FY-2022 Progress Report

Surface water *p*CO_2 measurements from ships

Period of Activity: 01 October 2021 – 30 September 2022

Principal Investigator
Denis Pierrot
Atlantic Oceanographic
and Meteorological Lab.
4301 Rickenbacker Causeway
Miami, Florida 33149
denis.pierrot@noaa.gov

Signature 12/15/2022 Date

Financial Contact
Dalynne Julmiste
Atlantic Oceanographic
and Meteorological Lab.
4301 Rickenbacker Causeway
Miami, Florida 33149
dalynne.julmiste@noaa.gov

Signature 12/15/2022 Date

Lab Director
John Cortinas
Atlantic Oceanographic
and Meteorological Lab.
4301 Rickenbacker Causeway
Miami, Florida 33149
john.cortinas@noaa.gov

Signature 12/15/2022 Date

Co-Principal Investigator
Simone R. Alin
Pacific Marine Environmental Lab.
7600 Sand Point Way NE
Seattle, Washington 98115

Co-Principal Investigator
Colm Sweeney
Earth System Research Lab.
325 Broadway
Boulder, CO 80305

Co-Principal Investigator
Nicholas R. Bates
Bermuda Institute of Ocean Studies
17 Biological Station Lane
Ferry Reach, GE01, Bermuda

Co-Principal Investigator
Gustavo Goni
Atlantic Oceanographic and
Meteorological Lab.
4301 Rickenbacker Causeway
Miami, Florida 33149

Co-Principal Investigator
Leticia Barbero
RSMAS, U. Miami
4600 Rickenbacker Causeway
Miami, Florida 33149

BUDGETS SUMMARY: Oct. 1, 2020 - Sept. 30, 2024

	FY21	FY22	FY23	FY24
AOML[1](CO_2)	$464,927	$514,719	$566,192	$622,811
(TSG)	$60,116	$66,127	$72,740	$80,014
PMEL	$410,218	$452,890	$498,179	$547,997
BIOS[2]	$114,733	$126,206	$138,826	$152,709
RSMAS[2]	$45,242	$49,767	$54,744	$60,218
GML[2]	$395,367	$442,835	$487,118	$535,830
SOCONET	$21,855	$24,040	$26,444	$29,088
RSMAS overhead CIMAS Task 1 - 2.5%[3]	$3,999	$4,399	$4,839	$5,323
TOTAL	$1,516,458	$1,680,984	$1,849,081	$2,033,990

(1) The Joint Institute Task I Administrative fee of $ 5,066 (= 2.5% of CIMAS budget) will be covered as a matching contribution by AOML

(2) Performance Period: Oct. 1, 2021 - Sept. 30, 2025

(3) Task 1 fee for funds sent to RSMAS and subcontracts

Surface water pCO_2 measurements from ships

Denis Pierrot[1], Rik Wanninkhof[1], Richard A. Feely[2], Simone R. Alin[2], Colm Sweeney[3], David Munro[3], Nicholas R. Bates[4], Gustavo Goni[1], and Leticia Barbero[5].
[1] Atlantic Oceanographic and Meteorological Laboratory, NOAA, Miami, FL
[2] Pacific Marine Environmental Laboratory, NOAA, Seattle, WA
[3] Earth System Research Laboratory, NOAA, Boulder, CO
[4] Bermuda Institute of Ocean Studies, Ferry Reach, Bermuda
[5] Rosenstiel School of Marine, Atmospheric and Earth Science of University of Miami, Miami, FL

Table of Contents

1. Project Summary

The oceans are the largest sustained sink of anthropogenic carbon dioxide (CO_2) with a flux into the ocean of about 2.9 petagrams (i.e., 2.9 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., 2022). 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 outfitted 17 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 are underway 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. Furthermore, we are the largest contributor and assemble, document quality control and serve global datasets through the Surface Ocean CO_2 Atlas (SOCAT version

2022; Bakker et al., 2016) coordinated under the auspices of the International Ocean Carbon Coordination project (IOCCP). Approximately a quarter of the SOCAT version 2022 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 (Alin et al., 2022; Feely et al., 2021), and annual updates on the state of the carbon cycle (Friedlingstein et al., 2022) 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 2022 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 *Le Commandant Charcot, Equinox, Flora* and *Allure of the Seas*, and UNOLS research vessels *Atlantic Explorer* (ship owned and operated by BIOS) and *Walton Smith* (owned and operated by Rosenstiel). 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 FY2022, mostly because of access restrictions due to the COVID-19 pandemic. Approximately 520,000 new data points are acquired during FY 2022 (*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. During the extended COVID-19 pandemic, some ships resumed sailing but others which had at least partial occupations in FY2021 were not able to sail at all this fiscal year, which caused a further decrease in our number of observations.

Table 1:SOOP Data Summary FY-2022. Total Observations: ~ 519,925

SHIP	# Cruises	# Data Points	% Recovery*
R/V Brown	*7*	*61,875*	*98.4%*
M/V Equinox	*0*	*0*	*0%*
M/V Allure of the Seas	*0*	*0*	*0%*
M/V Flora	*0*	*0*	*0%*
R/V Gordon Gunter	*2*	*12,166*	*97.3%*
R/V Bigelow	*13*	*71,544*	*97.2%*
M/V Le Commandant Charcot	*12*	*57,707*	*54.9%*
R/V Walton Smith	*10*	*19,727*	*97.0%*
R/V Thompson	*14*	68,582	*84.5%*
R/V Bluefin	*0*	*0*	*0%*
R/V Roger Revelle	*3*	48,338	*97.9%*
RVIB Palmer	*2*	*30,163*	*99.0%*
R/V Gould	*6*	*12,603*	*99.0%*
USCGC Healy	*5*	*28,940*	*98.0%*
R/V Sikuliaq	*15*	*65,810*	*98.0*
R/V Atlantic Explorer	*36*	*42,500*	*95.0%*
M/V Oleander	*0*	*0*	*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: 36
Number of publications authored/co-authored by PI: 6 (see list)
Number of peer-reviewed publications that list SOCAT as a data source (see here):
56(2022) 55(2021) 56(2020)

Number of updated products: 3 SOCATv2022, BAMS SoC and Global Carbon Budget (GCB 2022).

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

Data Site: http://www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *7*
Number of fCO_2 data points: *61,875*
% Data return: *98.4%*

Description: The cruise tracks for each cruise of the *Brown* for FY 2022 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_2022.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 email 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 keeps working very reliably and the high data return is directly related to the great support we get from the crew.

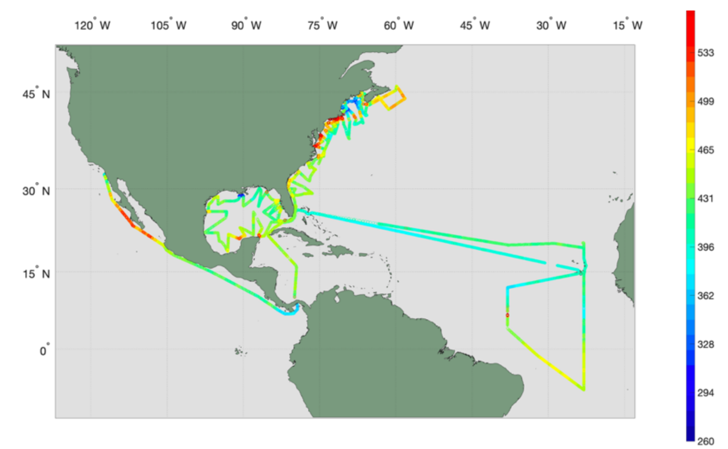

Figure 1. R/V Ronald H. Brown cruise tracks and surface xCO_2 values for FY 2022.

Causes for non-return: This installation has been performing well and the data return remains excellent. The pandemic has made organizing cruises very difficult. The *Brown* resumed international cruises but some (A13.5) had to be cancelled due to mechanical problems and a COVID outbreak among ship personnel. The spatial coverage remains substantial ranging from the West coast of America to the East Coast of Africa. However, besides WCOA and GOMECC-4, we have not been able to fully process the data as we are still awaiting the final CTD data for PNE to determine the SST and SSS corrections we need to apply to our data. We should be able to do that soon.

.

Cruise ship *Equinox* - 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*:** 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 Explorer of the Seas but with less 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).

Causes for non-return: Our collaborators from the University of Miami for this platform as well as the *Allure of the Seas* and the *Flora*, were unable to secure a financial commitment from Royal Caribbean International for this fiscal year. We have decided to show our good faith effort by restarting the system on the Equinox on our own funds. The system started collecting data in December 2022 and we should be able to maintain it throughout the year.

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 FY2022. See the Equinox for more details.

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 FY2022. See the Equinox for more details. We are in the process of trying to reach the vessel to restart the operation. We expect to start getting data in FY23.

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

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *2*
Number of fCO₂ data points: *12,166*
% Data return: *97.3%*

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 operation 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. The system has been working very reliably.

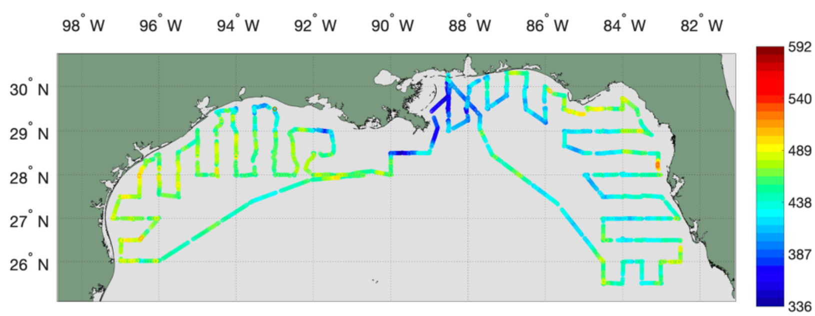

Figure 2. NOAA ship Gordon Gunter cruise tracks and surface fCO_2 values for FY 2022.

Causes for non-return: The *Gunter* spent the entirety of last fiscal year in dry dock. It started sailing again at the end of August 2022 and has done 2 cruises this fiscal year. The system is performing well and we expect our data return will back to pre-pandemic levels next fiscal year FY23.

***R/V Henry B. Bigelow* - AOML lead**

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *13*
Number of fCO_2 data points: *71,544*
% Data return: *97.2%*

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 of the crew and the scientific 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 if 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.

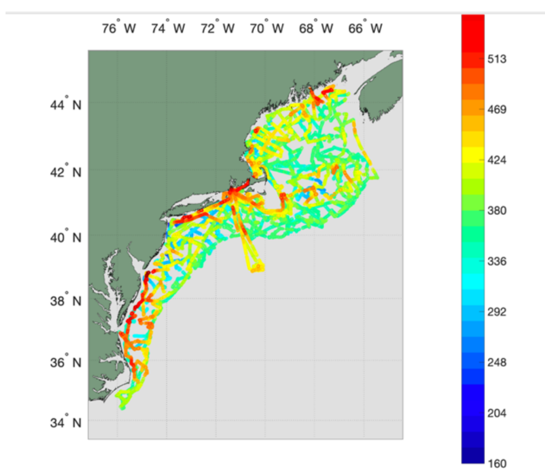

Figure 3. NOAA ship Henry Bigelow cruise tracks and surface fCO_2 values for FY 2022.

***Causes for non-return*:** The system performed very well this fiscal year. The only issue we have is with the sea surface temperature sensor which, although it seems to be correctly installed, continues to record temperatures which do not align well with the other temperature sensors on the ship. We are still in the process of troubleshooting that issue. In the meantime, unfortunately, our data from this vessel will not be able to have a SOCAT flag higher than C.

***M/V Le Commandant Charcot* - AOML lead (new installation during FY2022)**

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *12*
Number of fCO_2 data points: *57,707*
% Data return: *54.9%*

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 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.

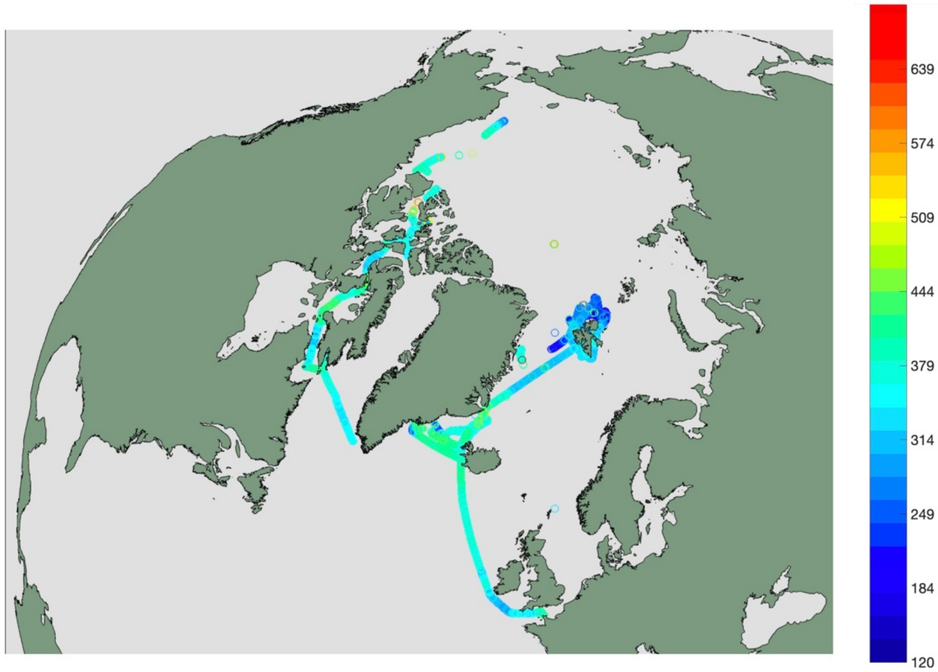

Figure 4. MV Le Commandant Charcot cruise tracks and surface xCO_2 values for FY 2022.

***Causes for non-return*:** The system has been performing very well since the beginning of the installation. The low data return is due to the fact that 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. They will try to resolve it at the next dry dock period sometime next year. Other issues affecting the data include the pressure transducer of the LICOR misbehaving and forcing us to use the atmospheric pressure measurements of the ship to estimate it. Unfortunately, communications with the ship are difficult and we are working on an automated solution to get that data. We also lost GPS for a while but were able to fill in the gap with the GPS data collected by other sensors so our data was not lost. These cruises have not been submitted to SOCAT yet as we are still awaiting the atmospheric pressure data.

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

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises: *14*
Number of fCO_2 data points: 68,582
% Data return: *84.5%*

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 FY2022 having data collection in coastal and open ocean environments of the NE Pacific Ocean. All data collected on the *Thompson* during FY22 are in the final processing stage and will be submitted to NCEI for archiving, to SOCAT prior to the January 2023 deadline, and posted to the PMEL CO_2 website.

Causes for non-return: For four of the 14 cruises during FY2022, the system encountered gas flow and other technical issues but was not within geographic range where our team could repair the system. The ~15% reduction in data return reflects these four cruises, when the system was running, but the measurements being collected were not deemed accurate enough to submit.

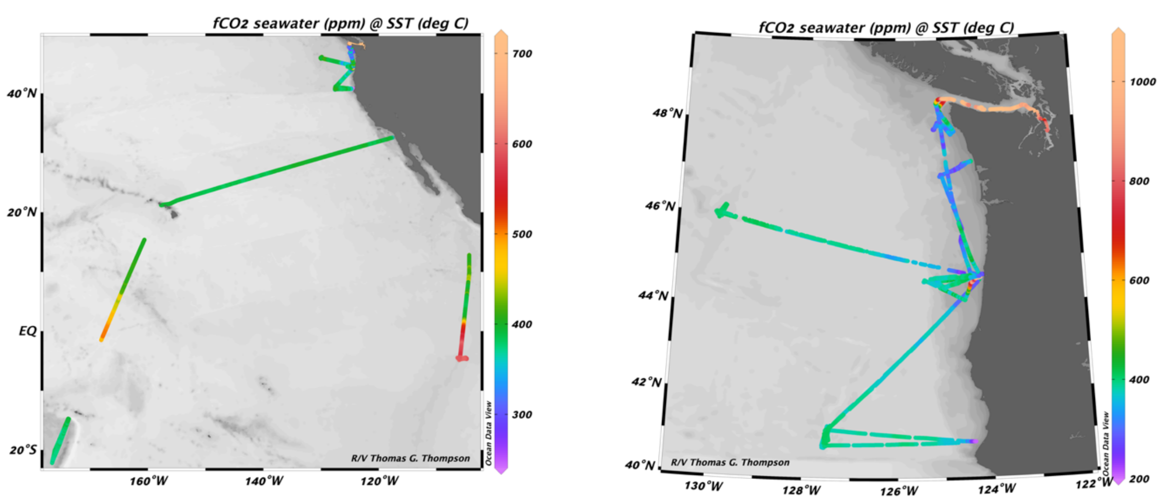

Figure 5. FY2022 fCO_{2sw} (μatm) measurements collected from the R/V *Thomas G. Thompson* during all cruises in 2022 (left) and a closer view of underway data during coastal cruises (right).

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

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises: *3*
Number of $\boldsymbol{f}$***CO₂ data points:*** 48,338
% Data return: *97.9%*

Description: In recent years, 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 the PMEL underway team had lead responsibility for repairing and maintaining the *Revelle* underway fCO_2 system for GO-SHIP cruise P02 during April–July 2022. Further, because we were down a platform this year with the *Bluefin* system not being reinstalled and the *Revelle* was scheduled to cover infrequently sampled parts of the South Pacific and Southern Ocean, we negotiated a short-term plan with Scripps staff and the GEOTRACES inorganic carbon PI (Ryan Woosley) for our team to get the *Revelle*'s underway fCO_2 system into top shape before GEOTRACES transect GP17 (*Figure 6*). PMEL will take the lead in processing the data sets resulting from both legs of P02 and the pre-GEOTRACES transit from San Diego to Tahiti and submitting them to NCEI and SOCAT before the upcoming SOCAT submission deadline (data shown in *Figure 7*). Underway data collected on the *Revelle* during GP17 (scheduled for December 2, 2022 to January 24, 2023) will be processed and submitted to NCEI for archiving, to SOCAT, and posted to the PMEL CO_2 website as soon as possible after GP17 concludes, with statistics for this important cruise in the South Pacific and Southern Ocean to be provided in the 2023 progress report.

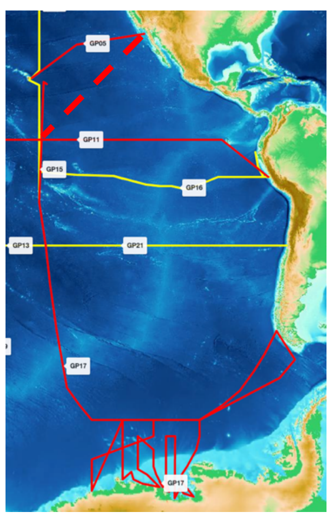

Figure 6. The GEOTRACES GP17 cruise route. The transit from San Diego to Tahiti also yielded good data (the statistics reported above, with the approximate San Diego–Tahiti transit route shown with a dashed red line here).

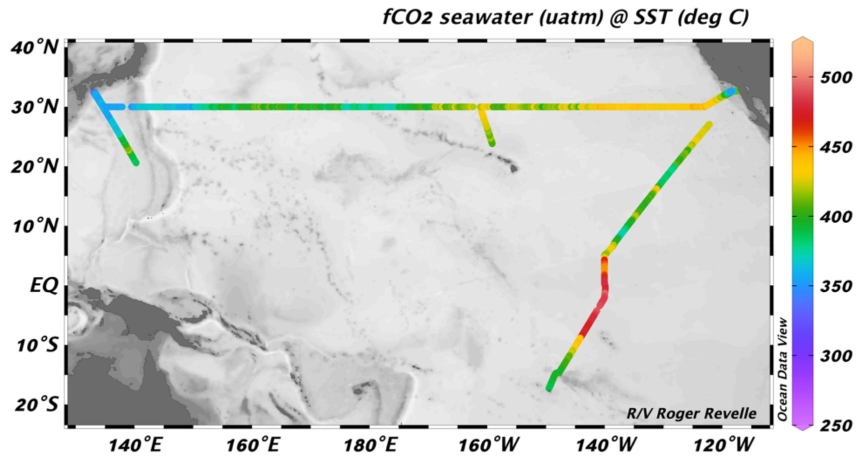

Figure 7. Underway fCO_2 data collected on the R/V *Roger Revelle* during 2022.

R/V *Bluefin* - PMEL lead

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises: *0*
Number of $\boldsymbol{fCO_2}$ ***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 have been told we can expect a better installation location at the end of 2022, so we are optimistic that we can resume data collections in FY2023.

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

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

Data Site: http://www.ldeo.columbia.edu/CO2
Number of cruises: *2*
Number of pCO_2 data points: *30,163*
% Data return: *99.0%*

Description: : The *RVIB Nathaniel B. Palmer* is one of two US research ships that operate primarily in the Southern Ocean including the seas surrounding Antarctica. Both research ships host pCO_2 systems maintained by the GML group. During FY2022, 30,163 pCO_2 measurements were obtained from two long research cruises which is more than 10,000 more than the total number of measurements obtained in FY2021. Prior to cruise, NBP2113 in November of 2021 which was the annual LTER cruise, a new Aanderaa optode was installed as part of the underway monitoring program. Measurements from FY2022, not including NBP2113 are shown in *Figure 8*. Measurements during FY2022 were obtained across the Drake Passage, along the West Antarctic Peninsula and on cruise NBP2202 to the Amundsen Sea. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

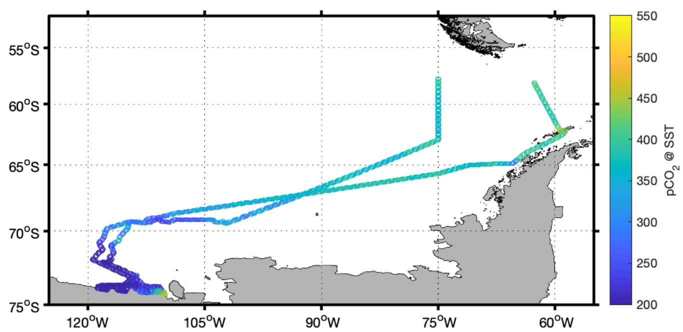

Figure 8. The locations and values of surface water pCO_2 measurements (in µatm) made from the RVIB Palmer during FY2022 (data points shown are from one of two cruises, NBP2202; NBP2113, LTER cruise to the West Antarctic Peninsula not included).

Causes for non-return: nearly all data passed QC during FY2022 as indicated by the high rate of return in *Table 1*; limitations on data collection unrelated to the functioning of the pCO_2 system are mainly due to lack of approval to collect data within the EEZ's of Argentina and Chile.

***ASRV L. M. Gould* – GML Lead:**

Data Site: http://www.ldeo.columbia.edu/CO2
Number of cruises: *6*
Number of ***fCO_2*** ***data points:*** *12,603*
Data return: *99.0%.*

Description: Data collection from the underway pCO_2 system aboard *ARSV Laurence M. Gould* began in March 2002 with observations collected mainly across the Drake Passage and along the West Antarctic Peninsula. The surface water pCO_2 system as well as discrete measurements of total CO_2 and macronutrients collected across the Drake Passage were previously supported by a grant from the Antarctic Sciences Section of the Office of Polar Programs at NSF to the University of Colorado. Starting with the 2020-21 Antarctic field season, the NOAA pCO_2 from Ships Program took full responsibility for the pCO_2 system and discrete seawater measurements. During FY2022, the number of measurements was substantially greater than FY2021 which was disrupted by COVID19. A total of 12,603 pCO_2 measurements were made from the *ARSV Gould* during FY22 (*Figure* 9) which is still more than 50% reduced from the number of measurements collected in most years prior to COVID19. These data are particularly valuable because they represent the only pCO_2 measurements routinely collected within the Antarctic Circumpolar Current during the austral winter months. Prior to COVID19, the *ARSV Gould* was authorized to make pCO_2 measurements within the Argentine EEZ which extends across the northern half of the Drake Passage; however, during FY21 and FY22 no authorization was submitted. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

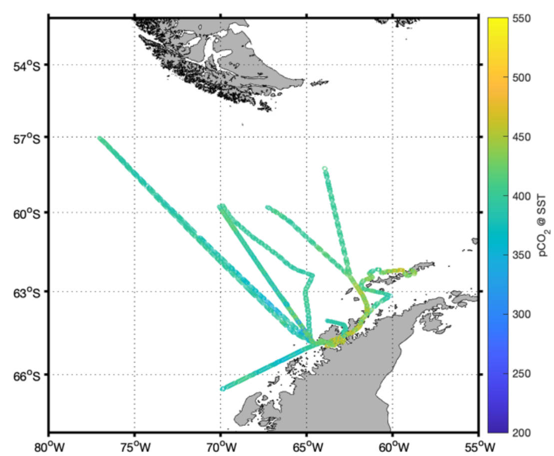

Figure 9. The locations and values of surface water pCO_2 measurements (in µatm) made from the ARSV Gould during FY2022.

Causes for non-return: nearly all data passed QC during FY2022 as indicated by the high rate of return in *Table 1*; limitations on data collection unrelated to the functioning of the pCO_2 system are mainly due to lack of approval to collect data within the EEZ's of Argentina and Chile.

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

Data Site: http://www.ldeo.columbia.edu/CO2.
Number of cruises: *5*
Number of fCO_2 data points: *28,940*
Data return: *98.0%*

Description: The *USCGC Healy* one of the few US ships that operates primarily in the Arctic Ocean. Scientific activities including the pCO_2 program typically begin in June and finish by November. Because of the lack of research ships operating in the Arctic, this measurement program represents a significant proportion of the Arctic Ocean pCO_2 observations that have been contributed to databases such as SOCAT. In May, a semi-permanent system for continuous high precision atmospheric measurements of CO_2 and CH_4 was installed in a forward storeroom to complement ongoing pCO_2 measurements. This system represents an update to previous systems deployed during past years. In total, 28,940 pCO_2 measurements were obtained during FY2022 which was significantly more compared to the previous year; locations of observations are shown in *Figure 10*. The 2022 field season 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.

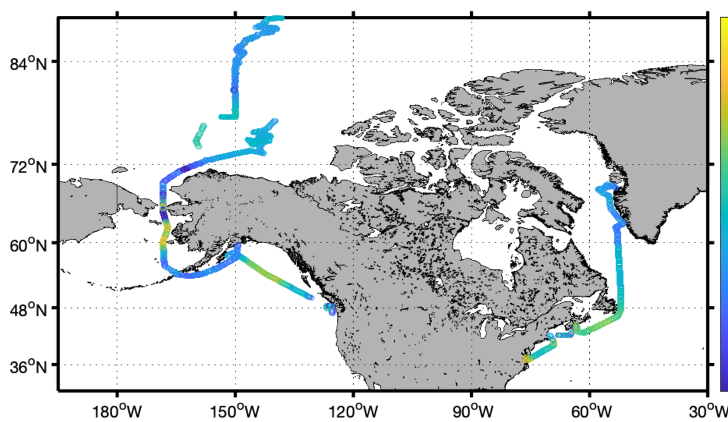

Figure 10. The locations and values of surface water pCO_2 measurements (in µatm) made from the USCGC Healy during FY2022.

Causes for non-return: nearly all data passed QC during FY2022 as indicated by the high rate of return in *Table 1*. The lag between the seawater intake and measurements from the pCO_2 system has consistently been around 15 minutes. The reasons for this change may be related to operation of the ship.

***R/V Sikuliaq* – GML Lead:**

Data Site: http://www.ldeo.columbia.edu/CO2.
Number of cruises: *15*
Number of pCO₂ data points: *65,810*
Data return: *98.0*

Description: The *R/V Sikuliaq* is operated by the University of Alaska with support from NSF. A total of *65,810* pCO_2 measurements were made during FY22 which is very similar to the number of measurements collected during FY21. This pCO_2 program yields observations that help improve understanding of the interactions and exchange of waters from the North Pacific, Bering Sea and the western Arctic Ocean. In February of 2022, a Sunburst AFT-pH system was installed adjacent to the pCO_2 system and a semi-permanent system for continuous high precision atmospheric measurements of CO_2 and CH_4 was installed in a forward storeroom to complement ongoing pCO_2 measurements. Co-PI Munro participated in a cruise off the coast of Oregon in February 2022 to collect discrete samples for validation of the AFT-pH system. Quality-controlled pCO_2 data are submitted to SOCAT and archived at NCEI OCADS for public access.

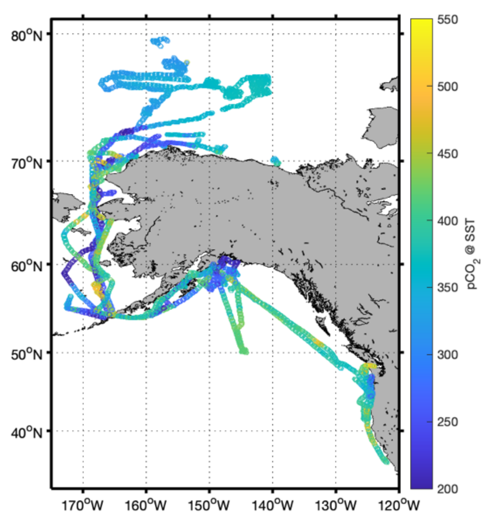

Figure 11. The locations and values of surface water pCO_2 measurements (in µatm) made from the R/V Sikuliaq during FY2022.

Causes for non-return: a small fraction of data failed QC during FY2022 due to low sample gas flow.

R/V *Atlantic Explorer* - BIOS lead

Data Site: **http://www.bios.edu/Labs/co2lab/vos.html**
Number of cruises: *36*
Number of fCO_2 data points: *42,500*
% Data return: *95.0%*

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

The geographic focus of data collection is primarily zone NA06, but included 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 groundtruthing 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.

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 2023.

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 will allow remote intervention and monitoring from BIOS and AOML. For the period of this report, the R/V *Atlantic Explorer* has collected data from thirty-two cruises, totaling 160 sea days of the ship. These cruises include those to BATS and Hydrostation S sites off Bermuda, several five to fifteen days cruises in the subtropical gyre of the North Atlantic Ocean, four transects between Bermuda and Puerto-Rico, and four transects between Bermuda and the US eastern seaboard.

In 2022, only 8 months of sampling so far on the R/V *Atlantic Explorer* occurred due to a long shipyard in the early part of the year. The easing of covid restrictions improved access to the ship. The CO_2-in-air standards were replaced. Minor issues included: (1) the chiller fails when left powered on for a long time and we have a replacement ready to install; (2) issues with the flow meter, but removed and cleaned the impellor, electrical connections have been redone and it is now working well; and, (3) the replacement tubing for the ATM line has been received and and we are waiting for an opportunity when the forward mast is down so that wecan replace the line. Matt Enright received highly useful training with Denis Pierrot and Kevin Sullivan. As with previous years, we are currently QA/QC'ing 2022 data (~16,000 datapoints so far) for early 2023 submission to SOCAT. R/V *Atlantic Explorer* data prior to 2022 is freely available at SOCAT as other GOMO ship underway data.

***Causes for non-return*:** In 2021, a total of ~22,200 pCO_2 measurements have been collected during 32 cruises. In 2022, up to the end of November, a total of ~16,000 pCO_2 measurements have been collected from 36 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.

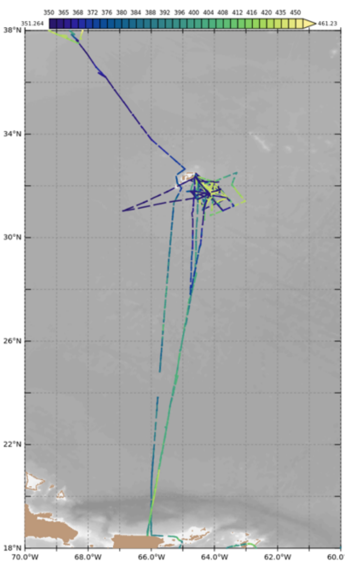

Figure 12. Seawater pCO₂ data from the R/V Atlantic Explorer in SOCAT for FY2022.

At present, we are in the process of undertaking QC/QA of 2022 data for transfer to SOCAT in mid-January 2023. We use protocols for post-cruise QC/QA, but pool the data for submission to SOCAT. We have completed the QC/QA data of cruises already conducted in 2020 and those data have been submitted to SOCAT. Data submitted to SOCAT for FY2022 is shown on *Figure 12*. As part of the BATS award, in 2015, we have now taken over responsibility for the processing of *Atlantic Explorer* underway/TSG data for each cruise rather than the ship Marine Technicians. Two BATS techs are responsible for processing of UW data and they are working with the AOML group to merge the pCO_2 data with position, temperature, and salinity data. The task of processing the underway data has not been trivial in terms of time and effort (different data binning, etc.,), but as part of the BATS project, we have been working on a new data management architecture for the past year that will serve CTD, bottle, and rate measurement data, as well as UW, and merged pCO_2 data.

Container Ship *MV Oleander* - BIOS lead

Data Site: **http://www.bios.edu/Labs/co2lab/vos.html**
Number of cruises: *0*
Number of fCO_2 data points: *0*
% Data return: *0%*

***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. However, since March 2020, access to the ship has been prohibited due to Covid-19. Fortunately, we have now been allowed access to the ship and in the process of setting up all of the plumbing and electrical supplies on the ship. In a collaboration between AOML and BIOS, a General Oceanics pCO_2 system from NOAA has been installed on the *Oleander* in 2022. However, we are awaiting the installation of a new seawater valve and pump to supply seawater to all the *Oleander* underway systems (e.g., TSG, pCO_2). 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-2023 (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*:** During the last performance period, we will resume data collection on transects between Bermuda and New Jersey in early 2023. 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. The original seawater line had no strainer installed on the inflow line and as the plumbing corroded, dhe debris flowed into the pump and destroyed the impellor. The impellor and corroded pipe have been replaced and a strainer has been installed. Once we get the sea cock valve installed, Matt will test this part of the system. The CO_2-in-air standards have been delivered to Charlie Flagg in New York city with installation planned for the *Oleander* in early December during the *Oleander* visit to the New Jersey dock. Once we have seawater flow, installing the system with Denis Pierrot will be the next step in early 2023. Initially we will only have water samples with no atmospheric line as yet. The *Oleander* engineers know that we will be installing the ATM line, but we have found it best to advance slowly one issue at a time when dealing with the ship operators. We have also had support with computer/internet networking issue on the ship from the BIOS marine technician team.

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

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *10*
Number of fCO₂ data points: *19,727*
% Data return: *97.0%*
Number of days at sea with data collected: 92

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 $p$$CO_2$ system has been installed onboard the *Walton Smith* since the beginning of July 2008. The installation is a close collaboration with AOML for system maintenance, data retrieval, reduction and archiving. The data collected by the $p$$CO_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.

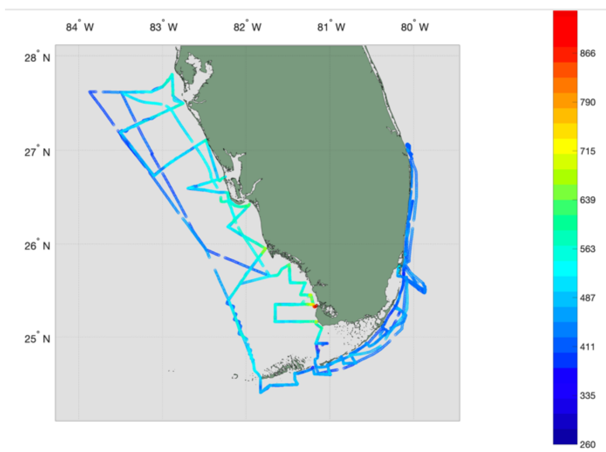

Figure 13. $f$$CO_2$ values along the tracks of the R/V Walton Smith for fiscal year 2022.

Causes for non-return: This fiscal year, the $p$$CO_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, except for a big break to rebuild the engine in April and May 2022.

TSG Operation – AOML/SOOP Lead

During FY2022 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 13 ships of the NOAA fleet (*RV Bell M. Shimada, RV Fairweather, RV Gordon Gunter, RV Henry Bigelow, RV Nancy Foster, 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. Additionally, TSG data was collected from MV Oleander but data processing and distribution were affected by personnel availability. From the ships of the NOAA fleet collecting TSG data during FY2022, 30% also collected pCO_2 observations.

Approximately 1 million TSG records (corresponding to more than 355,000 records with 3 minute temporal resolution) were processed at NOAA/AOML during FY2022 (Figure 14), and distributed through several data centers including NOAA's National Centers for Environmental Information (NCEI) and Global Ocean Surface Underway Data (GOSUD).

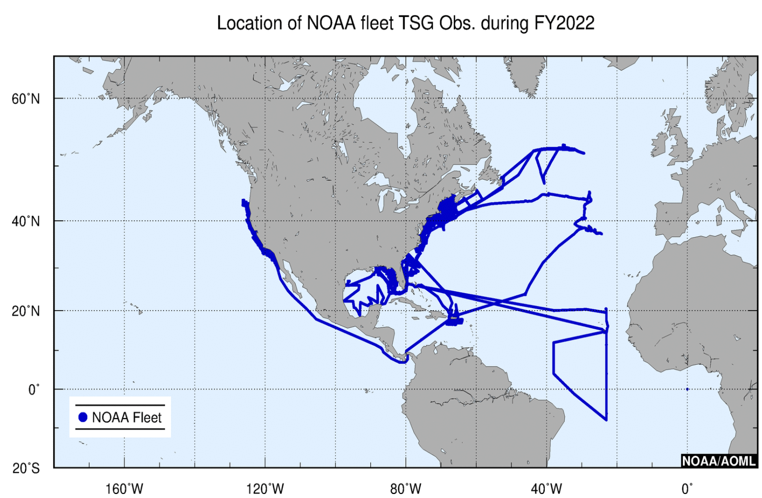

Figure 14. Location of more than 355,000 TSG observations (3-min. resolution) received and processed by NOAA/AOML during FY2022 from 13 ships of the NOAA fleet.

NOAA/AOML continues the partnership with the University of Miami's Rosenstiel School of Marine, Atmospheric & Earth Science (Rosenstiel), 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 Rosenstiel 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 / Rosenstiel. *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. However no data were obtained from these ships during FY2022 as restrictions to access the ship for maintenance still persist.

During FY2022 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.

TSG data were also received from 13 ships of the NOAA fleet. Data from these ships are mostly located in coastal regions of the U.S., with several cruises covering larger regions of the North Atlantic, 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 15*).

Despite some restrictions to travel and ship access that still affected the TSG operations during FY2022, a considerable 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 ships collecting data. 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.

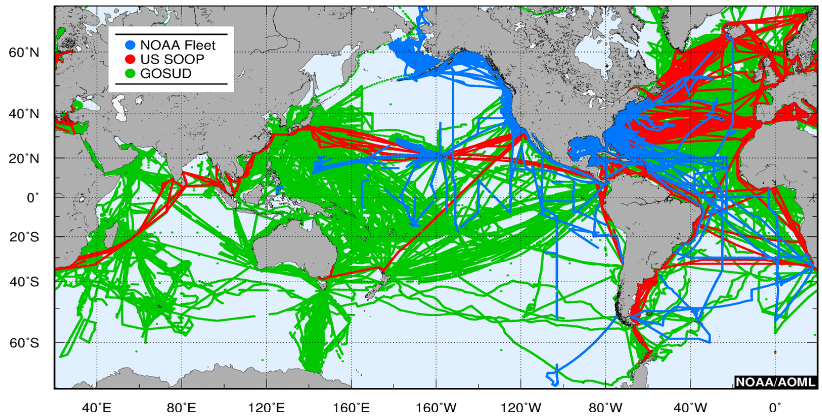

Figure 15. Location of all TSG observations in GOSUD since 2000. TSG data obtained from ships of the US-SOOP and the NOAA fleet represent approximately 20% of all global TSG records in GOSUD.

During FY2022, members of the NOAA/AOML team increased 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 pCO2 observations. These include Francis Bringas who was co-chair of the Ship Of Opportunity Program Implementation Panel (SOOPIP) and member of the GOSUD Steering Group, and Denis Pierrot who became 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. The focus in FY2022 has been on coordination and implementation of real-time data transmission that is being implemented by the groups in the NOAA consortium, and determining quality of air xCO_2 data. SOCONET investigators are working with others on a near-real-time automated QC product called Quince (Jones, pers. comm.). Significant coordination activities are undertaken focusing on harmonizing NOAA efforts on SOOP, mooring, and ASVs, and interactions with partners as described above. The component has been labelled NOAA-SOCONET and US-SOCONET, respectively. A NOAA SOCONET transition plan lead by Jennifer Lewis (Senior International Analyst, on rotation to AOML) is being prepared.
International engagement has commenced through the G7 FSOI, IOCCP and European partners.

The efforts are currently implemented 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) 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). The effort was highlighted by NOAA administrator Dr. Rick Spinrad at the United Nations Conference of the Parties COP-26, and described in an official fact sheet about NOAA's climate science and services work, prepared for COP26 (https://www.climate.gov/sites/default/files/2021-11/NOAA-Fact-Sheet-Climate-Smart-Decisions-in-Our-Changing-World-110121.pdf).

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 R/V 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. 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.

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 plan to re-install the Takahashi system onboard the *RV Brown* for A16N to continue the comparison.

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 GCP 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.

Dr. Wanninkhof was the surface water CO_2 representative of the scientific steering group of IOCCP and rotated off in FY21. He continues to advocate for improved coordination, data quality and dissemination of surface water data and metadata following Best Practices. He is a member of the scientific advisory board of ICOS and has facilitated interactions with the ICOS Ocean thematic center and the NOAA consortium under aegis of SOCONET. He was co-chair of the Integrated Ocean Coordination Research (IOC-R) effort of IOC/UNESCO until March 2022 that is integrating the ocean carbon research efforts executed by SOLAS, IMBER, GCP,

CLIVAR and IOCCP to provide the pertinent deliverables of the UN and the United Nations Decade of Ocean Science for Sustainable Development. He has provided overviews of IOC-R at 8 meetings at NOAA, national and international programs.
Dr. Barbero is a member of the U.S. GO-SHIP science committee and co-chair of international GO-SHIP. She also is active in outreach activities. In FY22 she participated as a trainer in the Regional Training Workshop on Carbonate System Measurements for Evaluating Marine Acidity (Sustainable Development Goal Indicator 14.3.1). The course, sponsored by the International Atomic Energy Agency and IOC UNESCO, hosted students from 17 countries from Latin America and the Caribbean.
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.
Again in FY22, Dr. Alin was invited to do an engagement interacting with Stanford University students studying the ocean.

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**

Berghoff, C.F., **Pierrot**, D., Epherra, L., Silva, R.I., Segura, V., Negri, R.M., Hozbor, M.C., Carignan, M.O., **Barbero**, L. and Lutz, V.A. (2023) Physical and biological effects on the carbonate system during summer in the Northern Argentine Continental Shelf (Southwestern Atlantic). Journal of Marine Systems 237, 103828.

Boyer, T., H.-M. Zhang, K. O'Brien, J. Reagan, S. Diggs, E. Freeman, H. Garcia, E. Heslop, P. Hogan, B. Huang, L.Q. Jiang, A. Kozyr, C. Liu, R. Locarnini, A. Mishonov, C. Paver, Z. Wang, M. Zweng, S. **Alin**, L. **Barbero**, J.A. Barth, M. Belbeoch, J. Cebrian, K. Connell, R. Cowley, D. Dukhovskoy, N.R. Galbraith, G. **Goni**, F. Katz, M. Kramp, F. Katz, A. Kumar, D. Legler, R. Lumpkin, C.R. McMahon, D. **Pierrot**, D. J. Plueddemann, E.A. Smith, A. Sutton, V. Turpin, L. Jiang, V. Suneel, R. **Wanninkhof**, R.A. Weller, and A.P. Wong (2022): Effects of the pandemic on observing the global ocean. Bull. Am. Meteorol. Soc., accepted.

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Gregor, L., Hauck, J., Le Quéré, C., Luijkx, I.T., Olsen, A., Peters, G.P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J.G., Ciais, P., Jackson, R.B., Alin, S.R., Alkama, R., Arneth, A., Arora, V.K., **Bates**, N.R., Becker, M., Bellouin, N., Bittig, H.C., Bopp, L., Chevallier, F., Chini, L.P., Cronin, M., Evans, W., Falk, S., **Feely**, R.A., Gasser, T., Gehlen, M., Gkritzalis, T., Gloege, L., Grassi, G., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Houghton, R.A., Hurtt, G.C., Iida, Y., Ilyina, T., Jain, A.K., Jersild, A., Kadono, K., Kato, E., Kennedy, D., Klein Goldewijk, K., Knauer, J., Korsbakken, J.I., Landschützer, P., Lefèvre, N., Lindsay, K., Liu, J., Liu, Z., Marland, G., Mayot, N., McGrath, M.J., Metzl, N., Monacci, N.M., **Munro**, D.R., Nakaoka, S.I., Niwa, Y., O'Brien, K., Ono, T., Palmer, P.I., Pan, N., **Pierrot**, D., Pocock, K., Poulter, B., Resplandy, L., Robertson, E., Rödenbeck, C., Rodriguez, C., Rosan, T.M., Schwinger, J., Séférian, R., Shutler, J.D., Skjelvan, I., Steinhoff, T., Sun, Q., Sutton, A.J., Sweeney, C., Takao, S., Tanhua, T., Tans, P.P., Tian, X., Tian, H., Tilbrook, B., Tsujino, H., Tubiello, F., van der Werf, G.R., Walker, A.P., **Wanninkhof**, R., Whitehead, C., Willstrand Wranne, A., Wright, R., Yuan, W., Yue, C., Yue, X., Zaehle, S., Zeng, J. and Zheng, B. (2022) Global Carbon Budget 2022. Earth Syst. Sci. Data 14, 4811-4900.

Long, M.C., et al. including **C. Sweeney** and **D. Munro** (2021), Strong Southern Ocean carbon uptake evident in airborne observations. Science **374**: 1275–1280. doi:10.1126/science.abi4355

Osborne, E., Hu, X., Hall, E.R., Yates, K., Vreeland-Dawson, J., Shamberger, K., **Barbero**, L., Martin Hernandez-Ayon, J., Gomez, F.A., Hicks, T., Xu, Y.-Y., McCutcheon, M.R., Acquafredda, M., Chapa-Balcorta, C., Norzagaray, O., **Pierrot**, D., Munoz-Caravaca, A., Dobson, K.L., Williams, N., Rabalais, N. and Dash, P. (2022) Ocean acidification in the Gulf of Mexico: Drivers, impacts, and unknowns. Progress in Oceanography 209, 102882.

Wanninkhof, R., **Pierrot**, D., Sullivan, K., Mears, P. and **Barbero**, L. (2022) Comparison of discrete and underway CO2 measurements: Inferences on the temperature dependence of the fugacity of CO2 in seawater. Mar. Chem. 247, 104178.

- In preparation

Cosca, C.E., S.R. Alin, A.U. Collins, Y. Takeshita, T. Martz, J. Herndon, and G. Lebon (in preparation). A decade of surface water fCO_2 and pH measurements from container ships transiting the Pacific Ocean, 2010–2019. To be submitted to Earth System Science Data.

Fay, A., et al. including D. Munro, C. Sweeney, R. Wanninkhof, and D. Pierrot (in preparation). An updated climatological mean surface ocean pCO_2, and net sea–air CO_2 flux over the global oceans. To be submitted to Global Biogeochemical Cycles.

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

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.

References:

Antonov, J. I., R. A. Locarnini, T. P. Boyer, A. V. Mishonov, and H. E. Garcia, (2006): World Ocean Atlas 2005, Volume 2: Salinity. S. Levitus, Ed. NOAA Atlas NESDIS 62, U.S. Gov. Printing Office, Wash., D.C.

Bakker, D. C. E., Pfeil, B., Landa, C. S., Metzl, N., O'Brien, K. M., Olsen, A., Smith, K., Cosca, C., Harasawa, S., Jones, S. D., Nakaoka, S.-I., Nojiri, Y., Schuster, U., Steinhoff, T., Sweeney, C., Takahashi, T., Tilbrook, B., Wada, C., Wanninkhof, R., Alin, S. R., Balestrini, C. F., Barbero, L., Bates, N. R., Bianchi, A. A., Bonou, F., Boutin, J., Bozec, Y., Burger, E. F., Cai, W.-J., Castle, R. D., Chen, L., Chierici, M., Currie, K., Evans, W., Featherstone, C., Feely, R. A., Fransson, A., Goyet, C., Greenwood, N., Gregor, L., Hankin, S., Hardman-Mountford, N. J., Harlay, J., Hauck, J., Hoppema, M., Humphreys, M. P., Hunt, C. W., Huss, B., Ibánhez, J. S. P., Johannessen, T., Keeling, R., Kitidis, V., Körtzinger, A., Kozyr, A., Krasakopoulou, E., Kuwata, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lo Monaco, C., Manke, A., Mathis, J. T., Merlivat, L., Millero, F. J., Monteiro, P. M. S., Munro, D. R., Murata, A., Newberger, T., Omar, A. M., Ono, T., Paterson, K., Pearce, D., Pierrot, D., Robbins, L. L., Saito, S., Salisbury, J., Schlitzer, R., Schneider, B., Schweitzer, R., Sieger, R., Skjelvan, I., Sullivan, K. F., Sutherland, S. C., Sutton, A. J., Tadokoro, K., Telszewski, M., Tuma, M., van Heuven, S. M. A. C., Vandemark, D., Ward, B., Watson, A. J., and Xu, S.(2016). A multi-decade record of high-quality fCO_2 data in version 3 of the Surface Ocean CO_2 Atlas (SOCAT), Earth Syst. Sci. Data, 8, 383-413, https://doi.org/10.5194/essd-8-383-2016, 2016.

Eyring, V., Righi, M., Lauer, A., Evaldsson, M., Wenzel, S., Jones, C., Anav, A., Andrews, O., Cionni, I., Davin, E. L., Deser, C., Ehbrecht, C., Friedlingstein, P., Gleckler, P., Gottschaldt, K.-D., Hagemann, S., Juckes, M., Kindermann, S., Krasting, J., Kunert, D., Levine, R., Loew, A., Mäkelä, J., Martin, G., Mason, E., Phillips, A., Read, S., Rio, C., Roehrig, R., Senftleben, D., Sterl, A., Van Ulft, L. H., Walton, J., Wang, S., Williams, K. D. (2016) ESMValTool (v1.0) - a community diagnostic and performance metrics tool for routine evaluation of Earth system models in CMIP. Geoscientific Model Development 9: 1747-1802, doi:10.5194/gmd-9-1747-2016.

Locarnini, R. A., A. V. Mishonov, J. I. Antonov, T. P. Boyer, and H. E. Garcia (2006): World Ocean Atlas 2005, Volume 1: Temperature. S. Levitus, Ed. NOAA Atlas NESDIS 61, U.S. Gov. Printing Office, Wash., D.C.

Monteiro, P., U. Schuster, M. Hood, A. Lenton, N. Metzl, B. Tilbrook, C. Sabine, T. Takahashi, R. Wanninkhof, A. Watson, A. Olsen, M. Bender, J. Yoder and K. Rogers (2010). A Global Sea Surface Carbon Observing System: Assessment of Changing Sea Surface CO_2 and Air-Sea CO2 Fluxes. Sustained Ocean Observations and Information for Society (Vol. 2), . J. Hall, H. D.E. and D. Stammer. Venice, Italy. ESA Publication WPP-306.

Ouyang, Z., Li, Y., Qi, D., Zhong, W., Murata, A., Nishino, S., et al. (2022). The changing CO2 sink in the western Arctic Ocean from 1994 to 2019. Global Biogeochemical Cycles, 36, e2021GB007032. https://doi. org/10.1029/2021GB007032

Rödenbeck, C., Conway, T. J., and Langenfelds, R. L. (2006). The effect of systematic measurement errors on atmospheric CO_2 inversions: a quantitative assessment, *Atmos. Chem. Phys.*, 6, 149-161, https://doi.org/10.5194/acp-6-149-2006.

Rödenbeck, C., Bakker, D. C. E., Gruber, N., Iida, Y., Jacobson, A.R., Jones, S., Landschützer, P., Metzl, N., Nakaoka, S., Olsen, A., Park, G.-H., Peylin, P., Rodgers, K. B., Sasse, T. P., Schuster, U., Shutler, J. D., Valsala, V., Wanninkhof, R., Zeng, J. (2015) Data-based estimates of the ocean carbon sink variability - First results of the Surface Ocean *p*CO2 Mapping intercomparison (SOCOM). Biogeosciences 12: 7251-7278. doi:10.5194/bg-12-7251-2015.

Takahashi, T., et al. (2009), Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans, *Deep -Sea Res II*, *2009*, 554-577, doi:10.1016/j.dsr2.2008.12.009.

Takahashi, T., Sutherland, S. C., & Kozyr, A. (2020). Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed During 1957-2019 (LDEO Database Version 2019) (NCEI Accession 0160492). Version 9.9. NOAA National Centers for Environmental Information.

Wanninkhof, R., R. Feely, A. Sutton, C. Sabine, K. Tedesco, N. Gruber and S. Doney (2012). An integrated ocean carbon observing system (IOCOS). Proceedings, U.S. Integrated Ocean Observing System (IOOS) Summit, Interagency Ocean Observation Committee (IOOC). Herndon, VA, November 13-16, 2012. Community white paper,7

Weiss, R. (1974). Carbon dioxide in water and seawater. The solubility of a non-ideal gas. Mar. Chem., 2, 203-215.

Zeng, J., T. Matsunaga, N. Saigusa, T. Shirai, S.-I. Nakaoka, and Z.-H. Tan (2017), Technical note: Evaluation of three machine learning models for surface ocean CO_2 mapping, Ocean Sci., 13, 303-313, doi:10.5194/os-13-303-2017.

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 is being developed from the LDEO data base following the same interpolation and gridding procedures of the 2009 climatology. The effort is spearheaded by S. Sutherland of LDEO and D. Munro of GML/CIRES. The climatology will be released during 2023.

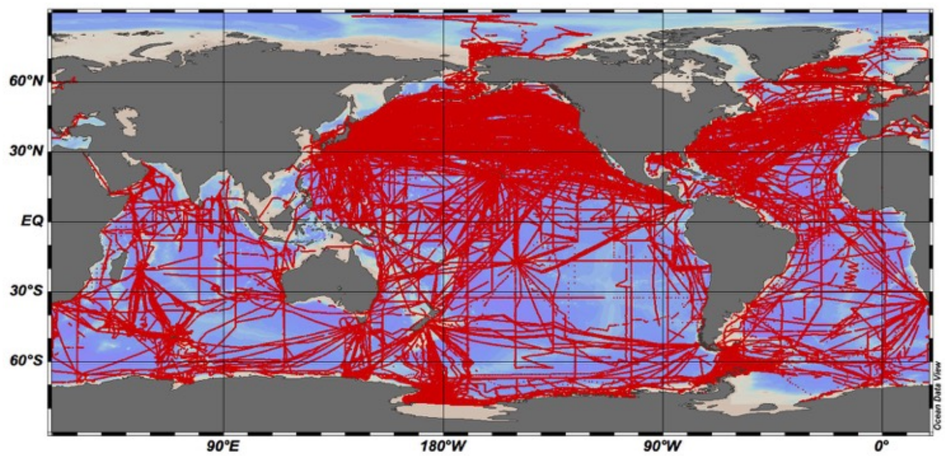

Figure 16. The location of surface water pCO_2 data in the LDEO database archived at the NOAA/NCEI/OCADS*. About 13.5 million data are listed in the uniform format.* (*Takahashi et al., 2020)*

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 FY22 from GOMO-supported PMEL vessels are given below.

Ship	Cruise Name	Expocode	Location	NCEI Accession Number and link
R/V *Thomas G. Thompson*	**TN387**	325020210127	North & South Pacific	0248063
	TN389	325020210316	North Atlantic	0248063
	TN390	325020210420	North Atlantic	0248063
	TN397	325020211119	North Pacific	0248063
	TN398	325020211218	North Pacific	0248063
M/V *Bluefin*	**BF20210311**	331I20210311	North Pacific	0247935
	BF20210413	331I20210413	North Pacific	0247935
	BF20210503	331I20210503	North Pacific	0247935
	BF20210518	331I20210518	North Pacific	0247935
	BF20210527	331I20210527	North Pacific	0247935
	BF20210805	331I20210805	North Pacific	0247935
	BF20210817	331I20210817	North Pacific	0247935
	BF20210829	331I20210829	Tropical Pacific	0247935
	BF20210908	331I20210908	Tropical Pacific	0247935
	BF20210926	331I20210926	North Pacific	0247935
	BF20211008	331I20211008	North Pacific	0247935

AOML provides data to the LDEO pCO_2 climatology effort and 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.

As can be seen in *Figure 17*, the coverage of the world's oceans is substantial.

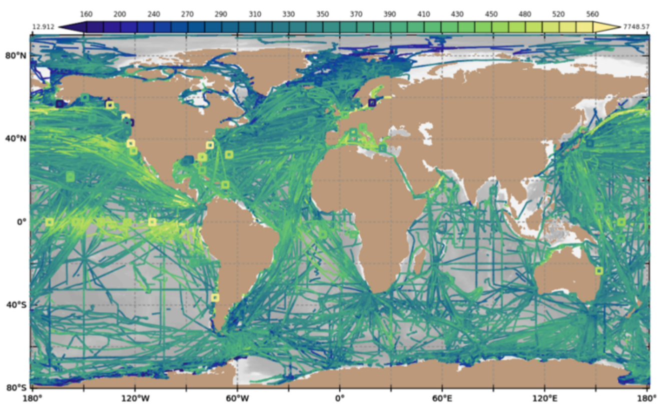

Figure 17. World's coverage of the Surface Ocean CO_2 *Atlas (SOCAT version 2022) database through 2021 (40.1M obs.)*

The contribution from the participants of this program since 2005 (~8.5M obs.) represent about a quarter of all observations (*Figure 18*). 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.

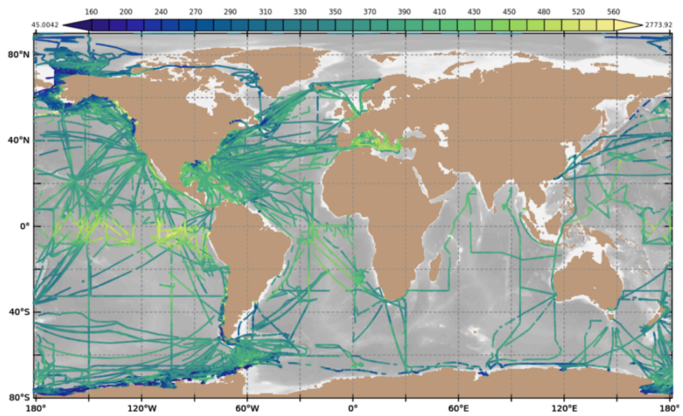

Figure 18. Contribution of this program of 8.5M points since 2005 to the Surface Ocean CO_2 Atlas (SOCAT version 2022) database through 2021

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 v2022 can be found at https://www.socat.info/index.php/products-using-socat/.

6. Project Highlight Slides

See accompanying slides. Accompanying text for slides is below.

6.1. Slide # 2

Finally, PMEL and AOML are collaborating 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 (Figure 19 and 20 below). PMEL PI Richard Feely is leading the paper, which we plan to submit to *Geophysical Research Letters*. 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.

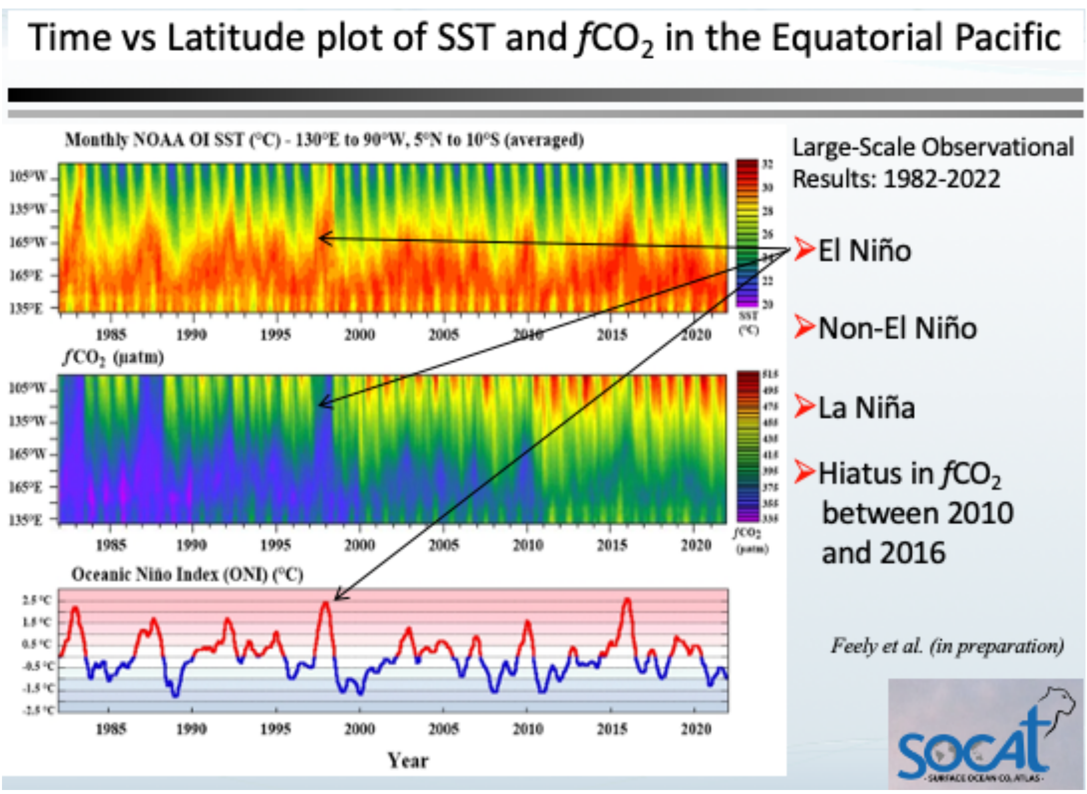

Figure 19. Time-series of sea surface temperature (SST, top in °C); fCO_2 (middle in µatm); and Ocean Niño Index (bottom in Δ°C) for the tropical Pacific Ocean from 1982 through 2021.

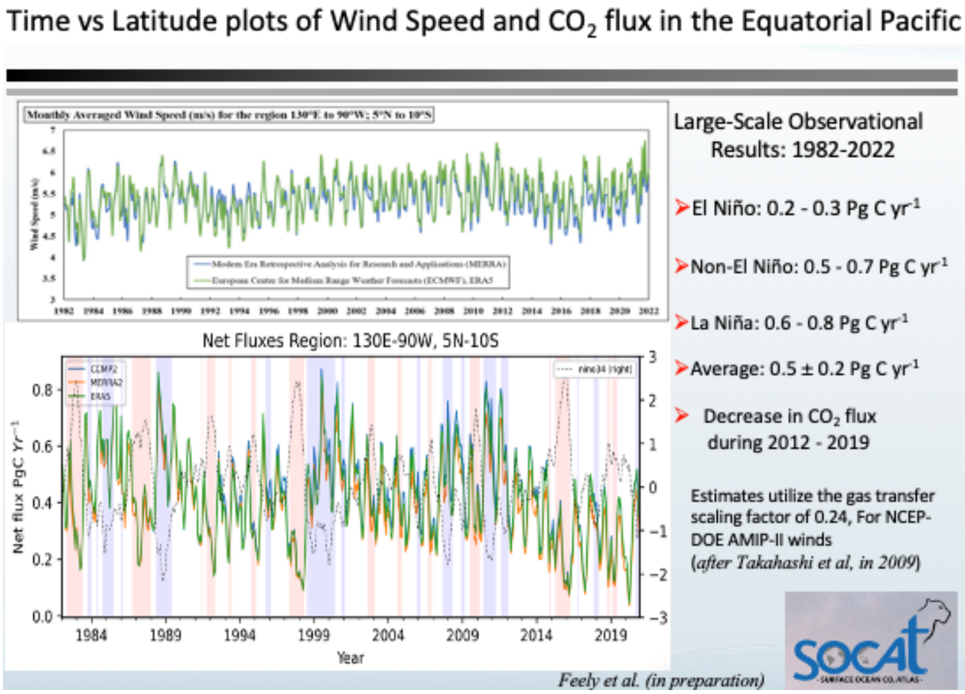

Figure 20. Time-series of monthly average wind speed (Top in m s^{-1}) and CO_2 outgassing flux (bottom in PgC yr^{-1}). The strong El Niños of 1982–83, 1987–88, 1996-97 and 2015–16 are associated with weak trade winds and lower CO_2 fluxes

6.2. Slide # 4

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 have been working on an updated climatological mean pCO_2 following the approach of Takahashi et al. (2009), (2002) and (1997). The new climatology (Fay et al, in prep) 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 (*Figure 21*) is constructed using both the LDEOv2019 and SOCATv2022 databases with several times the number of observations used to create the last climatology (Takahashi et al. 2009). Additionally, the new climatology is constructed using ΔpCO_2 ($pCO_{2oce} - pCO_{2atm}$) rather than pCO_{2oce}, avoiding the time normalization procedure used in Takahashi et al. (2009). The new climatology is compared to commonly used pCO_2 products which have become increasingly important tools in assessments of regional and global sea-air CO_2 flux such as the GCP. 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 and Trinañes, in prep) and a Kalman filter (Munro et al., in prep).

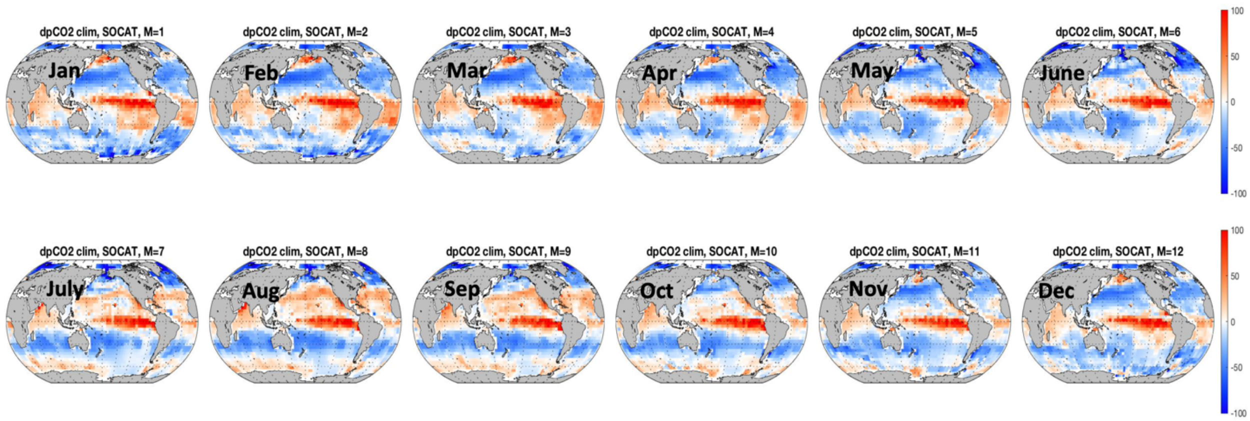

Figure 21. Updated climatological maps of ΔpCO_2 created using the Takahashi approach (Takahashi et al., 2009) and the SOCAT version 2022 database including the more than 8.5 million observations collected by the SOOP pCO_2 from ships program.

6.3. Slide # 5

Constraining Southern Ocean CO_2 uptake with atmospheric measurements from aircraft and ships

The Southern Ocean plays an important role in determining atmospheric CO_2, yet annual mean and time-varying estimates of air-sea CO_2 flux for the region diverge widely. A new analysis from Long et al. (2021) relates air-sea CO_2 fluxes to vertical and horizontal gradients in atmospheric CO_2 collected from aircraft campaigns, surface monitoring stations and ships including the *ARSV Laurence M. Gould*. Both flask samples collected from the *ARSV Gould* and underway atmospheric measurements collected from the NOAA pCO_2 system are utilized in this approach. This analysis relies mainly on aircraft-based measurements of the vertical atmospheric CO_2 gradient, but ship-based measurements that extend from present back to 2005 are also utilized due to extensive temporal coverage (see *Figure 22*). This analysis estimates an annual-mean flux of -0.53 ± 0.23 Pg C yr^{-1} (net uptake) south of 45°S which is consistent with estimates based on ship pCO_2 measurements but represents stronger uptake compared to recent estimates based on profiling-float observations.

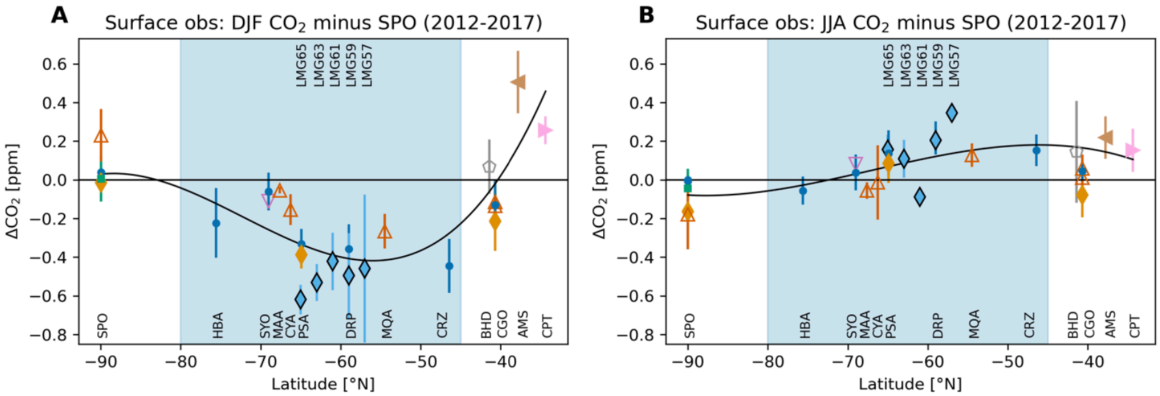

Figure 22. Recreated from Fig. S15 from Long et al. (2021). Compilation of mean CO_2 observed at surface monitoring stations and as sampled from ships minus the NOAA *in situ* record at the South Pole Observatory (SPO) over 2012-2017 for (**A**) winter (DJF) and (**B**) summer (JJA). The black line is a spline fit provided simply as a visual guide. Blue shading denotes the latitude band in which we designate "Southern Ocean stations." This record includes shipboard in situ measurements from the *ARSV Laurence M. Gould* (LMG), from the NOAA equilibrator pCO_2 system (cyan circles with black outlines) and from the NCAR atmospheric O_2 system (cyan diamonds with black outlines). The NOAA LMG data are available from 2005 to the present. The NOAA DRP flask record is collected from this same ship. The NOAA shipboard in situ atmospheric CO_2 data are available in the ObsPack GV+ v7.0 product (http://doi.org/10.25925/20210801).