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 2.6 petagrams (i.e., 2.6 x 10^{15} grams or 2.6 gigatons) of carbon each year thereby partially mitigating the rapid increase of this climate forcing gas in the atmosphere (Friedlingstein et al., 2020). 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 climatologies annually that was 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 2020; Bakker et al., 2016) coordinated under the auspices of the International Ocean Carbon

Coordination project (IOCCP). Approximately a third of the SOCAT version 2020 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 large 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 second international Regional Carbon Cycle Assessment Project (RECCAP-2), the annual state of the climate report of BAMS (Feely et al., 2020), and annual updates on the state of the carbon cycle (Friedlingstein et al., 2020) 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).

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 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 2019 performance period: NOAA ships *Ronald H. Brown, Gordon Gunter,* and *Henry B. Bigelow;* Research vessels *Bluefin, Thompson, Palmer*, *Gould, Sikuliaq,* and *Healy*, RCCL 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 550,000 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. Due to the COVID-19 pandemic, many ships were not able to sail, which caused a 30% loss in our number of observations.

Table 1:SOOP Data Summary FY-2020. Total Observations: ~ 550,000

SHIP	**# Cruises**	**# Data Points**	**% Recovery***
R/V Brown	*5*	*40,334*	*93.4%*
M/V Equinox	*23*	*53,361*	*86.6%*
M/V Allure of the Seas	*21*	*52,490*	*91.5%*
M/V Flora	*10*	*28,296*	*93.9%*
R/V Gordon Gunter	*3*	*16,688*	*99.3%*
R/V Bigelow	*3*	*20,096*	*87.7%*
R/V Walton Smith	*7*	*7,700*	*93.0%*
R/V Thompson	*2*	*TBD*	*TBD*
R/V Bluefin	*13*	*102,296*	*82.0%*
RVIB Palmer	*1*	*19,663*	*99.9%*
R/V Gould	*7*	*35,612*	*97.4%*
USCGC Healy	*5*	*26,877*	*99.9%*
R/V Sikuliaq	*7*	*40,281*	*95.7%*
R/V Atlantic Explorer	*20*	*105,000*	*95.0%*
M/V Oleander	*0*	*0*	*n.a.*

* 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: 166
Number of publications authored/co-authored by PI: 20 (see list)
Number of peer-reviewed publications that list SOCAT as a data source (see here):
in 2020: 44
in 2019: 62
Number of updated products: 2 (SOCATv2020 and Global Carbon Budget (GCB 2020).

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

Data Site: http://www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *5*
Number of fCO_2 data points: *40,334*
% Data return: *93.4%*

Description: The cruise tracks for each cruise of the *Brown* for FY 2020 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_2020.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.

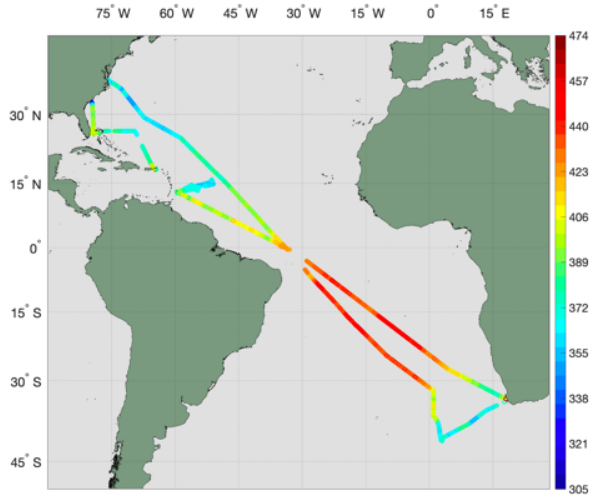


Figure 1. R/V Ronald H. Brown cruise tracks and surface xCO_2 values for FY 2020.

Causes for non-return: This installation suffered minor data losses due to ancillary data issues such as SST or SSS sensors not responding well. Some issues with water flow or system not being started by the survey technician also affect slightly our return. nevertheless, the data return remains excellent. Due to the pandemic, the Brown cancelled 3 cruises and modified another one. About 60 days at sea are estimated to have been lost.

Cruise ship *Equinox* - AOML lead

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *23*
Number of fCO_2 data points: *53,361*
% Data return: *86.6%*

***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 sailed only in the Caribbean during FY2020.

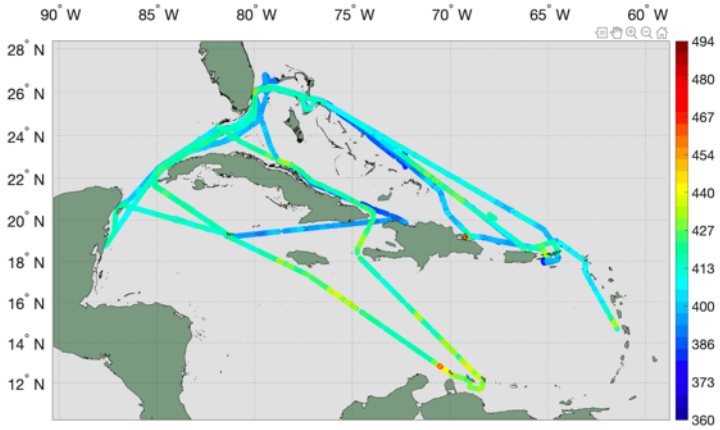


Figure 2. Celebrity Equinox cruise tracks and surface xCO_2 values for FY 2020.

Causes for non-return: Only minimal loss of data occurred due to malfunction of the University of Miami system, which controls the intake of seawater. The issues where quickly detected and resolved thanks to the VPN connection. The system keeps performing very well with a consistently high data return. Due to the pandemic, the Equinox executed only about 24 cruises (149 days at sea). Compared to last fiscal year, we estimate we lost about 70% of the data.

Cruise ship *Allure of the Seas* - AOML lead

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *21*
Number of fCO_2 data points: *52,490*
% Data return: *91.5%*

***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 ship was scheduled to go to dry dock in Spain just before the pandemic so we were able to collect data during the crossing. The ship is still in Europe to this day. 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).

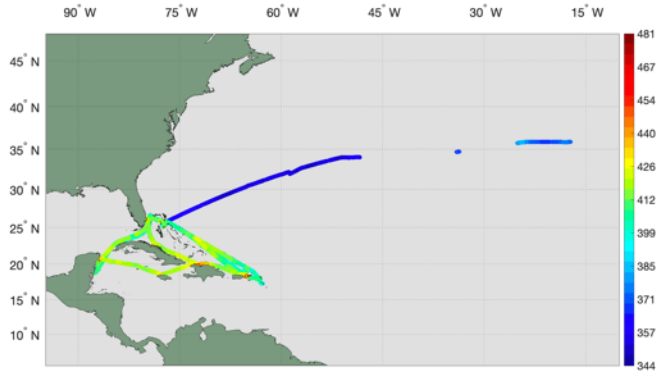


Figure 3. RCCL Allure of the Seas cruise tracks and surface xCO_2 values for FY 2020.

Causes for non-return: The issues that this system encounters are very similar to those of the *Equinox*: occasional loss of ancillary SST and SSS sensors or malfunction of the seawater intake system. Here again, the VPN access to the system allows for rapid detection and resolution of the issues, providing a high data return. Due to the pandemic, the Equinox executed about 22 cruises (89 days at sea). Compared to last fiscal year, we estimate we lost about 50% of the data.

Cruise ship *Flora* - AOML lead

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *10*
Number of fCO_2 data points: *28,296*
% Data return: *93.9%*

***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).

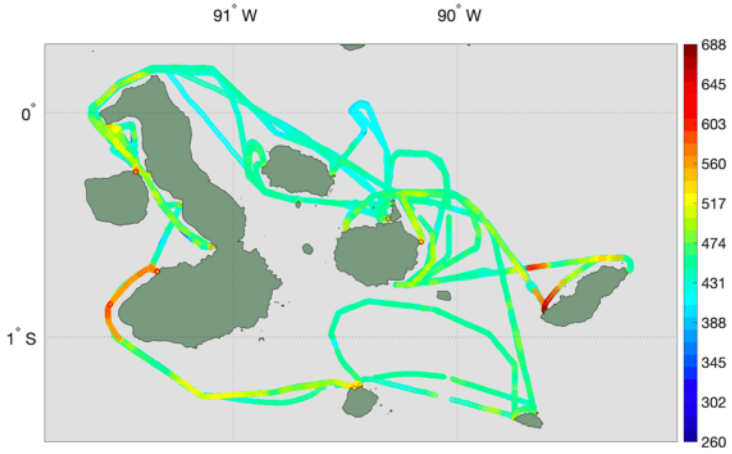


Figure 4. Celebrity Flora cruise tracks and surface xCO_2 values for FY 2020.

Causes for non-return: Unfortunately, we have lost the collaborator we had from the University of Ecuador who was supposed to visit the ship and perform maintenance. The system has developed an issue which requires the visit of a trained person. Until we find a replacement technician and travel restrictions due to the pandemic are lifted, we will not be able to run the system. Due to the pandemic, we estimate we lost about 50% of the data compared to last fiscal year.

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

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *3*
Number of fCO_2 data points: *16,688*
% Data return: *99.3%*

Description: This system was installed on the *Gordon Gunter* for our Northern Gulf of Mexico 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.

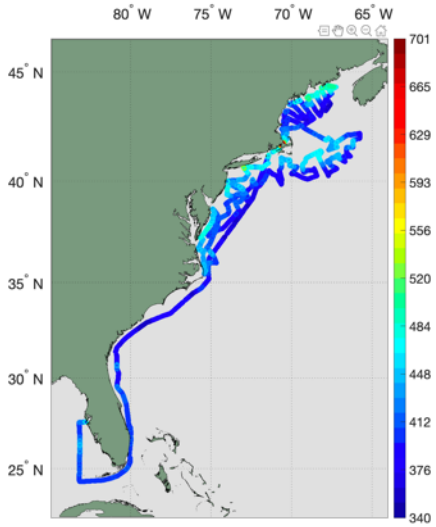


Figure 5. NOAA ship Gordon Gunter cruise tracks and surface xCO_2 values for FY 2020.

***Causes for non-return*:** The system is maintained by a field operation officer who has been trained on the instrument. We also obtain great support from the ETs on board. Some data loss occurred due to GPS failure. Overall, the system performed very well. Due to the pandemic, the Gunter cancelled 6 cruises (107 days at sea), which represents over 60% of our data from this ship.

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

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *3*
Number of fCO_2 data points: *20,096*
% Data return: *87.7%*

Description: The NOAA ship *R/V Henry B. Bigelow* is a new generation Fisheries survey vessel based in Newport, RI and operating primarily in coastal U.S. waters from Maine to North Carolina. The region includes Georges Bank, one of the world's best known and most productive marine areas. The installation was completed in February of 2011 and the system has been operating very well, due in part to the great collaboration 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.

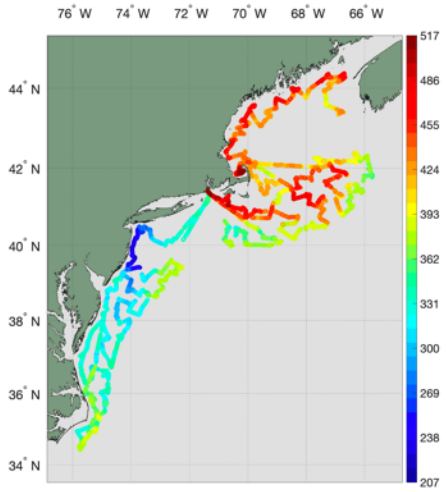


Figure 6. NOAA ship Henry Bigelow cruise tracks and surface xCO_2 values for FY 2020.

***Causes for non-return*:** Some minor data losses occurred this fiscal year due to issues with peripheral sensors such as SST and SSS, which have all been fixed in a timely manner. The presence of a survey technician onboard allows these issues to remain minor and the data return to stay high. Due to the pandemic, the Bigelow lost 6 cruises (89 days at sea), which represents over 60% of our data from this ship.

R/V *Bluefin* - PMEL lead

Data Site: http://www.pmel.noaa.gov/co2/
Number of cruises: *13*
Number of fCO_2 data points: *102,296*
% Data return: *82.0%*

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. All data collected on the *Bluefin* are in final processing and will be submitted to NCEI for archiving, and posted to the PMEL CO_2 website.

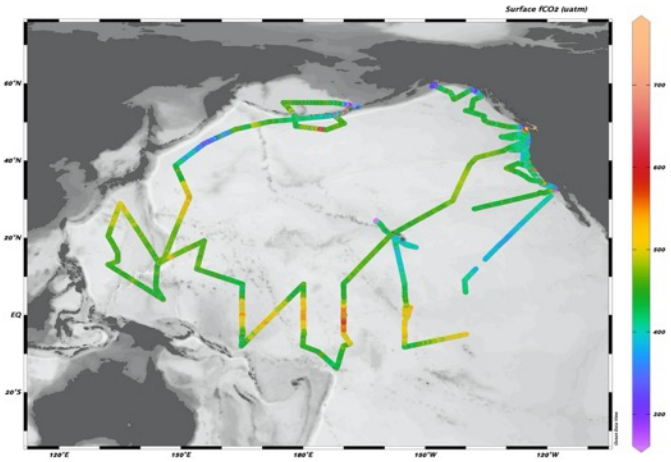


Figure 7. fCO2sw (µatm) measurements collected from the Bluefin in the Pacific Ocean, FY2020

Causes for non-return: The underway fCO_2 system on the *Bluefin* yielded an 82% data return during FY2020. Various technical issues were encountered with the system, including data dropouts of unknown derivation, which totaled 35 days throughout the field season, and one four-day loss of thermosalinograph data. COVID-19 did not significantly impact data collection on this platform for FY2020, other than preventing access to the ship for routine service and to troubleshoot data dropouts and instrument problems in person.

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

Data Site: http://www.pmel.noaa.gov/co2/
Number of cruises: *2*
Number of fCO_2 data points: *TBD*
% Data return: *TBD*

Description: In FY2019, PMEL successfully installed an underway pCO_2 system on the R/V *Thomas G. Thompson* in support of the IO6 Repeat Hydrography cruise. The system continues to operate, collecting fCO_2, pH, and O_2 data in the South Atlantic Ocean. All data collected on the *Thompson* are in final processing and will be submitted to NCEI for archiving, and posted to the PMEL CO_2 website.

Causes for non-return: The underway fCO_2 system on the *Thompson* was not in great working order during much of FY2020. Due to COVID restrictions, we were not able to access the ship in order to repair the system. The ship also experienced mechanical failures in FY2020, adding to the gaps in data collection. All told, we are assessing whether enough good data were collected on the *Thompson* during FY2020 to warrant final processing, submission to NCEI for archiving, and posting on the PMEL CO_2 website and data portal.

***RVIB N. B. Palmer* - GML/Univ. of Colo./LDEO Lead:**

Data Site: http://www.ldeo.columbia.edu/CO2
Number of cruises: *1*
Number of pCO_2 data points: *19,663*
% Data return: *99.9%*

Description: The GML/Univ. of Colo./LDEO group is responsible for the acquisition of surface water pCO_2 from the *RVIB Nathaniel B. Palmer* with GML/Univ. of Colo. taking the lead since the passing of former PI Taro Takahashi in late 2019. The data are processed and coordinated into a single uniform format along with supplemental data including the position, time, date, sea surface temperature (SST), salinity, wind speed, barometric pressure and atmospheric CO_2 concentration. During FY2020, 19,663 pCO_2 measurements were obtained from one research cruise to the Thwaites Glacier. This total is fewer than in recent years due in part to scheduling and to disruptions from COVID19. All measurements from FY2020 are shown in Fig. X. During a cruise in late 2019, the pCO_2 system was not operated due to the lack of approval for sampling within the Argentine and Chilean Exclusive Economic Zones (EEZ's). During boreal spring of 2020, the *RVIB Palmer* sailed from the Southern Ocean to Eureka, CA to evacuate scientists due to COVID19; operation of the pCO_2 system was also not possible during this unplanned cruise. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

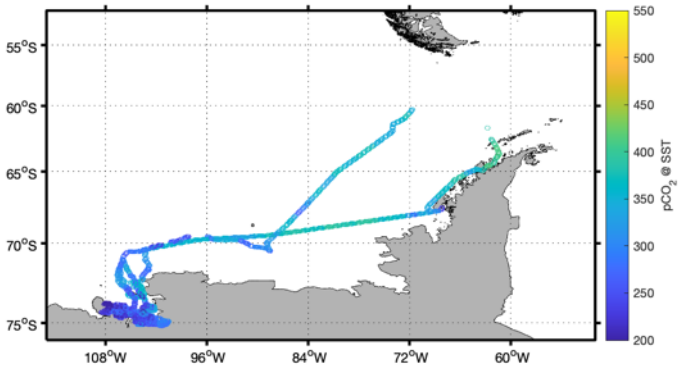


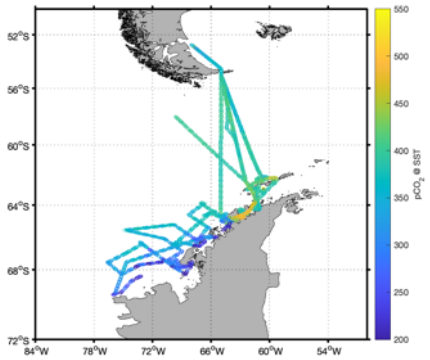
Figure 8. The locations and values of surface water pCO_2 measurements (in µatm) made from the RVIB Palmer during FY2020.

Causes for non-return: nearly all data passed QC during FY2020 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/Univ. of Colo./LDEO Lead:**

Data Site: http://www.ldeo.columbia.edu/CO2
Number of cruises: *7*
Number of fCO_2 data points: *35,612*
Data return: *97.4%.*

Description: Data collection from the underway pCO_2 system installed aboard the *ARSV Laurence M. Gould* began in March 2002 with observations in most years collected 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 has taken full responsibility for this pCO_2 system and as well as related discrete seawater measurements. During FY2020, the number of measurements was reduced from previous years due to disruptions in the latter part of the 2019-20 field season related to COVID19. A total of 35,612 pCO_2 measurements were made from the *ARSV Gould* during FY20 (
Figure 9). 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; for example, during FY20 sampling was conducted across the Drake Passage during June 2020 in addition to cruises in the warmer months of October through March. Unlike the *RVIB Palmer*, the *ARSV Gould* is authorized to make pCO_2 measurements within the Argentine EEZ which is especially important as the South American EEZ's extend nearly halfway across the Drake Passage. 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 FY2020.*

Causes for non-return: a small fraction of data failed to passed QC during FY2020 as indicated by the high rate of return in *Table 1*. Some of these data failed QC due to modifications that are typically made to seawater flow during the annual LTER cruise to accommodate other science

activities

***USCGC Healy* - GML/Univ. of Colo./LDEO Lead:**

Data Site: http://www.ldeo.columbia.edu/CO2.
Number of cruises: *5*
Number of fCO_2 data points: *26,877*
Data return: *99.9%*

Description: *USCGC Healy* is an ice breaker and one of the few US ships that operates primarily in the Arctic Ocean. As with the *RVIB Palmer* and the *R/V Sikuliaq*, the GML/Univ. of Colo. has taken the lead for this pCO_2 system since the passing of former PI Taro Takahashi in late 2019. 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 together with the observations from the *R/V Sikuliaq* contribute a significant proportion of the observations being made in the western Arctic Ocean that have been contributed to databases such as SOCAT (Ouyang et al., 2020). pCO_2 measurements from the *USCGC Healy* began in May 2011 and typically include observations in the North Pacific Ocean from Seattle, WA across the Gulf of Alaska, in the Bering Sea and the Arctic Ocean. In total, 26,877 pCO_2 measurements were obtained during FY2020 which was significantly more compared to the previous year; locations and values of observations are shown in Figure 10. The 2020 field season was cut short by several weeks due to an engine fire which occurred in August 2020 resulting in the ship returning to Seattle and entering drydock. As a result of ongoing repairs, data acquisition for FY2021will be impacted. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

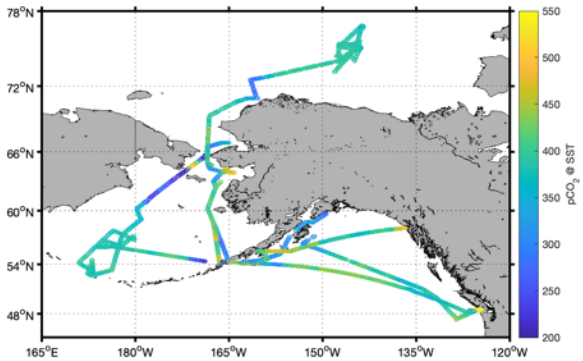


Figure 10. *The locations and values of surface water pCO_2 measurements (in µatm) made from the USCGC Healy during FY2020.*

Additionally, a high-precision system was deployed to measure atmospheric CO_2, CH_4 and CO from the *USCGC Healy* during summer 2020. This was done in part as an alternative plan due to

disruptions related to COVID19 and in part due to intriguing preliminary results from a deployment of the same system on the *USCGC Healy* during summer 2019 (see science slide). Data was collected across the North Pacific Ocean and in the Bering Sea during July and August of 2020. Prior to COVID19, deployment of the high precision system was planned for cruises along the East Coast of the United States and in the Gulf of Mexico to continue the primary objective of evaluation and improvement of atmospheric measurements made routinely by pCO_2 systems in the NOAA ships of opportunity network.

Causes for non-return: nearly all data passed QC during FY2020 as indicated by the high rate of return in Table X. During late 2020, the lag between the seawater intake and measurements from the pCO_2 system increased to over 15 minutes. We are assessing the causes for this change.

***R/V Sikuliaq* – GML/Univ. of Colo./LDEO Lead:**

Data Site: http://www.ldeo.columbia.edu/CO2.
Number of cruises: *7*
Number of pCO_2 data points: *40,281*
Data return: *95.7%*

Description: The underway pCO_2 program on the *Comer* family yacht, *M/V Turmoil* was terminated in 2012 because of a 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. As with the *RVIB Palmer* and the *USCGC Healy*, the GML/Univ. of Colo. group has taken the lead for this pCO_2 system since the passing of former PI Taro Takahashi in late 2019. A total of 40,281 pCO_2 measurements were made during FY20 which is lower than last year due to scheduling disruptions related to COVID19. Similar to the *USCGC Healy*, 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. During the upcoming off-season, extensive upgrades are planned to the pCO_2 system installed on the *R/V Sikuliaq* including installation of a rack mount computer and possible alterations to the equilibrator. Quality-controlled data are submitted to SOCAT and archived at NCEI OCADS for public access.

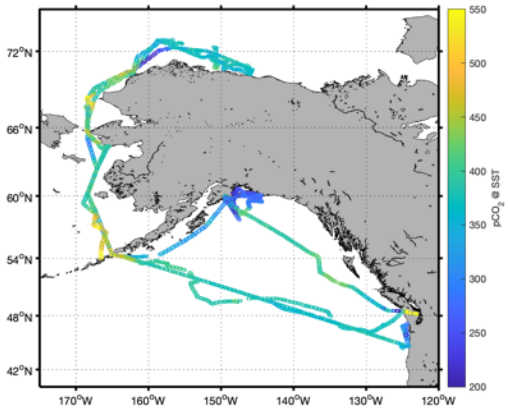


Figure 11. *The locations and values of surface water pCO_2 measurements (in µatm) made from the R/V Sikuliaq during FY2020.*

Causes for non-return: a small fraction of data failed QC during FY2020 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: *20*
Number of fCO_2 data points: *105,000*
% 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.

As a brief history, the pCO_2 system was installed on the RV *Atlantic Explorer* in April 2006. 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 and installed in early 2019 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 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 2019 as part of the QC/QA effort. This additional cost-in-kind contribution to the NOAA pCO_2 network is approximately ~$32,000, for a total of cost-in-kind contributions of ~$132,000 in 2019-2020.

A new CONTROS HydroFIA TA underway Alkalinity system was installed on the R/V *Atlantic Explorer* in September 2020. The purchase of the CONTROS system provides another cost-in-kind contribution to this award of ~$38,000. We are currently evaluating the data quality and return for the system but the early results have been very encouraging. We will at some point installed the system on the M/V *Oleander*, but at present we are undertaking comparisons of General Oceanics pCO_2 system data, HydroFIA TA underway Alkalinity, SAMI pH and pCO_2 and SeaFET pH.

The new General Oceanics pCO_2 system (GO196) installed on the R/V *Atlantic Explorer* has provided very good results for data collection and quality. The system is checked after every cruise, has required minor adjustments, and very few issues as of yet.

For the period of this report, the R/V *Atlantic Explorer* has collected data from about sixteen cruises, totaling 44 sea days of the ship in 2019. In 2020, we have collected 62 days during 6 cruises up until end of September 2020 (Figure 12). This represents 106 sea days for the performance period (1st Oct. 2019 to 30th Sept 2020). In 2020, the emergence of Covid-19 prompted us to send the ship to the shipyard in mid-March to mid-June (reorganizing from fall 2020 shipyard visit to spring 2020) to reduce to amount of ship-time potentially lost to cruise restrictions. With strict protocols in place, the R/V *Atlantic* resumed cruises at the end of June and maintain a normal ship schedule. We anticipate 209 ship days in 2020-2021. 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.

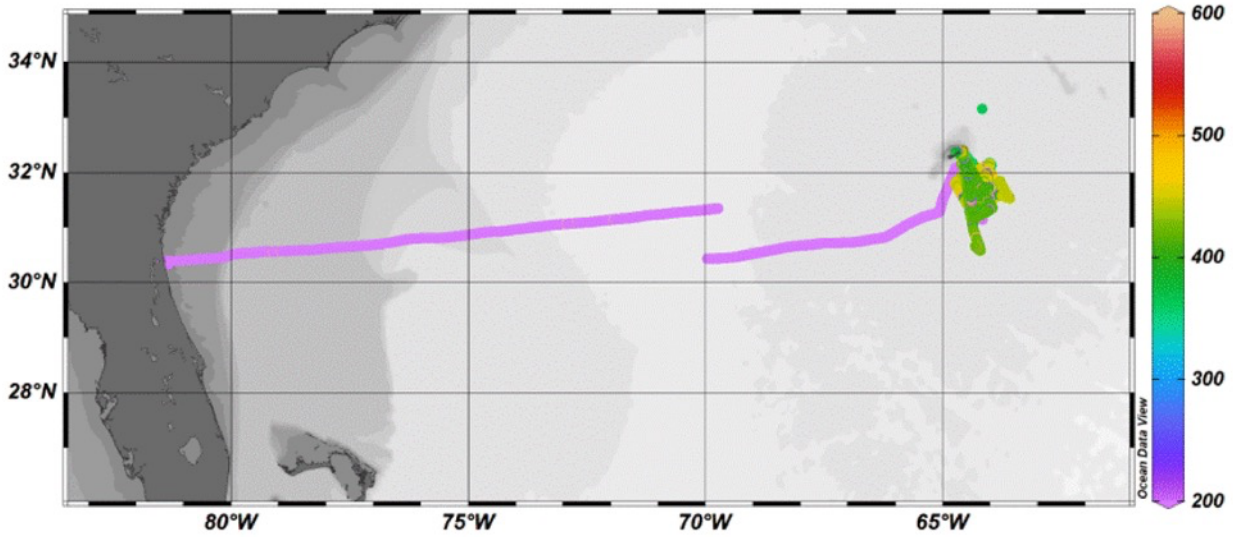


Figure 12. *Seawater pCO_2 data from the R/V Atlantic Explorer collected mostly in the North Atlantic Ocean. This represents approximately 75 days of pCO_2 data collected from January to September 2020 over a period of six months with no data collected for the period of mid-March to mid-June while the R/V Atlantic Explorer underwent its shipyard visit to Jacksonville, Florida. We unfortunately had a couple of system issues during the transits between the US and Bermuda.*

***Causes for non-return*:** In the last year, a total of ~100,000 pCO_2 measurements have been made. 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.

***Covid-19 restrictions*:** In 2020, the emergence of Covid-19 prompted us to send the ship to the shipyard in mid-March to mid-June (reorganizing from fall 2020 shipyard visit to spring 2020) to reduce to amount of ship-time potentially lost to cruise restrictions. With strict protocols in place, the R/V *Atlantic* resumed cruises at the end of June and maintain a normal ship schedule. We were fortunate that the covid-19 UNOLS ship restrictions did not impact the R/V *Atlantic Explorer*.

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: *n.a.*

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* has recently been launched in early October 2018 (photograph above) with final fitting of the ship. In the last couple of months, our group has closely worked the Chief Engineers of the *Oleander* and the TSG group (Charlie Flagg; Ruth Curry) to sort out the seawater supply, communications, and lab configurations on the *Oleander*. As with most ships, the new *Oleander* has experienced issues with the seawater supply, lab, TSG and ADCP setups. In late November 2019, our older General Oceanics pCO_2 system from the R/V *Atlantic Explorer* was installed on the ship and Matt Enright rode with the ship to New Jersey to identify and sort out issues for the pCO_2 system. This will resume the 80 to 100 crossing per year between New Jersey and Bermuda, representing approximately 250 days of data collection per year.

Early in 2020, we were in the process of setting up the installation of the pCO_2 system on the M/V *Oleander.* However, the emergence of Covid-19 delayed the completion of the installation of the pCO_2 system on the M/V *Oleander*.

In addition to the pCO_2 data stream, we have installed our dissolved oxygen (DO) optode and SAMI pH systems, and anticipate a possible Contros alkalinity system installation in early 2021. 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; We anticipate receiving a General Oceanics pCO_2 system from NOAA AOML that will be installed on the new *Oleander* in early spring 2021. 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**:** Due to the restrictions of access to the pCO_2, we have not been able to complete the installation of the pCO_2 system.

Covid-19 restrictions**:** In 2020, the emergence of Covid-19 delayed the installation of the pCO_2 system on the M/V *Oleander*. No access to the ship has been allowed since mid-March 2020 due to the restriction of non-essential personnel accessing the ship.

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

Data Site: www.aoml.noaa.gov/ocd/ocdweb/occ.html
Number of cruises: *7*
Number of fCO_2 data points: *7,700*
% Data return: *93.0%*

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

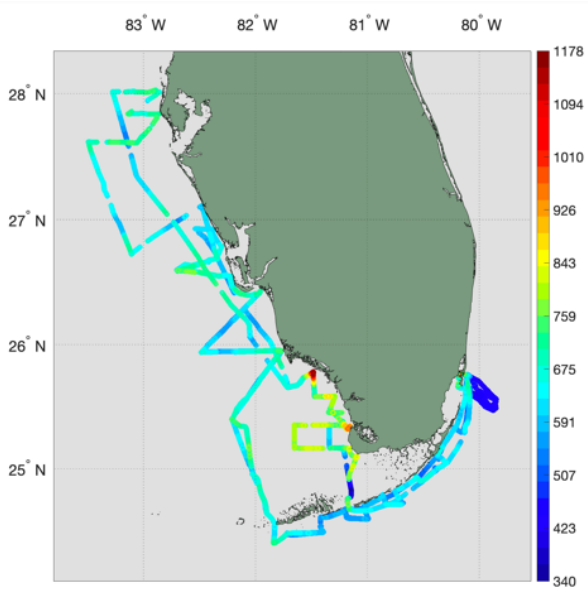


Figure 13. fCO_2 values along the tracks of the R/V Walton Smith for fiscal year 2020.

Causes for non-return: This fiscal year, the pCO_2 system has functioned well and shows a good return with no major technical issues. Between March and August 2020, all scheduled cruises were suspended due to concerns related to the COVID-19 pandemic. While research cruises were paused, the *Walton Smith* completed its 5-year ABS ship inspection.

TSG Operation – AOML/SOOP Lead

During FY2020 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 4 ships of the SOOP (*MV Oleander*, Royal Caribbean's *Allure of the Seas,* and *Equinox,* and Celebrity's *Flora* in collaboration with University of Miami/RSMAS) equipped with pCO_2 systems and from 9 ships of the NOAA fleet (*RV Henry Bigelow*, *RV Okeanos Explorer*, *RV Thomas Jefferson*, *RV Fairweather*, *RV Ronald H. Brown*, *RV Bell M Shimada*, *RV Oscar Elton Sette*, *RV Reuben Lasker*, and *RV Oscar Dyson*), two of which (*RV Henry Bigelow and RV Ronald H. Brown*) have an operational pCO_2 system. More than 17 million TSG records (corresponding to approximately 182,000 records with 3 minute temporal resolution) were processed at NOAA/AOML during FY2020 (*Figure 14*), and distributed through several data centers including NOAA's National Centers for Environmental Information (NCEI) and Global Ocean Surface Underway Data (GOSUD).

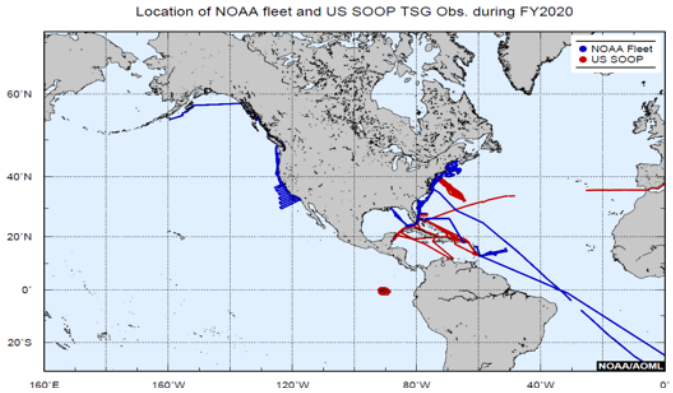


Figure 14. Location of approximately 182,000 TSG observations (3-min. resolution) received and processed by NOAA/AOML during FY2020 from 4 ships of the SOOP and 9 ships of the NOAA fleet.

The TSG operation on two Royal Caribbean cruise ships *Allure of the Seas* and *Equinox* continued during FY2020. 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 two ships also have pCO_2 systems installed. Additionally, during FY2020 NOAA/AOML processed and distributed TSG observations from Celebrity's ship *Flora*, which is operated by the University of Miami / RSMAS. *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 (*Figure 14*).

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*). This system is currently fully functional in real-time, providing important tools to automatically detect problems in data transmission, equipment calibration and marine operations.

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 (www.soconet.info) 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 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).

Answers to Questions

- Primary achievements during FY 2020.

  Our program collected ~550,000 fCO_2 measurements around the globe, using 15 ships of opportunity sailing from the Pacific to the Atlantic, at high latitudes ranging from the Arctic to the Antarctic Ocean. Most of that data has already been made publicly available, either through the websites of our institutions or through data centers and data products where it has been submitted.

- What scientific advances were made and/or facilitated through your activities? (For multi-institution proposals, provide your top 2 or 3 advances.)

  **Please refer to section 6 – Research Highlights, for more details. **

- Instrumental records of Essential Ocean Variables , Essential Climate Variables, and related ocean attributes that are relevant for 1) Routine delivery of a range of societally relevant services (e.g. products, forecasts, etc) and 2) advancing climate, ocean, and related research

  Our data feed directly into global assessments like the annual carbon assessment lead by the GCP (www.gcp.org). The measurement of carbon dioxide sources and sinks in the ocean is needed for improved understanding of how carbon dioxide is distributed in the atmosphere, oceans, and land; an accurate assessment of anthropogenic carbon dioxide emissions and their redistribution helps support projections of future climate change. NOAA's investment in improved observations and technology has reduced the uncertainty in the ocean carbon sink from 45 to 20 percent. Carbon is one of the three pillars of the overall scope of GCOS with surface water pCO_2/ocean acidification selected as one of the high-level climate indicators. The development of surface water maps of carbon and ocean acidification will be critical in this context.

- What is the significance of these advances?

  Each of these advances is a step closer to a better understanding of the oceanic carbon flux, both of its state and its fluctuations. They improve our estimate of the earth's global carbon budget, but also help us better define the variability of the system and therefore help us improve our models and predictions. Both of these factors ultimately lead to a better ability to understand and address the challenges of climate change. This has gained added significance with the recent framework on keeping global temperature rise to below 2 ˚C (COP-21) that was adopted in October, 2016[1] or with Special Report on Global Warming of 1.5˚ which was approved by the IPCC in October 2018. To assess the required atmospheric CO_2 trajectories, all sources and sinks, including the important

[1] On October 5th, 2016, the threshold for entry into force of the Paris Agreement was achieved. The Paris Agreement entered into force on November 4th, 2016

global ocean sink need to be quantified. With the USA re-joining the Paris agreement , the need for carbon accounting including the important ocean sink will take center stage.

- Deliverables that address societal needs related to the Earth's climate as detailed in the GCOS and GOOS vision, including delivering continuous instrumental records for global analyses of:
    - sea surface temperature and surface currents,
    - ocean heat content and transport,
    - air-sea exchanges of heat, momentum, and freshwater,
    - sea level, and
    - ocean carbon uptake and content

  Our program represents the world's largest consorted effort for the measurement of surface fCO_2 values. We provide measurements on most of the major world's oceans, as well as high latitude areas which are under-sampled but climatologically of vital importance. Along with fCO_2, we also measure climatological parameters such as temperature, pressure which, when combined with satellite data such as wind speed, allow for the calculation of ocean carbon flux through the sea-air interface. Most of our measurements are repeated on the same region, thus providing both spatial and temporal variation information on surface ocean carbon content.

- Progress on the milestones and performance measures included in your FY 2020 work plans

  Our performance measures are based on the percent data return of each ship. Our goal is to increase the data return in order to provide an even better coverage of the area sampled. overall, the data return is excellent but we have underperformed this fiscal year due to the COVID-19 pandemic preventing us from working in our labs, travelling to perform maintenance on the systems and in a couple cases, when travel would have been possible, preventing us from boarding commercial vessels who could not afford to take the risk of having outsiders aboard and contaminate the crew. From the number of data points collected, we estimate that we have lost about 35% of our data.

- Impacts of flat or reduced funding on your ability to carry out your work

  We have not experienced any significant impediment or loss of information due to a flat or reduced funding. However, the COVID-19 pandemic has decreased the data return in FY-2020 by approximately 30 % compared to previous years, as listed in the data return from each ship,. We did not travel as much as anticipated due to some ships not sailing, but they will need to be visited as soon as they sail again.

- Websites for your program
  http://www.aoml.noaa.gov/ocd/ocdweb/occ.html
  http://www.aoml.noaa.gov/phod/tsg/index.php
  http://www.pmel.noaa.gov/co2/story/Volunteer Observing Ships (VOS)
  http://www.ldeo.columbia.edu/res/pi/CO2/

3. Outreach and Education

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.

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 previous funding cycle, PI Alin did numerous outreach presentations in classrooms at a minority-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. Among possible actions the group may invest time and resources into is a partnership that Dr. Alin has proposed to Seattle Public School's (SPS) superintendent and the Technology Access Foundation (TAF)—which are currently in the beginning year of a partnership to redevelop an effectively segregated middle school, with separate tracks for "advanced learners" and all other students, who tend to be dominantly black and brown. The vision is to engage Seattle area ocean and climate scientists with SPS teachers and TAF to develop curriculum materials and project opportunities for students 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. 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.

Prof. Nick Bates gave several talks and presentations on the ocean carbon cycle and acidification in 2019 to 2020, with a couple given remotely in 2020. He participated in an ocean time-series analysis workshop in Seattle; provided a briefing for the Nature Sustainability Forum; contributed to the science case for a marine protected area in the Sargasso Sea for the Sargasso Sea Commission; contributed to the development of an integrated international North Atlantic/Arctic Ocean research program; and incorporated pCO_2 data generated as part of this award into one undergraduate and one graduate course focused on the ocean carbon cycle, ocean acidification and global biogeochemical cycles at the University of Southampton in 2020. Both were taught as remote, hybrid courses as a response to covid-19.
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 is still in contact with them and act as consultant.
Dr. Wanninkhof is the surface water CO_2 representative of the scientific steering group of IOCCP and advocates 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 gave a keynote presentation at the virtual ICOS open science conference attended by over 800 participants. 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.

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**

Bates, N.R., and Johnson, R.J., 2020. Acceleration of ocean warming, salinification, deoxygenation and acidification in the surface subtropical North Atlantic Ocean. Nature Communications in Earth and Environment. October 16, 2020, https://doi.org/10.1038/s43247-020-00030-5

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

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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 FY20 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:
The Lamont group is responsible for processing and managing the surface water pCO_2 data acquired by the members of the pCO_2 on ships consortium (SOOP), so that the participants of the program are able to access of the data in a uniform electronic format. For this purpose, we have established an open web site at the following URL: http://www.ldeo.columbia.edu/CO2. The site provides not only the numerical data, but also maps showing the ship's tracks for each data file and expedition. In each year, the new quality-controlled data are added to our database and submitted the NCDI OCADS of NODC NOAA for dissemination to the public. A newly updated Global Surface pCO2 (LDEO) Database V2019 (LDEO Database V2019) "Global

Ocean Surface Water Partial Pressure of CO_2 Database "has been assembled and made available to the public through the NCDI OCADS (Takahashi et al., 2019). As of the end of 2019, the database contains about 13.5 million measurements (*Figure 6*. Most of these data have been incorporated into the international global ocean CO_2 data base called SOCAT (Surface Ocean CO_2 Atlas) (www.socat.info; Bakker et al, 2014; Bakker et al., 2016). Our data are being used by a large number of recent scientific publications (e. g. Fay et al., 2013; Fay et al. 2018; Hauri et al., 2015; LeQuere et al. 2016; Olsen et al., 2016; Xue et al., 2018; Yasunaka et al., 2018). The data locations are shown in *Figure 15*. See also research highlight **6.4** in this report.
As part of the transition of operations from LDEO to GML after the passing of Dr. Takahashi, a 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 2021. See science highlight 6.4 below

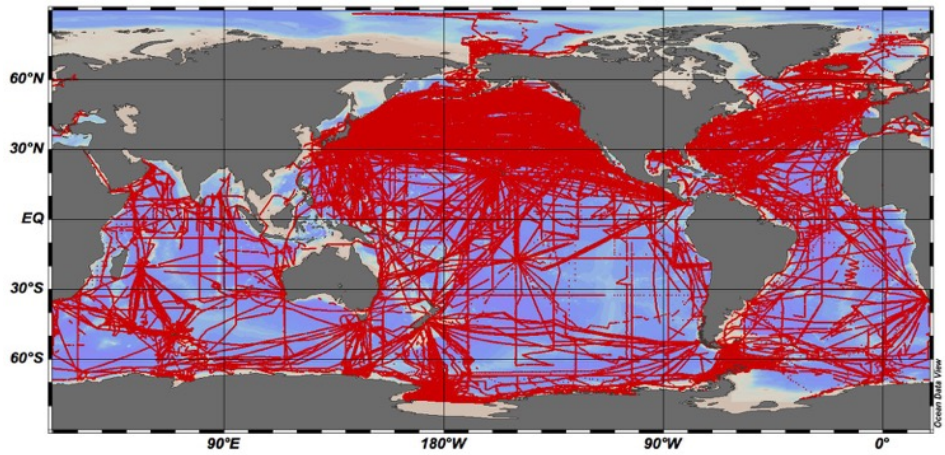

Figure 15. The location of surface water pCO_2 data in the LDEO database archived at the NOAA/NCEI/OCADS. *About 13.5 million data are listed in the uniform format.* (*Takahashi et al., 2019)*

Institutions' websites, data centers and data products:

The PMEL carbon data are also archived at the PMEL (www.pmel.noaa.gov/co2/) website which includes an interactive map 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). During FY2020, we have continued processing pH data from trans-Pacific container ship cruises that were collected via the complementary effort funded by NOAA's Ocean Acidification Program, which has provided for the installation and maintenance of pH sensors in tandem with tropical Pacific underway fCO_2 systems since 2010 (except the M/V *Bluefin*). Data sets with finalized pH data from 3 ships (*MV Cap Blanche, MV Natalie Schulte and RV Thompson*) dating back from 2010 have been submitted to NOAA's National Centers for Environmental Information (NCEI). Additional cruises will be added to this time series when remaining QC issues have been resolved. We are

also presently processing data sets consisting of discrete dissolved inorganic carbon and total alkalinity samples collected during the cruises (another OAP-leveraged effort), and these will also be submitted to NCEI when complete.

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 (updated web name, with previous link www.aoml.noaa.gov/ocd/gcc automatically redirected) 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 for the current version 5 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)[2] 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.

[2] 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.

As can be seen in *Figure 16*, the coverage of the world's oceans is substantial.

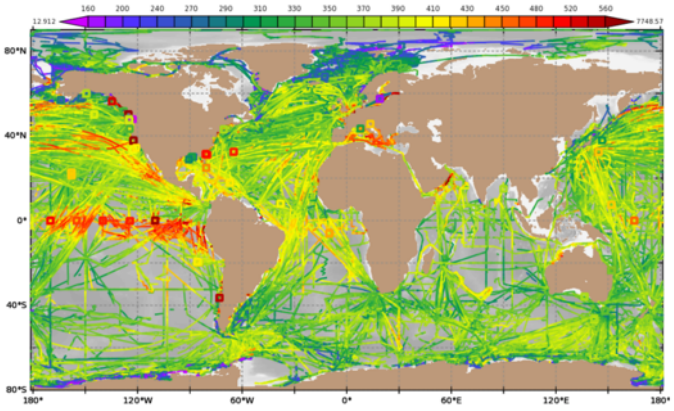

Figure 16. World's coverage of the Surface Ocean CO_2 *Atlas (SOCAT version 2020) database through 2019 (30.5M obs.)*

The contribution from the participants of this program (~8.7M obs.) represent about a third of all observations (*Figure 17*). 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.

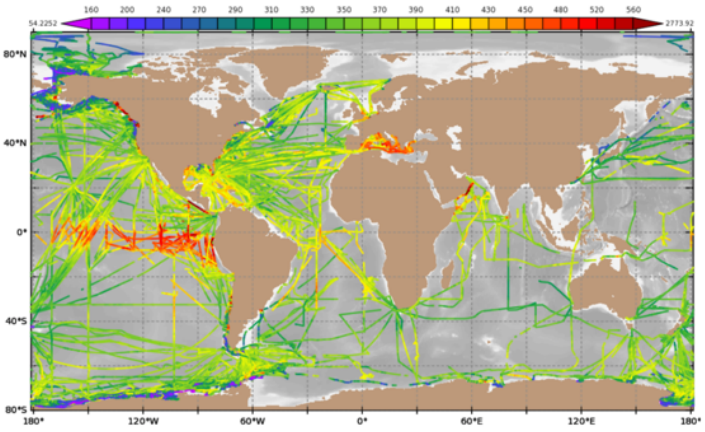

Figure 17. Contribution of this program of 8.7M points to the Surface Ocean CO_2 *Atlas (SOCAT version 2020) database through 2019*

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 v2020 can be found at https://www.socat.info/index.php/products-using-socat/.

6. Project Highlight Slides

6.1 *Contribution to the Global Carbon Project (GCP) annual update*

The surface water pCO_2 data and associated data products feed directly into global assessments. Of note is the annual carbon assessment lead by the Global Carbon Project (GCP) (www.globalcarbonproject.org), which includes data from autonomous instruments installed on research vessels, ships of opportunity, and moorings by PI's in this project to determine the variability of carbon dioxide at the ocean surface (Friedlingstein et al., 2020). The pCO_2 on ships group has been a primary contributor to this ocean carbon dataset.

The measurement of carbon dioxide sources and sinks in the ocean is needed for improved understanding of how carbon dioxide is distributed in the atmosphere, oceans, and land; an accurate assessment of anthropogenic carbon dioxide emissions and their redistribution helps support projections of future climate change. NOAA's investment in improved observations and technology has reduced the uncertainty in the ocean carbon sink from 45 to 20 percent.

6.2 *Monitoring the Carbonate System in the Northeast Pacific Ocean.*

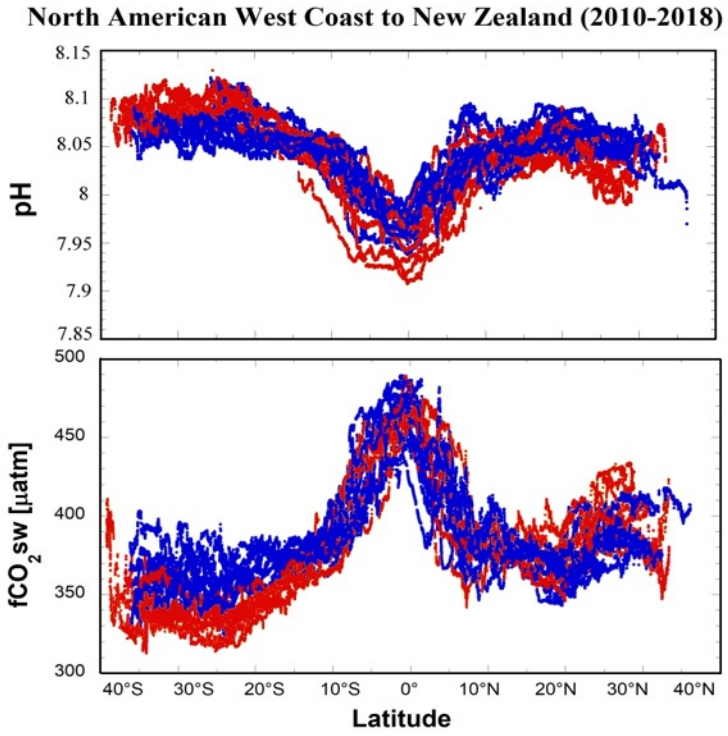

Figure 18. pH and fCO_2 data from trans-Pacific container ship crossings from the North American Pacific Coast to New Zealand during 2010–2018. Crossings shown in red occurred during months of April through September, while those in blue happened during October through March. These data will be included in an Earth Systems Science Data paper we are preparing (Cosca et al., in preparation).

6.3 Dramatic trends in summer ΔpCO_2 over the past two decades in the Canada Basin related to declines in sea ice

Our late colleague Taro Takahashi understood the importance of monitoring pCO_2 in the high latitude oceans and his efforts have contributed to many important studies. Last year, we reported that observations from the *USCGC Healy* and the *R/V Sikuliaq* were used to estimate an annual air-sea CO_2 flux for the Arctic Ocean of 0.18 ± 0.13 Pg C y^{-1} (Yasunaka et al., 2018) which represents nearly 10% of the contemporary air-sea CO_2 flux for the global oceans even though the Arctic Ocean accounts for just 3% of the global ocean by surface area. At the time of his passing, Dr. Takahashi was working with collaborators on a study of long-term trends in surface ocean pCO_2 in the Arctic Ocean that has now been published (Ouyang et al., 2020). This analysis reveals that summer pCO_2 has increased dramatically over the past two decades in the Canada Basin which is a sharp contrast to trends in the Chukchi Sea (*Figure 19*). An analysis of the drivers of pCO_2 trends in these regions indicates that summer sea ice loss in the Canada Basin has led to changes in the upper ocean that have caused this dramatic trend in pCO_2. Observations from the *USCGC Healy* and the *R/V Sikuliaq* account for most of the observations in the most recent five years of the study (2013 to 2017); in addition, observations from the pCO_2 system installed on the R/V *Ron Brown* contributed a substantial fraction of the observations made in 2014.

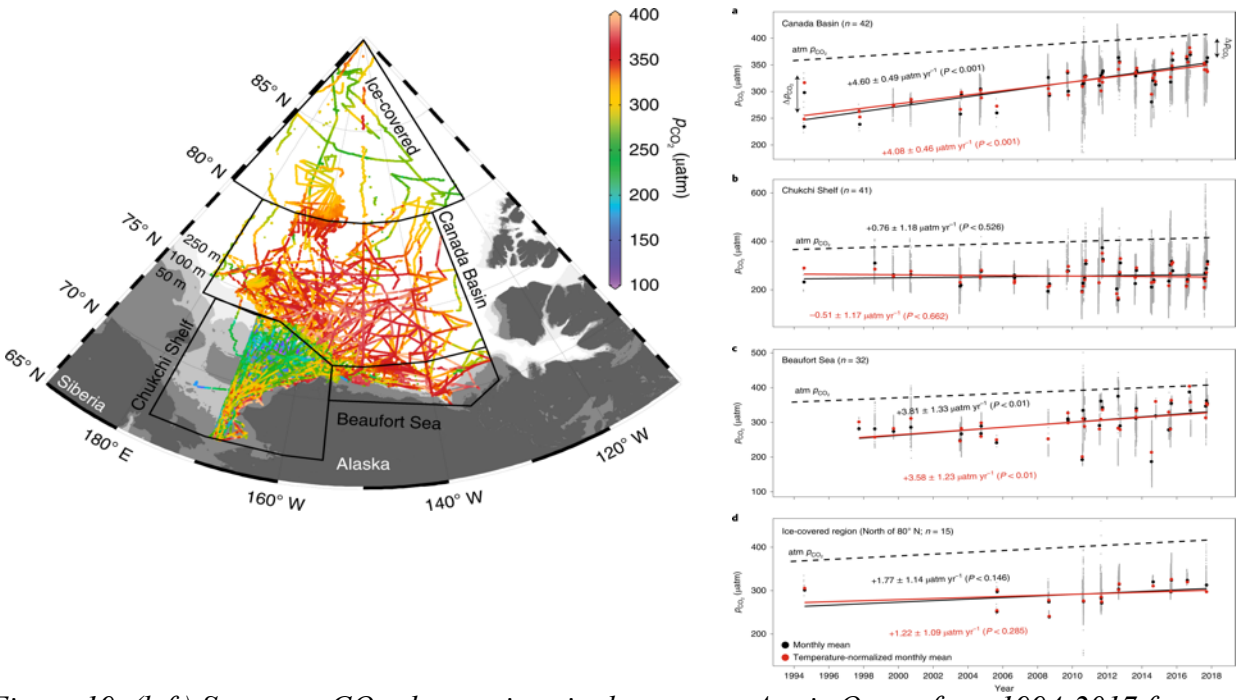

Figure 19. (left) Summer pCO_2 observations in the western Arctic Ocean from 1994-2017 from Fig. 1 of Ouyang et al. (2020). (right) Long-term trends in summer pCO_2 in different regions of the Arctic Ocean from Fig. 2 of Ouyang et al. (2020). Most observations in the later years were contributed by NOAA pCO_2 systems installed on the USCGC Healy (since 2011) and the R/V Sikuliaq (since 2015).

6.4 A final update of the canonical Takahashi climatology of surface ocean pCO_2

One of the most enduring aspects of the legacy of our late colleague Taro Takahashi was his climatology of surface ocean pCO_2 and air-sea CO_2 flux first created in the 1990's (Takahashi et al., 1997) and updated twice since (Takahashi et al., 2002; 2009). The latest published version of this climatology (Takahashi et al., 2009) was created using 2000 as a reference year with a dataset of nearly 3 million surface pCO_2 observations. We have recreated the climatology with a dataset of more than 12 million observations for the reference year 2010. We plan an additional experiment where we use all available data included in SOCAT to date (between 25 and 30 million observations) as well as experiments to understand the sensitivity of the annual air-sea CO_2 flux to the coverage of observations in space and time. The new version of the climatology revises the contemporary global ocean sink (defined as a flux from ocean to atmosphere) by nearly 25% from -1.42 to -1.76 Pg C yr^{-1} (*Figure 20*) in comparison to the Takahashi et al. (2009) product. The subtropics and the high latitude Northern Hemisphere accounts for most of this increase in ocean uptake which more than offsets a nearly 25% increase in outgassing from the tropics. A manuscript is currently in preparation for the journal *Earth System Science Data*.

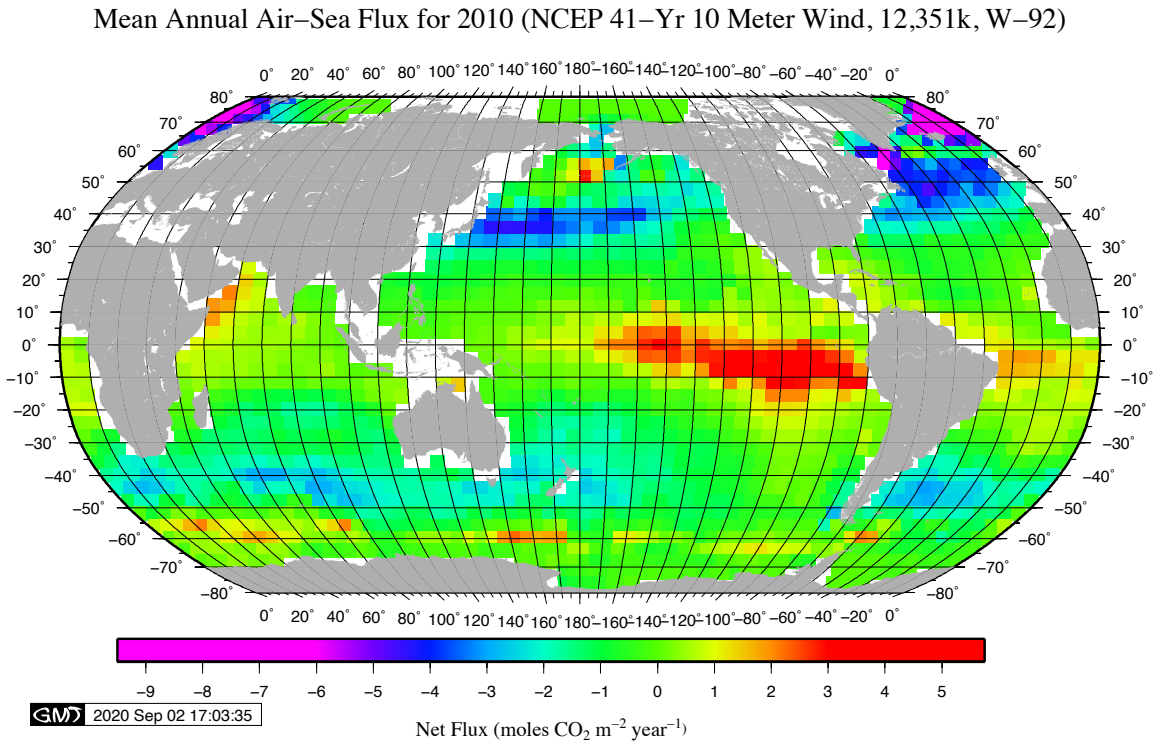

Figure 20 – Mean annual air-sea CO_2 flux from the updated climatology for reference year 2010 in mol C m^{-2} yr^{-1} defined such that negative (positive) values represent regions of ocean uptake (outgassing).

6.6 Large Decadal Changes in Air-Sea CO_2 Fluxes in the Caribbean Sea

Taking advantage of a 17-year dataset from ships of the Royal Caribbean Cruise Lines in the Northern Caribbean we created monthly maps at 1˚ by 1˚ using a multi-linear regression analysis with robust error analysis. The results showed surprisingly large decadal changes in surface water CO_2 and air-sea CO_2 fluxes. From 2002 to 2017, the Caribbean Sea became an increasing CO_2 sink until 2009-2010. The trend then reversed itself and the CO_2 flux became slowly less negative, while still remaining a sink (*Figure 21*-top). The reversal of the trend is mostly attributed to changes in sea surface temperature (SST) and mixed layer depth (MLD) which showed similar trends through the decade(*Figure 21*-middle). The reversal seems to be synchronous with large climate re-organizations such as the North Atlantic Oscillation (NAO) or the Atlantic Multidecadal Oscillation (AMO) (*Figure 21*-bottom).

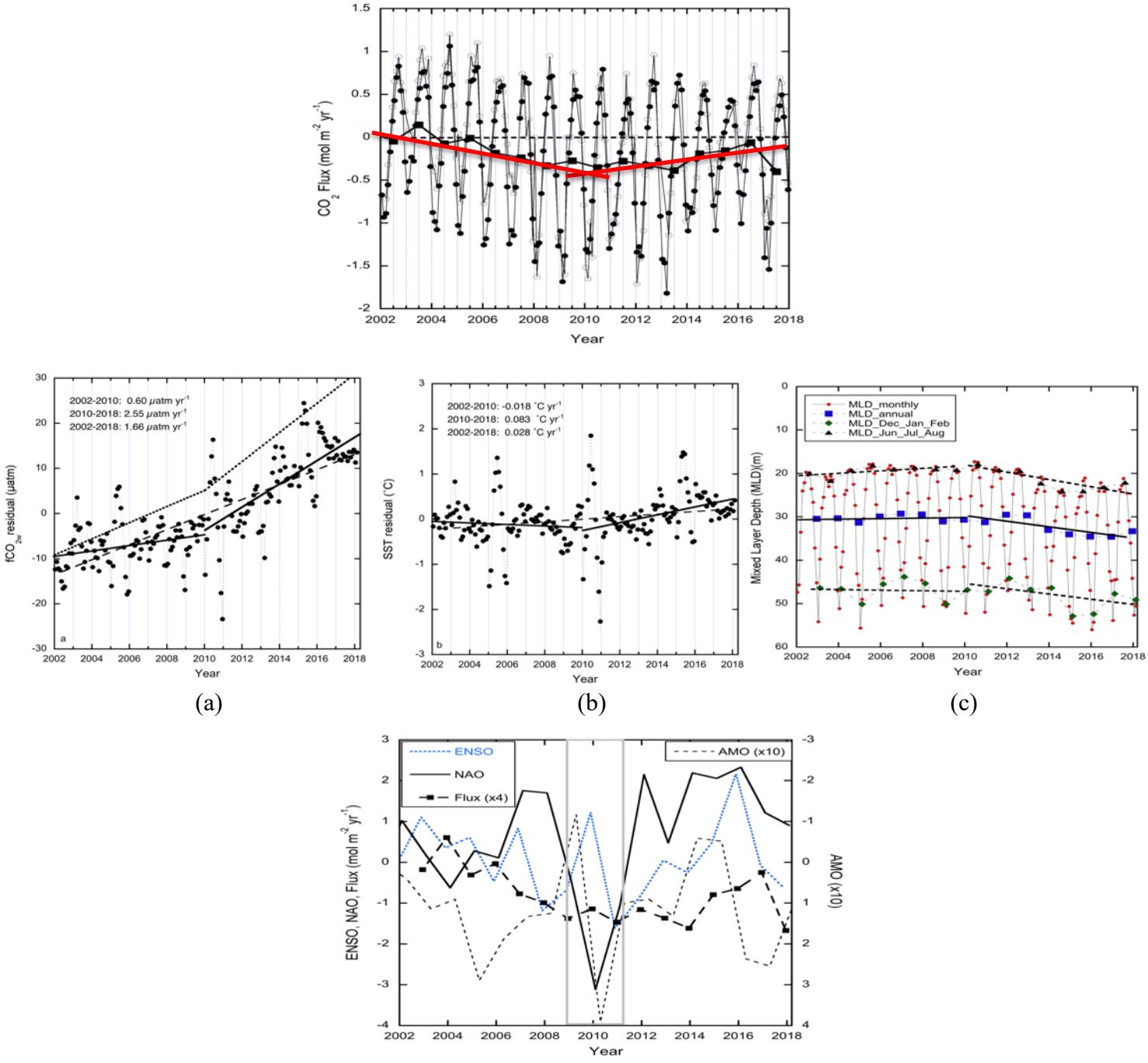

*Figure 21 – **(top)** Trend of air-sea CO_2 fluxes annual averages in the Caribbean Sea showing a reversal in 2009-2010. **(middle)** Monthly residuals of fCO_2w from a harmonic fit, and their trend lines. The short-dashed line is the expected trend if the fCO_2w followed atmospheric CO_2 increase and observed temperature trends as shown in panel (b). (c) is the MLD trends from the HYCOM model. Annual means are the blue squares. **(bottom)** Annual air-sea CO_2 fluxes (black squares, thick dashed line) and climate indices. (from Wanninkhof et al., 2019)*