FY-2023 Progress Report

Surface water pCO_2 measurements from ships

Period of Activity: 01 October 2022 – 30 September 2023

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BUDGETS REQUESTED: Oct. 1, 2022 - Sept. 30, 2023

	FY23
AOML(CO_2)	$540,455
(TSG)	$69,433
PMEL	$475,535
GML[1]	$464,977
BIOS[1]	$132,516
RSMAES[1]	$52,256
SOCONET	$25,242
CIMAS Task 1[2] (2.7%)	$4,989
AOML overhead (7.5% - not included)	$11,804
TOTAL	$1,765,403

(1) Performance Period: Oct. 1, 2023 - Sept. 30, 2024
(2) Task 1 fee for funds sent to RSMAES and subcontracts

Surface water pCO_2 measurements from ships

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1. Project Summary

The oceans are the largest sustained sink of anthropogenic carbon dioxide (CO_2) with a flux into the ocean of about 2.8 petagrams (i.e., 2.8 x 10^{15} grams or 2.8 gigatons) of carbon each year thereby partially mitigating the rapid increase of this climate forcing gas in the atmosphere (Friedlingstein et al., 2023). To provide meaningful projections of future atmospheric CO_2 levels, and surface oceanic CO_2 concentrations, we must constrain the flux of CO_2 across the air-water interface. The goal for the mature surface ocean CO_2 observing system is to accomplish this to within 20 % on regional and seasonal scales. This will be accomplished through creation of seasonal sea-air CO_2 flux maps that will feed directly into national and international assessments. Of particular interest is quantification and attribution of variability and trends. In this project, four NOAA investigators and three academic principal investigators have managed 18 research and commercial vessels with automated carbon dioxide analyzers as well as thermosalinographs (TSGs) to measure the temperature, salinity and partial pressure of CO_2 (pCO_2; or a nearly identical quantity of fugacity of CO_2 or fCO_2) in surface water and air in order to determine the carbon exchange between the ocean and atmosphere. Collaborative efforts were completed to combine datasets, and create and update global data climatology that was previously led by our late academic collaborator, Dr. T. Takahashi of Lamont Doherty Earth Observatory (LDEO) at Columbia University (Fay et al., 2024, submitted). Furthermore, we are the largest contributor and assemble, document quality control and serve global datasets through the Surface Ocean CO_2 Atlas (SOCAT version 2023; Bakker et al., 2016) coordinated under the auspices of the International Ocean Carbon Coordination project (IOCCP). Approximately a quarter of the

SOCAT version 2023 data release comes from the participants of the pCO_2 from ships effort funded by the NOAA Global Observing and Monitoring Ocean Program (NOAA/GOMO).

Documenting carbon sources and sinks relies critically on other efforts undertaken under sponsorship of the GOMO program including implementation of the GO-SHIP cruises, XBT lines, and moored and drifting buoys. By design, this sustained project is focused on automated measurement of pCO_2 in the surface ocean. The data from this effort, along with analysis and interpretation supported by other programs, provide climate and ecosystem services with knowledge and quantification of the radiatively important and acidic gas, carbon dioxide. The data are used along with robust interpolation methods utilizing remotely sensed products to produce monthly sea-air CO_2 flux fields that are served on the web with a 3-to-12-month lag. Products and data are used in the upcoming second international Regional Carbon Cycle Assessment Project (RECCAP-2), the annual state of the climate report of BAMS (Wanninkhof et al., 2023, Alin et al., 2022; Feely et al., 2021), and annual updates on the state of the carbon cycle (Friedlingstein et al., 2023) of the Global Carbon Program (GCP) and the information has been utilized in the latest IPCC assessment report (AR5). Furthermore, this data has proved critical for the Surface Ocean Carbon Observational Methods (SOCOM) effort that compares a dozen ways to optimally interpolate the pCO_2 fields in time and space (Rödenbeck et al., 2015). This work provides critical information for policies on greenhouse gas management and mitigation, and assessments of perturbations of the surface ocean chemistry (such as the impact of ocean acidification). More specifically, it will become crucial in assessing the effectiveness of the different carbon dioxide removal (CDR) methods, present and future, which will help nations of the world achieve "Net Zero Emissions".

2. Scientific and Observing System Accomplishments

The project is a partnership of the Atlantic Oceanographic and Meteorological Laboratory (AOML) including its TSG group, the Pacific Marine Environmental Laboratory (PMEL), the Global Monitoring Laboratory (GML) of the Environmental Systems Research Laboratory (ESRL), the Rosenstiel School of Marine and Atmospheric Science (Rosenstiel) of the University of Miami, and the Bermuda Institute of Ocean Sciences (BIOS). The partners are responsible for operation of the pCO_2 systems on the ships, auxiliary measurements, data reduction, quality control, and data management. The following ships had pCO_2 systems on them during part or all of the FY 2023 performance period: NOAA ships *Ronald H. Brown, Gordon Gunter,* and *Henry B. Bigelow;* Research vessels *Bluefin, Thompson, Palmer*, *Gould, Sikuliaq,* and *Healy*, RCG cruise ships *Equinox, Flora* and *Allure of the Seas*, La compagnie de Ponant cruise ship *Le Commandant Charcot*, Lindblad expeditions National Geographic *Islander II*, UNOLS research vessels *Marcus Langseth* (ship owned and operated by University of Colombia, *Atlantic Explorer* (ship owned and operated by BIOS) and *Walton Smith* (owned and operated by Rosenstiel) and finally Wallenius Wilhelmsen's car carrier *Tysla*. This effort is the largest single coordinated entity of obtaining surface water CO_2 data in the world. Not all the ships were operating during FY2023, as we are still trying to restart some systems that were stopped due to the COVID-19 pandemic. Approximately *591,352* new data points were acquired during FY 2023 (*Table 1*). As outlined below, outfitting and operating of some of the ships were funded from other sources but all the data was reduced and collated in a uniform manner and

provided to the National Center for Environmental Information (NCEI) as part of this effort. The final data sets are combined and sent to NCEI for dissemination and archival, and to the SOCAT effort. All work follows established principles of monitoring climate forcing gases and biogeochemical cycles.

The main metric for this program is obtaining, reducing, quality controlling and disseminating high quality surface water and marine air pCO_2 data. The number of cruises with pCO_2 observations from research ships and ships of opportunity (SOOP) that have been completed during the performance period are a major performance metric and are listed in *Table 1*. Details for each ship are provided below.

Table 1:SOOP Data Summary FY-2023. Total Observations: ~ 591,352

SHIP	# Cruises	# Data Points	% Recovery*
R/V Brown	*6*	*64,307*	*91.9%*
M/V Equinox	*16*	*33,689*	*84.3%*
M/V Allure of the Seas	*0*	*0*	*0%*
M/V Flora	*0*	*0*	*0%*
R/V Gordon Gunter	*7*	*37,367*	*74.3%*
R/V Bigelow	*9*	*56,979*	*96.7%*
M/V Le Commandant Charcot	*23*	*~140,000*	*~90%*
M/V Islander II	*1*	*~2,000*	*95%*
R/V Walton Smith	*15*	*37,295*	*90.0%*
R/V Thompson	*5*	23,397	*TBD*
R/V Bluefin	*0*	*0*	*0%*
R/V Roger Revelle	*1*	25,477	*99%*
M/V Tysla	*5*	*>21,000*	*~50%*
RVIB Palmer	*3*	*~24,400*	*99.0%*
R/V Gould	*6*	*~29,900*	*95.0%*
USCGC Healy	*4*	*26,346*	*99.9%*
R/V Sikuliaq	*15*	*78,884*	*99.7%*
R/V Atlantic Explorer	*32*	*~24,000*	*95.0%*

* The values are to illustrate overall performance of the program. They should be used with caution when making ship-to-ship comparisons. The number of data points is a function of frequency of measurements, number of cruises and instrument malfunction that differ for each ship. Percent recovery has been determined in different fashion by each investigator ranging from number of data points that could have been obtained if the units had operated whenever the ship was at sea to number of acquired data points that were deemed acceptable during quality control.

In addition, we report on the following performance measures for the project as a whole.

Number of cruises submitted to SOCAT during the fiscal year: 41
Number of publications authored/co-authored by PI: 9 (see list)
Number of peer-reviewed publications that list SOCAT as a data source as of the time of this report (see here):

61 (2023) 90 (2022) 68 (2021) 56 (2020) 63 (2019)

Number of updated products: 3 SOCATv2023, BAMS SoC and Global Carbon Budget (GCB 2023).

***NOAA* ship *Ronald H. Brown*- AOML lead**

Data Site: http://www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *6*
Number of fCO_2 data points: *64,307*
% Data return: *91.9%*

Description: The cruise tracks for each cruise of the *Brown* for FY 2023 are shown in Figure 1. Each individual track with links to the data can be found on our website at http://www.aoml.noaa.gov/ocd/ocdweb/brown/brown_2023.html.
The system is connected to the Scientific Computer System (SCS), which is on board most NOAA ships. It takes advantage of the array of sensors logged by the system and gets GPS, SST and TSG data from the ship. The data is automatically transmitted daily via ftp and displayed on AOML's website. Additional plots of the different sensor data are automatically generated and are internally accessible for quality control purposes. This allows the near real-time detection of potential problems. New flow sensors have been added to monitor the ship's TSG system and will help detect bad data. The system has worked reliably and the high data return is directly related to the great support we get from the crew. The ship has gone to the ship yard for it's mid-life renovations in June 2023 and is expected to come out in September 2024.

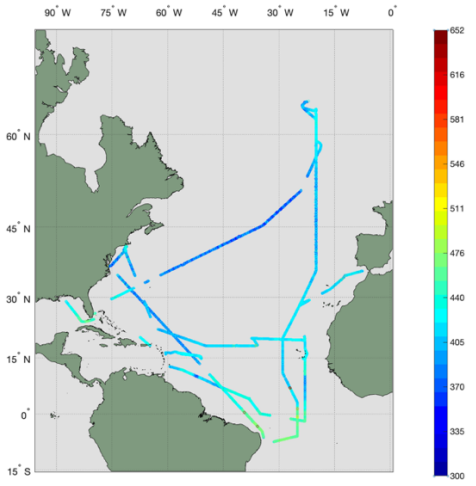

Figure 1. R/V Ronald H. Brown cruise tracks and surface xCO_2 values for FY 2023.

Causes for non-return: This installation has been performing well and the data return remains excellent. We lost some data due to the lack of supervision of the system during its last transit from Iceland to the yard in Pascagoula, MS. We are planning to upgrade the installation to a new GO8060 when comes the time to re-install the system. We have been delayed in the data processing due to the loss of our main data processor who retired this year.
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Cruise ship *Equinox* - AOML lead

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *16*
Number of fCO_2 data points: *33,689*
% Data return: *84.3%*

***Description*:** The overall program is led by the University of Miami's Rosenstiel School of Marine, Atmospheric & Earth Science. It is the continuation of the project on the RCG *Explorer* of the Seas but with fewer instruments. The installation is simpler and located in the Bow Thruster room. The pCO_2 system is in parallel with the University of Miami's array of instruments operated by the Marine Technology Group (MTG). All of the instrument's computers are linked together and to the outside via a Virtual Private Network (VPN) interface. Through this VPN, we have remote access to the system's computer to optimize the operations of the instrument and to access data on a daily basis. The data is automatically downloaded daily via FTP to a server at the University of Miami. It is then plotted on our website in near real-time (http://www.aoml.noaa.gov/ocd/ocdweb/equinox/equinox_realtime.html).

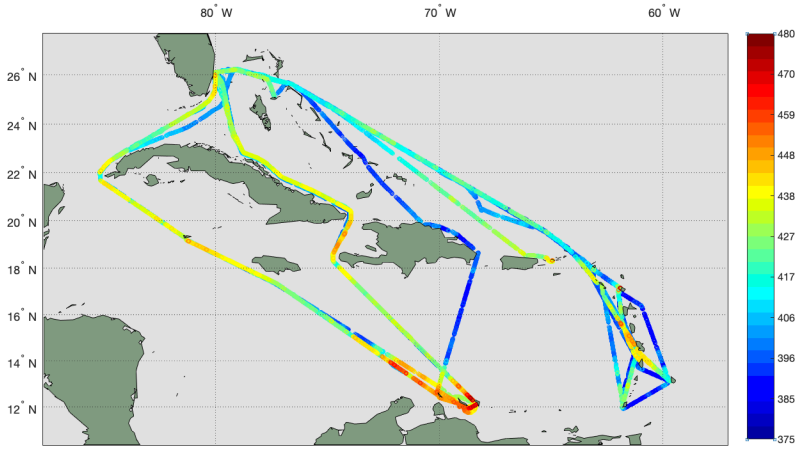

Figure 2. MV Equinox cruise tracks and surface fCO_2 values for FY 2023.

Causes for non-return: Our collaborators from the University of Miami for this platform as well as for the *Allure of the Seas* and the *Flora*, were finally able to secure a financial commitment from Royal Caribbean International for this fiscal year but they are experiencing a change of personnel and are struggling to fix the issues that a 2-year stop created. The system was restarted in November of 2022 but a hardware failure in the University of Miami system shut it down in May 2023 and we have not been able to restart it since then. We are concentrating our efforts on fixing the issue. In the meantime, we have re-established access to our system via the company's new VPN.

Cruise ship *Allure of the Seas* - AOML lead

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *0*
Number of fCO_2 data points: *0*
% Data return: *0%*

***Description*:** This installation is similar to the one on the *Equinox* and is also led by the University of Miami's Rosenstiel School of Marine, Atmospheric & Earth Science. However, this system does not measure air xCO_2 values. The pCO_2 system is in series with the University of Miami' system which controls the seawater intake and provides the SST and SSS measurements. All of the instruments' computers are linked together and to the outside via a Virtual Private Network (VPN) interface, which gives us remote access so we can optimize the operations of the instrument and to access data on a daily basis. The data is automatically downloaded daily via FTP to a server at the University of Miami. It is then plotted on our website in near real-time (http://www.aoml.noaa.gov/ocd/ocdweb/allure/allure_introduction.html).

Causes for non-return: Operations have not been restarted in FY2023. See the Equinox for more details. Once the Equinox is restarted, the Allure will be next. By then, its home port will probably be Miami again, which will greatly facilitate the maintenance.

Cruise ship *Flora* - AOML lead

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *0*
Number of fCO_2 data points: *0*
% Data return: *0%*

***Description*:** This installation is similar to the one on the *Equinox* and the *Allure of the Seas* and is also led by the University of Miami's Rosenstiel School of Marine, Atmospheric & Earth Science. The installation was performed in the Netherlands where the first voyage started in May of 2019. The ship sailed through the Panama Canal to reach the Galapagos where it has been doing weekly cruises among the various islands or the archipelago. The pCO_2 system is in series with the University of Miami' system which controls the seawater intake and provides the SST and SSS measurements. All of the instruments' computers are linked together and to the outside via a Virtual Private Network (VPN) interface, which gives us remote access so we can optimize the operations of the instrument and to access data on a daily basis. The data is automatically downloaded daily via FTP to a server at the University of Miami. It is then plotted on our website in near real-time (https://www.aoml.noaa.gov/ocd/ocdweb/flora/flora_introduction.html).

Causes for non-return: Operations have not been restarted in FY2023. See the Equinox for more details. Our collaborators from the University of Miami have recently visited the vessel and were able to restart the temperature and salinity measurements. Unfortunately, they were not able to make the pCO_2 drain pump work. The LICOR 840 in the system is also malfunctioning and will have to be replaced before we can restart the system. We are counting on the engineers onboard to help with both tasks and we have good hope that we can restart the pCO_2 data collection without having to visit the vessel.

***NOAA* ship *Gordon Gunter* - AOML lead**

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *7*
Number of fCO_2 data points: *37,367*
% Data return: *74.3%*

Description: This system was installed on the *Gordon Gunter* for our Northern Gulf of Mexico Institute (NGI) collaborative project and has been collecting data since March of 2008. This project ended in 2010 and we are continuing to maintain the operation under the auspices of the GOMO and OAP funded programs. The system is performing well, being attended continuously by a field operations officer on board. It is interfaced with the ship's computer system (SCS) and takes advantage of the array of sensors being recorded by the ship. The data is automatically being transmitted daily via email, reproducing the setup that was done for the NOAA ship *Ronald Brown* (see above). The data is plotted daily on the near real-time display of our website (http://www.aoml.noaa.gov/ocd/ocdweb/gunter/gunter_realtime.html). The ship has now a high-accuracy sea surface temperature probe close to the seawater intake, which greatly improves the accuracy of our fCO_2 measurements reported at sea surface temperature.

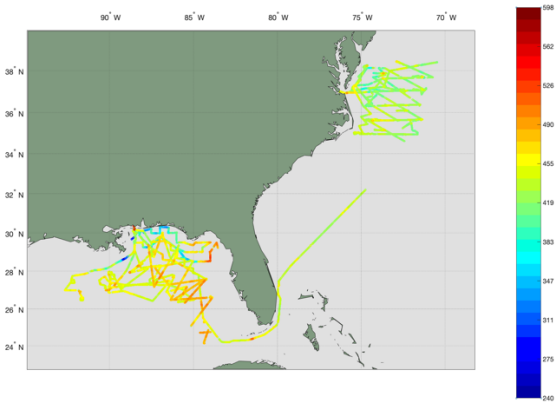

Figure 3. NOAA ship Gordon Gunter cruise tracks and surface fCO_2 values for FY 2023.

***Causes for non-return*:** The *Gunter* had a few mechanical issues coming out of dry dock and the uncertainty it created in its schedule, along with our lack of personnel to keep track impacted the reliability of the system and the quality of our data. We were still able to get a reasonable data return in FY23. Next fiscal year, the Gunter is scheduled to do the Pirata Northeast Extension (PNE) cruise (around 100 DAS in total) and we will make sure that the system is fully operational.

***NOAA* ship *Henry B. Bigelow* - AOML lead**

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *9*
Number of fCO_2 data points: *56,979*
% Data return: *96.7%*

Description: The NOAA ship *R/V Henry B. Bigelow* is a new generation Fisheries survey vessel based in Newport, RI and operating primarily in coastal U.S. waters from Maine to North Carolina. The region includes Georges Bank, one of the world's best known and most productive marine areas. The installation was completed in February of 2011 and the system has been operating very well, due in part to the great collaboration with the crew and the survey technician on board. We are also collaborating with the NOAA fisheries in Narragansett, RI with funding from the NOAA Ocean acidification program to have the ship visited regularly to perform maintenance when necessary. The system is connected to the Ship's Computer System (SCS) and collects co-located data from the sensors installed on board. The data is automatically emailed on a daily routine and displayed on our website for troubleshooting purposes. This installation also includes dissolved oxygen sensor from Aanderaa and a Submersible Ultraviolet Nitrate Analyzer (SUNA) from Satlantic.

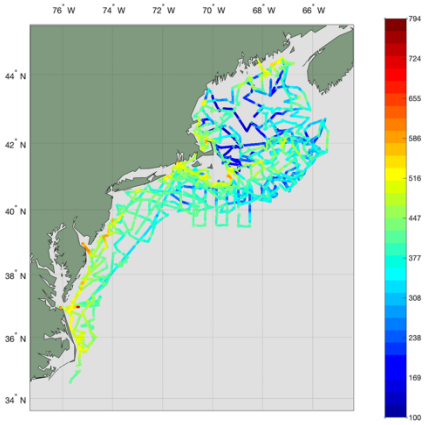

Figure 4. NOAA ship Henry Bigelow cruise tracks and surface fCO_2 values for FY 2023.

***Causes for non-return*:** The system performed very well this fiscal year. The issue we had with the sea surface temperature sensor which, although it seems to be correctly installed, used to record temperatures which did not align well with the other temperature sensors on the ship, is still present but to a lesser extent. We are still in the process of troubleshooting that issue.

***M/V Le Commandant Charcot* - AOML lead**

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *23*
Number of fCO_2 data points: *~140,000*
% Data return: *~90%*

Description: *The M/V Le Commandant Charcot* is an icebreaking cruise ship operated by the French operator: La Compagnie du Ponant. It is a Polar Class 2 rated icebreaking vessel capable of reaching remote polar destinations such as the Geographic North Pole. She features a hybrid power plant powered by liquefied natural gas (LNG) and 5 MWh electric batteries, capable of briefly driving the ship without engines running.
Le Commandant Charcot is a unique cruise expedition vessel designed for extreme polar conditions that give the rare opportunity to 270 passengers to explore remote polar areas. Since the beginning of the project, Ponant has designed the vessel as a "Ship of Opportunity" for the scientific community. It has a dedicated infrastructure for making measurements, experiments and has autonomous data acquisition available for researchers. The Ponant Science Program has a dedicated science coordinator onboard for the maintenance and operation of the different instruments.
In April of 2022, in collaboration with Ponant and Dr. Nicolas Cassar of Duke University in Durham, NC, our group installed an autonomous instrument on this vessel to measure pCO_2 in the surface water and the overlaying atmosphere above it. The unique geographic areas that the ship will visit are rarely sampled and will provide a unique data set that will further our understanding of the carbonate system in high latitude regions
In addition to the GO pCO_2 system, a Ferrybox (https://eurogoos.eu/ferrybox-task-team/) is also installed in the same space and on the same seawater line. That Ferrybox controls the flow of seawater through the SBE45 sensor which provides our salinity data. It also has an Aanderaa optode incorporated and we should have access to that data.

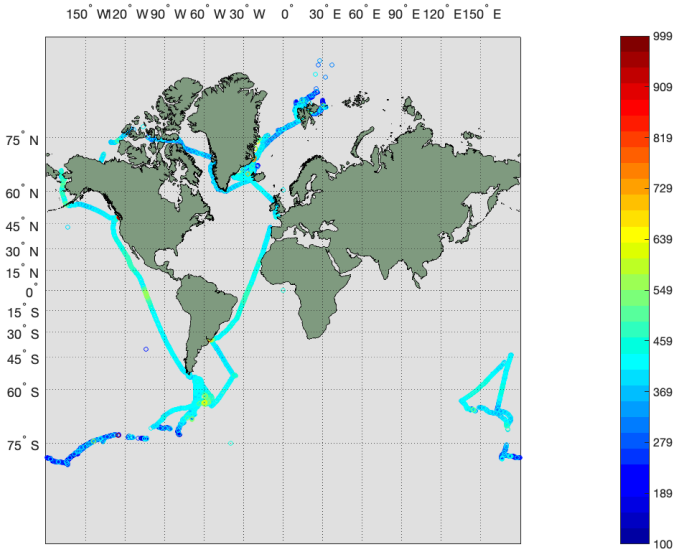

Figure 5. MV Le Commandant Charcot cruise tracks and surface xCO_2 values for FY 2023.

***Causes for non-return*:** The system has been performing very well since the beginning of the installation. Unfortunately, the ship turns off the seawater when the ship is in the ice as the ice tends to clog the lines. The vessel recognized that this is a problem and has talked to engineers about it. As far as we know, they will try to resolve it at the next dry dock period sometime in the near future. We also still have to resolve an issue of the equilibrator pressure measurements which is the reason why we have not submitted our data to SOCAT yet. To resolve the issue, we have to confirm the pressure difference between the lab where the instrument is and the outside pressure. We built a kit to do so and we are collecting the data now. Once we have that data, we will be able to back calculate the equilibrator pressure from the offset with the outside pressure and the data will be submitted.

***M/V* National Geographic *Islander II* - AOML lead (new installation during FY2023)**

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *1*
Number of fCO_2 data points: *~2,000*
% Data return: *95%*

Description: In August of 2023, in collaboration with Dr. Nicolas Cassar of Duke University, our group installed one of our autonomous instruments on this vessel to measure pCO_2 in the surface water. An air line was also installed to measure the overlaying atmosphere above it. In addition, the system incorporates an Aanderaa Optode which measures dissolved oxygen. The region is extremely biologically active and we expect our data to reflect that. With additional carbonate parameters measurements, it will also give us an indication of the vulnerability of the region to ocean acidification. The system was first installed in December 2022 but was not fully operational until end of August 2023. We have very good support from the onboard engineers who are overseeing the system. The vessel owners were keen on being able to display the instrument which is located in a space open to the passengers. We are working on a way to visually display the program and our data on the screens of the ship for the passengers to view.

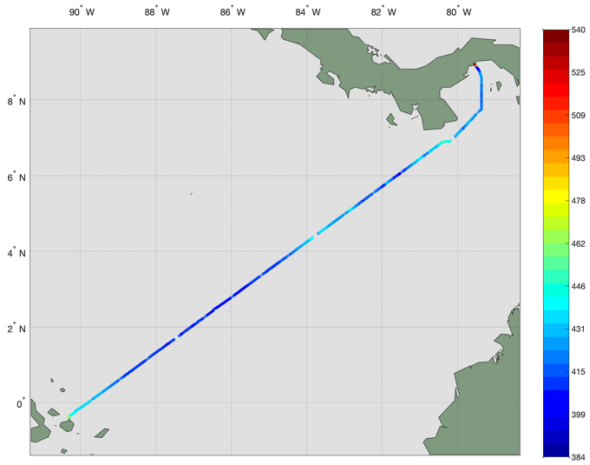

Figure 6. MV Islander II cruise tracks and surface xCO_2 values for FY 2023.

Causes for non-return: The installation was only fully completed in August of 2023, 8 months after the instrument was mounted. The tubing to connect the standard gases had disappeared from the shipment. Then the LICOR (model 840) suffered a malfunction and had to be replaced. Getting supplies to the Galapagos, although facilitated by the cruise line, is slow, which delayed the start of the data collection. A few days after the system was started, the vessel went into drydock for the rest of the fiscal year so we were only able to collect data on the way to the dry dock. We expect a good data return next fiscal year.

R/V *Thomas G. Thompson* - PMEL lead

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises: *5*
Number of fCO_2 data points: 23,397
% Data return: *TBD*
Days at sea w/instrument running: 62

Description: In FY2019, PMEL successfully installed an underway fCO_2 system on the R/V *Thomas G. Thompson* in support of the I06 Repeat Hydrography cruise. The *TGT* underway system continues to operate, collecting fCO_2, pH, and O_2 data across multiple ocean basins, with FY2023 having data collection in coastal and open ocean environments of the equatorial and south Pacific Ocean (Figure 7). We note, however, that the pH and O_2 sensors were provided by NOAA's Ocean Acidification Program, and they have chosen to descope all non-coastal pH and O_2 measurements. Thus, when these sensors next require repair, they will be permanently removed from the *TGT*. All data collected on the *Thompson* during FY23 are in the final processing stage and will be submitted to NCEI for archiving, to SOCAT prior to the January 2023 deadline, with metadata posted to the PMEL CO_2 website.

Causes for non-return: Additional cruises had data collected that were not of acceptable quality for submission, because the system encountered gas flow and other technical issues but was not within geographic range where our team could repair the system.

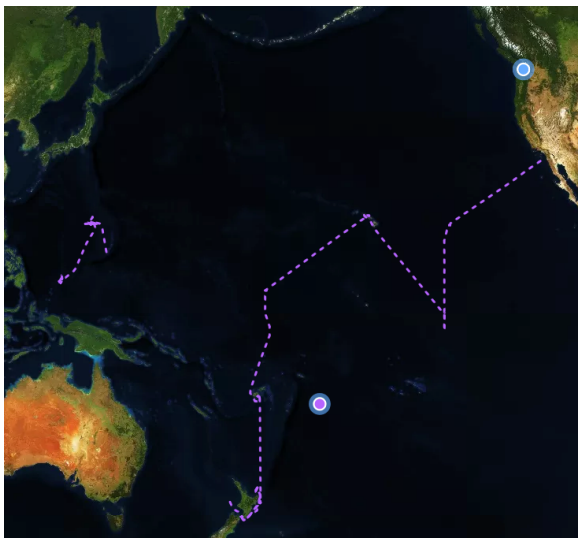

Figure 7. Tracklines for FY2023 fCO_{2sw} (µatm) measurements collected from the R/V Thomas G. Thompson that will be submitted in advance of the January SOCAT submission deadline (map from https://www.ocean.washington.edu/dataSet/ships).

R/V *Roger Revelle* - PMEL lead (temporary)

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises: *1*
Number of fCO_2 data points: 25,477
% Data return: *99%*

Description: A few years ago, Scripps Institution of Oceanography installed an underway fCO_2 system on the R/V *Roger Revelle* in support of research cruises happening on that platform. This underway system does not presently have personnel to conduct regular maintenance and data processing. PMEL does not have a long-term role in the maintenance of this system or the processing of the resulting data, but we have voluntarily collaborated with SIO to ensure data from important regions were finalized and submitted to SOCAT and NCEI in the last two years. During FY2023, the PMEL underway team had lead responsibility for maintaining the *Revelle* underway fCO_2 system for GO-SHIP cruise I05 during July–September 2023. Underway data collected on the *Revelle* during I05 (July 22–September 13, 2023) have been processed (*Figure 8*) and will be submitted to NCEI for archiving, to SOCAT, and posted to the PMEL CO_2 website by the SOCAT submission deadline in January 2024.

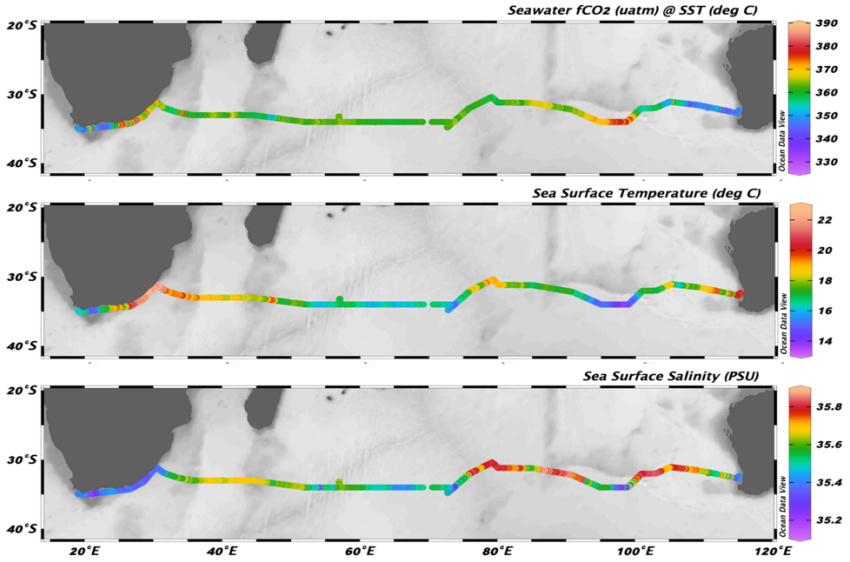

Figure 8. Finalized underway fCO_2, sea surface temperature, and sea surface salinity data from GO-SHIP cruise I05

R/V *Bluefin* - PMEL lead

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises: *0*
Number of fCO_2 data points: *0*
% Data return: *0%*

Description: In FY2017, PMEL successfully installed an underway fCO_2 system on the R/V *Bluefin* and collected fCO_2 measurements to continue a four-decade-long time-series of fCO_2 measurements in the equatorial Pacific on ships servicing the TAO buoy array. During a typical year, the *Bluefin* typically circumnavigates the North Pacific, collecting fCO_2 measurements from coastal to open-ocean and from temperate-high latitudes to pan-equatorial Pacific environments. With 75,750 data points returned from the field to date, the *Bluefin* system had excellent data return of 98% in FY2021. Unfortunately, we were asked to remove the underway fCO_2 system from the *Bluefin* for their extensive drydock repairs during late 2021–early 2022. At the end of the repairs and inspection phases, the ship was not able to provide us a suitable installation location and safe working conditions to re-install the system. We were given a much more appropriate installation location at the end of 2022, however the ship did not remain in port long enough to facilitate a complete reinstallation. Further opportunities to visit the ship to complete the installation prior to its equatorial Pacific mooring array work unfortunately conflicted with the timing when we needed to send staff to GO-SHIP I05 and to visit the *Tysla*. That said, the installation is of high quality and should be back in operation during 2024. We have also recently been informed by the ship's owner that he has another vessel (R/V *Nemo*) that will likely service the equatorial Pacific mooring array in future years, making it a desirable expansion platform if BIL funding allows for the purchase of additional new GO8060 systems and LICOR 7815s.

Causes for non-return: Not being able to re-install the underway fCO_2 system on the *Bluefin*.

M/V *Tysla* - PMEL lead

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
(will be featured on the PMEL metadata portal once data have been finalized and submitted)
Number of cruises: *5*
Number of fCO_2 data points: *>21,000*
% Data return: *~50%*
Days at sea w/instrument running: 63

Description: We are very excited to report that in FY2023, PMEL was (finally!) able to install a new underway fCO_2 system on the M/V *Tysla.* This follows several years of difficulty identifying a commercial platform that was likely to remain on the same shipping line over a long enough period to justify the large amount of work involved in installing it. Through a partnership cultivated by Julian Herndon (PMEL/CICOES technical staff) with Science RoCS at WHOI, we have worked with the engineers and port staff of Wallenius Wilhelmsen, a global car carrier company, to install a new General Oceanics 8060 pCO_2 system, which is the first of the next-generation GO systems we have installed for underway measurements (*Figure 9*).

A few great aspects of this new partnership are that the company is enthused to work with us, and may represent an opportunity for expansion as we seek to expand SOCONET. This translates to the engineering staff on board having willingness to operate the system even when we cannot send a rider. Unlike previous platforms we have used for the equatorial Pacific crossings, the ship transits among ports in the Pacific and Atlantic in a figure-eight pattern (a schematic map of their global network is in **(***Figure 9*, right), representing an opportunity for closer collaboration between AOML and PMEL staff in visiting the ship, depending on port location. The flip side of the expanded observational coverage this ship provides is that we are still adjusting to being able to visit the ship in more far-flung ports of call than usual when the instrumentation requires attention.

The new GO system operates with a LICOR 7815, which uses OF-CEAS (Optical Feedback – Cavity Enhanced Absorption Spectroscopy) rather than infrared gas absorption to measure CO_2. According to LICOR, this system is expected to "provide a wider measurement range and low drift characteristics" compared to the LI-7000s that we used previously. However, because we are still adjusting our workflow to handle data from the new system, and we recently lost a critical staff member (during data processing season), we have not yet finalized the 2023 data from this new platform (*Table 2*). That said, we collected ~63 days of underway data at sea, of which about half looked good (QC=2) preliminarily, and the other half require added attention to determine whether the data are salvageable (preliminary QC=3, due to an equilibrator temperature sensor that ceased to function; see table below).

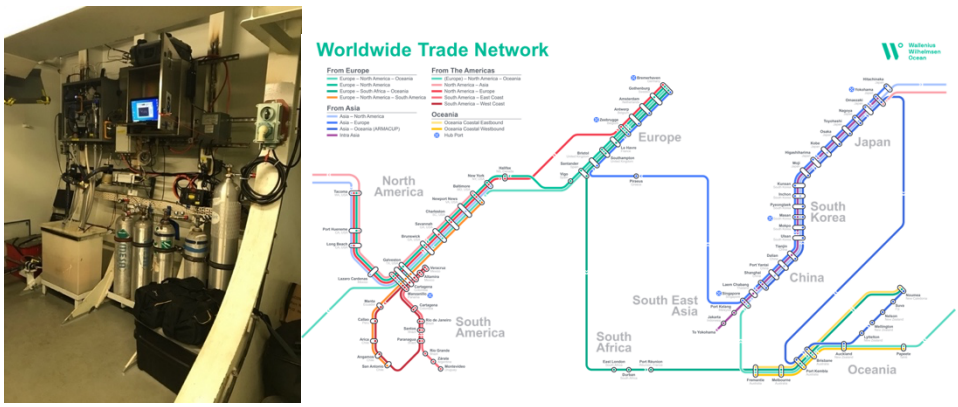

Figure 9. Picture of the pCO_2 system installation on the M/V *Tysla (left) and the Wallenius Wilhelmsen global car carrier port network (right)*

Table 2 Preliminary results from new PMEL equatorial Pacific flagship platform, Wallenius Wilhelmsen's M/V Tysla.

Leg (cruise)	Dates (2023)	Days of data collection	Preliminary data quality	Operator	Region
TY2301	04/23-05/13	16	Good	PMEL Herndon	Pacific Eq crossing (Panama to NZ)
TY2302	09/16-09/17	2	Good	Tysla Engineer	US East Coast
TY2303	09/20-09/26	7	Good	Tysla Engineer	Caribbean, between US and Panama
TY2305	10/02-10/27	28	4-5 day Good and 21-22 days questionable (no EQU temp)	Tysla Engineer	Pacific transit between Panama and Japan
TY2306	11/3-11/12	10	Questionable (no EQU temp)	Tysla Engineer	Pacific transit between Japan and Tacoma, WA

The *Tysla* installation is our new "flagship" underway fCO_2 platform that we will focus on to continue the four-decade-long time-series of fCO_2 measurements in the equatorial Pacific. In future years, we hope to get 3–4 good quality equatorial Pacific crossings annually, with the added bonus of observations from the north Pacific and north Atlantic as well.

Causes for non-return: Equilibrator temperature sensor malfunction caused about half of the preliminary data to be of questionable quality. It's not clear why the equilibrator temperature may have failed so soon after deploying this brand new system, but this particular system is one of the first built by GO of this model, and early units of any new technology can experience such challenges. We will evaluate whether the data are recoverable and submit any data that can be finalized with acceptable quality.

***RVIB N. B. Palmer* - GML Lead:**

Data Site: https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/VOS_Program/palmer.html
Number of cruises: *3*
Number of pCO_2 data points: *~24,400*
% Data return: *99.0%*

Description: The RVIB Nathaniel B. Palmer is one of two United States Antarctic Program (USAP) research ships that operate primarily in the high latitude Southern Hemisphere oceans. Both research ships host pCO_2 systems maintained by the TTEA group at GML. During FY23, approximately 24,400 pCO_2 measurements were obtained from three research cruises, slightly less than the total obtained during FY22. The FY23 total includes a rough estimate from cruise NBP2302 which is currently being reprocessed. Measurements from FY22 not including those collected during NBP2302 are shown in *Figure 10*. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

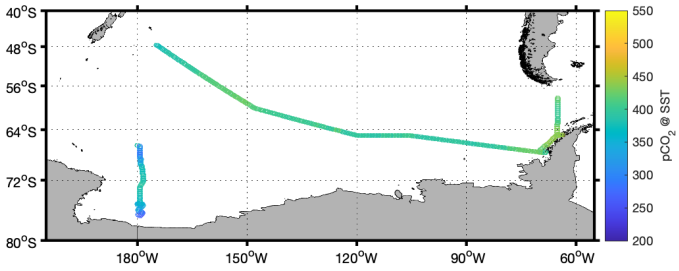

Figure 10. The locations and values of surface water pCO_2 measurements (in µatm) made from the RVIB Palmer during FY23 (data points shown are from one of two of three cruises, including NBP2301 and NBP2304. Data from NBP2302 is not included in this map but an estimate of the number of measurements from this cruise is included in the total reported in Table 1).

Causes for non-return: so far, nearly all data passed QC during F023 for cruises NBP2301 and NBP2304 as indicated by the high rate of return in Table 1. Data from NBP2302 is not included in this assessment.

***ASRV L. M. Gould* – GML Lead:**

Data Site: https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/VOS_Program/LM_gould.html
Number of cruises: *6*
Number of fCO_2 data points: *~29,900*
Data return: *95.0%.*

Description: Observations from the ARSV Laurence M. Gould are collected mainly across the Drake Passage and along the West Antarctic Peninsula (*Figure* 11). In addition to the surface water pCO_2 system, discrete measurements of total CO_2 and macronutrients are collected across the Drake Passage on up to five crossings per year. Data from two of six cruises is currently being reprocessed. However, the number of observations made during FY23 was more than twice that made during FY22 representing a substantial improvement from recent COVID-19-affected years. Christine Smith of GML participated in cruise LMG2303 from Punta Arenas to Palmer Station and back and performed several maintenance tasks on the pCO_2 system. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

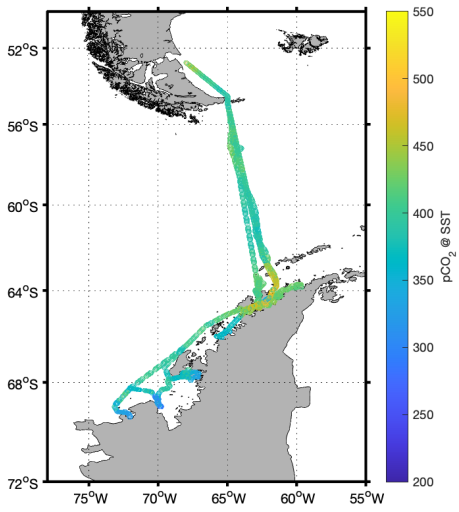

Figure 11. *The locations and values of surface water pCO_2 measurements (in µatm) made from the ARSV Gould during FY23 including cruises LMG2311, LMG2303, LMG2305, and LMG2306; cruises LMG2213 and LMG 2301 are not included in this map.*

Causes for non-return: data for cruises LMG2213 and LMG2301 are currently being reprocessed but non-return was greater than in past years due in part to USAP technician turnover related to COVID-19 disruptions. Several technicians were unfamiliar with the pCO_2 system prior to sailing. Additionally, a leak in the supply of nitrogen to the system was responsible for lost data on LMG2303 and possibly other cruises. Non-return was generally greater in late 2022 and early 2023 and improved in the last half of the field season.

***USCGC Healy* - GML Lead:**

Data Site: https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/VOS_Program/CGC_Healy.html
Number of cruises: *4*
Number of fCO_2 data points: *26,346*
Data return: *99.9%*

Description: The USCGC Healy operates primarily in the Gulf of Alaska, Bering Sea and Arctic Ocean. For the past several years, a semi-permanent system for continuous high precision atmospheric measurements of CO_2 and CH_4 has operated in a forward storeroom. This system is necessary since an atmospheric line cannot be run to the seawater pCO_2 system which is located in an interior corridor adjacent to the engine room. In total, 26,346 pCO_2 measurements were obtained during FY23 similar to the previous year. Locations of FY23 observations are shown in *Figure 12*. Both the 2022 and 2023 field seasons have included sampling throughout the Arctic Ocean including near the North Pole. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

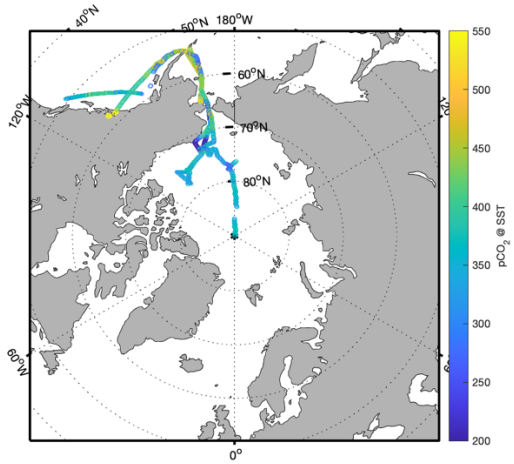

Figure 12. The locations and values of surface water pCO_2 measurements (in µatm) made from the USCGC Healy during FY2023.

Causes for non-return: nearly all data passed QC during FY2023 as indicated by the high rate of return in *Table 1*. However, the time lag between the seawater intake and measurements from the pCO_2 system has consistently been around fifteen minutes which is several times the lag of other SOOP ships. This lag, determined by comparison of data from temperature sensors, is associated with an observed warming around a half a degree Celsius from the seawater intake to the equilibrator at near freezing sea surface temperatures which is similar to the warming observed on the R/V Sikuliaq despite a shorter lag time on that ship. This warming is nearly twice that

***R/V Sikuliaq* – GML Lead:**

Data Site: https://www.ncei.noaa.gov/access/ocean-carbon-acidification-data-system/oceans/VOS_Program/CGC_Healy.html
Number of cruises: *15*
Number of pCO_2 data points: *78,884*
Data return: *99.7%*

Description: The R/V Sikuliaq, like the USCGC Healy, operates primarily in the Gulf of Alaska, Bering Sea, and Arctic Ocean. A total of *78,884* pCO_2 measurements were made during FY23 which is significantly more than the number of measurements collected during FY22. In February of 2023, a SUNAv2 for the continuous measurement of surface nitrate was installed with the assistance of University of Alaska technicians. A plan for calibration of the SUNAv2 was developed and implemented. The instrument experienced a lamp failure in June of 2023 and was sent back to Seabird for repairs covered under warranty. Additional underway systems also include a Sunburst AFT-pH system and a semi-permanent system for continuous high precision atmospheric measurements of CO_2 and CH_4 installed in a forward storeroom similar to the USCGC Healy. David Munro participated in a cruise from Seattle, WA to Newport, OR in February of 2023 and Amanda Fay participated in a cruise from Seattle, WA to Seward, AK in April of 2023 to collect discrete samples for validation of the SUNAv2 and AFT-pH systems. Quality-controlled pCO_2 data are submitted to SOCAT and archived at NCEI OCADS for public access.

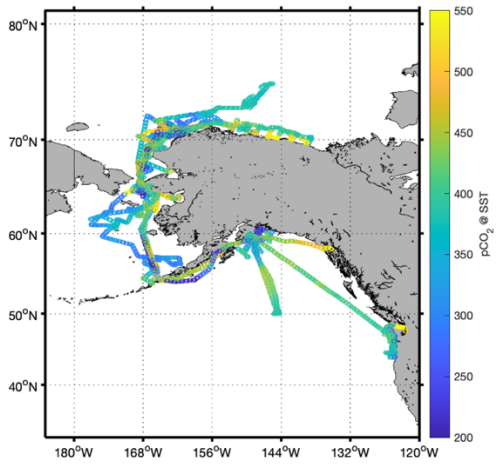

Figure 13. The locations and values of surface water pCO_2 measurements (in µatm) made from the R/V Sikuliaq during FY2023.

Causes for non-return: nearly all data passed QC during FY23 as indicated by the high rate of return in Table 1.

R/V *Atlantic Explorer* - BIOS lead

Data Site: **http://www.bios.edu/Labs/co2lab/vos.html**
Number of cruises: *32*
Number of fCO_2 data points: *~24,000*
% Data return: *95.0%*

***Description*:** The R/V *Atlantic Explorer* operates in the North Atlantic Ocean servicing three oceanographic time-series (i.e., Bermuda Atlantic Time-series Study, BATS, Hydrostation S, and Ocean Flux Program), research projects such as BIOS-SCOPE (Simons Foundation International) and an NSF Science and Technology Center (Chemical Currencies for a Microbial Planet, C-CoMP), and other research projects conducted on the ship.

The geographic focus of data collection is primarily zone NA06, but includes several transects between Bermuda and Puerto Rico (across an infrequently sampled part of the permanently stratified oligotrophic gyre of the North Atlantic) and Bermuda and Norfolk, Virginia. This data stream provides ground truthing pCO_2 datasets for the subtropical gyre of the North Atlantic Ocean. The R/V *Atlantic Explorer* typically has ~135-170 ship days per year with most work undertaken in the North Atlantic Ocean in zone NA06. However, this also includes transects between Bermuda and Puerto Rico, and repositioning/shipyard visits resulting in transects between Bermuda and the US eastern seaboard.

In 2023, we collected data during a suite of research cruises from a total of 240 sea days. These cruises include visits to BATS and Hydrostation S sites off Bermuda, as well as transects between Bermuda, Puerto Rico, the US Eastern Seaboard, and the Gulf of Mexico.

A General Oceanics pCO_2 system (~$75,000) and LiCOR (~$20,000) for the R/V *Atlantic Explorer* was purchased as part of the BATS NSF award, and is a cost-in-kind contribution to the NOAA pCO_2 network of approximately ~$100,000. In addition, we have purchased two Contros hydro-fias (alkalinity and pH) for an additional ~$80,000 contribution to the GOMO project funded by other projects. In addition to the pCO_2 data stream, we have installed our dissolved oxygen (DO) optode and SAMI pH systems. We have recently undertaken side-by-side comparisons of our Contros hydro-fia alkalinity and pH systems in the Arctic and installed them on the R/V *Atlantic Explorer*. We will be merging TSG and navigation data along with the underway GO pCO_2 data, and hydro-fia alkalinity and pH data in early 2024.
Notable activities and maintenance performed in 2023 included:

1. The relocation of CO_2-in-air standards inside the aft laboratory.
2. Replacement of the chiller.
3. Maintenance on the flow meter, involving the removal and cleaning of the impeller.
4. Replacement or swapping out of the LICOR and Hart thermometer.

The General Oceanics pCO_2 system (GO-8050 #196) is checked after every cruise, has required minor adjustments, and very few issues as of yet. It has new software and data architecture that allows remote intervention and monitoring from BIOS and AOML. Minor issues have been addressed promptly with routine maintenance on the ship systems while it is at the BIOS dock in St. Georges, Bermuda. The ease of maintenance, repairs and replacements, and

testing of other underway sensors alongside the pCO_2 system is a great benefit of BIOS laboratories and workshops being less than 50 m distance from the dock and ship. Research specialists Matt Enright and Becky Garley routinely join BATS cruise allowing at sea maintenance and checks of the pCO_2 system.

We are currently in the process of completing QA/QC for the 2023 data with the target of submitting to SOCAT for the mid-January 2024 deadline. Matt Enright has received high useful pCO_2 system and data processing training with Denis Pierrot and Kevin Sullivan. All of the 2022 R/V *Atlantic Explorer* pCO_2 system data was submitted to SOCAT in January 2023, available to the public, and a contribution to the 2023 Global Carbon Budget paper (Friedlingstein et al., 2023; published 8th December 2023). All of the R/V *Atlantic Explorer* pCO_2 system data prior to 2023 is freely available at SOCAT as other GOMO ship underway data. Data submitted to SOCAT for 2022 is shown on Figure 14.

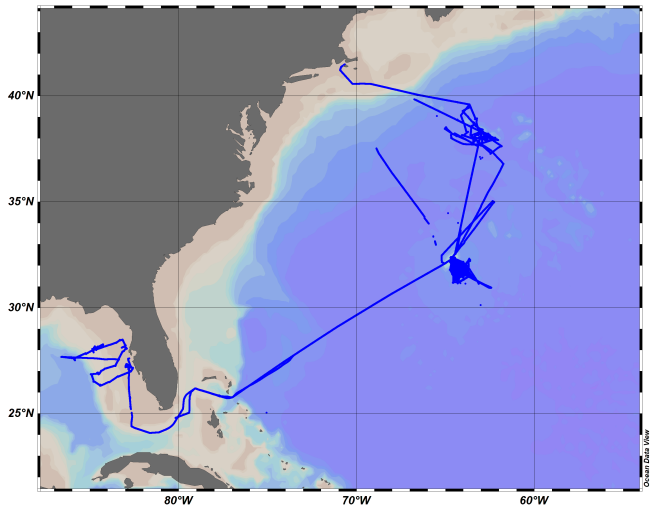

Figure 14. *Seawater pCO_2 data from the R/V Atlantic Explorer in SOCAT for FY2023.*

***Causes for non-return*:** In 2023, up to the end of November, a total of ~24,000 pCO_2 measurements have been collected from 32 cruises. Initial QC has been undertaken at BIOS with an approximate ~95% good data recovery. The non-return rates typically represent data that were flagged mainly due to problems with low seawater flow rates from the underway system.

Container Ship *MV Oleander* - BIOS lead

Data Site:
http://www.bios.edu/Labs/co2lab/vos.html
Number of cruises: *Error! Reference source not found.*
Number of fCO_2 data points: *Error! Reference source not found.*
% Data return: *Error! Reference source not found.*

***Description*:** The MV *Oleander* crosses weekly between New Jersey and Hamilton, Bermuda. Given the ~100 crossings a year, this gives excellent temporal and spatial coverage of the North Atlantic subtropical gyre, Gulf Stream, Middle Atlantic Bight and coastal zone. The MV *Oleander* transits the region of Subtropical Mode Water (STMW) formation during the winter southeast of the Gulf Stream, and the highly productive coastal zone of the US Eastern Seaboard.

The new *Oleander* was launched in early October 2018 (photograph above) with final fitting of the ship, with service to Bermuda beginning in late 2019. In a collaboration between AOML and BIOS, a General Oceanics pCO_2 system from NOAA has been installed on the *Oleander* in 2023 during New Jersey shipyard visits. Exciting progress has been made with the Oleander. The sea cock valve was successfully installed at the end of August, and the pCO_2 system, shipped to Charlie Flagg in New York, began installation in mid-September with the great help of Denis Pierrot. Although there have been some initial challenges with system components like the Equ pump and pump priming, the plumbing is now functional. The standards are in place and have undergone leak testing. Once the atmospheric line and Deck box are installed during the shipyard session in January 2024, we'll be ready to test the system for data collection. In addition to the pCO_2 data stream, we anticipate installing our dissolved oxygen (DO) optode and SAMI pH systems, and a possible Contros alkalinity system installation in mid-2024 (funding dependent). The pCO_2 system has new software and data architecture that will allow remote intervention and monitoring from BIOS and AOML.

***Causes for non-return*:** We will resume data collection on transects between Bermuda and New Jersey in early 2024. As outlined for the R/V *Atlantic Explorer*, we anticipate that the new software and data architecture will allow for easier merging and integration of data into the SOOP database.

The major issue has been the sea cock valve which needs to be replaced with not only the pCO_2 observations impacted but also the TSG and other underway measurements. Any through hull maintenance requires surveyors and certification for which we are awaiting inspection. Research Specialist Matt Enright will be joining the ship (with others including Charlie Flagg) in the shipyard visit in Spain in January 2024 to complete the installation of water lines servicing the pCO^2 system, and complementary TSG, ADCP and other sensor systems installed on the ship.

***R/V F.G. Walton Smith*- Rosenstiel lead**

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *15*
Number of fCO_2 data points: *37,295*
% Data return: *90.0%*

Description: The *R/V Walton Smith* is a shallow draft catamaran, which is based at the University of Miami. As a University-National Oceanographic Laboratory System (UNOLS) vessel, its destinations vary, but range from the Florida Keys, Florida Bay to the Caribbean, the Gulf of Mexico and occasionally the east coast. In a typical year, the ship spends about 200 days at sea. It has the capability of routinely measuring sea surface temperature and salinity. A pCO_2 system has been installed onboard the *Walton Smith* since the beginning of July 2008. The installation is a close collaboration with AOML for system maintenance, data retrieval, reduction and archiving. The data collected by the pCO_2 system is transmitted from the ship via FTP using the program developed by AOML's TSG group and the ship's permanent internet connection. The data is not available in real time due to processing requirements. The delayed mode data is made publicly available when submitted to NCEI and submitted for inclusion in SOCAT. The data is archived annually.

Figure 15. fCO_2 values along the tracks of the R/V Walton Smith for fiscal year 2023.

Causes for non-return: This fiscal year, the pCO_2 system has functioned well and shows a good return with no major technical issues. The Walton Smith has been sailing regularly this fiscal year.

TSG Operation – AOML/SOOP Lead

During FY2023 NOAA/AOML continued the thermosalinograph (TSG) operation, a component of its Ship Of Opportunity Program (SOOP), in support of the pCO_2 operations. During this period, NOAA/AOML received, processed and distributed TSG data from 12 ships of the NOAA fleet (*RV Bell M. Shimada, RV Fairweather, RV Gordon Gunter, RV Henry Bigelow, RV Okeanos Explorer, RV Oregon II, RV Oscar Dyson, RV Oscar Elton Sette, RV Pisces, RV Reuben Lasker, RV Ronald H. Brown, RV Thomas Jefferson*), including 3 (*RV Henry Bigelow, RV Ronald Brown, and RV Gordon Gunter*) with operational pCO_2 systems. Although the new *MV Oleander* was delivered before the pandemic, because of the interruption of the pandemic and errors made by the shipyard, the observing systems (including TSG component) are not fully online yet. It is expected that all systems will be operational in early 2024. From the ships of the NOAA fleet collecting TSG data during FY2023, 25% also collected pCO_2 observations.

More than 1 million TSG records from ships of the NOAA fleet (corresponding to approximately 345,000 records with 3 minute temporal resolution) were processed at NOAA/AOML during FY2023 (*Figure 16*), and distributed through several data centers including NOAA's National Centers for Environmental Information (NCEI) and Global Ocean Surface Underway Data (GOSUD).

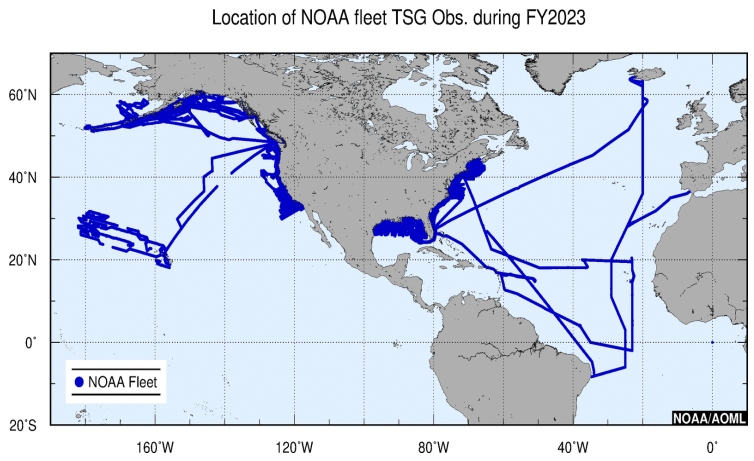

Figure 16. Location of approximately 345,000 TSG observations (3-min. resolution) received and processed by NOAA/AOML during FY2023 from 12 ships of the NOAA fleet.

NOAA/AOML continues the partnership with the University of Miami's Rosenstiel School of Marine, Atmospheric and Earth Science (RSMAES), to collect TSG observations from two Royal Caribbean cruise ships *Allure of the Seas* and *Equinox*. As part of this partnership NOAA/AOML provides the TSG instruments, equipment calibration, as well as data processing and distribution, while RSMAES scientists conduct the installation and operation of the system. These two ships also have pCO_2 systems installed. Similar partnership also continues for the

collection of TSG observations from Celebrity's ship *Flora*, also operated by the University of Miami / RSMAES. *Flora* travels in the region of the Galapagos islands off the coast of Ecuador, collecting observations in one of the most delicate ecosystems in the world. Data collection from those ships has been interrupted because of the pandemic, but Royal Caribbean cruise ship *Equinox* has been collecting data until May 2023 when the computer failure occurred. Data collection from *Flora* is expected to start in November 2023. However, data distribution from these ships was affected during FY2023 due to difficulties to access the ships for maintenance.

During FY2023 NOAA/AOML continued its long-standing partnership with the University of Rhode Island, Stony Brook University and the Bermuda Institute for Ocean Sciences, in support of the operations in the *MV Oleander* covering the route between New Jersey and Bermuda. Operations onboard *MV Oleander* started in 1981 with the collection of eXpendable BathyThermograph (XBT) and Continuous Plankton Recorder (CPR) observations, and since then extended to include Acoustic Doppler Profiler (ADCP), TSG and pCO_2. In particular TSG observations have been collected on *MV Oleander* since 2001, providing an important data-set in an area of intense ocean variability as the ship crosses the Gulf Stream. While in collaboration with our partners, we are able to keep the XBT system running without much interruption, because of the pandemic and the retirement of old *MV Oleander*, the TSG system has yet to be operational on the new *Oleander*.

TSG data received from ships of the NOAA fleet are mostly located in coastal regions of the U.S., with several cruises covering larger regions of the North Atlantic and North Pacific, and with a large number of observations collected at high latitudes. These data are very important for coastal studies, current frontal variability analysis, pCO_2 ocean inventory, and for calibration of satellite observations.

All the TSG data received at NOAA/AOML are quality controlled through several steps based on the GOSUD (Global Ocean Surface Underway Data Pilot Project) real-time control tests. Among other parameters, the quality control procedures check the data for errors in date, location, platform identification, ship speed, global and regional temperature and salinity ranges compatibility, gradient and the presence of spikes. The TSG data were also compared with a monthly climatology (Locarnini et al 2006 and Antonov et al 2006). The data approved in the quality control tests is then reduced to one point every three minutes. The whole data set is distributed by NOAA/NCEI (*www.ncei.noaa.gov*) and GOSUD (*www.gosud.org*). NOAA/AOML has contributed to approximately 20% of all global TSG observations in GOSUD since 2000 (*Figure 17*).

Despite some difficulties to travel and ship access that still affected the TSG operations during FY2023, an increase in the number of TSG observations from ships of the NOAA fleet was observed, as a consequence of the increase in the number of cruises and days at sea. Work is underway to reinstate full operation and real-time data distribution from all ships of the SOOP and the NOAA fleet, for which software updates are underway to accommodate for recent changes in data file formats and software updates.

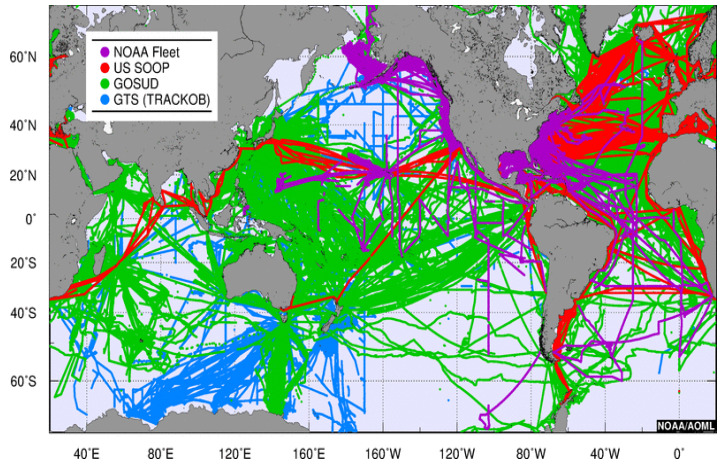

Figure 17. Location of all TSG observations collected globally since 2000, with colors highlighting the contribution of the US-SOOP and NOAA fleet, which account for approximately 20% of all global TSG records in GOSUD.

During FY2023, members of the NOAA/AOML team continued their participation in international panels sponsored by the World Meteorological Organization (WMO) for the coordination of operation and data collection from ships, including TSG and pCO_2 observations. These include Francis Bringas who is co-chair of the Ship Of Opportunity Program Implementation Panel (SOOPIP) and member of the GOSUD Steering Group, and Denis Pierrot who is co-chair of GOSUD.

Surface Ocean CO_2 Observing Network (SOCONET) - AOML lead

In fiscal year 2020, we started implementing an effort to create a reference network for high-quality surface ocean and marine boundary layer CO_2 observations from ships of opportunity and moorings. The societal and scientific imperatives of such a network are described in an Ocean Obs-19 community white paper (Wanninkhof et al., 2019). The need for ocean carbon networks was also articulated in a previous Ocean-Obs conference paper (Monteiro et al., 2010) and in an Integrated Ocean Observing System (IOOS) Summit manuscript (Wanninkhof et al., 2012). The SOCONET initial actions focus on operational improvements and coordination. SOCONET (https://www.aoml.noaa.gov/ocd/gcc/SOCONET/) is currently a loosely knit group that provides data of known high quality and at regular intervals through SOCAT for two main products: surface water CO_2 maps and the global air-sea CO_2 fluxes at monthly resolution and 1˚ by 1˚ grid that will be served annually. In FY2023 the project received increased attention with the initiation of the WMO Global Greenhouse Gas Watch (G3W) and a closely aligned NOAA initiative on Greenhouse gas monitoring. While these effort focus on anthropogenic CO_2 emissions, SOCONET is envisioned to provide key data to determine the ocean carbon sink with minimum delay . Participants in this project were actively engaged in planning and coordination an international meeting in Oostende (November, 2023) where the groundwork was laid to strengthen international engagement in SOCONET and to implement a value chain approach of production

of products though seamless SOCONET- SOCAT-SOCOM interactions. A NOAA SOCONET transition plan lead by Adrienne Sutton of PMEL has been completed and is in the process of being endorsed by all cognizant parties.

The transition efforts are to evolve from current effort in research mode by different groups with a view to make them operational under aegis of SOCONET. Advances in collation of data from groups worldwide (Takahashi et al., 2009; SOCAT, Bakker et al., 2016) and the development of sophisticated approaches in temporal and spatial data gap filling (Rödenbeck et al., 2006, 2015; Zeng et al., 2017; DeVries et al., 2023; Wanninkhof et al., 2024 submitted) have aided the product development. All current surface ocean CO_2 mapping efforts rely on interpolation and/or creating algorithms of pCO_2 with environmental fields that are available at higher resolution. The ability to create realistic, near real-time maps will depend on the amount of pCO_2 data available, its timeliness, and, because the fluxes are greatly influenced by bias, on the accuracy of pCO_{2w} and pCO_{2a} values. The MBL and surface water CO_2 values are systematically changing with time due to emission of anthropogenic CO_2 into the atmosphere, such that obtaining values in a timely fashion is critical.
SOCONET is a multi-PI distributed network which relies heavily on established interactions in SOCAT and is largely focused on operations and its development will follow the network attributes under development by the Observation Coordination group (OCG) of the Global Ocean Observing System (GOOS). More recently, the need to establish such a network has gained the support of IOCCP G7 Future of the Seas and Oceans Initiative (FSOI), the European research infrastructure program ICOS, and the European JPI Oceans (Joint Programming Initiative Healthy and Productive Seas).

pCO_2 intercomparison exercises

In July 2021, Dr Tobias Steinhoff, under the umbrella of ICOS OTC, organized an inter-comparison of multiple *p*CO_2 measuring instruments currently operating in the field in Oostende, Belgium. In all, 29 separate instruments of 18 different types (6 surface, 4 submersible and 8 underway) were tested against each other. The results have not been finalized yet, but preliminary data shows that the two GO systems which participated performed extremely well and were by far the best of all the instruments. A manuscript is in preparation that includes a full instrument description, advice on best practices and high-level take aways. A major finding was that systems with onboard standards for calibration performed far better than those without. Results for each instrument are compared to the average of three systems believed to be most accurate. Two of the systems were those used the NOAA SOOP-CO2 consortium: the GO 8050 and the GO 8060. The latter is the new system optimized for the new generation laser-based CO_2 analyzers with superior linearity and stability.

Many US institution could not participate in the ICOS OTC inter-comparison due to COVID. Instead, we decide to do our own system comparison. In early September 2021, a second pCO_2 system was installed on the NOAA ship Ronald Brown in order to compare and evaluate differences between the two pCO_2 systems deployed in the NOAA Ships of Opportunity network, the General Oceanics and LDEO Takahashi systems. Although these systems share much in common, important differences exist and a comprehensive comparison is warranted.

Differences between the systems include the design of the equilibrator; the Takahashi equilibrator holds nearly ten times more water than the GO equilibrator. The Takahashi system also uses nitrogen in the nafion drying process and within the reference side of the Licor analyzer. Differences have evolved in part due to the environments in which these systems are deployed with the Takahashi system installed on ships operating primarily in high latitude cold waters.
Past comparisons of these two systems indicated small offsets on the order of several µatm on a cruise in the Gulf of Mexico in late summer and early autumn. To investigate potential offsets over a larger range of oceanic conditions in particular SSTs, AOML and GML collaborated on a second comparison on the R/V Brown on a transit from Newport, RI to Recife, Brazil prior to A16N. Additionally, GML installed a high precision atmospheric system with an independent atmospheric line to isolate differences related to equilibration. Comparisons during this transit were closer than the previous Gulf of Mexico cruise with offsets in atmospheric measurements between all three systems within 0.2 ppm and ocean measurements between the GO and Takahashi within 1.5 µatm.
We are currently running both Takahashi and GO systems in the lab at AOML to try to explain the small offset we seem to see at sea. We have re-installed the Takahashi system onboard the *NOAA ship Ronald Brown* for A16N to continue the comparison. We are in the process of analyzing the data.

3. Outreach and Education

Communicating and describing GOMO-supported activities and resulting outcomes has received increased attention as ocean climate connections continue making headlines and opportunities arise to educate the public about our activities. Please describe the following:

- Activities to inform (e.g., through websites, articles in mass media) the wider community of your work.
- Efforts working with students, schools, teachers, the general public, museums, aquaria, etc., and ways that you are helping train our next generation scientists to understand and appreciate ocean climate science, either directly or indirectly.

Investigators in this project have been active in several outreach efforts. They presented public lectures; given guest lectures at schools and universities and are members of national and international steering committees.
Drs. Pierrot, Wanninkhof, and Alin are active members of the SOCAT group that includes an active effort to entrain developing nations in global CO_2 measurements.
The R/V *Walton Smith* is used by the University of Miami's Department of Marine Science to provide undergraduate students with at sea experience in marine chemistry. The pCO_2 data collected during these cruises are used by the students in exercises designed to introduce them to the collection and analysis of oceanographic data, and the preparation of a cruise data report. The pCO_2 on ships and GCB effort were highlighted in the OAR research news.

With partial help from NOAA's Pier2Peer program, Dr. Pierrot still act as consultant to Dr. Carla Berghoff of INIDEP in Argentina. They have one pCO_2 system installed on their research vessel, the R/V Victor Angelescu. A paper was published on this effort (Berghoff, et al., 2022).
They also plan to outfit the new research vessel they have commissioned recently. Since 2023, Dr. Pierrot is also mentoring Dr. Luana Pinho of the Universidade Federal do Rio de Janeiro (UFRJ) through the same Pier2Peer program in order to help her ensure that their pCO_2 system is producing the best data. Finally, he is a co-chair of the GOSUD steering committee and a member of the SDG14.3.1 metadata working group.
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 (G3W), and the US Global Greenhouse Gas Monitoring Program. He is post-doc adviser of Katelyn Schockman who obtained her PhD degree at USF.
Dr. Barbero is a member of the U.S. GO-SHIP science committee and co-chair of international GO-SHIP. As part of her role co-chairing GO-SHIP she contributes to the Global Climate Observing System (*GCOS*), and is part of the IOCCP / GOOS Biogeochemistry Expert Panel working towards the addition of N2O and CH4 as EOVs. She is actively involved in the science working groups for the southeast and Gulf of Mexico coastal ocean acidification regional networks (SOCAN and GCAN, respectively). On FY23 she coordinated outreach and communication activities with GOMO, AOML and OAR international affairs to highlight GO-SHIP A16N. She presented at ASLO 2023 on a collaborative effort between AOML and the National Park Service to monitor changes in coastal carbonate chemistry at select national park sites. She is currently in the PhD committee for Macarena Martin-Mayor a graduate student working towards her PhD under the direction of Dr. Robert Byrne at USF.
PMEL Carbon Group PIs are actively involved in education and outreach activities. As an example of a local education/outreach partnership, we have an underway CO_2 analysis system installed at the Seattle Aquarium to measure atmospheric and seawater pCO_2 on the Seattle waterfront. While the system is not explicitly funded yet (and thus is the first system to have data gaps when equipment is not available), there has been tremendous interest by groups involved with the Washington State Marine Resources Advisory Council in the atmospheric CO_2 records from this analytical system, which reflects the role of regional emissions on state air and water quality. We hope to obtain funding to make the operation of this system sustainable.
During the earlier funding cycles, PI Alin did numerous outreach presentations in classrooms at a "global majority" Seattle Public School. With recent increases in institutions paying attention to engaging underrepresented groups in STEM, NANOOS (the IOOS Regional Association "Networked Association of Northwest Ocean Observing Systems") has convened a Diversity, Equity, and Inclusion working group on which Dr. Alin is the PMEL representative. Dr. Alin proposed a partnership between NANOOS's Enabling Change group and the Technology Access Foundation (TAF) to engage Seattle area ocean and climate scientists with SPS teachers and TAF to develop curriculum materials and project opportunities for underserved/underrepresented students at a "global majority" middle school to work with, including tutorials, mentoring, and activities related to the voluminous publicly available data produced by NOAA-funded projects

and available on NANOOS. This partnership has encountered some bumps along the way, but we are still trying to get it off the ground.
Dr. Feely is involved with presenting an annual workshop on ocean acidification at Sound Waters, a "one day university for all," bringing together people passionate about life in Puget Sound. Held since the early 1990′s on the first Saturday in February on Whidbey Island, WA; Sound Waters now attracts 500 to 600 people yearly.
The BIOS Carbon Group is actively involved in education and outreach activities at BIOS. In August 2023, BIOS was acquired by Arizona State University, and BIOS is now part of the Julie Ann Wrigley Global Futures Laboratory at ASU. In addition, a new School of Ocean Futures (SoOF) has been initiated at ASU-BIOS, and Prof. Bates (who is now a Full Professor within the new ASU School as well as remaining Senior Scientist at BIOS) is currently incorporating SOOP carbon measurements into new graduate level courses within SoOF with anticipated start of teaching in fall 2024.

Over the summer of 2022, David Munro and Colm Sweeney of the GML group hosted a graduate student from the City University of New York through the NOAA Experiential Research and Training Opportunities (NERTO) program on a project focused on the impacts of freshwater fluxes and changing sea ice conditions on the marine biogeochemistry of the Coastal Arctic. This project utilized pCO2 measurements collected from the USCGC Healy and R/V Sikuliaq in combination with a wide range of data products from the coastal Arctic. The NERTO program is part of the José E. Serrano Education Partnership Program with Minority Serving Institutions (EPP/MSI). The NERTO program provides EPP/MSI Cooperative Science Center-supported students participating in NOAA mission-aligned research and training at NOAA facilities.

4. Publications and Reports

4.1. Publications by Principal Investigators

- Published

** where applicable a pre-publication version of the manuscripts listed below is available at the NOAA Institutional Repository, thus satisfying NOAA's Public Access to Research Results (PARR) requirements for publication**

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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, https://doi.org/10.5670/oceanog.2023.222.

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Munro, D., A. Jacobson, and A Fay (in preparation). The Surface Carbon State Estimate (SCSE). To be submitted to Global Biogeochemical Cycles.

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4.2. Other Relevant Publications

also see list of relevant publications related to the Global Carbon Project and SOCAT data products, which include pCO_2 mooring data, in the FY22 Data Synthesis annual report

See list of peer-reviewed and other publications based on SOCAT products listed on the SOCAT website here.

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5. Data and Publication Sharing

There have only been minor updates to the Data Management Plan that was included in our FY21 Work Plan. Our data can be found on the Ocean Carbon Data System (OCADS) operated by NOAA's National Centers for Environmental Information (NCEI) at https://www.nodc.noaa.gov/ocads/. In addition, each institution collecting data for this project has its own data sharing process, which are described below.

Global Ocean Surface Water pCO_2 Data Base:
As part of the transition of operations from LDEO to GML after the passing of Dr. Takahashi, an updated climatology centered at 2010 was developed from the LDEO data base following the same interpolation and gridding procedures of the 2009 climatology. Two versions were produced, one that uses the data in the Takahashi database, and one using SOCAT V2022 data. The latter is used as default as it contains more data including most of the LDEO data base. A comparison of the two climatologies shows close correspondence with detail in Fay et al., 2024 (submitted) The effort is spearheaded by S. Sutherland of LDEO and D. Munro of GML/CIRES. The climatology was released during 2023. The LDEO data base is no longer updated as the individual groups in this project have improved their QC approaches and SOCAT has been able to take on its database functions.

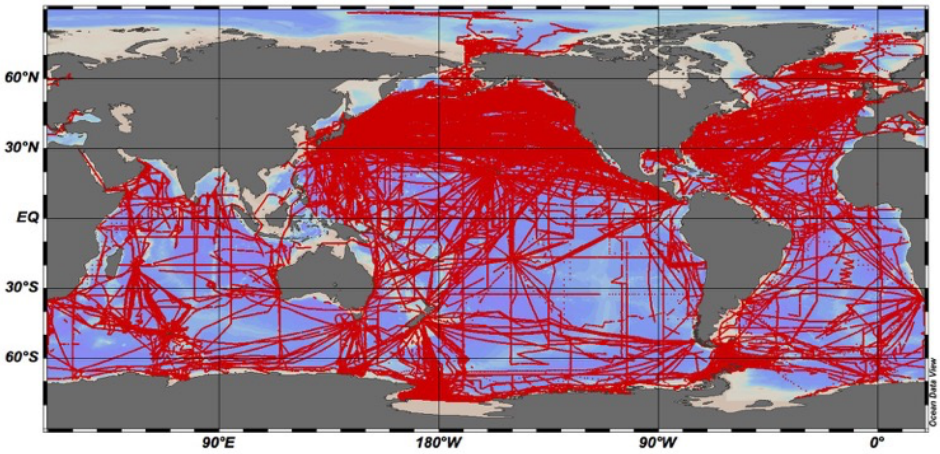

Figure 18. The location of surface water pCO_2 data in the LDEO database archived at the NOAA/NCEI/OCADS. *About 13.5 million data are listed in the uniform format.* (*Takahashi et al., 2020)*

Institutions' websites, data centers and data products:

The PMEL carbon data are also archived at the PMEL website which includes an interactive map (https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery) allowing quick access to underway fCO_2 data collected by PMEL since 1982. To date, fCO_2 data from over 160 cruises have been posted on the interactive map. The carbon data management plan is accessible at the PMEL website. All quality-controlled underway pCO_2 data recovered from the field up to 2

years ago can be publicly accessed at NCEI and through the SOCAT data product (https://www.socat.info).

Accession numbers and NCEI links for underway data submitted to SOCAT and NCEI during FY23 from GOMO-supported PMEL vessels are given below. Cruise data sets submitted to NOAA/NCEI/OCADS during FY2023. FY2022 observations on the R/V *Thomas G. Thompson* were in coastal western US waters and the eastern equatorial and subtropical Pacific. FY2022 cruises on the R/V *Roger Revelle* included observations throughout GO-SHIP cruise P02 in the subtropical northern Pacific Ocean and GEOTRACES cruises GP17 in an infrequently sampled part of the southern Pacific Ocean.

Ship	*Cruise Name*	*Expocode*	*NCEI Accession and link*
R/V *Thomas G. Thompson*	TGT22_01	325020220122	
	TGT22_02	325020220312	
	TGT22_03	325020220331	
	TGT22_05	325020220527	
	TGT22_06	325020220620	0276136
	TGT22_10	325020220906	
	TGT22_11	325020220912	
	TGT22_12	325020220924	
	TGT22_13	325020220930	
	TGT22_14	325020221009	
R/V *Roger Revelle*	RR2204	33RR20220501	276433
	RR2205	33RR20220614	276433
	RR2213	33RR20221115	

AOML submits its data to NCEI and SOCAT databases. The in-house serving of data on AOML website http://www.aoml.noaa.gov/ocd/ocdweb/occ.html provides an important venue to give access to more information and data than is submitted to the data centers and provides the user easy access to the holding of the quality data. The website has recently been updated to improve data accessibility and appearance. This resource is also helpful for investigators who have done projects on the ships and require access to the co-located pCO_2, temperature, and salinity data.

As soon as the data is reduced, posted on our websites and submitted to NCEI, it is also submitted to SOCAT. It undergoes a secondary QA/QC procedure by other scientists organized in regional groups who flag the data on a per cruise basis and incorporate the data into the next SOCAT release. The submission process is now automated, which not only greatly facilitates the task for data submitters but also reduces the errors involved in data ingestion, providing a product of higher quality.

SOCAT is a global surface ocean CO_2 data collection that incorporates fugacity or partial pressure of CO_2 (fCO_2, pCO_2)[1] data for the open oceans and coastal seas into a uniform dataset. Throughout the years, several versions have been released with increasing number of observations. In order, they are:

[1] The chemical potential of CO_2 gas in water is either expressed as a partial pressure (pCO_2) or, when accounting for the non-ideality of CO_2, fugacity (fCO_2) with a conversion using virial coefficients as described in Weiss (1974). The $fCO_2 \approx 0.993\ pCO_2$. Here we generally use the term fCO_2 as this is the reported quantity in the SOCAT dataset.

- Version 1.5 (2011): 6.3 M (million) observations.
- Version 2 (2013): 10 M observations (Bakker et al. 2014)
- Version 3 (2015): 14.5 M observations (Bakker et al. 2016)
- Version 4 (2016). 18.5 M observations
- Version 5 (2017). 21.5 M observations.
- Version 6 (2018). 23.4 M observations.
- Version 2019. 25.7 M observations.
- Version 2020. 28.2 M observations with accuracy < 5 µatm.
  2.3 M observations with accuracy between 5-10 µatm.
- Version 2021. 30.6 M observations with accuracy < 5 µatm.
  2.1 M observations with accuracy between 5-10 µatm.
- Version 2022. 33.7 M observations with accuracy < 5 µatm.
  6.4 M observations with accuracy between 5-10 µatm.
- Version 2023. 35.6 M observations with accuracy < 5 µatm.
  7.2 M observations with accuracy between 5-10 µatm.

As can be seen in *Figure 19*, the coverage of the world's oceans is substantial.

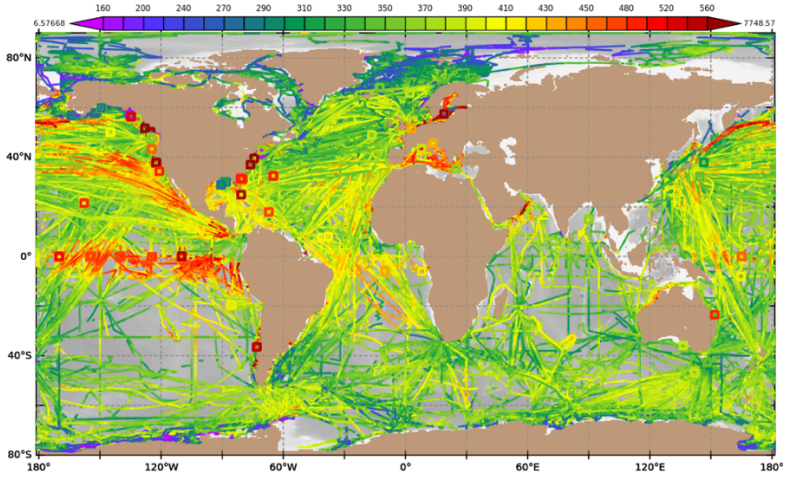

Figure 19. World's coverage of the Surface Ocean CO_2 *Atlas (SOCAT version 2023) database through 2022 (42.8M obs.)*

The contribution from the participants of this program since 2005 (~9M obs.) represent about a quarter of all observations (*Figure 20*). These datasets are iterations upon which the international marine carbon research community continues to build using agreed data and metadata formats, and standard quality-control procedures. The effort is endorsed and partially supported by several international ocean science programs.

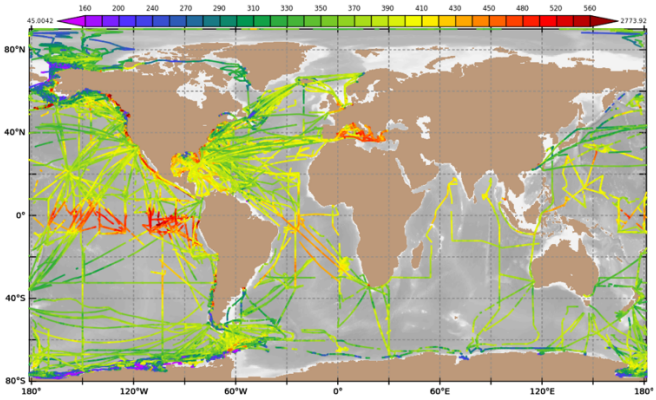

Figure 20. Contribution of the GOMO sponsored SOOP_CO2 program of 9M points since 2005 to the Surface Ocean CO_2 Atlas (SOCAT version 2023) database through 2022

Version 4, released on September 1st, 2016 was the first annual release which used the automated data upload. Automation of data upload and initial data checks speeds up data submission and allows annual releases of SOCAT from version 4 onwards.
SOCAT enables quantification of the ocean carbon sink and ocean acidification and evaluation of ocean biogeochemical models. SOCAT represents a milestone in research coordination, data access, biogeochemical and climate research and in informing policy. Several products are making use of the freely available data, such as the ESMValTool (v1.0) (Eyring et al., 2016) or the Surface Ocean pCO_2 Mapping Intercomparison (SOCOM) (Rödenbeck et al., 2015). A list of other products using SOCAT v2023 can be found at https://www.socat.info/index.php/products-using-socat/.

6. Project Highlight Slides

See accompanying slides. Accompanying text for some slides is below.

Slide 3.

The paper in the PMEL 50th Anniversary Special Volume in *Oceanography* magazine led by Richard Feely used a combination of GO-SHIP and SOOP underway surface observations to evaluate changes in surface ocean carbonate chemistry between 1961 and 2020 (Feely et al. 2023). Using this combination of observations, Feely et al. 2023 discuss the roles played by air-sea anthropogenic CO_2 uptake, warming, upwelling, and changing buffering capacity and conclude that conditions are changing rapidly in regions that would normally be considered refugia, with implications for stocks of sensitive species (Figure 21).

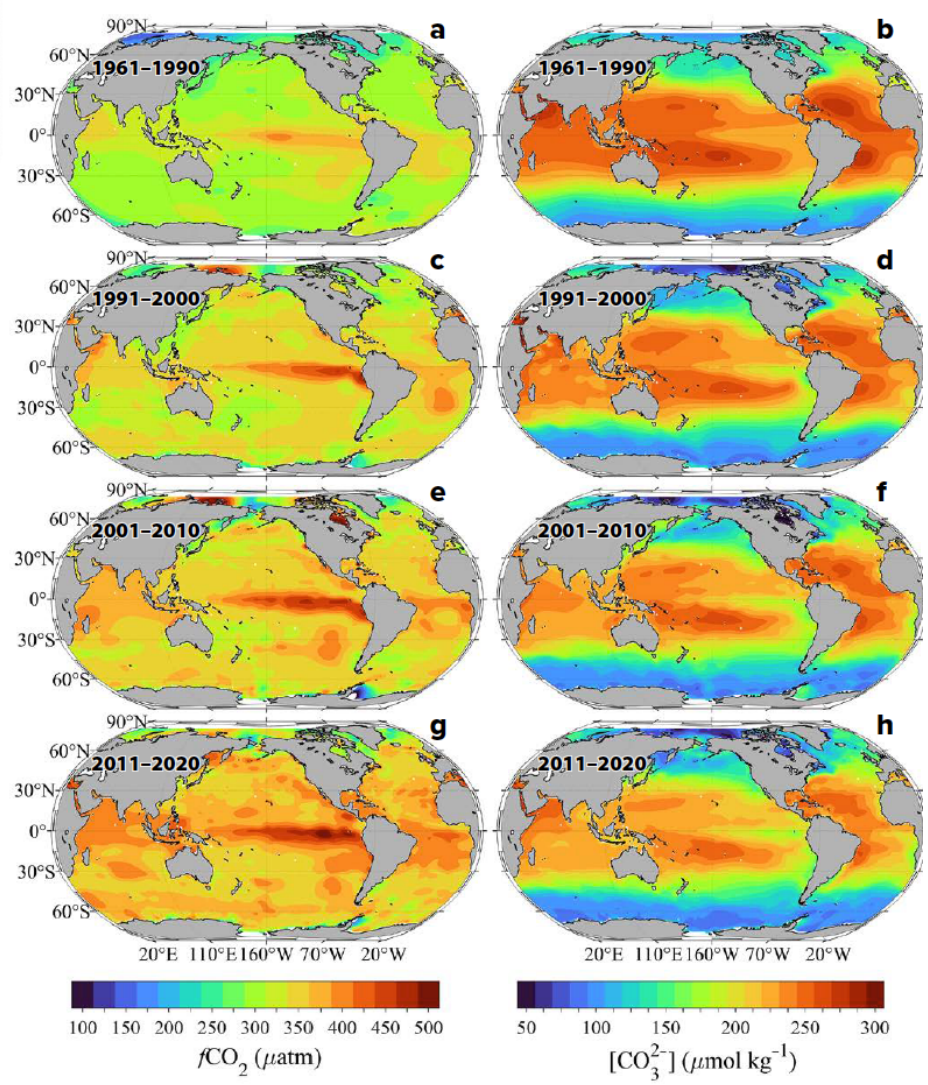

Figure 21. Distribution of carbon dioxide fugacity and carbonate ion content in surface waters between 1961 and 2020. From Feely et al., 2023.

Slide 4.

In the *Journal of Advances in Modeling Earth Systems*, Jiang et al. (2023) show the trajectories of carbonate system parameters in the global surface ocean under different emissions scenarios (Figure 22). This model-data fusion analysis used SOCAT observations (a significant percentage of which are produced annually by PIs funded by GOMO through this project) and other observational data products to adjust CMIP6 Earth System Model results to better agree with observations. The paper makes an important contribution in providing 1° × 1° decadal averages for surface ocean fCO2, pH (total scale), [H+], carbonate ion content, Ωarag, Ωcalc, Revelle factor, DIC, and TA content values for 1750 (pre-industrial conditions), historical conditions (1850–2010), and five Shared Socioeconomic Pathways for 2020–2100, representing different future emissions scenarios (SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5).

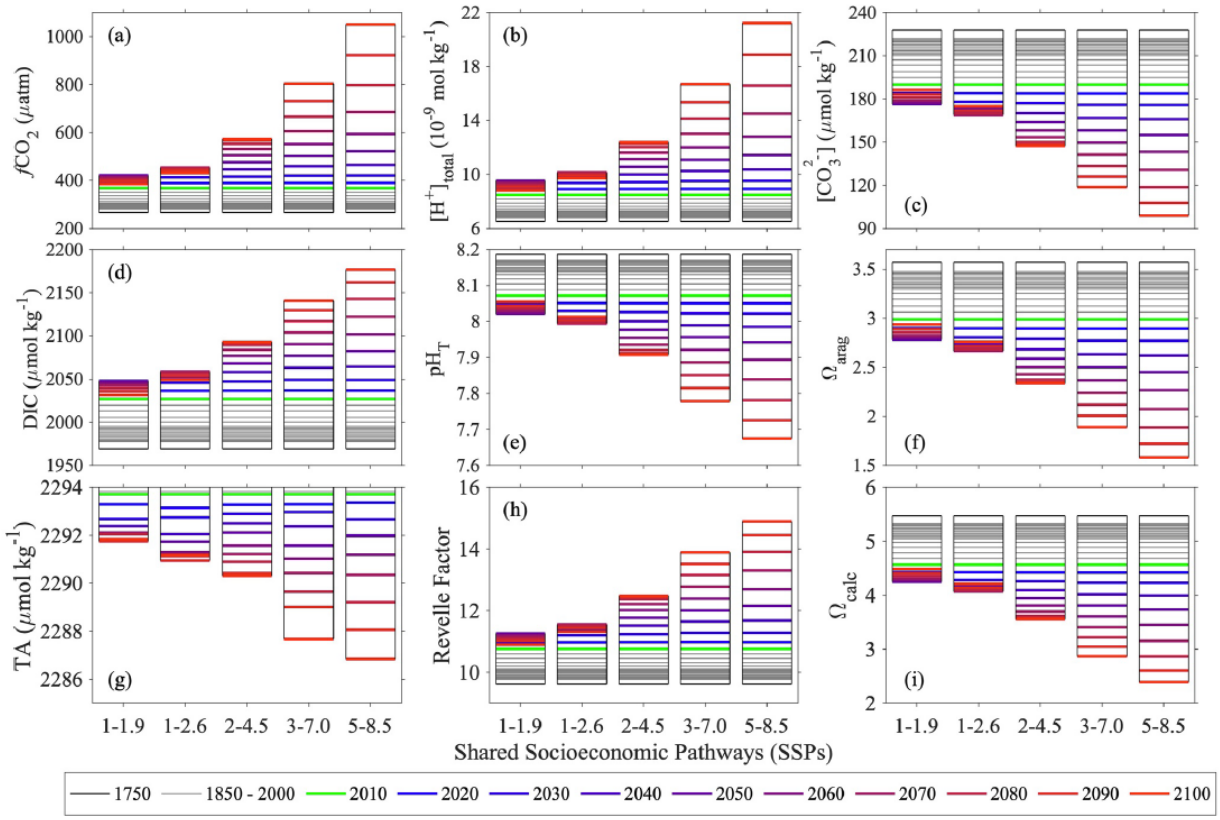

Figure 22. Temporal changes of global surface ocean acidification indicators (inter-model median values out of 14 CMIP6 Earth System Models after applying adjustments with observational data [including SOCAT data], area-averaged). The *x*-axes labels, 1–1.9, 1–2.6, 2–4.5, 3–7.0, and 5–8.5 indicate the Shared Socioeconomic Pathways: SSP1–1.9, SSP1–2.6, SSP2–4.5, SSP3–7.0, and SSP5–8.5, respectively. From Jiang et al. 2023.

Slide 5.

An updated climatological mean surface ocean pCO_2, and net sea–air CO_2 flux over the global oceans

Amanda Fay, David Munro, Stew Sutherland, Colm Sweeney, Rik Wanninkhof and Denis Pierrot completed an updated climatological mean fCO_2 product following the approach of Takahashi et al. (2009), (2002) and (1997). The new climatology (Fay et al, submitted to ESSD) is meant to be a final update of the Takahashi climatology which has been a cornerstone of carbon cycle studies for more than two decades. The updated climatology is constructed using the SOCATv2022 databases with approximately seven times the number of observations used to create the last climatology (Takahashi et al. 2009).

Additionally, the new climatology is constructed using ΔfCO_2 ($fCO_{2oce} - fCO_{2atm}$) rather than pCO_{2oce}, avoiding the time normalization procedure used in Takahashi et al. (2009). The new

climatology is compared to commonly used fCO_2 products which have become increasingly important tools in assessments of regional and global sea-air CO_2 flux such as the GCP and RECCAP. SOOP investigators are involved in several related projects focused on different approaches for time-varying estimates of pCO_2 and sea-air CO_2 fluxes including a random forest (Wanninkhof et al., 2024. submitted to GBC) and a Kalman filter (Munro et al., in prep).

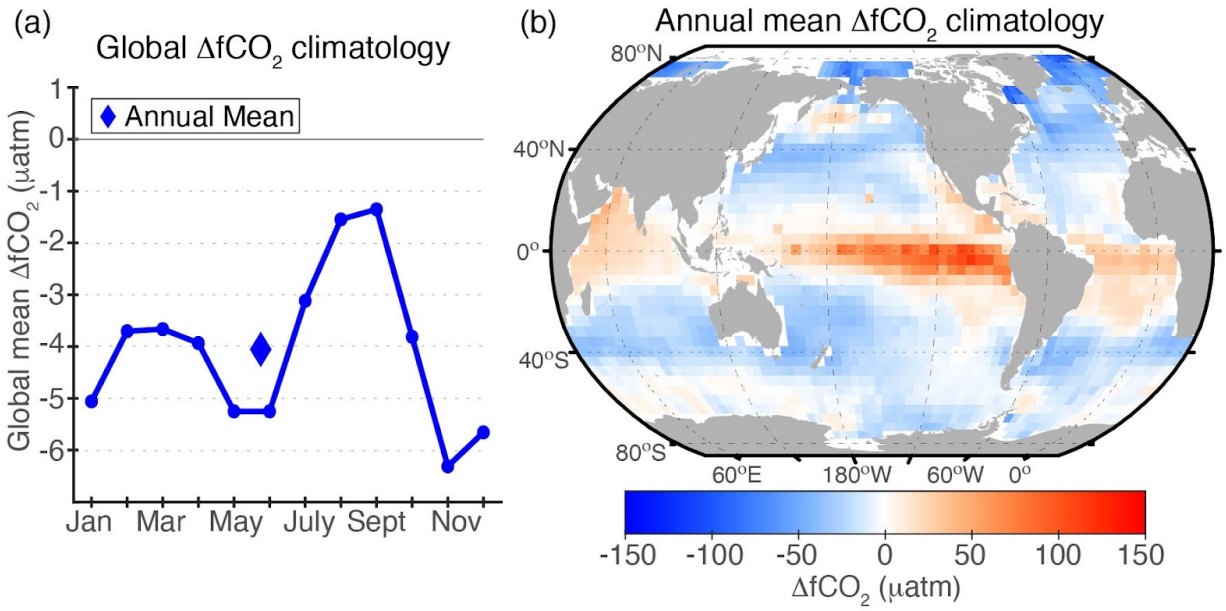

Figure 23. from Fay et al. (submitted): (a) Global mean ΔfCO_2 seasonal climatology from the SOCAT database; annual mean value is indicated by the diamond (-4.1µatm). (b) Map of annual ΔfCO_2 climatology.

Other Highlight (no slide)

PMEL and AOML continue to collaborate on the preparation of a manuscript on the synthesis of the decadal changes in fCO_2, wind speeds, and air-sea CO_2 fluxes across the equatorial Pacific Ocean. PMEL PI Richard Feely is leading the paper, which we plan to submit to *Geophysical Research Letters*. (This paper has been delayed by the publication of the PMEL 50th Anniversary Special Volume in *Oceanography* magazine, so the description below is the same as in last year's report.) The time-series of surface ocean fCO_2 and temperature observations on NOAA-led cruises from 1982 through 2021 has revealed that the eastern and central equatorial Pacific are large sources of CO_2 to the atmosphere during non-El Niño and La Niña events, near neutral during strong El Niño events, and weak sources during weak El Niño events. The warm El Niño phase of the ENSO cycle is also characterized by a large-scale weakening of the trade winds, decrease in upwelling of CO_2- and nutrient-rich subsurface waters, and a corresponding warming of SST. La Niña, the opposite phase of the ENSO cycle, is characterized by strong trade winds, cold tropical SSTs, and enhanced upwelling of CO_2- and nutrient-rich water along the equator. Time-longitude plots of SST and fCO_2 for the tropical Pacific region from 5°N to 10°S and 130°E to 95°W, and the Oceanic Niño Index (ONI) for the 40-yr period from 1982 through 2021, delineate the strong eastern Pacific El Niño events of 1982–83, 1997–1998, and 2015–16 in

which the cold waters of the eastern equatorial Pacific disappear and fCO_2 values are close to equilibrium with respect to the atmosphere. In contrast, during the weaker central Pacific El Niños of 1991–1994, 2002–2005, and 2006-07, the equatorial cold tongue is present but less pronounced, and fCO_2 values are higher than atmospheric values but lower than corresponding values for non-El Niño periods. The strongest El Niño event of 1997–1998 has SST anomalies exceeding 4°C and the lowest fCO_2 values throughout most of the equatorial Pacific. The 2015–16 El Niño event had SST anomalies that were similar to the 1997–98 event yet the fCO_2 values were significantly higher because the upwelling-favorable winds were stronger in the easternmost and westernmost parts of the region. By the 2018–2021 timeframe, the region returned to non-El Niño conditions and elevated fCO_2 levels. Over the first three decades of the observational record, fCO_2 values increased at a rate of 1.2 ± 0.7 µatm yr^{-1}. In contrast, the trend of the fCO_2 increase dropped off dramatically during the most recent decade, from 2012 through 2021.