FY 2023 Progress Report

Submitted to the Global Ocean Monitoring and Observing Division

GO-SHIP Repeat Hydrography/CO_2/Tracer surveys in Support of CLIVAR and Global Carbon Objectives: Carbon Inventories and Fluxes

Period of Activity: 01 October 2022 – 30 September 2023

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Budget Summary FY 2023:

Tot: $1,112,201
CTD $175,262
CO_2 $437,379
Tracers $331,366
Nutrients $143,194
Chief Scientist
$25,000

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GO-SHIP Global Repeat Hydrographic/CO_2/Tracer surveys in Support of CLIVAR and Global Cycle objectives: Carbon Inventories and Fluxes

AOML Component
Period of Activity: 01 October 2022 – 30 September 2023

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Budget Summary AOML FY 2023:

Total:	$1,313,379
CO_2:	$400,768
O_2:	$218,130
CTD/O_2:	$271,146
Nutrients:	$127,656
Chief Sci	$295,768

GO-SHIP Global Repeat Hydrographic/CO_2/Tracer Surveys in Support of CLIIVAR and Global Cycle Objectives: Carbon Inventories and Fluxes

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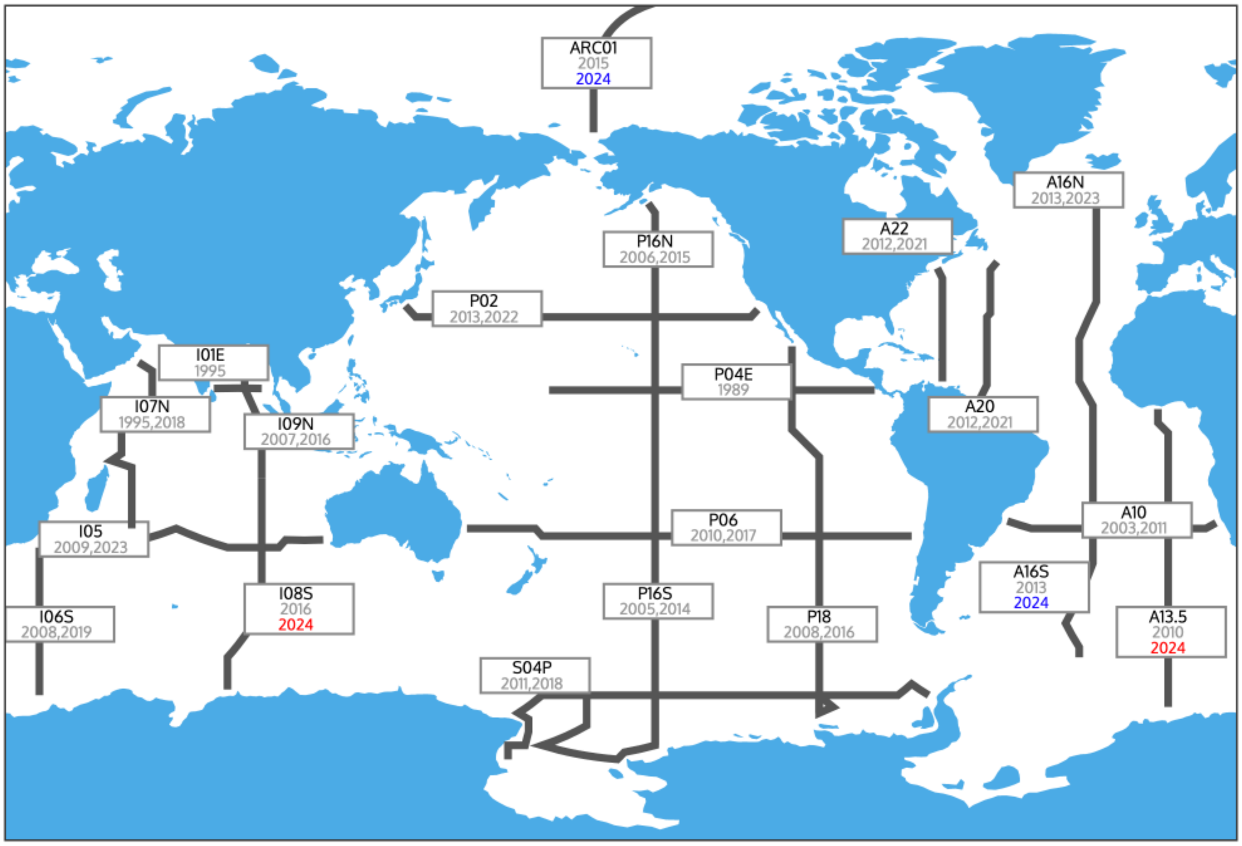
1. Project Summary

This research program contributes to the Global Ocean Ship-Based Hydrographic Investigations Program (GO-SHIP), a systematic and global re-occupation of select hydrographic sections to quantify changes in storage and transport of heat, fresh water, carbon dioxide (CO_2), chlorofluorocarbon (CFC) tracers, and related parameters (Figure 1). It builds upon World Ocean Circulation Experiment (WOCE)/Joint Global Ocean Flux Study (JGOFS) surveys during the 1990s and CLIVAR/CO_2 surveys during the 2000s. GO-SHIP reveals much about internal pathways for heat, carbon, and other constituents and their variability, which impacts carbon and heat sinks on decadal time scales. It is designed to document and assess changes in the ocean's biogeochemical cycles and transport of heat and freshwater in response to natural and/or man- induced activities. Below the 2000-m depth of core Argo floats, GO-SHIP provides the bulk of global-scale ocean measurements. The program also provides float deployment opportunities and data for Argo sensor calibration, both physical and biogeochemical (e.g., www.argo.ucsd.edu and

http://soccom.princeton.edu/), and support for continuing model development that will lead to improved forecasting skill for oceans and global climate.



(Map updated Oct. 11, 2023)

Figure 1. Map of the planned US Global Ocean Ship based Hydrographic Investigation Program (GO-SHIP) hydrographic sections decadal survey (2021-2024) https://usgoship.ucsd.edu/hydromap/

This coordinated approach contributes to the following overlapping scientific objectives: 1) data for model calibration and validation; 2) carbon inventory and transport estimates; 3) heat and freshwater storage and flux studies; 4) deep and shallow water mass and ventilation studies; 5) studies on biogeochemical cycling; and 6) calibration of existing and new autonomous sensors.

Cruise data are posted on the CLIVAR and Carbon Hydrographic Data Office (http://cchdo.ucsd.edu/) and the Ocean Carbon Data System at NCEI (https://www.ncei.noaa.gov/products/ocean-carbon-acidification-data-system).

They are used for research publications, global carbon and heat inventory assessments, atlases, and outreach materials, as well as to assess and validate physical and biogeochemical ocean models that in turn predict future impacts to ocean biological ecosystems resulting from acidification, deoxygenation, stratification, and circulation changes. The US program is co-sponsored by NOAA and the National Science Foundation in support of national and international research programs, such as CLIVAR; GOOS and the North American Carbon

Program (NACP).

During FY 2023 two GO-SHIP cruises were executed. Zonal line A16N is a NOAA led expedition consisting of two legs in the North Atlantic (Figure 2) and I05 is a meridional section in the Southern Indian Ocean (Bleu line in Figure 1). For I05 PMEL and AOML scientists did DIC and underway pCO_2 analyses. The 2-leg NOAA led A16N cruise was successfully executed with PMEL and AOML scientists taking charge of cruise preparation and staging, cruise leadership, CTD/O_2, nutrient, O2, DIC, discrete pCO_2 and underway pCO_2 analyses. In addition, a successful Bio GOSHIP effort was executed on both cruises under a separate GOMO workplan.

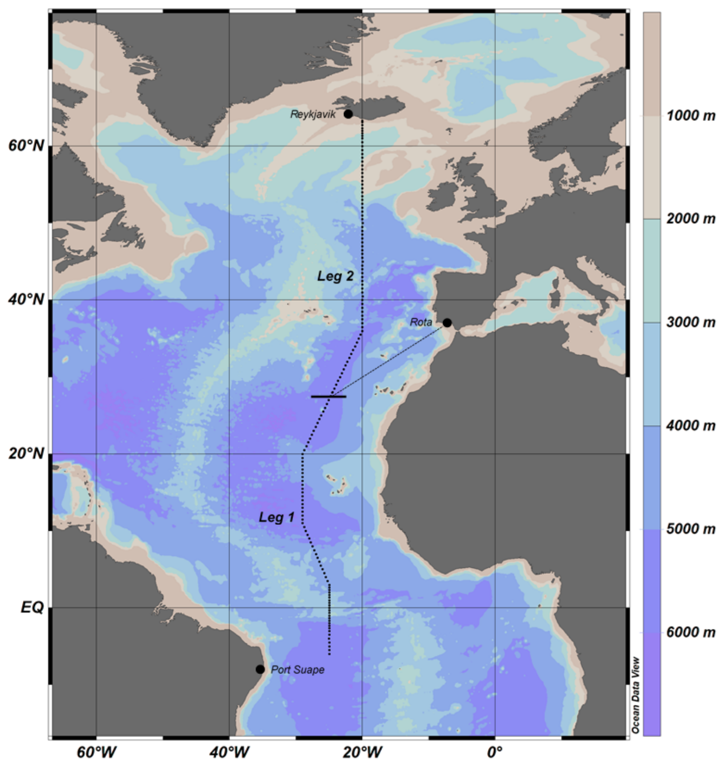


Figure 2. Cruise track of NOAA ship *Ronald H. Brown* on GO-SHIP cruise A16N.

2. Scientific and Observing System Accomplishments

2.1 Cruise Summaries and Science Results

The FY 2023 A16N cruise was executed on NOAA ship *Ronald H. Brown.* For leg 1 the ship departed from Suape, Brazil on March 6 and arrived in Rota, Spain on April 7, 2023. Leg 2 commenced on April 13, and ended in Reykjavik, Iceland on May 9, 2023. The GO-SHIP cruise I05 from Fremantle, Australia to Cape Town South Africa took place on the R/V *Roger Revelle* from July 22, 2023 to September 14, 2023. The I05 cruise with Brendan Carter

(PMEL/CICOES) as chief scientist was completed successfully with PMEL and AOML personnel leading DIC and underway pCO_2 measurements. They also assisted with TA and pH measurements and coordination of inorganic carbon sampling Cruise Logical details are provide in Table 1. Cruise reports for the I05 and bottle data for the cruise can be found at: (https://cchdo.ucsd.edu/cruise/33RR20230722).

Table 1. Logistical details of the GO-SHIP A16N cruise (from cchdo.ucsd.edu/cruise/33RO20230306 and cchdo.ucsd.edu/cruise/33RO20230413)

Expo Code	33RO20230306
Occupation name	A16N_2023_leg 1
Ship:	RONALD H. BROWN
Chief Scientist:	Zachary Erickson
Co-chief	Katelyn Schockman
Dates	2023-03-06 to 2023-04-07
Ports of call	Suape, Brazil; Rota Spain
Stations occupied	75
Equipment deployed	3 BGC Argo Floats; 4 Argo; 5 Surface Drifters
Expo Code	33RO20230413
Occupation name	A16N_2023_leg 2
Ship:	RONALD H. BROWN
Chief Scientist:	Leticia Barbero
Co-chief	Laura Cimoli
Dates	2023-04-13 to 2023-05-09
Stations occupied	95
Equipment deployed	3 BGC Argo Floats; 4 Argo; 5 Surface Drifters

Table 2. Logistical details of the GO-SHIP I05 cruise (from: cchdo.ucsd.edu/data/41036/I05CruiseReport_v1.0.pdf)

Section Name I05	
Expocode	33RR20230722
Occupation Name	I05_2023
Ship	Roger Revelle
UNOLS designation	RR2308
Chief Scientist	Brendan Carter
Co-Chief Scientist	Kay McMonigal
Dates	07/22/2023 to 09/14/2023 (55 DAS)
Ports of call	Fremantle, Australia to Cape Town, South Africa
Stations occupied	196, with 195 “bottle” casts and 50 “bio” stations
Equipment deployed	15 floats and 22 drifters

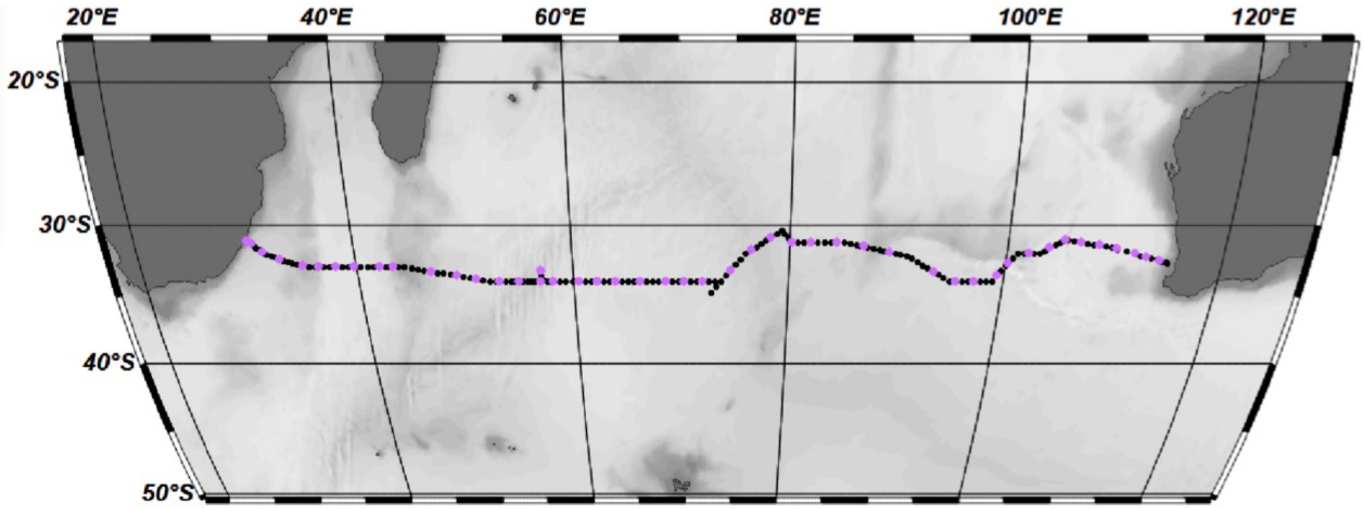


Figure 3. FY 2023 I05 Cruise track 22 July to 14 September 2023.

2.1.1 PMEL and AOML CTD/O_2

The major activity in FY2023 for the PMEL CTD/O_2 group was preparing for the March - May 2023 reoccupation of A16N. A16N was comprised of two legs, the first from Recife, Brazil to Rota, Spain and the second from Rota, Spain to Reykjavik, Iceland. K. McTaggart (PMEL), J. Hooper (AOML), and C. Saiz (AOML; Leg 1), and P. Peña (AOML; Leg 2) comprised the CTD/O_2 team, with Hooper, Saiz, and Peña additionally leading the measurements of discrete salinity. Z. Erickson (PMEL) was Chief Scientist for Leg 1 of the cruise.

A major accomplishment from this cruise was the rapid building and deployment of a secondary CTD frame and rosette. Following the loss of a CTD rosette due to a snapped cable, the CTD/O_2 team was able to prepare a backup unit in approximately 8 hours, resulting in minimal loss of ship time despite the significant loss of equipment. The CTD/O2 team at AOML built a full CTD/rosette package and air-shipped it to Spain within days of the CTD loss to ensure that leg 2 would have sufficient spares. The combined AOML and PMEL CTD/O_2 teams also spent a substantial amount of time in the last half of FY2023 identifying funding for and ordering equipment to replace instruments lost to sea during A16N.

2.1.1.2 Science Results. The scientific results from CTD and oxygen GO-SHIP measurements are being used in a variety of research publications at PMEL and AOML. As part of the October 2023 Oceanography special issue celebrating PMEL's 50th anniversary, Erickson led an overview paper on PMEL's contributions to oceanographic observations through the GO-SHIP program (Erickson et al., 2023).

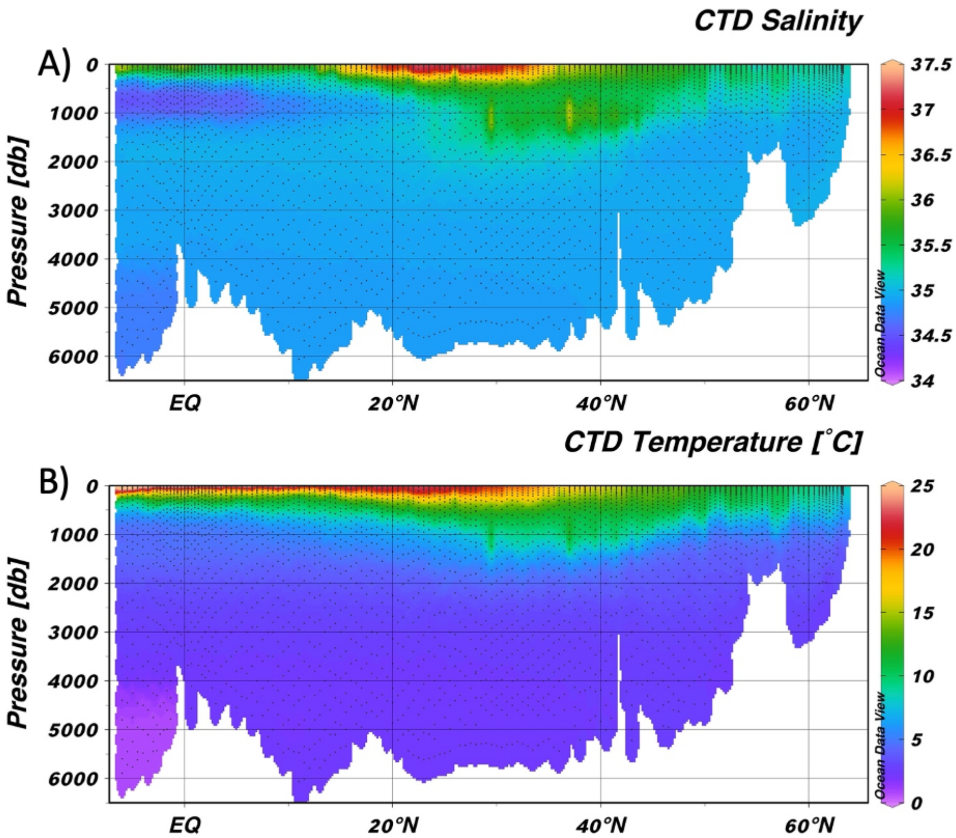


Figure 4. South-to-north salinity (A) and temperature (B) sections for A16N_2023.

2.1.2 AOML Ocean Carbon Group

The AOML-CO_2 group had six objectives and milestones for FY 2023.The accomplished milestones and deliverables are provided in the table below. They address the overall goal of the program to acquire high-quality quality surface and subsurface physical, biogeochemical, and carbon data as part of U.S. GO-SHIP to reduce the overall uncertainty in global ocean anthropogenic CO_2 inventories. This effort has recently expanded to provide data to validate and adjust GO-BGC and SOCOM biogeochemical Argo float (BGC-Argo) data. All milestones were completed or will be completed by the date listed in Table 3 with detail provided in the footnotes.

Table 3. AOML Ocean carbon group U.S. GO-SHIP Milestones

Milestones (footnote #)	Deliverable	Date
Prepare project instructions A16N (1)	Submit to OMAO	Oct. 2022
Submit cruise clearances for A16N (2)	Submit to Department of State	Oct 2022
UWpCO_2 data reduction for A16N (3)	Submission to SOCAT/NCEI	Sept. 2023
Post-cruise requirements for A16N (4)	Country Cruise Reports	Sept.2023

Data reduction DIC A16N (5)	Submission to NCEI/CCHDO	April 2024
Data reduction discrete fCO_2 A16N	Data and metadata on web	April 2024

1. Project instructions for A16N_2023 were submitted to OMAO in November 2022. A website was created https://www.aoml.noaa.gov/ocd/gcc/A16N_2023/ containing pertinent cruise information.
2. Clearance requests were submitted through OMAO and the Department of State for Spain, Portugal (for transit only), and Iceland. All clearances were approved (Spain: ref CO/23/41, Portugal: consent ref. 39984, Process DGPE/USEN-111/2022, Iceland: consent # UTN22110189/34.R.611).
3. UW pCO_2 data submission has been delayed for leg 2 as final CTD data to verify SST and SSS from the thermosalinograph is not available. pCO_2 system operated well and preliminary reduction and QC are completed.
4. Post-cruise requirements for Spain and Iceland have been completed. The ship did not cross Portuguese EEZ.
5. QC of DIC and discrete fCO_2 of A16N data has been completed and final files for leg 1 have been submitted to CCHDO. See cchdo.ucsd.edu/cruise/33RO20230306) Final submission of leg 2 data to CCHDO and NCEI will occur when leg 2 CTD data has undergone final processing.

The AOML ocean carbon group had the lead in running DIC, discrete fCO_2 and underway fCO_2 during the A16N 2023 cruise with PMEL personnel serving as the second analyst for DIC on leg 2. AOML personnel served as second analyst on I05 with detail in the section below. All operations were preformed following Standard operating procedures for GO-SHIP cruises (Hood et al. 2010). Analyses proceeded smoothly with high-quality datasets for all parameters. Pertinent performance measures of analysis are provided in Table 4 below and cross sections for DIC and $fCO_2(20)$ in Figures 5 and 6.

Table 4. Sample Statistics of the A16N cruise- first number is the leg 1; the second number is for leg 2

A16N_2023 leg 1 /leg 2	Discrete fCO_2	DIC AOML 3*	CRM adj AOML3**	DIC AOML 4	CRM adj AOML 4
Total Number of Samples	1712/1639	991/916	40/33	965/866	37/30
Total Number of replicates	75/75	105/79	N/A	103/79	N/A
Av. diff replicates (µM/kg)		1.61/1.46	4.21/1.77***	1.46/1.49	1.16/0.94***
Relative Standard Dev. (%)	0.11% /0.05%				

* Two DICE instruments are used designated as AOML3 and AOML4

**CRM adjustment is the adjustment applied to each sample based on the difference in CRM analyses and assigned value (Leg 1 CRM batch #202, assigned value 2043.33 µmol/kg and Leg 2 CRM batch #201, assigned value 2048.19 µmol/kg).

*** These are the adjustments applied to all DIC data

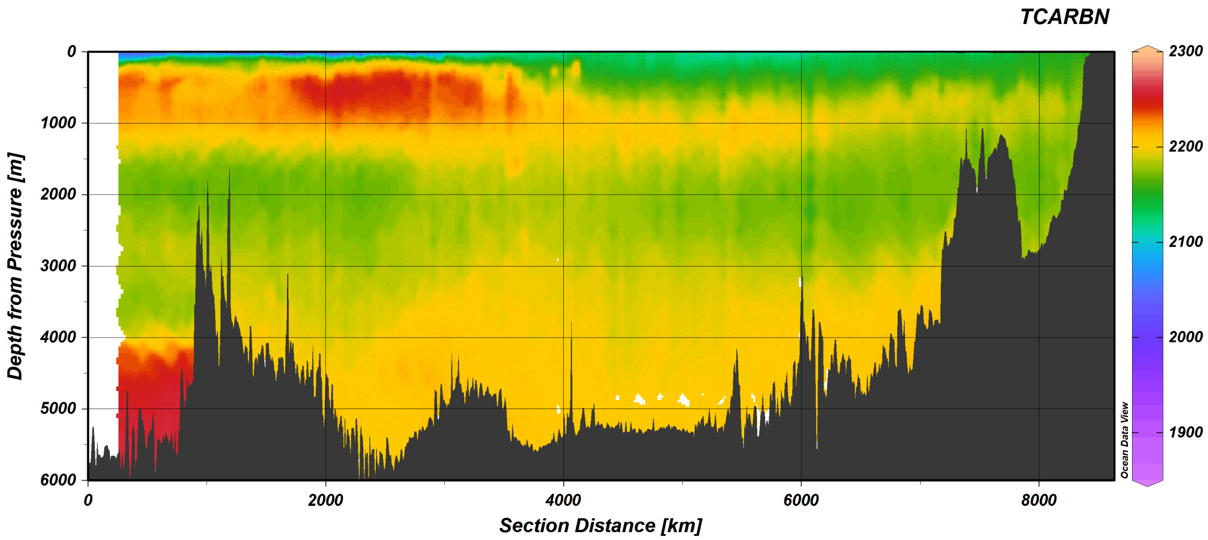


Figure 5. Cross section of DIC for A16N_2023. The plots were created in ODV with weighted-average gridding routine. The x axis is the distance travelled from the start of the section (6 ˚S, 28 ˚W) to Iceland (63 ˚N, 20 ˚W) (for cruise track see Figure 2).

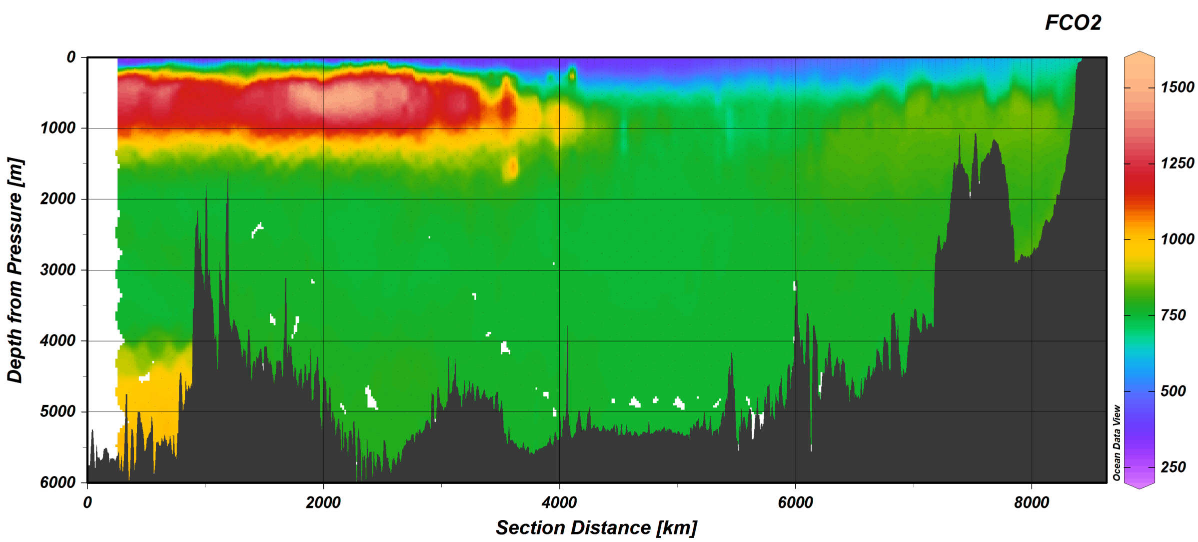


Figure 6 Cross section of $fCO_2(20)$ for A16N_2023. See Figure 5 for detail.

2.1.3. PMEL Carbon Group

As components of the FY 2023 workplan, the PMEL Carbon Group had three objectives and corresponding milestones: 1) contribute to the DIC sample for the A16N carbon system measurements in collaboration with AOML; 2) contribute to the analysis of the I05 DIC and underway pCO_2 sample analysis and data synthesis in collaboration with AOML; and 3) contribute to the synthesis of the global carbon data. These objectives address the overall goals of the GO-SHIP program to acquire high-quality carbon measurements to decrease the uncertainty in global ocean anthropogenic CO_2 inventories. This effort has recently been expanded to provide data to calibrate and validate the BGC-Argo biogeochemical float data and the newly developed BIO-GO-SHIP effort. The milestones are listed in tabular form in Table 5 below.

Table 5. PMEL Carbon Group Milestones

Milestones	**Deliverable**	**Date**
Participation in A16N	Cruise data completed	6 March – 9 May 2023
Decadal global carbon uptake paper	AGU Advances	August 2023
Prepare for and lead the I05 Cruise	Cruise instructions submitted	July 2023
Perform DIC and pCO_2 measurements	Carbon data completed	Aug – Sept 2023
Complete I05 Cruise report	Cruise report submitted	Sept 2023

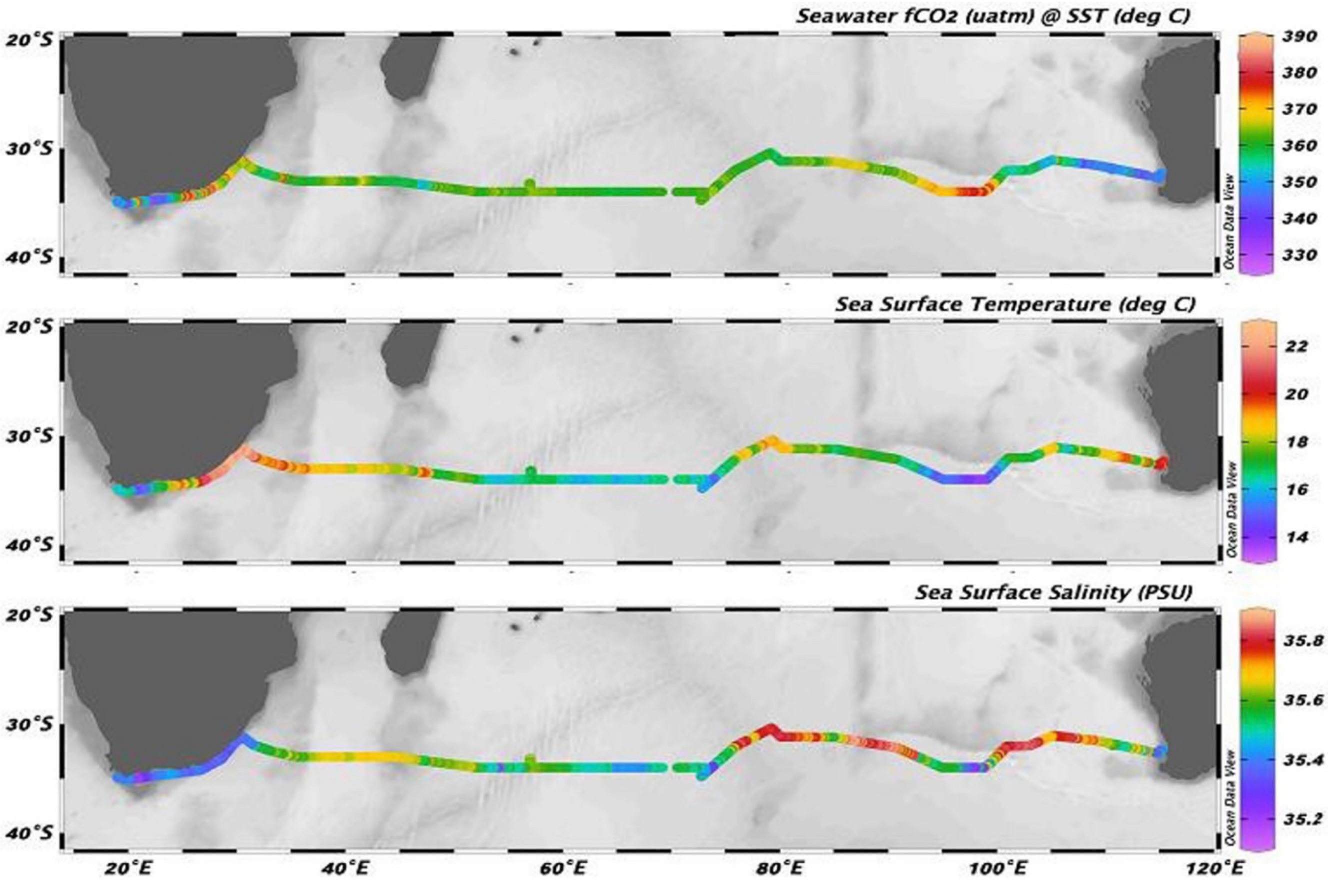


Figure 7. Plots of fCO_2 (top); SST (middle); and SSS (bottom) on the I05 cruise

2.1.3.1 A16N cruise. Working collaboratively with AOML, PMEL Carbon Group scientists prepared for the A16N cruise and conducted the DIC measurements and data analysis for the cruise, With Dana Greeley being the DIC analyst from PMEL onboard the *Ronald H. Brown.* The quality of the DIC data collected was excellent, with good resolution throughout the water column (see Table 4).

2.1.3.2 I05 Cruise. For the IO5 cruise in the Indian Ocean, PMEL provided the chief scientist (Brendan Carter) and also took the lead in the DIC and underway pCO_2 measurements. Mr. Andrew Collins of PMEL and Mr. Charles Featherstone from AOML made the DIC and pCO_2 measurements on the cruise (Figures 7 and 8). Table 6 shows the sample statistics for the CO_2 measurements on the I05 cruise.

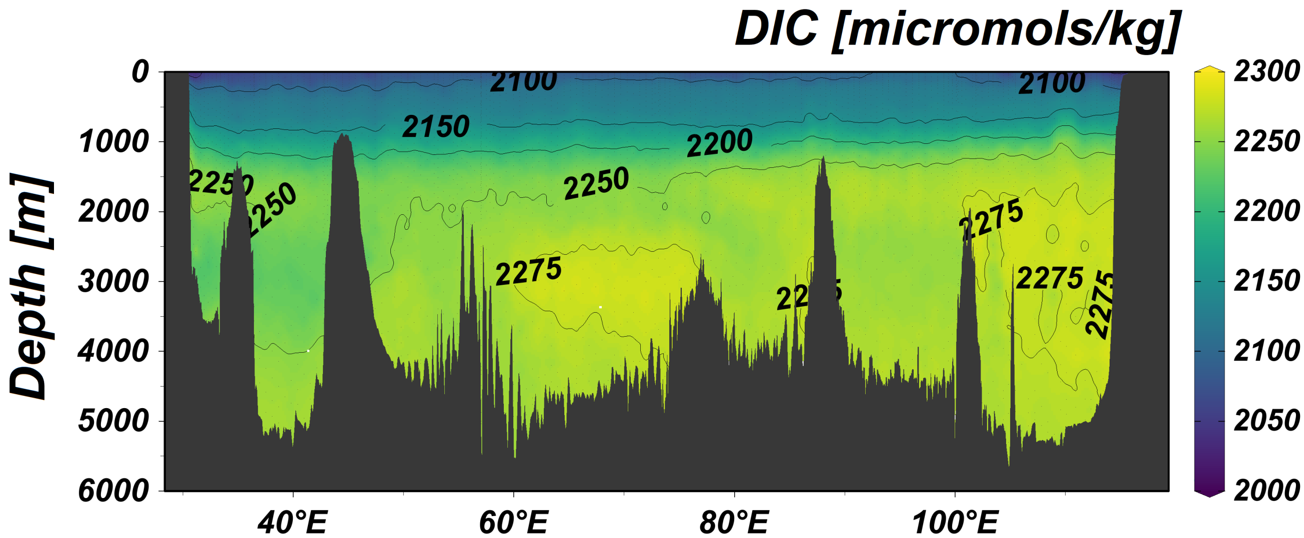


Figure 8. 2023 I05 vertical section of DIC in μmol kg^{-1}.

Table 6. Carbon measurement sample statistics of the I05 cruise.

I05	pCO_2	DIC
Total Number of Samples	25,733	4128
Total Number of replicates	NA	401
Av. Diff replicates (μmol kg^{-1})		0.86
Relative Standard Dev. (%)		0.04

Table 6. CRM results for the I05 cruise.

Calibration data during this cruise:

SYSTEM	Average Gas Loop Cal Factor	Pipette Volume	Duplicate[2]
PMEL1	1.00809	27.4847 ml	0.76
PMEL2	1.00427	26.4014 ml	0.98

CRM Info[1]	PMEL1			PMEL2		
Batch - Cert.	Average	*n*	Std. Dev.	Average	*n*	Std. Dev.
206 – 2021.55	2024.24	91	2.09	2018.42	98	2.11

2.1.3.3 Science Results Carbon Cycle

In FY2023 Drs. Feely, Wanninkhof and Carter were authors of 7 key refereed scientific publications using GO-SHIP data in FY 2023. The Friedlingstein et al. (2023) Global Carbon Project paper provided an accurate assessment of anthropogenic carbon dioxide (CO_2) emissions and their redistribution among the atmosphere, ocean, and terrestrial biosphere in a changing climate which is critical to better understand the global carbon cycle, support the development of climate policies, and project future climate change.

The Jiang et al. (2023) paper developed new and updated ocean acidification indicators for oceanographic observations of the carbon cycle. These indicators have been developed with the goals of improving and consolidating the benchmarks to document changes in the ocean carbon cycle and their impact on ocean acidification.

The Müller et al. manuscript applied the eMLR(C*) regression method to ocean interior observations collected repeatedly since the 1990s largely on GO-SHIP cruises. The global ocean storage of C_{ant} grew from 1994 to 2004 by 29 ± 3 Pg C dec^{-1} and from 2004 to 2014 by 27 ± 3 Pg C dec^{-1}(±1σ). The storage change in the second decade is about 15 ± 11% lower than one would expect from the first decade and assuming proportional increase with atmospheric CO_2. This is attributed to the reduction in sensitivity to a decrease of the ocean buffer capacity and changes in ocean circulation. In the Atlantic Ocean, the maximum storage rate shifted from the Northern to the Southern Hemisphere, plausibly caused by a weaker formation rate of North Atlantic Deep Waters and an intensified ventilation of mode and intermediate waters in the Southern Hemisphere. The C_{ant} accumulation differ from cumulative net air-sea flux estimates by several Pg C dec^{-1}, suggesting a substantial and variable, but uncertain net loss of natural carbon from the ocean. The findings indicate a considerable vulnerability of the ocean carbon sink to climate variability and change.

The DeVries et al. (2023) paper provides an assessment of the global ocean carbon cycle as part of the second REgional Carbon Cycle Assessment and Processes effort, or RECCAP2. The paper focuses on the ocean carbon sink, and investigates the processes that control its magnitude, trends and variability. Observation-based techniques estimate that the net transfer of CO_2 from the atmosphere to the ocean, averaged over 1985-2018, is 1.6 billion tonnes of carbon per year, and that oceanic CO_2 uptake is increasing by 0.61 billion tonnes of carbon per year each decade. Models say that most of this CO_2 entering the ocean, and its increase over time, is driven by anthropogenic CO_2 emissions, which causes the ocean to take up 2.1-2.4 billion tonnes of carbon per year. There are some hints that climate change might be accelerating ocean carbon uptake, but the errors in the estimates are too large to know for sure right now.

The Wanninkhof et al. (2023) contribution to the BAMS SoC report describes the 2022 air sea CO_2 flux estimates based on a self-organizing maps feed-forward neural network (SOM-FNN). The 2022 maps use sea-surface temperature (SST), Chlorophyll-a, atmospheric CO_2, mixed-layer depth, and salinity as predictor variables. The fluxes are determined using ERA5 winds The SOM FNN results show a slightly increasing ocean sink from 1982 to 1994, followed by a period of rapidly decreasing uptake from 1995 to 2002. There is a strong increase in the ocean sink from 2002 onward that continues through 2016. The amplitude of seasonal variability is ≈1.2 Pg C with a minimum uptake in the June–September timeframe. Variability in seasonal amplitudes does not correlate with annual uptake or its variability. The C_{ant} flux of 3.3 Pg C yr^{-1} for 2022 was 23% above the 1990–2020 average of 2.68(±0.52) Pg C yr^{-1}. The report further describes how the nascent and growing biogeochemical Argo program combined with GO-SHIP data will greatly increase the fidelity and resolution of the C_{ant} estimates. BGC-Argo provides total scale seawater pH (pH_T) measurements over the top 2000 m at 10-day resolution throughout the various ocean basins, co-located with temperature, salinity, oxygen, and nitrate measurements. This information can be combined with estimates of seawater total alkalinity (TA), and macronutrients to allow for calculations of DIC in the top 2000 m of the ocean at significantly greater temporal resolution than is achievable from only discrete shipboard TA measurements.

The Feely et al (2023) paper used both GO-SHIP and SOCAT underway measurements to provide a high-resolution regionally varying view of global surface ocean carbon dioxide fugacity, carbonate ion content, total hydrogen ion content, pH on total scale, and aragonite and calcite saturation states on selected time intervals from 1961 to 2020. They demonstrated that air-sea CO_2 uptake of anthropogenic CO_2, warming, local upwelling processes, and declining buffer capacity are the primary mechanisms controlling spatial variability for these parameters in the surface ocean. These changes are rapidly occurring in regions that would normally be considered OA refugia, which is threatening the protection that these regions provide for stocks of sensitive species and increasing the potential for expanding biological impacts.

2.1.4 Nutrient Analyses.

The primary task of the nutrient group in FY 2023 was to collect nutrient data on the A16N GO-SHIP repeat hydrographic section in the Atlantic Ocean. On the A16N cruise, E. Wisegarver from PMEL teamed with A. Fine and I. Smith from AOML/CIMAS. They conducted high precision shipboard analysis of nitrate, phosphate, nitrite, and silicic acid on 3667 samples collected from the CTD rosette at discrete depths. Nutrients were analyzed with a Seal Autoanalyzer (AA3) using the standard and analysis protocols for the GO-SHIP program including calibration of labware, preparation of primary and secondary standards, and corrections for blanks and refractive index. Standard concentrations were validated against Nutrient Certified Reference Material (CRM) made by Japanese Meteorological Laboratory and standards from OSIL (http://www.osil.co.uk/). During the A16N cruise, nutrient CRMs were analyzed at an interval of ten stations (Table 7).

Table 7. Comparison CRM concentrations (bold) with samples run at given stations during A16N 2023 cruise (units in micromole/l).

A16N	**PO4**	**Si**	**NO3**	**NO2**
CRM	**2.28**	**66.5**	**30.6**	**0.0**
2	2.28	69.5	30.5	0.06
9	2.27	69.6	30.5	0.08
24	2.27	68.4	30.6	0.06
34	2.25	68.0	30.3	0.06
44	2.26	67.9	30.4	0.05
54	2.27	68.2	30.5	0.06

64	2.27	68.5	30.5	0.05
74	2.26	68.9	30.5	0.05

The precision of nutrient analysis on A16N is shown in Table 8. The precision of all species meets international quality standards for these measurements, and potential offsets in silicic acid from the CRMs are under investigation. Data collected on this cruise will be archived at the CLIVAR & Carbon Hydrographic Data Office (CCHDO): http://cchdo.ucsd.edu/

Table 8. Precision of nutrient measurements on the 2023 A16N hydrographic cruise determined from replicate analysis of deep-water samples with concentrations >10 µmol kg^{-1} nitrate.

A16N	Phosphate	Nitrate	Silicate
# of replicates	602	601	602
Std. dev. of replicates	0.007	0.09	0.06
% RSD	0.5	0.3	0.3

The sections of the major nutrients from the A16N cruise are shown in Figure 9. Major features include low nutrient concentrations in surface waters; an intense sub-surface (~500 – 1000 m) phosphate and nitrate maximum in the tropics resulting from remineralization of sinking particulate organic matter; lower concentrations in North Atlantic Deep Water; and the presence of nutrient-rich Antarctic Bottom Water in the South Atlantic. These data will be used to examine changes in nutrient and oxygen content in the oceans and examine to what extent such changes might be coupled to carbon inventory changes. Changes in carbon, nutrients and dissolved oxygen in the ocean are similarly driven by ocean circulation, biological productivity in surface waters and ocean interior biogeochemical cycles.

Most of the milestones and deliverables set forth in the FY2023 workplan were achieved including preparation and logistics for A16N, and analysis of nutrient concentrations on samples collected during the cruise (Table 9). However, delivery of final QC data was delayed until December 2023. This delay was due to a subsequent cruise in the Arctic Ocean.

Table 9. FY23 Nutrient Group Milestones

Milestones for Nutrient Group	**Deliverable**	**Date**
Preparation & logistics for A13.5 cruise	Shipment of Equipment	November 2023
Measure nutrients on A16N cruise	Submit data to CCHDO	April 2024

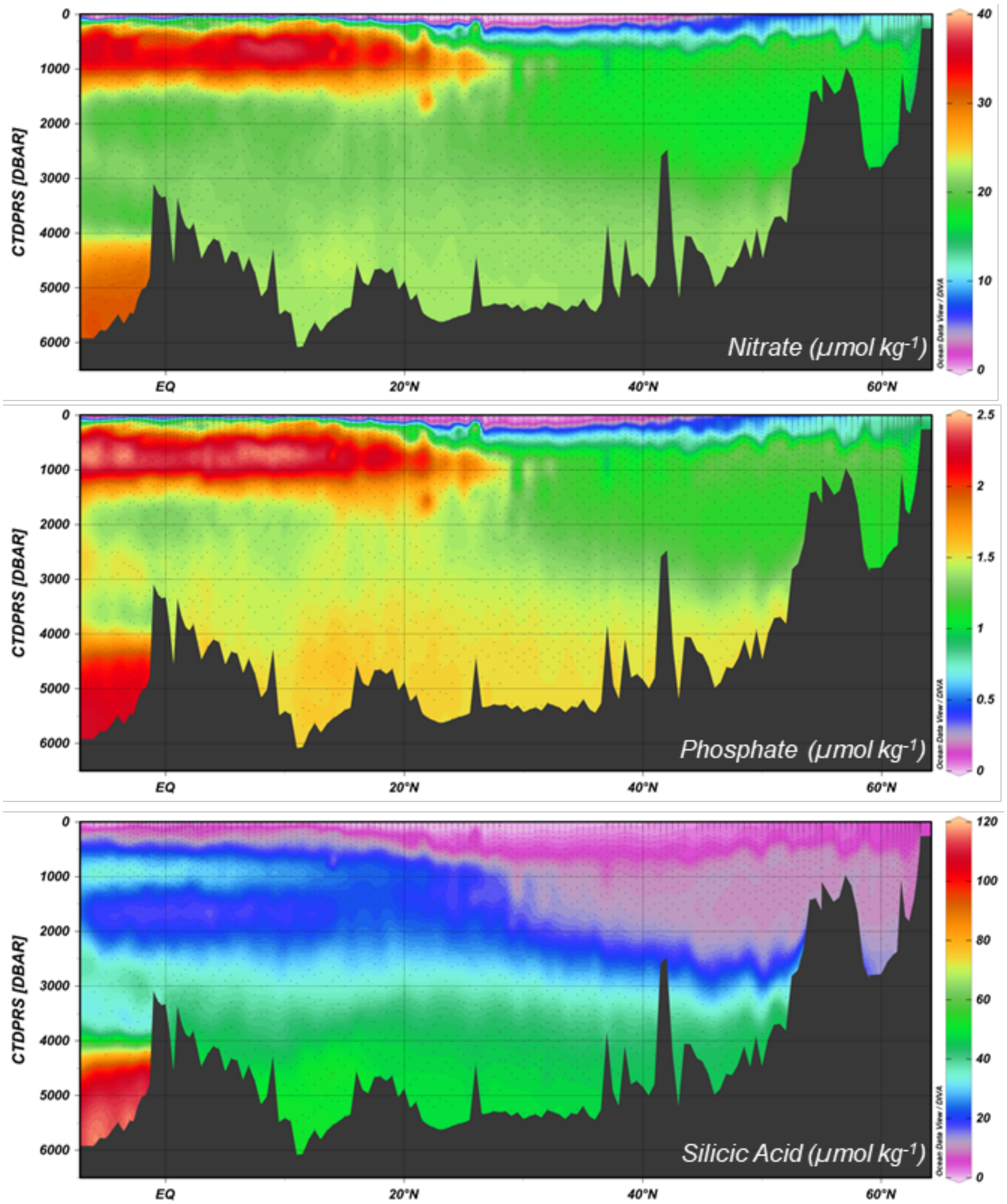


Figure 9. Sections of nitrate (top), phosphate (middle) and silicic acid (bottom) along the 2023 A16N cruise track.

2.1.5 AOML/U. Miami Discrete Oxygen Group

In FY2023, AOML CTD/O_2 personnel conducted GO-SHIP A16N (Mar 6- May 9, 2023). A total of 150 stations were occupied and 3645 discrete oxygen determinations were made comprised of all tripped bottles (Table 10). QC of the leg 1 data is complete. QC of leg 2 data has been delayed because PMEL has not finished QC of the CTD/O2 data. A contour plot of preliminary O_2 data is shown in Figure 10. The Oxygen group is currently prepping for GO-SHIP A13.5 which will leave from the Azores Feb 1 and end in Cape Town, SA on Mar 23, 2024.

Other activities in 2023 have included the purchase of a trace oxygen meter. This equipment will used to investigate the performance of the oxygen titration at very low oxygen levels. There is a growing interest in the Oxygen Minimum Zones. Will they expand and/or intensify because of climate change? OMZs are important sites of denitrification. They may also be important sites for carbon sequestration. Near-zero oxygen concentration is critical for both processes. Knowing whether the oxygen concentration is >2 ˜µmol kg^{-1} or in the nanomolar range is critical to understanding what is happening biogeochemically. The Winkler titration method is known to have interference issues from nitrite and iodate at oxygen concentration of 2 umol/kg and lower. Dr. Langdon plans to investigate the use of the Presens Trace Oxygen meter to measure the oxygen concentration of water samples collected from OMZs on future GO-SHIP and GOMECC cruises. He also plans to conduct studies in the lab to better understand how the Winkler method performs with water samples with oxygen concentrations manipulated to fall in the nanomolar range. Interference from nitrite and iodate will also be investigated.

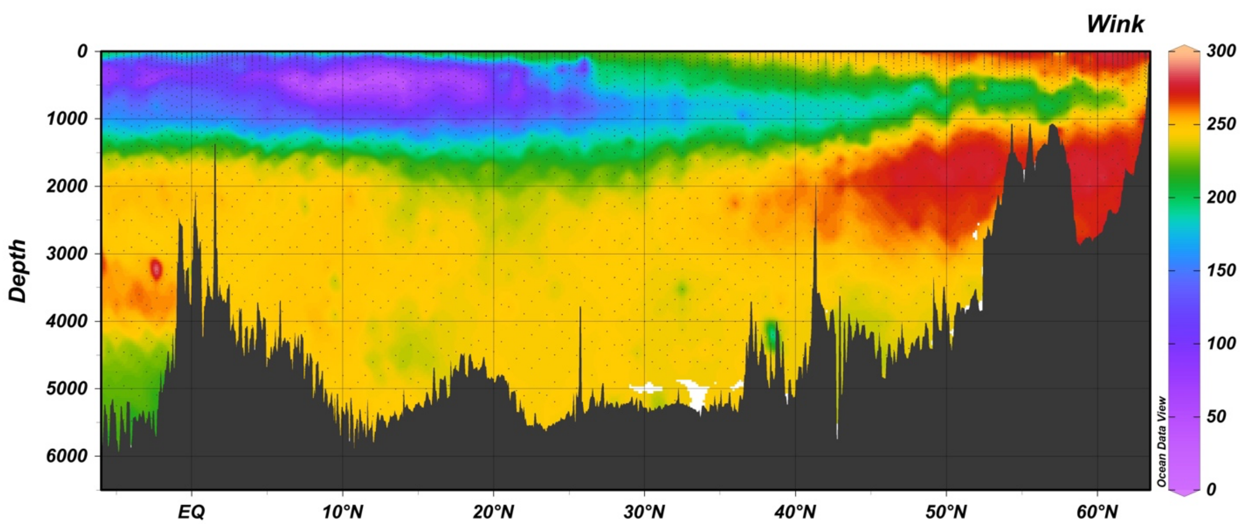


Figure 10. A16N 2023 Dissolved Oxygen Section

Table 10. Oxygen sampling statistics using the WOCE quality flag criteria for A16N_2023

A16N	O_2
Total Number of Samples	3351
Total Number of replicates	238

2.1.5.1 Science Results Dissolved Oxygen

A manuscript titled "The Influence of Skin Temperature Correction on Air-Sea Gas Exchange Models: A Comparative Study of Oxygen and Carbon Dioxide" B. Yang and C. Langdon is currently under review at Marine Chemistry. A manuscript titled "Below the four main oceanic mesopelagic oxygen deficit layers: vertical structure and implications for carbon transport" H. Maske, A. Paulmier and C. Langdon is in preparation.

2.1.6 Ocean Tracers: CFC and SF_6

In FY2023 the Ocean Tracers group at PMEL successfully accomplished measurements of CFC-11, CFC-12, SF_6, and N_2O during A16N (Figure 11). This cruise was split into two legs, the first from Recife, Brazil to Rota, Spain and the second from Rota, Spain to Reykjavik, Iceland. David Cooper, Melissa Miller (Leg 1), and Carol Gonzales (Leg 2) were hired as temporary analysts through the University of Washington Cooperative Institute for Climate, Ocean, & Ecosystem Studies (CICOES), with Cooper acting as the lead technician for the cruise. Rachel Bramblett (U. Georgia; Leg 1) and Isabel Schaal (WHOI; Leg 2) also joined as student CFC analysts through NSF funding via the U.S. GO-SHIP program. CFC and SF6 concentrations from Leg 1 of this cruise were provided as preliminary data. In the absence of a permanent PI for this program, Zachary Erickson (PMEL; acting PI) is working with Dr. Mark Warner (University of Washington) to submit a preliminary dataset for Leg 2 and also to work up the preliminary data from both Legs of the cruise into a final dataset to be submitted.

In the second half of FY2023, acting PI Erickson worked to prepare the CFC van for the upcoming A13.5 cruise, with support from Rolf Sonnerup (NSF) and Mark Warner (U. Washington).

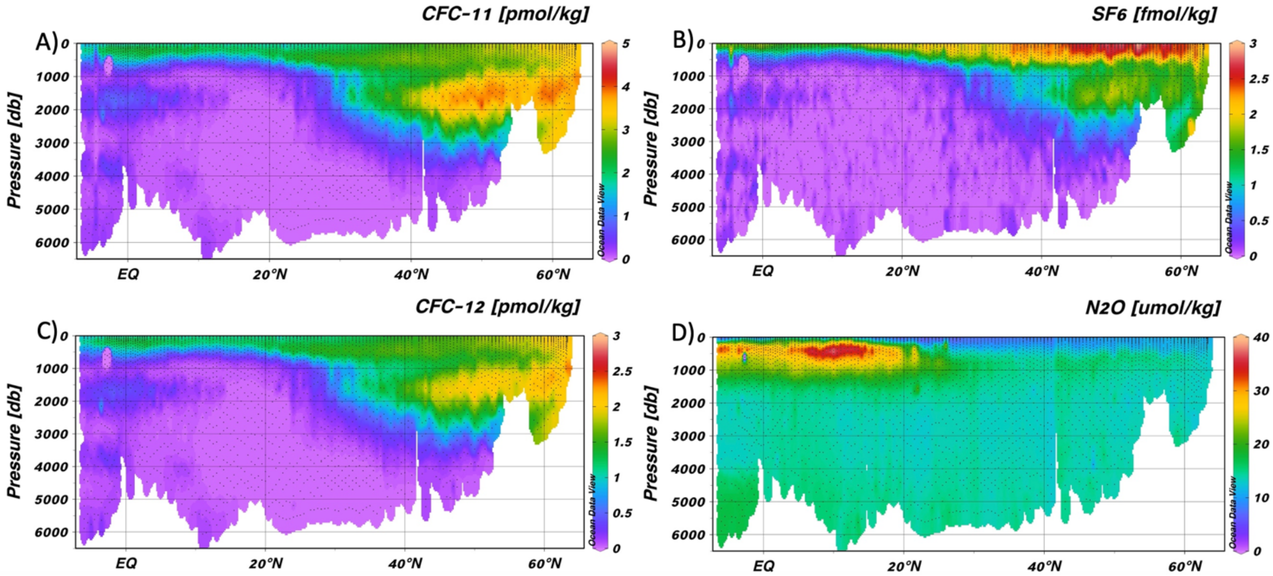


Figure 11. A16N 2023 Tracer Sections

Table 11. PMEL Ocean Tracers Group Milestones

Milestone	Deliverable	Date
Completion of A16N cruise	CFC/SF_6 data submitted	June 2023

2.1. Scientific Advances

The GO-SHIP project, through its delivery of temperature, salinity, oxygen, carbon, nutrient, and tracer profile data, contributes to the following NOAA Global Ocean Monitoring and Observing Program Deliverables (in rough order of impact and relevance):

- ***Ocean Carbon Uptake and Content***, to better understand the extent to which the ocean sequesters CO_2 and how cycling among ocean-land-atmosphere carbon reservoirs varies on seasonal-to-decadal time scales across the air-sea interface and extending through the entire water column. As noted above, this is the part of the GOMO Program that delivers the observed distribution of dissolved inorganic carbon content directly, from which uptake can be inferred through either observed changes with previous sections (e.g. anthropogenic carbon) or through convergence/divergence estimates between GO-SHIP sections (Muller et al, 2023; deVries et al, 2023; Gruber et al., 2019; Carter et al., 2017, 2019).

- ***Ocean Heat Content and Transport***, to better understand the extent to which the ocean sequesters heat; to identify where heat enters the ocean and where it emerges to interact with the atmosphere; and to identify changes in thermohaline circulation and monitor for indications of possible abrupt climate change. The GO-SHIP project specifically addresses this NOAA climate goal by providing long-term integrated indicators of the global thermohaline (overturning) circulation and heat transport that directly addresses the program deliverable on "***ocean heat content and transport***". Chomiak et al, 2023 has used GO-SHIP data in the North Atlantic, including the 2023 A16N occupation, to study equatorward spreading pathways and timescales of Labrador Sea Water and the role they play on the export of subpolar climate signals. In addition, GO-SHIP sections provide the primary data source for the quality control of Argo so that the Argo program can meet accuracy benchmarks necessary for a climate time series.

- ***Sea Surface Temperature and Surface Currents***, to identify significant patterns of climate variability and change. The GO-SHIP project provides direct current estimates from shipboard and lowered ADCP measurements and surface temperature measurements from CTD observations and underway thermosalinograph data. Repeat sections of temperature can directly estimate the horizontal and vertical patterns of change in the subsurface ocean.

- **Air-Sea Exchanges of Heat, Momentum, and Fresh Water**, to identify changes in forcing functions driving ocean conditions and atmospheric conditions; and to elucidate oceanic influences on the global water cycle. The GO-SHIP project provides an *in-situ* ocean heat and mass transport estimates that can be used as a constraint on air-sea flux estimates and numerical model validation. This type of direct oceanic-transport-based flux estimate helps to reduce errors in surface products and assess numerical models.

- ***Sea Level***, to identify changes resulting from trends and variability in climate. The GO-SHIP project provides indirect indicators that can influence sea-level variability through estimates of the Meridional Overturning Circulation and heat transport and heat content. Changes in heat content (e.g. induced by changes in the divergence of heat transports) and the meridional overturning circulation can affect sea level.

2.2. Deliverables Addressing Societal Needs

NOAA's Climate Goal is focusing on an initial set of societal challenges:

- Reduce vulnerability to extreme weather (extremes);
- Prepare for drought and water resource challenges (drought);
- Manage risks to coastlines and coastal infrastructure (coastal inundation); and
- Sustainably manage marine ecosystems (marine ecosystems)

The GO-SHIP project provides data and information that can serve to understand and better predict weather and oceanic processes that address these societal challenges. The program provides direct estimates ocean heat content, heat transport and freshwater transport that are linked to extreme weather, drought and the hydrological cycle. The ocean chemistry information provided by GO-SHIP directly impacts our understanding of marine ecosystems through nutrient supply and ocean acidification processes. In addition, ancillary observations of the boundary current transports can provide information that kinematically relate to coastal sea level. Similarly, changes in the net meridional overturning circulation can influence long-term sea-level. Extreme weather (e.g., hurricanes) and drought (e.g., rainfall) have been linked to the strength of the meridional overturning circulation and heat content changes. Continued analysis of boundary currents and the meridional overturning circulation and heat transport may improve forecasts of coastal inundation, seasonal forecasts of hurricanes, etc.

2.3. Websites

GO-SHIP information and data is available at several websites, including laboratory sites:
AOML cruise data, cruise web pages (carbon):
http://www.aoml.noaa.gov/ocd/ocdweb/occ.html PMEL cruise data, outreach materials (carbon): https://www.pmel.noaa.gov/co2/
PMEL data Portal:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery GO-SHIP home page: https://www.go-ship.org/
US GO-SHIP home page: https://usgoship.ucsd.edu/
US GO-SHIP data depository: https://cchdo.ucsd.edu/search?q=GO-SHIP
NOAA data repository:
NOAA Ocean Carbon: https://www.ncei.noaa.gov/access/ocean-carbon-data-system/
https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system-portal/
The Lowered and Ship ADCP data for the GO-SHIP cruises are available at: https://currents.soest.hawaii.edu/go-ship/flastik_ladcp_goship_beta/list_n_map_view/dates/0/index.html (LADCP) and https://currents.soest.hawaii.edu/go-ship/sadcp/list_n_map_view/cruises/0/index.html (SADCP)
https://www.facebook.com/rosenstielcoraloceanacidificationlab/

3.0 Outreach and Education

All PI's and associates in this effort present their scientific research from the GO-SHIP Repeat Hydrography Program to the public in several forums including universities, invited open public lectures, and laboratory tours. Moreover, as listed below, several have positions in advisory boards and steering committees that have as focus advocating for GO-SHIP and integrating GO-SHIP cruises data into interdisciplinary science efforts.

Dr. Zachary Erickson is leading a U.S. GOSHIP subcommittee on developing a Code of Conduct for GOSHIP cruises, as well as a set of recommendations on steps to take to improve morale and communication during cruises and to provide resources to address culture or harassment issues that may arise during a GOSHIP cruise. He also serves on the Scientific Steering Committee for Ocean Carbon & Biogeochemistry (OCB) program and is a co-convener of an upcoming workshop on Pathways Connecting Climate Changes to the Deep Ocean, a partnership between the OCB, CLIVAR, and Deep Ocean Observing Strategy (DOOS) communities. He is also co-lead for an Early Career Ocean Professionals (ECOP) group at

NOAA PMEL and a member of the PMEL Scientific Advisory Board.

Dr. Rik Wanninkhof has provided presentations to international scientific audiences on the science efforts and is advocating for a collaborative international surface CO_2 observing network, SOCONET. He works closely with GO-SHIP steering committee members, IOOCP and JCOMMOPS to provide community outreach in bulletins and presentations on the importance of the decadal global ocean surveys and the major accomplishments of this program. He is actively involved in the WMO Global Greenhouse Gas Watch (G2W), and the US Global Greenhouse Gas Monitoring Program. He is post-doc adviser of Katelyn Schockman who obtained her PhD degree at USF.

Dr. Richard Feely is an Affiliate Professor at the UW School of Oceanography and is a member of the US GO-SHIP Steering Committee. During FY 2023, he gave 3 presentations at scientific meetings on his carbon research, including a presentation at the 5th International Symposium on the Effects of Climate Change on the World's Ocean in Bergen Norway. Dr. Feely was member of the PhD committee of Katelyn Schockman of USF. Dr. Feely was a co-author of her PhD publications.

Dr. Rick Lumpkin is director of AOML's Physical Oceanography Division. During FY23, he served as US focal point of the Data Buoy Cooperation Panel, contributed information for a Washington Post Story, worked with climate.gov and "The Sargassum Podcast" on stories about Sargassum, and conducted interviews with NPR, ABC-25 WPBF (West Palm Beach), WCBS 880 Radio (New York), The Associated Press, WMBS Pittsburgh, Forbes, Spectrum News, "As It Happens" (Canadian Broadcasting Corporation), and The Hill.

Dr. Brendan Carter gave 4 scientific talks that featured DMSP research to various external audiences. He also served on the GO-SHIP executive committee, the GLODAP reference team, and the Biogeochemical Argo Steering committee, began as US GO-SHIP Co-Chair starting in FY23, and was nominated as the GLODAP co-chair starting in FY24. He peer-reviewed 12 research papers and proposals during the last 12 months. In FY-22 Carter became an affiliate faculty member of the University of Washington. He is now the primary advisor for two postdocs and two graduate students. He serves on the committee for a third graduate student. PI Carter also mentored numerous scientists at sea as part of the I05 research cruise, and co-hosted Hollings Scholar Jonathan Tran at PMEL in summer of 2023.

Prof. Chris Langdon has developed a new hands-on research course for marine science students at the University of Miami. MBE 408 Climate Change – Limits of Adaptability of Marine Invertebrates introduces students to the latest findings from the IPCC AR6 report on the changing physical and chemical conditions in the ocean. Then the course covers two emerging theories (Ocean- and Capacity-limited Thermal Tolerance OCLTT and Dynamic Energy Budgets DEB) that seek to relate how thermal performance curves for marine ectotherms will be impacted by ocean acidification and deoxygenation.

4.0 Publications and Reports

4.1 Publications by Principal Investigators

Carter, B.R., Sharp, J.D., Dickson, A.G., Álvarez, M., Fong, M.B., García-Ibáñez, M.I., Woosley, R.J., Takeshita, Y., Barbero, L., Byrne, R.H., Cai, W.-J., Chierici, M., Clegg, S.L., Easley, R.A., Fassbender, A.J., Fleger, K.L., Li, X., Martín-Mayor, M., Schockman, K.M. and Wang, Z.A. (2023), Uncertainty sources for measurable ocean carbonate chemistry variables. Limnol Oceanogr. https://doi.org/10.1002/lno.12477

DeVries, T., Yamamoto, K., Wanninkhof, R., Gruber, N., Hauck, J., Müller, J. D., et al. (2023). Magnitude, trends, and variability of the global ocean carbon sink from 1985-2018. *Global Biogeochemical Cycles,* https://doi.org/10.1029/2023GB007780

Fay, A. R., Munro, D. R., McKinley, G., Pierrot, D., Sutherland, S., Sweeney, C., & Wanninkhof, R. (2023). Updated climatological mean delta fCO2 and net sea–air CO2 flux over the global open ocean regions. *Earth System Science Data submitted*.

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C. E., Hauck, J., et al. (2023). Global Carbon Budget 2023. *Earth Syst. Sci. Data, 15*(12), 5301-5369. https://essd.copernicus.org/articles/15/5301/2023/

Bange, H. W., Mongwe, N. P., Shutler, J. D., Arévalo-Martínez, D. L., Bianchi, D., Lauvset, S. K., et al. (2023). Advances in understanding of air-sea exchange and cycling of greenhouse gases in the upper ocean. *Elementa: Science of the Anthropocene, 11(1)*. https://doi.org/10.1525/elementa.2023.00044

Jiang, L.-Q., Dunne, J., Carter, B. R., Tjiputra, J. F., Terhaar, J., Sharp, J. D., et al. (2023). Global Surface Ocean Acidification Indicators From 1750 to 2100. *Journal of Advances in Modeling Earth Systems, 15*(3), e2022MS003563. https://doi.org/10.1029/2022MS003563. https://doi.org/10.1029/2022MS003563

Müller, J. D., Gruber, N., Carter, B., Feely, R., Ishii, M., Lange, N., et al. (2023). Decadal Trends in the Oceanic Storage of Anthropogenic Carbon From 1994 to 2014. *AGU Advances, 4*(4), e2023AV000875. https://doi.org/10.1029/2023AV000875

Wanninkhof, R., Triñanes, J. A., P. Landschützer, R. A. Feely, & Carter, B. R. (2023). Global ocean carbon cycle In J. Blunden & T. Boyer (Eds.), *State of the Climate in 2022* (Vol. 104(8) pp. S70-S74): Bull. Amer. Meteor. Soc.

4.2 Other Relevant Publications (published or in preparation)

Erickson, Z.K., B.R. Carter, R.A. Feely, G.C. Johnson, J.D. Sharp, and R.E. Sonnerup (2023): PMEL's contribution to observing and analyzing decadal global ocean changes through sustained repeat hydrography. Oceanography, 36(2–3), 60–69, doi: 10.5670/oceanog.2023.204.

Feely, R.A., L.-Q. Jiang, R. Wanninkhof, B.R. Carter, S.R. Alin, N. Bednaršek, and C.E. Cosca (2023): Acidification of the global surface ocean: What we have learned from observations. Oceanography, 36(2–3), 120–129, doi: 10.5670/oceanog.2023.222,

Hood, E. M., C.L. Sabine, & Sloyan, B. M. (Eds.). (2010). *The GO-SHIP Repeat Hydrography Manual: A Collection of Expert Reports and Guidelines. IOCCP Report Number 14*.

Available online at http://www.go-ship.org/HydroMan.html.: ICPO Publication Series number 134.
Bednaršek, N., K.-A. Naish, R.A. Feely, C. Hauri, K. Kimoto, A.J. Hermann, C. Michel, A. Niemi, and D. Pilcher (2021): Integrated assessment of ocean acidification risks to pteropods in the northern high latitudes: regional comparison of exposure, sensitivity and adaptive capacity. *Front. Mar. Sci.*, *8*, doi: 10.3389/fmars.2021.671497
Carter, B. R., and Coauthors, Progress Toward Ocean Carbonate System Inter-consistency, Marine Chemistry, planned submission Feb. 2024
Chomiak, L., D.L. Volkov, and C. Schmid, 2023. The interior spreading story of Labrador Sea Water. Frontiers in Marine Science, 10:1270463. https://doi.org/10.3389/fmars.2023.1270463
DeVries, T., R. Wanninkhof and Coauthors, The Global Regional Carbon Cycle Assessment and Processes (RECCAP2) carbon data synthesis report
Garcia, N.S., Talmy, D., Fu, W.W., Larkin, A.A., Lee, J. and Martiny, A.C., 2022. The diel cycle of surface ocean elemental stoichiometry has implications for ocean productivity. Global Biogeochemical Cycles, 36(3), p.e2021GB007092.
Gao, H., Cai, W.J., Jin, M., Dong, C. and Timmerman, A.H., 2022. Ocean ventilation controls the contrasting anthropogenic CO2 uptake rates between the western and eastern South Atlantic Ocean basins. *Global Biogeochemical Cycles*, *36*(6), p.e2021GB007265.
Ishii, M, B. R. Carter and Coauthors, The Pacific Regional Carbon Cycle Assessment and Processes (RECCAP2) carbon data synthesis report
Lauvset, S. K., and Coauthors, 2022. GLODAPv2.2022: the latest version of the global interior ocean biogeochemical data product. Earth Syst. Sci. Data. 14, 5543-5572. https://doi.org/10.5194/essd-14-5543-2022.
Liang, Z., Letscher, R.T. and Knapp, A.N., 2022. Dissolved organic phosphorus concentrations in the surface ocean controlled by both phosphate and iron stress. *Nature Geoscience*, *15*(8), pp.651-657.
Marshall, T., Granger, J., Casciotti, K.L., Dähnke, K., Emeis, K.C., Marconi, D., McIlvin, M.R., Noble, A.E., Saito, M.A., Sigman, D.M. and Fawcett, S.E., 2022. The Angola Gyre is a hotspot of dinitrogen fixation in the South Atlantic Ocean. Communications Earth & Environment, 3(1), pp.1-10.
Schockman, K. M., R. H. Byrne, B. R. Carter, and R. A. Feely, Spectrophotometric Determination of the Bicarbonate Dissociation Constant in Seawater for $20 \leq S_P \leq 40$ and $3 \leq t \leq 35$ °C and CO_2 System Internal Consistency at Low Temperatures, in prep for Limnology and Oceanography
Zeidan, S., 2022. *Radiocarbon (Δ14C) and Stable Carbon (δ13C) Isotopic Composition of Dissolved Inorganic Carbon (DIC) in Baffin Bay* (Doctoral dissertation, Université d'Ottawa/University of Ottawa).

We have satisfied NOAA's Public Access to Research Results (PARR) requirements for publications. This includes submitting a digital copy of final pre-publication manuscripts to the NOAA Institutional Repository.

5.0 Data and Publication Sharing

Below are the URLs for access to the cruise data submitted.

A16N data:
https://www.nodc.noaa.gov/ocads/oceans/RepeatSections/clivar_S04P.html

I05 data: https://cchdo.ucsd.edu/cruise/33RR20230722

6.0 Project Highlight Slides

The project highlights slides were sent as a separate file to Kathy Tedesco

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