

Global Data Management and Synthesis Project

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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 pCO₂ on ships effort, and the pCO₂ on moorings effort. 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 CO₂ storage to within 2 Pg C decade⁻¹ and regional sea-air CO₂ 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.

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 (Prentice et al., 2001; Canadell et al., 2007; Le Quéré et al., 2009). This absorption of CO₂ 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; Feely et al., 2013). 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 CO₂ 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 pCO₂, and CO₂ 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 CO₂ 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 CO₂ 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 CO₂ 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 FY2013 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 CO₂ 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 the last section.

2.1 Surface Ocean CO₂

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 CO₂ flux climatology (Takahashi et al., 2009; Takahashi et al., 2012), developing the algorithms to make seasonal CO₂ flux maps using satellite observations¹ and working with the international ocean carbon community on the release of the first Surface Ocean CO₂ Atlas (SOCAT) (Pfeill et

¹ <http://cwgcom.aoml.noaa.gov/erddap/griddap/aomlcarbonfluxes.graph>.

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 FY2013, PMEL and AOML received daily underway CO₂ data files from ships of opportunity sailing the Atlantic and Pacific oceans. Improvements are made to the telemetry and diagnostic software to quality control pCO₂, temperature, salinity, barometric pressure, pumps, water flow and gas flow data. During the time in review, data from over 50 cruises have been processed and submitted to CDIAC and SOCAT. All current and previous underway pCO₂ data files are quality controlled using the data protocols outlined in Pierrot et al. (2009).

Data from 11 mooring sites were also processed at PMEL and submitted to CDIAC following the Pierrot et al. protocols in FY13. The processing included not only the latest data, but also a reprocessing of older data to ensure that all our mooring data are available in the agreed format. In total, we processed and submitted 10.5 buoy years of data in FY2013, bringing the grand total to 54.5 years of open ocean data finalized and available to the public at CDIAC since the inception of the project. A synthesis of pCO₂ mooring observations in the Niño 3.4 area includes 10 ENSO events and represents a quantum leap in our ability to understand the mechanisms governing ocean events (Sutton et al. in revision). This synthesis also shows that anthropogenic CO₂ uptake and increased upwelling since the PDO shift of 1997–1998 are resulting in higher surface seawater pCO₂ (+2.3 to +3.5 $\mu\text{atm yr}^{-1}$) growth rates than previously reported. This decadal shift is likely impacting pCO₂ outgassing from the region supplying the largest oceanic source of CO₂ to the atmosphere

As detailed in the “pCO₂ from ships” report over 500,000 new underway pCO₂ 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)

The data management and synthesis effort is by nature a highly collaborative effort between, AOML, PMEL, US academic, and international partners. During the performance period several synthesis products were completed that fed directly into the fifth annual assessment (AR5) of the Intergovernmental Panel on Climate change (IPCC). Below is a summary of the execution of the FY-13 work plan. The work plan is based on four performance measures whose milestones for FY-13 have been accomplished in full.

Performance Measures (FY2012-2014)					
Measure of Performance	2013	2014-flat budget	2014-restore	2015-flat budget	2015-maintain
CO ₂ flux maps	Bi-monthly, 6-month lag	Every 3 months, 9-month lag	Bi-monthly, 6-month lag	Quarterly, 1-year lag	Bi-monthly, 6-month lag
Ocean interior synthesis	No PM	No PM	GOSC12 public release	No PM	Decadal assessment
Data processing surface data	All data from SOOP-pCO ₂ ships processed within 9-months	All data from SOOP-pCO ₂ ships processed within 12-months	All data from SOOP-pco2 ships processed within 9-months	All data from SOOP-pCO ₂ ships processed within 18-months	All data from SOOP-pCO ₂ ships processed within 9-months
Data processing interior data	Submit A10 to CDIAC	Submit A20/22 data	Submit A20/22 data	Submit A16N/P2 data	Submit A16N/P2 data

Seasonal air-sea CO₂ Flux Maps

A new assessment of air-sea CO₂ fluxes and temporal trends as part of RECCAP

Our efforts in the first phase of regional carbon cycle assessment and projection (RECCAP) project were successfully completed with a global assessment of global air-sea CO₂ fluxes and temporal trends over the past 19 years (Wanninkhof et al. 2013) (**Figure 1**). The major conclusion is that global ocean CO₂ inventory changes over the last two decades, based on different observational and modeling approaches, show good agreement with an estimate centered on 2000 of 2.2 +/- 0.4 Pg C. The values based on sea-air CO₂ fluxes are on the lower side of the estimates from models and interior estimates. While the magnitude appears well constrained, the interannual variability and trends between different approaches are quite different (Table1) pointing towards the need for continued work on observational time-series. Basin specific detailed analyses of the Atlantic and Pacific Basin were presented in Schuster et al., 2013 and Ishii et al. 2013. The results were presented at the 9th International Carbon Dioxide Conference in Beijing, June 3-7, 2013.

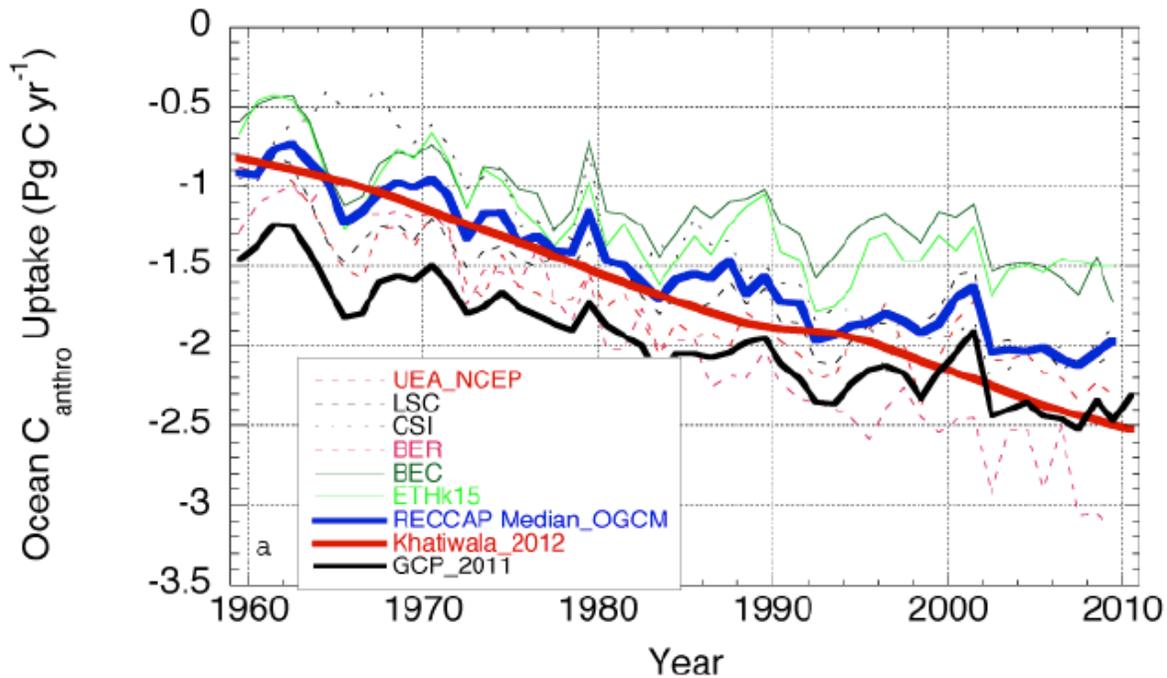


Figure 1. The 50 yr globally integrated ocean anthropogenic CO₂ uptake from OBGCMs used in RECCAP. The thin solid and dashed lines show the increasing annual uptake of the different models and their interannual variability (Tables 2 and 4). The thick solid blue line is the median of the OBGCMs; the thick solid red line is the output of the Green function method (Khatiwala et al., 2012) and the thick black line is the result from the GCP ocean model ensemble

(<http://www.globalcarbonproject.org/carbonbudget/index.htm>) (From Wanninkhof et al., 2013a)

As part of the synthesis effort J. Trinanes continues to provide and improve updated monthly CO₂ flux estimates based on the empirical approach of Park et al., 2010. The fluxes for 2012 are provide in **Figure 2** showing a global minimum in uptake in the Boreal Summer that is stronger than average based on the flux anomaly that is now provided as a user specified option in the graphical user interface <http://cwcgom.aoml.noaa.gov/erddap/griddap/aomlcarbonfluxes>. The decreased uptake/increase release during the January 2012 compared to the 30-year average January value is particularly pronounced in the Western Pacific, North Atlantic and Southern Ocean (**Figure 3**).

Table 1 (from Wanninkhof et al. 2013a)

Median sea-air anthropogenic CO₂ fluxes for the different approaches centered on year 2000.

Approach	Anthr. CO ₂ flux Pg C yr ⁻¹	Uncertainty Pg C yr ⁻¹	IAV ^e Pg C yr ⁻¹	SAV ^f Pg C yr ⁻¹	Trend (Pg C yr ⁻¹) decade ⁻¹
Empirical	-2.0	±0.6 ^a	0.20	0.61	-0.15
OBGCM	-1.9	±0.3 ^b	0.16	0.38	-0.14
Atm. Inversion	-2.1	±0.3 ^c	0.40	0.41	-0.13
Ocean Inversion	-2.4	±0.3 ^d			-0.5 ^j
Interior (Green function) ^g	-2.2	±0.5	-	-	-0.35
O ₂ /N ₂ ^h	-2.2	±0.6			
O ₂ /N ₂ ⁱ	-2.5	±0.7			

^a Root mean square of uncertainty in different components of the flux (see Table 1). ^b Median absolute deviation of the six model outputs used to determine the median (for 6 model outputs: LSC, UEAN_{CEP}, CSI, BER, BEC and ETH_{k15}). ^c Median absolute deviation of eleven model outputs used to determine the median. ^d Median absolute deviation of the ten model outputs used to determine the median. ^e Interannual variability (IAV) for the median values for the 6 models listed in ^b. ^f Subannual variability (SAV) for the median values (for 5 model outputs: LSC, UEAN_{CEP}, CSI, BEC and ETH_{k15}). ^g Based on interior ocean changes using transient tracers and a Green function (Khaliwala et al., 2009, 2012). ^h For 1993–2003 (Manning and Keeling, 2006). ⁱ For 2000–2010 (Ishidoya et al., 2012). ^j Calculated assuming steady ocean circulation and CO₂ uptake proportional to atmospheric CO₂ increases.

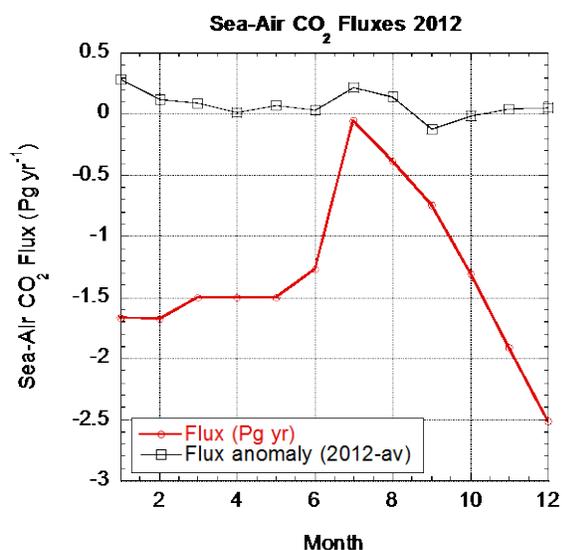


Figure 2. Monthly global sea-air CO₂ fluxes for 2012 using the empirical approach of Park et al. 2012 and remotely sensed wind and SST data from NOAA Coastwatch

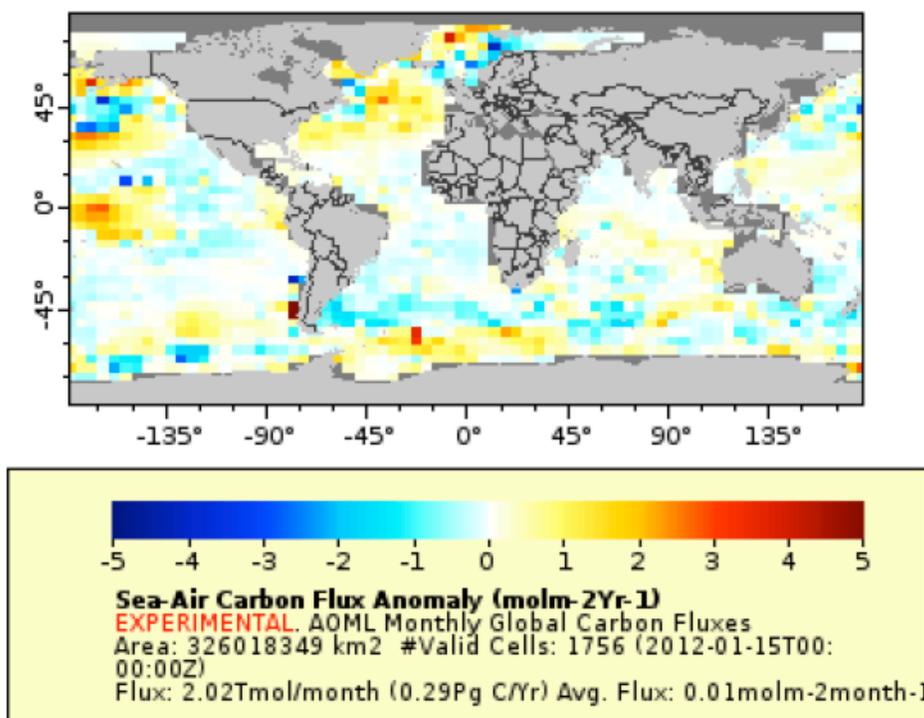


Figure 3. Global sea-air CO₂ flux anomaly for January 2012 compared to the 30-year average from the graphic user interface

A new, large-scale synthesis effort in the Pacific Basin that was led by our Japanese colleagues during this reporting period showed a large net CO₂ influx into the extra-tropics is associated with a robust seasonal cycle, and a large net CO₂ efflux from the tropics is associated with substantial inter-annual variability. This work showed estimates of the net air-sea CO₂ flux from a variety of products drawing upon a variety of approaches in three sub-basins of the Pacific Ocean, i.e., the North Pacific extra-tropics (18° N–66° N), the tropical Pacific (18° S–18° N), and the South Pacific extra-tropics (44.5° S–18° S). These approaches included those based on the measurements of CO₂ partial pressure in surface seawater ($p\text{CO}_{2\text{sw}}$), inversions of ocean interior CO₂ data, forward ocean biogeochemistry models embedded in the ocean general circulation models (OBGCMs), a model with assimilation of $p\text{CO}_{2\text{sw}}$ data, and inversions of atmospheric CO₂ measurements. Long-term means, inter-annual variations and mean seasonal variations of the regionally-integrated fluxes were compared in each of the sub-basins over the last two decades, spanning the period from 1990 through 2009. A simple average of the long-term mean fluxes obtained with surface water $p\text{CO}_{2}$ diagnostics and those obtained with ocean interior CO₂ inversions are $-0.47 \pm 0.13 \text{ Pg C yr}^{-1}$ in the North Pacific extra-tropics, $+0.44 \pm 0.14 \text{ Pg C yr}^{-1}$ in the tropical Pacific, and $-0.37 \pm 0.08 \text{ Pg C yr}^{-1}$ in the South Pacific extra-tropics, where positive fluxes are into the atmosphere. This suggests that approximately half of the CO₂ taken up over the North and South Pacific extra-tropics is released back to the atmosphere from the tropical Pacific. These estimates of the regional fluxes are also supported by the estimates from OBGCMs after adding the riverine CO₂ flux, i.e., $-0.49 \pm 0.02 \text{ Pg C yr}^{-1}$ in the North Pacific extra-tropics, $+0.41 \pm 0.05 \text{ Pg C yr}^{-1}$ in the tropical Pacific, and $-0.39 \pm 0.11 \text{ Pg C yr}^{-1}$ in the South Pacific extra-tropics. The estimates from the atmospheric CO₂ inversions

show large variations amongst different inversion systems, but their median fluxes are consistent with the estimates from climatological $p\text{CO}_2\text{sw}$ data and $p\text{CO}_2\text{sw}$ diagnostics. In the South Pacific extra-tropics, where CO_2 variations in the surface and ocean interior are severely under-sampled, the difference in the air-sea CO_2 flux estimates between the diagnostic models and ocean interior CO_2 inversions is larger ($0.18 \text{ Pg C yr}^{-1}$). The range of estimates from forward OBGCMs is also large (-0.19 to $-0.72 \text{ Pg C yr}^{-1}$). Regarding inter-annual variability of air-sea CO_2 fluxes, positive and negative anomalies are evident in the tropical Pacific during the cold and warm events of the El Niño Southern Oscillation in the estimates from $p\text{CO}_2\text{sw}$ diagnostic models and from OBGCMs. They are consistent in phase with the Southern Oscillation Index, but the peak-to-peak amplitudes tend to be higher in OBGCMs ($0.40 \pm 0.09 \text{ Pg C yr}^{-1}$) than in the diagnostic models ($0.27 \pm 0.07 \text{ Pg C yr}^{-1}$) (Ishii et al., 2013).

In the Northeastern Pacific, Lockwood et al., 2012 determined rates of air-sea CO_2 flux in the Northeast Pacific subarctic, transition zone and subtropical regions based on a cruise in August–September 2008 by continuous measurement of surface values of the ratio of dissolved oxygen to argon (O_2/Ar) and the partial pressure of CO_2 ($p\text{CO}_2$). These estimates were compared with simultaneous measurements of sea surface temperature (SST), chlorophyll-a (chl-a), flow cytometry, and discrete surface nutrient concentrations. CO_2 influx was greatest in the subarctic and northern transition zone. Contrastingly, the southern transition zone and subtropics had mean CO_2 efflux. In the subarctic and transition zone, biological production was highly correlated with CO_2 influx, indicating strong coupling between the biological pump and CO_2 uptake (Lockwood et al., 2012).

Two new synthesis efforts in the Gulf of Alaska in FY13 (Evans and Mathis, 2013; Palevsky et al., 2013) calculated sea–air CO_2 fluxes over two interconnected domains: the coastal ocean defined by the Surface Ocean CO_2 Atlas (SOCAT) Continental Margin Mask, and the continental margin shoreward of the 1500 m isobath. The continental margin in this region lies within the coastal ocean. Climatological sea–air CO_2 fluxes were calculated by constructing monthly climatologies of sea–air $p\text{CO}_2$ difference ($\Delta p\text{CO}_2$), sea surface temperature, salinity, and CO_2 solubility, coupled with the monthly second moment of wind speeds from the Scatterometer Climatology of Ocean Winds (SCOW; <http://cioss.coas.oregonstate.edu/scow>). Climatological sea–air CO_2 fluxes showed instances of atmospheric CO_2 uptake and outgassing in both domains for nearly all months; however, uptake dominated from April through November, with distinct spring and autumn peaks that coincided with periods of strong winds and undersaturated surface seawater $p\text{CO}_2$ with respect to atmospheric levels. Atmospheric CO_2 uptake during the spring and autumn peaks was stronger on the continental margin compared with the coastal ocean. Annual mean area-weighted fluxes for the coastal ocean and continental margin were -2.5 and $-4 \text{ mmol CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, respectively. Scaling these annual means by the respective surface areas of each domain resulted in estimates of substantial atmospheric CO_2 uptake between 34 and 14 Tg C yr^{-1} . This region is a large sink for atmospheric CO_2 , which impacts the current view of weak net CO_2 emission from coastal waters surrounding North America (Evans and Mathis, 2013). Biological productivity was shown to be a key factor controlling the ocean’s ability to take up carbon dioxide from the atmosphere in this region. However, the ecological dynamics that drive regions of intense productivity and carbon export are poorly understood. High-spatial-resolution estimates of air-sea CO_2 flux, net community production (NCP) rates calculated from O_2/Ar ratios, and phytoplankton population abundances

were determined by continuous underway measurements on a cruise across the Gulf of Alaska in May 2010. The highest rates of oceanic CO₂ uptake (air-sea flux of -42.3 ± 6.1 mmol C m⁻² d⁻¹) were observed across a transition zone between the high-nitrate low-chlorophyll (HNLC) waters of the Alaskan Gyre and the coastal waters off the Aleutian Islands. While the transition zone comprises 20% of the total area covered in crossing the Gulf of Alaska, it contributed 67% of the total CO₂ uptake observed along the cruise track (Palevsky et al., 2013).

Release of data for SOCAT version 2

In 2013, the second release of SOCAT went public. Dr. Denis Pierrot is part of the SOCAT committee responsible for release of version 2 that includes data through 2011 with over 4 million new data points for a total of over 10 million (Bakker et al., 2013). Approximately half of all the data originates from the CPO/COD pCO₂ from ships program. AOML and PMEL participants are actively engaged in submission and 2nd level quality control for version 3, including recommendation of inclusion of alternative sensors into the database (Wanninkhof et al., 2013b), automation of data ingestion, and improved metadata submission necessary to have the dataset meet climate quality data standards.

Updated sea-air sea CO₂ flux maps

The data from the pCO₂ from ships project are assembled into a combined dataset including data from international collaborators that is served through CDIAC (Takahashi et al., 2013). A primary purpose of this data is to create global climatologies on intervals of 5-years. The most recent release is the climatology centered on 2005 can be obtained at:

http://www.ldeo.columbia.edu/res/pi/CO2/carbondioxide/global_ph_maps/pco2_maps.html

We are charged with using the pCO_{2sw} fields to create the corresponding climatological sea-air flux. The updated net sea-air flux is -1.33 Pg C yr⁻¹ for the 2005 climatology (**Figure 4**) compared to the value of -1.22 Pg C yr⁻¹ for the 2000 climatology using the same consistent treatment of Δ pCO₂ fields, gas transfer and wind speeds.

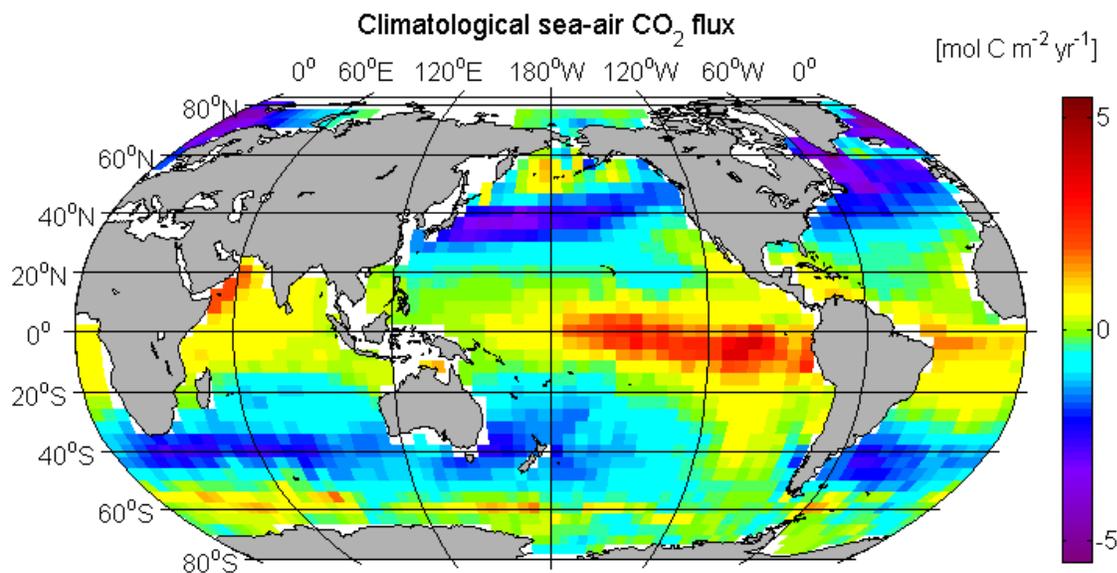


Figure 4. Updated sea-air CO₂ flux climatology for 2005 yielding a net global sea-air CO₂ flux of -1.33 Pg C yr⁻¹.

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 CO₂ (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 ΔpCO₂ 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 5**. An important result of the work is that that the trends in CO₂ uptake by the ocean based on approaches relying on sea-air CO₂ surface fluxes is appreciably smaller than the estimates based on changes in the ocean interior such as the ocean inverse and Green function (Khatiwala et al., 2012; Rödenbeck et al., 2013).

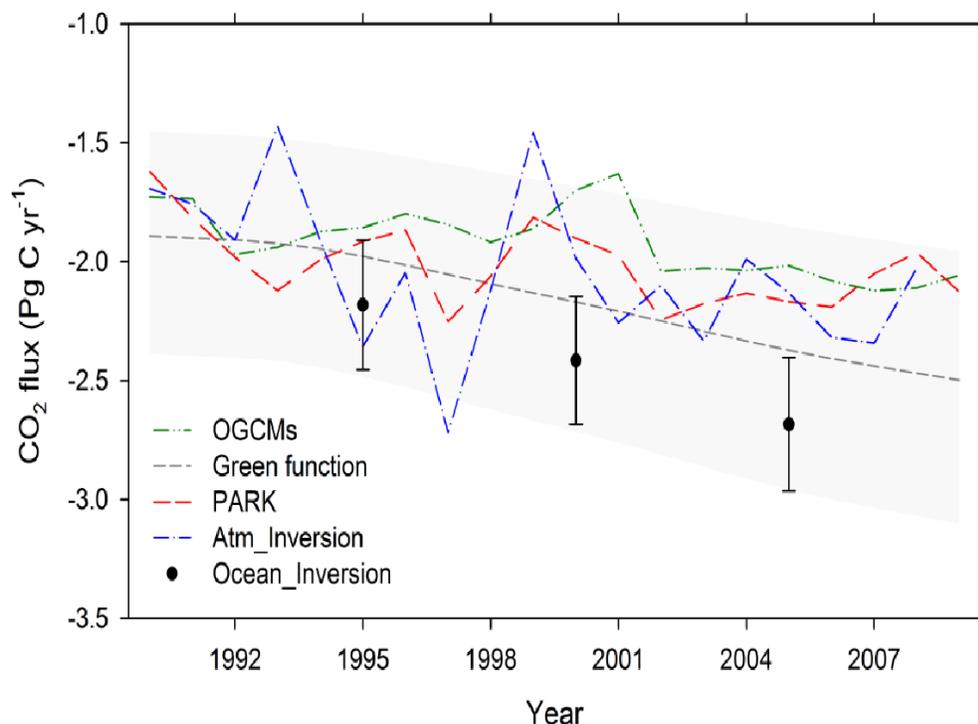


Figure 5. Anthropogenic sea-air CO₂ fluxes based on the empirical approach of Park et al. (2010a), and different modeling approaches, from Wanninkhof et al. (2012).

Surface Ocean CO₂ Atlas

SOCAT is an international effort that strives to integrate all publicly available surface CO₂ 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 data set increasingly serves as the foundation upon which the community evaluates the controls on air-sea CO₂ fluxes.

The SOCAT effort produces two distinct data products: 1) a 2nd-level quality controlled, global surface ocean $f\text{CO}_2$ (fugacity of CO_2) cruise data collection; and 2) gridded summary fields on $1^\circ \times 1^\circ$ (open ocean) and $1/4^\circ \times 1/4^\circ$ (coastal) resolutions. The initial release of SOCAT, version 1.5, was made available in October of 2011. In June of this year at the Ninth International Carbon Dioxide Conference in Beijing, China, version 2.0 of SOCAT was announced. SOCAT was featured at this conference through a plenary presentation, two posters, and a dedicated SOCAT side-event. SOCAT publications in 2013 provided details on the v1.5 cruise collection (Pfeil et. al. 2013) and the gridded fields (Sabine et. al., 2013). 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 Pangaea² and CDIAC³.

Version 2.0 of SOCAT incorporated new cruise and mooring data, extending the 1968-2007 interval of version 1.5 to include 2008-2011 data. Version 2.0 expanded the number of cruises from 1851 to 2669 and the number of observations from 6.3 million to 13 million. **Figure 6** shows a global snapshot of the full version 2.0 collection. The incorporation of new cruises into version 2.0 was closed as of November 2012, followed by the collaborative QC process that extended until 15 January, 2013. The QC process flagged approximately 40 thousand points as questionable or rejected. Data curatorship activities at PMEL to address problems found in the data that had been submitted were continual throughout this period, illustrating the importance of further automating the data submission process (discussed below).

The SOCAT Web site includes data viewers built upon the PMEL Live Access Server (LAS) (**Figure 7**). 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 offers custom plots and animations; the ability to difference fields (e.g. compare the 1990 annual average $f\text{CO}_2$ with the 2000 average); simple analysis tools to compute averages, extrema and variances over areas and time; and displays on Google Earth.

Version 2.0 of SOCAT was assembled using similar procedures to those used for the version 1.5 effort. PIs made data available through submission to national data centers, to CDIAC or via email to the Bjerknes Centre for Climate Research in Bergen, Norway. Benjamin Pfeil at Bjerknes Center reformatted data as required and passed them to PMEL for ingestion into the shared database. PIs organized into regional teams then applied second-order QC to ensure uniform quality using a combination of tools available on the SOCAT LAS server and desktop QC tools in Matlab contributed by Olsen, A. and D. Pierrot (2010)⁴. The SOCAT LAS system at PMEL includes a “training” server, which allowed SOCAT members familiarize themselves the group QC tools without risk to the integrity of the collection.

The community has recognized that the level of effort required to maintain and grow the SOCAT collection using current procedures is not sustainable over the long term. As a result an effort was undertaken to design and implement an enhanced, Web-based SOCAT data system that

² <http://doi.pangaea.de/10.1594/PANGAEA.811776>

³ <http://cdiac.ornl.gov/ftp/oceans/SOCATv2/>

⁴ http://www.socat.info/upload/Images_Header/Matlab_Final_Routines_2012_02%2014.zip

streamlines the processes. Key requirements of the design are: i) to minimize the effort required of scientists to contribute their data and metadata; ii) to the degree feasible to accommodate variations in file formats between participating groups; iii) to provide immediate, automated feedback regarding file formats, metadata content, and level 1 QC “sanity” checks of the data; and iv) to support an on-going QC process that occurs in parallel with the submission of new cruises and moorings.

The effort to implement this so-called “version 3 automation system” was undertaken in earnest in FY13 – the first year of a 2-year effort. Primary responsibility for the development and integration of the system lies with PMEL with major components contributed by University of East Anglia (UK), and CDIAC. Most components of the system will be new or re-designed software, including a “dashboard” from which users may upload data files, create metadata, and perform level 1 QC prior to submitting cruises to SOCAT; an automated “sanity checker” adaptable to PI-preferred formats; on-line metadata entry and editing; expanded QC evaluation tools; a QC flagging system that addresses multiple observed variables as well as fCO₂; version control for PI cruise files; and a new, higher performance database strategy. To minimize the need for travel in this collaborative software development heavy use has been made of Web tools, such as Skype and Google Hangout. Design documents that outline the intended experience for users and the software components required for implementation may be viewed on line⁵. The current project planning for the rollout of the V3 automation system includes its usage by the SOCAT data managers to ingest and process the SOCAT V3 collection data in early 2014. This will serve as a testing opportunity for the system, before it is made available directly to SOCAT PIs later in the year.

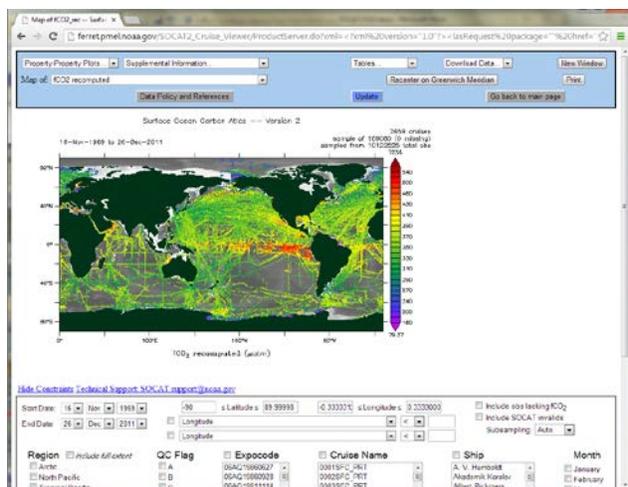


Figure 6. Screen shot of the SOCAT version 2 Quality control editor and viewer

⁵ <https://drive.google.com/a/noaa.gov/?tab=mo#folders/0B5BUjI4ZYU6IRUhqNmJBVDFoWDg>



Figure 7. SOCAT.info main page.

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/CO₂ 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 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

Data processing for GO-SHIP repeat hydrography – Atlantic

The CLIVAR/CO₂ Repeat Hydrographic cruise lines A16N, and A20/22 were performed in the past two years. UW pCO₂, and DIC data for A20/22 were reduced and submitted to CDIAC and CCHDO during FY-13. Discrete bottle data for DIC and discrete pCO₂ and UW pCO₂ data for A16N are being processed. The processing involved contextual quality assessment, data and metadata submission. The contextual quality assessment included comparison with older cruise data, and internal consistency checks of the inorganic carbon parameters pH, TALK, and DIC. The TALK and pH measurements are lead by our academic partners, Profs. Dickson and Millero. The disbanding of the science team has hampered and delayed this aspect of the work plan and has contributed to data quality degradation of TALK measurements on A16N. Discrete pCO₂ (20) and DIC contour plots based on the preliminary data from the A16N_2013 cruise (which ended in Natal, Brazil on Oct 4, 2013) are shown in **Figure 8**. The absence of “bulls eyes” and systematic spatial trends provide an indication of the high ship-based analytical quality and quality control of the data during the cruise. For quantification of trends over the previous decade a second level of scrutiny and quality and standardization will be required. The unique application to discern anthropogenic CO₂ changes in deep water based in pCO₂ described in the FY-12 report was published in Wanninkhof et al. (2013c).

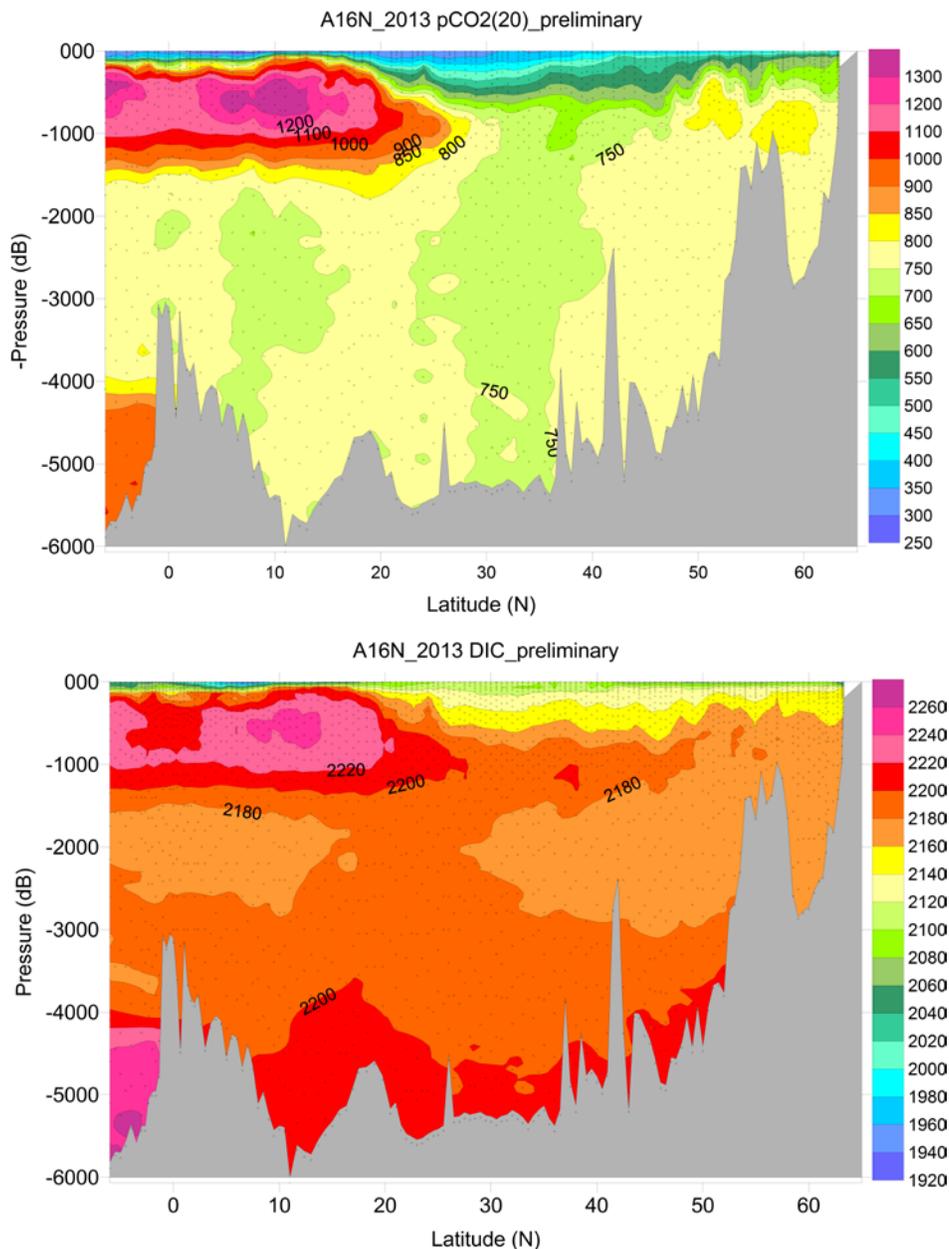


Figure 8. Cross-sections of preliminary data for discrete $p\text{CO}_2$ and DIC for the 2013 occupation of A16N. The characteristic inorganic carbon fingerprints of the major water masses are apparent. The faint dots are the sample locations showing excellent coverage.

Data processing for GO-SHIP repeat hydrography – Pacific/Indian

The synthesis effort has continued its basin wide approach with focus on the Pacific and Indian Ocean 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 two years the PACIFICA group, which includes several of the Global Carbon Data Management and Synthesis Project PIs collected and assessed the quality of approximately 250 new cruises not previously available to the public. The effort was 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. Feely and Sabine are regional leaders in the QC process. The PACIFICA data is stored at CDIAC and the final release occurred in 2013. This data is now being included in the more extensive 2nd Global Ocean Data Analysis Project (GLODAP-2) (Key et al., 2004).

An important component of the Global Carbon Data Management and Synthesis Project is the analysis of decadal changes in ocean carbon storage (Wallace, 2001; Sabine and Tanhua et al., 2010). These analyses are initially conducted along specific lines occupied as part of the CLIVAR/CO₂ Repeat Hydrography program. In FY13, new analyses were done using data from three occupations of the P2 Line in the Pacific (Figure 9) and I9N/18S Line in the Indian Ocean (Figure 10).

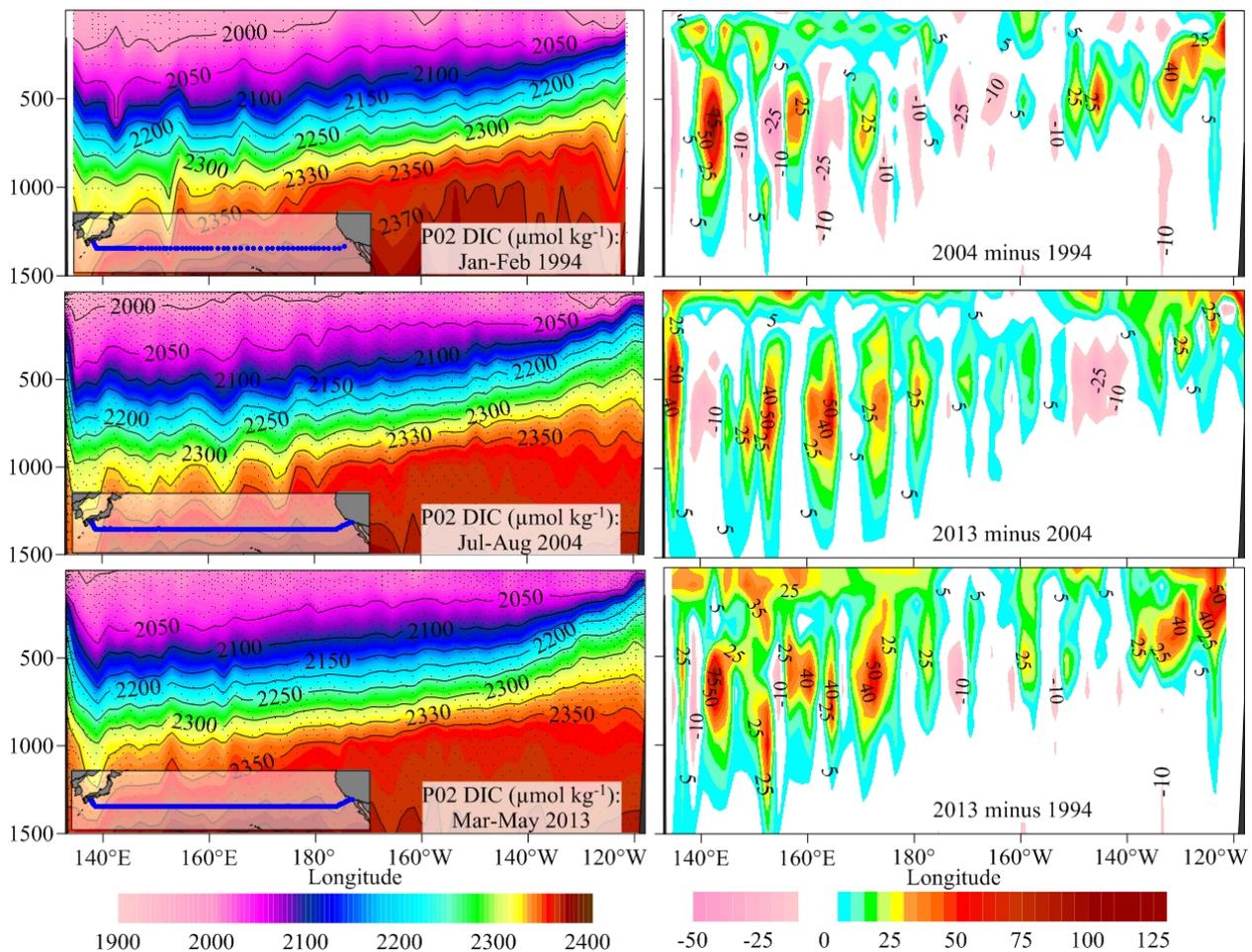


Figure 9. Cross-section of discrete DIC data ($\mu\text{moles kg}^{-1}$) from the P2 line taken in 1994, 2004, and 2013. The panels in the column on the right show the differences in DIC concentrations between the occupations.

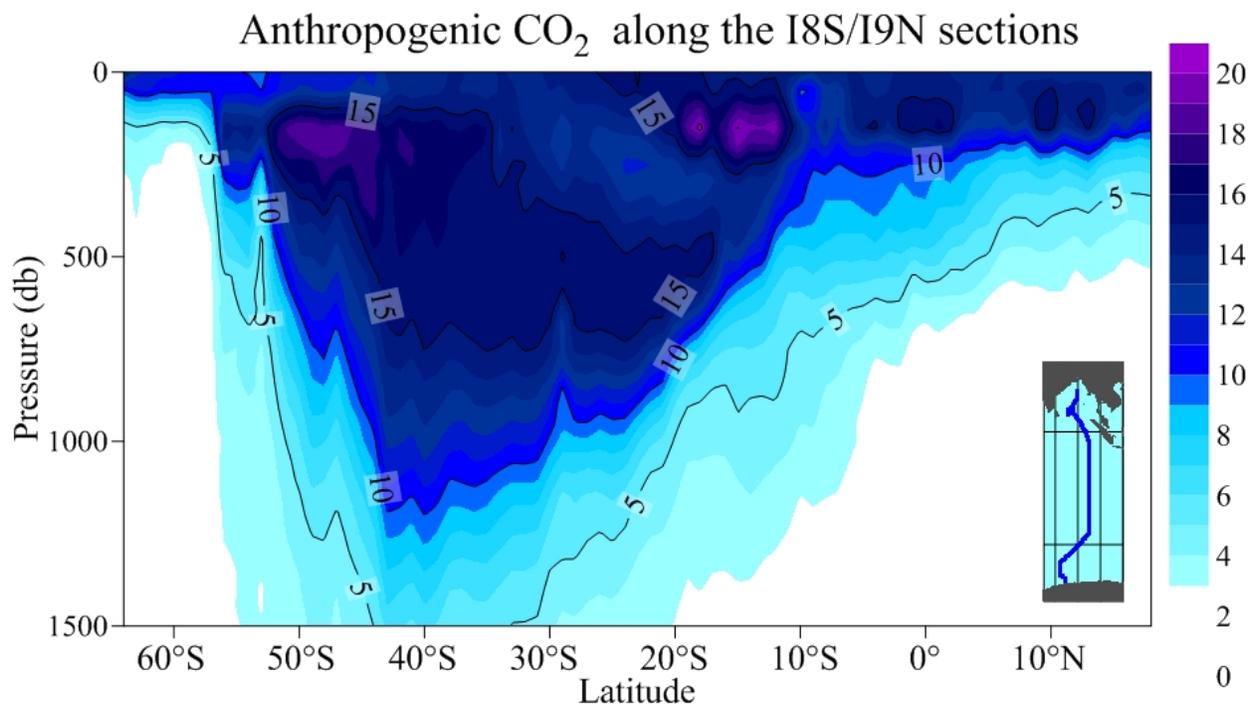


Figure 10. Cross-section of calculated anthropogenic CO₂ values (μmoles kg⁻¹) in the Indian Ocean basin from occupations of the I8S/I89 transects in 1995 and 2007.

The analyses of both basins show that the changes in DIC are being driven by air-sea exchange at the surface, but also by ventilation at depth. The high DIC values shown in the right hand column of **Figure 9** between 500 and 1000 m, particularly in the western Pacific are a result of deep ventilation in these areas. The accumulation of DIC in surface waters is much more pronounced between the 2004 and 2013 occupations due to increasing levels of CO₂ in the atmosphere during that decade. Over the 20 year span of data observations DIC accumulation in the upper 500 m ranged from <10 μmoles kg⁻¹ in the central Pacific to >35 μmoles kg⁻¹ in the eastern and western regions.

In the Indian Ocean, an analysis of DIC concentrations between 1995 and 2007 showed that anthropogenic CO₂ has penetrated to ~1500 m, with the highest concentrations exceeding 15 μmoles kg⁻¹, particularly between 30 and 40° S. This work is being fully described in an upcoming publication on the Indian Ocean (Mathis et al., in prep.).

Ocean Interior Carbon in the Regional Carbon Cycle Assessment and Processes (RECCAP)
RECCAP is an international activity coordinated through the Global Carbon Project (GCP)⁶ with the goal of producing global and regional assessments of the sources and sinks of CO₂. 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 (Feely, Wanninkhof, Kozyr,

⁶ www.globalcarbonproject.org/reccap/

Mathis) 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).

Ocean Acidification

The uptake of anthropogenic CO₂ 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 CO₂ survey, the CLIVAR/CO₂ Repeat Hydrography Program in the Indian Ocean (**Figure 10**), we have observed that the saturation horizon for both aragonite and calcite is shoaling on an order of magnitude of $2.3 \pm 1.2 \text{ m yr}^{-1}$ north of the equator and $3.4 \pm 1.8 \text{ m yr}^{-1}$ south of the equator. In the decade spanning 1995 to 2007 the saturation state for aragonite decreased by more than 0.15 in the upper 200 m between 10 and 20° S. The upward migrations of the aragonite and calcite saturation horizons are the direct result of the uptake of anthropogenic CO₂ by the oceans (Feely et al., 2012) and regional changes in circulation and biogeochemical processes (Mathis et al., in prep). The shoaling of the saturation horizon is regionally variable, with more rapid shoaling in the Southern Indian Ocean where there is a larger uptake of anthropogenic CO₂ (**Figure 10**). If CO₂ 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 Indian Ocean 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. Additional synthesis efforts for each basin (Pacific, Atlantic and Indian) are currently underway, with an integrated global synthesis of all three ocean basins planned for FY14.

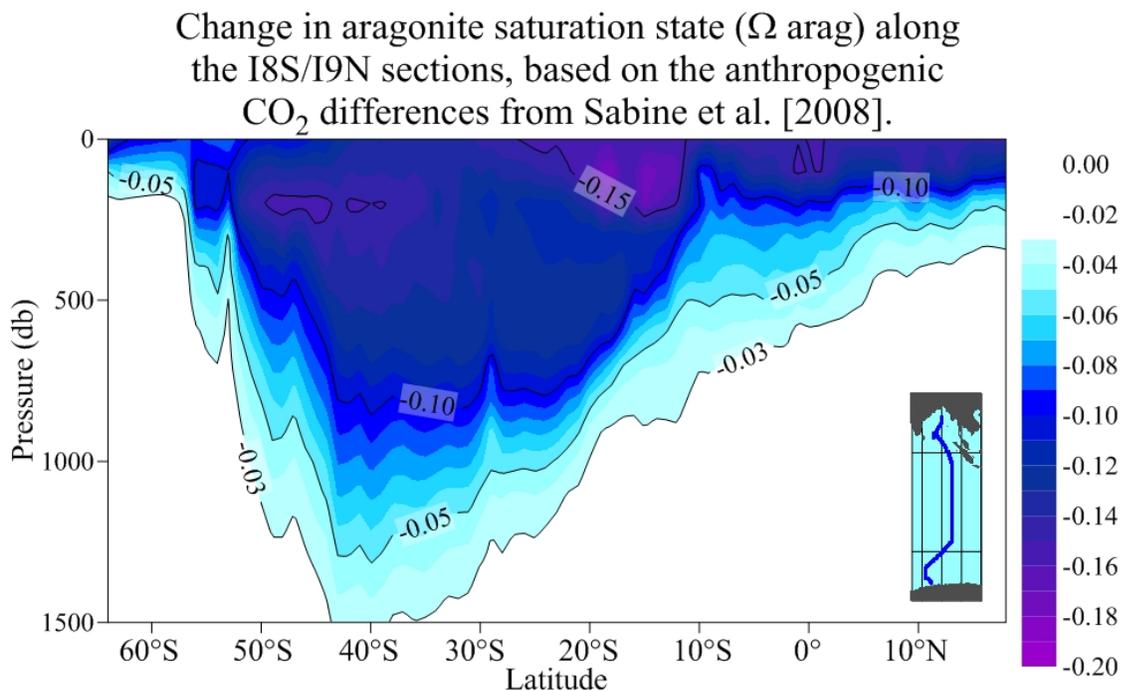


Figure 11. Calculated changes in aragonite saturation states (Ω) in the Indian Ocean basin from occupations of the I8S/I89 transects in 1995 and 2007.

2.3 References

- Atlas, R., Hoffman, R.N., Ardizzone, J., Leidner, S.M., Jusem, J.C., Smith, D.K., Gombos, D., 2011. A cross-calibrated multiplatform ocean surface wind velocity product for meteorological and oceanographic applications. *Bull. Amer. Meteor. Soc.* 92, 157-174.
- Bakker, D.C.E., Pfeil, B., Olsen, A., Sabine, C., Metzl, N., Hankin, S., Koyuk, H., Kozyr, A., Malczyk, J., Manke, A and Telszewski, M. (2012) Global synthesis products for assessing changes in the ocean carbon sink. *EOS, TRANSACTIONS AMERICAN GEOPHYSICAL UNION, VOL. 93, NO. 12, PAGE 125, 2012*
doi:10.1029/2012EO120001
- Bakker, D.C.E., B. Pfeil, K. Smith, S. Hankin, A. Olsen, S.R. Alin, C. Cosca, S. Harasawa, A. Kozyr, K.M. O'Brien, U. Schuster, M. Telszewski, B. Tilbrook, C. Wada, J. Akl, L. Barbero, N. Bates, J. Boutin, W.-J. Cai, R.D. Castle, F.P. Chavez, L. Chen, M. Chierici, K. Currie, H.J.W. de Baar, W. Evans, R.A. Feely, A. Fransson, Z. Gao, B. Hales, N. Hardman-Mountford, M. Hoppema, W.-J. Huang, C.W. Hunt, B. Huss, T. Ichikawa, T. Johannessen, E.M. Jones, S.D. Jones, S. Jutterström, V. Kitidis, A. Körtzinger, P. Landschützer, S.K. Lauvset, N. Lefèvre, A.B. Manke, J.T. Mathis, L. Merlivat, N. Metzl, A. Murata, T. Newberger, T. Ono, G.-H. Park, K. Paterson, D. Pierrot, A.F. Ríos, C.L. Sabine, S. Saito, J. Salisbury, V.V.S.S. Sarma, R. Schlitzer, R. Sieger, I. Skjelvan, T. Steinhoff, K. Sullivan, H. Sun, A.J. Sutton, T. Suzuki, C. Sweeney, T. Takahashi, J. Tjiputra, N. Tsurushima, S.M.A.C. van Heuven, D. Vandemark, P. Vlahos, D.W.R. Wallace, R. Wanninkhof, and A.J. Watson (2013): An update to the surface ocean CO₂ atlas (SOCAT version 2). *Earth Syst. Sci. Data Discuss.*, 6, Discussion paper online, doi: 10.5194/essdd-6-465-2013, 465–512.
- Bates, N.R., 2007. Interannual variability of the oceanic CO₂ sink in the subtropical gyre of the North Atlantic Ocean over the last 2 decades. *J. Geophys. Res.-Oceans*, 112(C9).
- Bates, N.R. and Peters, A.J., 2007. The contribution of atmospheric acid deposition to ocean acidification in the subtropical North Atlantic Ocean. *Mar. Chem.*, 107(4): 547-558.
- Caldeira, K. and Wickett, M.E., 2003. Anthropogenic carbon and ocean pH. *Nature*, 425(6956): 365-365.
- Caldeira, K. and Wickett, M.E., 2005. Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. *J. Geophys. Res.-Oceans*, 110(C9).
- Canadell, J. G., P. Ciais, C. Le Quere, S. Luysaert, R. Raupach, and S. Sitch, 2012. REgional Carbon Cycle Assessment and Processes (RECCAP): Methods and Data, Biogeosciences, in preparation.
- Canadell, J. G., C. Le Quere, et al., 2007. "Contributions to accelerating atmospheric CO₂ growth from economic activity, carbon intensity, and efficiency of natural sinks." *Proceedings Of The National Academy Of Sciences Of The United States Of America* 104(47): 18866-18870.
- 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.
- 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.

- Key, R.M. et al., 2004. A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP). *Global Biogeochemical Cycles*, 18(4).
- Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S.C., Graven, H.D., Gruber, N., McKinley, G.A., Murata, A., Ríos, A.F., Sabine, C.L., Sarmiento, J.L., 2012. Global ocean storage of anthropogenic carbon. *Biogeosciences Discuss.* 9, 8931-8988.
- Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S. C., Graven, H. D., Gruber, N., McKinley, G. A., Murata, A., Ríos, A. F., Sabine, C. L., and Sarmiento, J. L.: Global ocean storage of anthropogenic carbon, *Biogeosciences Discuss.*, 9, 8931-8988, doi:10.5194/bgd-9-8931-2012, 2012.
- Le Quéré, C., et al., 2009. Trends in the sources and sinks carbon dioxide. *Nat. Geosci* 2, 831-836, doi:810.1038/ngeo1689.
- Olafsson, J., Olafsdottir, S.R., Benoit-Cattin, A., Danielsen, M., Arnarson, T.S., Takahashi, T., 2009. Rate of Iceland Sea acidification from time series measurements. *Biogeosciences* 6, 2661-2668, www.biogeosciences.net/2666/2661/2009/.
- Park, G.-H., Wanninkhof, R., 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.
- Park, G.-H., Wanninkhof, R., Doney, S. C., Takahashi, T., Lee, K., Feely, R. A., Sabine, C., Triñanes, J., and Lima, I., 2010a. Variability of global net sea-air CO₂ fluxes over the last three decades using empirical relationships. *Tellus*, 62B: 352-368.
- Park, G.-H., Wanninkhof, R., Trinanes, J., 2010b. Procedures to Create Near Real-Time Seasonal Air-Sea CO₂ Flux Maps, Atlantic Oceanographic and Meteorological Laboratory NOAA Technical Memorandum-98, OAR AOML , Miami, p. 21.
- Pfeil, B., Olsen, A., Bakker, D. C. E., Hankin, S., Koyuk, H., Kozyr, A., Malczyk, J., Manke, A., Metzl, N., Sabine, C. L., Akl, J., Alin, S. R., Bellerby, R. G. J., Borges, A., Boutin, J., Brown, P. J., Cai, W.-J., Chavez, F. P., Chen, A., Cosca, C., Fassbender, A. J., Feely, R. A., González-Dávila, M., Goyet, C., Hardman-Mountford, N., Heinze, C., Hood, M., Hoppema, M., Hunt, C. W., Hydes, D., Ishii, M., Johannessen, T., Jones, S. D., Key, R. M., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lourantou, A., Merlivat, L., Midorikawa, T., Mintrop, L., Miyazaki, C., Murata, A., Nakadate, A., Nakano, Y., Nakaoka, S., Nojiri, Y., Omar, A. M., Padin, X. A., Park, G.-H., Paterson, K., Perez, F. F., Pierrot, D., Poisson, A., Ríos, A. F., Santana-Casiano, J. M., Salisbury, J., Sarma, V. V. S. S., Schlitzer, R., Schneider, B., Schuster, U., Sieger, R., Skjelvan, I., Steinhoff, T., Suzuki, T., Takahashi, T., Tedesco, K., Telszewski, M., Thomas, H., Tilbrook, B., Tjiputra, J., Vandemark, D., Veness, T., Wanninkhof, R., Watson, A. J., Weiss, R., Wong, C. S., and Yoshikawa-Inoue, H.: 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., Neil, C., Sullivan, K., Castle, R., Wanninkhof, R., Lueger, H., Johannson, T., Olsen, A., Feely, R.A., Cosca, C.E., 2009. Recommendations for autonomous underway pCO₂ measuring systems and data reduction routines. *Deep -Sea Res II* 56, 512-522.
- Prentice, I.C. et al., 2001. The carbon cycle and atmospheric CO₂. 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.
- 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.
- Sabine, C.L., and T. Tanhua, 2010. Estimation of anthropogenic CO₂ inventories in the ocean. *Annu. Rev. Mar. Sci.*, 2: 175–198.
- Sabine, C. L., Hankin, S., Koyuk, H., Bakker, D. C. E., Pfeil, B., Olsen, A., Metzl, N., Kozyr, A., Fassbender, A., Manke, A., Malczyk, J., Akl, J., Alin, S. R., Bellerby, R. G. J., Borges, A., Boutin, J., Brown, P. J., Cai, W.-J., Chavez, F. P., Chen, A., Cosca, C., Feely, R. A., González-Dávila, M., Goyet, C., Hardman-Mountford, N., Heinze, C., Hoppema, M., Hunt, C. W., Hydes, D., Ishii, M., Johannessen, T., Key, R. M., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lourantou, A., Merlivat, L., Midorikawa, T., Mintrop, L., Miyazaki, C., Murata, A., Nakadate, A., Nakano, Y., Nakaoka, S., Nojiri, Y., Omar, A. M., Padin, X. A., Park, G.-H., Paterson, K., Perez, F. F., Pierrot, D., Poisson, A., Ríos, A. F., Salisbury, J., Santana-Casiano, J. M., Sarma, V. V. S. S., Schlitzer, R., Schneider, B., Schuster, U., Sieger, R., Skjelvan, I., Steinhoff, T., Suzuki, T., Takahashi, T., Tedesco, K., Telszewski, M., Thomas, H., Tilbrook, B., Vandemark, D., Veness, T., Watson, A. J., Weiss, R., Wong, C. S., and Yoshikawa-Inoue, H., 2012. Surface Ocean CO₂ Atlas (SOCAT) gridded data products, *Earth Syst. Sci. Data Discuss.*, 5, 781-804, doi:10.5194/essdd-5-781-2012.
- Santana-Casiano, J.M., Gonzalez-Davila, M., Rueda, M.J., Llinas, O. and Gonzalez-Davila, E.F., 2007. The interannual variability of oceanic CO₂ parameters in the northeast Atlantic subtropical gyre at the ESTOC site. *Glob. Biogeochem. Cyc.*, 21(1).
- Schuster, U., McKinley, G., Bates, N., Chevalier, F., Doney, S.C., Fay, A.R., Gonzalez-Davila, M., Gruber, N., Jones, S., Landschützer, P., Lefevre, N., Manizza, M., Mathis, J.T., Metzl, N., Olsen, A., Santana-Casiano, J.M., Takahashi, T., Wanninkhof, R., Watson, A., 2012. Atlantic and Arctic Sea-air CO₂ fluxes, 1990-2009. *Biogeosciences Discuss.* 9, 10669-10724.
- 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., et al. 2009. Climatological mean and decadal change in surface ocean pCO₂, and net sea-air CO₂ flux over the global oceans. *Deep-Sea Res. II*, 56(8–10), 554–577.
- Wallace, D.W.R., 2001. Storage and transport of excess CO₂ in the oceans: The JGOFS/WOCE Global CO₂ 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., et al., 2012a. Global ocean carbon uptake: Magnitude, variability, and trends, *Biogeosciences Discuss.*, 9, 10961-11012.
- Wanninkhof, R., G.-H. Park, T. Takahashi, R. A. Feely, J. L. Bullister, and S. C. Doney, 2012b, Changes in deep-water CO₂ concentrations over the last several decades determined from discrete pCO₂ measurements, *Deep -Sea Res I.*, submitted.
- Wanninkhof, R., Park, G.-H., Takahashi, T., Feely, R. A., Bullister, J. L., and Doney, S. C.: Changes in deep-water CO₂ concentrations over the last several decades determined from discrete pCO₂ measurements, *Deep -Sea Res I.*, 74, 48-63, <http://dx.doi.org/10.1016/j.dsr.2012.12.005>, 2013c.

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 pCO₂ 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.
- Feely, R.A., R. Wanninkhof, C.L. Sabine, J.T. Mathis, T. Takahashi, S. Khatiwala, and G.-H. Park (2013): Global ocean carbon cycle. In *State of the Climate in 2012, Global Oceans*. View full report online, *Bull. Am. Meteorol. Soc.*, 94(8), S72–S75.
- Mathis, J.T., R.A. Feely, S.R. Alin, C.L. Sabine, Cross, J.N., and D. Greeley (2014): Decadal changes in carbon dioxide and carbonate mineral saturation states in the Indian Ocean. *Global Biogeochem. Cycles*. [In preparation]
- Sabine, C.L., and T. Tanhua, 2010. Estimation of anthropogenic CO₂ inventories in the ocean. *Annu. Rev. Mar. Sci.*, 2: 175–198.
- Sabine, C.L., Feely, R.A., Wanninkhof, R., Takahashi, T., Khatiwala, S., Park, G.-H., 2011. Global oceans: The global ocean carbon cycle. In: Blunden, J., Arndt, D.S., Baringer, M.O. (Eds.), *In State of the Climate in 2010, Bulletin of the American Meteorological Society*, pp. 92(96):S100-S105), doi:110.1175/1520-0477-1192.1176.S1171.
- Sabine, C. L., Hankin, S., Koyuk, H., Bakker, D. C. E., Pfeil, B., Olsen, A., Metzl, N., Kozyr, A., Fassbender, A., Manke, A., Malczyk, J., Akl, J., Alin, S. R., Bellerby, R. G. J., Borges, A., Boutin, J., Brown, P. J., Cai, W.-J., Chavez, F. P., Chen, A., Cosca, C., Feely, R. A., González-Dávila, M., Goyet, C., Hardman-Mountford, N., Heinze, C., Hoppema, M., Hunt, C. W., Hydes, D., Ishii, M., Johannessen, T., Key, R. M., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lourantou, A., Merlivat, L.,

- Midorikawa, T., Mintrop, L., Miyazaki, C., Murata, A., Nakadate, A., Nakano, Y., Nakaoka, S., Nojiri, Y., Omar, A. M., Padin, X. A., Park, G.-H., Paterson, K., Perez, F. F., Pierrot, D., Poisson, A., Ríos, A. F., Salisbury, J., Santana-Casiano, J. M., Sarma, V. V. S. S., Schlitzer, R., Schneider, B., Schuster, U., Sieger, R., Skjelvan, I., Steinhoff, T., Suzuki, T., Takahashi, T., Tedesco, K., Telszewski, M., Thomas, H., Tilbrook, B., Vandemark, D., Veness, T., Watson, A. J., Weiss, R., Wong, C. S., and Yoshikawa-Inoue, H., 2012. Surface Ocean CO₂ Atlas (SOCAT) gridded data products, *Earth Syst. Sci. Data Discuss.*, 5, 781-804, doi:10.5194/essdd-5-781-2012.
- Sutton, A.J., R.A. Feely, C.L. Sabine, M.J. McPhaden, T. Takahashi, F.P. Chavez, G.E. Friederich, and J.T. Mathis (2013): Natural variability and anthropogenic change in equatorial Pacific surface ocean pCO₂ and pH. *Global Biogeochem. Cycles*. [In revision]
- Wanninkhof, R., et al., 2012a. Global ocean carbon uptake: Magnitude, variability, and trends, *Biogeosciences Discuss.*, 9, 10961-11012.
- Wanninkhof, R., G.-H. Park, T. Takahashi, R. A. Feely, J. L. Bullister, and S. C. Doney, 2012b, Changes in deep-water CO₂ concentrations over the last several decades determined from discrete pCO₂ measurements, *Deep -Sea Res I*, submitted.
- Wanninkhof, R., Doney, S., Bullister, J.L., Levine, N.M., Warner, M.J., Gruber, N., 2010. Detecting anthropogenic CO₂ changes in the interior Atlantic Ocean between 1989 and 2005. *J Geophys. Res.* 115, C11028, doi:10.1029/2010JC006251.
- Wanninkhof, R., Park, G.-H., Chelton, D., Resien, C., 2011. Impact of small-scale variability on air-sea CO₂ fluxes. In: Komori, S., McGillis, W., Kurose, R. (Eds.), *Gas transfer at water surfaces 2010*. Kyoto University Press, Kyoto, pp. 431-444.
- Wanninkhof, R., Park, G.-H., Takahashi, T., Sweeney, C., Feely, R., Nojiri, Y., Gruber, N., Doney, S. C., McKinley, G. A., Lenton, A., Le Quéré, C., Heinze, C., Schwinger, J., Graven, H., and Khatiwala, S.: Global ocean carbon uptake: magnitude, variability and trends, *Biogeosciences*, 10, 1983-2000, doi:10.5194/bg-10-1983-2013, 2013a.
- Wanninkhof, R., Bakker, D., Bates, N., Olsen, A., and Steinhoff, T.: Incorporation of alternative sensors in the SOCAT database and adjustments to dataset quality control flags, *Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee*, 25, 10.3334/CDIAC/OTG.SOCAT_ADQCF, 2013b.
- Wanninkhof, R., Park, G.-H., Takahashi, T., Feely, R. A., Bullister, J. L., and Doney, S. C.: Changes in deep-water CO₂ concentrations over the last several decades determined from discrete pCO₂ measurements, *Deep -Sea Res I*, 74, 48-63, <http://dx.doi.org/10.1016/j.dsr.2012.12.005>, 2013c.

4.2. Publications with PI as co-author

- Canadell, J., P. Ciais, K. Gurney, C. Le Quere, S. Piao, M. Raupach, and C. Sabine, 2011. An international effort to quantify regional carbon fluxes. *Eos Trans. AGU*, 92(10), doi: 10.1029/2011EO100001, 81–82.
- Evans, W., and J.T. Mathis (2013): The Gulf of Alaska coastal ocean as an atmospheric CO₂ sink. *Cont. Shelf Res.*, 65, doi: 10.1016/j.csr.2013.06.013, 52–63.
- Ishii, M., Feely, R. A., Rodgers, K. B., Park, G.-H., Wanninkhof, R., et al. Sea-air CO₂ flux in the Pacific Ocean for the period 1990-2009, *Biogeosciences Discuss.*, 2013.
- Khatiwala, S., T. Tanhua, S. Mikaloff Fletcher, M. Gerber, S.C. Doney, H.D. Graven, N. Gruber,

- G.A. McKinley, A. Murata, A.F. Ríos, and C.L. Sabine (2013): Global ocean storage of anthropogenic carbon. *Biogeosciences*, 10, doi: 10.5194/bg-10-2169-2013, 2169–2191.
- Lee, K., C.L. Sabine, T. Tanhua, T.-W. Kim, R.A. Feely, and H.-C. Kim, 2011. Roles of marginal seas in absorbing and storing fossil fuel CO₂. *Energy Environ. Sci.*, 4(4), doi: 10.1039/C0EE00663G, 1133–1146.
- Lockwood, D., P.D. Quay, M.T. Kavanaugh, L.W. Juranek, and R.A. Feely (2012): High-resolution estimates of net community production and air-sea CO₂ flux in the northeast Pacific. *Global Biogeochem. Cycles*, 26, GB4010, doi: 10.1029/2012GB004380.
- Park, G.-H., Wanninkhof, R., 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.
- Palevsky, H.I., F. Ribalet, J.E. Swalwell, C.E. Cosca, E.D. Cokelet, R.A. Feely, E.V. Ambrust, and P.D. Quay (2013): The influence of net community production and phytoplankton community structure on CO₂ uptake in the Gulf of Alaska. *Global Biogeochem. Cycles*, 27(3), doi: 10.1002/gbc.20058, 664–676.
- Rödenbeck, C., R.F. Keeling, D.C.E. Bakker, N. Metzl, A. Olsen, C. Sabine, and M. Heimann (2013): Global surface-ocean pCO₂ and sea-air CO₂ flux variability from an observation-driven ocean mixed-layer scheme. *Ocean Sci.*, 9, doi: 10.5194/os-9-193-2013, 193–216.
- Schuster, U., McKinley, G., Bates, N., Chevalier, F., Doney, S.C., Fay, A.R., Gonzalez-Davila, M., Gruber, N., Jones, S., Landschutzer, P., Lefevre, N., Manizza, M., Mathis, J.T., Metzl, N., Olsen, A., Santana-Casiano, J.M., Takahashi, T., Wanninkhof, R., Watson, A., 2012. Atlantic and Arctic Sea-air CO₂ fluxes, 1990-2009. *Biogeosciences Discuss.* 9, 10669-10724.
- Schuster, U., McKinley, G. A., Bates, N., Chevalier, F., Doney, S. C., Fay, A. R., Gonzalez-Davila, M., Gruber, N., Jones, S., Krijnen, J., Landschützer, P., Lefevre, N., Manizza, M., Mathis, J. T., Metzl, N., Olsen, A., Rios, A. F., Rödenbeck, C., Santana-Casiano, J. M., Takahashi, T., Wanninkhof, R., and Watson, A. J.: An assessment of the Atlantic and Arctic sea-air CO₂ fluxes, 1990-2009, *Biogeosciences*, 10, 607-627, 10.5194/bg-10-607-2013, 2013.