Global Data Management and Synthesis Project

Jeremy T. Mathis[1], Richard A. Feely[1], Steve Hankin[1], Rik Wanninkhof[2]

[1]NOAA Pacific Marine Environmental Laboratory, 7600 Sand Point Way NE Seattle, WA 98115
[2]NOAA Atlantic Oceanographic and Meteorological Laboratory, 4301 Rickenbacker Causeway, Miami FL 33149

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1. Project Summary

1.1 Introduction

The global data management and synthesis project (DMCP) of ocean carbon observations focuses on quality control, collating, managing, storing, and dissemination of inorganic carbon and associated data. The creation of data products for the community at large and interpretation of results are important goals. Emphasis is on the data obtained by the efforts funded by the Climate Observation Division (COD) but appreciable efforts are extended to incorporate data from investigators worldwide in order to create truly global databases. Outreach activities include training in best practices, and advocacy for new technologies and new approaches. The COD observational efforts that feed into this project include the repeat hydrography program, the pCO_2 on ships effort, and the pCO_2 on moorings effort (See figure PS1, below). The data synthesis addresses the core questions:

1. Where has the anthropogenic (i.e. carbon produced by man's activities) entered the ocean and where is it stored?
2. What is the current pattern of uptake and storage and how will this change? And:
3. How is the increase in inorganic carbon impacting the inorganic carbon chemistry and biota of the ocean?

The last question is addressed largely with resources from the NOAA/OAR/Ocean Acidification program. The goal of the effort is to synthesize global data and create methods and products to meet the overall goal of the COD ocean carbon program 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 large-scale 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. Interior ocean physical, tracer and biogeochemical data are synthesized under an ongoing project GLODAP (Global Data Analyses project that is set to release its first update GLODAP-2 in two years). The first release GLODAP (Key et al., 2004) is the most used consistent global product for ocean model initiation and/or assessment. The surface data is assembled in the Surface Ocean Carbon Atlas effort (SOCAT). The release with over 6 million quality controlled data points occurred during this performance period and a second release is planned in 2014. Both GLODAP and SOCAT benefitted immensely from the Live Access Server (LAS) utilities of lead investigator S. Hankin. The data visualization opportunities and "on the fly" product generation provide a means for contextual quality control and interpretation.

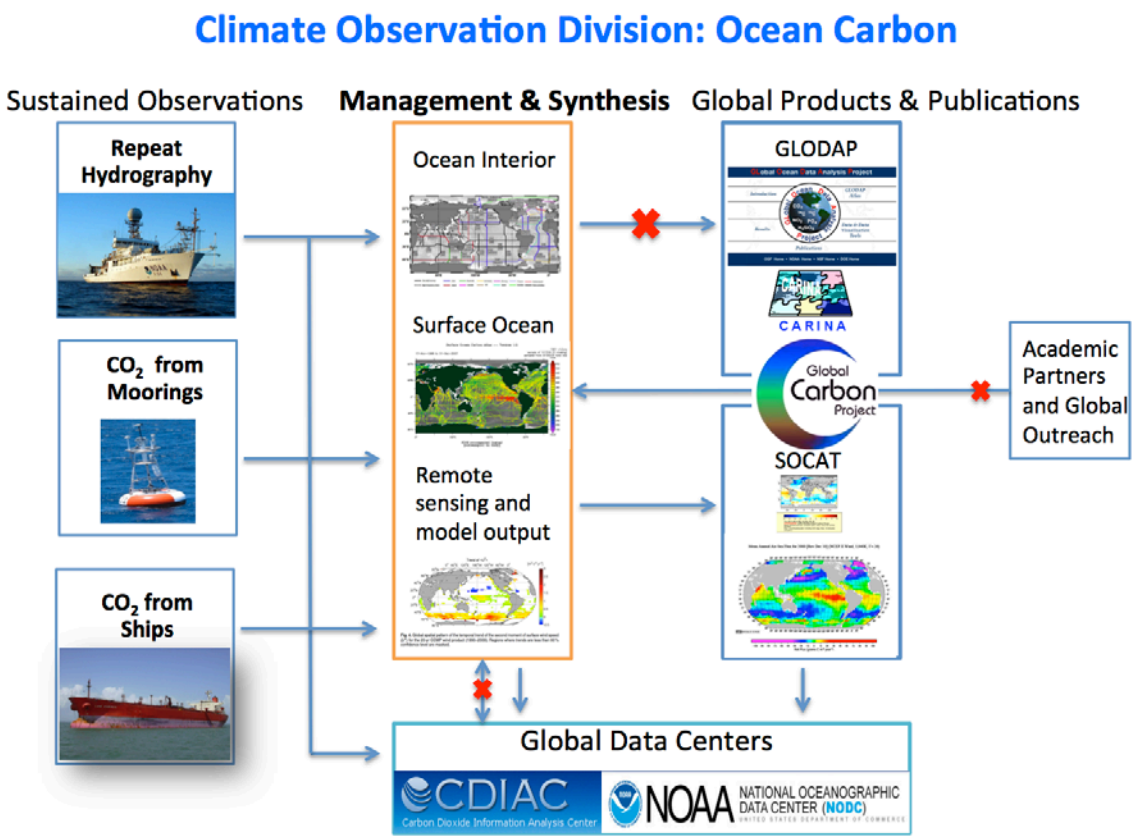

Figure PS1. Schematic of the data and product flow in the COD funded ocean carbon projects. The red "X"s indicate broken links due to programmatic cutbacks.

1.2 Project justification

The overriding issues that drive the ocean carbon programs in COD is that over the past two and a half centuries, the surface oceans have absorbed approximately 30% of the total anthropogenic carbon dioxide emissions from the atmosphere (Canadell et al., 2007). This absorption of CO_2 from the atmosphere has reduced the accumulation of greenhouse gases in the atmosphere, thus

slowing the rate of climate change (IPCC, 2007; Sabine and Feely, 2007). The details of this uptake and storage as well as the mechanisms controlling them are still not fully understood. Continued monitoring and scientific analysis of the ocean carbon cycle is critical for understanding how this important sink for anthropogenic CO_2 is functioning and how ocean carbon storage might change in the future.

It is not sufficient, however, simply to collect and archive the data if we expect the data to improve our understanding of the global carbon cycle and the role of the ocean in climate change. Many pieces of the puzzle are interlinked and data management and synthesis must be done in a comprehensive and inclusive fashion. For example, the NOAA Climate Observations Division's (COD) Carbon Network (hydrographic sections, underway pCO_2, and CO_2 moorings) is a valuable contribution to the Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). Carbon scientists and oceanographers are the primary direct users of ocean carbon data, but there is an increasing need to provide data and interpretation to climate scientists and modelers. Ultimately scientists are working to produce meaningful products from these observations, such as assessments, that a wide range of decision makers and the public can use to make informed decisions about current and future CO_2 emissions.

The Global Carbon Data Management and Synthesis Project works together with the COD carbon measurement projects as well as other national and international colleagues with high-quality ocean carbon data to take the fundamental carbon observations and turn them into products that are useful for scientists and the public for understanding the ocean carbon cycle and how it is changing over time. This effort ranges from ensuring that the observations are of the highest quality and are mutually consistent with each other to combining the observations into a common data set that is available and easy for the community to use and explore to evaluating the time rate of change in global ocean carbon uptake and storage. This project brings together ocean carbon measurement experts and information technology experts working closely with data managers at the National Ocean Data Center (NOAA/NODC) and the Carbon Data Information and Analysis Center (CDIAC) and to ensure the most efficient and productive management and synthesis of the COD carbon observations.

2. Scientific Accomplishments

The COD ocean carbon network makes two basic types of observations: surface CO_2 observations (with ships of opportunity and moorings) and water column carbon observations (with repeat hydrography cruises). The surface observations are aimed at quantifying and understanding the exchange of CO_2 across the air-sea interface (i.e. ocean carbon uptake and release). The interior ocean observations help quantify the ocean carbon inventory and how it is changing with time (i.e. ocean carbon storage). Uptake is not necessarily the same as storage, because ocean transport can move carbon that is removed from the atmosphere in one place and store that carbon in another place. Although the spatial and temporal patterns of carbon uptake may be different from the storage patterns, these two measures of the ocean carbon cycle are closely related to each other. Integrated over large enough time and space domains, the net uptake should be reconcilable with the storage. An added challenge is separating the anthropogenic fluxes and inventories from the contemporary fluxes and inventory changes.

The Global Carbon Data Management and Synthesis Project addresses both observational approaches for understanding the role of the oceans in the global carbon cycle. Because surface observations are collected in a different manner and have different requirements for developing the final product than the repeat hydrography data, the data management and synthesis for these two data types is discussed separately. The activities and accomplishments for both data types in FY2012 are discussed below.

While the COD ocean carbon network is primarily aimed at understanding the uptake and storage of ocean carbon, it is used as an important template for the Ocean Acidification Network that provides information on the consequences of that carbon on the chemistry of the oceans. 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), with a decrease of ~0.0018 yr^{-1} observed over the last quarter century at several open ocean time-series sites (Olafsson, et al., 2009; Bates, 2007; Bates and Peters, 2007; Santana-Casiano et al., 2007). The advancements in our understanding in ocean acidification made through this project are discussed in a section 2.3 below.

2.1. Surface Ocean CO_2

The surface ocean component of the Global Carbon Data Management and Synthesis Project involves continued processing of the carbon data generated from the COD volunteer observing ships and moorings, working with Taro Takahashi (LDEO) to generate updates to his air-sea CO_2 flux climatology (Takahashi et al., 2012), developing the algorithms to make seasonal CO_2 flux maps using satellite observations[1] and working with the international ocean carbon community on the release of the first Surface Ocean CO_2 Atlas (SOCAT) (Pfeill et al. 2012; Bakker et al., 2012). An important component of the effort is national and international outreach and coordination to improve data quality, and assemble data into coherent unified datasets. As described below the participants of the ocean carbon synthesis projects have been active participants and leaders of efforts such as SOCAT and RECCAP (Regional Carbon Cycle Analysis Project) that provide critical data products for interpretation and testing/verification of models of ocean carbon dynamics and change. Each of these is briefly discussed below.

Processing of New Data

During FY2012, PMEL and AOML received daily underway CO_2 data files from ships of opportunity sailing the Atlantic and Pacific oceans. Improvements are made to the telemetry and diagnostic software to quality control pCO_2, temperature, salinity, barometric pressure, pumps, water flow and gas flow data. During the time in review, data from over 150 cruises have been processed and submitted to CDIAC and SOCAT. All current and previous underway pCO_2 data files are quality controlled using the data protocols outlined in Pierrot et al. (2009).

Data from 20 mooring sites were also processed at PMEL and submitted to CDIAC following the Pierrot et al. protocols. The processing included not only the latest data, but also a

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

reprocessing of older data to ensure that all our mooring data are available in the agreed format. In total, we processed and submitted 28 buoy years of data in FY2012.

As detailed in the "pCO_2 from ships" report over 500,000 new underway pCO_2 data points have been processed by the consortium following uniform data reduction and quality control. Data and plots are posted on the publically accessible websites
http://www.aoml.noaa.gov/ocd/gcc/index.php
and
http://www.pmel.noaa.gov/co2/story/Volunteer+Observing+Ships+%28VOS%29. Data and metadata are contributed to the global database at CDIAC, as well as direct submissions to the LDEO and SOCAT databases (Takahashi et al., 2012; Pfeill et al., 2012)

Seasonal air-sea CO_2 Flux Maps

The work by Park et al. (2010a) has provided an improved approach for estimating air-sea CO_2 fluxes on seasonal timescales from historical pCO_2 data, sea surface temperature and wind speed. The algorithms provide a means to estimate air-sea CO_2 fluxes on regional and seasonal scales to the near-present. The global sea-air CO_2 flux maps continuously updated quarterly and served from a graphical user interface (**Figure 1**). The metadata for the approach is described in a NOAA data report (Park et al. 2010b). In addition to monthly global fluxes, monthly ΔpCO_2 and flux anomalies compared to the 30-year mean are provided. Enhancements have been provided during this performance period including providing numerical values of the total flux for the region and time selected, as well as more data display (time-property, and space-property) and data output options using a graphical user interface (ERDDAP).

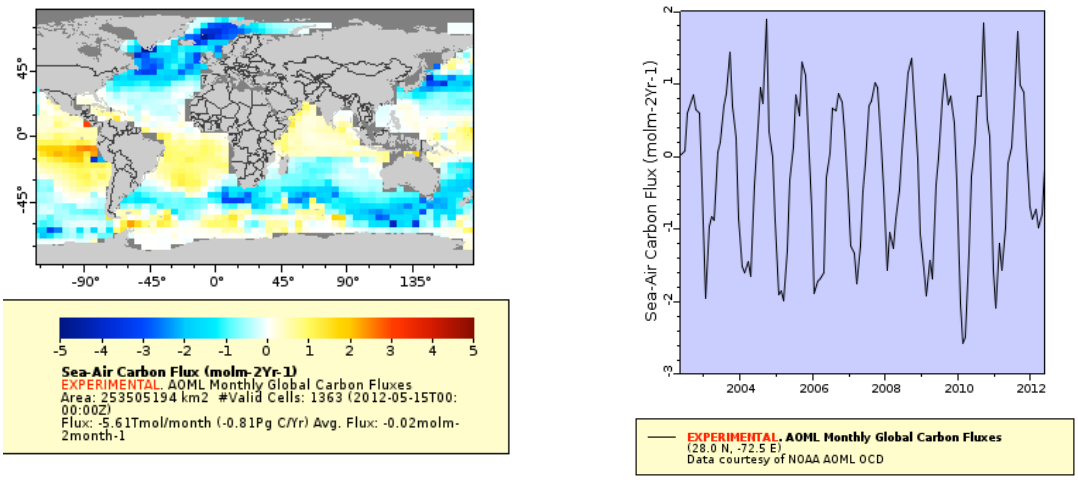

Figure 1. Screen shot of the graphical user interface used to serve the monthly global estimates and pCO_2 and sea-air fluxes. Left, ΔpCO_2 anomaly map for May. 2012 yielding an contemporary flux of -0,8 Pg C yr^{-1}; right, time series plot for a 28˚N, 73˚W in the Western subtropical Atlantic (from: http://cwcgom.aoml.noaa.gov/erddap/griddap/aomlcarbonfluxes.graph).

Air-Sea Fluxes in the Regional Carbon Cycle Assessment and Processes (RECCAP)

RECCAP is an international activity under the auspices of the Global Carbon Program (GCP) to produce a regional assessment of the sources and sinks of CO_2 (Canadell et al., 2012). The global ocean baseline was re-assessed using the Takahashi et al. (2009) climatology utilizing a consistent global wind field derived from the cross-calibrated multi-platform wind product (CCMP) (Atlas et al., 2011). The ΔpCO_2 fields of Takahashi et al. (2009) with the new wind fields and new gas exchange algorithms are used such that consistent regional and global estimates is made over 19-years using the approach of Park et al. (2010a). These results are compared with the output of 6 ocean biogeochemistry models, and ocean inverse models and atmospheric inverse models as provided in the RECCAP effort for the last two decades in **Figure 2**. An important result of the work is that that the trends in CO_2 uptake by the ocean based on approaches relying on sea-air CO_2 surface fluxes is appreciably smaller then the estimates based on changes in the ocean interior such as the ocean inverse and Green function (Khatiwala et al., 2012).

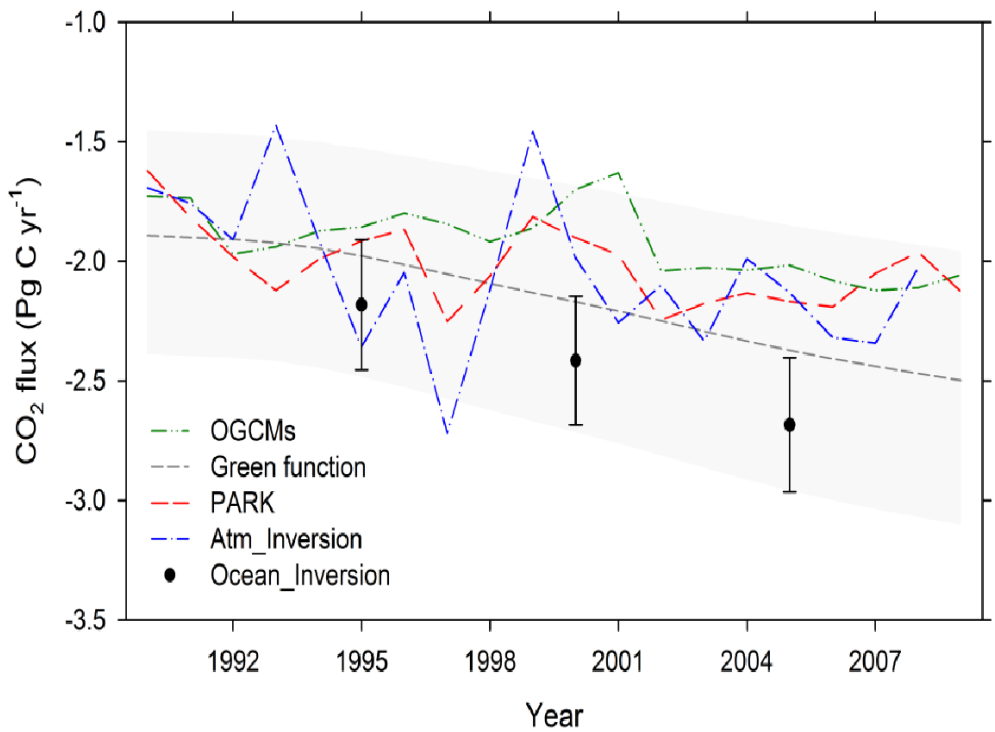

Figure 2. Athropogenic sea-air CO_2 fluxes based on the empirical approach of Park et al. (2010a), and different modeling approaches, from Wanninkhof et al. (2012).

Surface Ocean CO_2 Atlas

FY2012 was another year of noteworthy accomplishments in the international Surface Ocean CO_2 Atlas (SOCAT) data synthesis project. SOCAT is an international effort to establish a global surface CO_2 data set that integrates together, in a common format, all publicly available surface CO_2 data for the surface oceans. This activity has been requested by many international groups for a number of years. This data set will serve as a foundation upon which the community will evaluate the controls on air-sea CO_2 fluxes. It will continue to be a resource as the data base continues to grow in the future.

The first public release of the SOCAT collection (version 1.5) was announced at the IOCCP Surface Ocean CO_2 Data-to-Flux Workshop in Paris in September of 2011. The dataset includes two distinct SOCAT data products: 1) a 2nd-level quality controlled, global surface ocean fCO_2 (fugacity of CO_2) cruise data collection containing 1851 cruises or moorings and 6.3 million observations; and 2) gridded summary fields on 1° x 1° and ¼° x ¼° resolutions. In October 2011, the data were made available through the public SOCAT.INFO web site. The Web site includes data viewers built upon the PMEL Live Access Server (LAS) (Figure 3). The SOCAT cruise viewer provides users with the ability to select arbitrary subsets of the data, based upon region, date, season, ship and cruise name, and quality control level. Subsets can be mapped, downloaded, and analyzed with a property-property viewer. The SOCAT gridded data viewer (see http://ferret.pmel.noaa.gov/SOCAT_gridded_viewer/) offers custom plots and animations; the ability to difference fields (e.g. compare the 1990 annual average fCO_2 with the 2000 average); simple analysis tools to compute averages, extrema and variances over areas and time; and displays on Google Earth.
Version 1.5 was the start of an on-going roll-out process, through which new data will be added to the SOCAT collection as they are made available by PIs, and second-order QC applied to ensure uniform quality. In order to make this process as efficient as possible the community recognized the need to automate the data management to the degree that is feasible. During FY12 the activities were twofold: to add newly available cruises and begin QC of the Version 2 collection using the manual data management processes of Version 1; and to define and agree upon the strategy for automated data handling in version 3 and beyond.

In preparation for the second SOCAT group QC process, cruise and mooring data that became available after SOCAT 1 were added to the collection. The version 2 (Figure 4) collection expands the scope of SOCAT to approximately 3100 cruises and 15 million fCO_2 observations. The SOCAT LAS system at PMEL was initialized to the expanded dataset to support the version 2 QC process. A “training” server was added, so that SOCAT members could explore and understand the use of the QC system without risk to the integrity of the collection. PMEL hosted a 3-day QC workshop bringing the coastal CO_2 science community together in early October. (A more detailed report will be provided in FY13.) The inclusion of coastal and Arctic data is a unique part of the 2.0 release. The target date for the completion of version 2 QC is December, 2012.

At the September 2011 meeting the SOCAT community agreed that the future success of SOCAT depended upon reducing the level of effort and man-power needed to release subsequent versions of the collection. PMEL was tasked with leading the design of a more streamlined and automated approach. In May 2012 PMEL hosted a technology-oriented workshop for this purpose. The overall design of the automation system was agreed upon and components of the system were assigned to individuals for implementation. The system will be built as a collaborative effort between PMEL, University of East Anglia (UK), CDIAC, and Bjerknes Centre for Climate Research. Key requirements of the design are: i) to minimize the effort required of contributing scientists to contribute their data and metadata; ii) to the degree feasible to accommodate variations in file formats between participating groups; and iii) to provide immediate, automated feedback regarding file formats, metadata completeness, and level 1 QC “sanity” checks of the data.

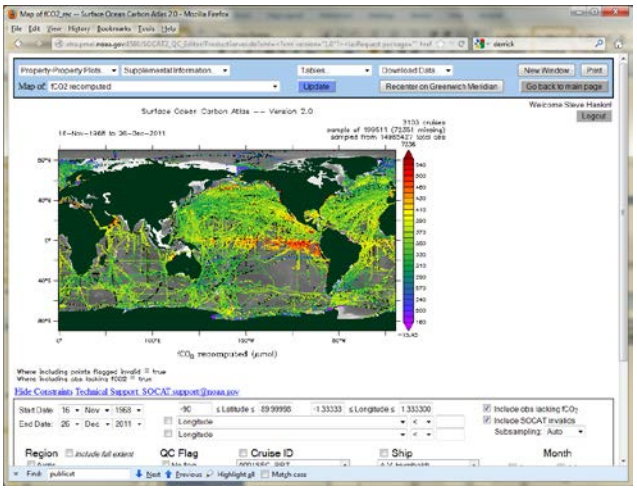

Figure 3. SOCAT.info main page. Screen shot of the front page of the SOCAT Live access Server.

Figure 4. Screen shot of the SOCAT version 2 Quality control editor and viewer

The quality control of the data is aided by developing Matlab routines:
Olsen, A. and D. Pierrot (2010) MATLAB routines to aid QC of SOCAT data[2]

2.2 Ocean interior

The ocean interior component of the Global Carbon Data Management and Synthesis Project involves continued processing and assessment of the CLIVAR/CO_2 Repeat Hydrography data, an international synthesis of high-quality carbon data for the period from GEOSECS to CLIVAR, and a global assessment of decadal changes in ocean carbon inventories. As with the surface data, an important component of the effort is national and international outreach and coordination to improve data quality, and assemble data into coherent unified datasets. As

[2] http://www.socat.info/upload/Images_Header/Matlab_Final_Routines_2012_02%2014.zip

described below the participants of the ocean carbon synthesis efforts have been active participants and leaders of efforts such as CARINA, PACIFICA and RECCAP that provide critical data products for interpretation and testing/verification of models of ocean carbon dynamics and change. Each of these is very briefly discussed below.

Processing Repeat Hydrography Data

In FY2012, the NOAA DIC data from the A13.5 cruise, from South Africa to Ghana in the Eastern South Atlantic were finalized and submitted to CDIAC. DIC data from the A10 cruise across the South Atlantic had data quality issues (see CLIVAR/CO_2/Tracer Repeat Hydrography Program Report) and required more data workup time than estimated and will be submitted to CDIAC shortly. PIs Millero and Dickson finalized the total alkalinity data collected on the CLIVAR S4P and A10 cruises. The accuracy of pH data for S4P is currently being further investigated due to use of a non-optimal dye for low pH levels encountered in the Southern Ocean. The DIC S4P data has been submitted to CDIAC and final cruise reports have been made publically available. Over the past year biogeochemical tracer and hydrographic data from the following datasets available to the general public[3]: I05_2009, P06_2009, P21_2009, P15S_2009, A13.5, and S4P (except for pH).

Ocean Interior Data Synthesis

The synthesis effort has continued its basin wide approach with focus on the Pacific with a project led by PICES called PACIFICA. This is a data synthesis effort that is scientifically similar to CARINA in all aspects except that the data are primarily from the North Pacific. Over the past year the PACIFICA group, which includes several of the Global Carbon Data Management and Synthesis Project PIs collected and began assessing the quality of approximately 250 new cruises not previously available to the public. The effort is lead by the Japanese partners and it has resulted in many previously embargoed datasets being released to the global scientific community. The importance of this development as a result of many years of interactions between the global scientists must be recognized as a major advance in global collaborations. While Princeton's involvement in PACIFICA has been less than it was for the prior data collection efforts, the lessons learned in the GLODAP and CARINA efforts, as well QC tools and approaches have been shared with the PACIFICA partners. Japanese scientists have assembled all of the data for the collection. They have also had the primary responsibility for 1st level QC of the data. R. Key's has participated in all the critical PACIFICA data QC meetings and offered open and extensive guidance. All of the PACIFICA data is in the Princeton data system and have been checked in collaboration with the PACIFICA group. Feely and Sabine are regional leaders in the QC process. The PACIFICA data is stored at CDIAC but the final release has not yet occurred due to some remaining issues regarding data exchange and data repositories within the Japanese funding agencies.

Global Assessment of Decadal Changes in Ocean Carbon Storage

An important component of the Global Carbon Data Management and Synthesis Project is the analysis of decadal changes in ocean carbon storage. These analyses are initially conducted along specific lines occupied as part of the CLIVAR/CO_2 Repeat Hydrography program. During the

[3] Data can be obtained from http://cdiac.ornl.gov/oceans/RepeatSections/ and http://cchdo.ucsd.edu/

WOCE program, east-west cruise line P6 and North-South P18 lines in the South Pacific occupied in 1992 and 1994, respectively. P06 was occupied as part of the Japaneses BEAGLE cruises that circumnavigated the globe along nominally 30 ˚S in 2003. They were re-occupied as part of the CLIVAR/CO_2/Tracer Repeat Hydrography program to investigate the temporal changes in total dissolved inorganic carbon (DIC) in 2010 and 2008 along these cruise lines. The results are shown in **Figure 5**. The estimated DIC increases for P6 over the 18-year interval range from about 0 µmol kg^{-1} below 1000 m to values greater than 25 µmol kg^{-1} near the surface with the dramatic increases between the surface and 300m between 2003 and 2010. Similar analyses using the extended multiple linear regression (eMLR) approach along the P18 line along 110˚W shows that the strong increase is centered in the subtropical gyre (Waters et al., 2011).

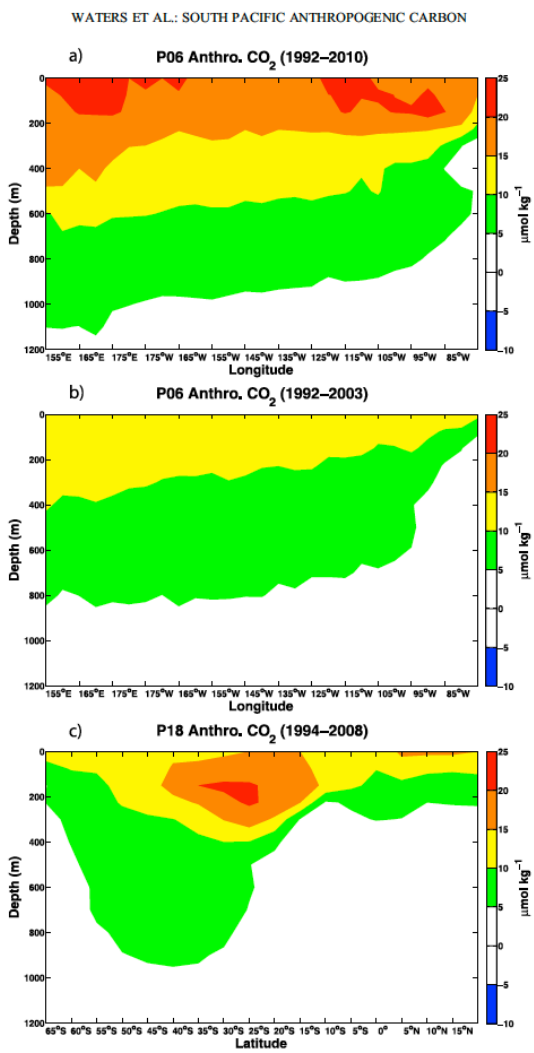

Figure 5. Anthropogenic CO_2 uptake along P06 between 1992 and 2010 (a); and 1992 and 2003 (b). The change along P18 between 1994 and 2008 is shown in the bottom panel (in µmol kg^{-1}). From Waters, Millero and Sabine, (2011).

Ocean Interior Carbon in the Regional Carbon Cycle Assessment and Processes (RECCAP)
RECCAP is an international activity coordinated through the Global Carbon Project (GCP)[4] with the goal of producing global and regional assessments of the sources and sinks of CO_2. An important component of this effort is the evaluation of the global carbon inventories and how they are changing with time. Several of the COD carbon project PIs (Sabine, Feely, Wanninkhof, Key, Kozyr) are a part of this effort and are taking the lead on different aspects of the project. Sabine is a co-author in the global assessment of anthropogenic carbon inventories (Khatiwala et al. 2012) and Wanninkhof is the lead author of the paper on ocean carbon uptake and trends for the past two decades based on observations, empirical approaches and models (Wanninkhof et al. 2012a).

Another effort supported by the DMSP is detection and attribution of hydrographic and biogeochemical changes in the deep ocean (≈> 2000 m). This is challenging due to limited accurate data and small changes over time. There are indications though that anthropogenic and climate change signals are starting to manifest themselves at depth. During the performance period we submitted a paper determining the changes in deep water inorganic carbon content along meridional transects in the Atlantic and Pacific Ocean on decadal time scales using observations from the World Hydrographic Program in the 1980s and 1990's, and the CLIVAR/CO_2 repeat hydrography effort in the past decade (Wanninkhof et al., 2012b). Decadal changes of DIC in deep water cannot currently be measured with confidence in the ocean interior removed from the outcrop regions. Changes based on discrete pCO_2 (20) measurement show appreciable rates of inventory change that are in general agreement with the age of water masses. The cruises in the Atlantic central basin show deep-water changes at a rate of changes of 0.5 mol m^{-2} yr^{-1} **(Figure 6)**, the South eastern South Atlantic basin shows changes of 0.12 mol m^{-2} yr^{-1} and the Southeastern Pacific at 0.07 mol m^{-2} yr^{-1}. The changes are appreciably higher than the output of the NCAR CCSM-1 model but this model also shows less CFC11 at depth than measured CFC11 (**Figure 7**). The CFC11 ages based on the measured CFC11 concentrations indicate that the dissolved inorganic carbon (DIC) changes based on pCO_2 (20) measurements are plausible and from anthropogenic origin. The results indicate that appreciably more anthropogenic CO_2 is entering the ocean interior than several current observation based techniques indicate. However, the paucity in pCO_2 (20) data and largely uniform specific inventory changes ΔDIC_{pCO2} with latitude (**Figure 6**) make the quantification of this signal tentative (Wanninkhof et al., 2012b).

[4] www.globalcarbonproject.org/reccap/

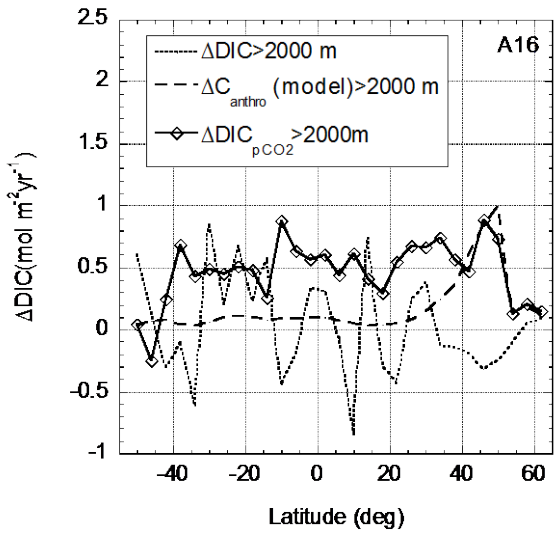

Figure 6. Specific inventory changes of ΔDIC, ΔDIC_{pCO2}, and ΔC_{anthro} (model) below 2000 m versus latitude for the A16 line from 54˚ S to 62˚ S between 1993 and 2005. The measured change in DIC is very variable and attributed to the uncertainty in the measurements. The calculated DIC change based on $pCO_2(20)$, ΔDIC_{pCO2}, is plausible. The ΔC_{anthro} (model) is from a model and suggests shortcoming of the model carrying anthropogenic CO_2 into the interior ocean (see figure 7).

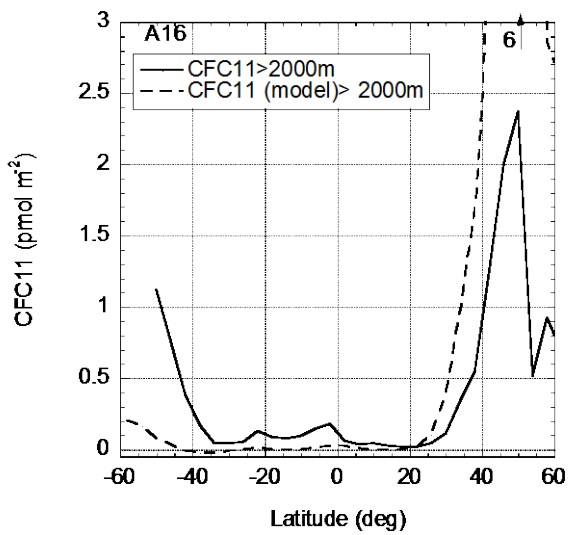

Figure 7. Specific inventory for measured CFC11 and modeled CFC11 greater than 2000m for 2010 for the A16line. The model data is systematically lower except at high Northern latitudes suggesting issues in (some) models with deep ventilation processes.

R. Key has collaborated with M. Manizza improve understanding of the carbon system in the Arctic Ocean. This research is based on data assembled as part of the CARINA project and more recent cruises, and results from a numerical ocean model. The model suggests a regional uptake

of 59TgC yr^{-1} in agreement but with much better constraints than the estimate from very limited data (29-199TgC yr^{-1}). Because of limited circulation, broad shelf areas and numerous rivers, and rapid climate change, the carbon chemistry of this region is particularly interesting (Manizza et al. 2011).

Ocean Acidification

The uptake of anthropogenic CO_2 by the global ocean induces fundamental changes in seawater chemistry that could have dramatic impacts on biological ecosystems in the upper ocean. Based on measurements from the WOCE/JGOFS global CO_2 survey, the CLIVAR/CO_2 Repeat Hydrography Program in the Pacific Ocean, we have observed an average 0.34% yr^{-1} decrease in the saturation state of surface seawater with respect to aragonite and calcite. The upward migrations of the aragonite and calcite saturation horizons, averaging about 1 to 2 m yr^{-1}, are the direct result of the uptake of anthropogenic CO_2 by the oceans and regional changes in circulation and biogeochemical processes (Feely et al. 2012; Table 1). The shoaling of the saturation horizon is regionally variable, with more rapid shoaling in the South Pacific where there is a larger uptake of anthropogenic CO_2 (Figure 8). In some locations, particularly in the North Pacific Subtropical Gyre and in the California Current, the decadal changes in circulation are the dominant factor in controlling the migration of the saturation horizon. If CO_2 emissions continue as projected over the rest of this century, the resulting changes in the marine carbonate system would mean that many coral reef systems in the Pacific would no longer be able to sustain a sufficiently high rate of calcification to maintain the viability of these ecosystems as a whole and perhaps could seriously impact the thousands of species that depend on them for survival.

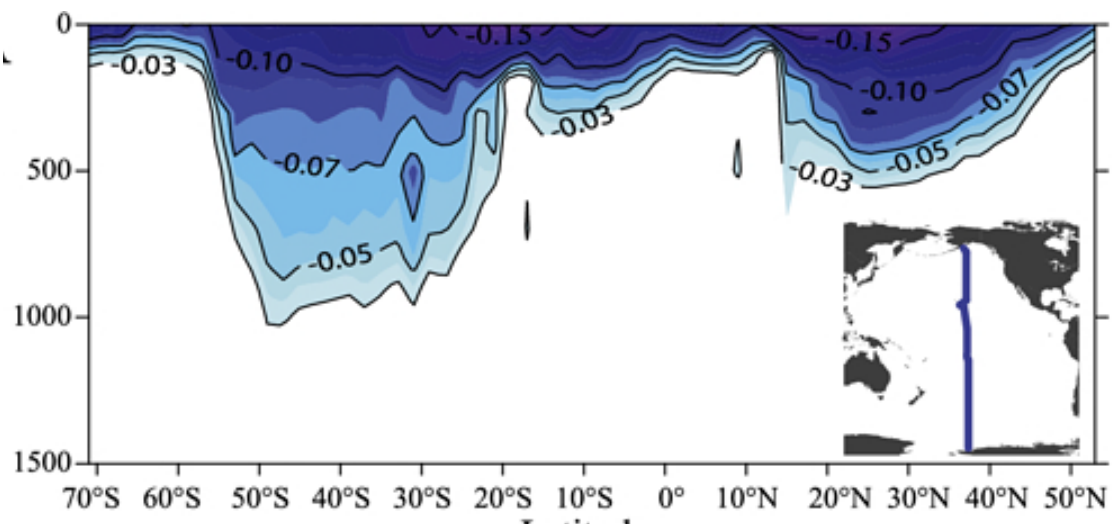

Figure 8. Change in aragonite saturation state in the Pacific Ocean between 1991-92 and 2005-06 as a result of the uptake of anthropogenic CO_2 (from Feely et al., 2012).

In the surface mixed layer (depths to ~100 m), the extent of pH change is consistent with that expected under conditions of seawater/ atmosphere equilibration, with an average rate of change of -0.0017 yr^{-1}. Future mixed layer changes can be expected to closely mirror changes in atmospheric CO_2, with surface seawater pH continuing to fall as atmospheric CO_2 rises.

Table 1. Average shoaling of the aragonite saturation horizon (Ωarag =1.0) and decrease in the aragonite saturation state in the upper 100 m in the South and North Pacific due to the uptake of anthropogenic CO_2.

Region	P16 (m yr^{-1})	P18 (m yr^{-1})	P16 Ωarag decrease % yr^{-1}	P18 Ωarag decrease % yr^{-1}
South Pacific	2.01 ± 0.80	1.81 ± 0.85	0.34 ± 0.05	0.35 ± 0.05
North Pacific	0.81 ± 0.71[#]	1.14 ± 0.55	0.34 ± 0.07[#]	0.33 ± 0.01

[#]includes PO2 value at the cross-over point.

2.3 References

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3. Education and Outreach

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, and official congressional testimonies. We have also given numerous press interviews and have been quoted in printed and online media, radio, and television.

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 with Principal Investigators as First Author

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.

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