FY-2021 Progress Report

Surface water pCO_2 measurements from ships

Period of Activity: 01 October 2020 – 30 September 2021

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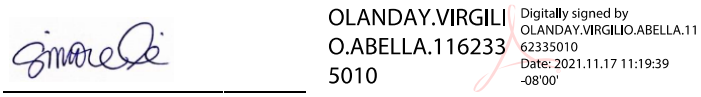
BUDGETS SUMMARY: Oct. 1, 2020 - Sept. 30, 2024

	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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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., 2021). 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 15 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 2021; Bakker et al., 2016) coordinated under the auspices of the International Ocean Carbon Coordination project (IOCCP). Approximately a quarter of the SOCAT version 2021 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 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., 2021; Feely et al., 2021), and annual updates on the state of the carbon cycle (Friedlingstein et al., 2021) 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 (RSMAS) 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 2021 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,* and UNOLS research vessels *Atlantic Explorer* (ship owned and operated by BIOS) and *Walton Smith* (owned and operated by RSMAS). This effort is the largest single coordinated entity of obtaining surface water CO_2 data in the world. Currently approximately 480,500 new data points are acquired each year (*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 a few which has at least a partial year last year 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-2021. Total Observations: ~ 480,500

SHIP	# Cruises	# Data Points	% Recovery*
R/V Brown	*6*	*70,603*	*98.3%*
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	*8*	*44,765*	*81.7%*
R/V Bigelow	*9*	*64,145*	*97.2%*
R/V Walton Smith	*16*	*42,980*	*95.7%*
R/V Thompson	*2*	*25,953*	*99%*
R/V Bluefin	*11*	*75,750*	*98.0%*
RVIB Palmer	*3*	*18,974*	*99.2%*
R/V Gould	*2*	*4,258*	*99.9%*
USCGC Healy	*3*	*24,428*	*99.7%*
R/V Sikuliaq	*16*	*65,063*	*98.9%*
R/V Atlantic Explorer	*36*	*43,600*	*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: 51
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):
in 2021: 55
in 2020: 56
Number of updated products: 3 (SOCATv2021, BAMS SoC and Global Carbon Budget (GCB 2021).

***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: *70,603*
% Data return: *98.3%*

Description: The cruise tracks for each cruise of the *Brown* for FY 2021 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_2021.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.

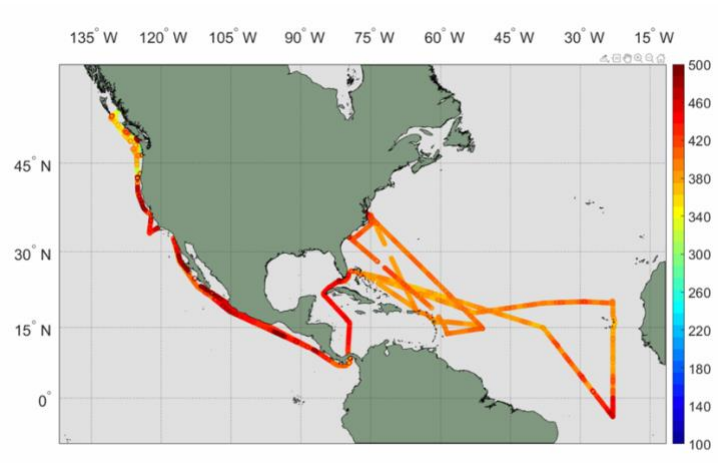

Figure 1. R/V Ronald H. Brown cruise tracks and surface fCO_2 values for FY 2021.

Causes for non-return: This installation had some minor data losses partly due to human error but also some electrical issues and gas flow pump problems. These issues were resolved quickly and the data loss was kept to a minimum. The data return remains excellent. The pandemic has made organizing cruise very difficult with stringent COVID safety procedures to follow and Shelter-in-place periods taking a substantial amount of time out of the science but the *Brown* managed to perform a full schedule, although the ship did not do any international travel. The international cruises that were not done in 2020 will be done starting in 2022. Even though our data return is back to pre-COVID level, the surface coverage was limited this year.

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 and Atmospheric 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).
The ship did not sail during FY2021. Operations should resume in FY2022.

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 and Atmospheric 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: The ship did not sail during FY2021. Operations should resume in FY2022.

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 and Atmospheric 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: The ship did not sail during FY2021. Operations should resume in FY2022.

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

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *8*
Number of fCO_2 data points: *44,765*
% Data return: *81.7%*

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 *f*CO_2 measurements reported at sea surface temperature. The system has been working very reliably.

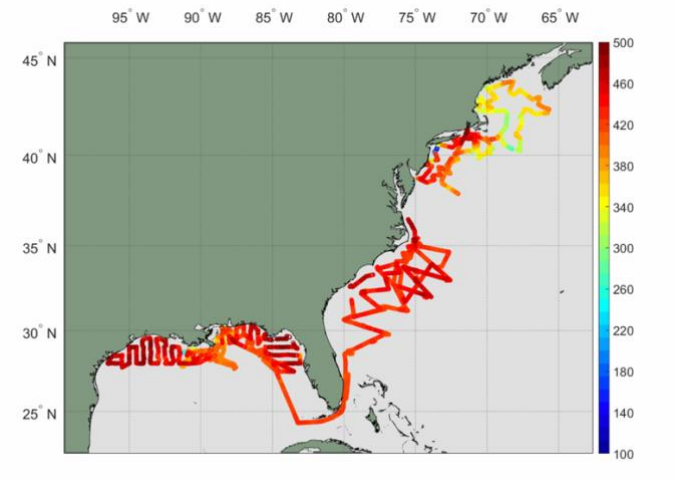

Figure 2. NOAA ship Gordon Gunter cruise tracks and surface fCO₂ values for FY 2021.

***Causes for non-return*:** The system is maintained by a field operation officers who rotate quite frequently. However, we manage to give them some training remotely and they are able to maintain the system very effectively. We also obtain great support from the ETs on board. Similar to the *Ronald H. Brown*, we experienced some electrical failures which shutdown the system several times until we were able to diagnose the origin of the failures. Overall, the system performed very well. This fiscal year, the Gunter performed a full schedule of cruises and our data return is back to pre-pandemic levels.

***R/V 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: *64,145*
% 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.

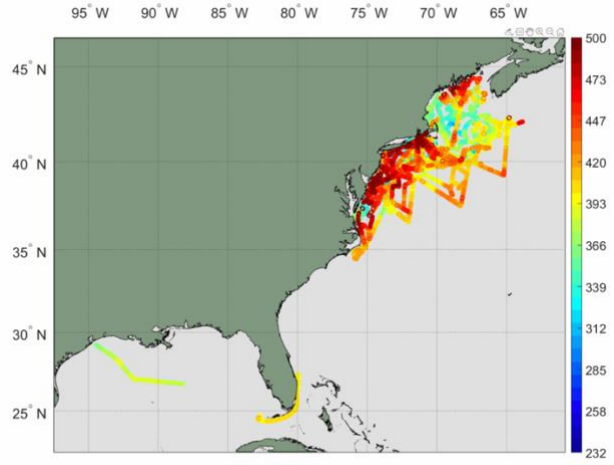

Figure 3. NOAA ship Henry Bigelow cruise tracks and surface fCO_2 values for FY 2021.

***Causes for non-return*:** The system performed very well this fiscal year. The only issue we had was the atmospheric air line intake which was re-installed upside down after the dry dock period and introduced water into the system. A new air line was promptly re-installed with the help of the ship. Also this year, the ship experienced unusually long period of severe weather which delayed its operations for several days but the amount and percent data return stayed high. Like all the NOAA ships, the *Bigelow* performed a full schedule of cruises this fiscal year.

R/V *Bluefin* - PMEL lead

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises:~ *11*(to be confirmed)
Number of fCO_2 data points: *75,750*
% Data return: *98.0%*
Days at sea w/instrument running: *approx.* 219

Description: In FY2017, PMEL successfully installed an underway pCO_2 system on the R/V *Bluefin* and collected fCO_2 measurements to continue a three(-and-a-half)-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 an excellent data return of 98% in FY2021, based on preliminary analysis of data in hand. All data collected on the *Bluefin* during FY2021 (*Figure 4*) are in preliminary processing and will be submitted to SOCAT in advance of the January 2022 deadline, to NCEI for archiving, and posted to the PMEL CO_2 website.

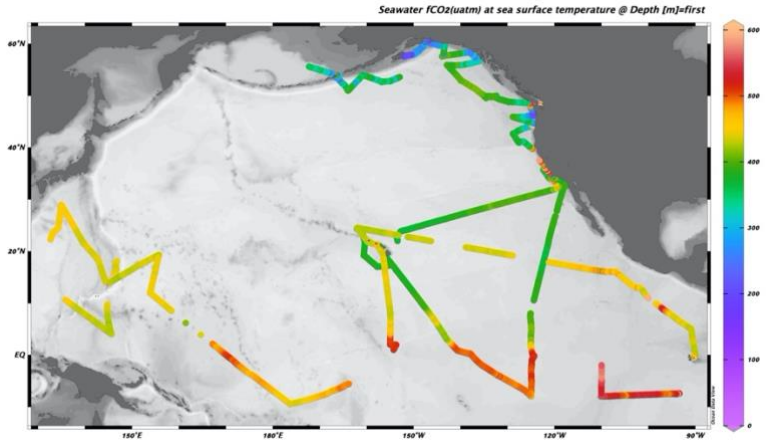

Figure 4. fCO2sw (µatm) measurements collected from the Bluefin in the Pacific Ocean, FY2021

Causes for non-return: Our biggest challenge with respect to processing of FY2021 data is that sometimes the FTP system does not transfer files, so we have some large apparent data gaps (e.g., between Dutch Harbor, AK, and Guam). We expect we will be able to recover much or all of the currently missing data once we can access the data onboard the *Bluefin* after it returns to Seattle. COVID-19 did not significantly impact data collection on this platform for FY2021, other than preventing access to the ship for routine service.

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

Data Site:
https://www.pmel.noaa.gov/co2/story/CO2+Data+Discovery
Number of cruises: *2*
Number of fCO_2 data points: *25,953*
% Data return: *99%*

Description: In FY2019, PMEL successfully installed an underway fCO_2 system on the R/V *Thomas G. Thompson* in support of the IO6 Repeat Hydrography cruise. This underway system continues to operate, collecting fCO_2, *p*H, and O_2 data across multiple ocean basins, with FY2021 seeing the successful completion of GO-SHIP cruises A20/A22. All data collected on the *Thompson* are in the final processing stage and will be submitted to NCEI for archiving, to SOCAT prior to the January 2022 deadline, and posted to the PMEL CO_2 website.

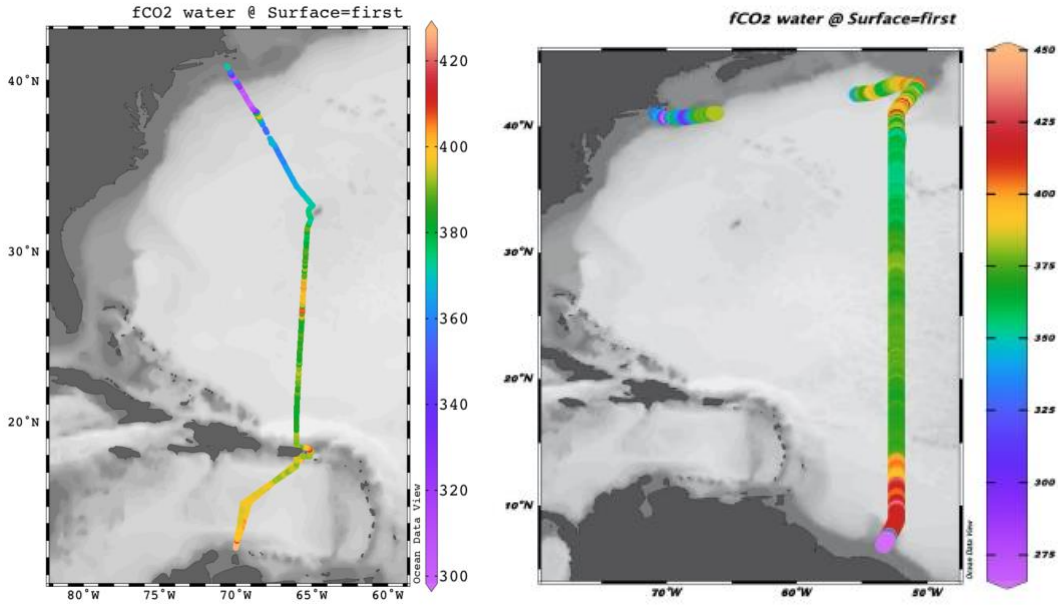

Figure 5. fCO_2sw (µatm) measurements collected from the R/V *Thomas G. Thompson* during GO-SHIP cruises A22 (left) and A20 (right), FY2021. The A20 research cruise took place March 16–April 16, 2021, and A22 occurred during April 20–May 16, 2021, with the pair of cruises starting and ending in Woods Hole, with a between cruise port stop in the U.S. Virgin Islands.

Causes for non-return: The underway fCO_2 system on the *Thompson* had technical problems during much of FY2021. Due to COVID restrictions, we were not able to access the ship in order to repair the system. However, one of our technical staff (Andrew Collins) was onboard during GO-SHIP cruises A20/A22, and we have good data for the duration of his presence on board. All data for FY2021 will undergo final processing and submission to NCEI for archiving in advance of the SOCAT deadline in January 2022. They will subsequently be updated on the PMEL CO_2 website and data portal.

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

Data Site: http://www.ldeo.columbia.edu/CO2
Number of cruises: *3*
Number of pCO_2 data points: *18,974*
% Data return: *99.2%*

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 FY2021, 18,974 pCO_2 measurements were obtained from three research cruises which is slightly less than the total number of measurements obtained in FY2020. Research activities continue to be influenced by disruptions due to COVID19. All measurements from FY2021 are shown in *Figure 6*; measurements during FY2021 were concentrated in waters surrounding the West Antarctic Peninsula. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

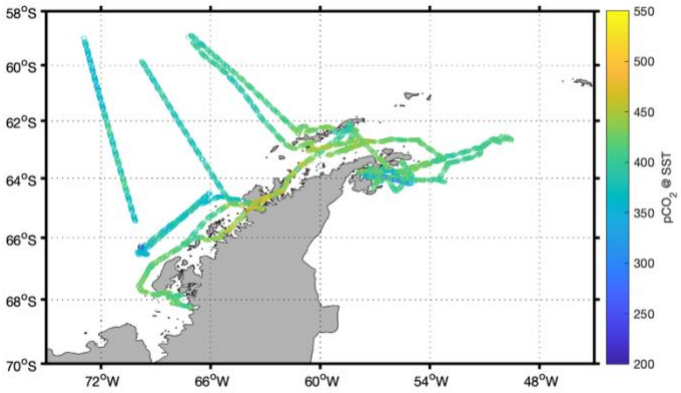

Figure 6. The locations and values of surface water pCO_2 measurements (in µatm) made from the RVIB Palmer during FY2021.

Causes for non-return: nearly all data passed QC during FY2021 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.

***RVIB L. M. Gould* – GML Lead:**

Data Site: http://www.ldeo.columbia.edu/CO2
Number of cruises: *2*
Number of fCO_2 data points: *4,258*
Data return: *99.9%.*

Description: Data collection from the underway pCO_2 system aboard *ARSV Laurence M. Gould* began in March 2002 with observations collected mainly within 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 FY2021, the number of measurements was substantially reduced from previous years due to COVID19. A total of 4,258 pCO_2 measurements were made from the *ARSV Gould* during FY21 (*Figure* 7) which represents only 10% of the total number collected annually. 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 no authorization was possible due to COVID19. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

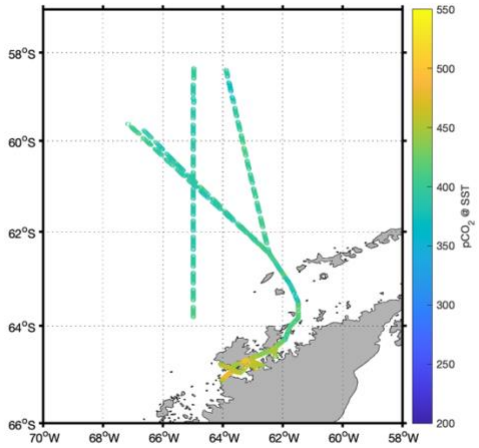

Figure 7. *The locations and values of surface water pCO_2 measurements (in µatm) made from the ARSV Gould during FY2021.*

Causes for non-return: nearly all data passed QC during FY2021 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: *3*
Number of fCO_2 data points: *24,428*
Data return: *99.7%*

Description: *USCGC Healy* is an ice breaker and one of the few US ships that operates primarily in the Arctic Ocean. Scientific activities including the pCO_2 program on this ship are limited to the warmer Northern Hemisphere months with cruises typically occurring from June through October. Because of the lack of research ships operating in the Arctic, this measurement program represents a significant proportion of the Arctic Ocean observations that have been contributed to databases such as SOCAT. pCO_2 measurements from the *USCGC Healy* began in May 2011 and typically include observations in the Pacific Ocean from Seattle, WA across the Gulf of Alaska, in the Bering Sea and the Arctic Ocean. In total, 24,428 pCO_2 measurements were obtained during FY2021 which was slightly less compared to the previous year; locations of observations are shown in *Figure 8*. Several modifications were made to the pCO_2 system on the *USCGC Healy* during FY2021 including installation of a new equilibrator. The 2021 field season included a cruise through waters near Alaska, Canada, and Greenland. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

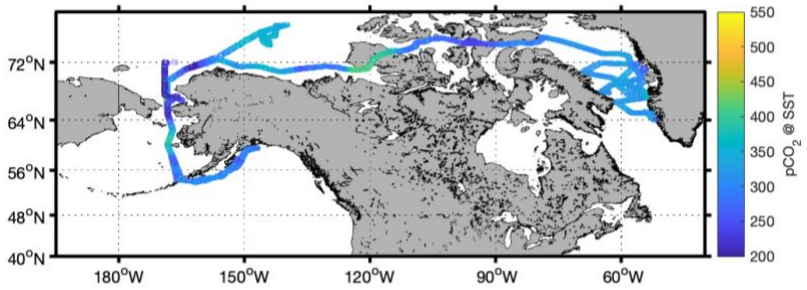

Figure 8. The locations and values of surface water pCO_2 measurements (in µatm) made from the USCGC Healy during FY2021.

Causes for non-return: nearly all data passed QC during FY2021 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: *16*
Number of pCO_2 data points: *65,063*
Data return: *98.9%*

Description: The underway pCO_2 program on the *Comer* family yacht, *M/V Turmoil* was terminated in 2012 because of change in ownership and the Comer Education and Science Foundation agreed to transfer the pCO_2 system to the *R/V Sikuliaq*, which is operated by the University of Alaska with support from NSF. The underway pCO_2 program was started successfully in August 2015. A total of *65,063* pCO_2 measurements were made during FY21 which represents a more than 50% increase from the number of measurements collected last year. Disruptions due to COVID19 were minimal for the *R/V Sikuliaq* during FY21. Several modifications were made to the pCO_2 system on the *R/V Sikuliaq* during FY2021 including installation of a new equilibrator. 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. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

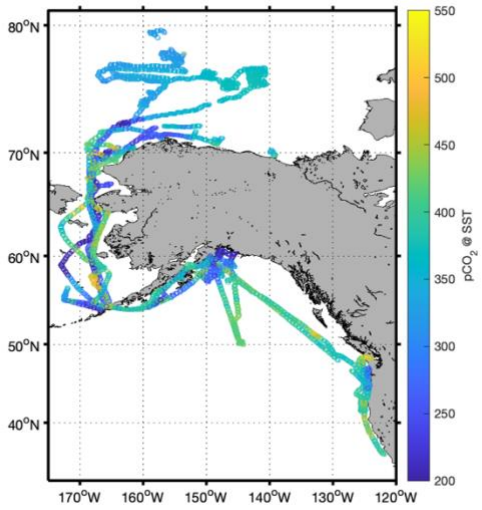

Figure 9. *The locations and values of surface water pCO_2 measurements (in µatm) made from the R/V Sikuliaq during FY2021.*

Causes for non-return: a small fraction of data failed QC during FY2021 due to failure of a temperature sensor within the equilibrator in September 2020.

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: *43,600*
% 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. 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 that results in transects between Bermuda and Norfolk.

A new General Oceanics pCO_2 system (~$75,000) and LiCOR (~$20,000) for the R/V *Atlantic Explorer* has been 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. This is equivalent to the annual funding to BIOS as part of the NOAA pCO_2 network and please note that NOAA funding to BIOS was insufficient to cover the cost of new instrumentation. There is also a contribution of four month of technician time that will be supported by BATS for 2022 as part of the QC/QA effort. This additional cost-in-kind contribution to the NOAA pCO_2 network is approximately ~$32,000 in 2021-2022. In addition to the pCO_2 data stream, we have installed our dissolved oxygen (DO) optode and SAMI pH systems, and a Contros alkalinity system installation in late 2020. At present, we are sorting out the integration of ship navigation, TSG, pCO_2, pH, DO data stream, with a flexible architecture to include alkalinity in 2021.

The new 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 twenty cruises, totaling 135 sea days of the ship. These cruises include those to BATS and Hydrostation S sites off Bermuda, several 5-18 day cruises in the subtropical gyre of the North Atlantic Ocean, four transects between Bermuda and Puerto-Rico, and four transects between Bermuda and Norfolk.

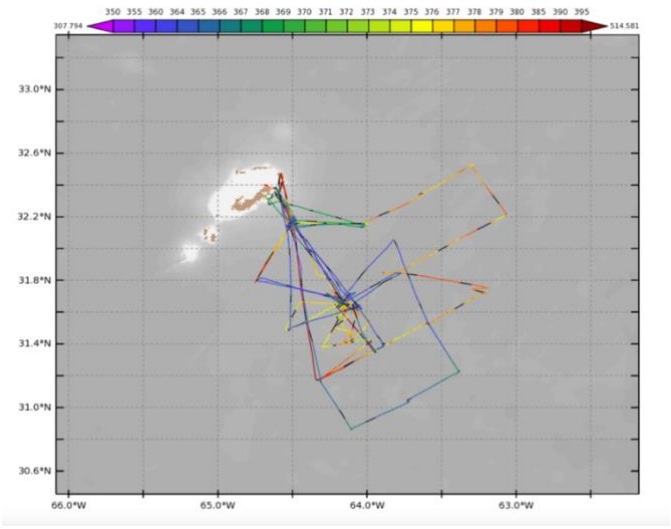

Figure 10. *Seawater pCO_2 data from the R/V Atlantic Explorer in SOCAT for FY2021.*

***Causes for non-return*:** In 2020, a total of ~17,200 pCO_2 measurements have been collected during 21 cruises. In 2021 up to the end of October, a total of 26,400 pCO_2 measurements have been collected from 36 cruises with several other cruises and ~8,000 to 9,000 data points expected to be collected by the end of 2021. 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.

At present, we are in the process of undertaking QC/QA of 2021 data for transfer to SOCAT in mid-December 2021 to mid-January 2022. We are currently setting up the protocols for six monthly 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 FY2021 is shown on Figure 10. 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: *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. 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. We anticipate receiving a General Oceanics pCO_2 system from NOAA AOML in early 2022 that will be installed on the new *Oleander* in early Spring 2022. In addition to the pCO_2 data stream, we have installed our dissolved oxygen (DO) optode and SAMI pH systems, and a possible Contros alkalinity system installation in mid-2022. 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 mid-2022. 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.

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

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *16*
Number of fCO_2 data points: *42,980*
% Data return: *95.7%*
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 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.

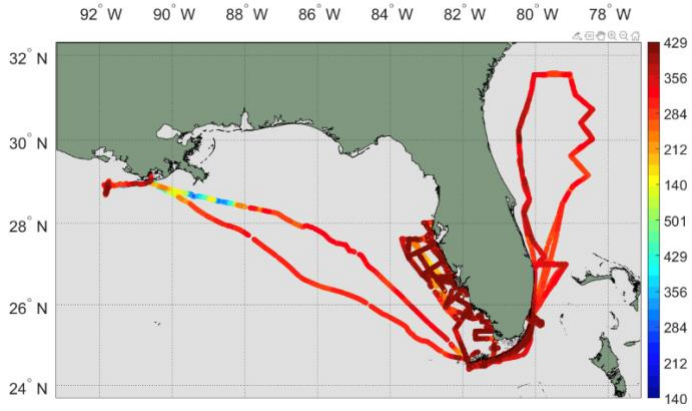

Figure 11. fCO_2 values along the tracks of the R/V Walton Smith for fiscal year 2021.

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 started sailing promptly in August 2020 as the University of Miami reopened its doors to in-person classes. Therefore, COVID did not affect the data from this ship much and the data return has been similar to pre-pandemic levels.

TSG Operation – AOML/SOOP Lead

During FY2021 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 6 ships of the NOAA fleet (*RV Henry Bigelow*, *RV Okeanos Explorer*, *RV Fairweather*, *RV Ronald H. Brown*, *RV Bell M Shimada*, *RV Oscar Elton Sette*, *RV Reuben Lasker*, and *RV Gordon Gunter*), 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 was not possible due to restrictions to visit the ships. From the ships of the SOOP and the NOAA fleet collecting TSG data during FY2021, 60% also collected pCO_2 observations.

Approximately 8 million TSG records (corresponding to more than 250,000 records with 3 minute temporal resolution) were processed at NOAA/AOML during FY2021 (*Figure 12*), and distributed through several data centers including NOAA's National Centers for Environmental Information (NCEI) and Global Ocean Surface Underway Data (GOSUD).

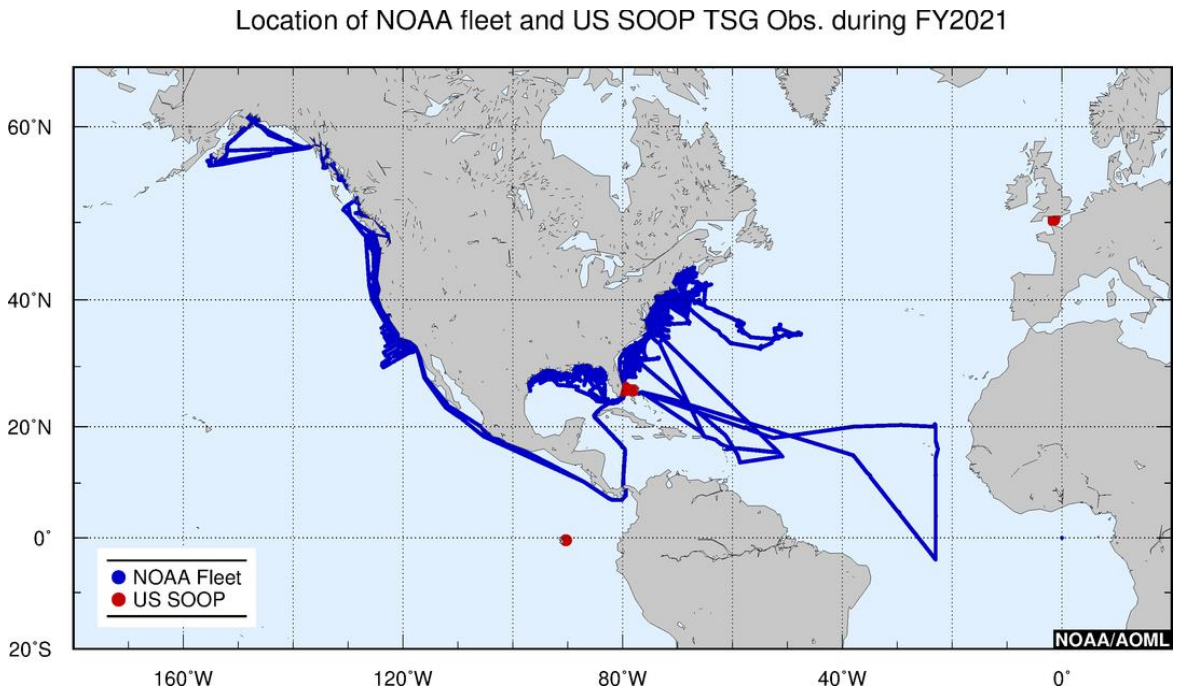

Figure 12. Location of more than 250,000 TSG observations (3-min. resolution) received and processed by NOAA/AOML during FY2021 from 6 ships of the NOAA fleet.

The TSG operation on three Royal Caribbean cruise ships *Allure of the Seas*, *Flora* and *Equinox* were halted during FY2021. This operation is a collaboration between NOAA/AOML and the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS), in

which NOAA/AOML provides the TSG instruments, equipment calibration, as well as data processing and distribution, while RSMAS scientists conduct the installation and operation of the system. These three ships also have pCO_2 systems installed.

During FY2021 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 6 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 13*).

Restrictions in travel and ship access due to COVID-19 have affected the TSG operations during FY2021. While the number of observations received during FY2021 from the NOAA fleet represent a considerable increase from those received during FY2020, data processing and distribution from ships of the SOOP were more severely affected. Work is currently underway to resolve this situation and a large increase in data collection and distribution is expected for FY2022.

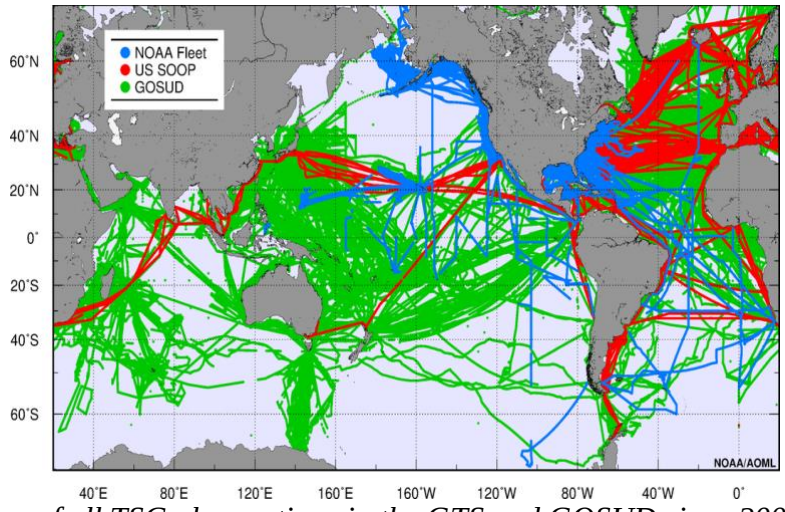

Figure 13. Location of all TSG observations in the GTS and GOSUD since 2000. TSG data obtained from ships of the US-SOOP and the NOAA fleet represent approximately 20% of all global TSG records in GOSUD.

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 FY2020 and FY2021 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.). Air values have been checked on the Brown with a portable reference system operated by GML scientists that was deployed on the Brown in FY-19. It is planned to be put on the Healy during FY20 to get quality air values in the Arctic.

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.
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 Ron 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. This experiment will continue until early 2022 with comparisons over a wide range of environments from the Gulf of Mexico and the tropical Atlantic to mid latitude waters in the Southern Hemisphere.

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.
Bates is a member of the Scientific Steering Group for the US Carbon Cycle Interagency Working Group.
Drs. Pierrot, Wanninkhof, Alin, and Ms. Cosca 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 trained a group of Argentinian scientists in Argentina and in Miami in the proper operation and data treatment of their newly acquired GO system. He also helped them acquire a Total Alkalinity system and provided them with the software to control it. He is still in contact with them and act as consultant.
Dr. Pierrot participated in a data reduction workshop organized by ICOS OTC. He also gave an overview of the SOOP-CO_2 program at the Ship Observations Team 11th Session of the GOOS Observations Coordination Group, a WMO and IOC event.
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 is co-chair of the Integrated Ocean Coordination Research (IOC-R) effort of IOC/UNESCO 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.
PMEL Carbon Group PIs are actively involved in education and outreach activities. As an example of a local education/outreach partnership, we have recently reinstalled an underway CO_2 analysis system to measure atmospheric and seawater pCO_2 at the Seattle Aquarium 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. A major goal is to empower local students from underserved communities to understand how climate and ocean change are relevant to their regional environment and to have awareness from an early age of the many ways they might become part of the solution to ocean and climate challenges.

Dr. Alin, along with Dr. Jessica Cross, contributed to planning keynote and science sessions at the 7th Open Science Meeting for the North American Carbon Program. The opening keynote featured a panel of young BIPOC climate leaders, moderated by the Director of Partnerships at Project Drawdown, describing how the carbon science community can engage with various communities respectfully and effectively to address climate change challenges and/or conduct research in partnership with these communities. Dr. Alin also co-organized/co-chaired, along with Dr. John Kim (USDA) and Dr. Cross, a science session at the North American 7th Open Science meeting on Indigenous Peoples and Multinational Experiences. Finally, Dr. Alin worked with Dr. Sarah Cooley to plan a breakout session on science communication with non-specialist audiences; the outstanding panelists from our science communication breakout gave great advice for anyone needing a sci-comm tune-up.

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.

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**

Alin, S.R., A.U. Collins, B.R. Carter, and R.A. Feely, 2021: Ocean acidification status in Pacific Ocean surface seawater in 2020 [in "State of the Climate in 2020"]. Bull. Amer. Meteor. Soc., 102 (8), S184–S185, https://doi.org/10.1175/ BAMS-D-21-0083.1.

Betts, R., C. Burton, R. **Feely**, M. Collins, C. Jones, and A. Wiltshire (2020): ENSO and the carbon cycle. Chapter 20 in El Niño Southern Oscillation in a Changing Climate, M.J. McPhaden, A. Santoso, and W. Cai (eds.), Geophysical Monograph 253, American Geophysical Union, Wiley, 453–470

Feely, R.A., R. **Wanninkhof**, P. Landshutzer, B.R. Carter, J.A. Trinanes, and C. Cosca, 2021: Global ocean carbon cycle [in "State of the Climate in 2020"]. Bull. Amer. Meteor. Soc., 102 (8), S185–S189, https://doi.org/10.1175/ BAMS-D-21-0083.1.

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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 FY21 Data Synthesis annual report

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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 FY17 Work Plan. The Carbon Dioxide Information Analysis Center (CDIAC) ceased operations in September 2017. The Oceanic Trace Gas data (where CO_2 belongs) have been transitioned to the new 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 *p*CO_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 2022.

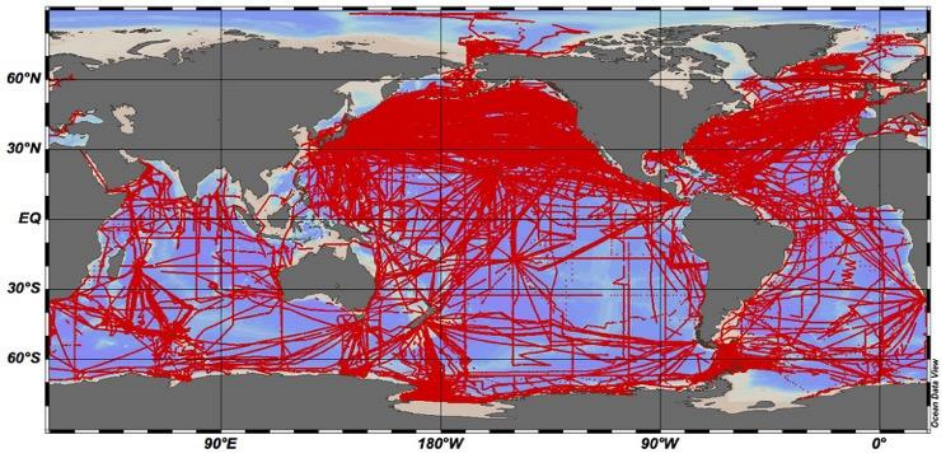

Figure 14. The location of surface water pCO_2 data in the LDEO database archived at the NOAA/NCEI/OCADS. *About 13.5 million data are listed in the uniform format.* (*Takahashi et al., 2020)*

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).

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:

- 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.

As can be seen in *Figure 15*, the coverage of the world's oceans is substantial.

[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.

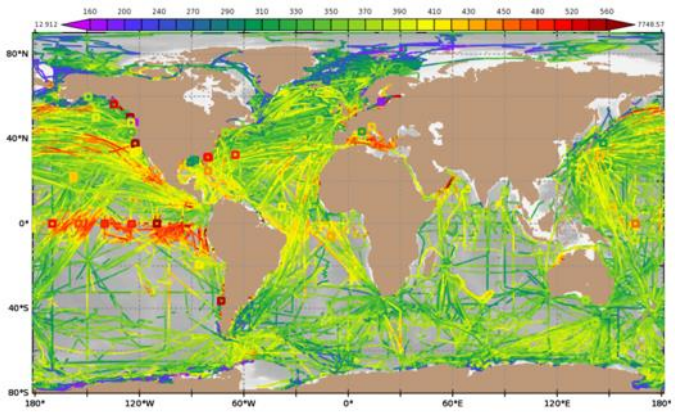

Figure 15. World's coverage of the Surface Ocean CO_2 *Atlas (SOCAT version 2021) database through 2020 (32.7M obs.)*

The contribution from the participants of this program since 2005(~8.4M obs.) represent about a quarter of all observations (*Figure 16*). 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.

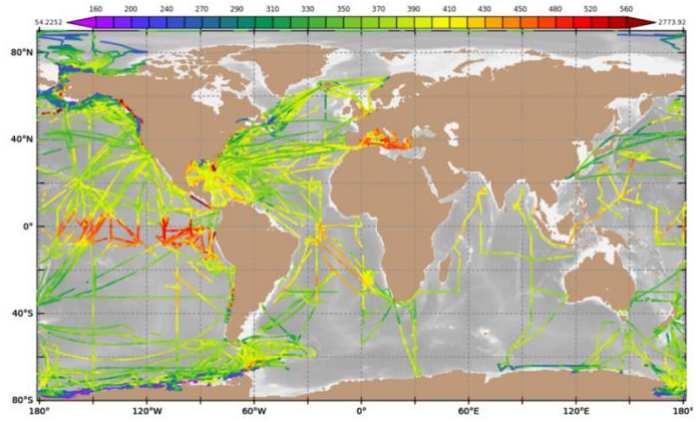

Figure 16. Contribution of this program of 8.4M points since 2005 to the Surface Ocean CO_2 *Atlas (SOCAT version 2021) database through 2020*

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 v2021 can be found at https://www.socat.info/index.php/products-using-socat/.

6. Project Highlight Slides

See accompanying slides

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 17*). 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.

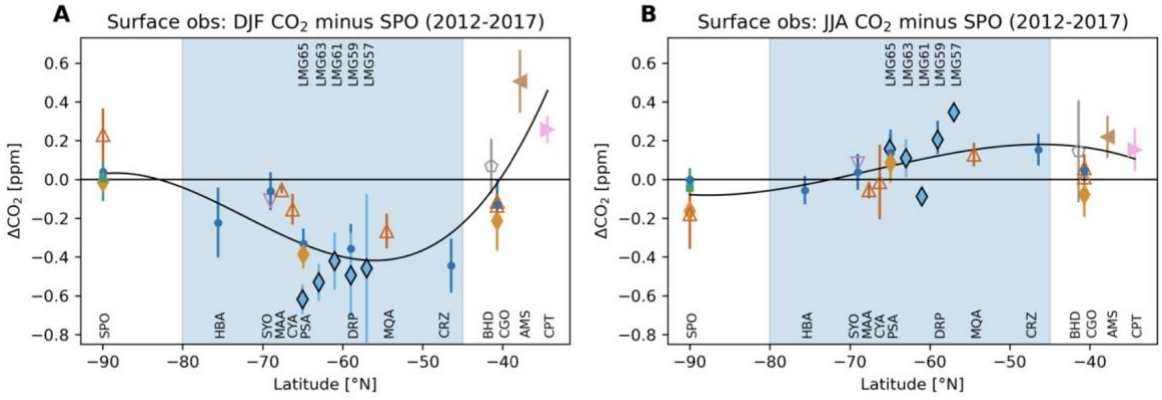

Figure 17. Recreated from Fig. S15 from Long et al. (2021). Compilation of mean CO_2 observed at surface monitoring stations and as sampled from ships minus the NOAA *in situ* record at the South Pole Observatory (SPO) over 2012-2017 for (**A**) winter (DJF) and (**B**) summer (JJA). The black line is 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).