High-Resolution Ocean and Atmosphere pCO_2 Time-Series Measurements

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1. 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, we must first have the observations that clearly tract 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 or dust deposition events are particularly important with regard 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 15 years have led to autonomous moorings capable of sampling properties of chemical, biological, and physical interest 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 the variability 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). The Moored Autonomous pCO_2 ($MAPCO_2$) system collects CO_2 data from surface seawater and marine boundary air every three hours for up to a year at a time before they need servicing. Daily summary files of the measurements are transmitted back to PMEL where the data are examined and plots of the results are posted to the web in near-real time. In FY2014, PMEL maintained twelve sites initiated in previous years.

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. The 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 the network of Ocean Sustained Interdisciplinary Timeseries Environment observation System (OceanSITES; www.oceansites.org) so that CO_2 fluxes will become a standard part of the global flux mooring network. This effort has been endorsed by the OceanSITES science team. Additional information can be found at: www.pmel.noaa.gov/co2/story/Buoys+and+Autonomous+Systems.

2. 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 (2013-2017). 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).

In FY2014, PMEL maintained twelve sites. There were a total of nine servicing visits to these sites in FY2014. 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. The long term goal of this program is to populate 50 OceanSITES flux reference moorings with pCO_2 systems (Figure 1). With twelve moorings currently fitted with pCO_2 systems, we are currently at 24% completion of the open ocean moored CO_2 program goal. In addition, five platforms with $MAPCO_2$ systems are also hosting additional ocean acidification

(OA) instrumentation, which would not be possible without the partnership between NOAA's Climate Observation Division (COD) and OA Program (OAP). COD 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 mooring platforms, and as a result, these sites touch an even broader set of NOAA goals than th2014ey would without coordinated investments. The additional OA data also facilitates the interpretation of the CO_2 measurements and vice versa.

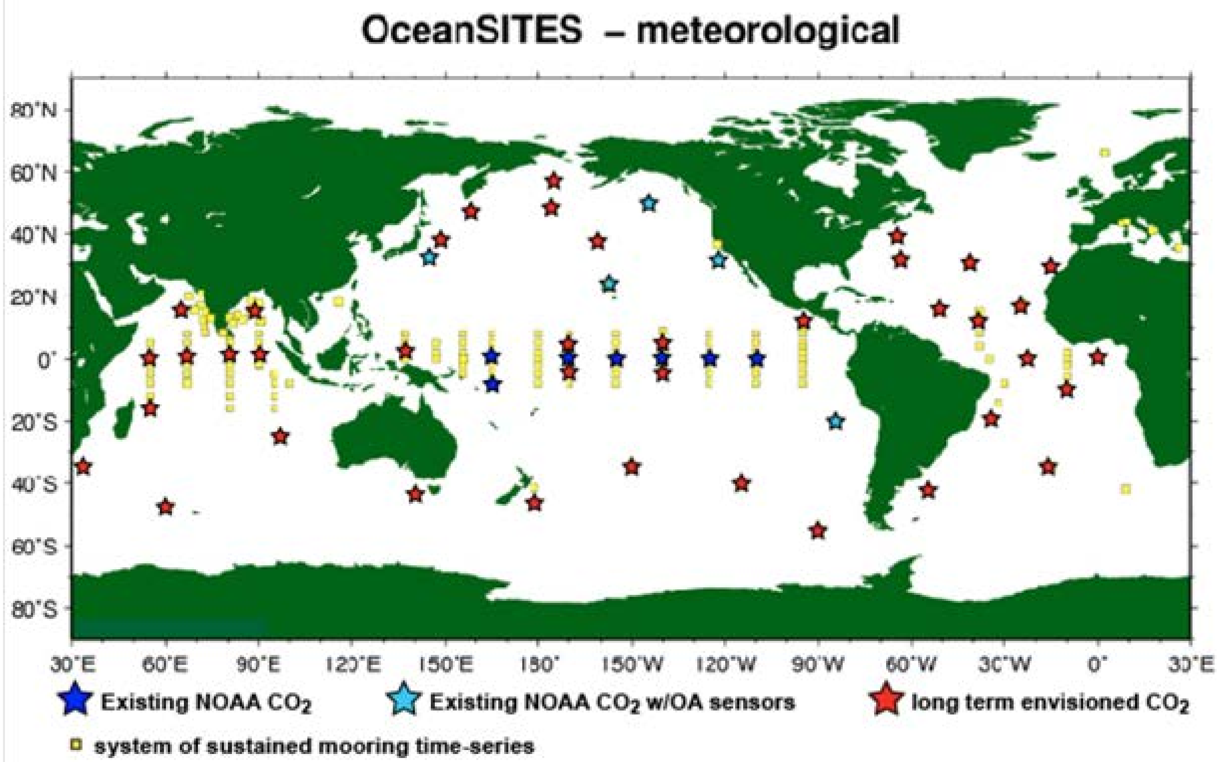

Figure 1. Map of the OceanSITES meteorological moorings (yellow squares) with stars indicating locations of moored pCO$_2$ systems currently planned and deployed as part of this program. Light blue stars indicate moorings with additional ocean acidification (OA) sensors.

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 (PMEL) as part of an COD 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.

2.1. Instrument/Platform Operations in FY2014

Equatorial Pacific on TAO Moorings

General Note about the Equatorial Pacific Moorings. With the reduction in TAO ship days followed by the continual mechanical problems of the R/V KOK in FY2013 and then the NOAA Ship Ronald H BROWN in FY2014, the service to TAO moorings was greatly reduced and at some sites, non-existent. The lack of service in FY2013 and FY2014 following several unfortunate vandalism incidents that happened in FY2012 made it a less than ideal year on the TAO array. Fortunately by the time of writing of this report in early FY2015, all but one of the TAO MAPCO$_2$ sites were visited and new systems were deployed. We look forward to FY2015 with the continuance of a more solid servicing schedule. 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. 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 - At the start of FY2014, the buoy was adrift and the equilibrator was damaged. The buoy and system were recovered. A new buoy and MAPCO$_2$ system were deployed June and the system was fully operational the remainder of the year.
Mooring Operational Time (MOT) in FY2014: 28%, Lifetime: 44%
Percent of MOT that MAPCO$_2$ returned data in FY2014: 100%, Lifetime: 84%

0°, 125°W – Transmissions from the buoy at the equator and 125°W have not be received since June 2012, likely due to vandalism. Before September 2014, this site was last serviced in April 2012. The NOAA Ship Ronald H Brown was in transit to this site in the spring but had to turn back due to mechanical issues. The buoy and MAPCO$_2$ system could not be located during the servicing visit and are presumed lost. A new buoy and MAPCO$_2$ system were deployed in September 2014. The system was fully operational for the remainder of the year.
Mooring Operational Time (MOT) in FY2014: 7%, Lifetime: 69%
Percent of MOT that MAPCO$_2$ returned data in FY2014: 100%, Lifetime: 81%

0°, 140°W - This location was unoccupied by a buoy for most of FY14. Evidence suggests that the previously deployed buoy was hit by a ship which broke the buoy free. The buoy was recovered in 2013. A new buoy and MAPCO$_2$ system were deployed September 2014 and the MAPCO$_2$ operated well for the remainder of the year.
Mooring Operational Time (MOT) in FY2014: 4%, Lifetime: 78%
Percent of MOT that MAPCO$_2$ returned data in FY2014: 100%, Lifetime: 89%

0°, 155°W - This site was last serviced at the end of FY2013. The system at this site operated well the entire year. It is due to be serviced in early FY15.
Mooring Operational Time (MOT) in FY2014: 100%, Lifetime: 74%
Percent of MOT that MAPCO$_2$ returned data in FY2014: 100%, Lifetime: 87%

0°, 170°W - This site was last serviced May 2012. Unfortunately all systems on the buoy stopped transmitting that same month. This site was not visited in FY2013 or FY2014. By the time of this report, the site was visited and a new buoy was deployed in early

FY2015. The recovered buoy and system were in pretty bad shape and it is unclear if either are salvageable.
Mooring Operational Time (MOT) in FY2014: 0%, Lifetime: 72%
Percent of MOT that $MAPCO_2$ returned data in FY2014: N/A, Lifetime: 95%

0°, 165°E – This site was not visited in FY2014. All systems stopped transmitting in August 2013. By the time of writing this report in early FY2015 however, a new buoy and $MAPCO_2$ system were deployed and operating well.
Mooring Operational Time (MOT) in FY2014: 0%, Lifetime: 73%
Percent of MOT that $MAPCO_2$ returned data in FY2014: N/A, Lifetime: 100%

8°S, 165°E – The system at this site was operating well until the end of November. Unfortunately the battery depleted very prematurely. The site was scheduled to be serviced in the fall of 2014, but clearance was not obtained in time for the ship to service this site.
Mooring Operational Time (MOT) in FY2014: 100%, Lifetime: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2014: 16%, Lifetime: 84%

WHOI Moorings

WHOI Hawaii Ocean Time-series Station (WHOTS) (22°N, 157°W) – The system at this site ran well during FY2014. The system was replaced in July of 2014.
Mooring Operational Time (MOT) in FY2014: 100%, Lifetime: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2013: 73%, Lifetime: 100%

Stratus (19.7°S, 85.5°W) – The buoy that was deployed in May 2012 and was adrift in the fall of 2013. After producing good data for 445 days, the $MAPCO_2$ battery was depleted. Due to reduced shiptime, a maintenance visit did not happen until March 2014. At that time, the drifting buoy and system were recovered and a new system was deployed. The system at this site ran well for the remainder of FY2014.
Mooring Operational Time (MOT) in FY2014: 57%, Lifetime: 85%
Percent of MOT that $MAPCO_2$ returned data in FY2014: 100%, Lifetime: 100%

Scripps Moorings

California Current #1 (CCE1) (33.5°N, 122.5°W) – The buoy and $MAPCO_2$ system at this site were recovered and redeployed on September 30, 2013. The $MAPCO_2$ system operated well the entire year.
Mooring Operational Time (MOT) in FY2014: 100%, Lifetime: 83%
Percent of MOT that $MAPCO_2$ returned data in FY2014: 100%, Lifetime: 99%

Ocean Climate Stations Moorings

Kuroshio Extension Observatory (32.3°N, 144.5°E) – The $MAPCO_2$ system was recovered and replaced in June 2014. The system operated well the entire year. The past year was the eighth successful deployment at this location after moving to the high latitude buoy in September 2007. Lifetime calculations below only consider deployments in a high latitude buoy.
Mooring Operational Time (MOT) in FY2014: 100%, Lifetime: 100%
Percent of MOT that $MAPCO_2$ returned data in FY2014: 100%, Lifetime: 92%

Papa (50°N, 145°W) – The $MAPCO_2$ system was recovered and replaced in June 2014. The system operated well the entire year.
Mooring Operational Time (MOT) in FY2014: 100%, Lifetime: 98%

Percent of MOT that $MAPCO_2$ returned data in FY2014: 100%, Lifetime: 95%

FY2014 Supplemental Funding

In FY2014 we received supplemental funds to address "acute needs" for our observing system projects. Due to budget shortfalls in FY2012 and FY2013, we were not able to maintain the necessary schedule for purchasing and servicing the $MAPCO_2$ systems. After the reduction in TAO ship days in FY2013, the news that the array would be serviced in 2014/2015 meant that we needed to obtain additional equipment to replace old and potentially vandalized or lost at sea $MAPCO_2$ systems in the tropical Pacific. Supplemental funding allowed us to prepare for an intensive deployment schedule in FY2014 by adding two new $MAPCO_2$ systems to our instrument pool. The instruments allowed us to meet all of our deployment obligations and maintain the highest possible level of data return. This supplemental funding was critical to maintaining the open ocean moored CO_2 network and providing critical information regarding the oceanic uptake of CO_2 from the atmosphere and seasonal and temporal trends in CO_2 fluxes.

2.2. Quality Assurance and System Improvements

The $MAPCO_2$ program continues to be economical in its operations. The pCO_2 systems are mounted in buoys that are deployed in conjunction with another project that is covering the buoy deployment and maintenance costs and has already 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 man 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 pay to send our people to sea for every deployment. 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.

For almost 4 years, we have used the same version of firmware and have not made any hardware changes for the $MAPCO_2$ system. This fact demonstrates that the $MAPCO_2$ system has become very stable, dependable and robust. With this stability has come savings in engineering development time and technician testing time. The $MAPCO_2$ firmware has also alleviated the need for PMEL personnel to be on site during deployments. However, we have recently completed on a new version of firmware that has settings to make it more robust in the cold weather environments and to make the field testing more user friendly for our collaborators working in the field. Our partners at Battelle Memorial Institute are now beginning to develop their own $MAPCO_2$ firmware, modeled on our version, which will eliminate the need for our technicians and engineers to maintain the firmware in the future.

In FY2014, the moored CO_2 program continued the great strides made since FY2009 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. We continue to provide technical and advisory assistance to ensure that they are providing the best the $MAPCO_2$ systems to the public. Additionally, although on the surface the Battelle systems appear to cost more than producing them in-house, we are saving a great deal of engineering and technician time by not having to assemble the systems ourselves.

Throughout the year, many inter-comparisons were run between the PMEL MAPCO_2 systems, the underway pCO_2 systems and the Battelle built systems both in the laboratory and in the field on various ships. The MAPCO_2 system has consistently compared favorably with the shipboard systems over a wide range of conditions (*Sutton et al.* 2014a; *Sutton et al.* 2014b). We continue the process of upgrading our lab testing environment by building a tool that will gather the data from all the systems testing in the lab into one program. It will collect data from underway pCO_2 systems, MAPCO_2 systems and temperature and conductivity instruments. This tool will process data immediately and display everything on one screen enabling lab technicians to see in real time the precision and accuracy of the systems being tested.

Finally, we are very excited to report that we have just recovered the two additional sensors that we added to our equilibrator at 0^o, 155^oW in FY2013. The water level sensor allows us to observe how the equilibrator float rides in the buoy while deployed. If the equilibrator is not positioned at the air-sea interface, the air in the equilibrator may not completely equilibrate with sea surface pCO_2 values, and the subsequent seawater measurement in the MAPCO_2 may not be accurate. We believe this happens during times of high currents (e.g., in the equatorial Pacific) and large storms (e.g., typhoons at KEO). Sometimes we can diagnose this by evaluating the pressure measurements within the MAPCO_2. Up to now, when we observe the changes in pressure, we always mark the data questionable, but the additional diagnostic of equilibrator water level should help us to gain a firm understanding of data quality during these high-energy periods. We also deployed a very inexpensive “in/out” sensor, which we intend to validate using the water level data. Once validated, the “in/out” sensor will be easily integrated into the rest of our systems as a standard operating procedure. Now that these sensors are recovered, we will focus on analyzing the data in FY2015.

2.3. Data Processing

Over the past three years we have been working with a PMEL programmer to develop a sophisticated database that can handle the large quantities of data that are now coming in. The data stream coming into the lab has grown substantially since the beginning of this project and more automated programs for initially processing and plotting the daily satellite transmissions are required. Major components of the database development are complete, and we have transferred maintenance of the database to a programmer within the PMEL Carbon Group. In FY2013 this programmer also developed a new MAPCO_2 data quality control program that has cut the finalized data processing time by two thirds. All of these activities are designed to simplify data collection and processing to make the moored CO_2 program more streamlined and efficient.

Each of the 12 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/map). 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 new Google Earth data portal allows users to use a mapping interface to view near real time CO_2 data around the world.

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.

As all data become available, final calibrated values are archived at the Carbon Dioxide Information Analysis Center (CDIAC) and the National Oceanographic Data Center (NODC) 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 FY2014 workplan for this project). We have also successfully retrieved our data from these data archival centers to confirm the accessibility of the data. We continue to make significant progress in finalizing recovered CO_2 mooring data. As of the end of FY2014, the cumulative number of years of data processed, finalized, and submitted to CDIAC for public release is 62. This meets our FY2014 goal for the "years of finalized data available to the public" performance measure (see Section 2.5 in FY2014 Workplan). Finalized data are available to the public at cdiac.ornl.gov/oceans/Moorings/. A citation for the data is clearly presented on each mooring data webpage at CDIAC and metadata report, and we track use of the data by asking users to cite the data, reach out to us before publication, and ask us to coauthor and acknowledge COD support on peer-reviewed publications that rely heavily on our mooring data. Publications supported through COD funding are listed in the Publications and Reports section below and the PMEL website.

2.4. Analysis and Research Highlights

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 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 fluxes that we are only just beginning to examine. 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 statistical analyses that can address these high-priority research questions.

For example, Sutton et al. synthesize CO_2 mooring observations in the Niño 3.4 area with datasets encompassing 10 ENSO warm and cold events since 1997 [*Sutton et al.* 2014a]. This unprecedented high-resolution data set represents a quantum leap in our ability to understand the mechanisms governing ocean events. ENSO is the major natural driver of pCO_2 conditions on interannual time scales (Fig 2). However, high-frequency measurements also provide the opportunity to assess in more detail how surface ocean pCO_2 conditions change through individual ENSO events, during the transitions between events, and in relation with other physical parameters (e.g. the passing of tropical instability waves). The mooring pCO_2 time

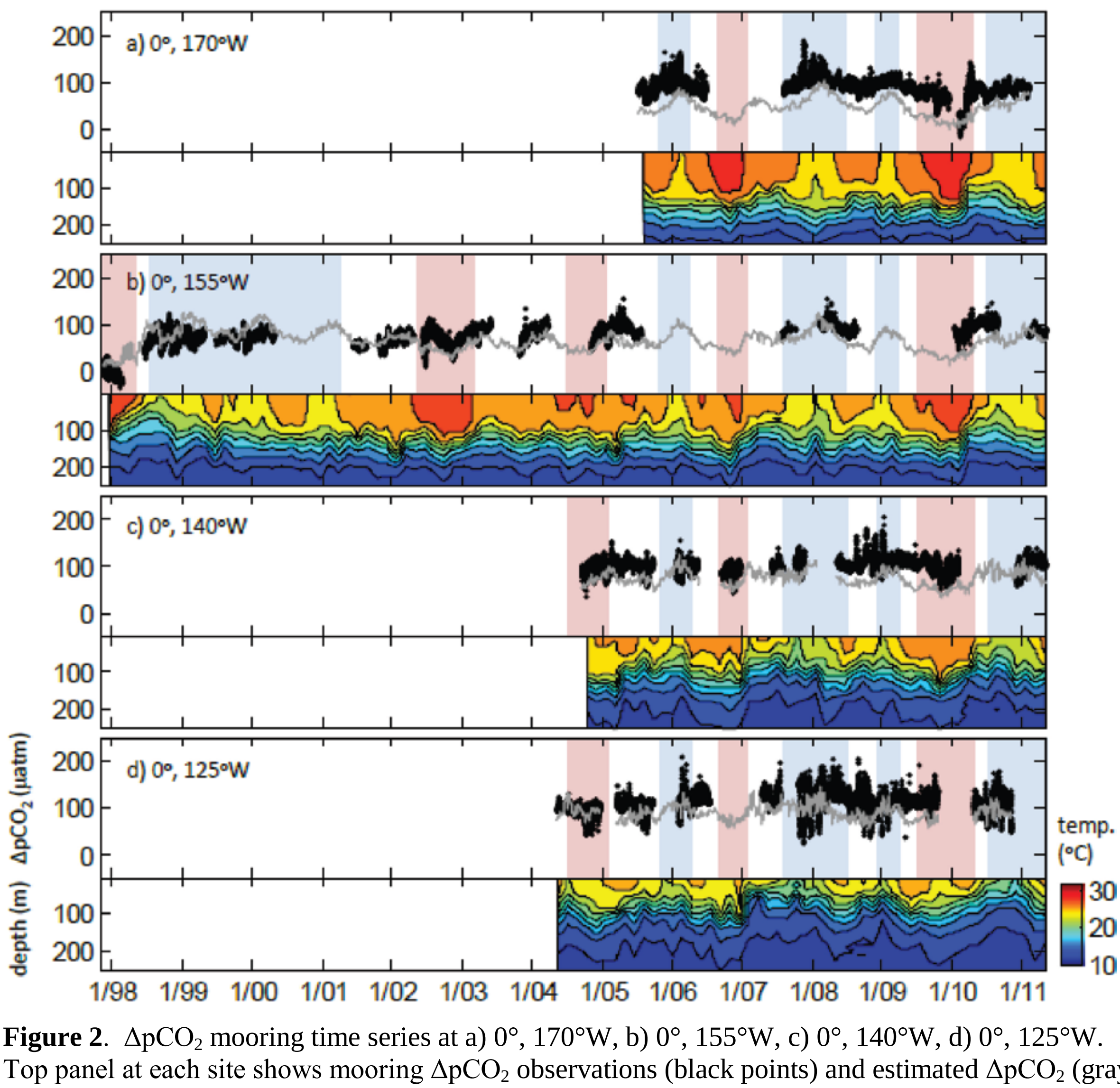

Figure 2. ΔpCO_2 mooring time series at a) 0°, 170°W, b) 0°, 155°W, c) 0°, 140°W, d) 0°, 125°W. Top panel at each site shows mooring ΔpCO_2 observations (black points) and estimated ΔpCO_2 (gray line) based on seawater pCO_2 and SST relationships developed by Feely et al. [2006]. Shaded areas represent El Niño (red) and La Niña (blue) periods as defined by the Oceanic Niño Index (ONI). Bottom panel at each site shows temperature time series (°C) from the surface to 250 m (data from NOAA TAO, www.pmel.noaa.gov/tao).   From *Sutton et al.* [2014a].

series are also approaching the length necessary for analyzing long-term trends. Observations suggest that seawater pCO_2 in the Niño 3.4 area of the equatorial Pacific, especially during upwelling (non-El Niño) periods, is changing faster than the mean global atmospheric CO_2 growth rate of 2 µatm yr^{-1} (Fig 2). These data suggest that anthropogenic CO_2 uptake and increased upwelling since the PDO shift of 1997–1998 are resulting in higher surface seawater pCO_2 (+2.3 to +3.3 µatm yr^{-1}) growth rates than previously reported, providing new evidence that CO_2 outgassing may be increasing from the equatorial Pacific. This region supplies the largest natural source of oceanic CO_2 to the atmosphere, and understanding the mechanisms driving changes in CO_2 outgassing, are critical to improving climate predictions.

In 2014, *Sutton et al.* [2014b] also published a $MAPCO_2$ system methods paper, which includes the most comprehensive comparison of observations from the CO_2 mooring network and ship-based carbon measurements to date. Based on laboratory tests and field intercomparisons at PMEL and other institutions, overall uncertainty of the $MAPCO_2$ system is <2 µatm for seawater pCO_2 and <1 µatm for air pCO_2. The $MAPCO_2$ maintains this level of uncertainty for over 400 days of autonomous operation. These comparisons show that the $MAPCO_2$ is the only moored autonomous pCO_2 sensor making climate quality measurements (i.e., data of quality sufficient to assess long term trends and detect anthropogenic change of 2 µatm yr^{-1}). The climate-quality data provided by the $MAPCO_2$ have allowed for the establishment of critical open-ocean observatories to track surface ocean pCO_2 changes around the globe. Data are available at doi:10.3334/CDIAC/OTG.TSM_NDP092 and http://cdiac.ornl.gov/oceans/Moorings/ndp092.

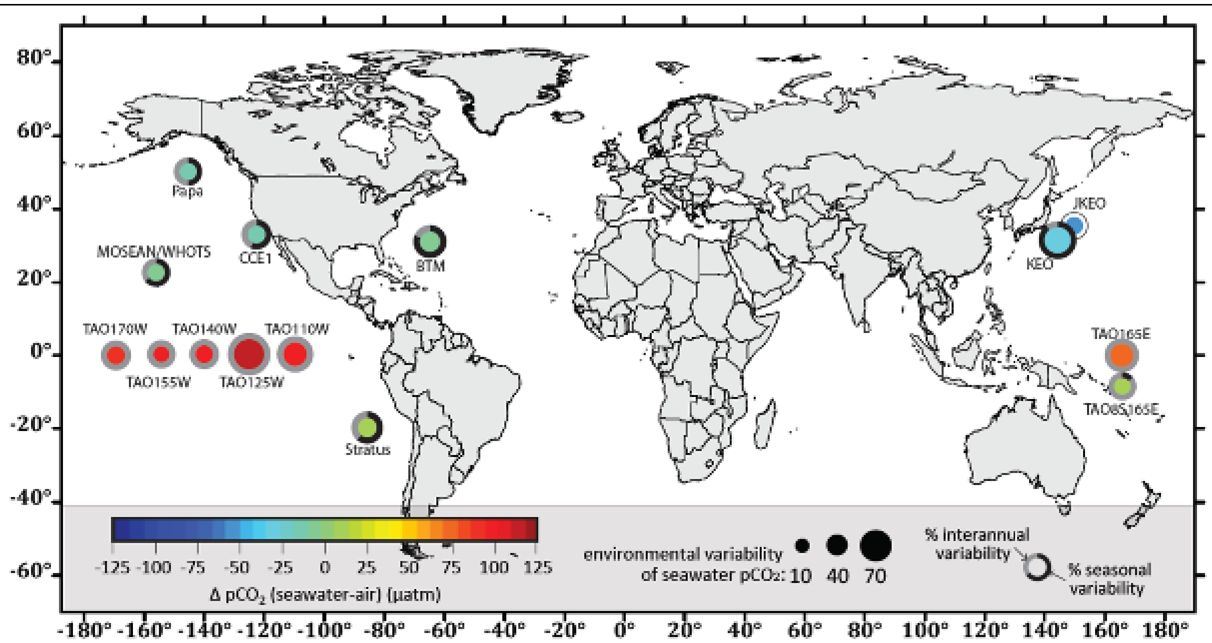

Figure 3. Location of open-ocean moorings in the *Sutton et al.* [2014b] $MAPCO_2$ data set. Inner circle color illustrates the mean ΔpCO_2 of the finalized data at that location. Inner circle size is relative to the environmental variability of seawater pCO_2 in the time series, and the outer ring shows the proportion of that variability due to the seasonal cycle (black) and interannual dynamics (gray).

This paper also presents a mooring data set, which includes 3-hourly seawater and atmospheric CO_2 observations from 14 moorings funded by COD since 2004 and includes over 100,000 individual measurements [*Sutton et al.* 2014b]. Figure 3 shows that temporal variability at the subtropical sites tends to be dominated by the seasonal cycle, and tropical sites tend to be dominated by interannual dynamics. At the subtropical sites, seawater CO_2 is typically highest in the summer and lowest in the winter. The Papa site is the highest-latitude mooring in this data set and exhibits approximately equal short-term variation driven by seasonal and interannual variability, which in this case are caused by strong weather events in the North Pacific. The highest interannual variability is observed in the equatorial Pacific driven by El Niño and La Niña events (Fig. 3) and dominates any minimal seasonal signal that may exist in this region.

For the first time, data from the CO_2 mooring network are also included in the most recent release of the Surface Ocean CO_2 Atlas (SOCATv2.0) [*Bakker et al.* 2014] and the annual release of the Global Carbon Budget [*Le Quéré et al.* 2014]. As a result of the recent mooring additions to these data synthesis products and assessments and the ~62 years of NOAA CO_2 mooring data now available at CDIAC, we expect the CO_2 mooring project to make a large impact on our efforts to model and understand the global carbon cycle in the coming years.

3. Outreach and Education

Drs. Sutton and Mathis both presented scientific research from the moored CO_2 program to the public in several forums including local grade schools, colleges, open public lectures (both in the US and abroad), public "webinars", and laboratory tours in FY2014. Since 2012, Dr. Sutton has also been a member of the UW College of the Environment's Science Communication Task Force, which is tasked with developing a strategy for the College to better communicate its research to the public. Our group continues the partnership with the Seattle Space Needle and Pacific Science Center to monitor local atmospheric CO_2 and communicate the implications of those observations in displays to the public. We continue 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.

As part of this program we transferred the PMEL moored pCO_2 system to private industry (Battelle Memorial Institute) so that the larger scientific community will have access to these moored systems. We have interacted with numerous laboratories around the US and internationally to explain how the $MAPCO_2$ systems work and the infrastructure requirement needed to deploy them. 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 FY2014, the PMEL Carbon Group website (www.pmel.noaa.gov/co2/) had approximately 66,000 unique visits, which shows steady traffic since the new website was launched in FY2011. The website includes detailed background information on ocean carbon uptake (www.pmel.noaa.gov/co2/story/Ocean+Carbon+Uptake) and how our research contributes to a better understanding of the role of the ocean in the global carbon cycle. We also include a detailed description of each CO_2 mooring (www.pmel.noaa.gov/co2/story/Buoys+and+Autonomous+Systems) and a Google Earth data portal (www.pmel.noaa.gov/co2/map).

4. Publications and Reports

4.1. Publications by Principal Investigators

Published

Bakker, D.C.E., B. Pfeil, K. Smith, S. Hankin, A. Olsen, S.R. Alin, C. Cosca, S. Harasawa, A. Kozyr, Y. Nojiri, K.M. O'Brien, U. Schuster, M. Telszewski, B. Tilbrook, C. Wada, J. Akl, L. Barbero, N. Bates, J. Boutin, W.-J. Cai, R.D. Castle, F.P. Chavez, L. Chen, M. Chierici, K. Currie, H.J.W. de Baar, W. Evans, R.A. Feely, A. Fransson, Z. Gao, B. Hales, N. Hardman-Mountford, M. Hoppema, W.-J. Huang, C.W. Hunt, B. Huss, T. Ichikawa, T. Johannessen, E.M. Jones, S.D. Jones, S. Jutterström, V. Kitidis, A. Körtzinger, P. Landschützer, S.K. Lauvset, N. Lefèvre, A.B. Manke, J.T. Mathis, L. Merlivat, N. Metzl, A. Murata, T. Newberger, T. Ono, G.-H. Park, K. Paterson, D. Pierrot, A.F. Ríos, C.L. Sabine, S. Saito, J. Salisbury, V.V.S.S. Sarma, R. Schlitzer, R. Sieger, I. Skjelvan, T. Steinhoff, K. Sullivan, H. Sun, A.J. Sutton, T. Suzuki, C. Sweeney, T. Takahashi, J. Tjiputra, N. Tsurushima, S.M.A.C. van Heuven, D. Vandemark, P. Vlahos, D.W.R. Wallace, R. Wanninkhof, and A.J. Watson (2014): An update to the surface ocean CO2 atlas (SOCAT version 2). Earth Syst. Sci. Data, 6, doi: 10.5194/essd-6-69-2014, 69–90.

Feely, R.A., R. Wanninkhof, C.L. Sabine, J.T. Mathis, T. Takahashi, and S. Khatiwala (2014): Global ocean carbon cycle. In State of the Climate in 2013, Global Oceans. Bull. Am. Meteorol. Soc., 95(7), S73–S80.

Le Quéré, C., R. Moriarty, R.M. Andrew, G.P. Peters, P. Ciais, P. Friedlingstein, S.D. Jones, S. Sitch, P. Tans, R.J. Andres, A. Arneth, T.A. Boden, A. Bondeau, L. Bopp, Y. Bozec, J.G. Canadell, F. Chevallier, C.E. Cosca, I. Harris, M. Hoppema, R.A. Houghton, J.I. House, A.K. Jain, T. Johannessen, E. Kat, R.F. Keeling, V. Kitidis, K. Klein Goldewijk, C. Koven, C. Landa, P. Landschützer, A. Lenton, I. Lima, G. Marland, J.T. Mathis, N. Metzl, Y. Nojiri, A. Olsen, W. Peters, B. Pfeil, B. Poulter, M.R. Raupach, P. Regnier, C. Rödenbeck, S. Saito, J.E. Salisbury, U. Schuster, J. Schwinger, R. Séférian, J. Segschneider, T. Steinhoff, B.D. Stocker, A.J. Sutton, T. Takahashi, B. Tilbrook, N. Viovy, Y.-P. Wang, R. Wanninkhof, G. van der Werf, A. Wiltshire, S. Zaehle, and N. Zeng (2014): Global Carbon Budget 2014. Earth Syst. Sci. Data Discuss., 7, 521-610, doi:10.5194/essdd-7-521-2014.

Sutton, A.J., R.A. Feely, C.L. Sabine, M.J. McPhaden, T. Takahashi, F.P. Chavez, G.E. Friederich, and J.T. Mathis (2014a): Natural variability and anthropogenic change in equatorial Pacific surface ocean pCO2 and pH. Global Biogeochem. Cycles, 28(2), doi: 10.1002/2013GB004679, 131–145.

Sutton, A.J., C.L. Sabine, S. Maenner-Jones, N. Lawrence-Slavas, C. Meinig, R.A. Feely, J.T. Mathis, S. Musielewicz, R. Bott, P.D. McLain, J. Fought, and A. Kozyr (2014b): A high-frequency atmospheric and seawater pCO2 data set from 14 open ocean sites using a moored autonomous system. Earth Sys. Sci. Data, 6, 353-366, doi:10.5194/essd-6-353-2014.

In press
Shadwick, E.H., T.W. Trull, B. Tilbrook, A.J. Sutton, E. Schulz, and C.L. Sabine (2014): Seasonality of biological and physical controls on surface ocean CO2 from hourly observations at the Southern Ocean Time Series site south of Australia. Global Biogeochem. Cycles. [in revision]

Proceedings from conferences
Cronin, M.F., M. Bourassa, C.A Clayson, J. Edson, C. Fairall, R.A. Feely, D.E. Harrison, S. Josey, M. Kubota, B. Praveen Kumar, K. Kutsuwada, B. Large, J.T. Mathis, M.J. McPhaden, L. O'Neill, R. Pinker, K. Takahashi, H. Tomita, R.A. Weller, L. Yu, and C. Zhang (2014): TPOS White Paper #11: Wind stress and air-sea fluxes observations: status, implementation and gaps. In Proceedings of the Tropical Pacific Observing System 2020 Workshop, A Future Sustained Tropical Pacific Ocean Observing System for Research and Forecasting, WMO and Intergovernmental Oceanographic Commission, La Jolla, CA, 27–30 January 2014.

Mathis, J.T., R.A. Feely, A. Sutton, C. Carlson, F. Chai, F. Chavez, M. Church, C. Cosca, M. Ishii, C. Mordy, A. Murata, J. Resing, P. Strutton, T. Takahashi, and R. Wanninkhof (2014): TPOS Whitepaper #6. Tropical Pacific biogeochemistry: Status, implementation and gaps. In Proceedings of the Tropical Pacific Observing System 2020 Workshop, A Future Sustained Tropical Pacific Ocean Observing System for Research and Forecasting, La Jolla, CA, 27–30 January 2014.

Data reports
Sutton, A.J., C.L. Sabine, J.T. Mathis, and A. Kozyr. 2014. A high-frequency atmospheric and seawater pCO2 data set from 14 open ocean sites using a moored autonomous system. ORNL/CDIAC-158, NDP-092. http://cdiac.ornl.gov/oceans/Moorings/ndp092.html Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/OTG.TSM_NDP092

4.2. Other Relevant Publications

Alin, S., R. Feely, J. Mathis, C. Sabine, J. Newton, and A. Sutton (2014): Atmospheric and surface seawater CO2 at the coast and Hood Canal. In Puget Sound Marine Waters: 2013 Overview, Moore, S.K., K. Stark, J. Bos, P. Williams, J. Newton, and K. Dzinbal (eds.), Published online, 9.

Alin, S., J. Mathis, C. Sabine, A. Sutton, S. Musielewicz, A. Devol, W. Reuf, J. Newton, and J. Mickett (2014): Ocean and atmospheric CO2 dynamics at Dabob Bay and Twanoh ORCA surface moorings. In Puget Sound Marine Waters: 2013 Overview, Moore, S.K., K. Stark, J. Bos, P. Williams, J. Newton, and K. Dzinbal (eds.), Published online, 22.

Alin, S., J. Mathis, C. Sabine, A. Sutton, S. Musielewicz, J. Newton, and J. Mickett (2014): Ocean and atmospheric CO2 dynamics at the Chá bă surface mooring. In Puget Sound Marine Waters: 2013 Overview, Moore, S.K., K. Stark, J. Bos, P. Williams, J. Newton, and K. Dzinbal (eds.), Published online, 7.

Ciais, P., A.J. Dolman, A. Bombelli, R. Duren, A. Peregon, P.J. Rayner, C. Miller, N. Gobron, G. Kinderman, G. Marland, N. Gruber, F. Chevallier, R.J. Andres, G. Balsamo, L. Bopp, F.-M. Bréon, G. Broquet, R. Dargaville, T.J. Battin, A. Borges, H. Bovensmann, M. Buchwitz, J. Butler, J.G. Canadell, R.B. Cook, R. DeFries, R. Engelen, K.R. Gurney, C. Heinze, M. Heimann, A. Held, M. Henry, B. Law, S. Luyssaert, J. Miller, T. Moriyama, C. Moulin, R.B. Myneni, C. Nussli, M. Obersteiner, D. Ojima, Y. Pan, J.-D. Paris, S. L. Piao, B. Poulter, S. Plummer, S. Quegan, P. Raymond, M. Reichstein, L. Rivier, C. Sabine, D. Schimel, O. Tarasova, R. Valentini, G. van der Werf, R. Wang, D. Wickland, M. Williams, and C. Zehner (2014): Current systematic carbon-cycle observations and the need for implementing a policy-relevant carbon observing system. Biogeosciences, 11, doi: 10.5194/bg-11-3547-2014, 3547-3602.

Drupp, P., E.H. De Carlo, F.T. Mackenzie, C.L. Sabine, R.A. Feely, and K.E. Shamberger (2013): Comparison of CO2 dynamics and air–sea gas exchange in differing tropical reef environments. Aquat. Geochem., 19(5–6), doi: 10.1007/s10498-013-9214-7, 371–397.

Rödenbeck, C., D.C.E. Bakker, N. Metzl, A. Olsen, C. Sabine, N. Cassar, F. Reum, R.F. Keeling, and M. Heimann (2014): Interannual sea–air CO2 flux variability from an observation-driven ocean mixed-layer scheme. Biogeosciences, 11, doi: 10.5194/bg-11-4599-2014, 4599–4613.

5. Slides

See attached Moored_CO2_Overview_FY14.ppt.