THE OCEANS AND CLIMATE: SUSTAINED GLOBAL OBSERVING SYSTEMS (ONE ARGO AND GO-SHIP)

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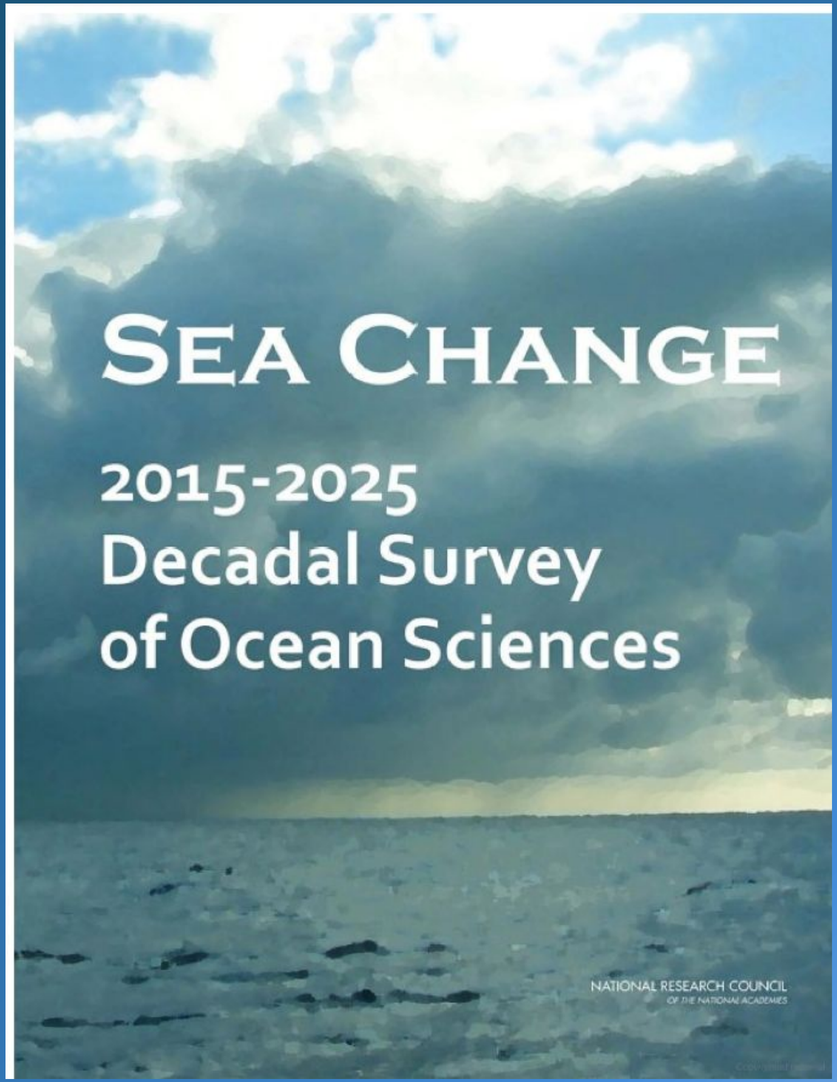
SEA CHANGE: 2015-2025 DECADAL SURVEY OF OCEAN SCIENCES

'How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?'

The fundamental science needed to answer this question will require sustained observing of the global ocean.

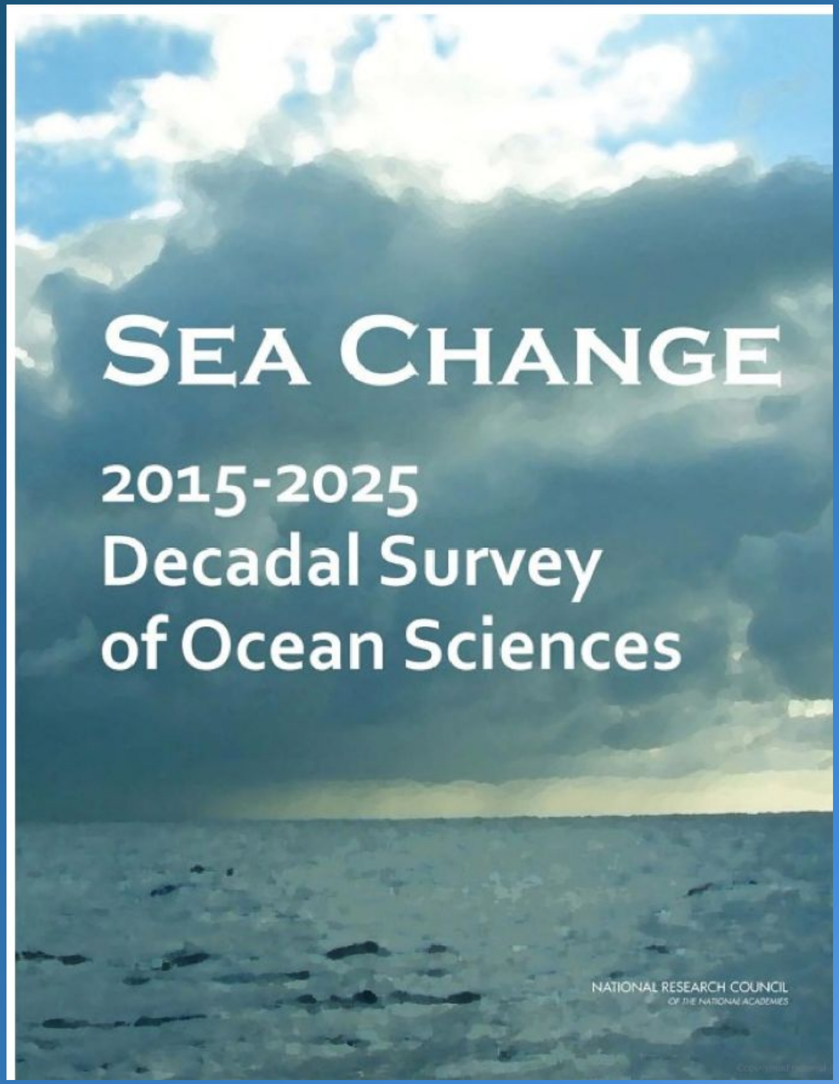


SEA CHANGE: 2015-2025 DECADAL SURVEY OF OCEAN SCIENCES

'How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change over the next century?'

The fundamental science needed to answer this question will require sustained observing of the global ocean.

This question is even more critical, with clear societal relevance, in this next decade.



We can’t project future climate without understanding Earth’s oceans – they are the fly-wheel of our climate system and they control the composition of the atmosphere

COP28 Dubai Ocean Declaration (December 2023):

“… human activity, particularly in the form of greenhouse gas emissions that adversely impact the heat content, sea level, and acidity of the oceans, interferes with the ocean’s ability to support marine and terrestrial life, and hinders sustainable development worldwide….” https://oceanpavilion-cop.org/dubai-ocean-declaration/

“We need to scale up ocean observing systems to fully understand climate impacts and build a more resilient society. With this Declaration, we want negotiators at COP28 to prioritize supporting ocean observations like Argo and other technologies that give us the full picture of what’s happening below the surface including changes to ocean ecosystems….” ***Margaret Leinen, Director, Scripps Institution of Oceanography***

https://www.whoi.edu/press-room/news-release/ocean-pavilion-partners-unveil-cop28-dubai-ocean-declaration-in-advance-of-un-climate-conference/

Outline

The Ocean and Climate Change

- Heat uptake and sea level rise
- Carbon uptake

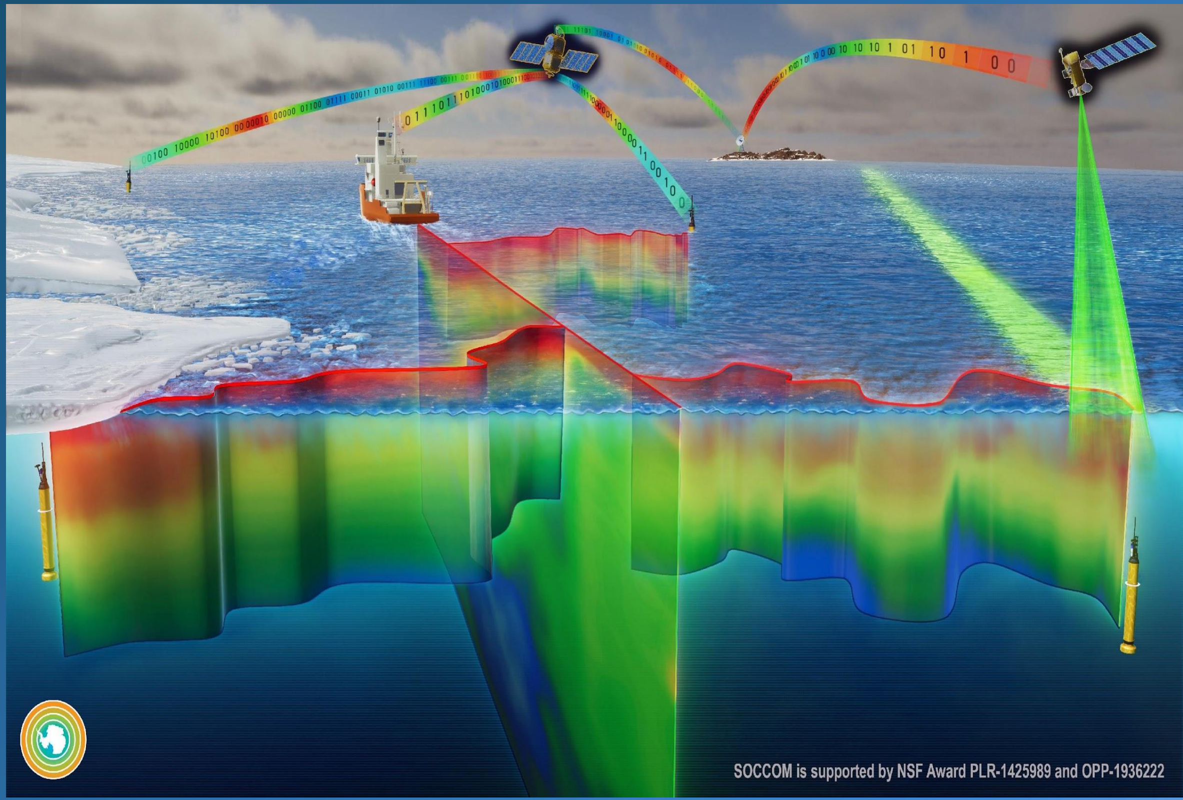
Open Ocean Observing Systems with global and deep ocean coverage

Elements of Global Ocean Observing System (GOOS)

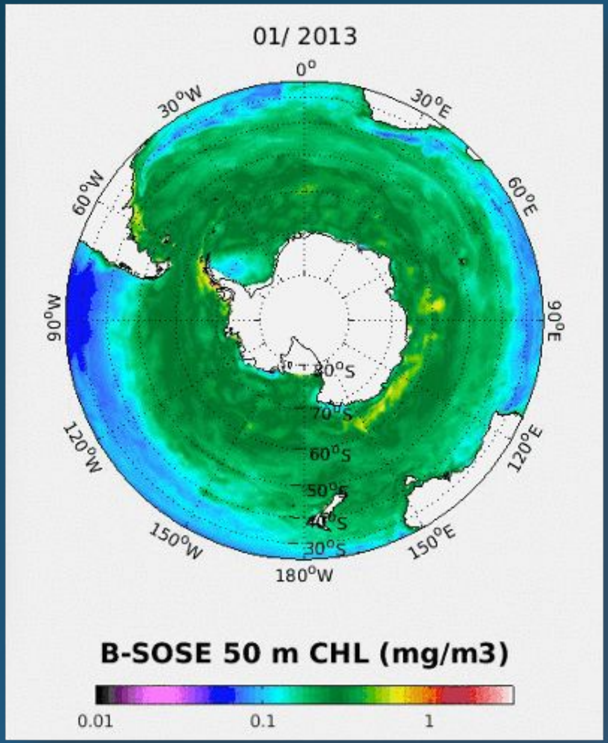
- Argo profiling floats
- GO-SHIP shipboard measurements

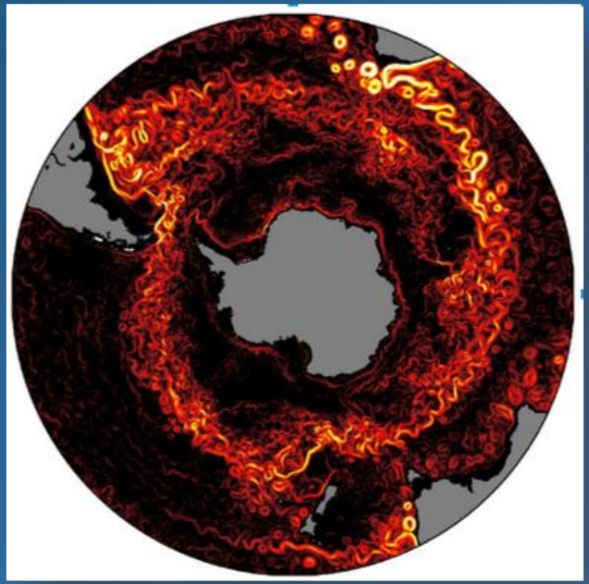
Further examples of climate findings

- Large-scale acidification
- Ocean ecosystem characterization and change



Focus today on ocean observations for climate



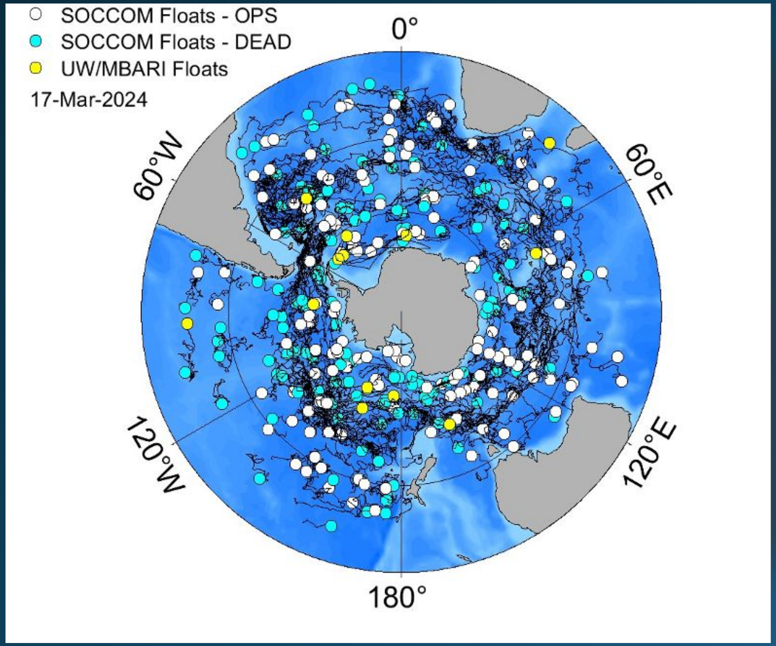


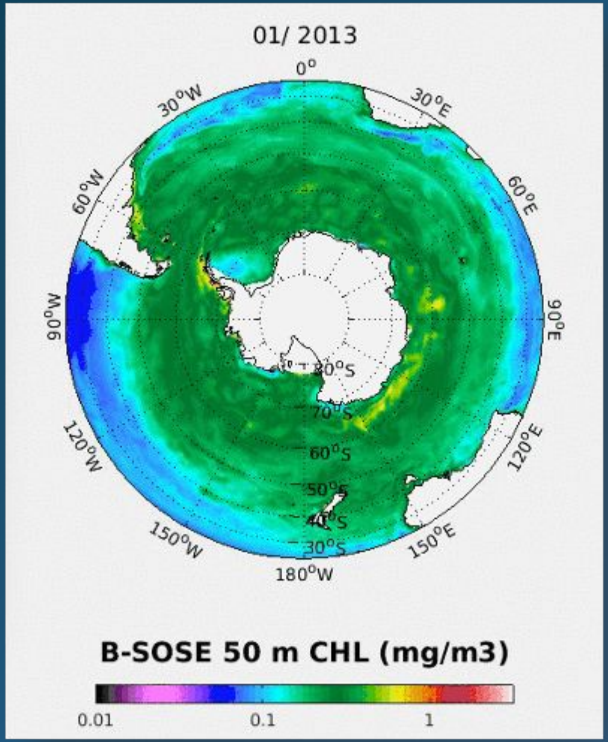
Observations
Observational products

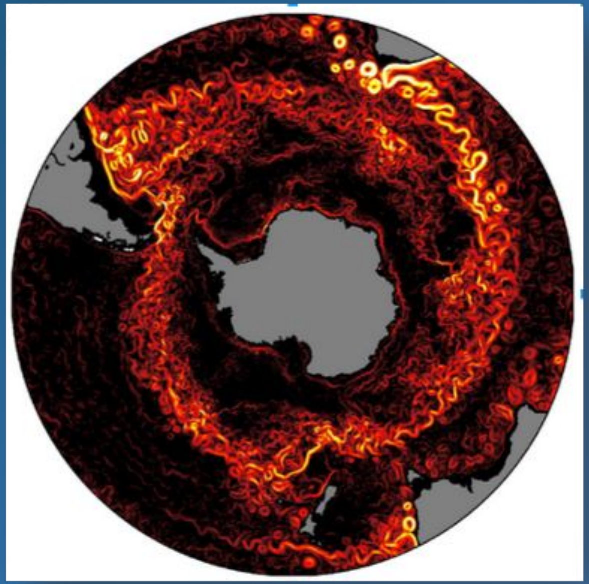
State estimation

Earth System modeling

Focus today on ocean observations for climate







Observations
Observational products

State estimation

Earth System modeling

Some resources among many

National Academies of Sciences, Engineering, and Medicine. 2017. Sustaining Ocean Observations to Understand Future Changes in Earth's Climate. Washington, DC: The National Academies Press. doi: https://doi.org/10.17226/24919

IPCC SROCC, Chapter 5. Bindoff, N.L., W.W.L. Cheung, J.G. Kairo, J. Arístegui, V.A. Guinder, R. Hallberg, N. Hilmi, N. Jiao, M.S. Karim, L. Levin, S. O'Donoghue, S.R. Purca Cuicapusa, B. Rinkevich, T. Suga, A. Tagliabue, and P. Williamson, 2019: Changing Ocean, Marine Ecosystems, and Dependent Communities. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 447–587. https://doi.org/10.1017/9781009157964.007

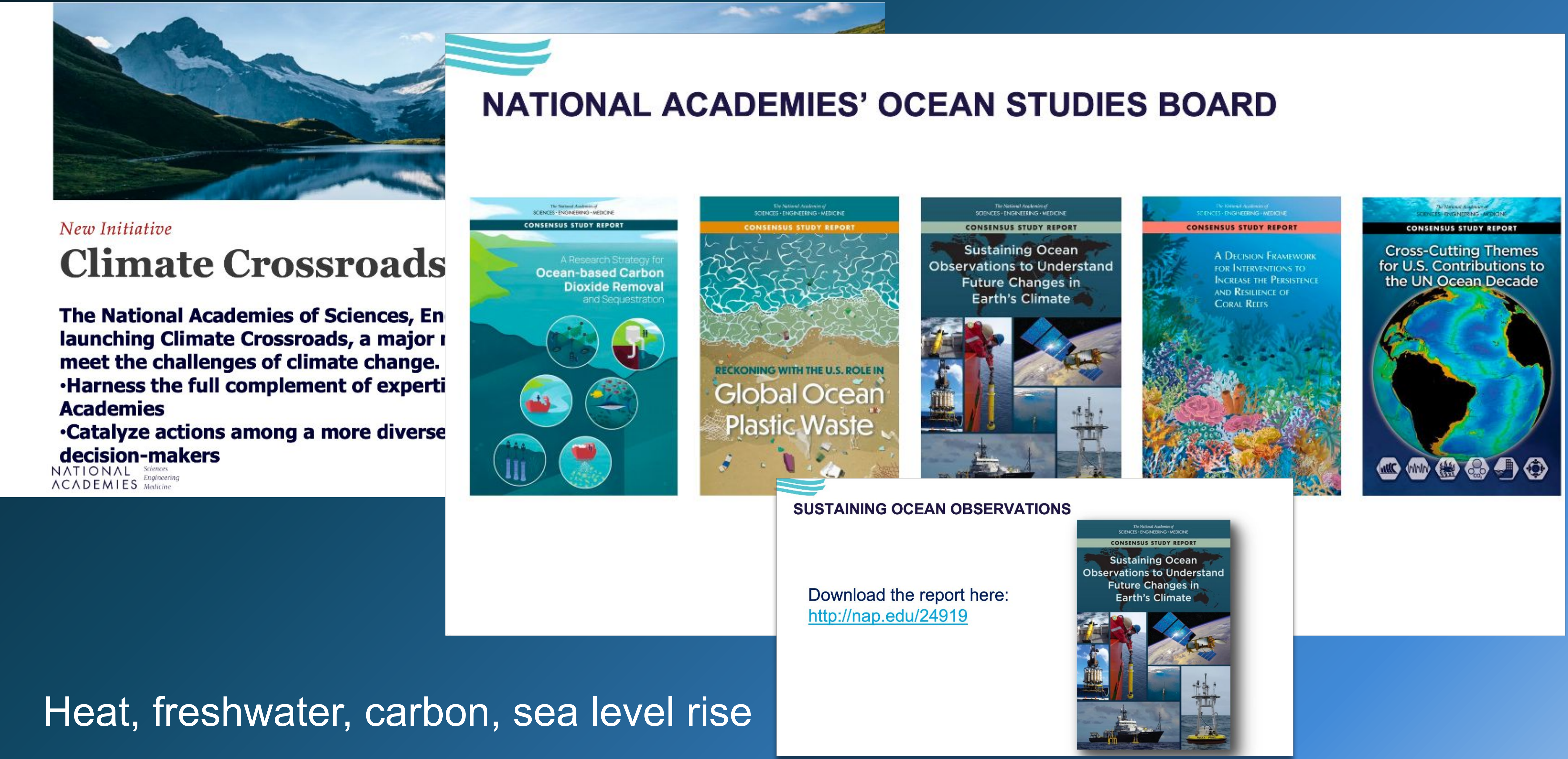
IPCC AR6, Chapter 9. Fox-Kemper, B., H.T. Hewitt, C. Xiao, G. Aðalgeirsdóttir, S.S. Drijfhout, T.L. Edwards, N.R. Golledge, M. Hemer, R.E. Kopp, G. Krinner, A. Mix, D. Notz, S. Nowicki, I.S. Nurhati, L. Ruiz, J.-B. Sallée, A.B.A. Slangen, and Y. Yu, 2021: Ocean, Cryosphere and Sea Level Change. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1211–1362, doi:10.1017/9781009157896.011.

Very recent: UN Decade Working Group white papers

Johnson, G.C., S.Hosoda, S.R. Jayne, P.R. Oke, S. C. Riser, D. Roemmich, T. Suga, V. Thierry, S.E. Wijffels, J. Xu, 2022. Argo—Two Decades: Global Oceanography, Revolutionized. Annual Review of Marine Science 14:1, 379-403

Talley, L.D., R.A. Feely, B.M. Sloyan, R. Wanninkhof, M.O. Baringer, J.L. Bullister, et al., 2016. Changes in ocean heat, carbon content, and ventilation: Review of the first decade of global repeat hydrography (GO-SHIP). Ann. Rev. Mar. Science 2016, 8, 185-215.

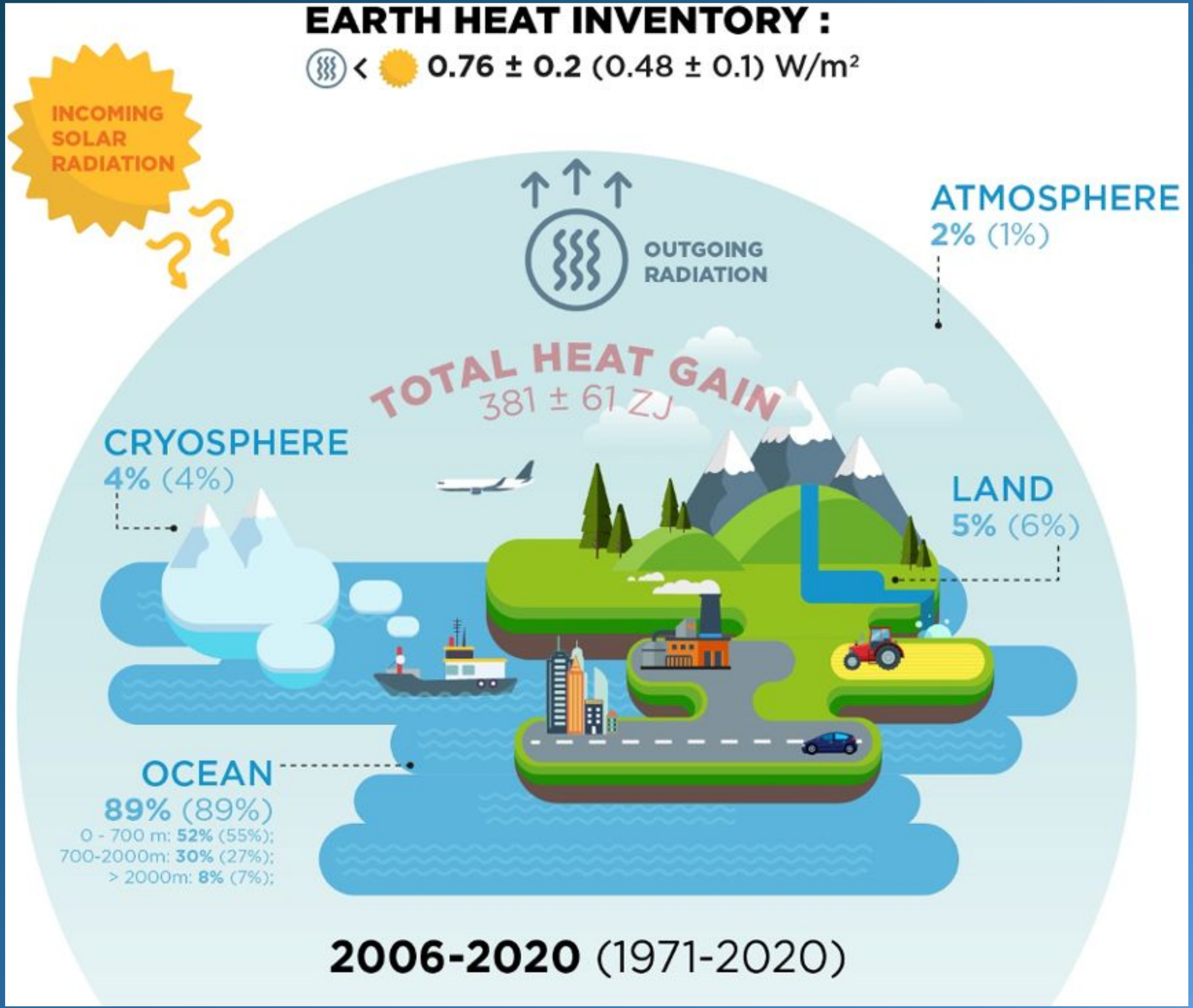
Some NASEM resources from Kelly Oskvig (COP28 Dubai)



Heat, freshwater, carbon, sea level rise

Ocean heat uptake

The Earth is out of energy balance from anthropogenic activity, and the majority (about 90%) of excess heat resulting from this imbalance is taken up by the ocean.

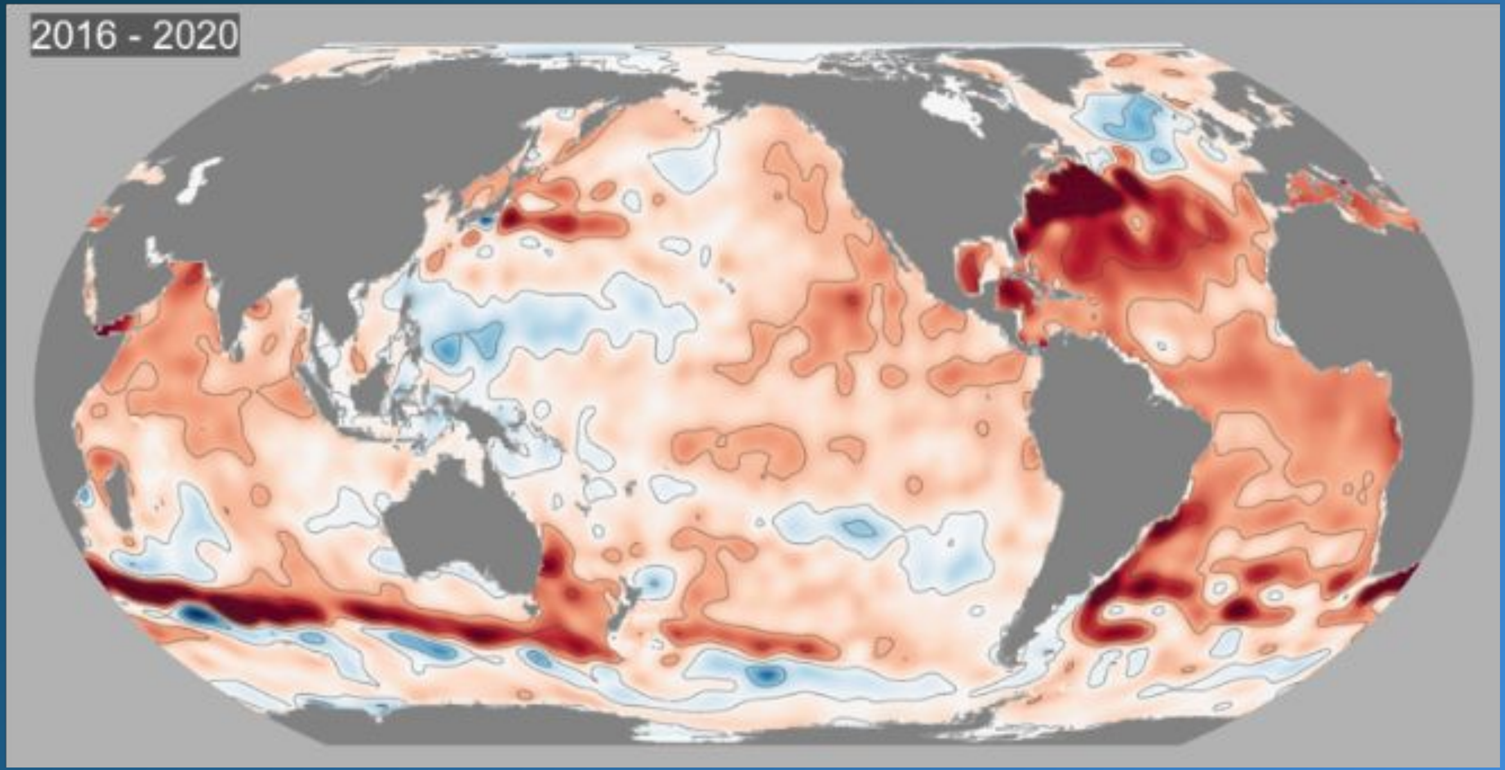


von Schuckmann et al. (Earth System Science Data, 2023)

Ocean heat uptake

This uptake of heat results in ocean warming, which is today affecting most areas of the global ocean, from the surface to the abyss

Argo measurements since 2004; shipboard for earlier baseline



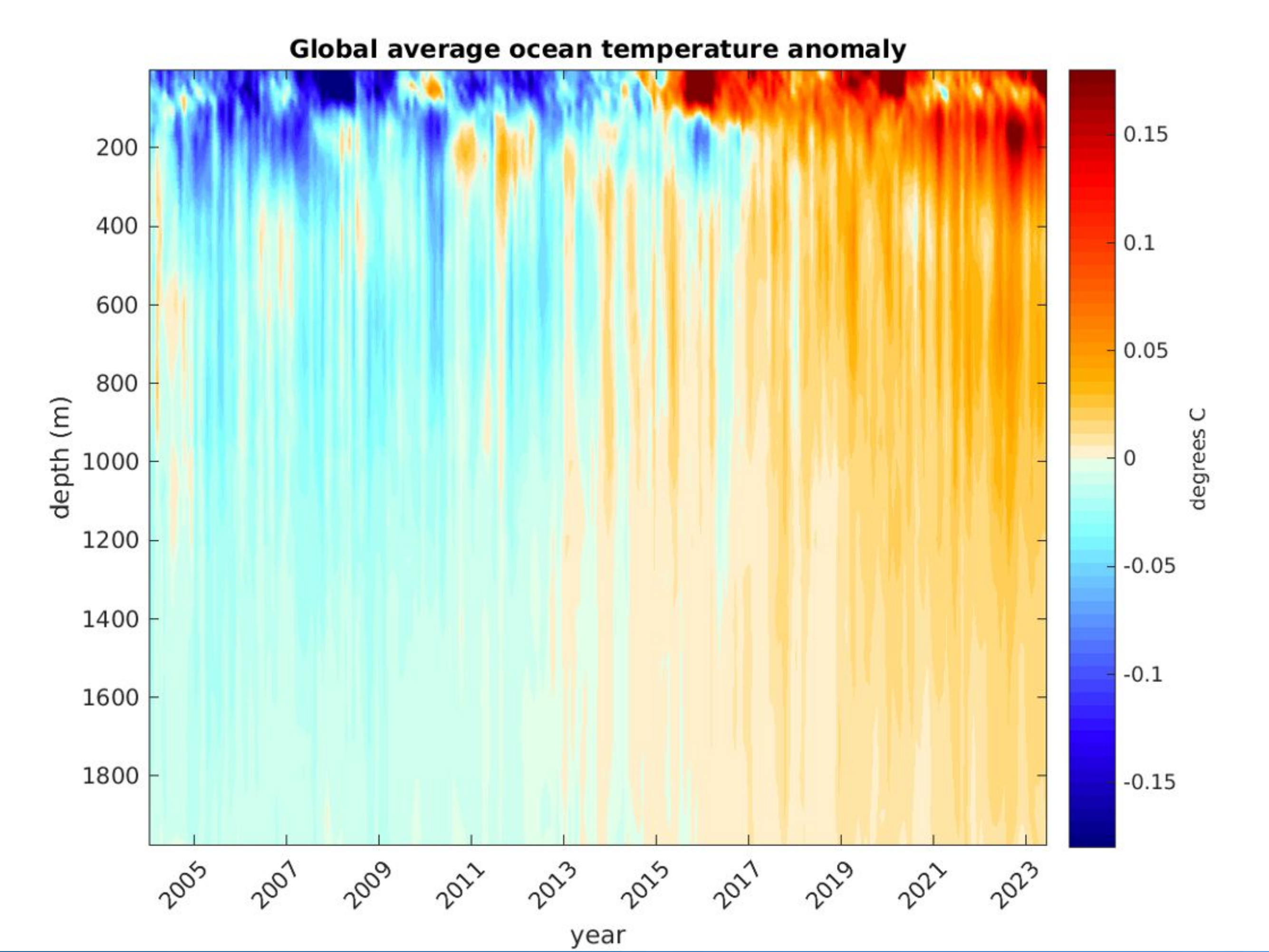
Heat content change 0-2000 m from 1955-2020

https://climate.nasa.gov/interactives/climate-time-machine/

Ocean heat uptake

Warming of the deep ocean tells us that these changes are irreversible for centuries to millennia

Argo measurements



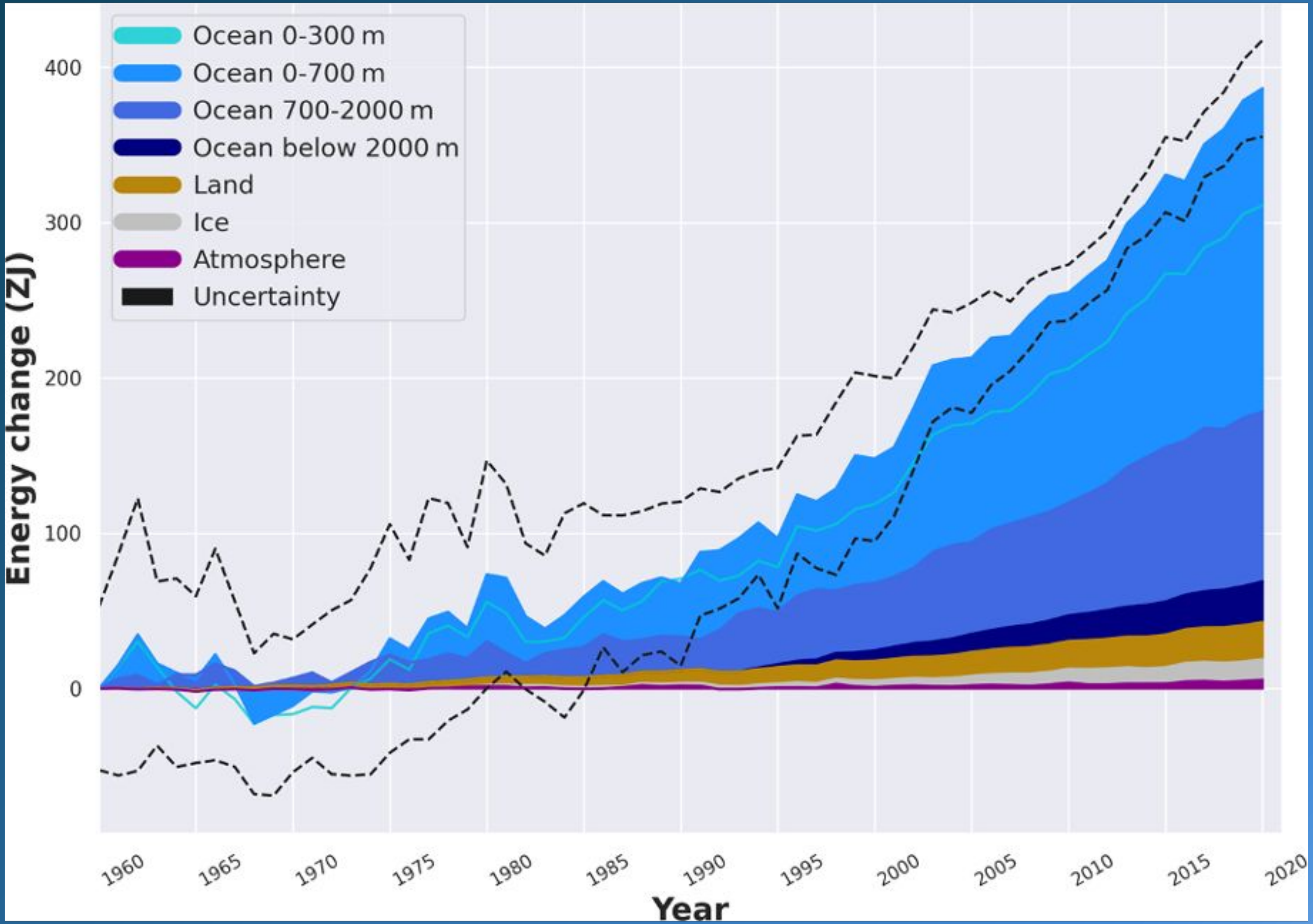
Temperature change with depth from 2004-2023

https://argo.ucsd.edu/science/argo-and-climate-change/

Ocean heat uptake

Besides the uptake of the major part of anthropogenic surplus heat by the ocean, heat is also available to warm the land, the atmosphere, and to melt the ice.

Both a warming ocean and the melting of ice on land are driving sea level rise.



Argo measurements since 2004

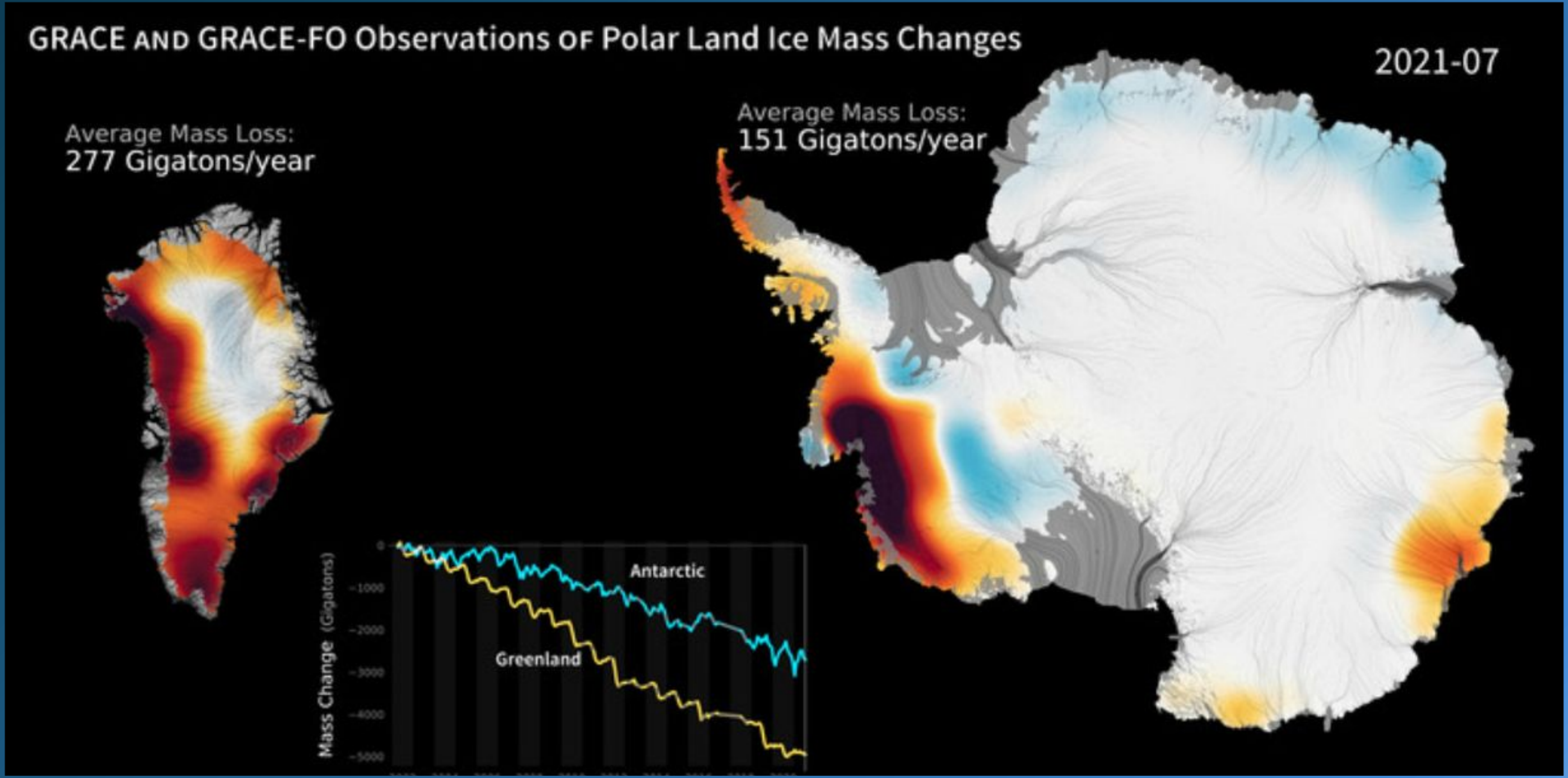
von Schuckmann et al. (Earth System Science Data, 2023)

Ice sheet melt

Warming climate is causing ice sheets to lose mass.

Ocean warming beneath ice shelves and at grounding lines is part of the reason.

Melting ice sheets contribute to sea level rise.



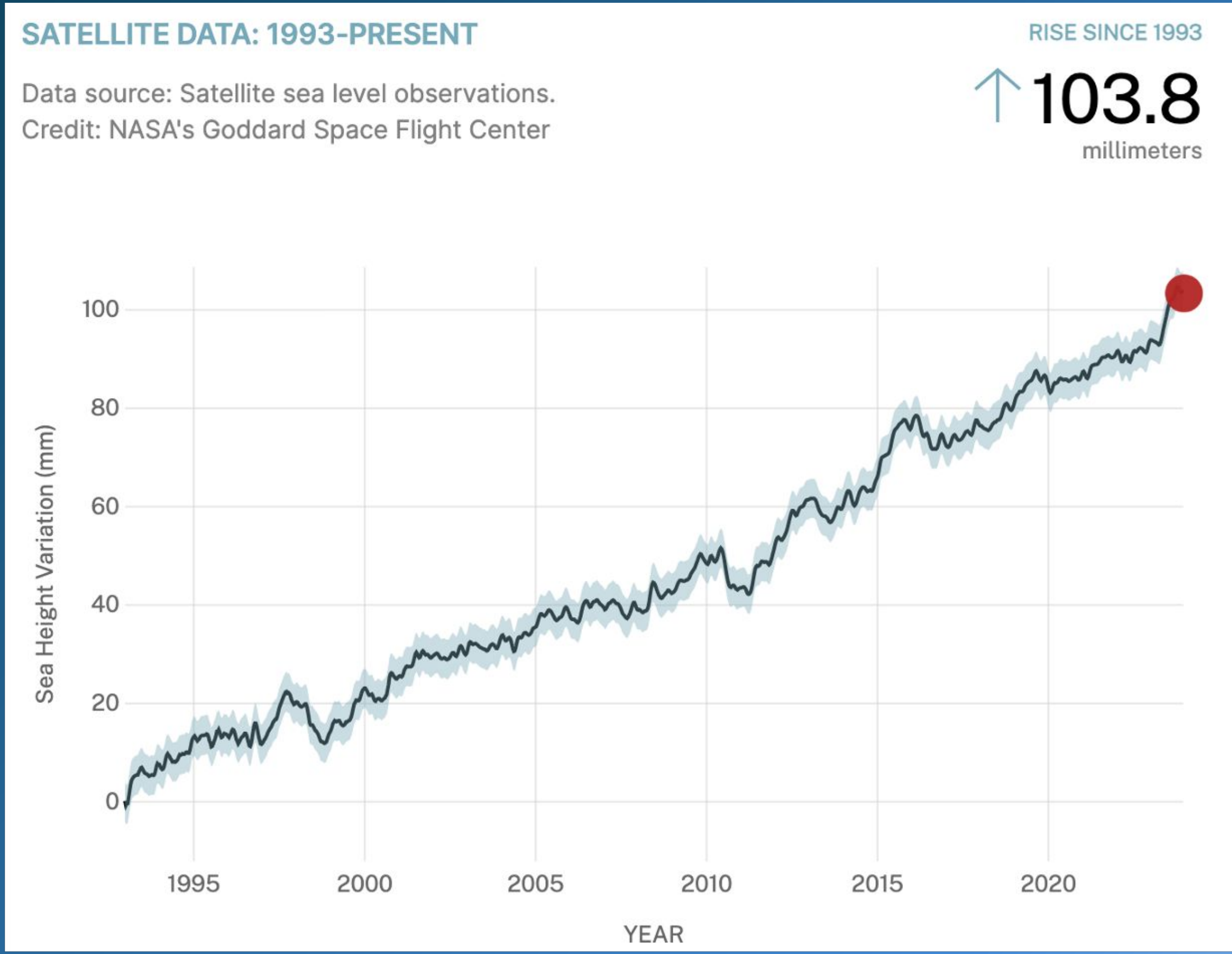
https://climate.nasa.gov/interactives/climate-time-machine/

Sea Level Rise

Global sea level has risen by 103.8 mm since 1993 - a rate of roughly 3.4 mm per year

Sea level rise is driven by:

- **Ocean mass changes** - addition of terrestrial water to the ocean e.g. melting ice sheets and glaciers ≈ 2.1 mm per year (since 2005)
- **Steric expansion** - ocean warming causing thermal expansion of seawater ≈ 1.3 mm per year (since 2005)

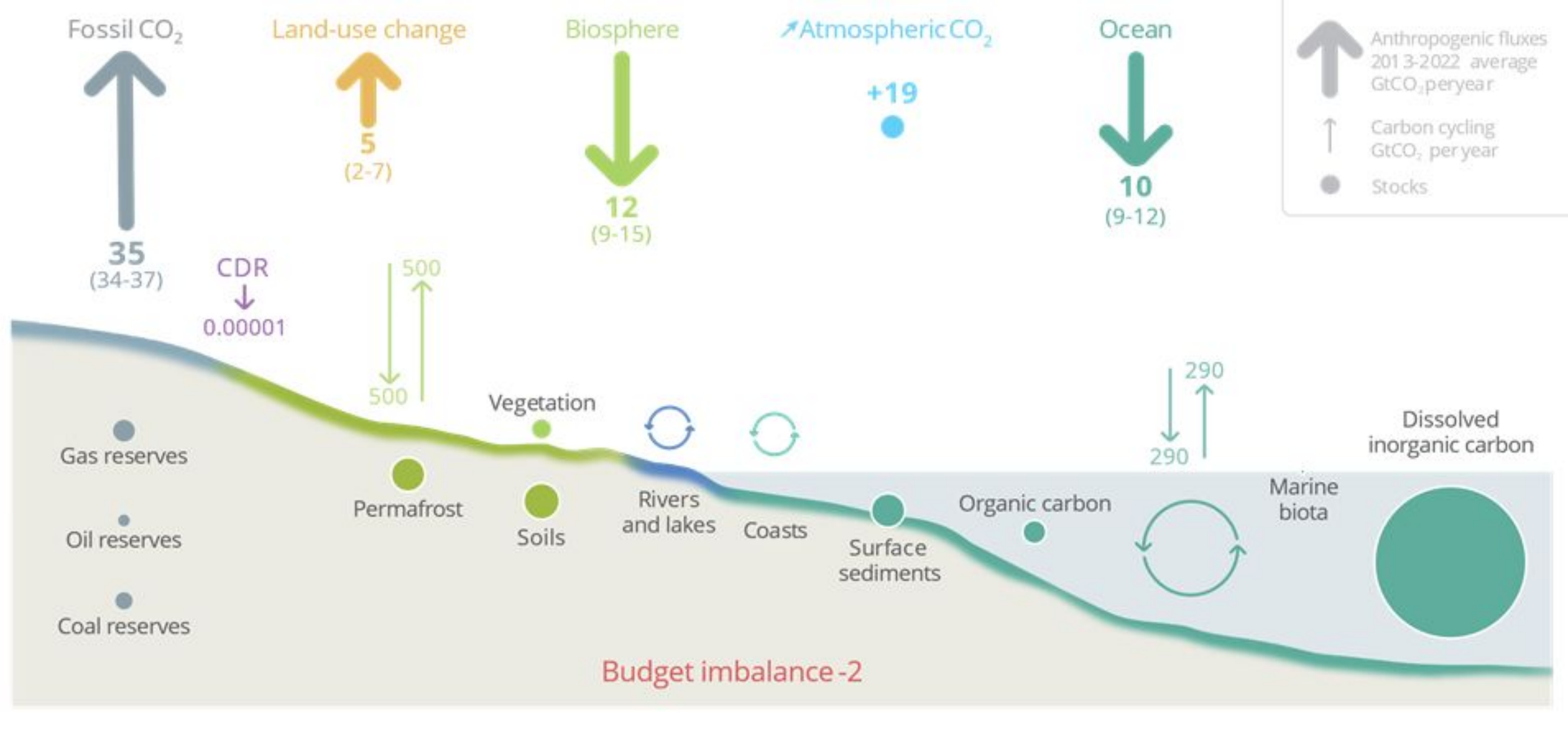


Data source: State of the Climate in 2022 (https://doi.org/10.1175/BAMS-D-23-0076.2)

Image credit: NASA

Ocean carbon uptake

The oceans play a major role in the atmospheric carbon budget



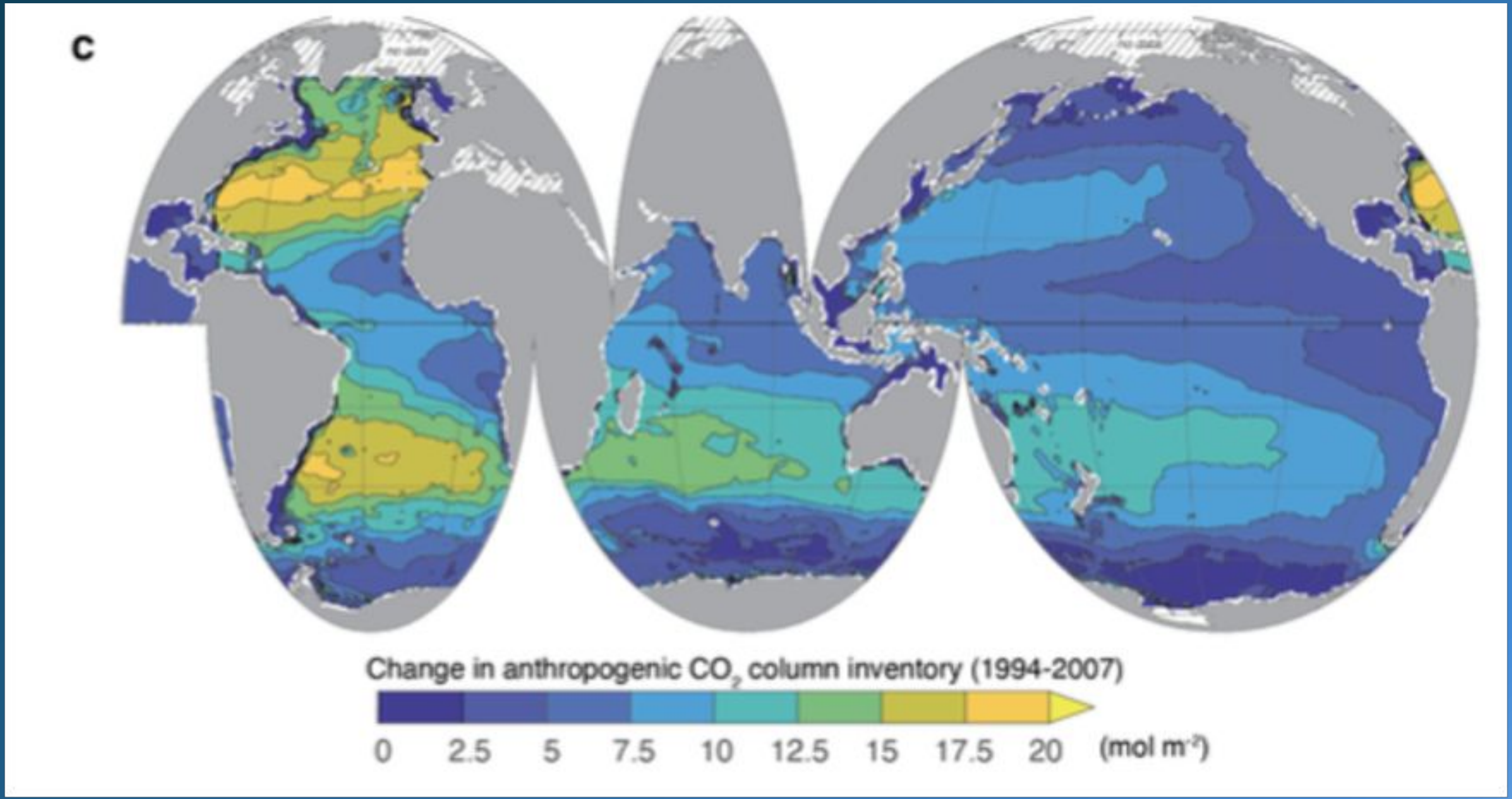
Anthropogenic perturbation of the global carbon cycle (Gt CO2/yr)

Friedlingstein et al.: Global Carbon Budget 2023

Ocean carbon uptake

The ocean takes up ~30% of the excess CO_2 in the atmosphere.

This service to the atmosphere results in ocean acidification.



Change in anthropogenic CO_2 column inventory (1994-2007) (mol m^{-2})

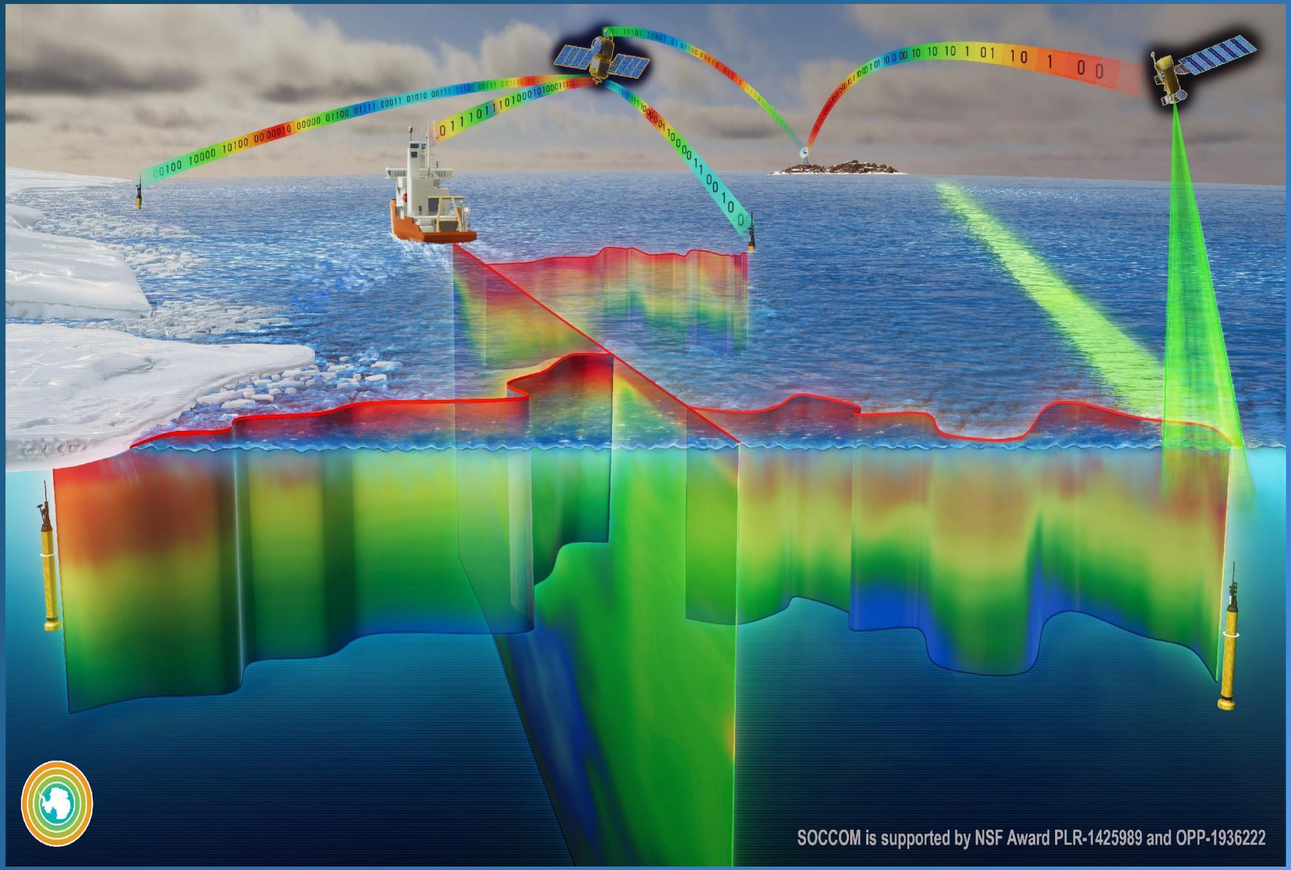
Shipboard GO-SHIP observations
(5-10 year repeats)

Gruber et al. (Nature 2023)

Understanding Climate Processes Requires Sustained, Global, Interior Ocean Observations

NSF is a major supporter of 3 critical tools for climate quality observations of the ocean interior:

- OneArgo's BGC Profiling Floats
  - SOCCOM (OPP)
  - GO-BGC (OCE)
- GO-SHIP repeat hydrography
- Fixed locations
  - Long-term ocean stations
  - Ocean Observatories Initiative (OOI moorings)



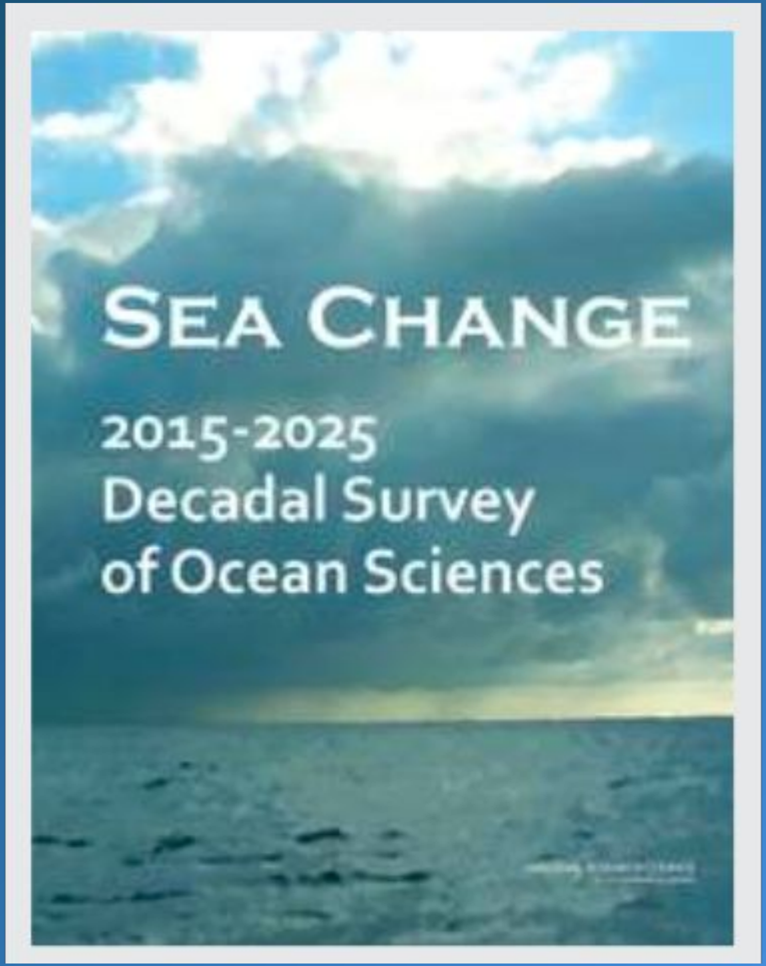
Revisiting
SEA CHANGE: 2015-2025 DECADAL SURVEY OF OCEAN SCIENCES

Special highlight box on

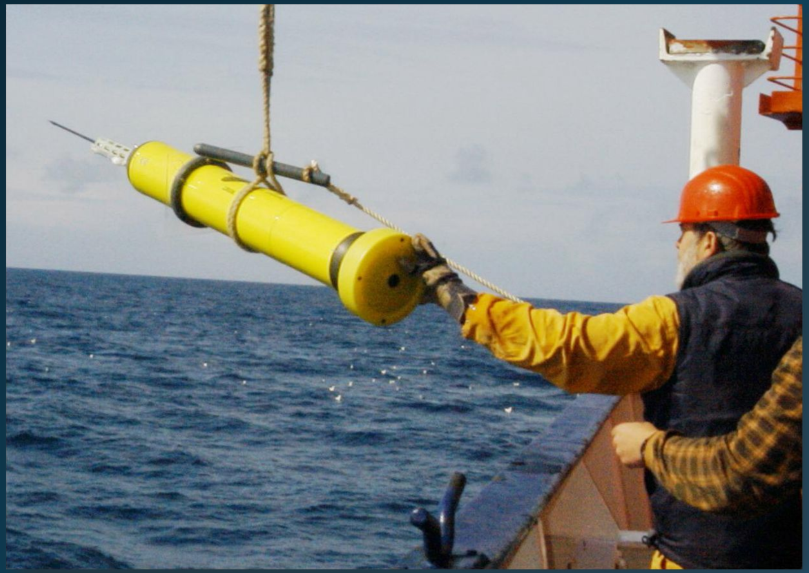
- Argo (temperature and salinity) = Core Argo

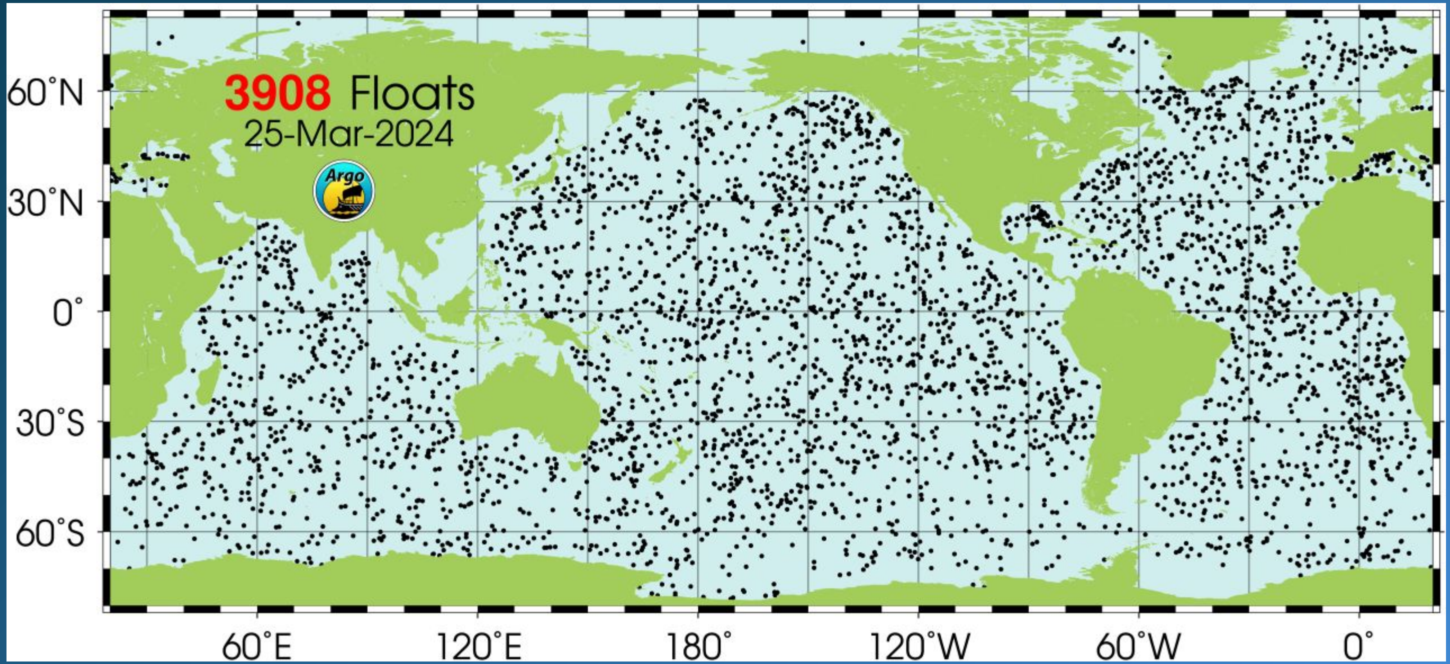
as a primary example of a transformative observing system that should serve as a model for other emerging observing systems.

NSF subsequently has supported emerging observing systems. Relevant to this presentation:
- BGC Argo
- Evolution of GO-SHIP



Sustained, Frequent Observations for Heat and Salinity





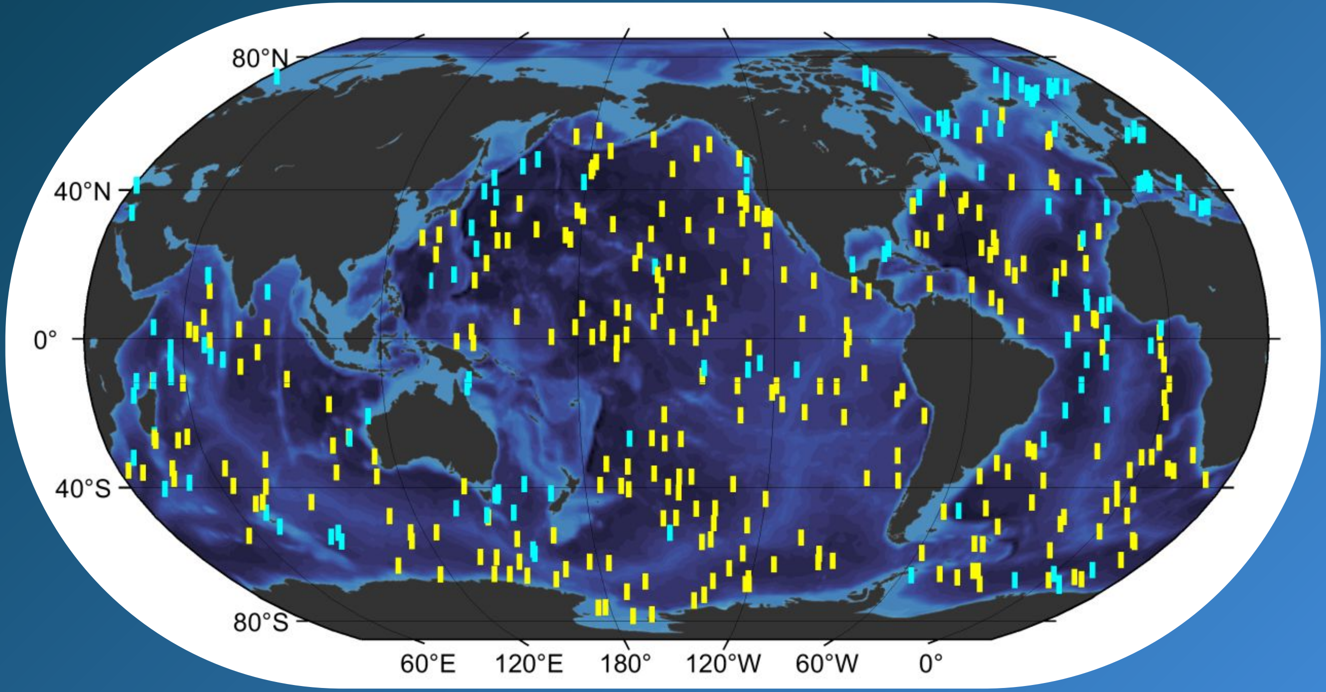
Core Argo (NOAA) - since 2000

- Every 10 days
- Temperature and salinity
- Surface - to - 2000m
- Target number: 4000 floats

Currently 3900 autonomous floats
30 nations contribute
Data are freely shared in real time

https://argo.ucsd.edu/about/status/

Sustained, Frequent Observations for Carbon, Oxygen, Ecosystem Health



Floats with 4 sensors: 67
Floats with 5 sensors: 297
Floats with 6 sensors: 49
NSF floats in yellow

BGC Argo - Emerging part of OneArgo

Essential data for ocean health, carbon budgets, effects of marine CO_2 removal (mCDR).

- **Sensors: pH, oxygen, nitrate, chlorophyll, particulate organic carbon, light**
- **Same mission as Core Argo (10 days, 0-2000 m)**

https://go-bgc.org

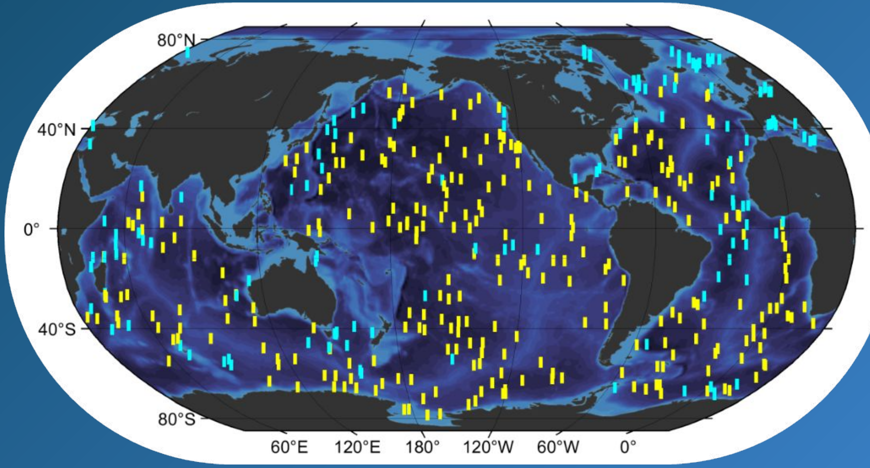
Funding of Biogeochemical Argo

Primary support is by NSF OCE, OPP thru

- GO-BGC (Global Ocean Biogeochemistry), building a 500 float array
- SOCCOM (Southern Ocean Carbon and Climate Observations and Modeling), a 200 float array, including deployments under southern sea ice.

GO-BGC deployments are funded with an NSF Mid-Scale RI-2 grant ($53M). This was “new”, one-time funding. Funding ends in 2025.

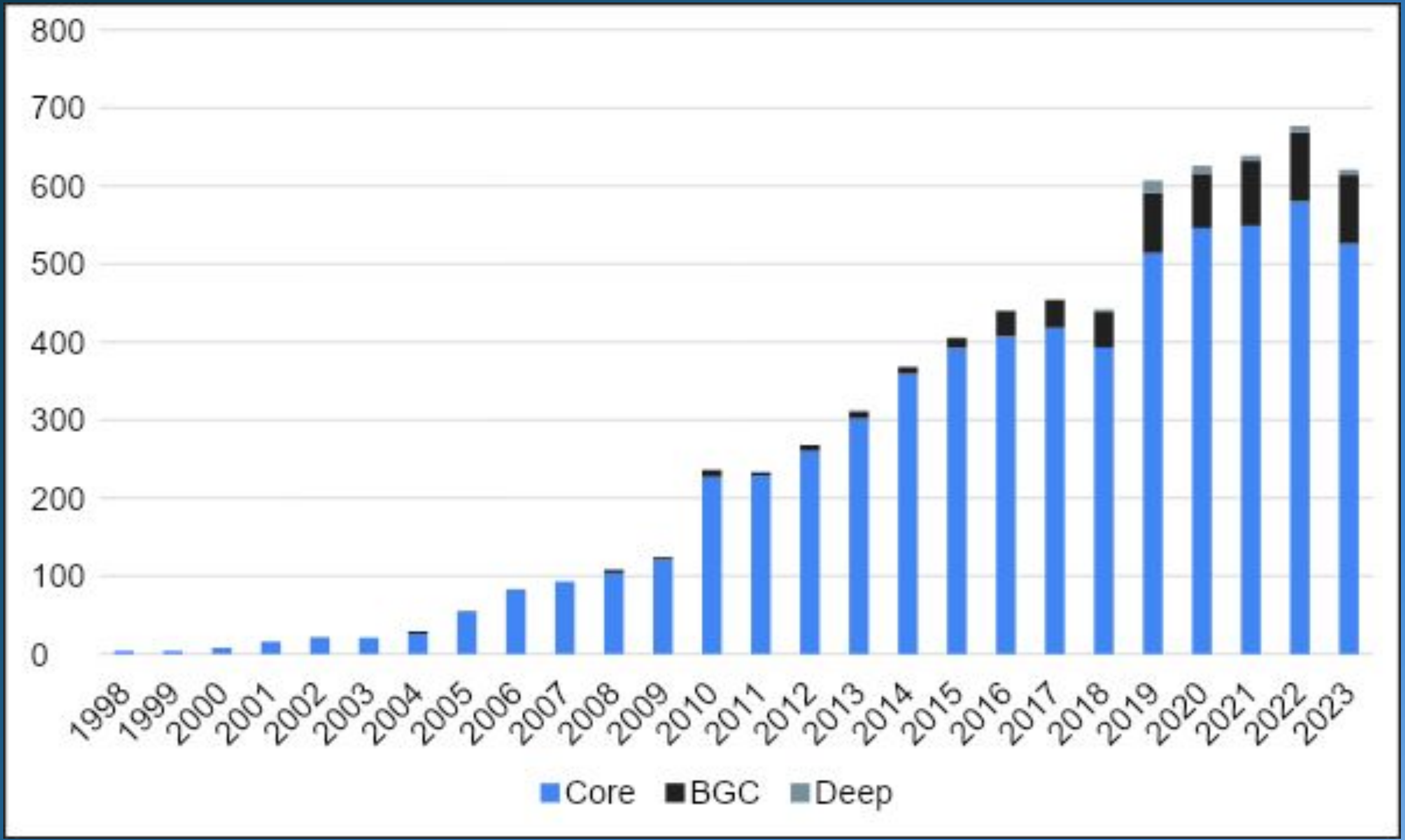
How do we sustain the system beyond 2025? It requires ~125 floats/year at ~$16M/year (+ inflation).



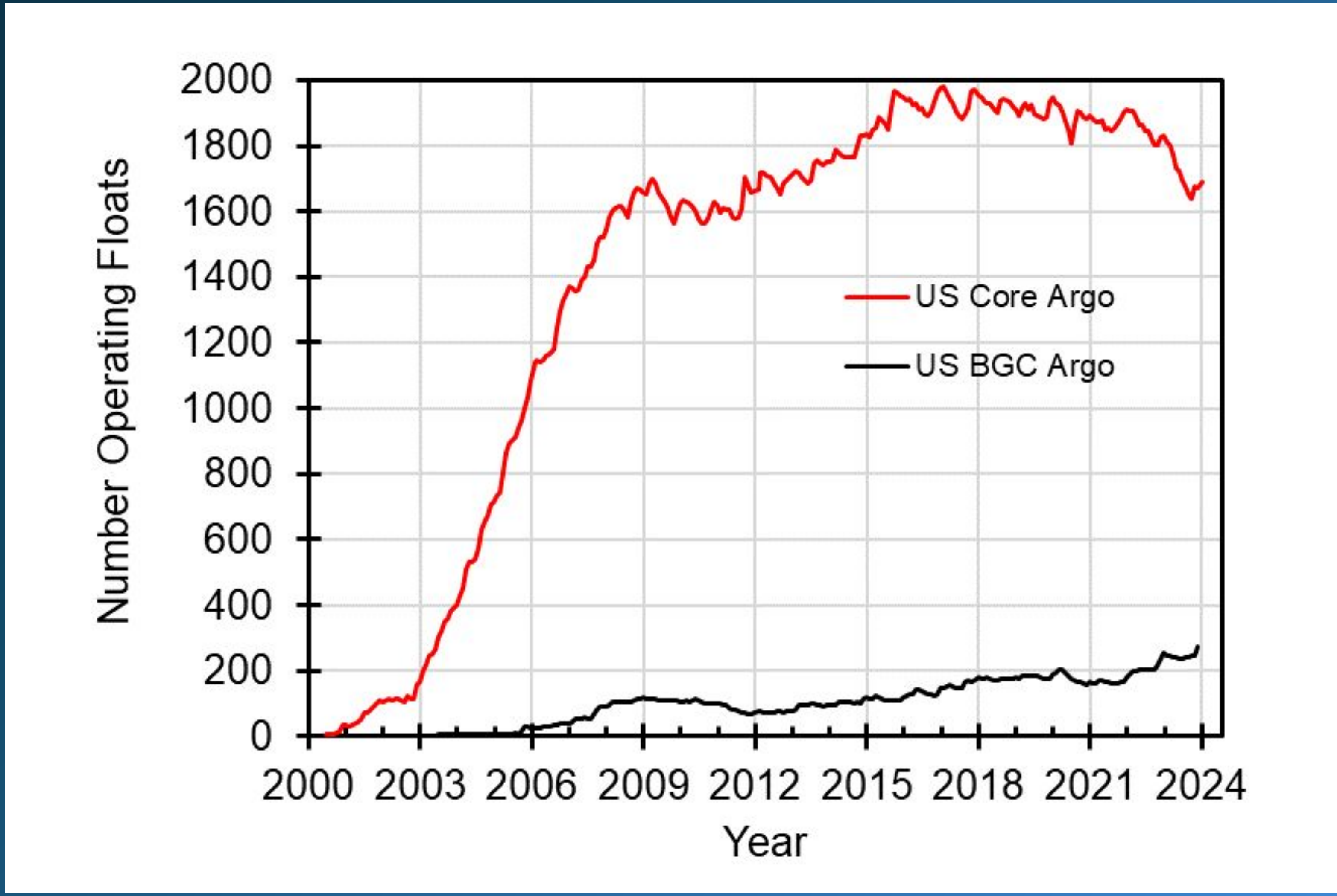
Argo supports huge amounts of discovery
More than 6000 papers; > 1 paper per day

Data are: freely shared in real-time; well documented and of known uniform quality

Strong use in education and research training



Current NOAA budgets are insufficient to support Core-Argo, and that array is in decline. BGC floats, mostly funded by NSF, are mitigating this decrease.



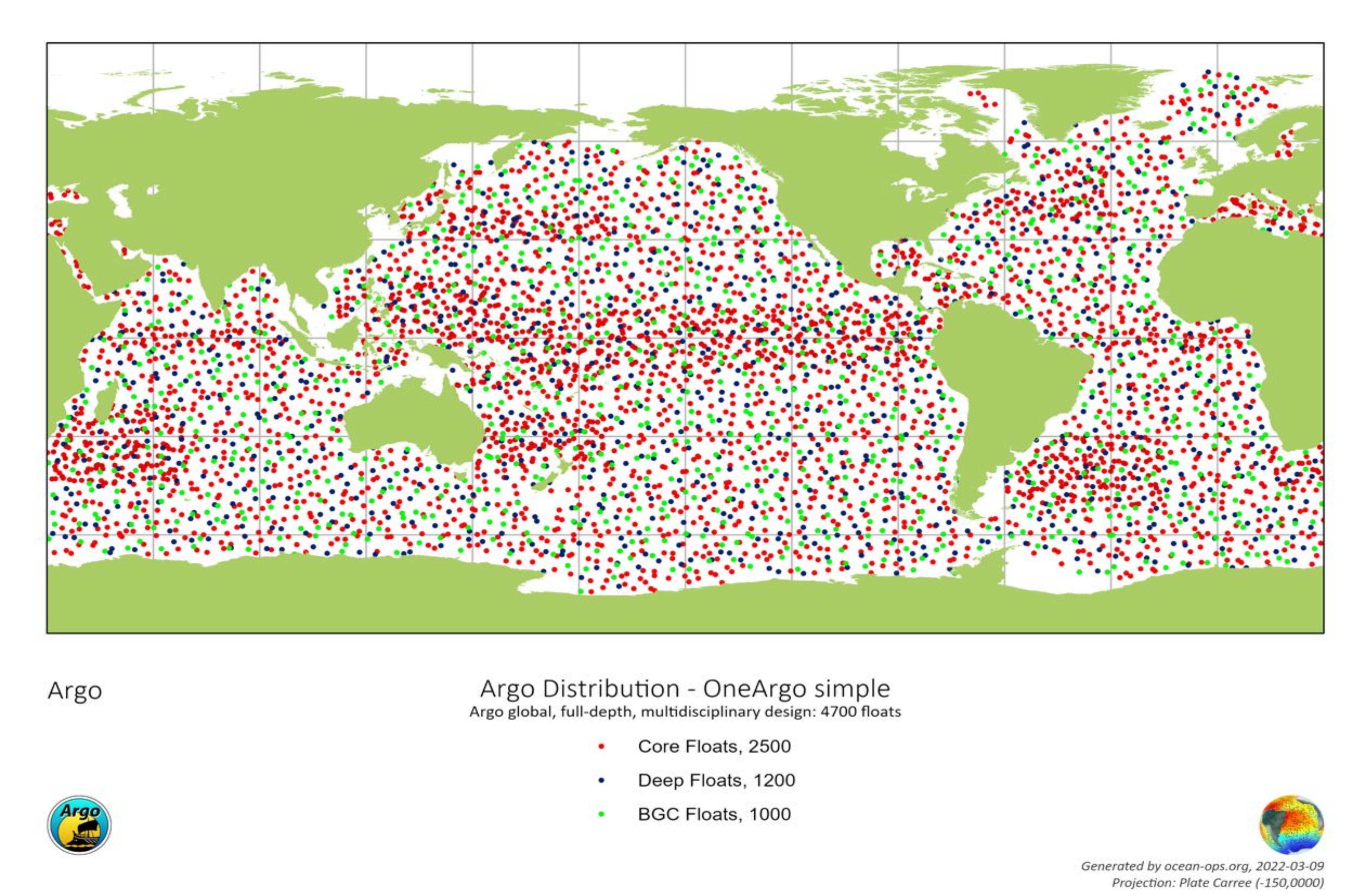
Addressing major gaps: OneArgo design

Below 2000m: Deep Argo mission

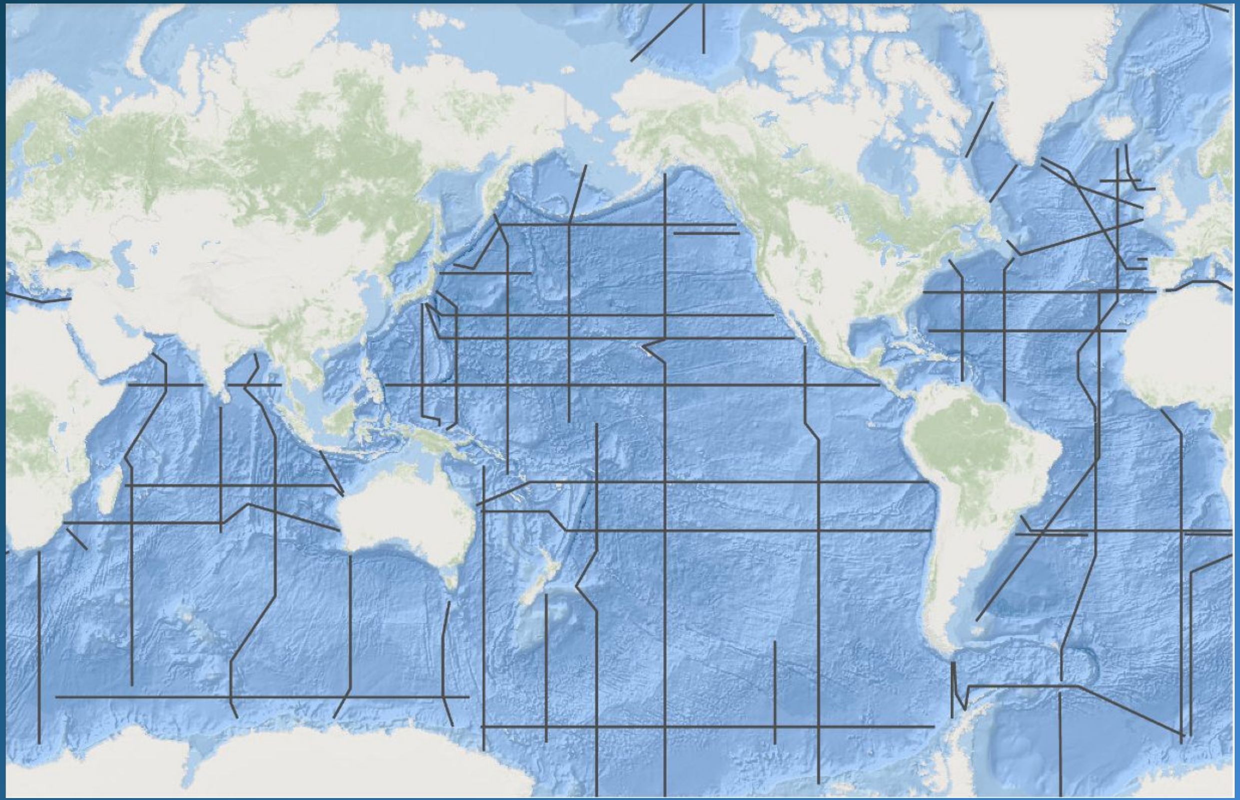
Carbon, chemistry and plankton: Biogeochemical Mission

Ice-covered oceans: Polar Mission

None of these extensions have sustained funding



Global Shipboard Observations – GO-SHIP



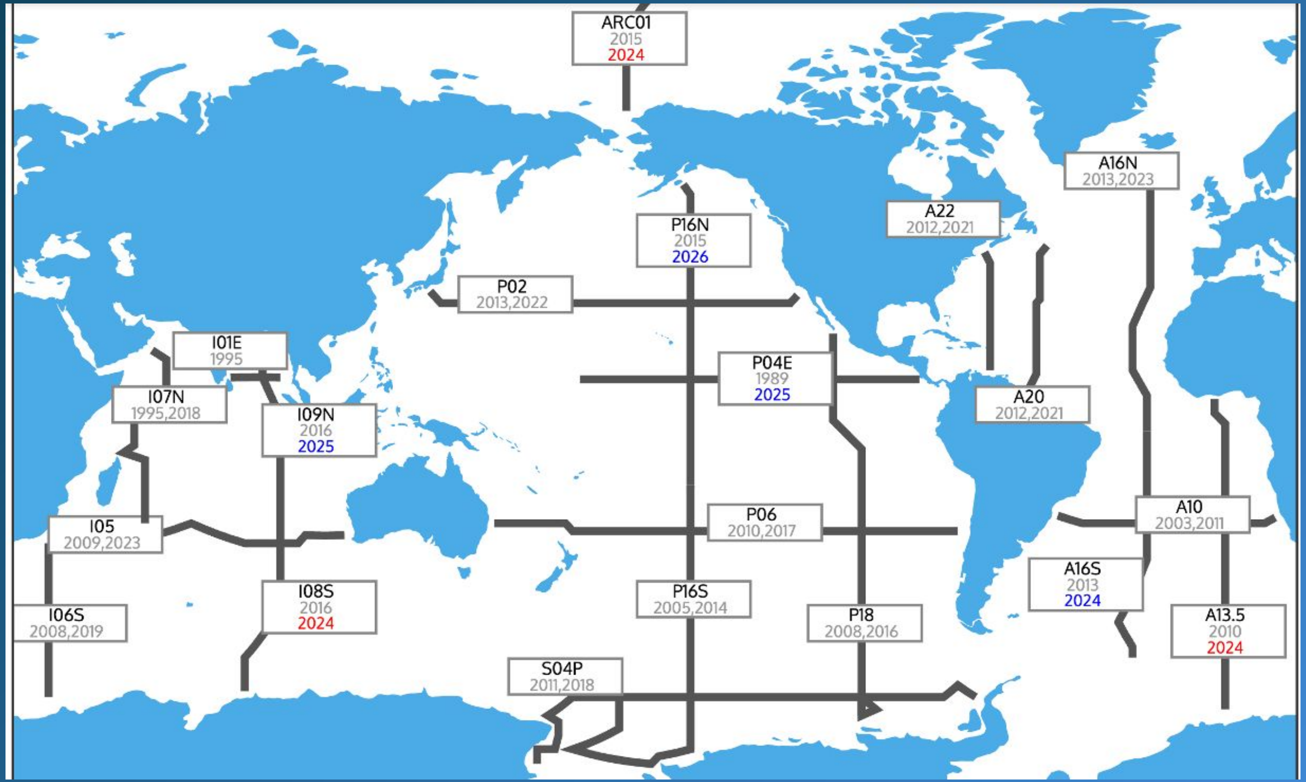
Repeat crossings of ocean basins to ocean bottom: 5 to 10 years apart since 1990s

Highest accuracy 'gold' reference standard, top to bottom

Emerging 'Bio GO-SHIP'

https://usgoship.ucsd.edu
https://www.go-ship.org
https://biogoship.org/

Global Shipboard Observations – U.S. GO-SHIP



Repeat crossings of ocean basins to ocean bottom: 5 to 10 years apart since 1990s

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https://biogoship.org/

Emerging 'Bio GO-SHIP'

GO-SHIP supports huge amount of discovery

> 640 publications in bibliography

h-index of 70

Does not include the very large number of publications and heavy use by modelers of the GLODAP data products

Global Ocean Ship-based Hydrographic Investigations Program

FOLLOW

GO-SHIP
Verified email at jcommops.org - Homepage
Oceanography

TITLE	CITED BY	YEAR
Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms JC Orr, VJ Fabry, O Aumont, L Bopp, SC Doney, RA Feely, ... Nature 437 (7059), 681	3897	2005
Ocean acidification: the other CO2 problem SC Doney, VJ Fabry, RA Feely, JA Kleypas Annual Reviews	2948	2009
Descriptive physical oceanography: an introduction LD Talley Academic press	1879	2011
Chemical oceanography FJ Millero CRC press	1320 *	2011
A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP) RM Key, A Kozyr, CL Sabine, K Lee, R Wanninkhof, JL Bullister, RA Feely, ... Global biogeochemical cycles 18 (4)	1265	2004
Expanding oxygen-minimum zones in the tropical oceans L Stramma, GC Johnson, J Sprintall, V Mohrholz science 320 (5876), 655-658	1063	2008
Ocean deoxygenation in a warming world RF Keeling, A Körtzinger, N Gruber Annual Reviews	898	2009

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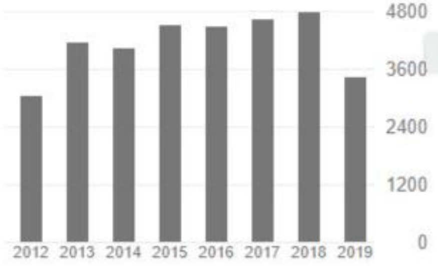
Citations	44366	26019
h-index	93	70
i10-index	408	340

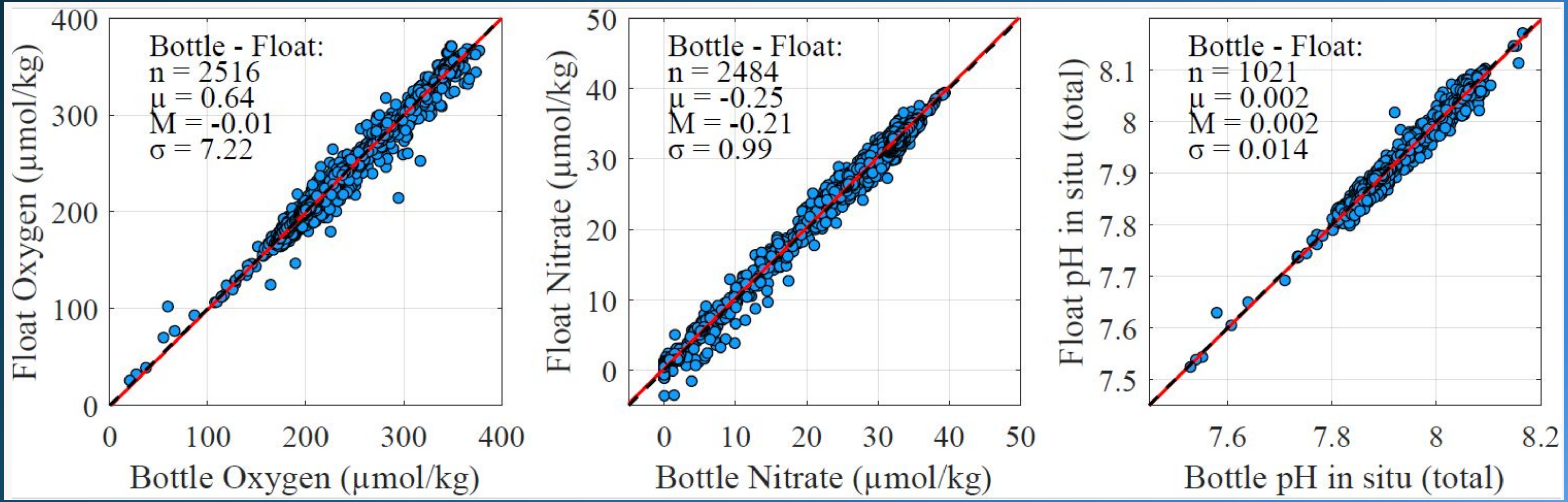


https://www.go-ship.org

GO-SHIP and Core/Deep & BGC-Argo synergy (cal/val)

- **GO-SHIP provides reference standard temperature, salinity, oxygen, nutrients, carbon system observations for reference climatologies (e.g. GLODAP) and T/S data bases, used for calibration of the autonomous Argo float sensors**

- **GO-SHIP provides the coincident validation needed to confidently use BGC-Argo data**



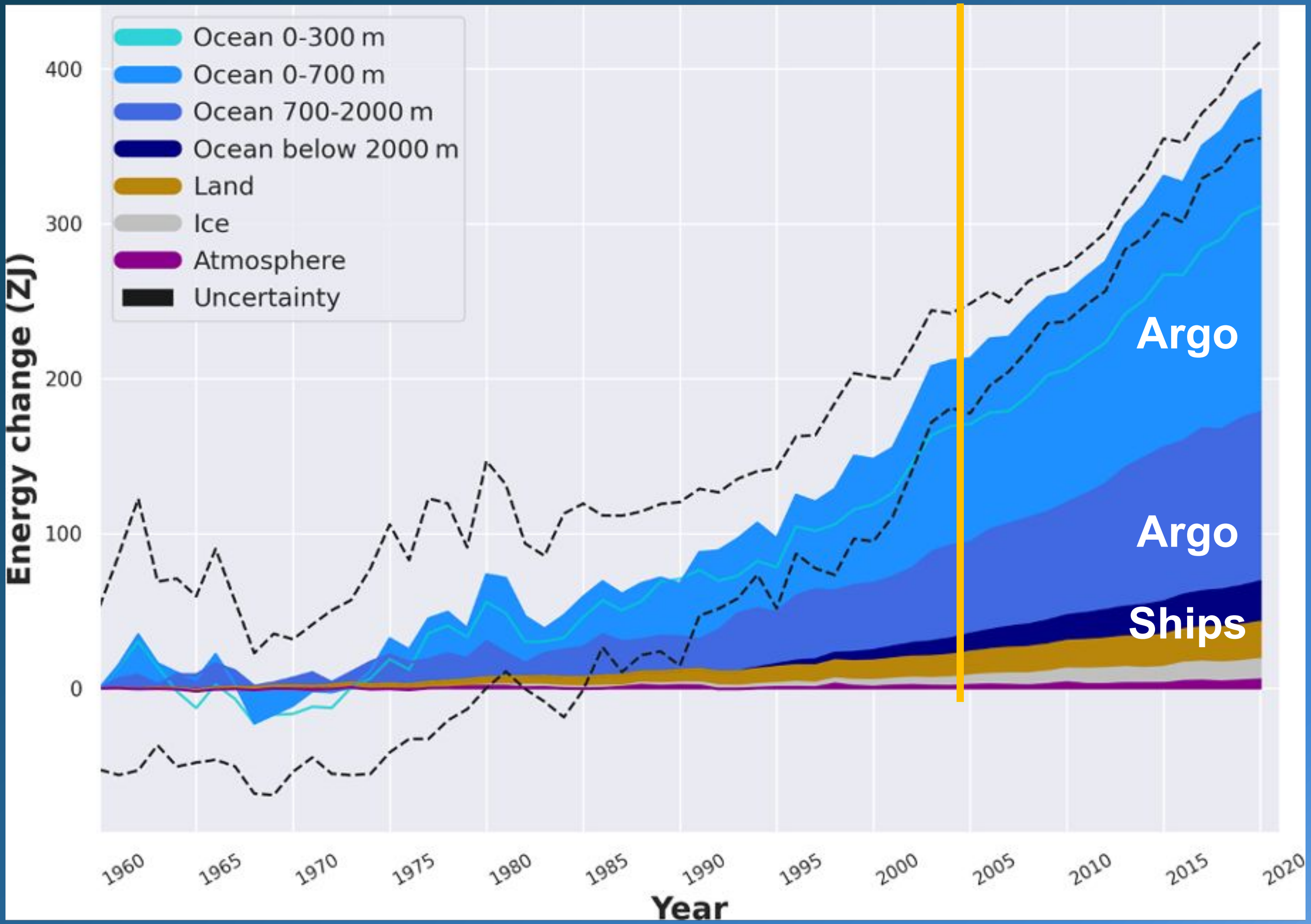
Sarmiento et al., Prog in Oceanogr. 2023

Ocean heat uptake: Argo and GO-SHIP

The ocean takes up 90% of the excess heat

We know this because of Argo T/S observations & GO-SHIP (deep ocean).

Argo T/S is essential for climate assessment.

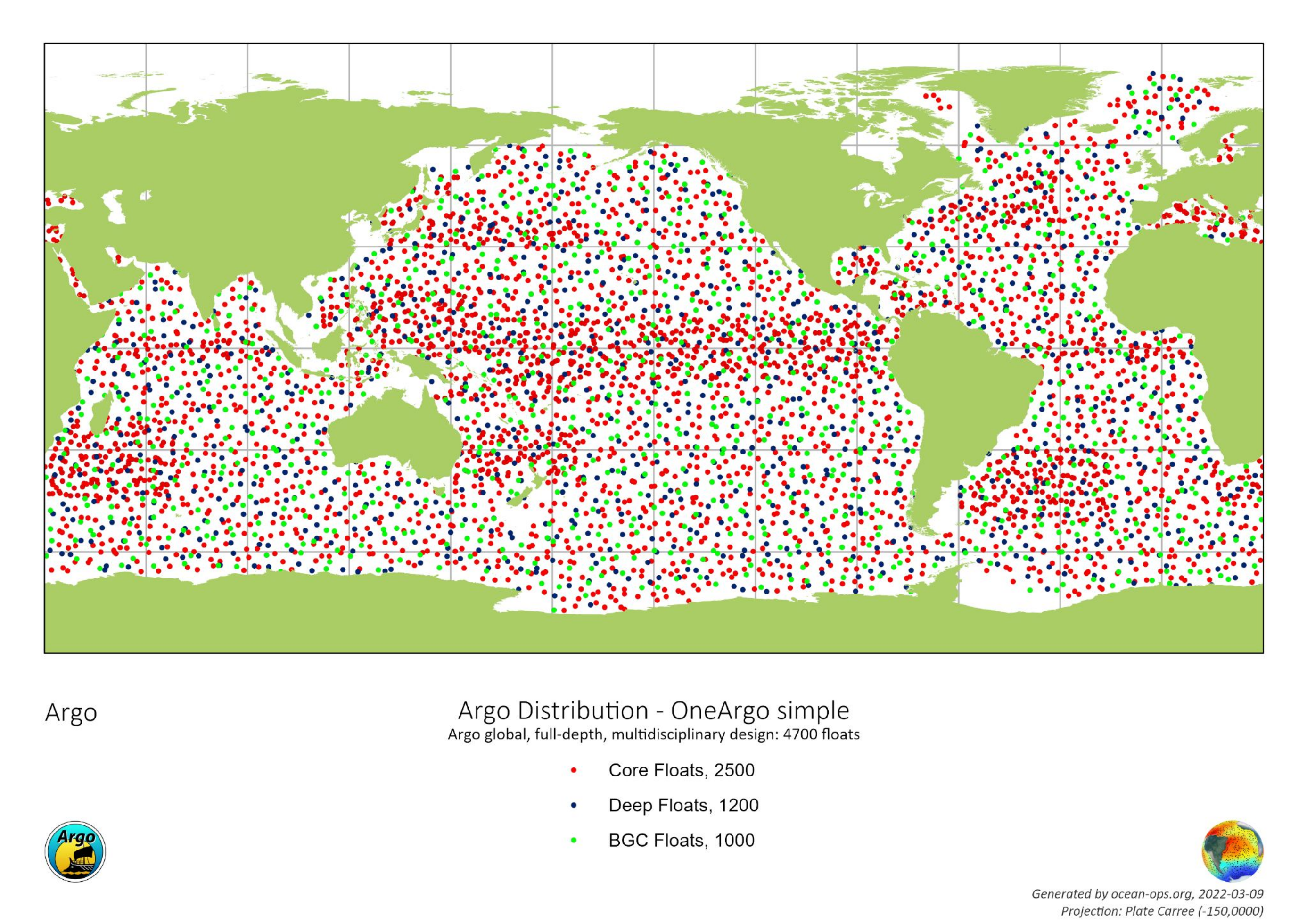


von Schuckmann et al. (Earth System Science Data, 2023)

Sea level rise: Argo and GO-SHIP

Argo (and GO-SHIP) provide the observations that are required to quantify the steric expansion contribution to sea level rise:

- ~1.3 mm per year in the upper-ocean (above 2000 m)
- ~0.1 mm per year in the deep-ocean (below 2000 m)



Proposed global Argo array (OneArgo)

Data sources:
State of the Climate in 2022 (https://doi.org/10.1175/BAMS-D-23-0076.2)
Desbruyères et al. 2016 (https://doi.org/10.1002/2016GL070413)

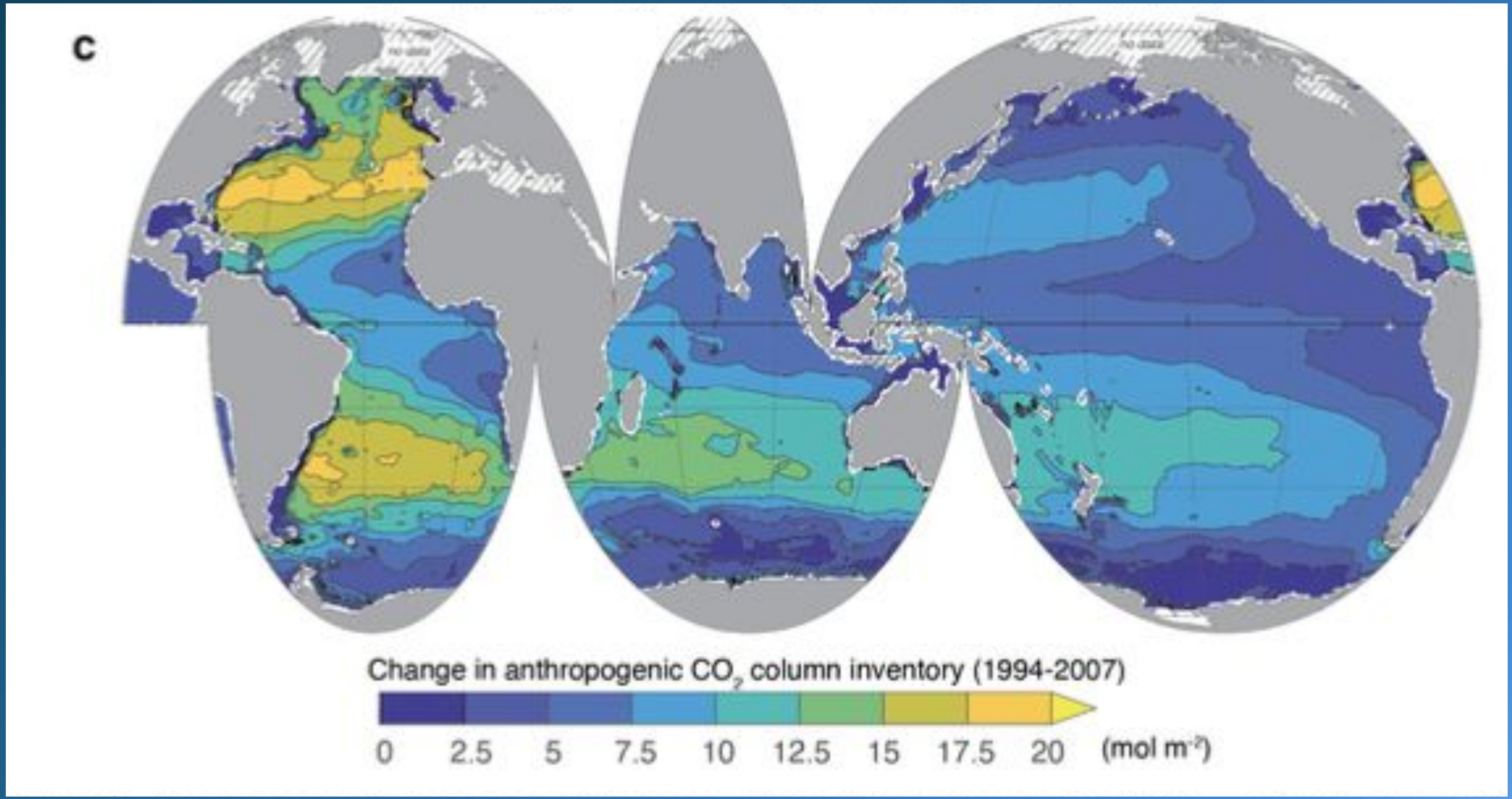
Image credit: OceanOPS

Ocean Carbon Uptake: GO-SHIP

The ocean takes up 25 to 30% of the excess CO_2 in the atmosphere.

GO-SHIP (5-10 yr repeats) used for the map

Seasonal sampling needed for regional resolution, closed C budgets and mCDR. -> BGC Argo sampling.



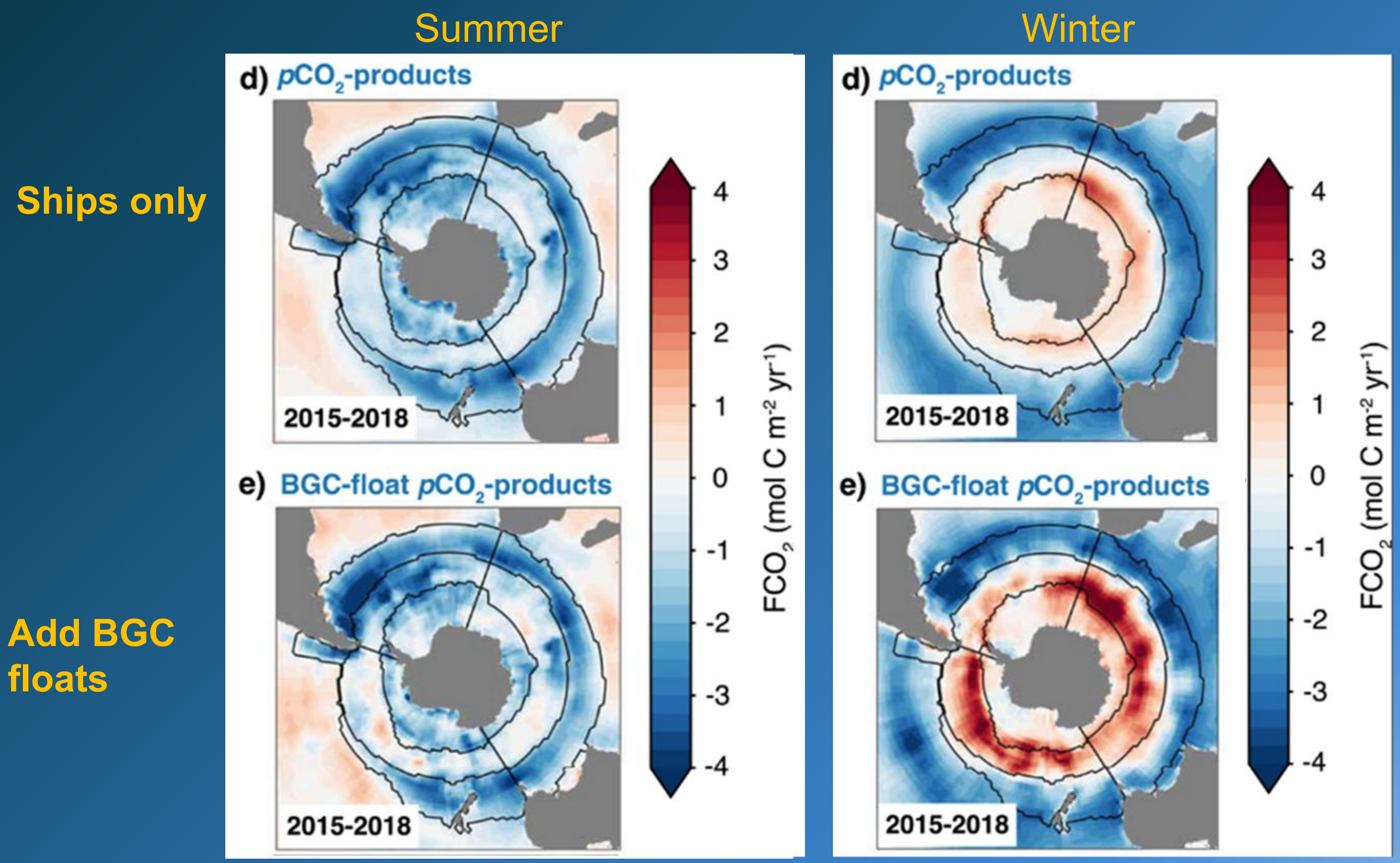
'Anthropogenic' Carbon (full ocean depth)

Gruber et al. (Nature, 2023)

BGC-Argo Enables Seasonal Assessment of Ocean Carbon Uptake

Air-sea flux of CO_2 mapped now using very sparse shipboard observations.

BGC Argo floats begin to provide seasonal fluxes.



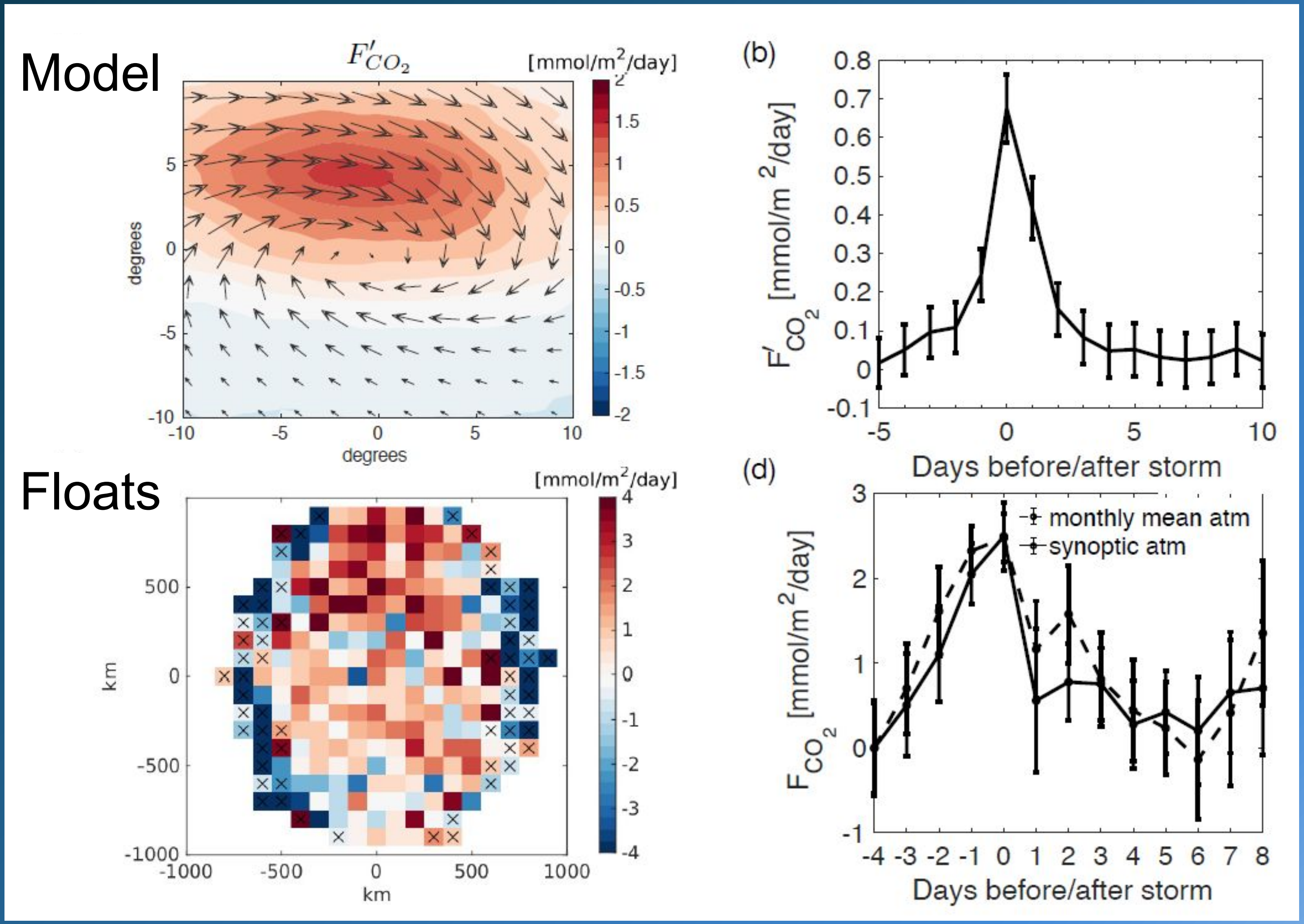
Hauck et al. (GBC, 2023)

BGC-Argo floats enable mechanistic understanding

Example:

SOCCOM floats show a 3X larger increase in air-sea CO_2 flux during storms relative to CESM model.

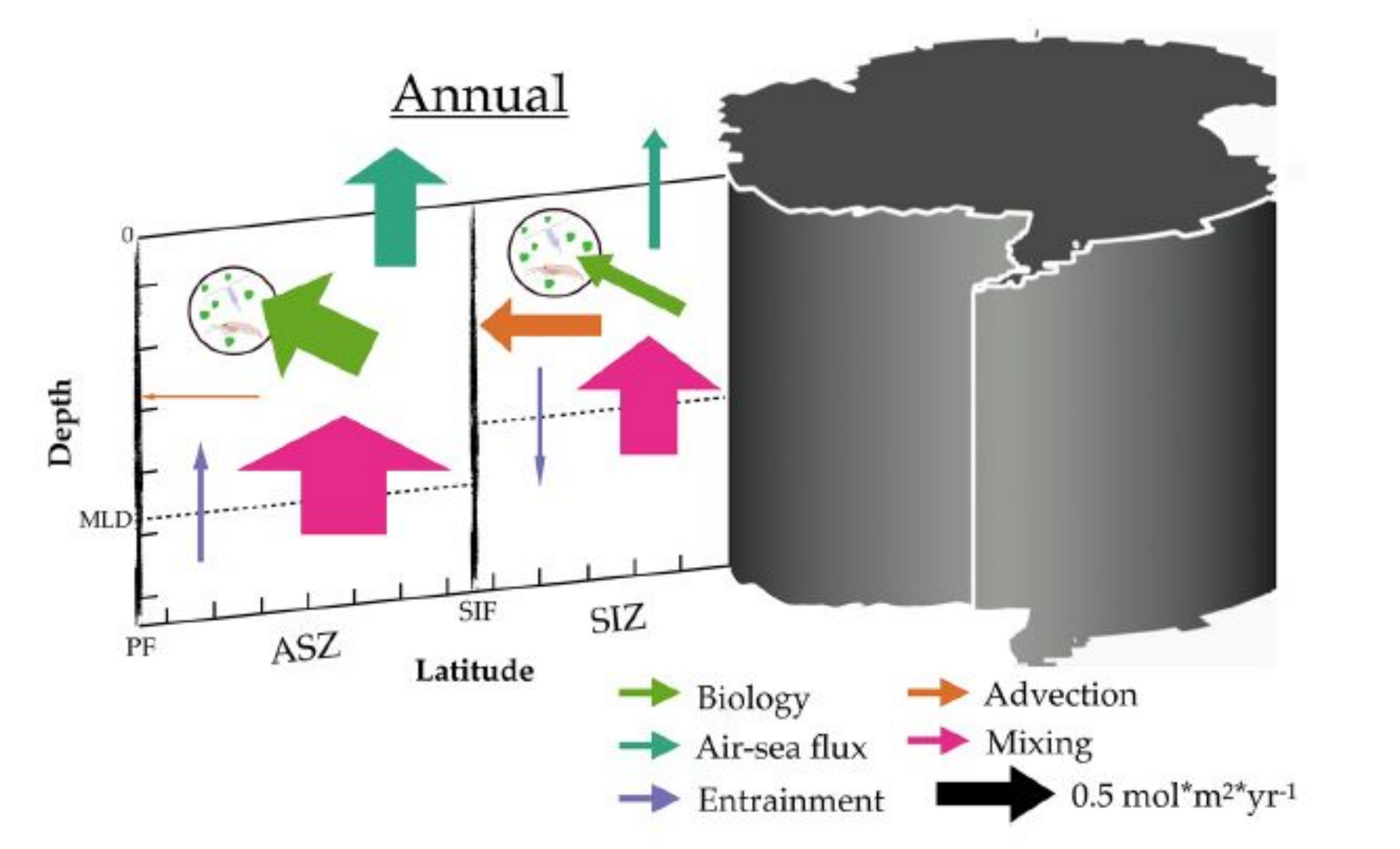
Storms contribute 26% of Southern Ocean flux, likely undersampled by ships.



Carranza et al., Nature Climate, prov. accepted

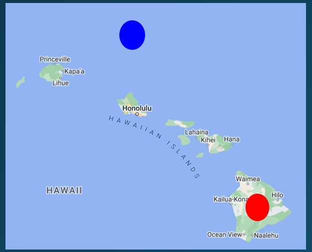
BGC-Argo provides high resolution, annual budgets

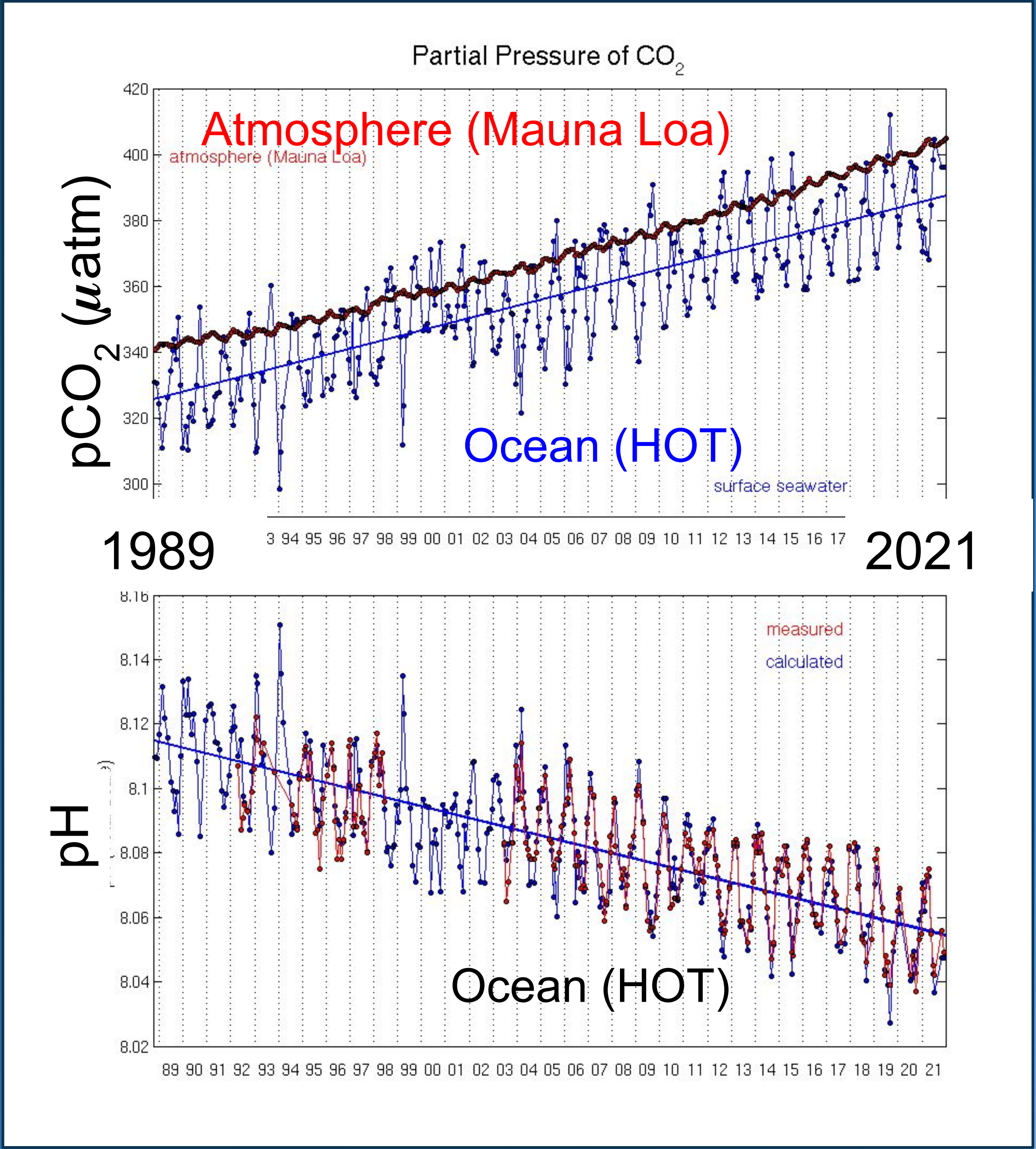
Antarctic Circumpolar Current carbon budget based on SOCCOM float observations



Sauve et al., JGR, 2023

Ocean Acidification





Fixed stations provide the definitive view, but there are few sustained stations.

Atmospheric CO_2 rises (Mauna Loa)

Ocean surface CO_2 rises with it (Hawaii)

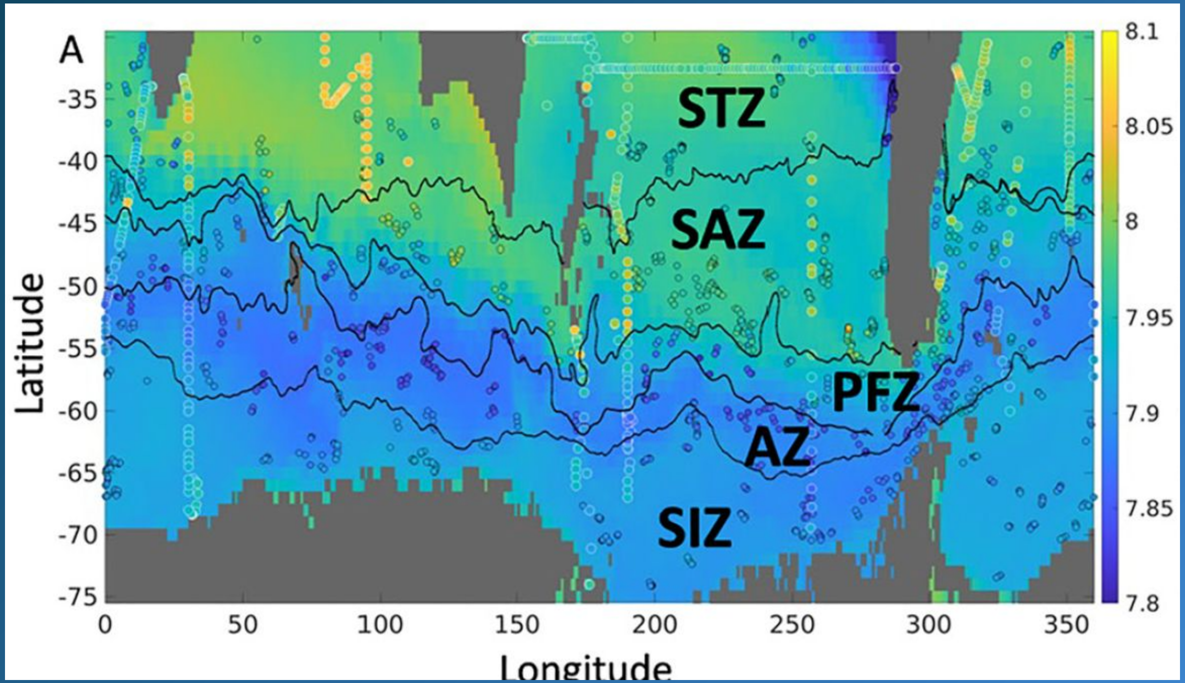
Ocean surface pH decreases (Hawaii)

Hawaii Ocean Time-series (HOT)

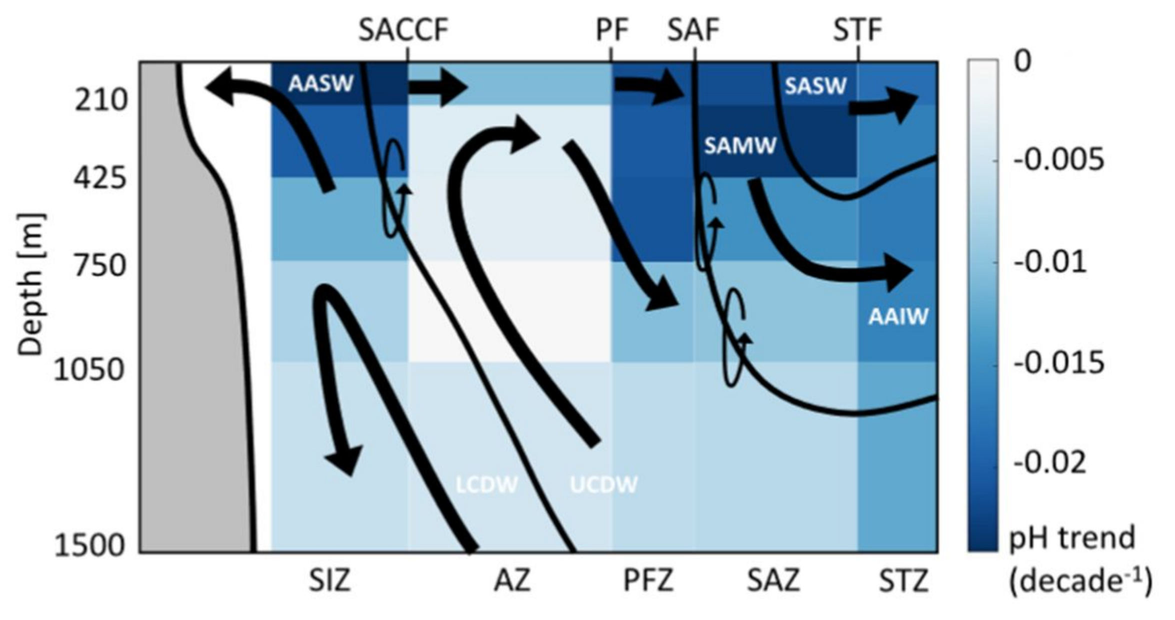
https://hahana.soest.hawaii.edu/hot/trends/trends.html

Ocean Acidification

Sustained ship and float observations merged with data assimilating models transform our understanding of ocean acidification



pH in summer, mapped (float & ship)



Rates of pH change (pH/decade) in each zone with overturning circulation overlaid

Mazloff et al. (JGR 2023)

Oxygen Variability from OneArgo and GO-SHIP

Monthly global oxygen distribution from BGC and Core Argo:

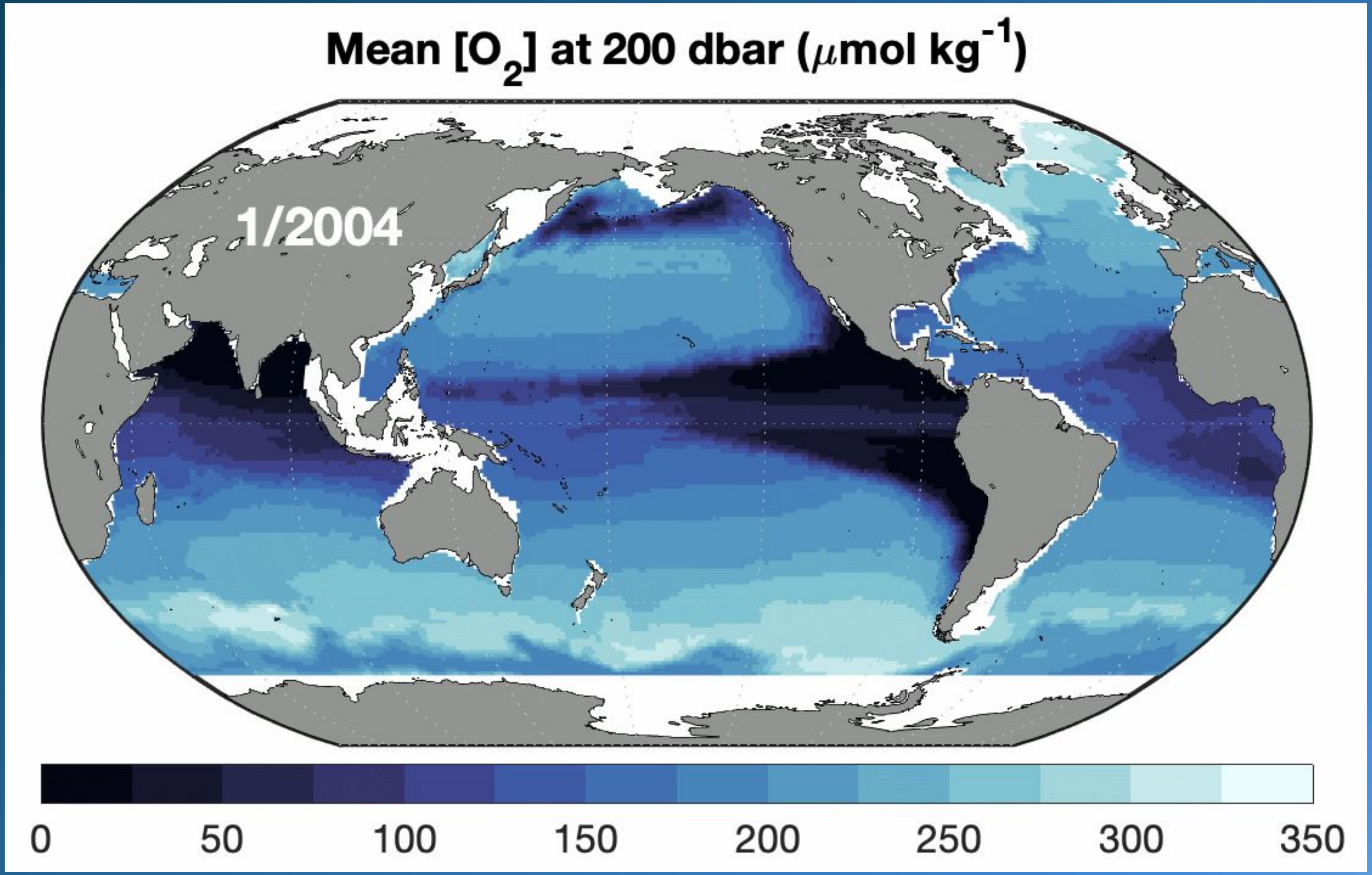
GO-SHIP oxygen
BGC Argo oxygen

⬇

Train machine learning to use much more completely sampled Argo T/S

⬇

Monthly, global oxygen

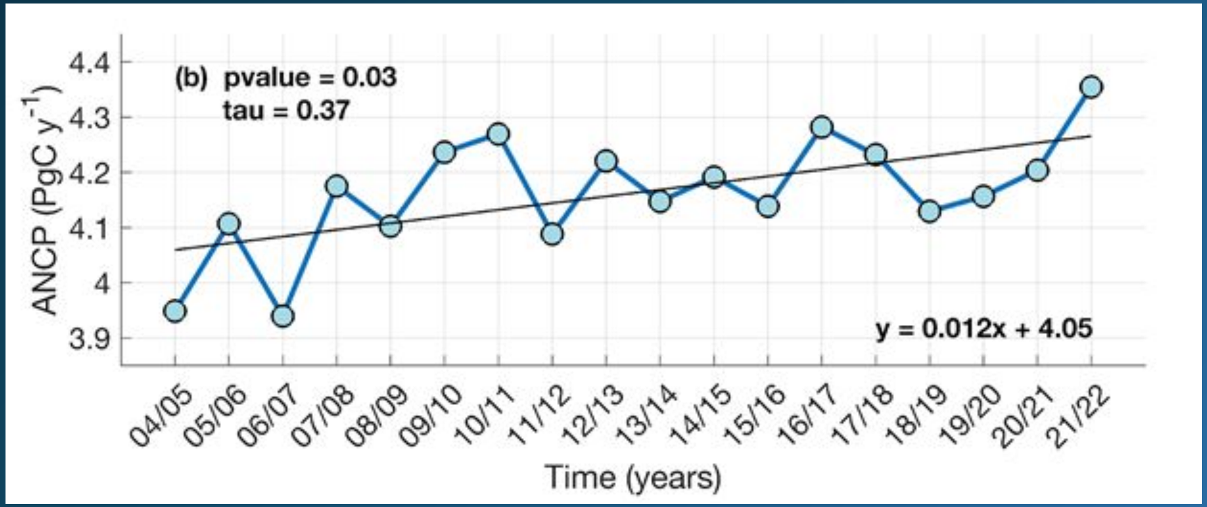


Sharp et al. (ESSD 2023)

Annual Net Community Production Changes over 18 years

Machine learning:
BGC-Argo nitrate used to train Neural Network

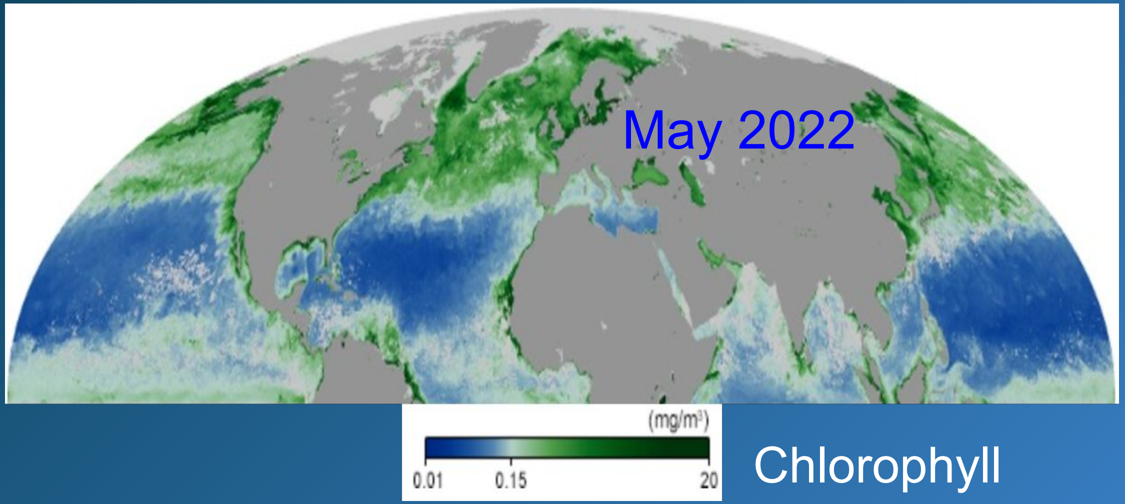
ANCP increase is consistent with satellite ocean chlorophyll change.



Liniger et al., in prep.

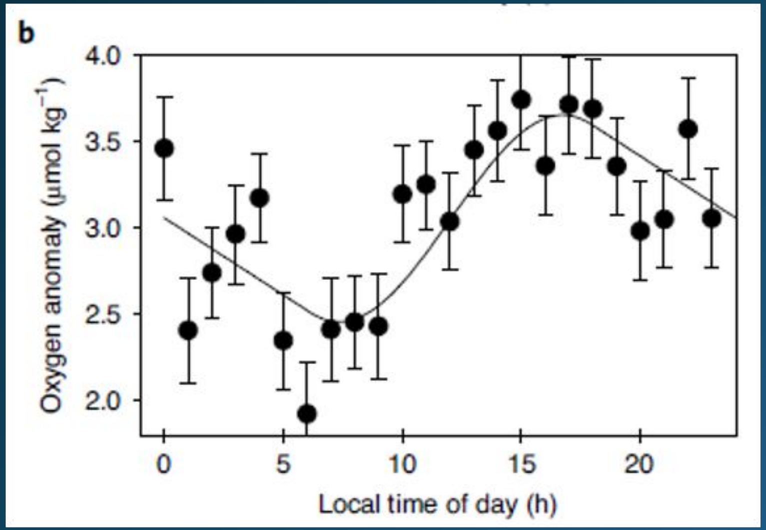
Ecosystem Variability

Diel and seasonal variability of oxygen production from BGC-Argo oxygen measurements

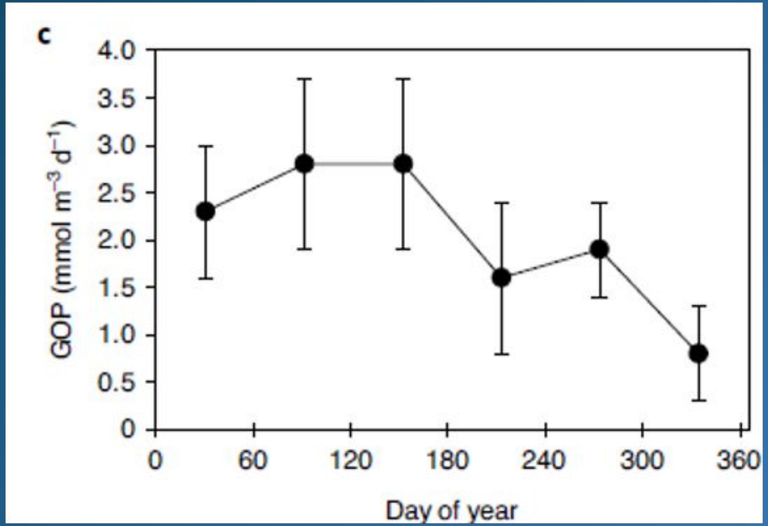


Chlorophyll from satellites

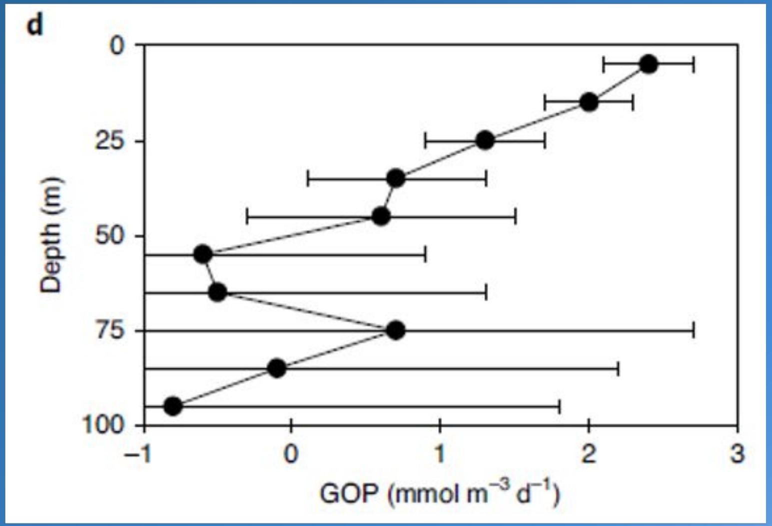
Northern Hemisphere Gross Oxygen Production using BGC Argo floats



Daily cycle



Seasonal cycle



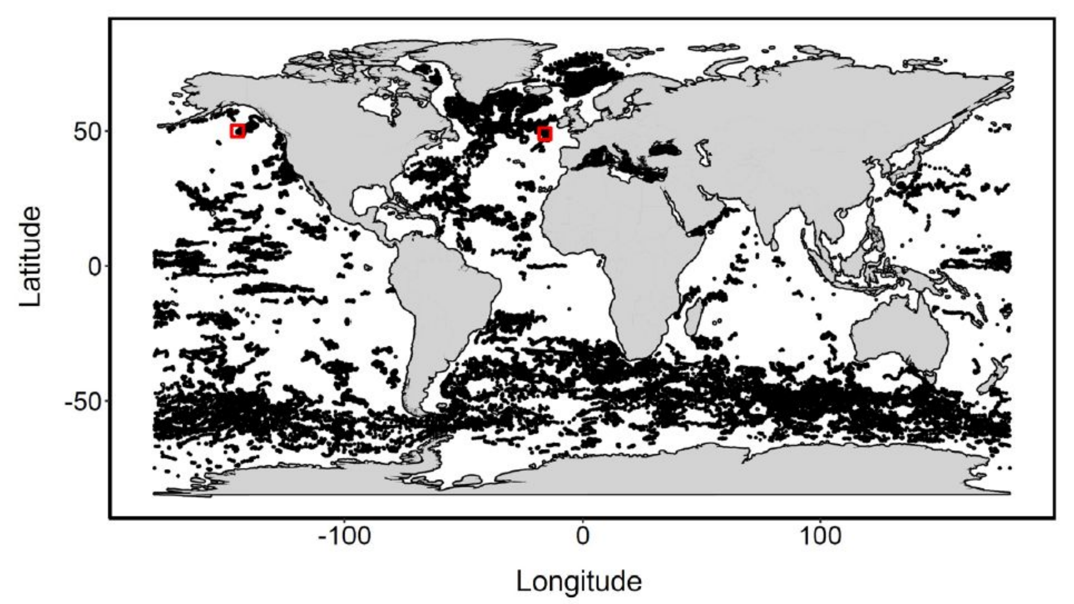
Depth dependence

Johnson and Bif (Nat. Geosci. 2021)

https://earthobservatory.nasa.gov/global-maps/MY1DMM_CHLORA

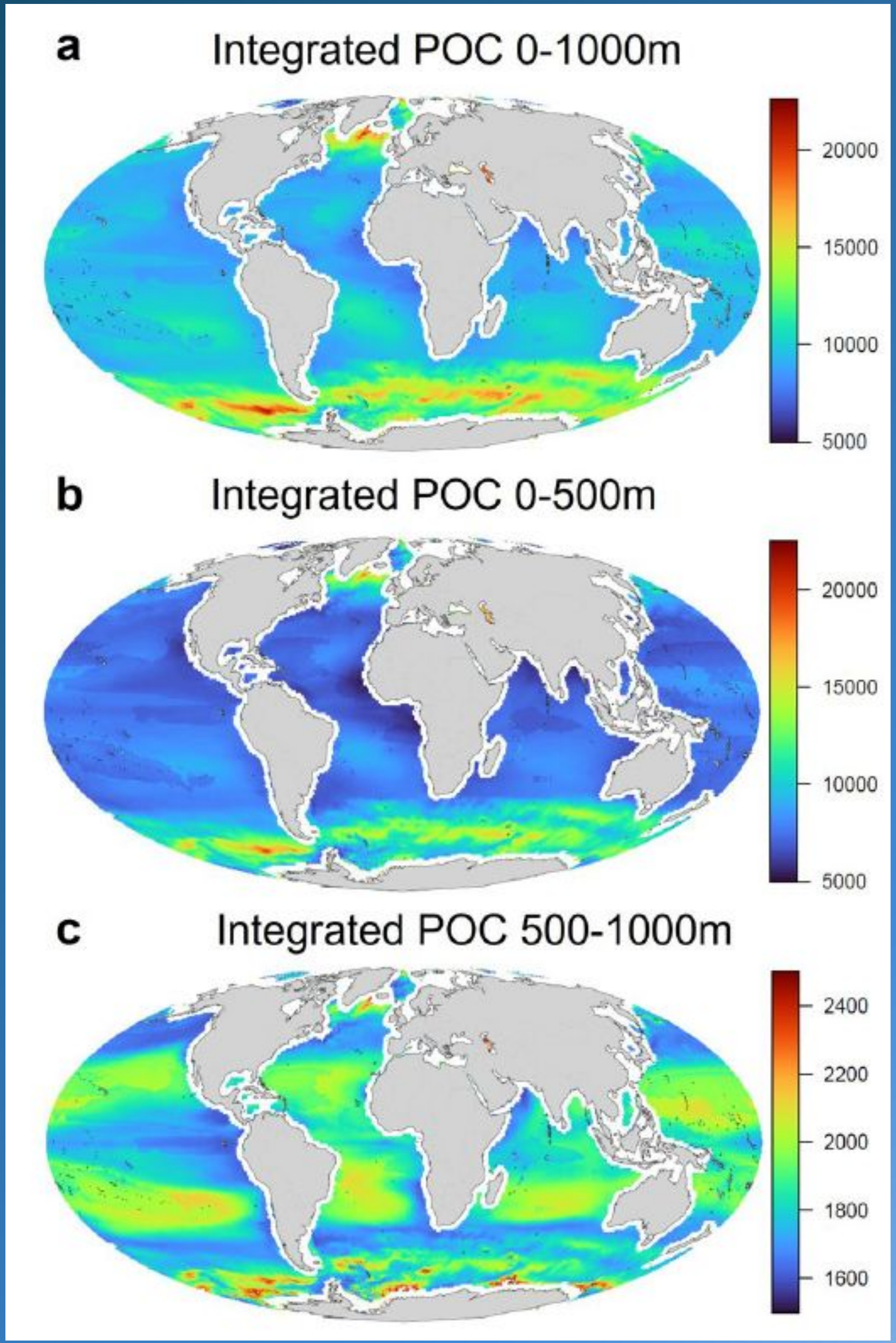
BGC-ARGO Extends Satellite Observations into the Interior

Merging float profiles of POC with high resolution satellite observations



Global estimates of particulate organic carbon from the surface ocean to the base of the mesopelagic

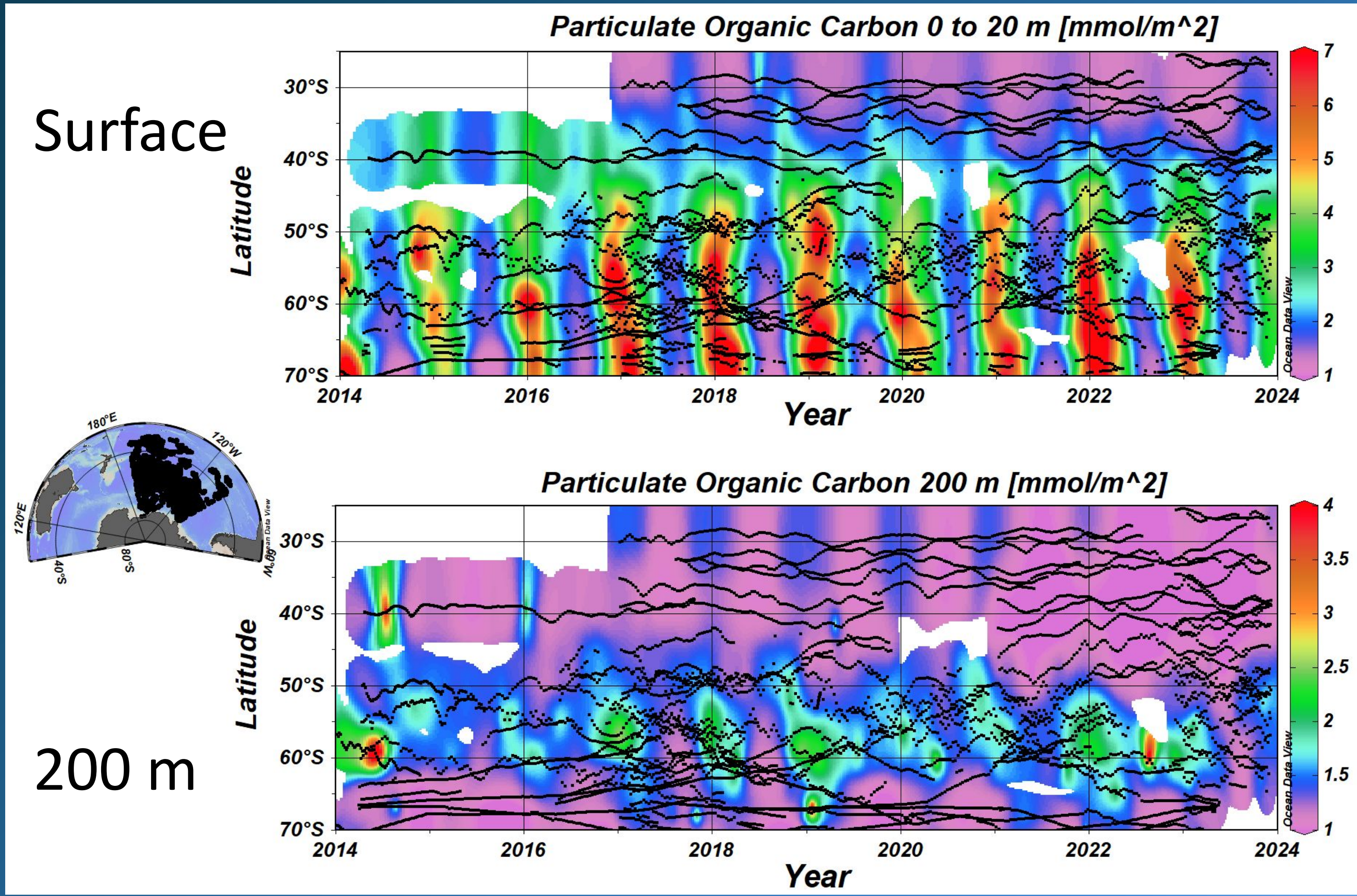
James Fox[1], Michael J. Behrenfeld[2], Kimberly H. Halsey[1], Jason R. Graff[2]



BGC-Argo defines background variability against which mCDR must be evaluated

SOCCOM observations 2014-2024

Seasonal cycles and interannual variability of particulate organic carbon



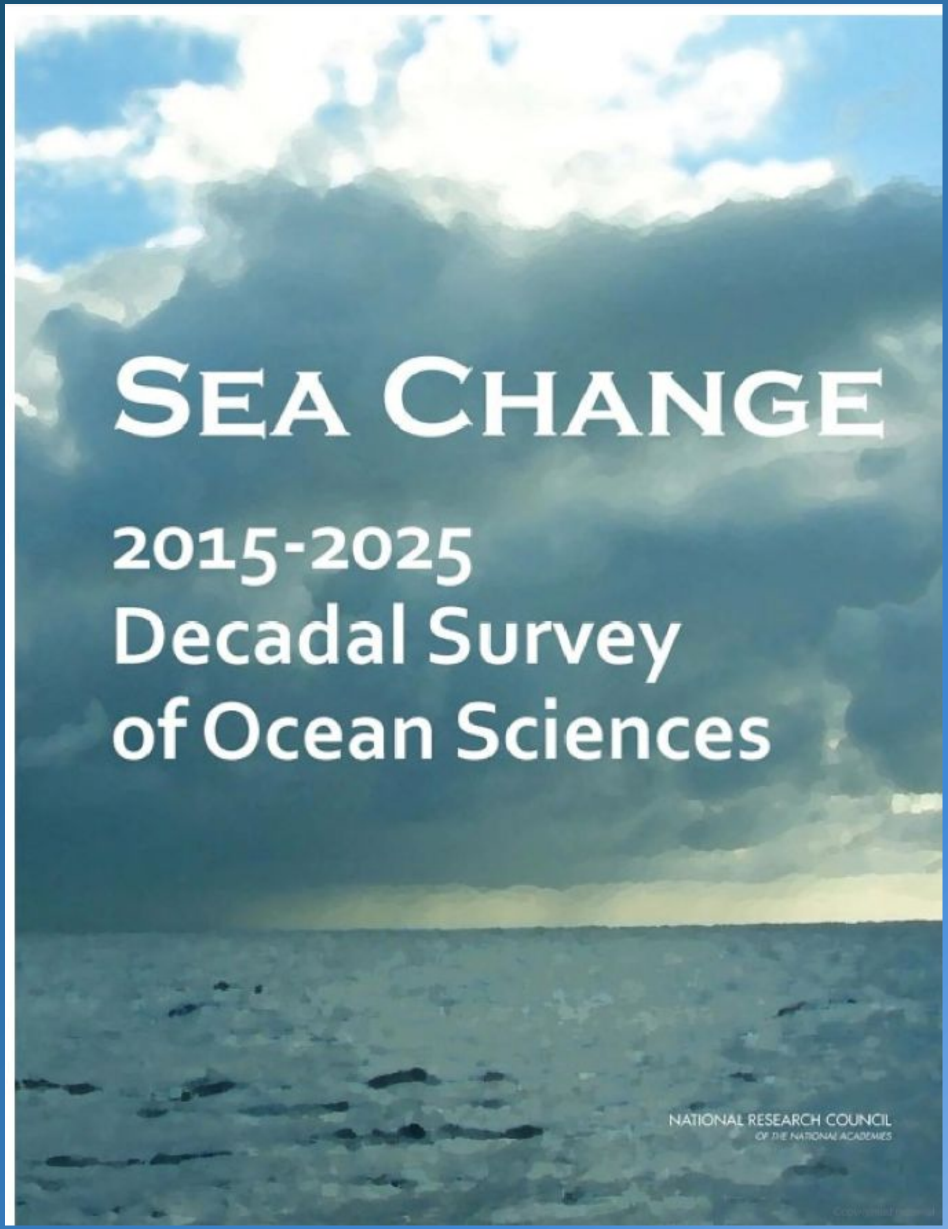
- **Production of organic carbon**
- **Transport into deep-ocean**
- **Change in air-sea CO_2 flux**

OneArgo will provide global network of frequent carbon profiles -> CRITICAL input to global carbon data products, which are essential for Monitoring-Reporting-Validation for mCDR

NSF OCE programs since SEA CHANGE to support climate science

- Sustained GO-SHIP
- Sustained HOT & BATS
- Initiated GO-BGC & sustained SOCCOM

Continuation of these programs is essential to understand “How have ocean biogeochemical and physical processes contributed to today’s climate and its variability”



DSOS tasks

The final report will address the following :

1. Identify novel opportunities ……for Technology, Innovation, and Partnerships (TIP).

BGC-Argo sensors developed by the science team have been licensed for commercial production and are transforming ocean science.

2. Identify opportunities and strategies to promote … multidisciplinary and multi-sectoral approaches … training the next generation of ocean scientists a….

SOCCOM and BGC-Argo have produced a strong, diverse set of early career, multi-disciplinary scientists.

3. Develop a concise portfolio of compelling, high-priority, scientific questions …. based on timeliness, societal benefits, technological advances, or other criteria as identified by the committee.

Sustained observing with GO-SHIP, BGC-Argo and time series stations directly addresses the key questions regarding the role of climate and oceans. It extends to societal impacts of sea-level rise, ocean warming, fishery science, mCDR/MRV ….

DSOS tasks (continued)

4. Identify the research infrastructure needed to advance the high-priority ocean science research questions …

Autonomous observing systems that scale to large numbers and cost-efficient operation are the only practical approach to observing the global ocean throughout the water column with seasonal to annual resolution.

5. Develop a framework that OCE can apply to leverage … its partners (other NSF units, federal agencies, private sector – such as ocean industries and foundations, and international organizations). …

Argo and GO-SHIP inherently link multiple agencies, nations, and institutions. The data are freely available in real-time and widely used.

Thank You

TAKE-HOMES FOR OPEN OCEAN OBSERVATIONS

1. Climate assessment [for process understanding, model incorporation and validation]]
    - where is the excess heat entering and going
    - where is the excess carbon entering and going
    - where is the ocean acidifying and how fast
    - is nutrient availability changing
    - are oxygen minimum zones expanding
    - is ocean productivity changing

2. Climate and biodiversity interventions; MCDR
    - how are each of these changing?

3. With Argo and BGC-Argo plus ships, data-based models, we have the tools, data management, and readiness

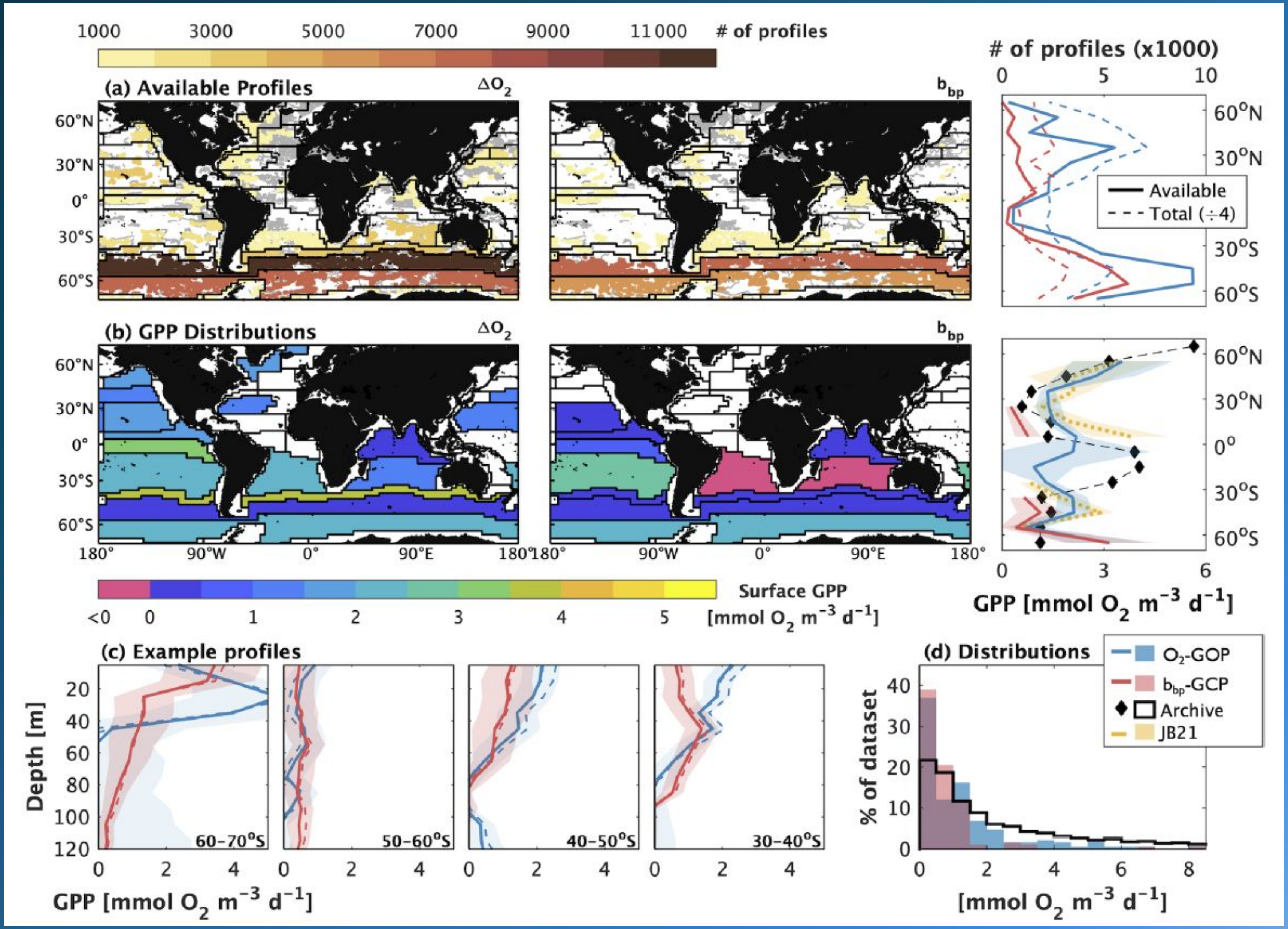
4. We need to fully implement and **sustain**

Ecosystem Variability

Diel variability of

POC (Particulate Organic Carbon)

Important for the biological carbon pump (movement of carbon through water column by biology)



Izett, Fennel, Stoer & Nicholson, 2024

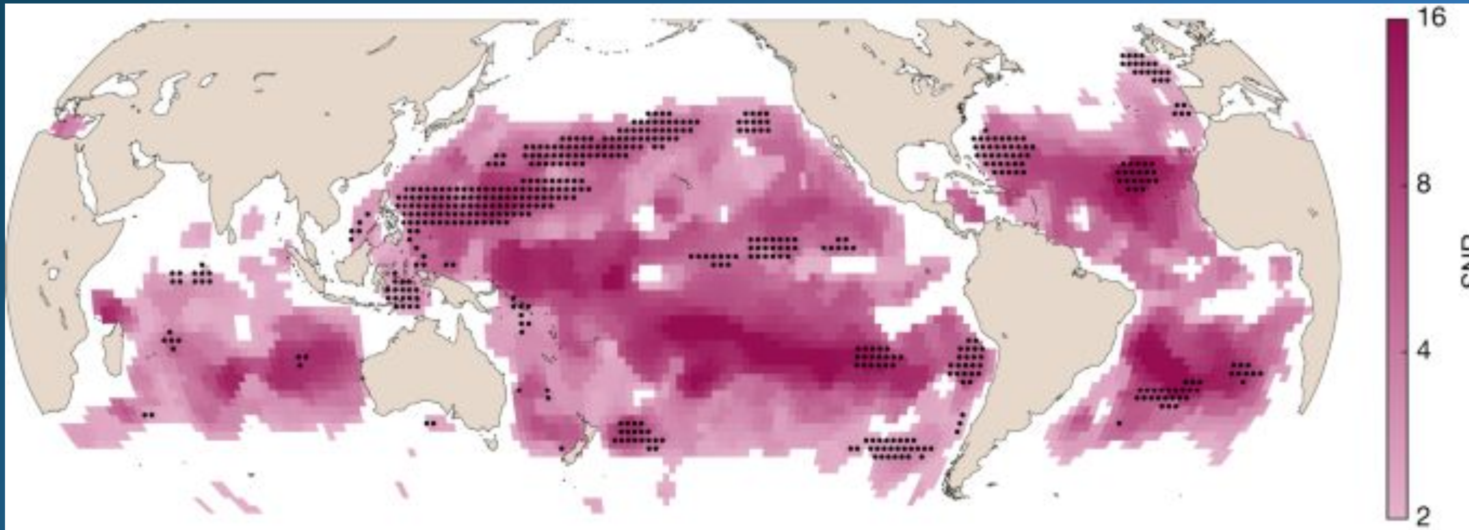
Greening of the Ocean

Surface greening over 20 years is consistent with climate change.

Warmer SST does not explain the greening trend

Greening could be due to greater stratification, change in nutrient supply, changes in currents, etc

Requires further investigation!
OneArgo can provide stratification, subsurface chlorophyll & nitrate



Satellite Ocean Color: greening trend

Map of Distribution of SNR (Signal to Noise Ratio) where 56% ocean is greening (magenta), black stippled areas indicate the 12% of the magenta which also have chlorophyll trends.

Cael et al. (Nature 2023)