FY 2023 Progress Report
High-Resolution Ocean and Atmosphere $p\mathrm{CO_2}$ Time-Series Measurements

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Budget Summary
FY 2023: $531,084

High-Resolution Ocean and Atmosphere pCO_2 Time-Series Measurements

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Project Summary

The ocean plays a critical role in global climate as a sink for both heat and carbon dioxide (CO_2) building up in earth's systems. In order to understand how the climate is changing and whether change is impacting marine ecosystems, observations must clearly track the state of the climate system. Observations collected over the past three decades show that the ocean is a vast reservoir of carbon that takes up a substantial portion of human-released CO_2 from the atmosphere. Advancements in the ocean observation network over the last decade, such as the establishment of a high-resolution CO_2 mooring network, are providing new information on the role of shorter-term variability on the global carbon system. This information is improving our understanding of key processes controlling the carbon system, which is essential to NOAA's mission to anticipate and respond to climate impacts and to conserve and manage healthy oceans, coastal ecosystems, and marine resources.

In a growing effort to distinguish between natural and anthropogenic variability, sustained ocean time-series measurements have taken on a renewed importance. They provide the long, temporally-resolved data sets required to characterize ocean climate, biogeochemistry, and ecosystem change. For example, the biological and chemical responses to natural perturbations such as the El Niño/Southern Oscillation are particularly important to evaluating potential responses to anthropogenic forcing and the models making future climate projections. Ship-based time-series measurements are impractical for routinely measuring variability over intervals from a week to a month, they cannot be made during storms or high-sea conditions, and they are too expensive for remote locations. Instrumental advances over the past 20 years have led to autonomous moorings capable of sampling chemical, biological, and physical properties with resolutions as good as a minute and duty cycles of a year or more. These technologies have been identified as a critical component of the global ocean observing system for climate.

The primary mission of this project is to evaluate variability and change in air-sea CO_2 fluxes by conducting high resolution time-series measurements of atmospheric boundary layer and surface ocean CO_2 partial pressure (pCO_2) with Moored Autonomous pCO_2 ($MAPCO_2$) systems. As a result of rigorous and well documented quality assurance and control procedures (https://doi.org/10.5194/essd-6-353-2014 and https://doi.org/10.5194/essd-11-421-2019), including the calibration of each CO_2 measurement with a standard reference gas, $MAPCO_2$ data are the only moored seawater pCO_2 time series considered reference measurements in the Surface Ocean CO_2 NETwork (SOCONET).

Scientific and Observing System Accomplishments

The high-resolution CO_2 mooring network plays a role in the majority of the goals and objectives in NOAA's Five-Year Research and Development Plan. Front and center in the Plan is NOAA's commitment to sustained climate records that contribute to our understanding of the state of the climate system and how it is evolving. Open ocean moorings are unique in this endeavor because they are a very cost-effective means for obtaining data from remote, data-sparse areas of the ocean. In addition, the CO_2 mooring observations capitalize on existing mooring platforms and servicing efforts. Since the CO_2 mooring network provides 3-hourly CO_2 observations in these data-sparse areas, the time-series fulfill a unique niche in providing the high-resolution data necessary to explore questions about short-term variability at fixed locations, especially important to modeling studies. Mooring observations are playing a large role in improving our ability to model, understand, and describe the ocean carbon cycle on all time scales. This work is distinctive to NOAA and contributes significantly to addressing two of NOAA's key climate societal challenges: vulnerability of climate extremes (by improving climate predictions) and sustainable management of marine ecosystems (by tracking ocean carbon changes that are likely impacting marine ecosystems).

This network provides instrumental records of atmospheric CO_2, an Essential Climate Variable, and seawater pCO_2, an Essential Ocean Variable. Users of these data include scientists investigating high-frequency variability in surface ocean properties, data synthesis groups developing seasonal CO_2 flux maps for the global oceans (e.g. Takahashi climatology, Surface Ocean CO_2 Atlas [SOCAT], NOAA flux maps) and researchers studying ocean acidification. These data are currently being used to evaluate regional and global carbon models. Several of the near real-time buoy displays are used in web pages and graphics used to inform the general public and policy makers about the ocean carbon system.

The long-term goal of this program is to populate 50 Ocean Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES; www.oceansites.org) open ocean flux reference moorings with pCO_2 systems. With twelve open ocean pCO_2 moorings currently supported by NOAA's Global Ocean Monitoring and Observing (GOMO) Program and an additional five supported by other partners, the global pCO_2 mooring network is currently at 34% completion of this goal (Figure 1). In addition, five platforms with $MAPCO_2$ systems are also hosting additional ocean acidification (OA) instrumentation (Papa, KEO, WHOTS, Stratus, and CCE1), which would not be possible without the partnership between NOAA's GOMO and OA Program (OAP). GOMO supports the testing, maintenance, and data quality control of the $MAPCO_2$ systems and the OAP supports the activities required to maintain the additional OA sensors. This is an example of leveraging resources within NOAA to expand biogeochemical measurements on existing platforms, and as a result, these sites touch an even broader set of NOAA goals than they would without coordinated investments. The additional OA data is also valuable to the science by facilitating the interpretation of the CO_2 measurements and vice versa.

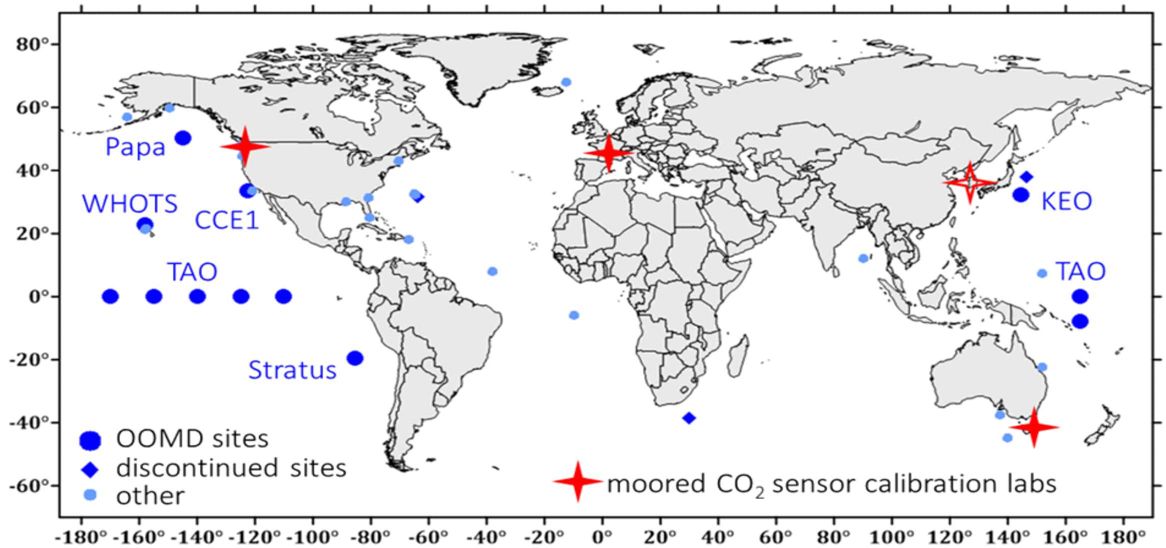

Figure 1. Location of the moored CO_2 time series included in SOCAT: CO_2 mooring time series funded by GOMO shown in dark blue circles; discontinued GOMO time series in dark blue diamonds; other time series in light blue. Other CO_2 sites are maintained by PMEL with the support of other partners with the exception of the tropical Atlantic sites maintained by Natalie Lefèvre (France) and the sites in coastal Australia maintained by Bronte Tilbrook (Australia).

Scientific Results

Decades of research have demonstrated that the ocean varies across a range of time scales, with anthropogenic forcing contributing added complexity. High-frequency mooring time series are uniquely suited to address the gaps in our knowledge related to the processes contributing to and the role of short-term variability in the ocean carbon cycle and distinguishing between natural and anthropogenic drivers. The primary deliverable from this project is the high-frequency data necessary to fill these knowledge gaps. The moored CO_2 network is providing a wealth of information about the time and space scales of variability in surface water pCO_2 and air-sea flux and the processes driving changes in ocean carbon. This is an exciting time in the history of the CO_2 mooring network: many of the time series have now approached the length and resolution necessary for the analyses that can address these high-priority research questions.

Since 2020, Sutton and colleagues have worked on a community service effort that resulted in a best practice for assessing trends of surface ocean carbonate time series available to the broader community in FY2023 ([Sutton et al., 2022]). The best practices publication has been viewed over 7700 times and used in at least half a dozen published peer-reviewed papers and submitted manuscripts since it was published one year ago. Because sub-seasonal resolution is so critical for calculating robust long-term trends, GOMO-funded time series represent a third of global surface ocean fixed time series (from both ships and buoys) that can be analyzed for trends without seasonality playing a large role in trend uncertainty. Even in the Strait of Juan de Fuca where there is relatively good coverage of underway pCO_2 observations, the bias in monthly measurement distribution can have a large impact on trend uncertainty (Figure 2D). The KEO buoy time series, on the other hand, has consistent measurement distribution over all months (Figure 2B), illustrating the unique role of high-frequency, fixed time series in global ocean observing. The best practices include open-source code for calculating trends and generating resulting figures and statistics to make the methods more accessible and easier to implement (https://github.com/NOAA-PMEL/TOATS).

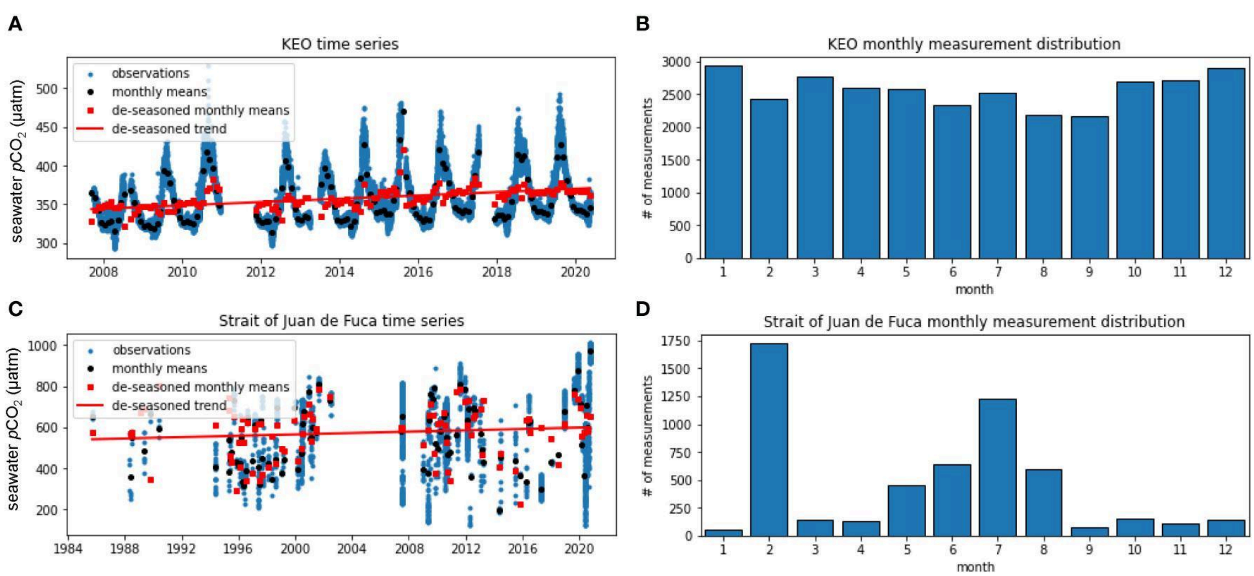

Figure 2. Surface seawater pCO_2 (µatm) from the KEO mooring (A) and ship-based underway measurements in the Strait of Juan de Fuca (C). Monthly measurement distribution of the KEO (B) and Strait of Juan de Fuca (D) time series are also shown. From Sutton et al. 2022.

The WHOTS time series has allowed for the first calculation of community calcification with a budget approach in the North Pacific Subtropical Gyre (Knor et al. 2023). Knor et al. find that the surface community photosynthesizes more than it respires, removing 53 g of CO_2 per square meter annually. Marine calcifiers also perform calcification, and our estimates are 4- to 7-fold higher than previous measurements from sediment traps deployed at this location. Key to this work is not only the surface ocean pCO_2 time series, but also the meteorological (wind speed) and physical (subsurface temperature and salinity) measurements led by Bob Weller and also supported by GOMO. Through this work, WHOTS provides a critical open-ocean endmember for assessing carbonate chemistry in coral reef ecosystems around Hawai'i.

While not GOMO-funded, the $MAPCO_2$ measurements on the CSIRO-led SOFS buoy time series provided another valuable contribution to assessing calculated surface pCO_2 from BGC-Argo floats. Wynn-Edwards et al. (2023) is the latest of at least half a dozen published results suggesting a bias in BGC-Argo predicted pCO_2. Wynn-Edwards et al. determined a bias of 7 µatm. While *random* error of calculated pCO_2 is not an issue when assessing regional to global CO_2 flux from a large array of floats, *systemic* error is a major issue when the disequilibrium of CO_2 between the atmosphere and the ocean is only 8 µatm. Only when the source of the bias is constrained and well-characterized (i.e., clear understanding of the bias across different floats, sensor age, and regions) can bias corrections be trusted. Identifying measurement bias and serving as datasets for intercomparisons are major benefits of having a reference network that is traceable to standards and produces the highest-quality measurements, like those produced by GOMO-funded surface buoy and ship-based underway projects.

An emerging application of high-frequency autonomous time-series observations that the PMEL moored carbon team and partners are spearheading is the development of ocean acidification (OA) exposure metrics. In collaboration with Jan Newton at University of Washington, the PMEL moored carbon team started testing a suite of OA metrics in 2022 that are co-designed with stakeholders and partners in the US West Coast states and tribal nations. Figure 3 shows the relative distribution of threshold exceedance in 2022 by season for the moored time series on the Washington and California coasts. In the California Current Ecosystem (CCE), spring was the season with the most exposure to conditions outside the pre-industrial range compared to the rest of the year of 2022. Assessing this metric over a decade (not shown here) reveals significant interannual variability in how often the CCE is exposed to conditions to which its organisms are not adapted and that may be harmful to their survival. Because of lower overall variability compared to the northern CCE, the southern CCE locations have longer exposure to conditions that did not exist in pre-industrial times. In some years, conditions at all sites rarely exceed pre-industrial natural variability, and in the highest exposure years, pre-industrial conditions are exceeded up to 40% of the year.

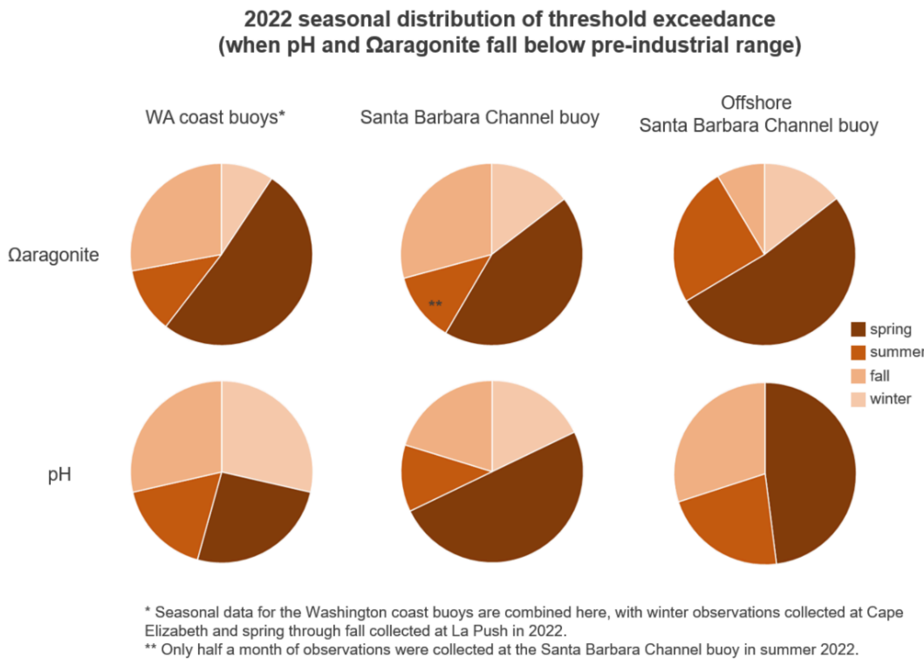

Figure 3. Seasonal distribution of threshold exceedance (i.e., when pH and aragonite saturation state fall below pre-industrial range), including data from three NOA-ON mooring locations: Chaba on the Washington coast and CCE2 and CCE1 in the Santa Barbara Channel and offshore, respectively. (NOAA internal)

It is also important to note that the seasons experiencing exposure to OA varies between CCE1 and CCE2 locations (Figure 3). Spring is the most dominant season with exposure below pH and aragonite thresholds at both sites. However, the season with the second-most dominant exposure to aragonite saturation state thresholds is fall for CCE2 and summer for CCE1. In the winter there are no exposure days for pH at CCE1, but winter exposure is just as dominant as fall and spring at CCE2. This illustrates the importance of CCE1 as a biogeochemical offshore endmember for observations within the Santa Barbara channel.

The distribution of the surface ocean pCO_2 mooring network has also allowed for regional to global data syntheses. Data from the CO_2 mooring network are included in the most recent release of SOCAT (Bakker et al. 2023) and the annual release of the Global Carbon Budget (Friedlingstein et al., 2022). As a result of the recent mooring additions to these data synthesis products and assessments and the over 132 cumulative years of GOMO-funded CO_2 mooring data now available at OCADS, the CO_2 mooring project will continue to make a large impact on our efforts to model and understand the global carbon cycle in the coming years.

Instrument/Platform Operations in FY2023

In FY2023, PMEL continues to maintain twelve sites initiated in previous years. There was a total of 10 completed servicing visits to these sites in FY2023. KEO and TAO 0, 155W were not serviced, however, the TAO site was serviced the last day of FY2022 and the 5th day into FY2024. Each servicing required the preparation of replacement systems so the MAPCO$_2$ equipment could be exchanged to maintain a continuous data stream. In some cases, new pCO_2

systems were needed to replace older less reliable systems or systems that were lost at sea during the year.

Here we summarize the deployment schedules and instrument performance over the last year. Systems are grouped into four categories: 1) seven systems are located in the equatorial Pacific on the TAO moorings operated by the National Data Buoy Center (NDBC), 2) two systems are on Woods Hole buoys operated by Bob Weller, 3) one system is located in the California Current operated by Uwe Send of Scripps, and 4) two systems are in high-latitude buoys operated by Meghan Cronin of PMEL as part of an GOMO funded Ocean Climate Stations project, one located off of Japan and one at Station Papa. At the end of each summary, we give two sets of percent data returns. The first is the Mooring Operational Time (MOT), which is the percent of time that the mooring was deployed, not-vandalized and anchored on station. Lifetime MOT is calculated from the first time that the $MAPCO_2$ system was deployed on that platform. The second is the $MAPCO_2$ data return, which only reports times as operational when a system returned both good quality seawater and atmospheric values. The PMEL CO_2 mooring observing project is compliant with the National Environmental Policy Act (NEPA) and other NOAA Environmental Statutes.

Equatorial Pacific on TAO Moorings

General Note about the Equatorial Pacific Moorings. Starting in FY2013, with the reduction in TAO ship days and a sequence of ship delays, the service to TAO moorings was greatly reduced and at some sites, non-existent. Fortunately, by early FY2015, all but one of the TAO $MAPCO_2$ sites were visited once and new systems were deployed. It should also be noted in FY2012 we began deploying extra-large battery packs on the TAO to try to maintain the time series even with a decrease in servicing frequency, which was originally every 6 months. Having this foresight paid off in several locations. Lastly, when the MOT is calculated, 18 months was used as the maximum amount of time that a buoy could remain in the water before it was considered inoperable.

0°, 110°W – The buoy and $MAPCO_2$ were serviced in April 2023 and the $MAPCO_2$ operated well during FY2023.
Mooring Operational Time (MOT) in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

0°, 125°W – The buoy and $MAPCO_2$ were serviced in October 2022 and operated well during FY2023.
MOT in FY2023: 92%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 82%

0°, 140°W – The buoy and $MAPCO_2$ were serviced in March 2023 and the $MAPCO_2$ operated well during FY2023.
MOT in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

0°, 155°W – The buoy and $MAPCO_2$ were serviced right before (September 2022) and after (October 2023) FY2023 and operated well during FY2023.
MOT in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 96%

0°, 170°W – This site was serviced in October 2022 and operated well during FY2023.

MOT in FY2023: 97%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

0°, 165°E – This site was serviced in August 2023. Diagnostic data suggests the equilibrator was stuck in the buoy for a portion of the previous deployment, causing a reduction in good data return during FY2023.
MOT in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 59%

8°S, 165°E – This site was finally serviced in August of 2023 after not being serviced since September 2020 due to lack of EEZ clearance. The location was moved in FY2023 approximately 100 km outside the Solomon Islands EEZ for this reason.
MOT in FY2023: 10%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

WHOI Moorings

WHOI Hawaii Ocean Time-series Station (WHOTS) (22°N, 157°W) – The buoy and $MAPCO_2$ were serviced in June 2023 and operated well during FY2023.
MOT in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

Stratus (19.7°S, 85.5°W) – The buoy and $MAPCO_2$ was serviced late February 2023 and re-establishes continuous air-sea CO_2 data after the last failed deployment due to a cable left behind by the WHOI team (these things happen).
MOT in FY2023: 59%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

Scripps Moorings

California Current #1 (CCE1) (33.5°N, 122.5°W) – The buoy and $MAPCO_2$ were serviced in July 2023 and this and the previous system operated well throughout the fiscal year.
MOT in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

Ocean Climate Stations Moorings

Kuroshio Extension Observatory (32.3°N, 144.5°E) – KEO was last serviced March 31, 2022. The MAPCO2 returned good data for 14 months. The next servicing is planned during FY2024.
MOT in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 68%

Papa (50°N, 145°W) – The buoy and $MAPCO_2$ were serviced in April 2023 and the $MAPCO_2$ operated well during FY2023.
MOT in FY2023: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 100%

MOT and Data Return Metrics for Moored pCO_2 Network

MOT in FY2023: 88%
Percent of MOT that $MAPCO_2$ returned data in FY2023: 92%

Quality Assurance and System Improvements

The CO_2 mooring program continues to be economical in its operations. The pCO_2 systems are mounted in buoys that are deployed in conjunction with other projects that cover the buoy deployment and maintenance costs and have allocated ship time. The pCO_2 systems are typically sent out on a cruise and are set up and deployed by a member of the scientific party as an ancillary task. This arrangement requires about 4 hours for setup and then approximately 10 additional person hours during the cruise. To keep expenses down we generally request that someone already involved in the cruise be trained to deploy the systems so we do not have to send our people to sea for deployments. During every deployment, someone from the PMEL CO_2 group stands by to remotely turn on the system after the buoy is deployed and to ensure that it is running properly before the ship leaves the site. In addition to turning the system on and off, all parameters can be changed remotely to optimize data collection. This approach requires that the systems be very robust and easy to setup.

The moored CO_2 program continued the great strides made since the beginning of the project to make the $MAPCO_2$ technology more accessible to the public, more reliable, and more accurate by transferring the $MAPCO_2$ technology from PMEL to Battelle Memorial Institute. However, as of December 2018 Battelle is no longer servicing or building $MAPCO_2$ systems. We have the capacity to do this servicing in house for several more years. Our goal is to maintain the existing $MAPCO_2$ systems until we complete development of the next generation system and transfer the technology to another commercial partner, which is work not supported by this project but leveraged by others.

The first stage of this technology development was supported by OAR's Ocean Technology Development project, NOPP, and IOOS. In FY2022 PMEL transferred the Autonomous Surface Vehicle CO_2 ($ASVCO_2$) sensor to Saildrone Inc, who we have collaborated with on the first deployments of the Saildrone-built $ASVCO_2$ sensors. The $ASVCO_2$ is the foundation for the next generation $MAPCO_2$ system that will measure both pCO_2 and dissolved inorganic carbon (DIC), partially funded by the Ocean Acidification Program, PMEL, and via leverage from other partnerships. Development of a benchtop system with pCO_2 and DIC components was delayed due to COVID-related lab closures and loss of personnel and funding at the Monterey Bay Aquarium Research Institute (MBARI), however, the benchtop prototype is complete and being deployed in its first intercomparison during winter 2024. PI Sutton is supported by OAP in FY2024 to evaluate the accuracy and precision of the benchtop prototype, but additional funding is needed for the next steps, including developing the embedded sensor capable of replacing the aging $MAPCO_2$ systems.

A few years ago, PMEL's $MAPCO_2$ system and $ASVCO_2$ sensor were a part of a [pCO_2 instrument intercomparison] organized by the Integrated Carbon Observation System. Preliminary results show the two systems performed within specifications. Final results, including how the systems compared to shipboard systems and other autonomous pCO_2 sensors, will be submitted for publication in FY2024.

Data Processing

Each of the currently deployed $MAPCO_2$ systems transmits a daily summary file of data to PMEL via Iridium satellite. The diagnostic information (battery condition, flow rates, etc.) is examined to ensure that the systems are still functioning properly. The raw CO_2 measurements are converted to a common scale (CO_2 mole fraction in dry air) and plotted on our website that is updated daily (www.pmel.noaa.gov/co2/story/Open+Ocean+Moorings). Launched in February 2011, the PMEL Carbon Group website (www.pmel.noaa.gov/co2) is completely revised and enhanced. The website includes detailed information on ocean carbon research, a description of each CO_2 mooring with links to our partners' websites, and a more user-friendly interface. The Google Earth data portal allows users to use a mapping interface to view near real time CO_2 data around the world (www.pmel.noaa.gov/co2/map/index).

Once the systems are recovered and returned to the laboratory, the full raw data set can be analyzed. We use a system for processing the moored pCO_2 data utilizing semi-automated quality control procedures developed within our group and updated in FY2013 to speed processing time. Based on the calibration information as well as other diagnostic measurements for each identified point relative to the surrounding points, the data point may be flagged as questionable or bad. Typically, less than 1% of the data are flagged. To finalize a dataset, the seawater values are compared to any ship-based pCO_2 data that are available and the atmospheric values are compared to Marine Boundary Layer (MBL) atmospheric CO_2 concentrations provided by NOAA's GLOBALVIEW-CO_2 network. Based on system diagnostics and these comparisons, the entire data set (air and water values) may be adjusted. Typically, these adjustments are less than a couple of parts per million. The data are then merged with sea-surface temperature and salinity data collected on the same buoy. These data quality control procedures are outlined in the following publication: Sutton, A. J., et al.: A high-frequency atmospheric and seawater pCO_2 data set from 14 open-ocean sites using a moored autonomous system, Earth Syst. Sci. Data, 6, 353–366, doi:10.5194/essd-6-353-2014, 2014.

As all data become available, final calibrated values are archived at NOAA's National Centers for Environmental Information (NCEI) Ocean Carbon Data System (OCADS) for public data access and archiving on a yearly basis. The CO_2 mooring data is a part of a larger effort to coordinate ocean carbon data, and we are heavily involved in the data management plans and implementation of those plans (e.g. Appendix A in the FY2023 workplan for this project). We have also successfully retrieved our data from OCADS to confirm the accessibility of the data.

We continue to meet our metrics for finalizing recovered CO_2 mooring data, exceeding milestones for data return, publications, and uptake of new data into data synthesis products. As of the end of FY2023, the cumulative number of years of data processed, finalized, and submitted to OCADS's for public release is 132, five years less than our target. The primary reason we did not achieve this milestone was due to lack of SST and SSS data available from the seven TAO sites. We rely on NDBC SST and SSS data to calculate pCO_2 and fCO_2 for our data submissions, and they were delayed in processing those data due to staff turnover. We plan to submit 10 years of data in January 2024, so this milestone should be recovered in FY2024. Finalized data are available to the public at OCADS: www.nodc.noaa.gov/ocads/oceans/time_series_moorings.html. Additional performance measures for FY2023 are shown in Table 1.

Table 1. PMEL CO_2 mooring program FY2023 performance measures, planned and actual.

Measure of Performance	2023 planned assuming flat budget	2023 actual
New moored CO_2 time series established	0	0
Number of $MAPCO_2$ sites maintained	12	10
% Mooring Operational Time (MOT) $MAPCO_2$ returns data	80%	92%
Years of finalized data available to the public	137	132
# of publications that use project's data in analysis	≥4	≥5
% new data uptake into synthesis studies each year	90%	100%

A citation for the data is clearly presented on each mooring data webpage and metadata report at OCADS, and we track use of the data by asking users to cite the data, reach out to us before publication, and acknowledge GOMO support on peer-reviewed publications that rely heavily on our mooring data. These data are also ingested approximately annually into SOCAT (www.socat.info/) and the Global Carbon Project (www.globalcarbonproject.org/carbonbudget/index.htm). Publications supported through GOMO funding are listed in the Publications and Reports section below and the PMEL website.

Outreach and Education

As part of Dr. Sutton's work on the GOA-ON Executive Council and IOCCP's Scientific Steering Group, she led one community service effort that has resulted in capacity building materials available to the broader community (Sutton et al. 2022) and two in development: 1) collaborative project to develop best practice documents and corresponding online training resources in data quality control for the ocean carbon and acidification observing community and 2) co-lead of the section on observing in the WMO Global Greenhouse Gas Watch Implementation Plan.

Dr. Sutton's work was featured in several PMEL web stories, a NOAA Story Map, and two external media (New York Times and arsTECHNICA). The moored CO_2 group continues the partnership with the Seattle Space Needle to monitor local atmospheric CO_2 and communicate the implications of those observations to the public. In FY2022 PMEL completed machine learning techniques for automated quality control of the Space Needle data and, as a result, are serving near-real time data publicly. CO_2 mooring group developers are now adapting those real-time quality control techniques to the mooring time series. The group also continues a partnership started in FY2013 with the Exploratorium in San Francisco to measure seawater pCO_2 in the bay and communicate that information in a display in the museum.

Dr. Sutton continues to actively mentor two young female BIPOC scientists: as official advisor to UW Oceanography graduate student Treasure Warren, as well as an informal mentor to Leah Hopson, a graduate student at University of Rutgers.

The moored CO_2 group **c**ontinues to interact with numerous laboratories around the US and internationally to explain how the $MAPCO_2$ systems work and the infrastructure requirement needed to deploy them. In FY2023 we continued to provide virtual support for our colleagues in refurbishment of the $MAPCO_2$ as well as data QC and management. As a result of this outreach as well as the consistently good performance of the system in inter-comparison studies, the $MAPCO_2$ system is considered the "gold standard" for moored CO_2 systems.

During FY2023, the PMEL Carbon Group website (www.pmel.noaa.gov/co2/) had over 80,000 unique visits, which shows steady traffic since the new website was launched in FY2011. We include a detailed description of each NOA-ON mooring (www.pmel.noaa.gov/co2/story/Buoys+and+Autonomous+Systems) and an interactive data portal (www.pmel.noaa.gov/co2/map).

Publications and Reports

Publications by Principal Investigator

Published in FY23

*led by graduate student**
*led by postdoc***

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Proceedings from conferences

No scientific conferences attended in FY23

Other Relevant Publications

All the pCO_2 data described in this report are incorporated into the Global Carbon Budget and SOCAT data products. Publications that use these products are too numerous to list here. As of November 2022, SOCAT identified 61 publications using SOCAT data in 2023, the paper describing SOCAT Version 3 (Bakker et al., 2016) was viewed over 14,000 times and cited 351 times, and the paper describing the 2022 Global Carbon Budget was viewed over 106,000 times and cited 265 times.

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Data and Publication Sharing

No updates to the Data Management Plan included in the FY2023 Work Plan are necessary. All quality-controlled $p\mathrm{CO_2}$ mooring data recovered from the field up to 2 years ago can be publicly accessed at NCEI (www.nodc.noaa.gov/ocads/oceans/time_series_moorings.html), through the SOCAT data product (www.socat.info/), and through the PMEL CO_2 time series product maintained since 2019 (www.pmel.noaa.gov/co2/timeseries/ or via ERDDAP).

Slides

See attached GOMO_FY23_Highlight moored pCO2.ppt