Global Ocean Monitoring and Observing
NATIONAL OCEANIC & ATMOSPHERIC ADMINISTRATION

Determining the Global Ocean Anthropogenic Carbon Sources, Sinks, and Long-term Trends

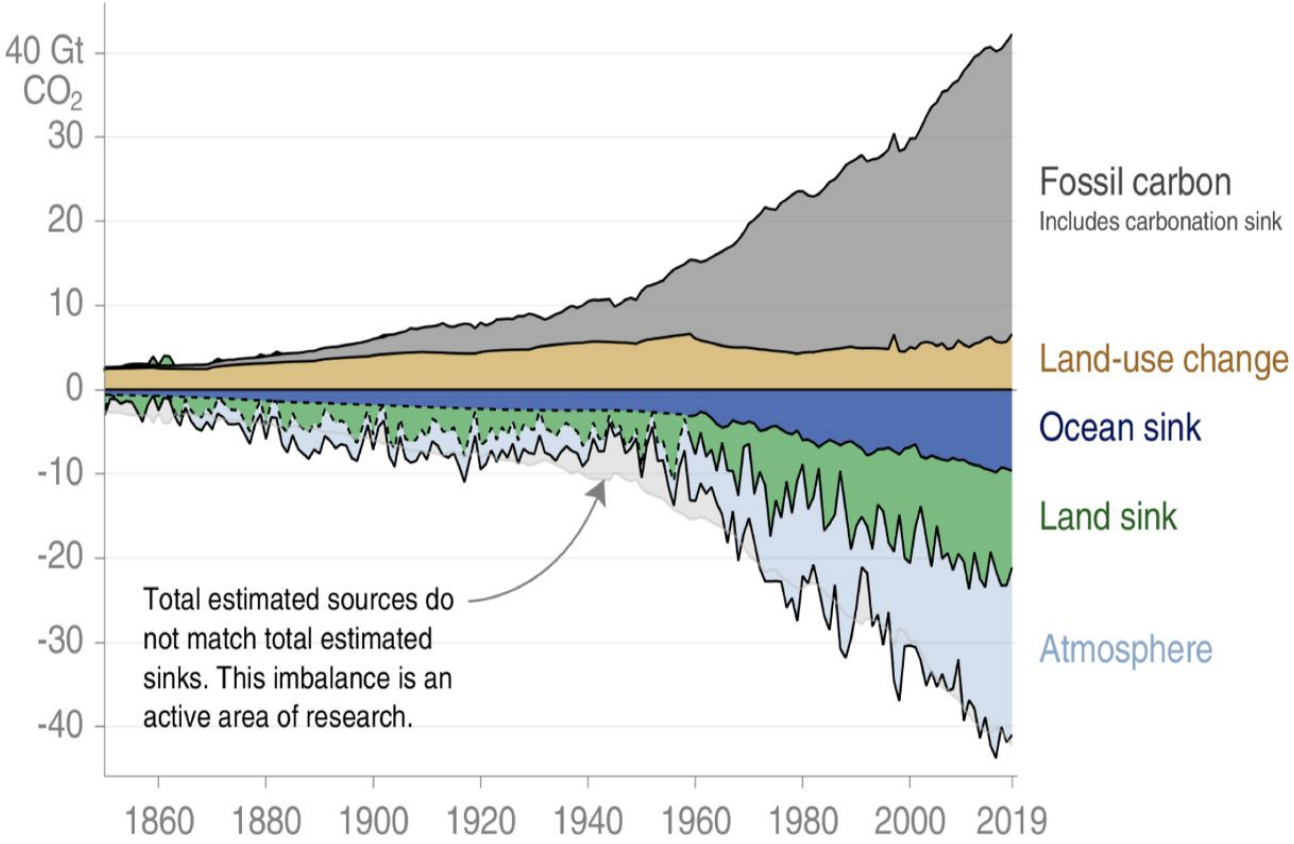
Richard A. Feely, Rik Wanninkhof, Dorothee Bakker, Andrea Fassbender, Brendan Carter, Adrienne Sutton, Denis Pierrot, Leticia Barbaro, Simone Alin and Jonathan Sharp

Partners: NOAA Labs (PMEL, AOML, GFDL & GML) Programs (OAP, IOOS); Federal Agencies (NSF, NASA) and academia (UW/CICOES, Miami/CIMAS, CU, LDEO, BIOS, SIO, WHOI, and >30 International partners

State of Knowledge: Global Carbon Budget

Major Scientific Questions

- What is the partitioning of CO_2 emissions between land, air, and ocean?
- What controls decadal variations in ocean CO_2 uptake and transport?
- Is the ocean uptake of anthropogenic carbon keeping pace with the atmosphere or does it respond to climate change?



Friedlingstein et al 2021

GOMO Global Ocean Carbon Observing Network

providing long-term observations of carbon from the sea surface to the ocean interior at a range of spatial and temporal scales

Global GO-SHIP Repeat Hydrographic/CO_2/Tracer Surveys

To quantify the ocean sink, transport, and storage of anthropogenic CO_2

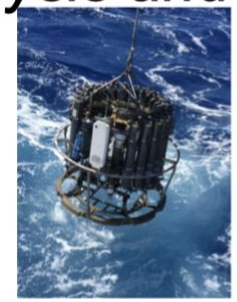
Surface water pCO_2 Measurements from Ships

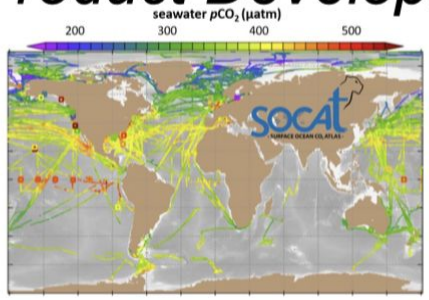
High-Resolution Ocean and Atmosphere pCO_2 Time Series Measurements

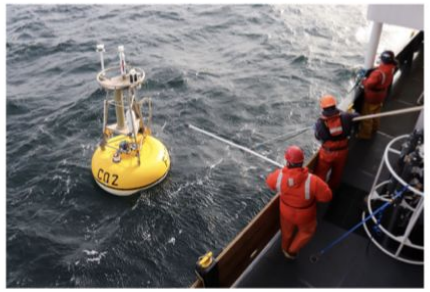
To evaluate the variability in air-sea CO_2 fluxes to provide meaningful projections of future atmospheric CO_2 levels

Global Carbon Data Management and Synthesis Project

Data Analysis and Product Development



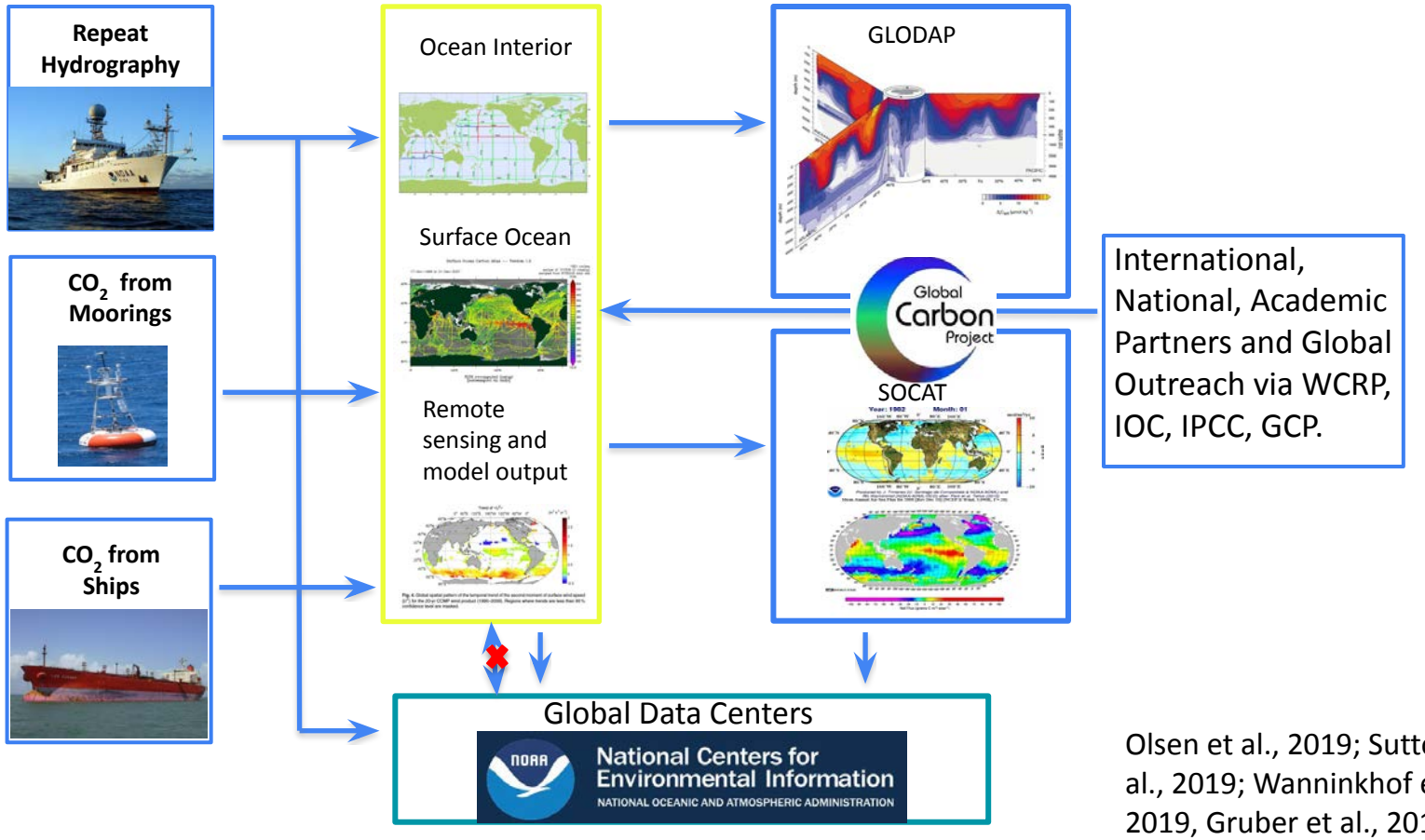




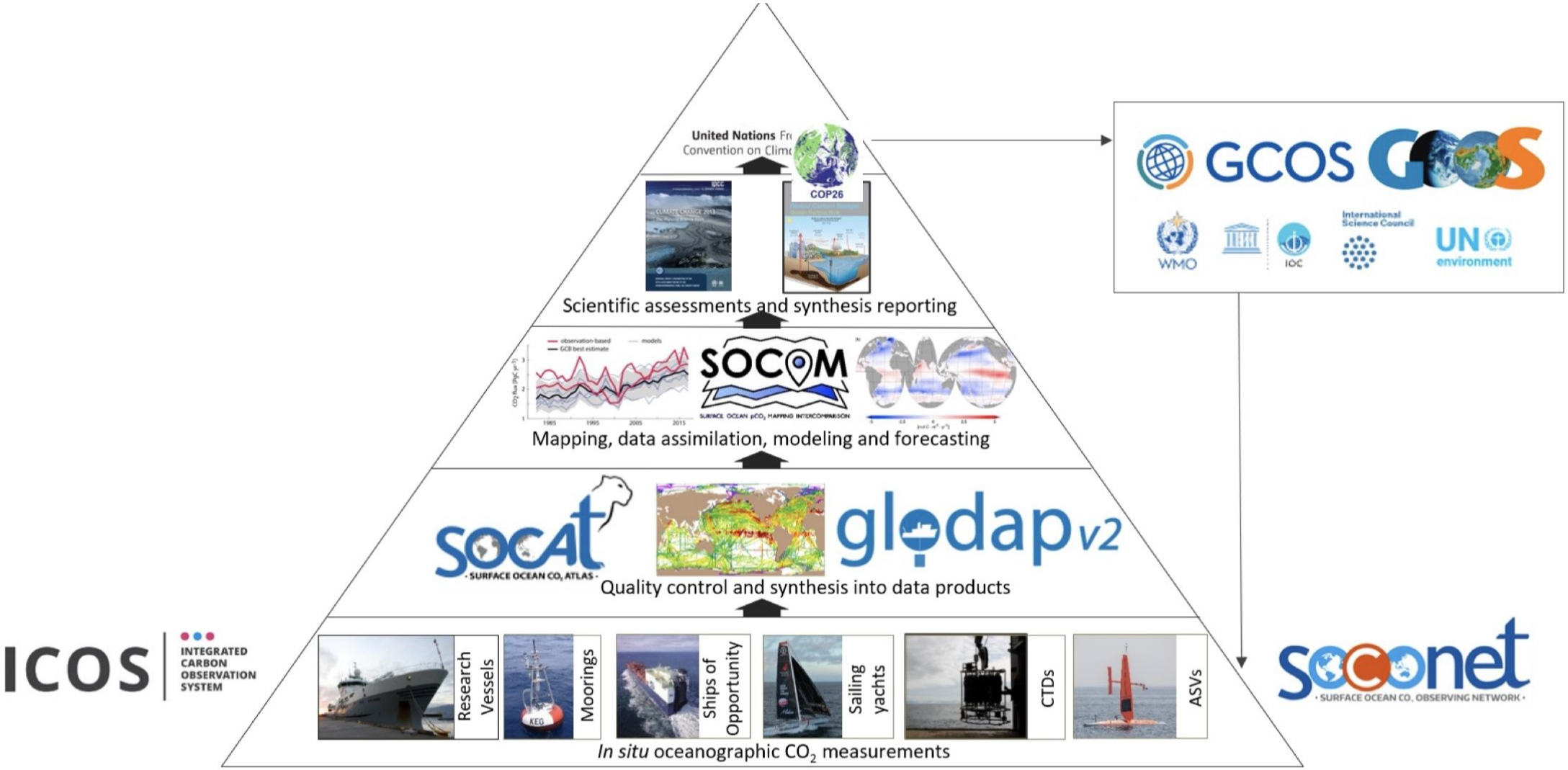
NOAA Global Ocean Observing and Monitoring Division: Ocean Carbon

Strategy

- Repeat GOSHIP cruises with surface to bottom sampling;
- Fixed $MAPCO_2$ mooring stations;
- SOCONET Underway pCO_2 measurements on research and volunteer observing ships.



Olsen et al., 2019; Sutton et al., 2019; Wanninkhof et al., 2019, Gruber et al., 2019



Ocean Carbon Science-to-Society Value Chain

(Modified from Guidi et al. (2020) Big Data in Marine Science. EMB Future Science Brief 6, doi:10.5281/zenodo.3755793)

Surface Ocean CO_2 Atlas

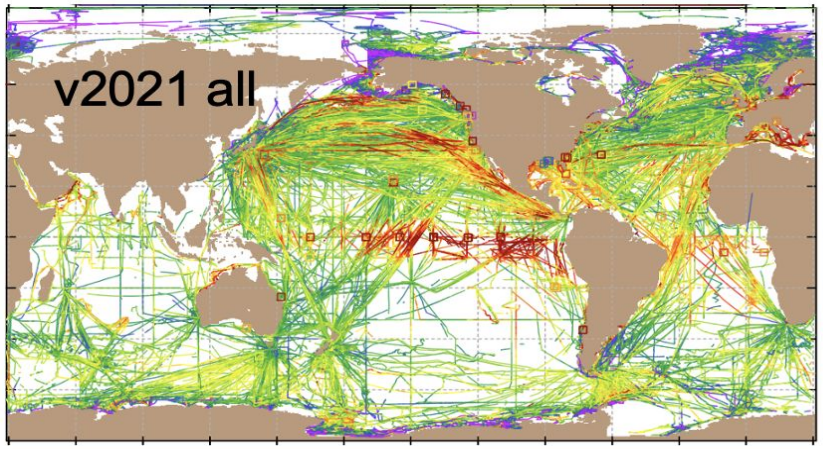
Oceanic Uptake = 2.8 ± 0.4 Pg C yr^{-1} for 2011–2020

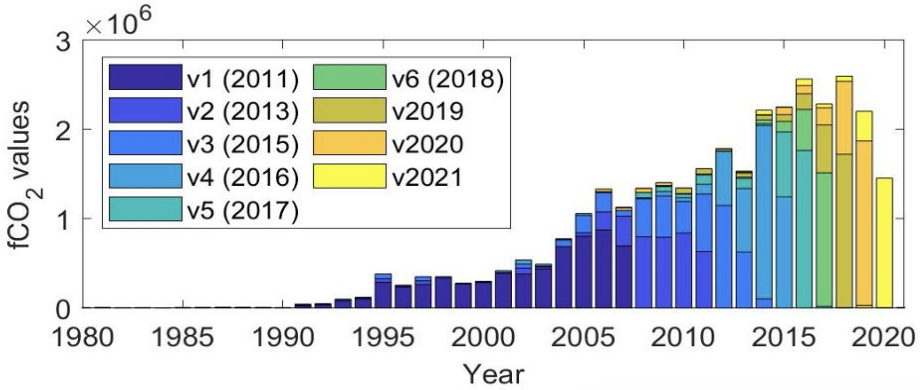
Key for

- Quantification of global ocean CO_2 uptake (~25% of fossil fuel emissions),
- Its year-to-year to decadal variation,
- Its response to net zero CO_2 emissions.

Surface Ocean CO_2 Atlas (www.socat.info)

- Quality-controlled synthesis products of *in situ* surface ocean CO_2 measurements
- 33 million CO_2 values (1957-2020)
- Standardized procedures
- Annual public release





(Bakker et al., 2016 ESSD)

Bakker et al., 2022

2022 OAR Outstanding Paper Award

RESEARCH ARTICLE

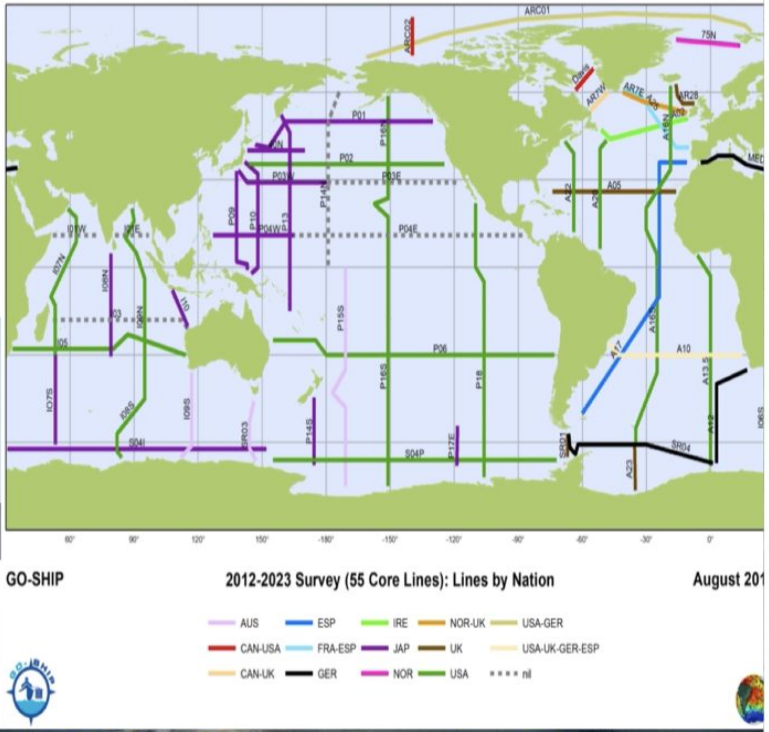
Science AAAS

CLIMATE CHANGE

The oceanic sink for anthropogenic CO_2 from 1994 to 2007

Nicolas Gruber[1*], Dominic Clement[1], Brendan R. Carter[2,3], Richard A. Feely[2], Steven van Heuven[4], Mario Hoppema[5], Masao Ishii[6], Robert M. Key[7], Alex Kozyr[8], Siv K. Lauvset[9,10], Claire Lo Monaco[11], Jeremy T. Mathis[12], Akihiko Murata[13], Are Olsen[10], Fiz F. Perez[14], Christopher L. Sabine[15], Toste Tanhua[16], Rik Wanninkhof[17]

We quantify the oceanic sink for anthropogenic carbon dioxide (CO_2) over the period 1994 to 2007 by using observations from the global repeat hydrography program and contrasting them to observations from the 1990s. Using a linear regression–based method, we find a global increase in the anthropogenic CO_2 inventory of 34 ± 4 petagrams of carbon (Pg C) between 1994 and 2007. This is equivalent to an average uptake rate of 2.6 ± 0.3 Pg C year^{-1} and represents 31 ± 4% of the global anthropogenic CO_2 emissions over this period. Although this global ocean sink estimate is consistent with the expectation of the ocean uptake having increased in proportion to the rise in atmospheric CO_2, substantial regional differences in storage rate are found, likely owing to climate variability–driven changes in ocean circulation.



18 Scientists representing 14 countries

Web of Science Citations (as of 12/22/20): 88

Web of Science Highly Cited Paper

Altmetric Score: 630

Mentioned by:

News, 43 news outlets

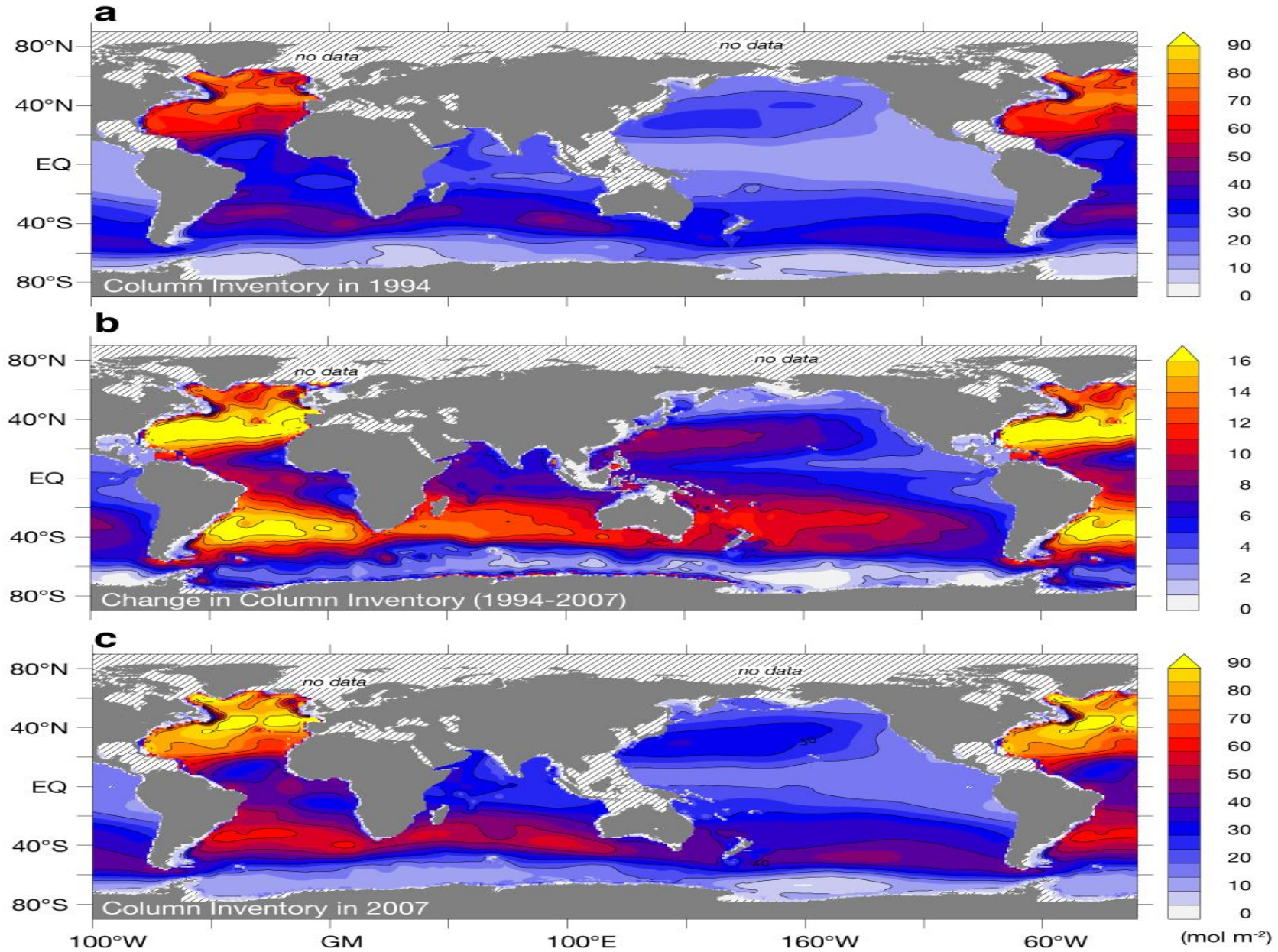
Blogs, 7 blogs

Policy, 1 policy source

Twitter, 415 tweeters

Facebook, 3 Facebook pages

Change in anthropogenic carbon in the global oceans



Sabine et al., Science 2004
Inventory = 118 ± 20 PgC
Thru 1994

Gruber et al., Science 2019
Inventory Increase = 33 ± 4 Pg C
from 1994 to 2007

Gruber et al., Science 2019
2007 Inventory = 151 ± 20 Pg C
thru 2007

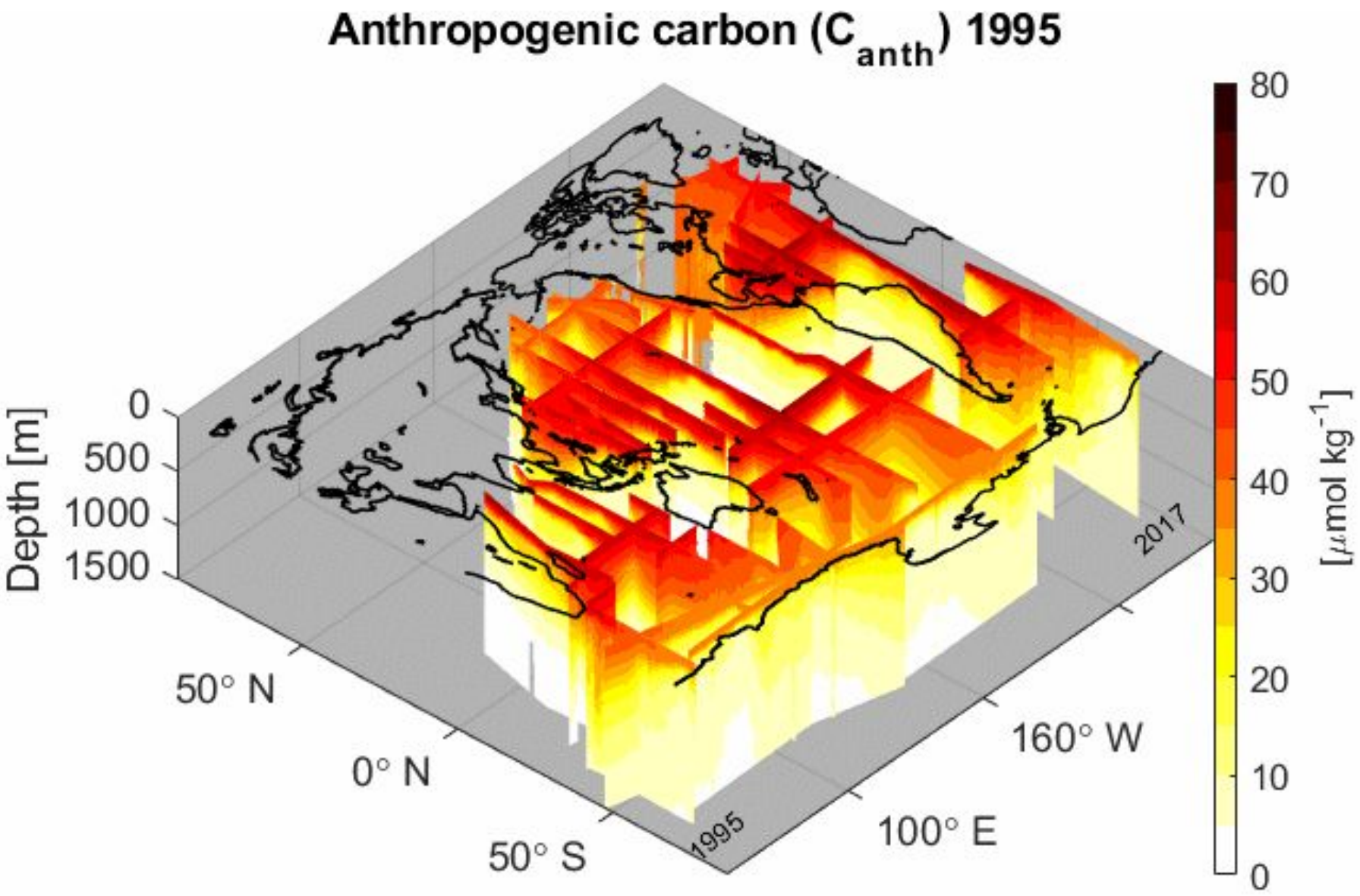
Change in anthropogenic carbon in the global oceans

Table 1. Change in the inventory of anthropogenic CO_2 between 1994 and 2007 as estimated on the basis of the eMLR(C*) method. Shown in italics are the estimated uncertainties based on the sensitivity and Monte Carlo analyses.

	Atlantic (Pg C)	Pacific (Pg C)	Indian (Pg C)	Other basins† (Pg C)	Global (Pg C)
Northern Hemisphere	6.0 ± *0.4**	5.2 ± *0.6*	0.8 ± *0.4*	1.5 ± *0.6*	13.5 ± *1.0*
Southern Hemisphere	5.9 ± *1.2**	8.0 ± *1.2*	6.3 ± *3.4*	~0	20.1 ± *3.8*
Entire basin	11.9 ± *1.3*	13.2 ± *1.3*	7.1 ± *3.4*	1.5 ± *0.6*	33.7 ± *4.0*

*Includes an estimated 1 Pg C to account for the accumulation below 3000 m, with 0.7 Pg C allocated to the North Atlantic and 0.3 Pg C to the South Atlantic (see main text). †Estimated storage in the Arctic and Mediterranean Sea (see supplementary materials).

Anthropogenic Carbon Concentration Increase in the Pacific Ocean



GO-SHIP Repeat Hydrography results demonstrate the growing global ocean carbon sink varies in the ocean interior (from Carter et al. 2017; Carter et al. 2019).

Surface water increase = 0.7 - 1.2 μmol kg^{-1} yr^{-1}

GOMO-supported New Technologies

BGC-Argo

From measurements to products

Technology: calibrated air-sea CO_2

MAPCO$_2$™

Moored Autonomous pCO_2 System

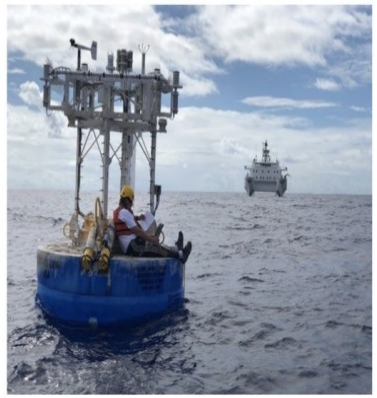
1990s: developed at MBARI

2000s: modified at PMEL

2009: transferred

2011: NOAA tech transfer award

Today: 50+ sites globally



ASVCO$_2$™

Autonomous Surface Vehicle CO_2 Sensor

2010: MAPCO$_2$ modified for ASVs

2019: 1st autonomous circumnavigation of Antarctica

Today: ASVCO$_2$ deployed on > 2 dozen missions; finalizing transfer

Derived Variables:

- dissolved inorganic carbon (DIC)
- **particulate organic carbon**
- anthropogenic carbon
- total alkalinity
- Phosphate
- silicate
- pCO_2
- **Chl-a**

Photos: NOAA PMEL, UH, Saildrone Inc.

PMEL

Ocean Carbon Technology: Southern Ocean

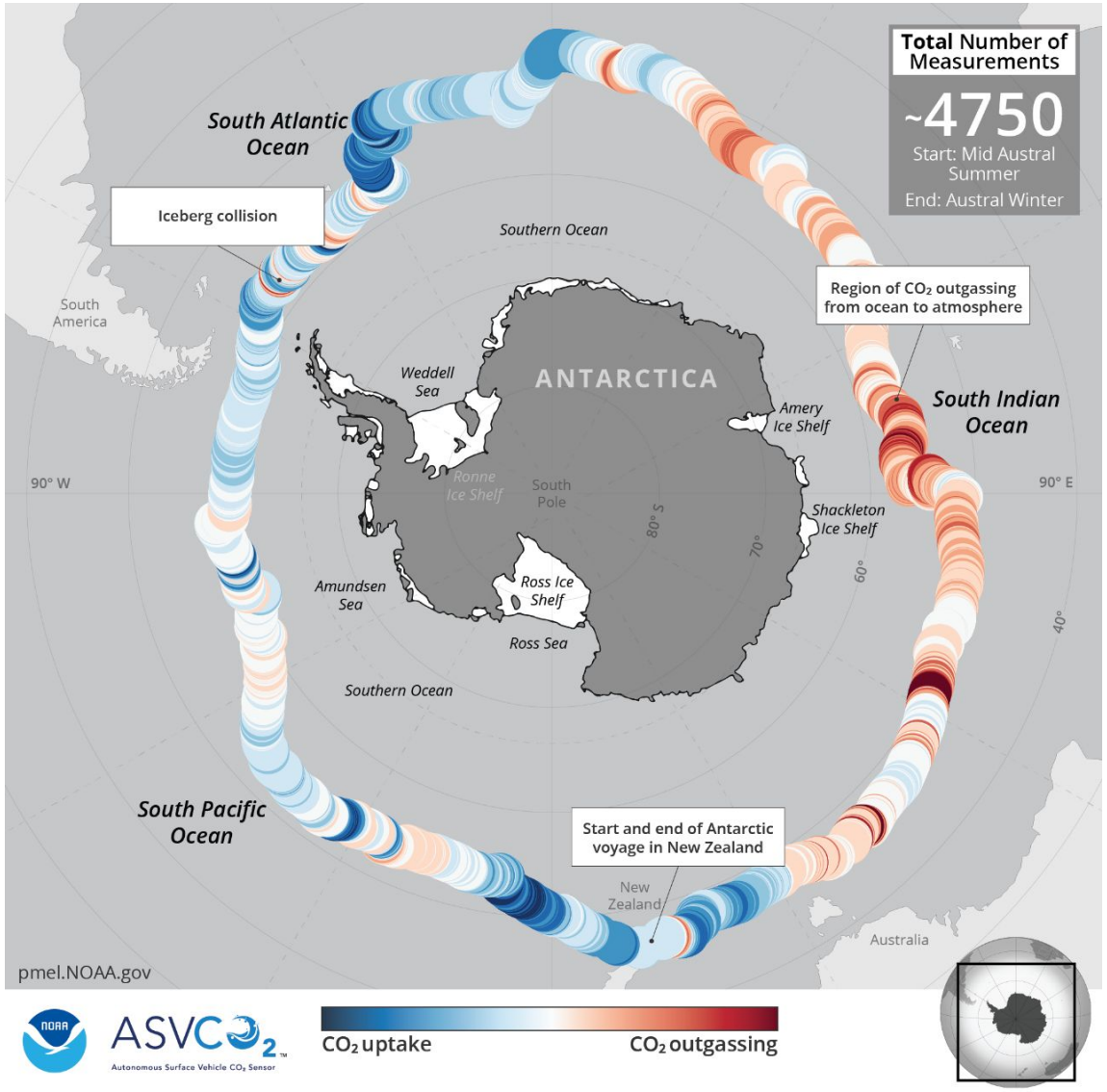
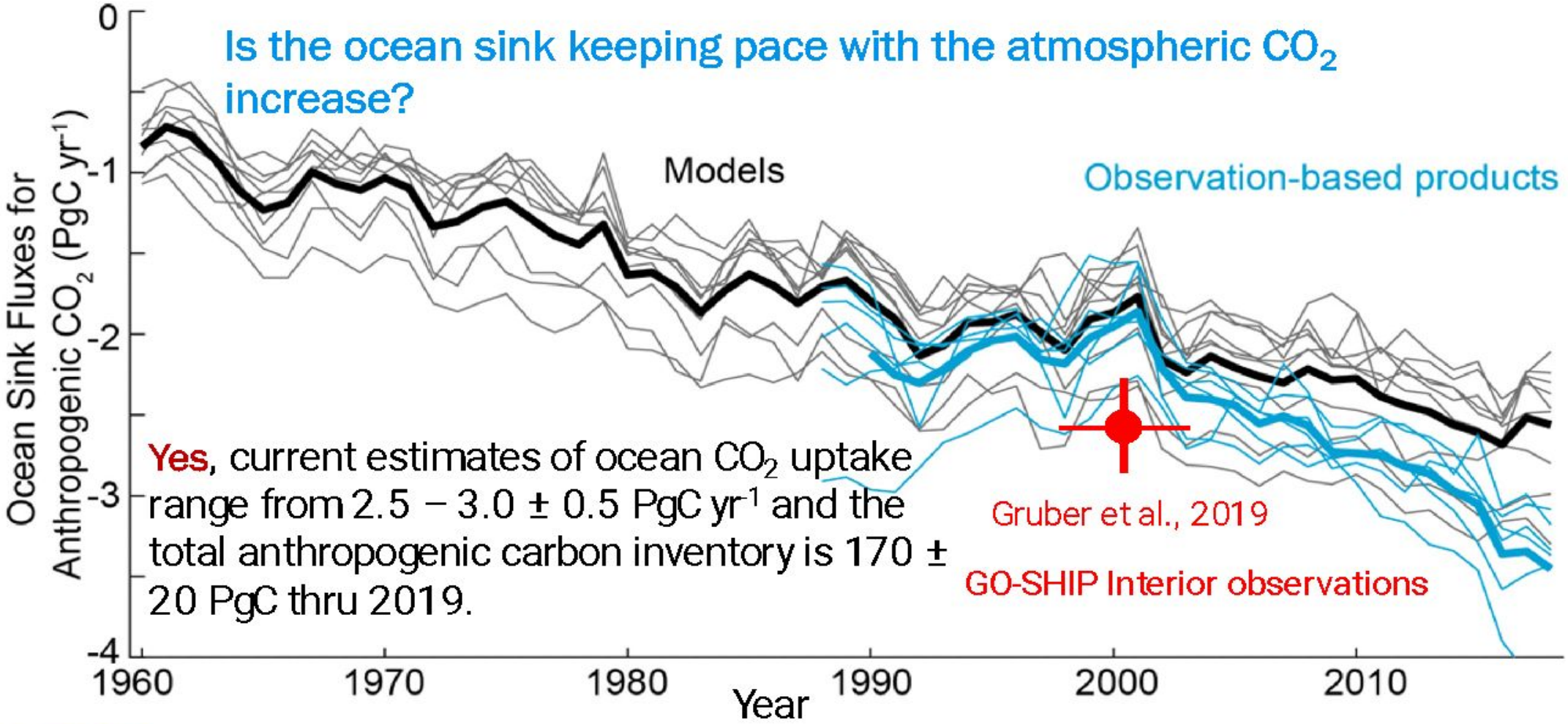


Photo: Saildrone Inc.

NOAA Gold Award for Technology Development!

Anthropogenic Carbon Uptake by the Oceans



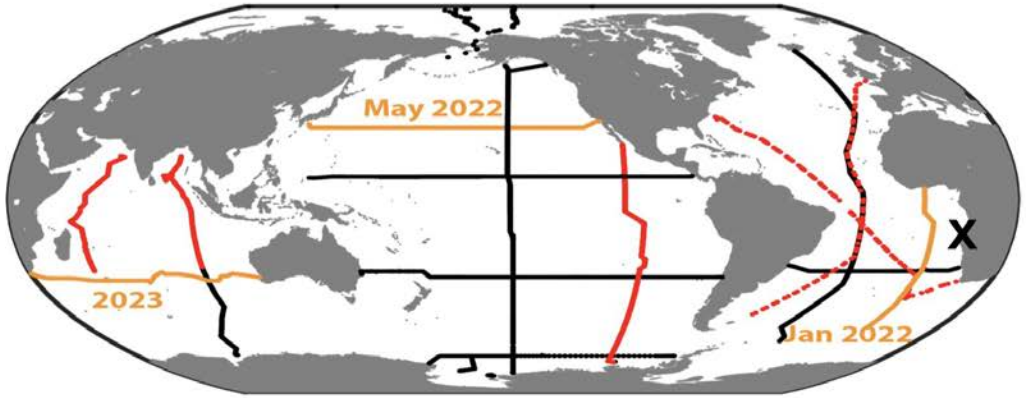
PMEL IPCC AR6 WG1 Report, Chap. 5 (2021)

Mean Flux = -2.5 ± 0.5 $PgC\ yr^{-1}$ (2010 – 2019)

Future Directions – Challenges and Opportunities

1. Continuing to Provide Support for Data Integration and Synthesis Efforts
2. Continuing to Resolve Differences Between Observations and Model Outputs
3. Integration of New Platforms and Technologies into the Observing Network
4. Integration of Biology into the Observing Network via BGC Argo and Bio-GO-SHIP

Bio-GO-SHIP: Sustained Global Scale Biological Observations



Finished sections of biology (pre-pilot project)

Pilot project (A13.5 cancelled, P02, I05)

Proposed sections (2023 – 2026)

Planned derived products:

1. Phytoplankton growth rates (continuous flow cytometry)
2. *In situ* biomass of functional groups (flow cytometry, imaging, particulates)
3. Size spectrum (flow cytometry, imaging)
4. Biodiversity (flow cytometry, imaging, ‘omics, bio-optics)
5. Chemical composition of sinking organic matter (particulates)
6. Attenuation of sinking organic matter (imaging, particulates)

Conclusions

Relevance

Thus far, the ocean CO_2 sink is keeping pace with atmospheric CO_2 increases. The next questions are how long will the ocean continue to take up the excess CO_2 from human sources in proportion with the atmospheric increase and how will the biology be impacted by the changing CO_2 and pH conditions.

Performance

GOMO has contributed to major advancements in our understanding of ocean carbon cycle

- Based on the GO-SHIP repeat hydrography observations and modeling the oceans have taken up 170 ± 20 Pg C since the beginning of the industrial era thru 2019.
- Discovery of decadal increases in carbon storage, primarily in the subtropical water masses due to increasing air-sea exchange and increasing ventilation in recent years.