Global Data Management and Synthesis Project

Richard A. Feely[1], Brendan R. Carter[1], Jeremy T. Mathis[1], Rik Wanninkhof[2]
[1]NOAA Pacific Marine Environmental Lab., 7600 Sand Point Way NE, Seattle, WA 98115
[2]NOAA Atlantic Oceanographic and Meteorological Lab., 4301 Rickenbacker Causeway, Miami FL 33149

Table of Contents

Global Data Management and Synthesis Project 3
1. Project Summary 3
   1.1. Project justification 3
   1.2. Project overview 4
2. Scientific and Observing System Accomplishments 5
   2.1. Surface ocean pCO_2 measurements 6
      2.1.1. Data quality control and automation for SOCAT version 3 6
      2.1.2. Moored pCO_2 network 8
      2.1.3. Air-sea CO_2 flux assessment 8
      2.1.4. Production of seasonal air-sea CO_2 flux maps 10
      2.1.5. Global Carbon Project (GCP) assessment 11
   2.2. Ocean interior 12
      2.2.1. Global interior carbon data synthesis 12
      2.2.2. Quality control of data from recent cruises 13
      2.2.3. Analysis of data from recent cruises 15
   2.3. Performance measures 20
3. Outreach and Education 20
4. Publications and Reports 21
   4.1. Publications by Principal Investigators 21
      4.1.1. Published 21
      4.1.2. In press 22
      4.1.3. Technical reports 22
   4.2. All references cited in this report 22

1. Project Summary

1.1. Project justification

Over the past two and a half centuries, the surface oceans have absorbed approximately 30% of mankind's carbon dioxide (CO_2) emissions (Prentice et al., 2001; Canadell et al., 2007; Le Quéré et al., 2009). Ocean CO_2 uptake has reduced the accumulation of greenhouse gases in the atmosphere and slowed the rate of climate change (IPCC, 2007; Sabine and Feely, 2007; Feely et al., 2013). When anthropogenic CO_2 is absorbed by seawater chemical reactions occur that reduce both seawater pH and the concentration of carbonate ions in a process known as "ocean acidification." The pH of ocean surface waters has already decreased by about 0.1 units since the beginning of the industrial revolution (Caldeira and Wickett, 2003; Caldeira and Wickett, 2005). Questions remain regarding the details, mechanisms, feedbacks, and consequences of

ocean carbon uptake and acidification. Continued monitoring and scientific analysis of the ocean carbon cycle is critical for understanding how this important sink for anthropogenic CO_2 is functioning; how ocean carbon storage might change in the future; and how we can best anticipate, mitigate, and adapt to potential future changes.

Carbon data synthesis is essential for monitoring ocean carbon uptake due to the global scale of uptake, the complexities of interpreting ocean carbon measurements, and the variety of ways carbon content is measured. Research programs from 11+ participating nations contribute measurements of many different aspects of seawater chemistry made with a wide variety of sensors and analytical techniques. These diverse measurements are ultimately used with Earth System Model assessments, data-assimilating models, property budgets, and measurement inversions designed to address scientific questions related to ocean carbon uptake. A common element of all of these analyses is that they benefit from consistently-formatted ocean carbon measurements with well-constrained uncertainties. Data synthesis is therefore necessary to translate the wealth of information provided by the measurement community into the quality controlled and assessed data products needed for advancing and communicating global carbon cycle science.

1.2. Project overview

The global ocean carbon data management and synthesis project (DMCP) exists to provide resources and leadership to efficiently address the ocean carbon data needs of the global scientific community, decision makers, and the public. The DMCP scientists are also charged with conducting original ocean carbon cycle research. DMCP investigator tasks include:

1. measuring ocean carbon and obtaining carbon data from foreign and domestic collaborators;
2. quality controlling ocean carbon data;
3. providing ocean carbon data in common, convenient, and accessible formats;
4. assessing ocean carbon data uncertainty;
5. interpreting ocean carbon data;
6. and communicating relevant findings to decision makers and the broader public.

The DMCP brings together ocean carbon measurement and information technology experts from the Atlantic Oceanographic and Meteorological Laboratory (AOML) and Pacific Marine Environmental Laboratory (PMEL). These scientists work closely with data managers at the National Ocean Data Center (NODC) and the Carbon Data Information and Analysis Center (CDIAC) to address the oceanographic community's carbon data synthesis needs. The DMCP prioritizes workup and analysis of data obtained through efforts funded by the Climate Observation Division (COD) including the repeat hydrography program, the partial pressure of CO_2 (pCO_2) on ships effort, and the pCO_2 on moorings effort. Appreciable efforts are also made to incorporate data from non-COD investigators worldwide. Data synthesis efforts are aimed at addressing the core questions:

1. Where has the anthropogenic (i.e. carbon produced by man's activities) entered the ocean?
2. … and where is it stored?
3. How are these patterns of uptake and storage changing?
4. How is ocean carbon uptake impacting marine inorganic carbon chemistry?

The DMCP aims to quantify global anthropogenic CO_2 storage to within 2 Pg C decade^{-1} and regional sea-air CO_2 fluxes to within 0.2 Pg C year^{-1}. The DMCP pursues this goal directly through original research, and indirectly by developing educational programs, methods, datasets, and data products to aid research efforts by the broader scientific community. DMCP scientists engage in additional outreach and educational programs tailored to the broader public with the goal of informing the public of significant advances in understanding of the role of the ocean in climate.

Transparency and accessibility are critical for DMCP research, data, and data products. Data and data products are made available online at CCHDO[1], CDIAC[2], and the AOML/PMEL[3] institutional websites. New data are not provided in real-time due to the need for post-measurement calibration and data quality control and synthesis. Instead, preliminary data and finalized data are provided following timetables specified by guidelines of the measurement programs. Once submitted, data and data products are continually updated and archived, and efforts have been made to verify these websites are providing up-to-date versions. As an example, data from the Explorer of the Seas pCO_2 program measured in Oct. 2014 can be found online[4]. Data use statistics are kept by the US Repeat-Hydro and Global Ocean Ship-Based Hydrographic Investigations Programs (GO-SHIP)[5]. Acknowledgement of COD and NSF funding is made on the front page of the CCHDO website. Publications can be found online for both AOML and PMEL[6].

2. Scientific and Observing System Accomplishments

DMCP scientists contributed to several notable advances in carbon data synthesis in FY-14 in addition to their continued core efforts processing and interpreting ocean carbon measurements. These major accomplishments include:

- contributions to the 2013 and 2014 Global Carbon Budgets (LeQuéré et al., 2014a; 2014b in review)[7],
- contributions to previous and upcoming updates to the Surface Ocean Carbon Atlas (SOCAT)[8] (Bakker et al., 2014)
- improvements to the automation of the SOCAT data submission and quality control,
- and contributions to the continued development of the GLODAPv2 data product.

These accomplishments are discussed alongside other core FY-14 activities and accomplishments below. Synthesis activities for surface ocean pCO_2 measurements (made from moorings, and underway measurements) and for ocean interior measurements (made on repeat hydrography cruises) are discussed separately from one another because these measurements are processed in different ways and typically used to answer different questions: Surface pCO_2 measurements are primarily used to determine where carbon enters the ocean (question 1 from section 1.2) and carbon measurements from repeat hydrography are primarily used to determine

[1] http://cchdo.ucsd.edu/
[2] http://cdiac.ornl.gov/
[3] http://www.aoml.noaa.gov/ and http://www.pmel.noaa.gov/
[4] http://www.aoml.noaa.gov/ocd/gcc/explorer_data2014_q4.php
[5] oco.noaa.gov/resources/Progress_Reports/FY13/Swift_CCHDO_FY13_ProgressReport.pdf
[6] http://www.aoml.noaa.gov/publications/ and pmel.noaa.gov/public/pmel/publications-search/
[7] http://www.globalcarbonproject.org/index.htm
[8] http://www.socat.info/

where in the ocean carbon resides (question 2). The discrepancy between ocean carbon uptake and storage results from the redistribution of carbon by interior ocean currents and biogeochemical cycling.

2.1. Surface ocean pCO_2 measurements

The ocean absorbs carbon from the atmosphere where the atmospheric pCO_2 exceeds ocean pCO_2, and releases carbon to the atmosphere where the reverse is true. Sea surface pCO_2 measurements are therefore ideal for determining the spatial and temporal patterns of ocean CO_2 uptake. Ocean pCO_2 measurements are made on buoys and other unmanned sensor platforms, Volunteer Observing Ships (VOS), and research ships. DMCP scientists work to gather pCO_2 observations into global datasets, quality control and assess pCO_2 measurements, improve the routines used to estimate air-sea CO_2 flux from air-sea pCO_2 differences, improve the relationships used to estimate pCO_2 from satellite measurements, and use the combined quality controlled products for original science. Data are posted on publicly-accessible websites[9,10]. Data and metadata are also contributed to the CDIAC, Lamont Doherty Earth Observatory[11] (LDEO), and SOCAT databases (Bakker et al., 2012; Pfeill et al., 2012; Takahashi et al., 2009; Takahashi et al., 2012).

2.1.1. Data quality control and automation for SOCAT version 3

SOCAT is an international effort that strives to integrate all publicly available surface CO_2 data for the global surface oceans into a consolidated collection in a common format utilizing common QC procedures. SOCAT was motivated by requests from science groups over many years. SOCAT is envisioned as an expanding data collection that will grow as new data become available. This dataset increasingly serves as the foundation upon which the community evaluates the controls on air-sea CO_2 fluxes.

The SOCAT effort produces two distinct data products: 1) a 2nd-level quality controlled, global surface ocean fCO_2 (fugacity of CO_2, related to pCO_2) cruise data collection; and 2) gridded summary fields on 1° x 1° (open ocean) and ¼° x ¼° (coastal) resolutions. The initial release of SOCAT, version 1.5, was made available in October of 2011. Version 2 was compiled during FY-13, and the paper describing it was published during FY-14 (Bakker et al., 2014). Version 3 was under development in FY-14. The SOCAT data products are available to the public at the SOCAT.INFO web site and are archived with data citations (DOIs) provided at both Pangaea[12] and CDIAC.

The third release of the Surface Ocean Carbon Atlas is scheduled for Fall of 2015. Dr. Denis Pierrot is part of the SOCAT committee responsible for release of version 3 that includes data through 2013 with over 2 million new data points. AOML and PMEL submitted 170+ underway pCO_2 datasets from ship of opportunity cruises and the A16 and P02 Climate Variability (CLIVAR/CO_2) cruises described in section 2.2.3. SOCATv3 increases the total number of features (i.e. cruise track or mooring deployment) from 2669 to 3908 and the number of observations from 13 million to 19 million. Figure 2.1.1 shows a global snapshot of the full

[9] http://www.aoml.noaa.gov/ocd/ocdweb/occ.html
[10] pmel.noaa.gov/co2/story/Volunteer+Observing+Ships+%28VOS%29
[11] http://www.ldeo.columbia.edu/res/pi/CO2/
[12] http://doi.pangaea.de/10.1594/PANGAEA.811776

version 3.0 collection. The incorporation of new data into version 3.0 was closed as of June 2014 and this has been followed by the collaborative QC process that will extend until January, 2015.

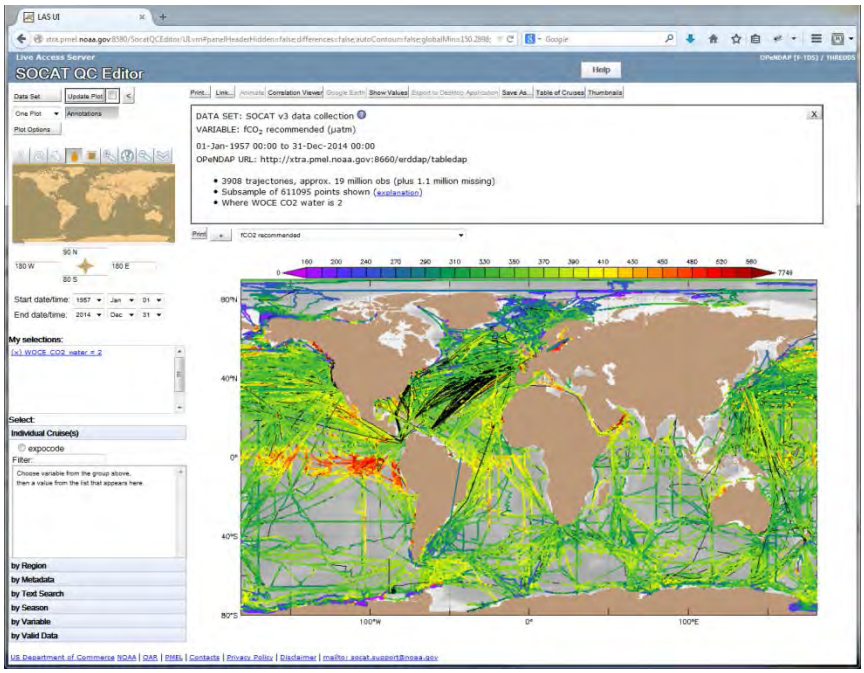

Figure 2.1.1. Screen shot of the SOCAT version 3 Quality control editor and viewer

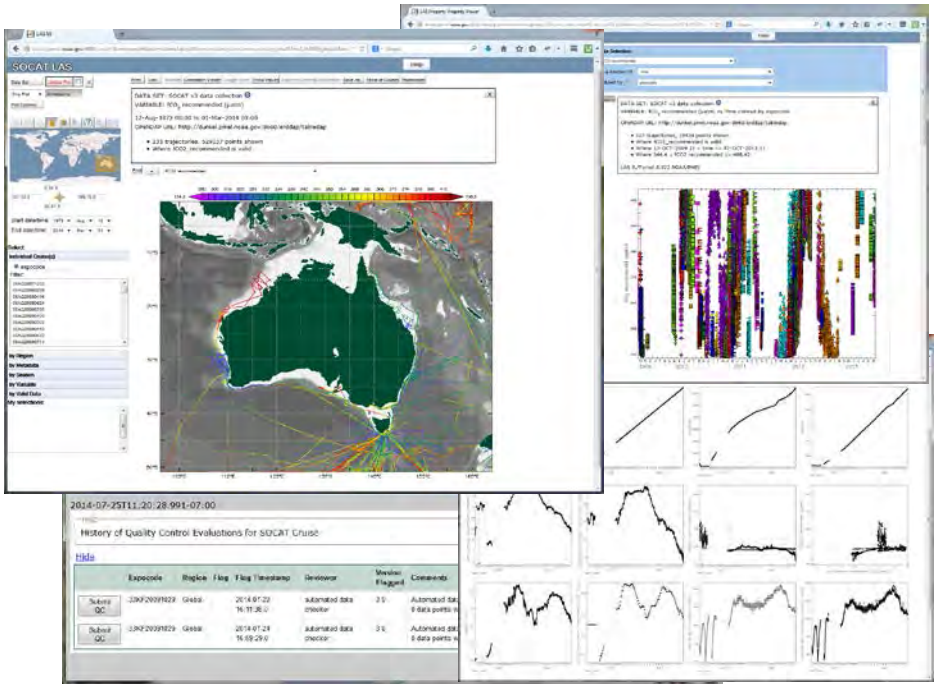

Figure 2.1.2. SOCAT version 3 quality control tools, including the main LAS user interface, the correlation viewer, the thumbnail viewer and the History of QC.

Version 3.0 of SOCAT is the result of an effort undertaken to design and implement an enhanced, Web-based data system that streamlines data ingestion and QC processes. It was clear

after SOCAT version 2 that the effort to continually produce SOCAT data and products was not sustainable without the introduction of such a streamlined processes. The new design must: i) minimize the effort required of scientists to contribute their data and metadata; ii) accommodate, to the degree feasible, variations in file formats between participating groups; iii) provide immediate, automated feedback regarding file formats, metadata content, and level 1 QC "sanity" checks of the data; and iv) support an on-going QC process that occurs in parallel with the submission of new cruises and moorings.

PMEL is leading the v3 and v4 software development, with partners at the University of East Anglia (UK) and CDIAC contributing essential software components. The enhanced system will include the "dashboard," a Web interface that enables contributors to upload data files, create metadata, and associate other documentation; an automated "sanity checker" that adapts to a range of PI-preferred data formats and scans data for implausible values; on-line metadata entry and editing; a new and more flexible Live-Access Server (LAS) user interface for visualizing data, that unifies gridded and non-gridded fields, and will support comparison between SOCAT versions; and a new, higher performance internal data management strategy. In preparation for the v3 SOCAT QC process, all of the new and updated data were submitted by SOCAT data managers using the newly designed automation dashboard. This allowed the automated functions, such as range checking and WOCE flag setting, to be thoroughly tested in preparation for SOCAT v4 deployment in early 2015. In addition, a significant side-benefit of the new data management strategy, which will utilize the ERDDAP server developed at NOAA/NMFS[13], will be improved access for SOCAT data users to the published versions.

The Live Access Server Quality Control system was also upgraded for SOCAT version 3 (see Figure 2.1.2). New features for setting cruise QC flags include: 1) Check-boxes that correspond to the criteria for data set quality control flags; 2) A data set quality control flag that can only be submitted if the corresponding check-boxes have been ticked and a text comment has been entered; 3) The Expocode of the cross-over data set must be specified for submission of a data set flag of A; 4) Capability to add a quality control comment without submitting a data set quality control flag. Also added to the v3 QC system was the ability to automatically identify high quality crossovers from a table of selected cruises.

2.1.2 Moored pCO_2 network

Measurements of pCO_2 from moorings are an important component of global carbon cycle monitoring. These platforms provide the long-term temporally-resolved datasets needed to study processes responsible for short term pCO_2 variability. The platforms can also provide cost-effective data from remote data limited regions. Data from pCO_2 mooring sites were processed at PMEL and submitted to CDIAC following the Sutton et al. (2014a) protocols. A total of 62 total years of mooring data has now been processed, finalized, and made available to the public at CDIAC since the inception of the project. FY-14 is the first year mooring pCO_2 data has been included in SOCAT and the Global Carbon Program's annual carbon budget (LeQuéré et al., 2014b). PMEL scientists used underway pCO_2 data to assess the quality of mooring pCO_2 measurements and determined the $MAPCO_2$ systems maintained with COD funding are the only moored pCO_2 platforms returning climate quality data (better than 2 µatm uncertainty for seawater and 1 µatm for air). Mooring pCO_2 records are now approaching the length, quality,

[13] http://coastwatch.pfeg.noaa.gov/erddap

and resolution needed for statistical analyses able to address high-priority carbon cycle research questions. Sutton et al. (2014b) examined moored pCO_2 measurements from the equatorial Pacific in the context of El Niño Ocean Niño Index (ONI), natural variability, and anthropogenic change. They found 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 2.1.3). This finding suggests 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 in this region is critical to improving climate predictions.

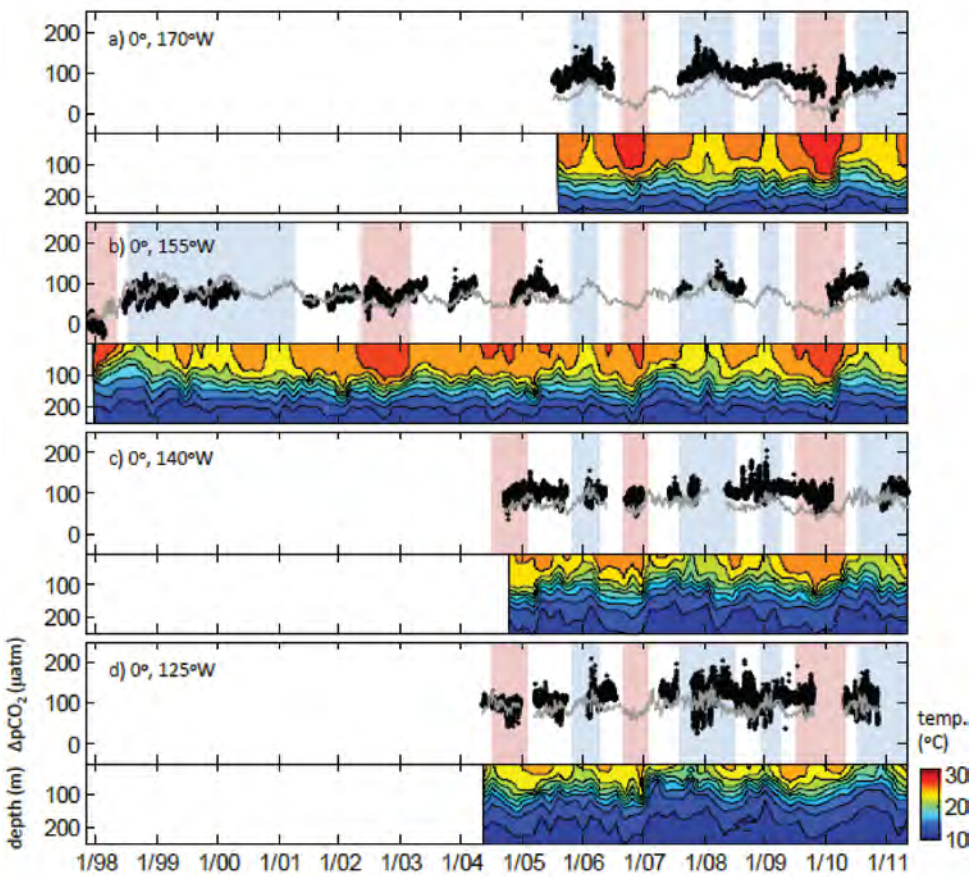

Figure 2.1.3. ΔpCO_2 mooring time series at a) 0°, 170°W, b) 0°, 155°W, c) 0°, 140°W, d) 0°, 125°W. Top panel at each site shows mooring ΔpCO_2 observations (black points) and estimated ΔpCO_2 (gray line) based on seawater pCO_2 and SST relationships. Shaded areas represent El Niño (red) and La Niña (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. (2014b).

2.1.3. Air-sea CO_2 flux assessment

We have worked with T. Takahashi on an update of the global sea-air fluxes based on a new monthly pCO_2 climatology centered on year 2005 and developed an updated relationship of gas

exchange and wind speed to be used for this purpose (Wanninkhof, 2014). J. Trinanes cataloged and synthesized remotely sensed products (winds, sea surface temperature SST, sea surface height SSH, and salinity) for the new assessment. Similarly, R. Feely and C. Cosca worked together to derive improved relationships between pCO_2 and SST for the tropics. The updated climatological flux centered on year 2005 is −1.32 PG C yr^{-1} that is 0.1 Pg C yr^{-1} greater than the flux from the 2000 revision. Global fluxes for February and differences with the previous February climatology are provided in Figure 2.1.4.

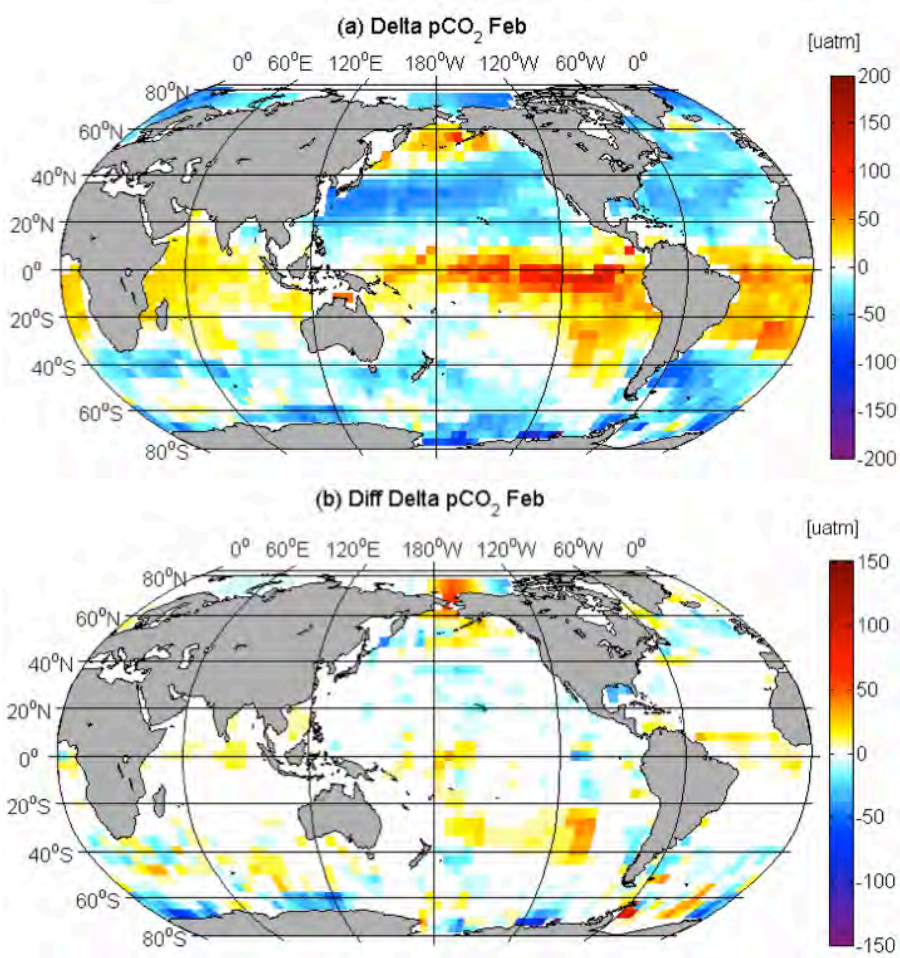

Figure 2.1.4. **a**. Global pCO_2 for February 2005, and **b**. the difference with the previous climatology produced by T. Takahashi of LDEO. Positive values in **a**. indicate pCO_2 is larger in the ocean than the atmosphere. Positive values in **b**. indicate ocean pCO_2 is larger relative to the atmosphere in 2005 than in 2000.

2.1.4. Production of seasonal air-sea CO_2 flux maps

The new algorithms for determining the air-sea flux variability—developed by Dr. Geun-Ha Park while she was a Cooperative Institute for Marine Studies (CIMAS) scientist sponsored by COD—have been evaluated with *in situ* observations from the pCO_2 on ships project and other sources available through SOCAT. A particular emphasis continues on seasonal variability and decadal trends (see e.g. Wanninkhof et al., 2013). Our results compare favorably with two

independent approaches recently implemented by Landschützer et al. (2014) and Rödenbeck et al. (2014). Dr. Barbero led the enhancements in the global flux product with focus on poorly-constrained coastal regions. In particular, she led an effort to create the first seasonal climatology of sea-air CO_2 fluxes in the Gulf of Mexico heavily utilizing the data from the *Las Cuevas, Gunter, and Brown* that are supported by the pCO_2 on ships program sponsored by COD. This product is an integral part of the Gulf of Mexico carbon synthesis effort led by Dr. Lisa Robbins of USGS and funded by NASA. The monthly air-sea CO_2 core flux product is updated every 3 months by J. Trinanes and served from website using the ERDDAP interface[14].

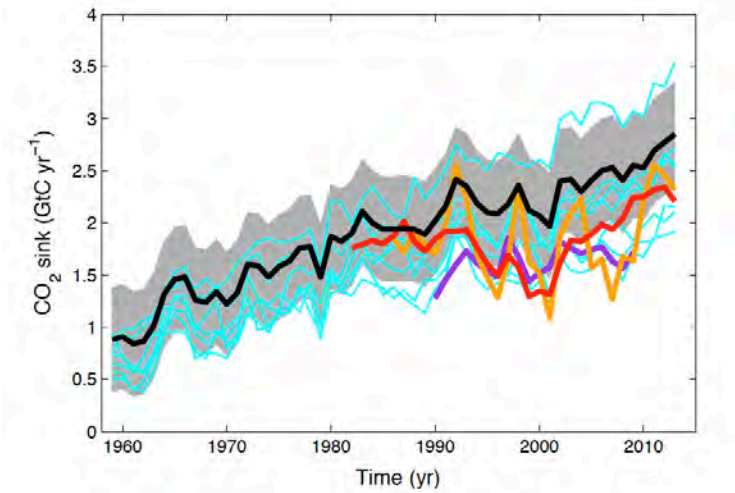

Figure 2.1.5. Comparison between the CO_2 budget values estimated from LeQuéré et al. (2014b) (black line), and other methods and models over the ocean (for individual models before normalization (blue lines), and the three data-based products (Rödenbeck et al. (2014) in orange; Landschützer et al. (2014) in red and Wanninkhof et al. (2013) in purple). Figure from LeQuéré et al. (2014b).

2.1.5. Global Carbon Project (GCP) assessment

We contributed to the Global Carbon Project annual "state of the carbon cycle" reports that, for the first time, included active participation and recent data contributions from ocean carbon cycle scientists (LeQuéré et al., 2014a). The quality controlled pCO_2 data and provided by DMCP investigators to the SOCAT and Takahashi databases were critical to this effort (see Figure 2.1.5). Wanninkhof was co-author of the 2013 and 2014 assessments. The 2014 Global Carbon Budget released by the GCP reported the significant finding that 26% of anthropogenic carbon emissions between 2004-2013 entered the ocean. This budget also reports that the ocean carbon sink increased with large annual variability over this decade. These findings are derived from three separate ocean carbon measurement-based estimates and estimates from seven biogeochemical ocean models initialized with ocean carbon data products. The findings also allowed similar conclusions to be reached regarding land carbon uptake. The Global Carbon Project represents a continuation of ongoing efforts including the Regional Carbon Cycle Assessment and Processes (RECCAP) project, which combines top-down atmospheric inversions with bottom-up forward models to assess regional CO_2 cycling. DMCP scientists coauthored a study on air sea CO_2 fluxes as part of this program in FY-14 (Ishii et al., 2014).

[14] http://cwcgom.aoml.noaa.gov/erddap/griddap/aomlcarbonfluxes.graph

2.2. Ocean interior

Dissolved inorganic carbon (DIC) is a direct measure of the carbon content of seawater, and is therefore an ideal measurement for exploring changes in ocean carbon storage. At least two properties must be measured in order to determine the effect of changes in carbon storage on ocean chemistry, however, so total alkalinity (TAlk) is also routinely measured. Seawater pH is also often measured as a constraint and as an independent check on other measurements. DMCP scientists are working to gather interior ocean carbon observations into global datasets, quality control and assess these measurements, improve the routines used to estimate carbon storage from DIC changes, improve the relationships used to estimate TAlk and similar quantities from other measured properties, and use the combined quality controlled products for assessments of ocean carbon uptake.

2.2.1. Global interior carbon data synthesis

Large-scale interior ocean data synthesis efforts are being done under the umbrella of the International Ocean Carbon Coordination Program (IOCCP). The program leads and personnel in the DMCP are leaders or active participants in these efforts. DMCP program personnel contributed to several significant advances in ocean interior carbon measurement synthesis through their involvement and leadership in the Global Data Analysis Project (GLODAP). GLODAP is set to release the second version of its data product in FY-15. The first GLODAP release (Key et al., 2004) has over 700 citations in peer-reviewed literature and is the most consistently used global product for ocean model initiation and assessment. The updated GLODAPv2 product incorporates and updates the Carbon in the North Atlantic (CARINA) and the Pacific Ocean Interior Carbon (PACIFICA) hydrographic data products. GLODAPv2 will span 1973-2013 and include approximately 775 cruises (~6 times as many as in v1). Figure 2.2.1 maps where viable DIC measurements are available in GLODAPv1 and GLODAPv2, demonstrating the vastly improved spatial coverage of v2. Significantly, GLODAPv2 will contain data in the Arctic Ocean and several marginal seas which were underrepresented in v1 (including the Gulf of Mexico, the Sea of Japan, and the Mediterranean Sea).

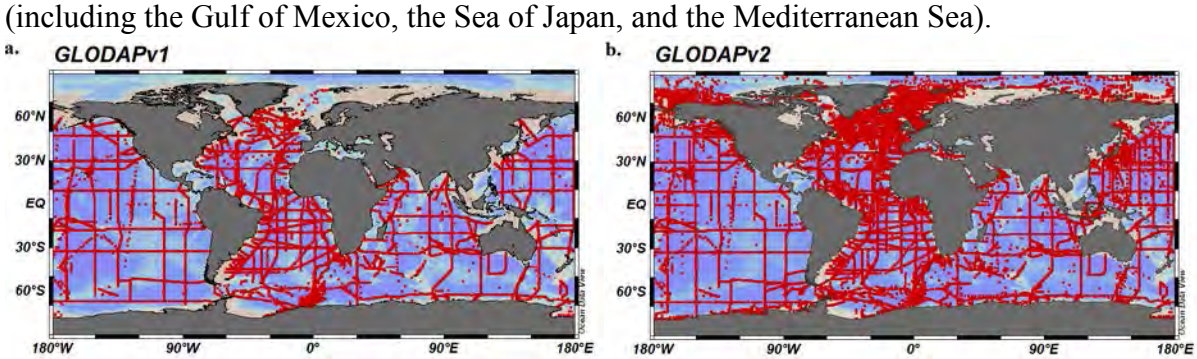

Figure 2.2.1. Maps showing locations where DIC measurements are available in **a**. GLODAPv1 and **b**. GLODAPv2 as red dots. Red dots appear as lines or solids in these maps due to their close spacing. Preliminary dataset versions courtesy of R. Key.

As part of the Surface Ocean Lower Atmosphere Study/Integrated Marine Biology and Ecosystem Research (SOLAS/IMBER) Surface Interior Carbon (SIC) effort, DMCP scientists are collaborating with other observationalists and modelers to provide an assessment of decadal change in anthropogenic CO_2 in the ocean. The effort involves a synthesis of all data obtained

during the Climate Variability (CLIVAR/CO_2) survey from 2002 to 2012. The synthesis effort applies an innovative multi-linear regression approach of mapping the quasi-conservative property C*—obtained from CO_2, CFC, nutrient TAlk and oxygen data—to data from the World Ocean Atlas. This international collaboration is led by Prof. N. Gruber of ETH Zurich. A meeting was held to discuss the new methods of extrapolating decadal changes obtained from the GO-SHIP cruises with international partners in conjunction with the Ocean Sciences Meeting in HI, February 2014.

A new DMCP scientist, B. Carter, submitted an analysis of the global alkalinity, salinity, and calcium carbonate saturation distributions using the PACIFICA, CARINA, and GLODAPv1 data products (Carter et al., 2014a). A major conclusion of this study is that the global surface ocean calcium carbonate saturation distribution variability is primarily the result of the influence of temperature on DIC solubility. This study is one example of the many made possible by data products created by DMCP collaborations, and that stands to benefit greatly from the marginal sea data that will be included in GLODAPv2.

2.2.2. Quality control of data from recent cruises

FY-14 saw the completion of repeat hydrographic cruise lines P16S and A16S in February and May of 2014, respectively. Data workup also continued for cruise lines P02 and A16N, which were completed in late FY-13. Preliminary P16S and A16N/S carbon data was made accessible on CCHDO and CDIAC within 2 months of landfall, and finalized carbon data has now been submitted for all four cruises. Carbon data is submitted to CDIAC and CCHDO, and made available on internal websites[15,16].

Figure 2.2.2 is a cross-section of quality controlled DIC measurements from the top 1500 m along P16S. The high precision of these measurements is demonstrated by the absence of bulls-eyes in this figure. Cruise measurement accuracy was monitored at sea with DIC reference materials and verified during secondary quality control using a contextual accuracy check with the help of the groups of Prof. F. Millero and Prof. A. Dickson. The Dickson and Millero groups measured two other inorganic carbon parameters (pH and TAlk) along these sections. These measurements allowed DMCP scientists to verify that DIC calculated from these two other measurements agreed with measured DIC to within tolerances. The contextual quality assessment also included comparison with older cruise data and a multi-linear regression (MLR) approach relating DIC to nutrients and oxygen. Figure 2.2.3 is a cross-section of the differences between DIC measured recently and measured on an older occupation of A16S. Large DIC changes are not expected along this section between 3000 and 4000 m and between of 30°S and 30°N. The small average DIC difference in this region suggests continued high measurement quality. However, disbanding of the science team continues to hamper collaboration with other institutions and full application of quality control in a timely fashion.

[15] pmel.noaa.gov/co2/story/P16S
[16] http://www.aoml.noaa.gov/ocd/gcc/A16S_2014/

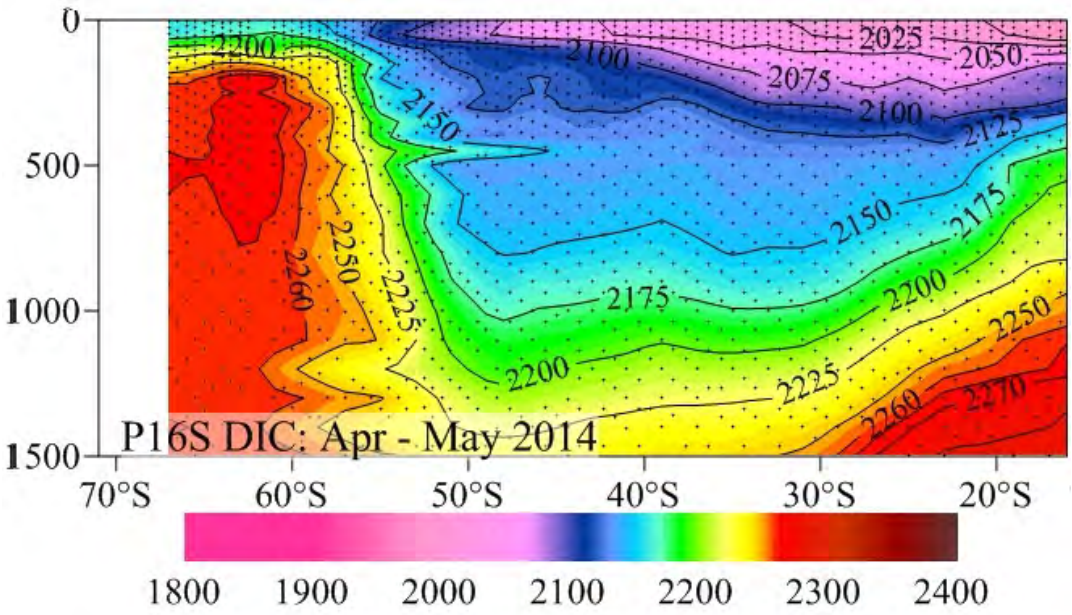

Figure 2.2.2. DIC measured along P16S in 2014. The light blue region of low DIC between 500-1000 m depth results from the local formation of intermediate depth water masses in the surface of the southernmost portion of this transect. During FY-14, a new DMCP scientist served as co-chief scientist on this cruise and finalized a research article on anthropogenic carbon uptake, mixing, and biogeochemical cycling in these intermediate depth water masses (Carter et al., 2014b).

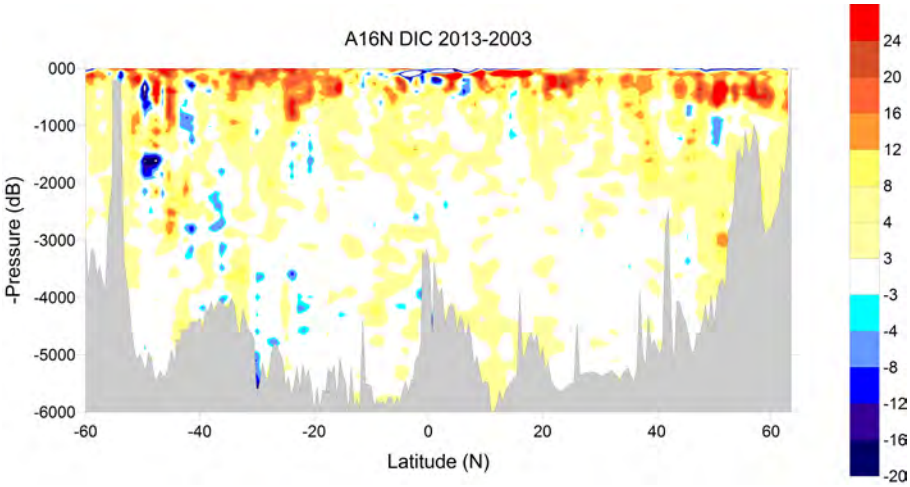

Figure 2.2.3 Difference in DIC between 2003 and 2013 along the A16 line. No systematic changes in DIC are expected in deep water and the comparison provides a powerful quality check that analytical procedures and accuracy are within the one part per thousand that is required to quantify anthropogenic CO_2 uptake on decadal time scales.

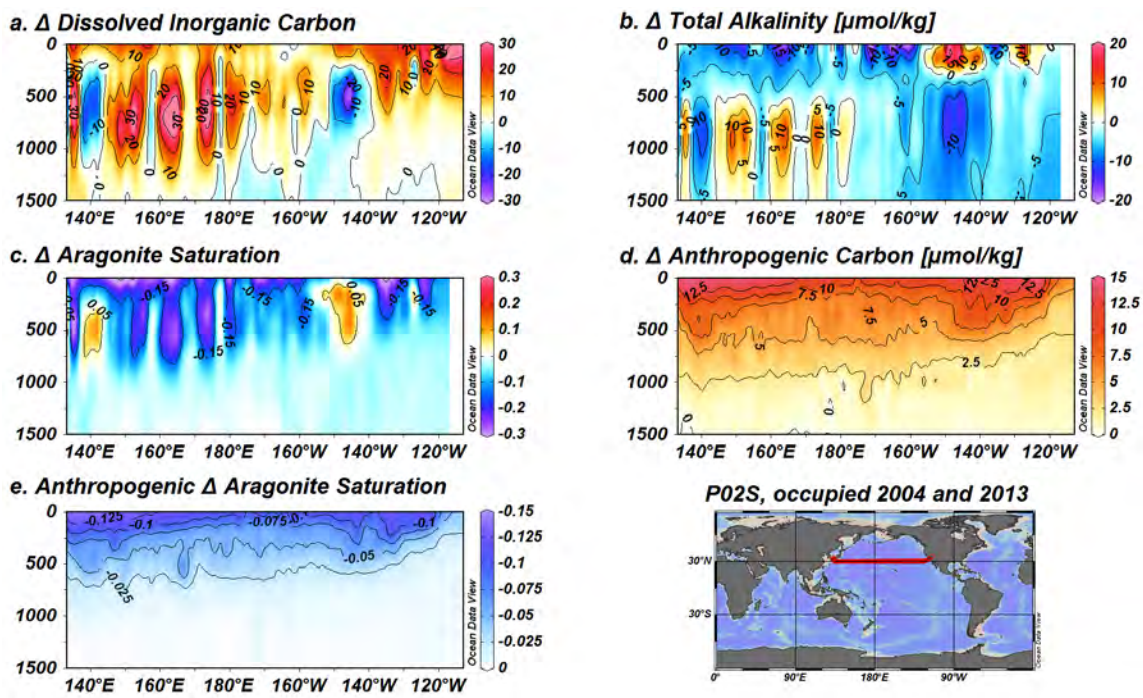

Figure 2.2.4. Cross sections of changes in quantities related to carbon uptake assessment along the top 1500 m of the P02 section. The estimates shown are **a**. changes in DIC concentrations, **b**. changes in total alkalinity concentrations, **c**. changes in the saturation state of the aragonite mineral form of calcite, **d**. changes in the anthropogenic carbon concentrations, and **e**. the changes in aragonite saturation that would be expected from **d**. alone. P02 is indicated as a red line on the map in the lower right section of this figure.

2.2.3. Analysis of data from recent cruises

Analysis of decadal changes in ocean carbon storage is an important component of the Global Carbon Data Management and Synthesis Project (Wallace, 2001; Sabine and Tanhua et al., 2010). In FY-14, new analyses were done using data from repeated occupations of the P02 Line and the southern portion of the P16 line. This analysis involves determining changes in DIC concentrations along sections, looking at changes in related carbon chemistry measurements such as TAlk, calculating the changes in marine calcium carbonate saturation that result from these changes, estimating how much DIC change can be attributed to anthropogenic carbon uptake, and estimating the effect of the anthropogenic carbon change on the calcium carbonate saturation state.

We plot these 5 estimates for P02 and P16S in Figures 2.2.4 and 2.2.5, respectively. The large and variable changes in DIC in 2.2.4a and 2.2.5a reveal the strong impact of short term water mass movements and biogeochemical cycling on the marine DIC distribution. However, these two processes also change the distribution of other measured properties such as temperature, TAlk, salinity, and nutrients. We can therefore estimate changes in the anthropogenic carbon concentrations (as we do in 2.2.4d and 2.2.5d) by examining changes in empirical relationships between DIC and these other properties.

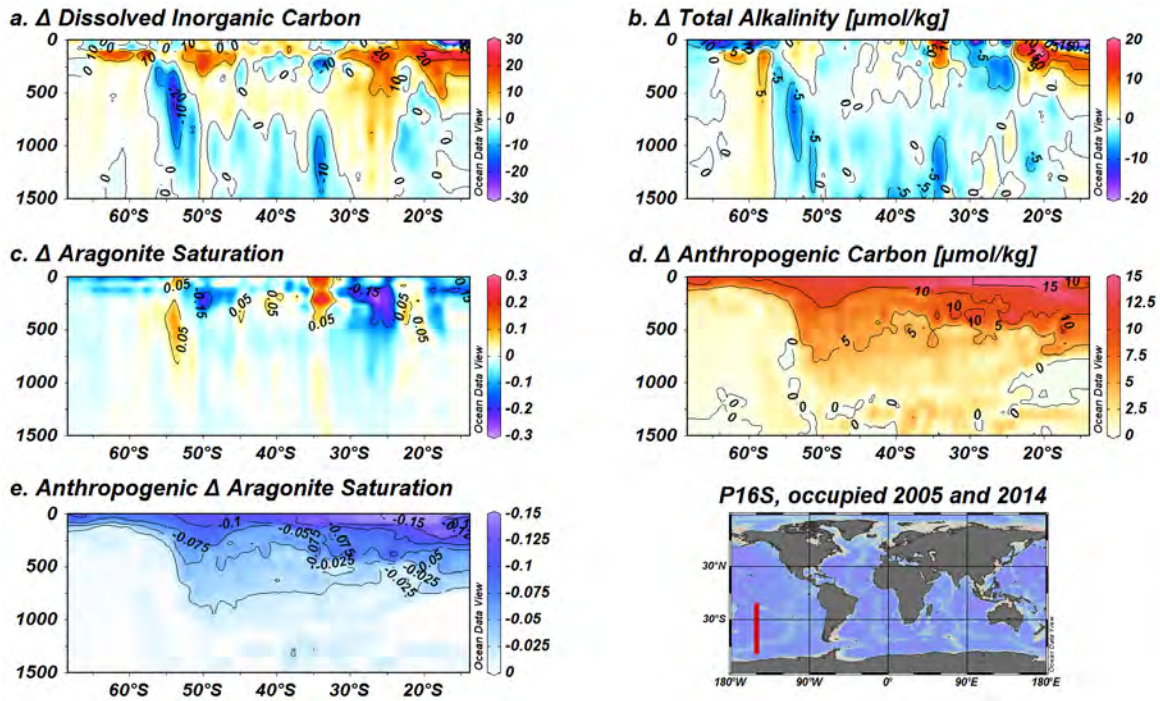

Figure 2.2.5. Cross sections of changes in quantities related to carbon uptake assessment along the top 1500 m of the P16S section. The estimates shown are **a**. changes in DIC concentrations, **b**. changes in total alkalinity concentrations, **c**. changes in the saturation state of the aragonite mineral form of calcite, **d**. changes in the anthropogenic carbon concentrations, and **e**. the changes in aragonite saturation that would be expected from **d**. alone. P16S is indicated as a red line on the map in the lower right section of this figure.

In Figure 2.2.4d, we see anthropogenic carbon penetrated deeper into the water column in the eastern and western ends of P02 (consider the depth of the 7.5 μmol kg^{-1} contour), consistent with increased uptake near the Kuroshio and California Currents. In Figure 2.2.5d, we see there is almost no anthropogenic carbon storage along P16S south of 55°S where there is water upwelling that has been isolated from the atmosphere for thousands of years. Storage increases dramatically along P16S north of 55°S in the intermediate-depth water masses which only recently left contact with the surface. The storage changes we find for P02 and P16S are nearly identical to those found for the same sections in the previous decade (Sabine et al., 2008), suggesting invasion of anthropogenic CO_2 occurred with similar regional patterns during both decades. Anthropogenic carbon uptake decreased aragonite saturation by as much as 0.15 during this decade with decreases of 0.025 extending as deep as 750 m along P02 and 1000 m along P16S.

Richard Feely mentored PMEL/University of Washington masters student N. Williams through the Joint Institute for Study of the Atmosphere and Ocean (JISAO). Williams' thesis includes an analysis of anthropogenic carbon uptake in the southernmost section of P16S (beyond the region shown in Fig. 2.2.5) and along the S4P section. As part of her analysis, Williams performed a global anthropogenic carbon storage rate estimate and ocean acidification rate comparison. The anthropogenic carbon accumulation and ocean acidification rate comparisons are given in Tables 2.2.1 and 2.2.2, respectively. We plot the results of her comparison in Figure 2.2.6, alongside

our preliminary estimates of anthropogenic carbon storage along P16S and P02. This figure shows the tendency of anthropogenic carbon to enter the ocean in the North Atlantic where deep water is formed and in the portions of the subtropical gyres ventilated by recently-formed mode and intermediate waters.

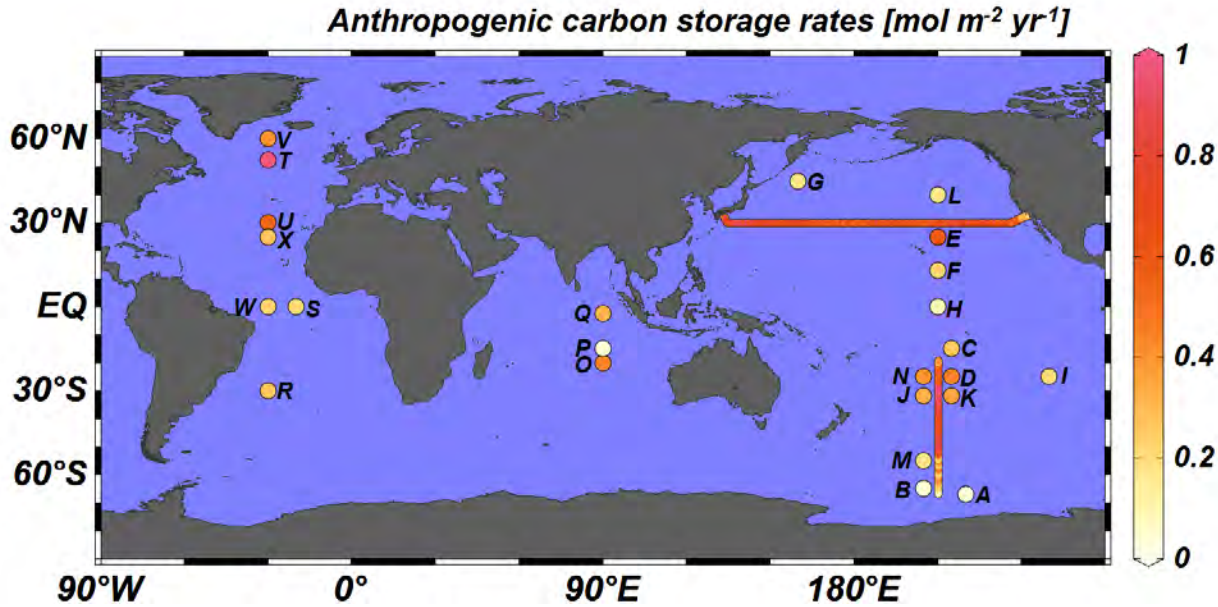

Figure 2.2.6. A summary of regional anthropogenic carbon storage rates presented in literature. Large dots indicate regional mean storage rates for broad regions specified in Table 2.2.1. Letters on this figure correspond to letters in Table 2.2.1. The two colored lines in the Pacific ocean are preliminary anthropogenic carbon storage estimates along P16S and P02 derived from the data presented in Figure 2.2.4d and 2.2.5d.

Table 2.2.1. Summary of global anthropogenic carbon accumulation rates, adapted from the thesis of N. Williams. Letters in study region are also labels in Figure 2.2.6.

Study Region		Storage Rate (mol m^{-2} yr^{-1})	Method	Study	Study Period
A.	67°S Pacific	0.10 ± 0.02	eMLR	this study	1992−2011
B.	60°S−71°S Pacific	0.10	eMLR	Sabine et al., 2008	1992−2005
C.	20°N−50°S Pacific	0.6 ± 0.1	eMLR	Sabine et al., 2008	1991−2006
D.	N. of 50°S in S. Pacific	0.9 ± 0.3	MLR	Peng et al., 2003	1974−1996
E.	N.E. Pacific	1.3 ± 0.5	MLR	Peng et al., 2003	1973−1991
F.	4°S−30°N Pacific	0.5 ± 0.2	ΔnC_T^{CAL}	Murata et al., 2009	1993−2005
G.	~160°E, ~45°N Pacific	0.4 ± 0.1	DIC with ΔC*	Wakita et al., 2010	1992−2008
H.	20°S−20°N Pacific	0.3 ± 0.1	eMLR	Sabine et al., 2008	1991−2006
I.	110°W in S. Pacific	0.46 ± 0.2	eMLR	Waters et al., 2011	1994−2008
J.	32°S Pacific	0.72 ± 0.2	eMLR	Waters et al., 2011	1992−2010
K.	32°S Pacific	0.79 ± 0.2	TTD	Waters et al., 2011	1992−2010
L.	North of 20°N Pacific	0.4 ± 0.2	eMLR	Sabine et al., 2008	1994−2004
M.	45°S−65°S Pacific	0.4 ± 0.2	CFC MLR	Matear and McNeil, 2003	1968−1996
N.	S. Pacific	1.0 ± 0.4	ΔnC_T^{CAL}	Murata et al., 2007	2003−1992
O.	20°S Indian	1.0 ± 0.1	ΔnC_T^{CAL}	Murata et al., 2010	1995−2004
P.	20°S−10°S Indian	0.10	DIC_n	Peng et al., 1998	1978−1995
Q.	10°S−5°N Indian	0.70	DIC_n	Peng et al., 1998	1978−1995
R.	30°S Atlantic	0.6 ± 0.1	ΔnC_T^{CAL}	Murata et al., 2008	1992−2003
S.	Atlantic	0.5 ± 0.3	eMLR	Peng and Wanninkhof, 2010	1973−1994
T.	40°N−65°N Atlantic	2.2 ± 0.7	eMLR	Friis et al., 2005	1981−1997
U.	20°N−40°N Atlantic	1.2 ± 0.3	eMLR	Tanhua et al., 2007	1981−2004
V.	Nordic Seas	0.9 ± 0.2	eMLR	Olsen et al., 2006	1981−2003
W.	Atlantic	0.53 ± 0.05	$eMLR_{dens}$	Wanninkhof et al., 2010	1989−2005
X.	North Atlantic	0.60	$\delta^{13}C$ MLR	Quay et al. 2007	1981−2003
	Global Average	0.55	DGOM	Sabine et al., 2008	Preind. to 2005
	Global Average	0.5 ± 0.2	Green's Function	Khatiwala et al., 2009	Preind. to 2008

Table 2.2.2. Summary of global ocean acidification rates, adapted from the thesis of N. Williams.

Region	pH Change (yr^{-1})	$\Omega_{Aragonite}$ Change (% yr^{-1})	Study	Study Period
Southern Ocean (S4P)	−0.0022 ± 0.0004	−0.47 ± 0.10	this study	1992-2011
Southern Ocean (P16S)	−0.0024 ± 0.0009	−0.50 ± 0.20	this study	1995-2011
Polar Zone Southern Ocean	−0.0020 ± 0.0003		Midorikawa et al. (2012)	1963-2003
Drake (PZ)	−0.0015 ± 0.0008	−0.46 ± 0.4	Takahashi et al. (2014)	2002-2012
Drake (SAZ)	−0.0023 ± 0.0007	−0.69 ± 0.4	Takahashi et al. (2014)	2002-2012
S.W. Pacific (Munida)	−0.0013 ± 0.0003	−0.43 ± 0.13	Bates et al. (2014)	1998-2012
S. Pacific		−0.35 ± 0.05	Feely et al. (2012)	1991-2005
S. Pacific	−0.0016		Waters et al. (2011)	1994-2008
N.W. Pacific	−0.0015 ± 0.005		Midorikawa et al. (2010)	1983-2007
N.W. Pacific	−0.002	−0.34	Ishii et al. (2011)	1994-2008
N. Pacific	−0.0017		Byrne et al. (2010)	1991-2006
N. Pacific		−0.34 ± 0.04	Feely et al. (2012)	1994-2004
N. Pacific (ALOHA)	−0.0018 ± 0.0001	−0.28	Dore et al. (2009)	1988-2007
N. Pacific (HOT)	−0.0016 ± 0.0001	−0.28 ± 0.04	Bates et al. (2014)	1988-2012
N. Pacific (HOT)	−0.0018 ± 0.0001	−0.27 ± 0.03	Takahashi et al. (2014)	1988-2009
Iceland Sea	−0.0023 ± 0.0003	−0.48 ± 0.07	Olafsson et al. (2009)	1985-2008
Irminger Sea	−0.0026 ± 0.0006	−0.40 ± 0.20	Bates et al. (2014)	1983-2012
N. Atlantic (BATS)	−0.0017 ± 0.0001	−0.26 ± 0.02	Bates et al. (2014)	1983-2012
N. Atlantic (BATS)	−0.0018 ± 0.0002	−0.34 ± 0.03	Takahashi et al. (2014)	1983-2010
N. Atlantic (ESTOC)	−0.0018 ± 0.0002	−0.34 ± 0.07	Bates et al. (2014)	1995-2012
N. Atlantic (ESTOC)	−0.0017 ± 0.0001	−0.36	González-Dávila et al. (2010)	1995-2004
N. Atlantic (ESTOC)	−0.0020 ± 0.0004	−0.29 ± 0.06	Takahashi et al. (2014)	1996-2010
Carribbean (CARIACO)	−0.0025 ± 0.0004	−0.18 ± 0.08	Bates et al. (2014)	1995-2012

2.3. Performance measures

Below is a summary of performance measures from the FY-14 work plan. These performance measures have been accomplished in full. Products resulting from these efforts are provided in the last column.

Measure of Performance	**2014**	**Relevant website/papers**
CO_2 flux maps	Bi-monthly, 6-month lag	http://www.aoml.noaa.gov/ocd/gcc/TGeunHaFlux/
Ocean interior synthesis	Decadal Repeat Hydro Report	http://www.us-ocb.org/publications/USRepeatHydrographyReport-Final.pdf
Data processing surface data	All data from opportunity-pCO_2 ships processed within 9-months	http://cdiac.ornl.gov/oceans/surface_underway.html
Data processing interior data	Submit A16N, P02, and P16S to CDIAC	http://cdiac.ornl.gov/oceans/bottle_discrete.html
GCP	2013 assessment	LeQuéré et al. 2014a

3. Outreach and Education

Synthesis Project investigators have been very active in educating the public about ocean carbon changes. Several of the PIs are routinely asked to give invited seminars of their results at national and international meetings and symposia. Several of the PIs regularly teach graduate and undergraduate classes in ocean carbon chemistry. These classes incorporate the scientific results coming from this work. Several of the PIs have graduate students or post-docs that are exposed to the work accomplished through this project. Several of the Synthesis Project PIs also serve on a number of national and international science committees that help guide and coordinate ocean carbon research. Interactions with the general public include presentations to local schools, open public lectures (both in the US and abroad), public "webinars" (seminars broadcast as streaming video onto the web e.g. for World Oceans Day), laboratory tours for groups ranging from school kids to Congressional Representatives, official congressional testimonies, and outreach blogs[17]. DMCP PIs have also given numerous press interviews and have been quoted in printed and online media, radio, and television.

Dr. Feely provides outreach presentations at the rate of approximately one per month on his carbon and climate research at local, local national and international meeting and symposia. He advises two graduate students, Nancy Williams and Andrea Fassbender (both from the University of Washington). Nancy Williams will complete her Master's thesis in December 2015. The title of her thesis is "Quantifying Anthropogenic Carbon Inventory Changes in the

[17] http://p16sonpalmer.blogspot.com/2014/03/first-post.html

Pacific Sector of the Southern Ocean" which will be submitted for publication in Marine Chemistry. Dr. Feely also provides regular interviews to the press on his research.

The 2014 GCP report release received significant press coverage as it coincided with the UN climate summit 23 September, 2014, in NY. The NOAA-SOOP-CO_2 effort and how it feeds into global Carbon Cycle Research was provided in the NOAA/OAR in depth features: http://research.noaa.gov/InDepth/Features.aspx "Never Missing an Opportunity, Ship of Opportunity That Is, to Collect Carbon Dioxide Data" and as a news article to coincide with the GCP report[18].

The R/V *Walton Smith* is used by the University of Miami 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.

4. Publications and Reports

4.1. Publications by Principal Investigators

4.1.1. Published

Bakker, D. C. E., and Coauthors, 2014: An update to the Surface Ocean CO2 Atlas (SOCAT version 2). *Earth Syst. Sci. Data*, **6**, 69-90, doi: 10.5194/essdd-6-465-2013.

Ballantyne, A. P., and Coauthors, 2014: Audit of the global carbon budget: estimate errors and their impact on uptake uncertainty. *Biogeosciences Discuss*., **11**, 14929-14979, doi:10.5194/bgd-11-14929-2014.

Cai, W.-J., and Coauthors, 2014: Chapter 8. Carbon fluxes across boundaries in the Pacific sector of the Arctic Ocean in a changing environment. The Pacific Arctic Sector: Status and Trends, J. M. Grebmeier, W. Maslowski, and J. Zhao, Eds., Springer, 199-222.

Carter, B.R., J. R. Toggweiler, R.M. Key, and J.L. Sarmiento, 2014a: Processes controlling the marine alkalinity and carbonate saturation state distributions, *Biogeosci. Discuss.* , doi:10.5194/bgd-11-11139-2014.

Carter B. R., L. D. Talley, and A. G. Dickson, 2014b: Mixing and remineralization in waters detrained from the surface into Subantarctic Mode Water and Antarctic Intermediate waters in the southeastern Pacific, *J. Geophys. Res*., **119** (6), 4001-4028, doi: 10.1002/2013JC009355

Pfister, C. A. and Coauthors, 2014: Detecting the Unexpected: A Research Framework for Ocean Acidification, *Envir. Sci. Tech.*, **48** (17), 9982-9994, doi: 10.1021/es501936p.

Ishii, M., and Coauthors, 2014: Air-sea CO_2 flux in the Pacific Ocean for the period 1990-2009. *Biogeosci.*, **11**, 709-734, doi:10.5194/bg-11-709-2014.

Le Quéré, C., and Coauthors, 2014: Global carbon budget 2014. *Earth Syst. Sci. Data Discuss*., 7, 521-610, doi:10.5194/essdd-7-521-2014.

Le Quéré, C., and Coauthors, 2014: Global Carbon Budget 2013. *Earth Syst. Sci. Data*, **6**, 1-29, doi:10.5194/essdd-6-689-2013.

[18] http://research.noaa.gov/News/NewsArchive/LatestNews/TabId/684/ArtMID/1768/ArticleID/10780/NOAA-contributes-key-carbon-dioxide-data-to-global-carbon-assessment.aspx

Majkut, J. D., B. R. Carter, T. L. Frölicher, C. O. Dufour, K. B. Rodgers, and J. L. Sarmiento, 2014: An observing system simulation for Southern Ocean carbon dioxide uptake, *Philos. T. Roy. Soc. A*, **372,** 2019, doi:10.1098/rsta.2013.0046.

Rodgers, K. B., and Coauthors, 2014: Strong sensitivity of Southern Ocean carbon uptake and nutrient cycling to wind stirring. *Biogeosci*, **11**, 4077-4098, doi: 10.5194/bgd-10-15033-2013.

Sutton, A.J., and Coauthors, 2014a: A high-frequency atmospheric and seawater pCO_2 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.

Sutton, A.J., R.A. Feely, C.L. Sabine, M.J. McPhaden, T. Takahashi, F.P. Chavez, G.E. Friederich, and J.T. Mathis 2014b: Natural variability and anthropogenic change in equatorial Pacific surface ocean pCO_2 and pH. *Global Biogeochem. Cycles*, **28**(2), 131–145, doi: 10.1002/2013GB004679.

Wanninkhof, R., 2014: Relationship between wind speed and gas exchange over the ocean revisited. *Limnol and Oceanogr: Methods*, **12**, 351-362, doi: 10.4319/lom.2014.12.351.

4.1.2. In press

Patsavas, M. C., R. H. Byrne, B. Yang, R. A. Easley, R. Wanninkhof, and X. Liu, 2014: Procedures for Direct Spectrophotometric Measurements of Carbonate Ion Concentrations: Measurements in Gulf of Mexico and East Coast US Waters. Marine Chemistry, in press

4.1.3. Technical reports

Feely, R. A., and Coauthors, 2014: The US Repeat Hydrography CO_2/Tracer Program (GO-SHIP): Accomplishments from the first decadal survey. A US CLIVAR and OCB Report, 47 pp.

Robbins, L. L., and Coauthors, 2014: Air–Sea Exchange, Report of The US Gulf of Mexico Carbon Cycle Synthesis Workshop, Ocean Carbon and Biogeochemistry Program and North American Carbon Program, 63 pp.

Wanninkhof, R., and Coauthors, 2014: Dissolved inorganic carbon, total alkalinity, pH, fugacity of carbon dioxide, and other variables from profile and surface observations using CTD, Niskin bottle, flow through pump and other instruments from the Ronald H. Brown in the Gulf of Mexico and East Coast of the United States from 2012-07-22 to 2012-08-13. National Oceanographic Data Center, NOAA. Dataset doi:10.7289/V5542KJ

Wanninkhof, R., D. Bakker, N. Bates, A. Olsen, and T. Steinhoff, 2013: Incorporation of alternative sensors in the SOCAT database and adjustments to dataset quality control flags, 25 pp.

4.2. All references cited in this report

Bakker, D.C.E., and Coauthors, 2012: Global synthesis products for assessing changes in the ocean carbon sink. *EOS, Transactions of the A.G.U.,* **6** (12), 125, doi:10.1029/2012EO120001.

Bakker, D.C.E., and Coauthors, 2014: An update to the surface ocean CO2 atlas (SOCAT version 2). *Earth Syst. Sci. Data,* **6**, 69-90, doi: 10.5194/essdd-6-465-2013.

Bates, N., Y. Astor, M. Church, K. Currie, J. Dore, M. Gonaález-Dávila, L. Lorenzoni, F. Muller-Karger, J. Olafsson, and M. Santa-Casiano, 2014: A Time-Series View of

Changing Ocean Chemistry Due to Ocean Uptake of Anthropogenic CO_2 and Ocean Acidification. *Oceanography*, **27**, 126–141. doi:10.5670/oceanog.2014.16

Byrne, R.H., S. Mecking, R. A. Feely, and X. Liu, 2010: Direct observations of basin-wide acidification of the North Pacific Ocean. *Geophys. Res. Lett.*, **37**, doi:10.1029/2009GL040999

Caldeira, K. and M. E. Wickett, 2003: Anthropogenic carbon and ocean pH. *Nature*, **425**(6956): 365-365, doi:10.1038/425365a.

Caldeira, K. and M. E. Wickett, 2005: Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *J. Geophys. Res.-Oceans*, **110** (C9), doi: 10.1029/2004JC002671.

Canadell, J. G., and Coauthors, 2007: Contributions to accelerating atmospheric CO_2 growth from economic activity, carbon intensity, and efficiency of natural sinks. *Proc.. Nat. Acad. Sci. U. S. A.*, **104** (47): 18866-18870, doi: 10.1073/pnas.0702737104.

Carter, B.R., J. R. Toggweiler, R.M. Key, and J.L. Sarmiento, 2014a: Processes controlling the marine alkalinity and carbonate saturation distributions, *Biogeosci. Discuss.* (*accepted for Biogeosci.*), doi:10.5194/bgd-11-11139-2014.

Carter, B. R., L. D. Talley, and A. G. Dickson, 2014b: Mixing and remineralization in waters detrained from the surface into Subantarctic Mode Water and Antarctic Intermediate waters in the southeastern Pacific, *J. Geophys. Res*., **119** (6), 4001-4028, doi: 10.1002/2013JC009355

Dore, J.E., R. Lukas, D. W. Sadler, M. J. Church, and D. M. Karl, 2009: Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc. Natl. Acad. Sci. U. S. A.*, **106**, 12235–40. doi:10.1073/pnas.0906044106

Feely, R. A., C. L. Sabine, R. H. Byrne, F. J. Millero, A. G. Dickson, R. Wanninkhof, A. Murata, L. A. Miller, and D. Greeley, 2012: Decadal changes in the aragonite and calcite saturation state of the Pacific Ocean, *Global Biogeochem. cycles*, **26**, GB3001, doi: 3010.1029/2011GB004157.

Friis, K., A. Kortzinger, J. Patsch, and D. Wallace, 2005: On the temporal increase of anthropogenic CO2 in the subpolar North Atlantic. *Deep. Sea Res.*, **52**, 681–698. doi:10.1016/j.dsr.2004.11.017

González-Dávila, M., J. M. Santana-Casiano, M. J. Rueda, O. Llinás, 2010: The water column distribution of carbonate system variables at the ESTOC site from 1995 to 2004. *Biogeosci*. **7**, 3067–3081. doi:10.5194/bg-7-3067-2010

IPCC, 2007. Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom, Cambridge University Press.

Ishii, M., and Coauthors, 2014: Air-sea CO_2 flux in the Pacific Ocean for the period 1990-2009. *Biogeosci.*, **11**, 709-734, doi:10.5194/bg-11-709-2014.

Ishii, M., N. Kosugi, D. Sasano, S. Saito, T. Midorikawa, H. Y. Inoue, 2011: Ocean acidification off the south coast of Japan: A result from time series observations of CO_2 parameters from 1994 to 2008. *J. Geophys. Res.,* **116**, doi:10.1029/2010JC006831

Key, R.M., and Coauthors, 2004. A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP). *Global Biogeochem. Cycles*, **18** (4), doi: 10.1029/2004GB002247.

Khatiwala, S., F. Primeau, and T. Hall, 2009: Reconstruction of the history of anthropogenic CO_2 concentrations in the ocean., *Nature*, **462**, 346–9. doi:10.1038/nature08526

Landschützer, P., N. Gruber, D. C. E. Bakker, and U. Schuster, 2014: Recent variability of the global ocean carbon sink. *Global Biogeochem. Cycles*, doi: 10.1002/2014gb004853.

Le Quéré, C., and Coauthors, 2009: Trends in the sources and sinks carbon dioxide. *Nature. Geosci.*, **2**, 831-836, doi:810.1038/ngeo1689.

Le Quéré, C., and Coauthors, 2014a: Global carbon budget 2014. *Earth Syst. Sci. Data Discuss*., 7, 521-610, doi:10.5194/essdd-7-521-2014.

Le Quéré, C., and Coauthors, 2014b: Global Carbon Budget 2013. *Earth Syst. Sci. Data*, **6**, 1-29, doi:10.5194/essdd-6-689-2013.

Matear, R.J., B. I. McNeil, 2003: Decadal accumulation of anthropogenic CO_2 in the Southern Ocean: A comparison of CFC-age derived estimates to multiple-linear regression estimates. *Global Biogeochem. Cycles*, **17**. doi:10.1029/2003GB002089

Midorikawa, T., and Coauthors, 2010: Decreasing pH trend estimated from 25-yr time series of carbonate parameters in the western North Pacific. *Tellus B*, **62B**, 649–659. doi:10.1111/j.1600-0889.2010.00474.x

Murata, A., Y. Kumamoto, K. Sasaki, S. Watanabe, and M. Fukasawa, 2008: Decadal increases of anthropogenic CO2 in the subtropical South Atlantic Ocean along 30°S. *J. Geophys. Res.*, **113**, C06007. doi:10.1029/2007JC004424

Murata, A., Y. Kumamoto, K. Sasaki, S. Watanabe, and M. Fukasawa, 2009: Decadal increases of anthropogenic CO 2 along 149°E in the western North Pacific. *J. Geophys. Res.*, **114**, C04018. doi:10.1029/2008JC004920

Murata, A., Y. Kumamoto, K. Sasaki, S. Watanabe, and M. Fukasawa, 2010: Decadal increases in anthropogenic CO2 along 20°S in the South Indian Ocean. *J. Geophys. Res.*, **115**. doi:10.1029/2010JC006250

Murata, A., Y. Kumamoto, S. Watanabe, and M. Fukasawa, 2007: Decadal increases of anthropogenic CO2 in the South Pacific subtropical ocean along 32°S. *J. Geophys. Res*. **112**, C05033. doi:10.1029/2005JC003405

Olafsson, J., S. R. Olafsdottir,A. Benoit-Cattin, M. Danielsen, T. S. Arnarson, and T. Takahashi, 2009: Rate of Iceland Sea acidification from time series measurements. *Biogeosci.*, **6**, 2661–2668. doi:10.5194/bg-6-2661-2009

Olsen, A., and Coauthors, 2006: Magnitude and origin of the anthropogenic CO2 increase and 13C Suess effect in the Nordic seas since 1981. *Global Biogeochem. Cycles***, 20**. doi:10.1029/2005GB002669

Park, G.-H., and R. Wanninkhof, 2012: A large increase of the CO2 sink in the western tropical North Atlantic from 2002 to 2009. *J Geophys. Res.*, **117**, C08029, doi:08010.01029/02011JC007803.

Laboratory NOAA Technical Memorandum-98, OAR AOML , Miami, p. 21.

Peng, T.-H., and R. Wanninkhof, 2010: Increase in anthropogenic CO_2 in the Atlantic Ocean in the last two decades. *Deep. Res. I*, **57**, 755–770. doi:10.1016/j.dsr.2010.03.008

Peng, T.-H., R. Wanninkhof, J. L. Bullister, R. A. Feely, and T. Takahashi, 1998: Quantification of decadal anthropogenic CO2 uptake in the ocean based on dissolved inorganic carbon measurements. *Nature*, **396**, 560–563, doi:10.1038/25103.

Peng, T.-H., R. Wanninkhof, and R. A. Feely, 2003: Increase of anthropogenic CO2 in the Pacific Ocean over the last two decades. *Deep. Res. II*, **50**, 3065–3082. doi:10.1016/j.dsr2.2003.09.001

Pfeil, B., and Coauthors, 2012: A uniform, quality controlled Surface Ocean CO2 Atlas (SOCAT), *Earth Syst. Sci. Data Discuss*., **5**, 735-780, doi:10.5194/essdd-5-735-2012, 2012.

Pierrot, D., and Coauthors, 2009: Recommendations for autonomous underway pCO2 measuring systems and data reduction routines. *Deep -Sea Res II*, **56**, 512-522, doi:10.1016/j.dsr2.2008.12.005.

Prentice, I.C. and Coauthors, 2001: The carbon cycle and atmospheric CO_2. In: J.T. Houghton and D. Yihui (Editors), *Climate Change: The Scientific Basis, Contribution of working group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press, Cambridge, UK, pp. 183-287.

Quay, P., R. Sonnerup, J. Stutsman, J. Maurer, A. Körtzinger, X. A. Padin, and C. Robinson, 2007: Anthropogenic CO2 accumulation rates in the North Atlantic Ocean from changes in the 13C/12C of dissolved inorganic carbon. *Global Biogeochem. Cycles*, **21**. doi:10.1029/2006GB002761

Rödenbeck, C., and Coauthors, 2014: Interannual sea–air CO2 flux variability from an observation-driven ocean mixed-layer scheme. *Biogeosci. Discuss.*, **11**, 3167-3207, doi:10.5194/bgd-11-3167-2014.

Sabine, C. L. and R. A. Feely, 2007: The oceanic sink for carbon dioxide. Greenhouse Gas Sinks. D. Reay, N. Hewitt, J. Grace and K. Smith. Oxfordshire, UK, CABI Publishing: 31-49, doi: 10.1126/science.1097403.

Sabine, C.L., R. A. Feely, F. J. Millero, A. G. Dickson, C. Langdon, S. Mecking, and D. Greeley, 2008: Decadal changes in Pacific carbon. *J. Geophys. Res.,* **113**, C07021. doi:10.1029/2007JC004577

Sabine, C.L., and T. Tanhua, 2010: Estimation of anthropogenic CO_2 inventories in the ocean. *Annu. Rev. Mar. Sci.*, **2**: 175–198, doi: 10.1146/annurev-marine-120308-080947.

Sabine, C. L., and Coauthors, 2012: Surface Ocean CO_2 Atlas (SOCAT) gridded data products, Earth Syst. Sci. Data Discuss., 5, 781-804, doi:10.5194/essdd-5-781-2012.

Sutton, A.J., and Coauthors 2014a: A high-frequency atmospheric and seawater pCO_2 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.

Sutton, A.J., R.A. Feely, C.L. Sabine, M.J. McPhaden, T. Takahashi, F.P. Chavez, G.E. Friederich, and J.T. Mathis 2014b: Natural variability and anthropogenic change in equatorial Pacific surface ocean pCO_2 and pH. *Global Biogeochem. Cycles*, **28**(2), 131–145, doi: 10.1002/2013GB004679.

Takahashi, T., and Coauthors, 2009: Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO_2 flux over the global oceans. *Deep-Sea Res. II*, **56**(8–10), 554–577, doi:10.1016/j.dsr2.2008.12.009.

Takahashi, T., S.C. Sutherland, and A. Kozyr. 2012: Global Ocean Surface Water Partial Pressure of CO2 Database: Measurements Performed During 1957-2011 (Version 2011). ORNL/CDIAC-160, NDP-088(V2011). Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, doi: 10.3334/CDIAC/OTG.NDP088(V2011).

Takahashi, T., S. C. Sutherland, D. W. Chipman, J. G. Goddard, and C. Ho, 2014: Climatological distributions of pH, pCO_2, total CO_2, alkalinity, and $CaCO_3$ saturation in the global surface ocean, and temporal changes at selected locations., *Mar. Chem.* **164**, 95–125. doi:10.1016/j.marchem.2014.06.004

Tanhua, T., A. Körtzinger, K. Friis, D. W. Waugh, and D. W. R. Wallace, 2007: An estimate of anthropogenic CO2 inventory from decadal changes in oceanic carbon content. *Proc. Natl. Acad. Sci. U. S. A.*, **104**, 3037–42. doi:10.1073/pnas.0606574104

Wakita, M., S. Watanabe, A. Murata, N. Tsurushima, and M. Honda, 2010: Decadal change of dissolved inorganic carbon in the subarctic western North Pacific Ocean. *Tellus B*, **62**, 608–620. doi:10.1111/j.1600-0889.2010.00476.x

Wallace, D.W.R., 2001: Storage and transport of excess CO_2 in the oceans: The JGOFS/WOCE Global CO_2 Survey. In: G. Siedler, J. Church and J. Gould (Editors), *Ocean Circulation and Climate: Observing and Modeling the Global Ocean*. Academic Press, San Diego, CA, pp. 489-521.

Wanninkhof, R., 2014: Relationship between wind speed and gas exchange over the ocean revisited. *Limnol and Oceanogr: Methods*, **12**, 351-362, doi: 10.4319/lom.2014.12.351.

Wanninkhof, R., and Coauthors, 2013: Global ocean carbon uptake: magnitude, variability and trends. *Biogeosci.*, **10**, 1983-2000, doi: 10.5194/bg-10-1983-2013.

Wanninkhof, R., S. C. Doney, J. L. Bullister, N. M. Levine, M. Warner, and N. Gruber, 2010: Detecting anthropogenic CO2 changes in the interior Atlantic Ocean between 1989 and 2005. *J. Geophys. Res.*, **115**. doi:10.1029/2010JC006251.

Waters, J.F., F. J. Millero, and C. L. Sabine, 2011: Changes in South Pacific anthropogenic carbon. *Global Biogeochem. Cycles*, **25,** doi:10.1029/2010GB003988.