forcing provided by ERA-Interim and boundary conditions from global ECCO-Darwin simulation



Clément Bertin (La Rochelle Université), *Biogeochemical River Runoff Drives Intense Arctic Ocean Outgassing* (in revision, Geophysical Research Letters)



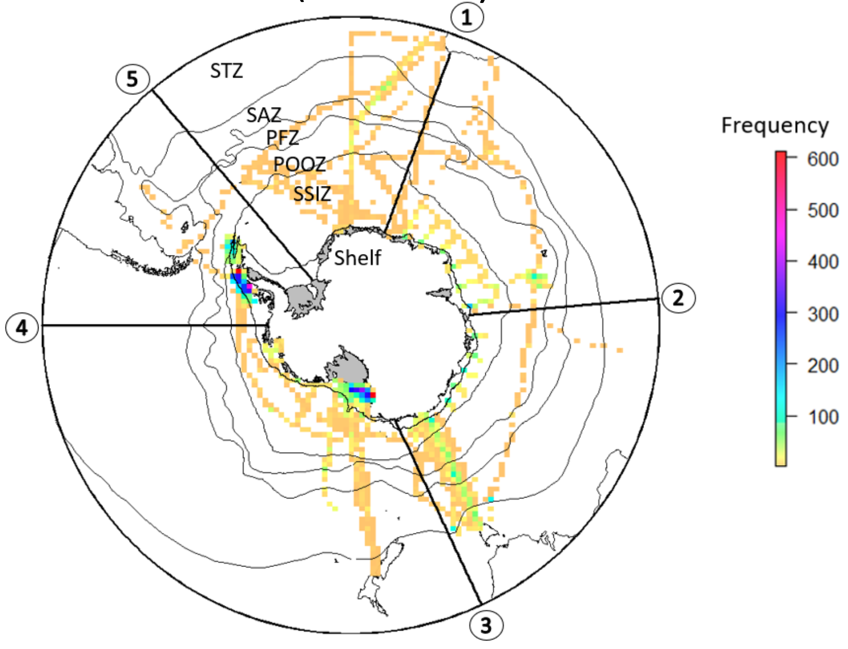
- Based on LLC 270 ECCO-Darwin (Carroll et al. 2020)
- 2 distinct DOC pools
- Daily terrestrial runoff from the Mackenzie River (2000–2019): freshwater, river temperature, and 6 biogeochemical tracers
- Interannual DOC, DIC, and alkalinity runoff



- **Regional ECCO-Darwin set-up reproduces Southeast Beaufort Sea dynamics**
- **Simulated surface-ocean DOC agrees well with satellite observations**
- **Captures the observed seasonal-to-interannual NPP and CO_2 flux amplitude and variability**

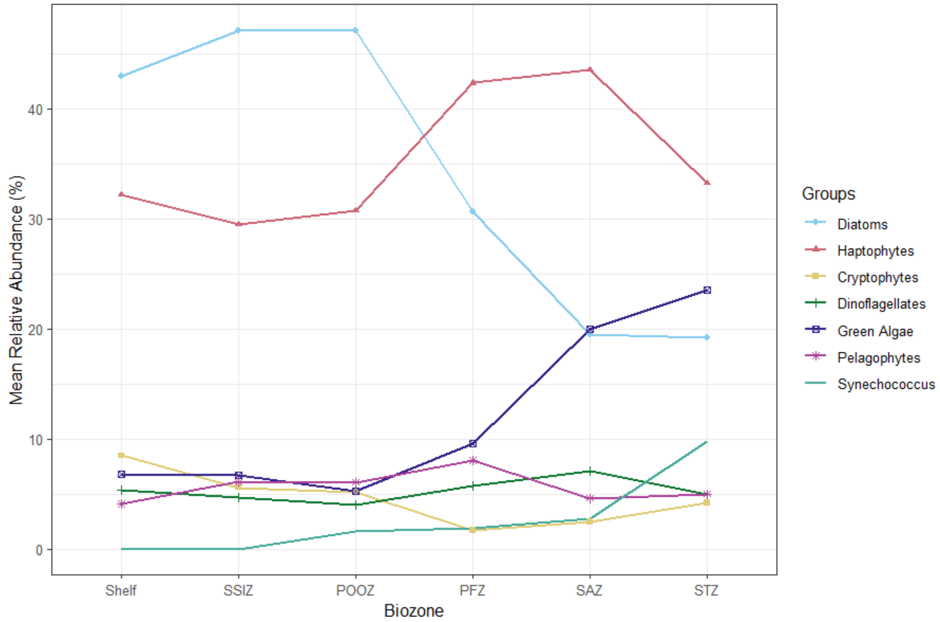
Alexander Hayward (University of Otago), Southern Ocean Temporal Modelling of phytoplankton groups using ECCO Darwin and Pigments

Distribution of pigment samples 1995 – 2021 (n =14 500)



Phytoclass inversion to phytoplankton biomass (Hayward et al., *in press*)

Training dataset - phytoplankton biomass in different oceanographic biozones



Circumpolar random forest model of phytoplankton biomass

Training dataset

Estimating the Circulation and Climate of the Ocean

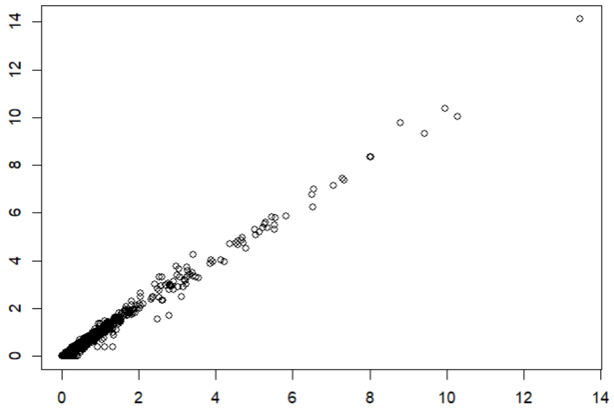
ECCO

National Aeronautics and Space Administration

K-fold cross validation

Explanatory variables (Nutrients, SSS, SST, MLD)

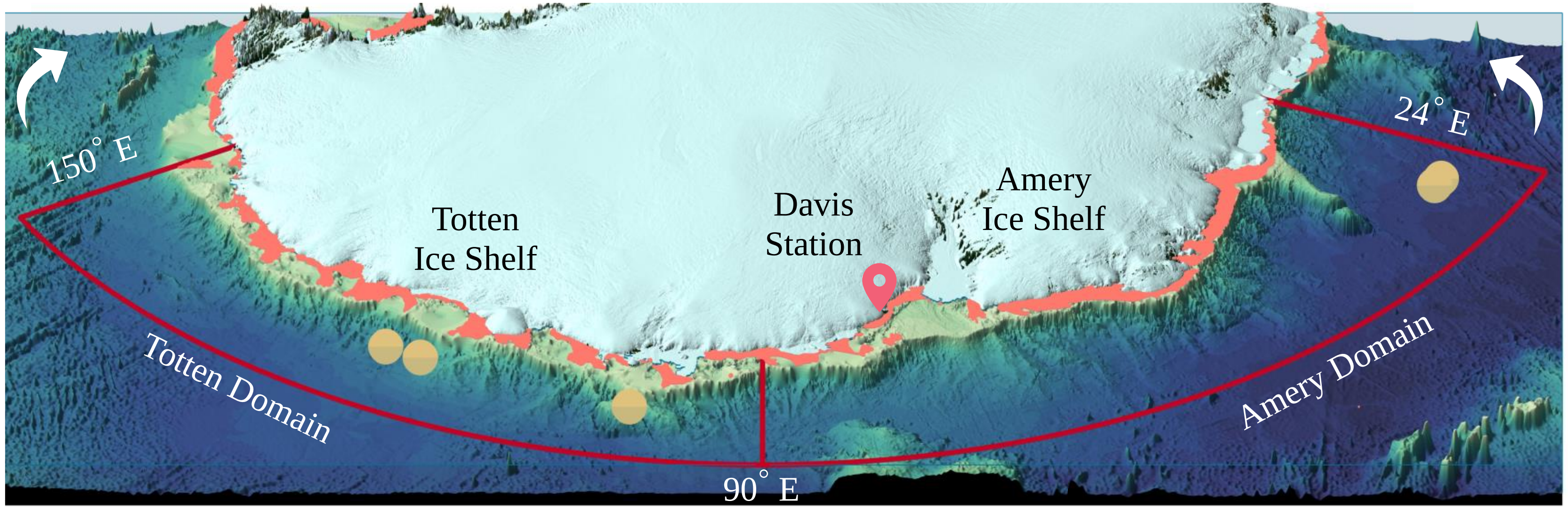
Diatoms $R^2 = 0.98$ Trees = 110 (example)



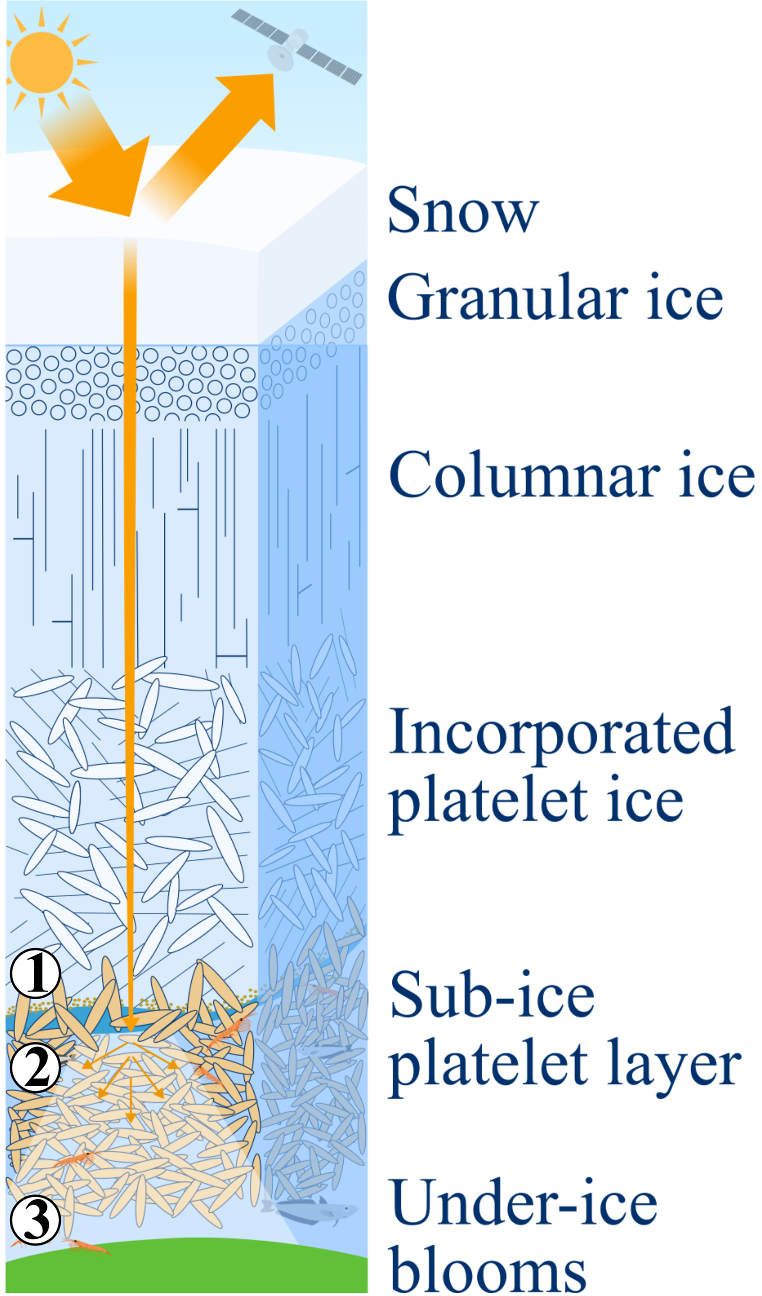
NIWA Taihoro Nukurangi

University of Otago
Te Whare Wānanga o Otāgo
New Zealand
Sapere Aude

Pat Wongpan (University of Tasmania):
Antarctic Under-ice Phytoplankton Blooms



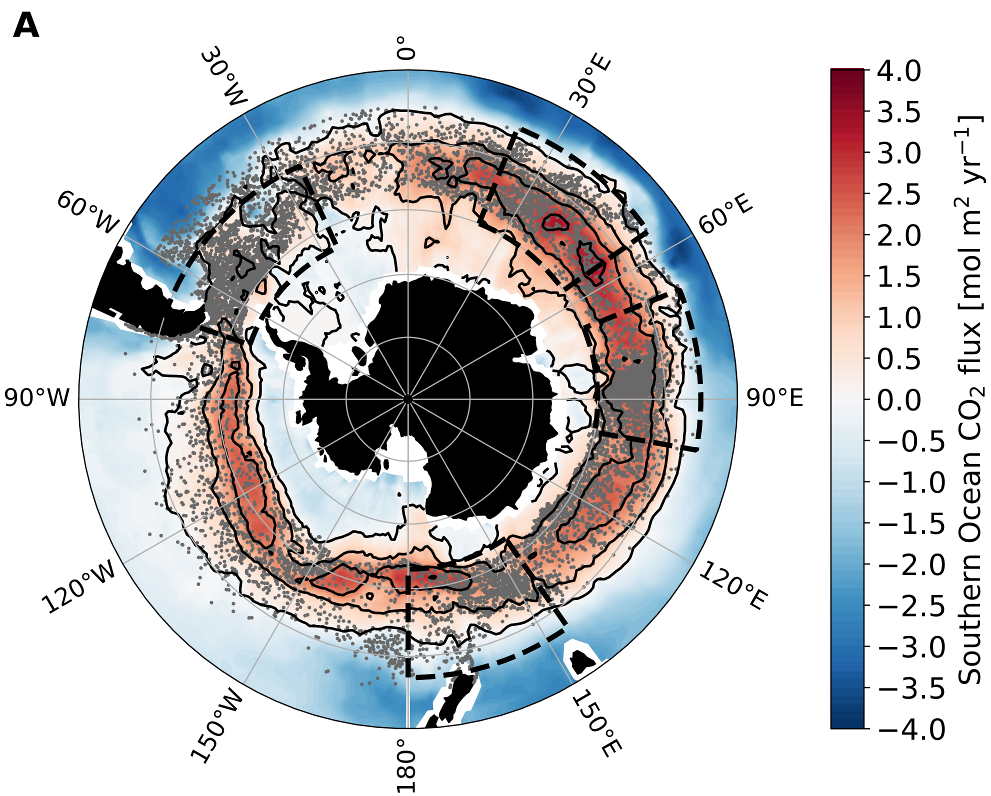
- Improve coastal sea-ice algal habitat representation in ECCO-Darwin by implementing accurate, data-constrained landfast ice distribution over the last 22 years (2000–2022) in East Antarctica
- Include the biological hotspot of sea-ice near ice shelves by developing the first regional ocean-ice model with semi-consolidated ice (platelet ice), and its accurate biogeochemistry
- Estimate the primary production from under-ice phytoplankton blooms by combining and leveraging detailed observations, including Argo floats and tagged-seal data, with a state-of-the-art data-constrained ocean biogeochemistry model (ECCO-Darwin)

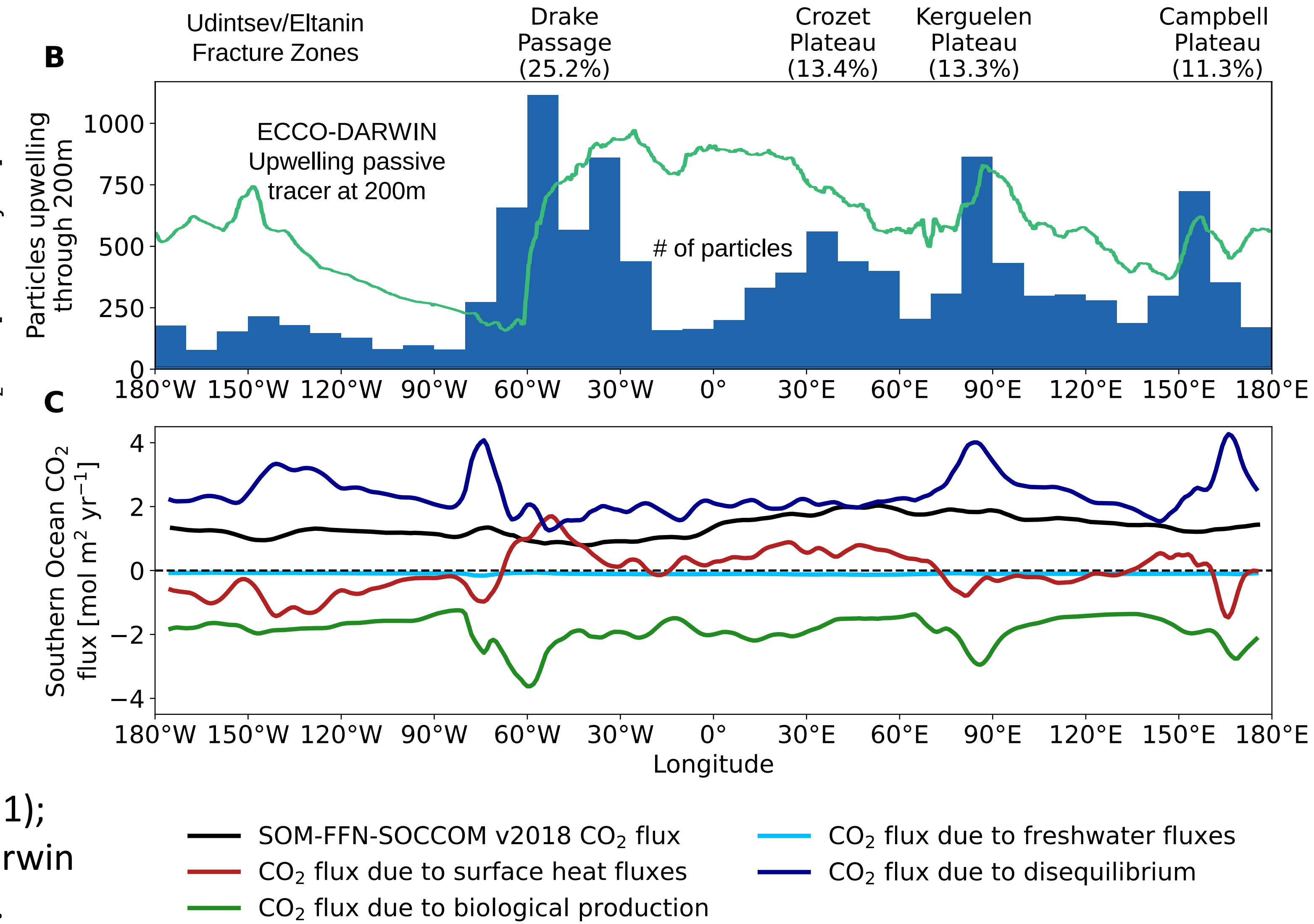


Jonathan Lauderdale (MIT): *Where does Southern Ocean upwelling cause CO_2 outgassing?*

Locations of particles upwelling from 200–2000m are guided by topographic interactions, indicating upwelling of DIC-rich waters.

Strong upwelling regions not associated with strong CO_2 outgassing – local compensation by physical/biological processes.



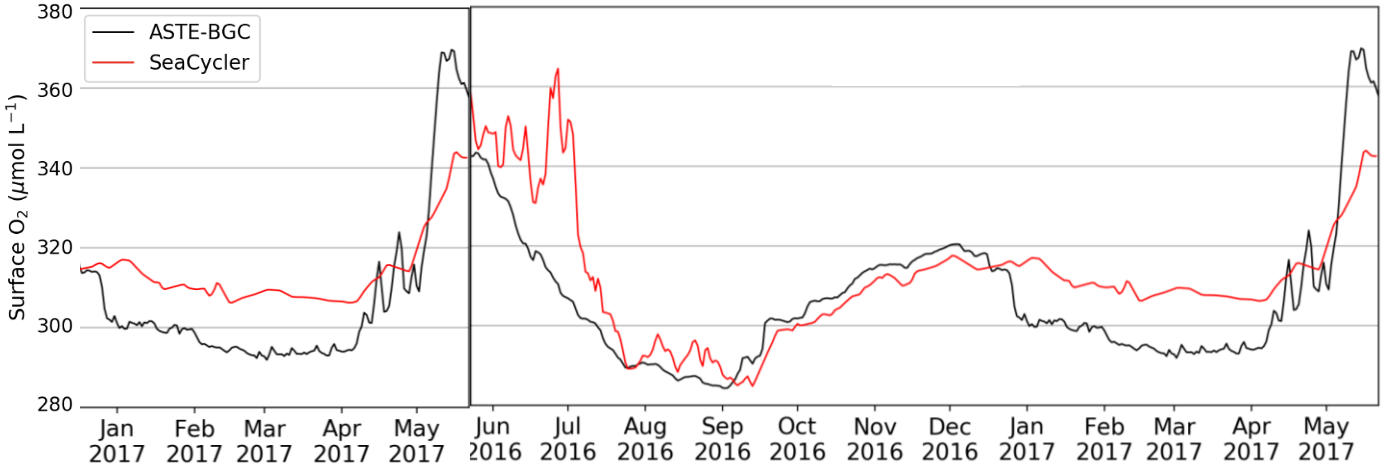


CO_2 fluxes from Bushinsky *et al.* (2019);
Upwelling particle locations from Brady *et al.* (2021);
Outgassing (Red/+ve), uptake (blue/-ve), ECCO-Darwin CO_2 flux attribution using Lauderdale *et al.* (2016).

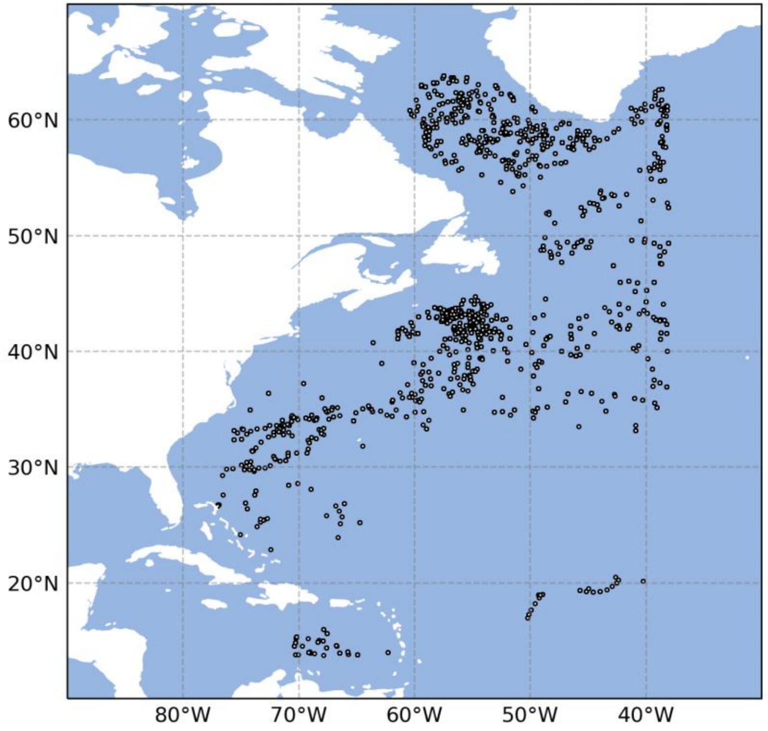
Lauren Moseley (Columbia University), *Optimizing the simulated O_2 of ASTE-BGC using BGC-Argo and ship-based observations*

We apply a Green's functions approach to fit **ASTE-BGC** biogeochemistry to O(10^6) in situ observations **(BGC-Argo)**

Surface oxygen against SeaCycler mooring data



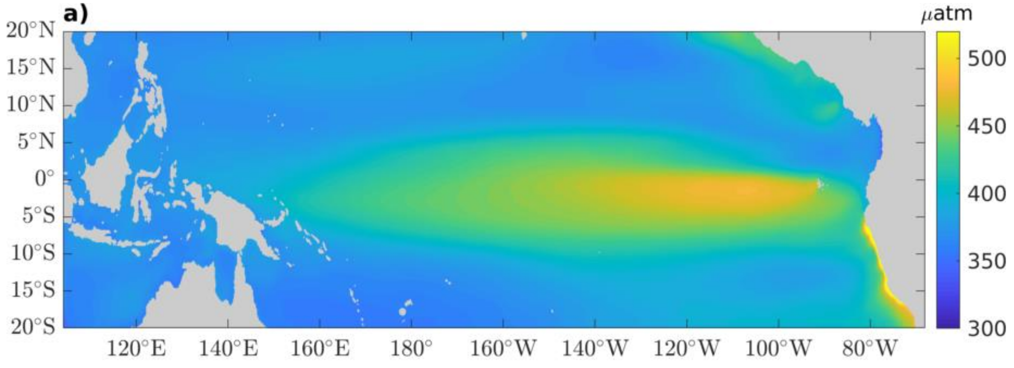
BGC-Argo O_2 data – spatial coverage



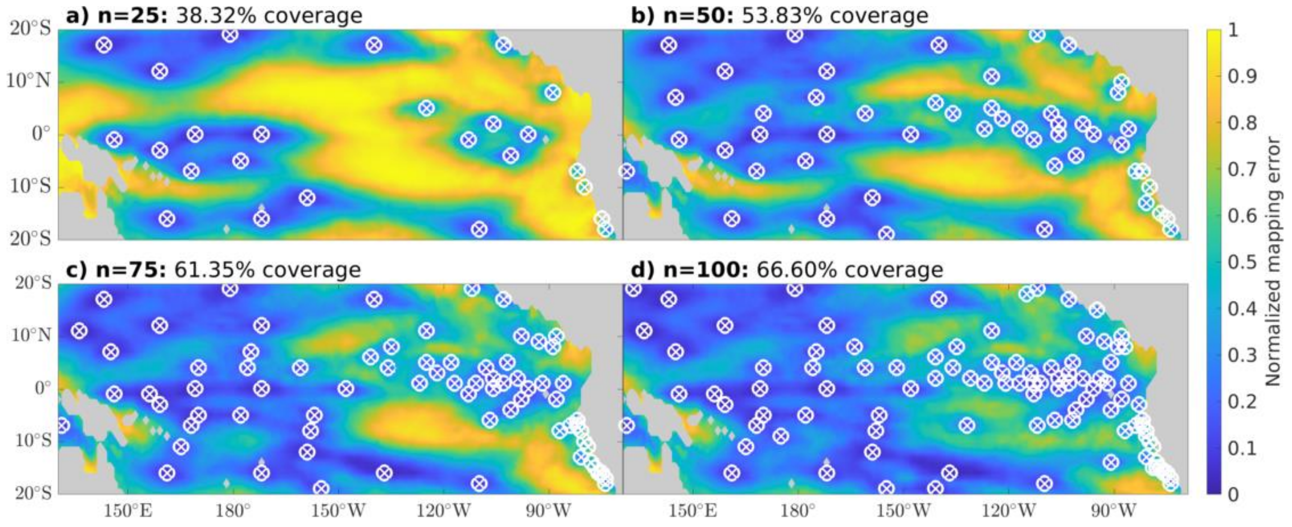
We will construct oxygen budgets using the optimized **ASTE-BGC** to examine interannual O_2 variability in the subpolar North Atlantic

Ariane Verdy and Matt Mazloff (UCSD/Scripps),
Tropical Pacific Ocean State Estimate (TPOSE)

Surface pCO_2 correlation scales: Winnie Chu et al.

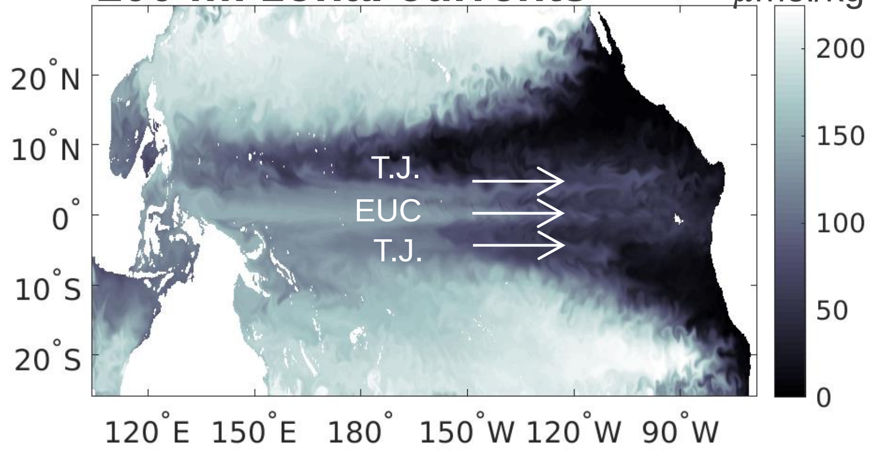


Mapping error vs. number of BGC-Argo floats

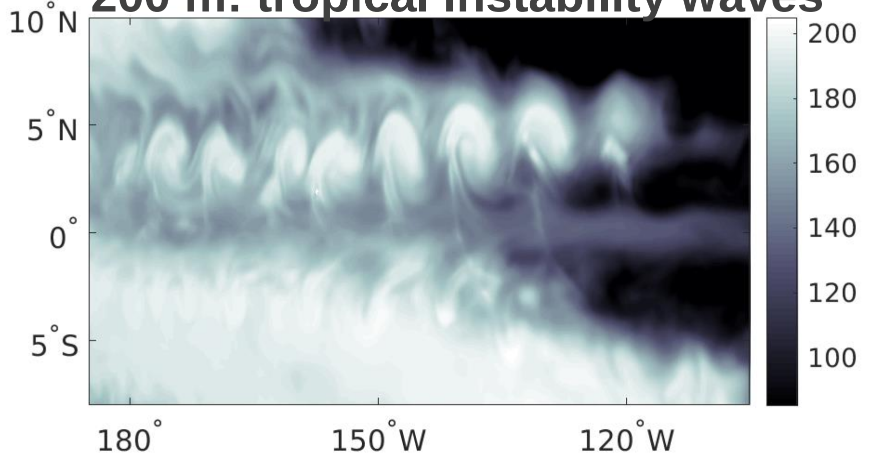


Oxygen budget: Yassir Eddebbar et al.

100 m: zonal currents



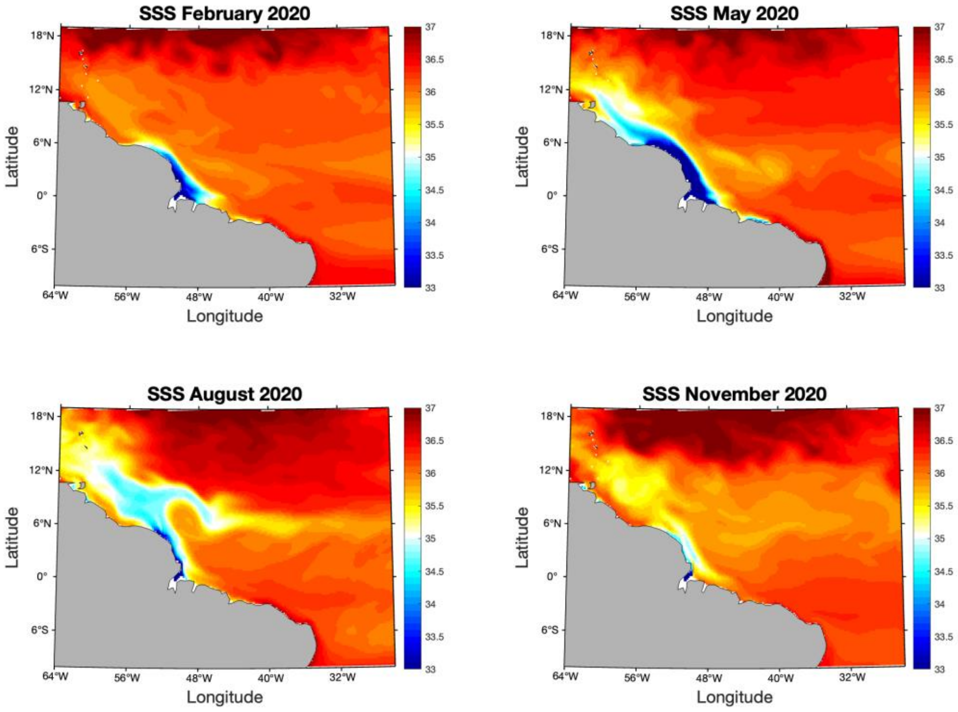
200 m: tropical instability waves



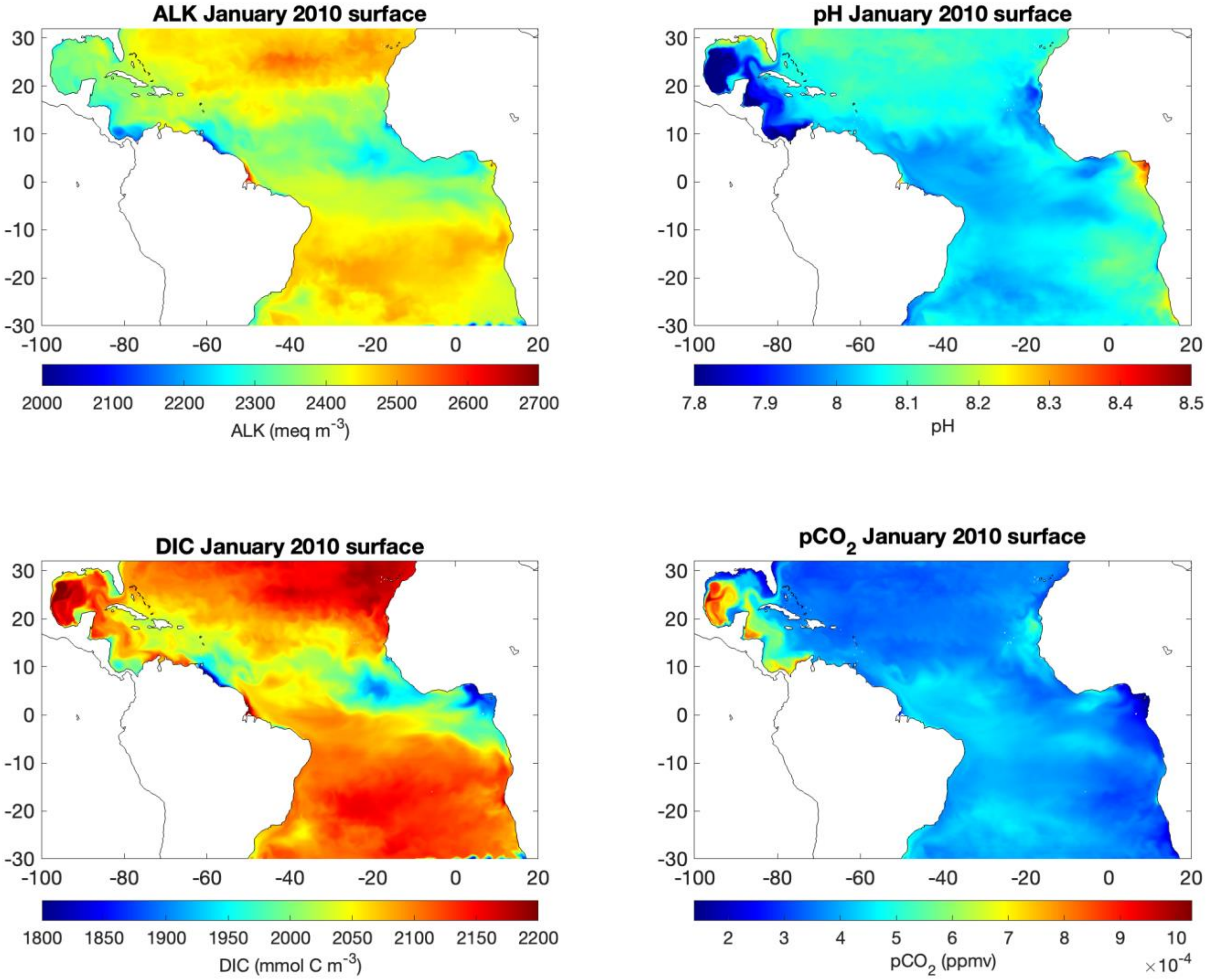
Karel Castro Morales (Friedrich Schiller University Jena, Germany),
Land-ocean-aquatic Carbon Exchange at the Amazonas Shelf System

Regional ECCO-Darwin simulation
Longitude = [99.5°W to 28.7 °E]
Latitude = [36.9 °N to 30.5 °S]
Horizontal resolution: 16 km (~1/6.2°)
Atm. Forcing: ERA-5

Model Representation of North Brazil Current rings



Model Biogeochemistry



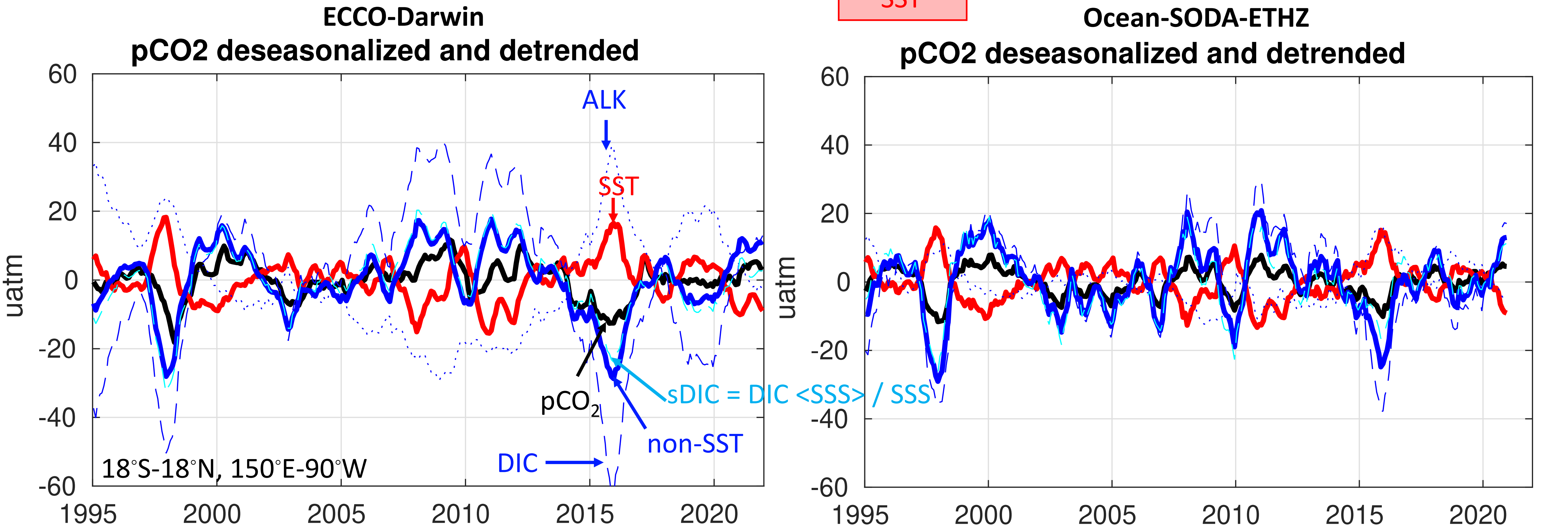
Daniel Whitt (NASA Ames), *Regional biogeochemical studies with ECCO-Darwin*

- NIP20 award – North Atlantic nutrients and biological productivity
- IDS22 proposal – Equatorial Pacific air-sea carbon fluxes

Thermal and non-thermal drivers of Equatorial Pacific ocean surface pCO_2 variability are consistent with a new machine-learning data product, but there are discrepancies in DIC and alkalinity due to SSS issues in LLC 270.

$$\Delta pCO_{2w} \approx \frac{\partial pCO_{2w}}{\partial DIC}\Delta DIC + \frac{\partial pCO_{2w}}{\partial Alk}\Delta Alk + \frac{\partial pCO_{2w}}{\partial T}\Delta T + \frac{\partial pCO_{2w}}{\partial S}\Delta S$$

SST



UNICORNS: *Understanding Interdecadal Changes in the Ocean Carbon Sink*

Andrew Watson[1], Neill Mackay[1], Ric Williams[2], Oliver Andrews[3], Jan Zika[4], Tobias Ehmen[1], Hemant Khatri[2]

1 University of Exeter
2 University of Liverpool
3 University of Bristol
4 UNSW Australia

Why?

- Observational data products suggest strong recent decadal variability of the ocean carbon sink that is not reproduced in models
- Explaining the variability requires reconciling observational estimates of the air-sea flux with those of the changing interior ocean carbon inventory
- This reconciliation means understanding both the surface uptake of carbon and its redistribution in the ocean interior by the ocean circulation

What?

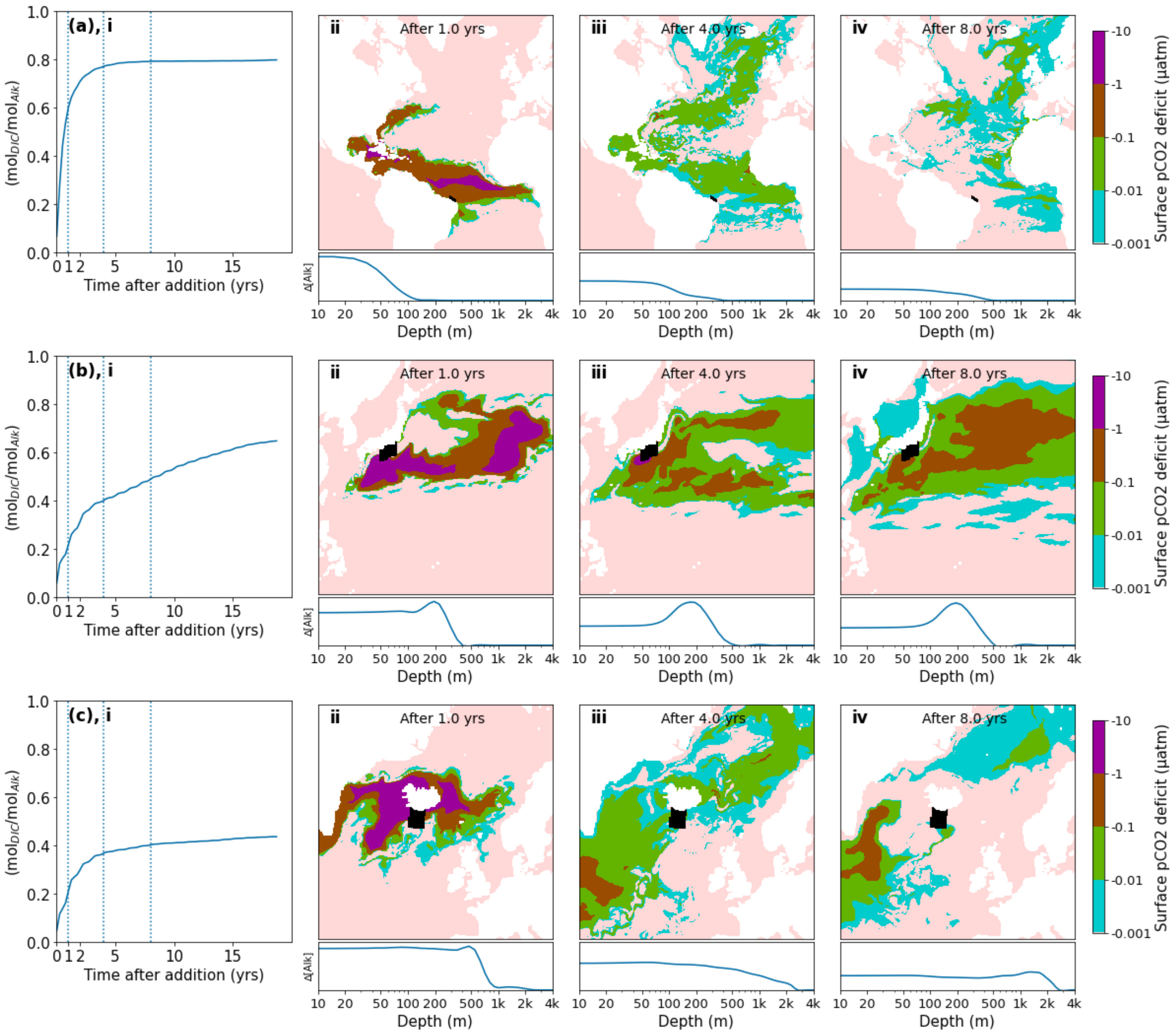
- Develop an inverse method using water mass theory that diagnoses the uptake of carbon and its redistribution by the ocean circulation from interior changes *(validation using **ECCO-Darwin**)*
- Apply a transport-based framework to model data that separates changes in interior carbon into ‘added’ and ‘redistributed’ components *(**ECCO-Darwin** outputs)*
- Reconstruct the time-dependent inventory of carbon in the interior from observations using machine learning techniques
- Apply inverse method to the machine-learning reconstructions to reconcile interior changes with the air-sea flux

Jing He (WHOI) and Mike Tyka (Google),
CO_2 Equilibration Dynamics Following Ocean Alkalinity Enhancement (OAE)

(i) Shows CO_2 uptake following a pulsed injection of surface alkalinity in a particular location (relative to an unperturbed reference simulation)

(ii–iv) Show geographical surface spread of CO_2 deficit and depth distribution of excess alkalinity.

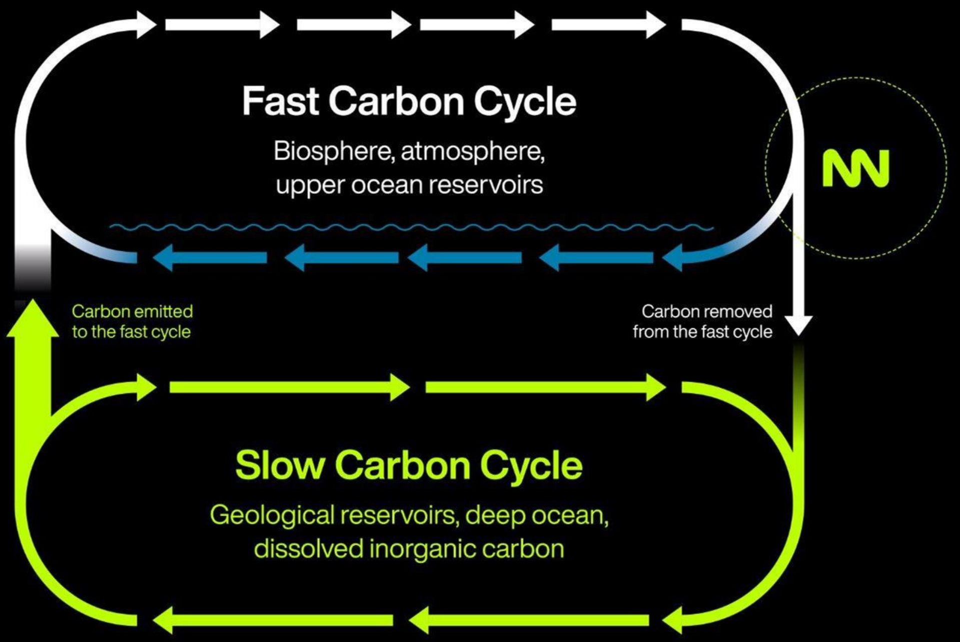
Model based on LLC 270 (0.3^o x 0.3^o) ECCO solution (1994–2014) (Zhang et al. 2018). Carbonate system modelled using MITgcm gchem and DIC packages, following Dutkiewicz et al. (2005)



[He, J., & Tyka, M. D. (2023). Limits and CO2 equilibration of near-coast alkalinity enhancement. Biogeosciences, 20, 27–43, 2023]

RUNNING TIDE

Running Tide is the global leader in carbon removal solutions, moving carbon from the fast cycle to the slow cycle.

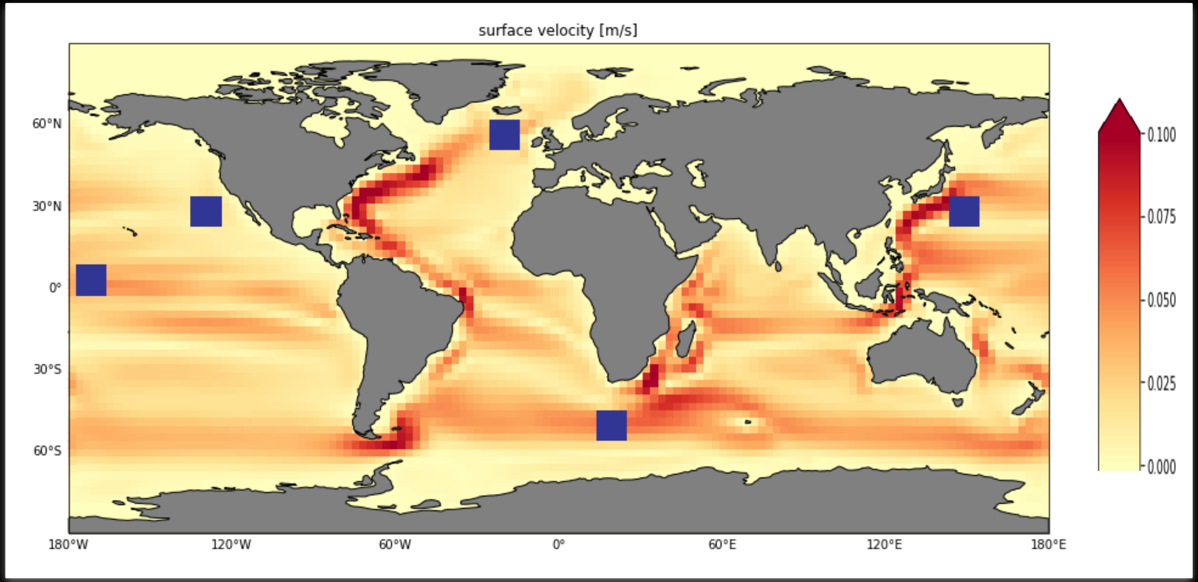


We've known for a generation that ocean health is in rapid decline. To invest in nature we need both the diagnostics systems capable of quantifying impacts and interventions at the scale of the problem.

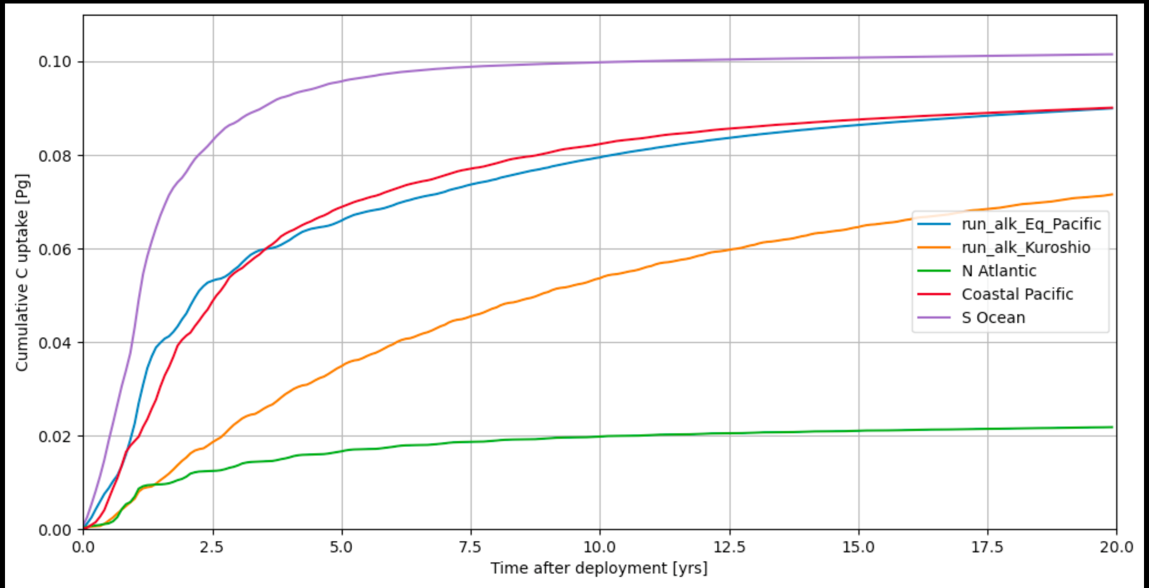
The Ocean Modeling Team at Running Tide uses ECCO-Darwin to understand the impact of ocean-based carbon dioxide removal (CDR) interventions on the planet, creatively design interventions, and support operations through careful planning, optimization, and evaluation.

Designing optimal mCDR strategies with ECCO-Darwin

- Understand regional differences in ocean carbon uptake due to alkalinity enhancement
- 5 numerical experiments: add the same amount of alkalinity to different regions over a period of 1 year
- Under ideal circumstances: alkalinity addition results in ~0.1 Pg C decrease in the atmosphere



5 alkalinity enhancement regions overlaid on surface-ocean velocity fields from ECCO-Darwin



Additional cumulative uptake of carbon by the ocean due to alkalinity enhancement for 5 regions. Note the large regional differences in efficiency of carbon uptake by the ocean due to alkalinity enhancement.

Take Home Messages

- Ocean carbon and biogeochemistry is a **"killer app"** for ECCO
- By marketing to carbon interests, we can rapidly expand our user base across other scientific disciplines
- Fosters creative thinking and interdisciplinary projects = innovation
- Forges timely connections with government agencies, national policy makers, and industry
- Can improve the fidelity of physical state estimates, i.e., additional data constraints and end-users identifying pertinent issues in hydrography/circulation/sea ice, etc.

Thank you!