

Global Carbon Data Management and Synthesis Project

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1. PROJECT SUMMARY

The ocean plays a critical role in the global carbon cycle as it is a vast reservoir of carbon, naturally exchanges carbon with the atmosphere, and consequently takes up a substantial portion of anthropogenically-released carbon from the atmosphere. Although the anthropogenic CO₂ budget for the last two decades, i.e. the 1980s and 1990s, has been investigated in detail (Prentice et al., 2001), the estimates of the oceanic sink were not based on direct measurements of changes in the oceanic inorganic carbon.

Recognizing the need to constrain the oceanic uptake, transport, and storage of anthropogenic CO₂ for the anthropocene and to provide a baseline for future estimates of oceanic CO₂ uptake, two international ocean research programs, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS), jointly conducted a comprehensive survey of inorganic carbon distributions in the global ocean in the 1990s (Wallace, 2001). After completion of the US field program in 1998, a five year effort – the Global Ocean Data Analysis Project (GLODAP) - was begun to compile and rigorously quality control the US and international data sets including a few pre-WOCE data sets in regions that were data limited (Key et al., 2004). Although these data have improved our understanding of the spatial distributions of natural and anthropogenic carbon in the ocean, they have yet to be fully exploited to examine the mechanistic controls on these carbon distributions or to understand the temporal patterns of variability.

Most of the approaches used to estimate anthropogenic CO₂ in the oceans are based on assumptions of steady state circulation and constant biology. It is becoming increasingly apparent that these assumptions may not hold especially in a time of global climate change. The most important component of an assessment of ocean biogeochemical change, whether of natural or anthropogenic origin, is high-quality observations. The WOCE/JGOFS data set provides an important point of reference for ocean carbon studies. Many other useful data sets have not been analyzed in such a context, however because there has not been a coordinated effort to bring these data together and no data management system to make navigation and exploitation of these data convenient.

The NOAA Office of Climate Observation's 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). 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.

Recognizing the need for proper data management and synthesis, NOAA's Office of Climate Observations (OCO) has funded several projects to manage and perform an initial interpretation of the data collected from the Carbon Network. In FY07 several of these projects were merged into one

management and synthesis project. The goal of the Global Carbon Data Management and Synthesis Project is to work together with the OCO carbon measurement projects 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, information technology experts and data managers to ensure the most efficient and productive processing possible for the OCO carbon observations.

2. BACKGROUND

Although ocean carbon uptake and storage plays a critical role in influencing global climate change, the community involved in studying ocean carbon is not as large nor is it as geared towards operational activities as the climate and physical oceanographic communities. There are no operational data centers ready to take the basic carbon observations and turn them into products like the climate forecasts or reanalysis products. As a consequence, the ocean carbon community is expected to provide the public with advanced analysis products, like global CO₂ flux maps or maps of the patterns of CO₂ uptake and storage, in addition to the basic observations. The generation of these products is the objective of this project, but it is a somewhat complicated process because it involves several data manipulation steps and coordination with many other investigators. For this report we divide the process into three categories: measurement coordination and initial quality control, data management and contextual quality control, then synthesis and interpretation.

The number of observations needed to address a global issue like ocean carbon uptake and storage is well beyond the capabilities of one lab or even one country. Thus, there are many laboratories from several countries involved in the assessment of global carbon distributions. To produce the greatest return on the US investment in ocean carbon measurements, we must ensure that all of the US laboratories are using consistent cutting-edge techniques, are assessing and documenting the data quality, and are coordinating the US measurements with the international programs so that once the data are combined we get the most extensive coverage possible. This is the measurement coordination and initial quality control portion of this project. Once the data are collected and the initial data quality has been documented, then the data must be pulled into a data management system that brings the individual laboratory data sets together into a common data base. At this point the data sets are large enough that it is awkward to manipulate without a data visualization program. Once the data set is assembled, the internal consistency of the data relative to any crossing or historical data must be checked. This is the data management and contextual quality control portion of the project. The final step in the process is taking the data set and examining it to understand how the current carbon distributions have changed and the mechanisms responsible for the observed changes. This last step is an evolving set of analyses that is continually improved and adapted as additional data are added to the data set. Each of these three steps is related and often requires iterative refinements of the previous steps to develop the final products leading to improved estimates of ocean uptake and storage.

The OCO 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 Global Carbon Data Management and Synthesis Project addresses both observation types. 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 for these two data types is discussed separately. The activities and accomplishments for both data types in FY08 are discussed below.

3. ACCOMPLISHMENTS

The work conducted as part of this project is intimately connected with the carbon measurement projects funded by the OCO as separate efforts. The details of these measurement projects are described in the measurement project reports and are not repeated here except minimally as necessary to place the data management and synthesis efforts in context. The funds received for Global Carbon Data Management and Synthesis Project are instrumental in providing quality controlled data to the scientific community at large; for promoting and allowing the global synthesis and interpretation of national and international surface and water column carbon data; and integration of the carbon program elements within the NOAA Climate Observation Program.

3.1. Measurement Coordination and Initial Quality Control

a) Repeat Hydrography

Sabine (PMEL) and Dickson (Scripps) were editors on a revised Guide to best practices for ocean CO₂ measurements that was published in February 2008 and made available from CDIAC in both electronic and hardcopy versions (Dickson et al., 2008). This is a detailed guide for researchers making carbon measurements in the field that will hopefully standardize the methods being used and improve data quality.

The Princeton CLIVAR data synthesis activities were described in detail in the interim report submitted by Key a few months ago and significantly more information is contained in the NOAA PI progress reports. Princeton activities are limited to checking quality control flags and checking the data against existing data for systematic bias. This work is now routine. Once final data are submitted to CDIAC, the final data checks by CDIAC and/or Princeton are completed quickly, generally less than a week, and the data are submitted to CLIVAR Carbon Hydrographic Data Office (CCHDO) for merge with other data. In spite of receiving high priority, the CCHDO merge/posting is the rate limiting step in final data release. Key is also working closely with A. Kozyr at CDIAC to add additional cruises to the CLIVAR collection. These are repeat sections funded by different means, but have valuable data for “CLIVAR-type” science. The OVIDE, FICARAM and OISO studies (European work) have already been added to the CDIAC CLIVAR collection and the CARINA data will provide additional sections.

Over the last fiscal year CDIAC has received and processed the data from seven CLIVAR/CO₂ Repeat Hydrography cruises [A20_2003 (TALK), P02_2004 (TALK), P16S_2005 (TALK), P16N_2006, I09N_2007, I08S_2007, I06S_2008 (only underway), and P18_2007 (TALK and DOC only)]. The data have gone through routine QA-QC procedures and have been placed online on the CDIAC Repeat Hydrography web page: http://cdiac.ornl.gov/oceans/RepeatSections/repeat_map.html.

CDIAC compiled information from R. A. Feely, C. L. Sabine, F. J. Millero, A. G. Dickson, R. A. Fine, C. A. Carlson, J. Toole, T. M. Joyce, W. M. Smethie, A. P. McNichol, and R. M. Key to produce a numeric data package (NDP-089) describing the A20/A22 cruises (Feely et al., 2008).

Two CLIVAR/CO₂ Repeat hydrography cruises were run during FY08. The P18 cruise departed San Diego on 15 December 2007 and arrived in Punta Arenas on 23 February 2008 onboard the NOAA Ship *Ronald H. Brown*. The Miami and PMEL groups were responsible for the alkalinity and DIC

measurements, respectively. Millero has made a preliminary evaluation of the P18 alkalinity data and a University of Miami Technical Report has been published: Global Ocean Repeat Hydrography Study: pH and Total Alkalinity Measurements in the Pacific Ocean P18 15th December 2007-18/21 January 2008-23 February 2008 (Millero et al. 2008a). The PMEL carbon group conducted the initial quality control of the P18 DIC data while on the ship using property plots: DIC-depth, DIC-potential temperature, DIC-salinity and DIC-LAT-depth contour plots were used to analyze the quality of the data (Figure 1). The difference plot indicates DIC anomalies ranging from 5-55 $\mu\text{mol/kg}$ in the upper 1000 m of the water column. These anomalies are due to uptake of anthropogenic CO_2 , changes in mixing and ventilation of the water masses, and changes in biogeochemical processes. We will continue to evaluate the relative contributions of each process to the total change in DIC over the 14-year interval once the data are finalized.

Cruise I06S on UNOLS vessel *Roger Revelle* departed Durban, South Africa on February 4, 2008 entering the southward-flowing Agulhas Current and traveled due south along a transect coinciding with Longitude 30 °E into the Antarctic Circumpolar Current down to the ice edge at 70 °S returning to Cape Town, South Africa on March 16, 2008. The Scripps and AOML groups were responsible for the alkalinity and DIC measurements, respectively. All of the data are still undergoing initial quality checks, but an initial examination of the carbon data has indicated very high DIC values in the shallow thermocline of the Southern Ocean south of 55°S. The penetration of North Atlantic Deep Water from the north at a depth of 2000-3500 m has lower DIC values. This difference is attributed to better ventilation of the North Atlantic water mass compared to the older waters of Antarctic origin.

Over the past year Dr. Andrew Dickson (Scripps) finalized outstanding alkalinity data for earlier CLIVAR cruises: A20, P02, P16S. The quality-controlled data from these cruises has been submitted to CDIAC along with the appropriate reports for use in the associated NDP. One of these NDPs has now been published (Feely *et al.*, 2008), the others are still in process. In addition, Dickson has been working on the alkalinity data from the two remaining Indian Ocean cruises: I08S (2007) and I06S (2008) with two students: Emily Bockmon (a new student at SIO) on I08S, and J. Adam Radich on I06S (a participant in that cruise). The I06S data are almost final – they had been waiting for final salinity data that they now have – and will be submitted to CDIAC within a week or so. They will submit the final alkalinity data from I08S by the end of November 2008.

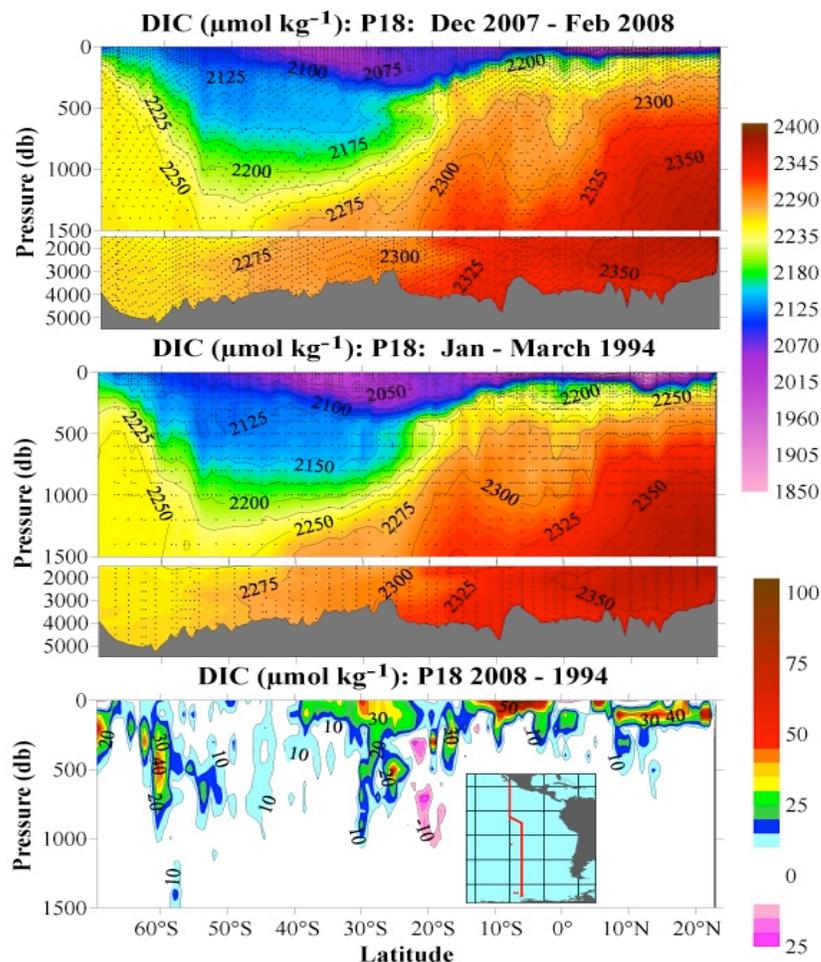


Figure 1. DIC in $\mu\text{mol kg}^{-1}$ along the P18 section in the Pacific Ocean along 110-103 °W. The gridded difference plot is shown on the bottom panel for the fourteen year time difference between the cruises. The increases in DIC are the result of a combination of processes including anthropogenic CO_2 invasion and changes in circulation and biogeochemistry.

b) Surface CO_2

To conform to internationally agreed standards for the reporting of surface CO_2 data, the substantial AOML data holdings were recalculated based on the procedures outlined in Pierrot et al. (2008) and collated into yearly files. Metadata was updated to conform to the recommended format as put forth by CDIAC. Four year's worth of data from the *Explorer of the Seas* were processed and five years of data from the *Ronald H. Brown*. The 2003-2007 data from the *Skogafoss* that sailed from Norfolk VA to Reykjavik Iceland is being re-analyzed to account for a temperature bias in the sea surface temperature that was determined in part by co-locating 200K data points from the $\frac{1}{4}$ degree daily Reynolds sea surface temperature climatology.

All data from the *Ronald H. Brown* through January 2008 were reduced and posted on the AOML CO_2 website (www.aoml.noaa.gov/ocd/gcc). In addition, data and metadata were posted from the ship of opportunity *Gordon Gunter*, *Explorer of the Seas*, and *Xue Long*. The AOML website was reorganized to include pull down menus per ship and consistent with metadata and file structures.

During the 2008 fiscal year, data from 15 PMEL VOS cruises in the Pacific Ocean were processed and submitted to CDIAC, and data from 2 cruises are in final data processing. All current and previous VOS data files are quality controlled using the data protocol outlined in Pierrot et al. (2008).

During the 2008 fiscal year, new diagnostic software was written at PMEL to automatically process daily underway data files when they arrive via iridium satellite from the NOAA Ships *Ka'imimoana*, *David Starr Jordan*, *McArthur II* and from VOS container ships *OOCL Tianjin*, and *Albert Rickmers* and *Cap Van Diemen*. This software creates diagnostic plots of pCO₂, temperature, salinity, barometric pressure, pumps, water flow and gas flow. The plots are posted on an internal website and are used as a diagnostic tool for data processing and quality control of the underway pCO₂ data.

CDIAC received and processed the data from four Volunteer Observing Ships (VOS) lines: *Ka'imimoana* 2007 Cruises, *C/S Explorer of the Seas* Lines 2003-2007, OISO 6-12 (2006-2007) lines and *R/V Astrolabe Minerve* 28-40 cruises (1996-1999). The data were run through routine QA-QC procedures and placed online on the CDIAC VOS web page: http://cdiac.ornl.gov/oceans/VOS_Program/VOS_home.html.

CDIAC also received and processed data from TAO mooring platforms for 2004-2005. The data were run through routine QA-QC procedure and placed online on the CDIAC Mooring web page: <http://cdiac.ornl.gov/oceans/Moorings/moorings.html>.

CDIAC received and processed the Global Surface pCO₂ (LDEO) Database (Version 1.0). The database consists of more than 3 million measurements of surface water partial pressure of CO₂ obtained over the global oceans during 1968 - 2006 are listed in the Lamont-Doherty Earth Observatory (LDEO) database, which includes open ocean and coastal water measurements. A numeric data package (NDP-88) describes the data set and how it was developed (Takahashi et al., 2007). The data are available at: http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/LDEO_home.html. Alex Kozyr, together with Misha Krassovski developed and opened the Underway Measurement WAVES System that was populated with the LDEO database: <http://cdiac3.ornl.gov/waves/underway/>. The LDEO database is also available in the ODV and LAS format.

3.2. Data Management and Contextual Quality Control

a) Repeat Hydrography

Late last summer Princeton/Key submitted a very detailed report on current and planned activities with respect to this grant. That report also included a bit of background material to provide context for the current activities which have been primarily focused on the development of the CARINA dataset.

Approximately 3.5 years ago the European Union sponsored a large research contract called CARBOOCEAN. The goals of this work are very similar to those of WOCE and CLIVAR and CARBOOCEAN sought and obtained varying degrees of participation and “membership” by U.S. scientists. One requirement of the contract was that funded scientists make all of their historical (older than 2 years) data public. CDIAC was asked to be the primary data distribution center with “CARINA” used as the banner name. As part of the OCO Global Carbon Data Management and Synthesis Project, Bob Key at Princeton became actively involved in collecting and helping with the quality assessment/quality control of these data. Progress with the CARINA collection was steady until an international group of carbon scientists met in Iceland in July 2006. The primary reason for this workshop was to transfer GLODAP experience on secondary QC to the EU scientists. By this time the CARINA cruise list had grown to 89. This was the first CARINA meeting attended by other NOAA science team members (Sabine, Feely, Wanninkhof & Kozyr). Also attending were prominent Japanese ocean carbon scientists. By the end of the meeting the scope of CARINA had grown significantly. Rather than being a pure EU data set focused on the northern North Atlantic, CARINA would be 3 collections: the Arctic and its marginal seas, the Atlantic, and the entire Southern Ocean. Additionally,

the collection would include all US and Japanese data in these 3 regions that had been generated since WOCE. Over the next six months the inflow of new cruise data exploded. The increase was partly due to the expanded scope, but mostly due to the fact that CARBOOCEAN is a contract rather than a grant and has deadlines that are strictly enforced. Including the US data wasn't a problem because these cruises had already been added to the Princeton holdings as part of the funded NOAA science team work. Also, adding the Japanese data was relatively easy because the number of cruises they had in the Southern Ocean was small and the data files were in excellent condition, only needing reformat and primary QC in most cases. One year later when the CARINA group met the cruise total was up to 160+ and this number does not include the US cruises. The final number is around 185 cruises none of which were in GLODAP and very few of which had previously been available to the scientific community. Accumulating high quality data from 185 cruises which had previously been available only to the original PIs is a clear indication that this synthesis effort has been successful beyond any expectation. The inflow of about 100 partial data sets in less than a year also meant that the workload required to complete the processing, do QC, etc. was no longer manageable – in fact it wasn't possible given the CARBOOCEAN deadlines. This became obvious shortly after the Iceland meeting and additional NOAA funding was requested via a new proposal to the GCC program. This proposal was ranked highly and was funded in full. Xiaohua Lin was immediately hired to help with the data processing.

Collection of new data for the CARINA project has now ended. The total number of “cruises” in the collection is 185 and 5 of these are actually compilations of cruises in a specific area. The cruises represent measurements from 1982 through 2006. Where data exist and where possible, salinity, oxygen, nutrients (nitrate, phosphate, silicate), alkalinity, total inorganic carbon and pH have been subjected to secondary quality control (quantification of systematic data bias: 2ndQC). The 2ndQC for this data collection was more complex than for the earlier GLODAP synthesis because the data covered a much longer time interval and many of the cruises were from regions known to have short time scale variability even in deep water. The derived adjustment factors from the 2ndQC are on-line and will be transferred to Princeton shortly. Preliminary versions of the adjustment table have already been used for software development at Princeton.

Recently, Princeton also developed the code to produce data files in EXCHANGE format (used by both CCHDO and CDIAC for web-based data distribution). As expected, this task was difficult, but the output from our code was recently vetted by CCHDO. Since these data distribution centers will not have to do any reformatting, the CARINA cruise data should be available on-line much quicker. Currently, neither CCHDO nor CDIAC has any public data for the Arctic. The CARINA-Arctic cruises will “initialize” the public data for both data centers. We will submit data from all of the CARINA cruises to the data centers by early December.

Both PMEL and AOML investigators from the Global Carbon Data Management and Synthesis Project are involved in the CARINA synthesis effort. Dr. Denis Pierrot (AOML) is a co-lead on the CARINA (Carbon in the North Atlantic) synthesis effort for dissolved inorganic carbon (DIC) in the North Atlantic Ocean which involves checking the data of 104 cruises. The tedious effort involves quality control and assessment of biases based on methods developed during the GLODAP effort (Key et al., 2004). Crossover routines were automated in Matlab, and tested and modified at AOML as part of this effort. The derived offsets are presented in Figure 2. The work will be detailed in a new journal: Earth System Science Data (ESSD) which is an international, interdisciplinary journal for the publication of articles on original research data.

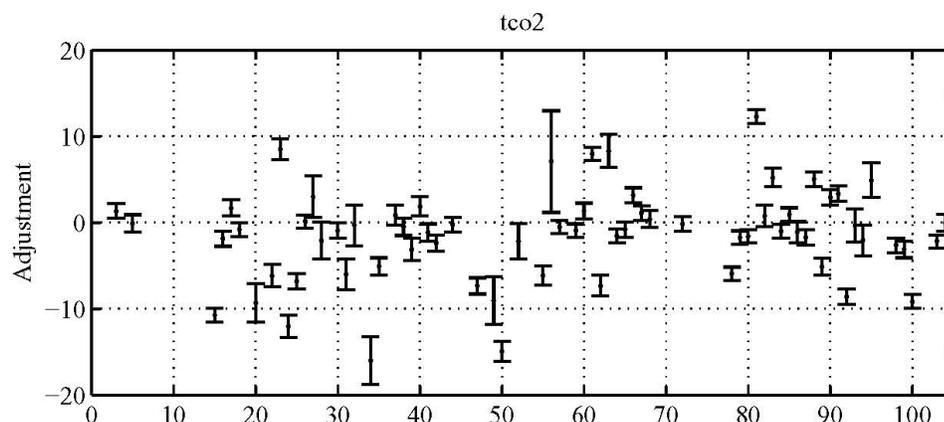


Figure 2. Derived DIC offsets for 104 cruises in the North Atlantic as part of the CARINA project. The Y axis shows the “TCO₂ offset” and the X-axis is an arbitrary sequence number. Offsets of less than 4 $\mu\text{mol kg}^{-1}$ are considered within the uncertainty limit.

Dr. Chris Sabine (PMEL) is a co-lead on the Southern Ocean CARINA sub group. As with the Atlantic group, the Southern Ocean cruises have been examined for data quality and final adjustments have been determined. The synthesis results will be published in a series of articles in ESSD during FY09. Drs. Sabine and Feely are also working with members of the North Pacific Marine Science Organization (PICES) to begin a synthesis effort similar to CARINA for the Pacific. Nearly 200 Pacific cruises that have not been previously released have been identified for the effort.

Brendan Carter, a Scripps graduate student, has been working on a model for Antarctic Intermediate Water Formation based on data from an NSF-supported winter cruise off the coast of Chile (2005). This winter data has allowed him to identify plausible end-members (based on salinity and potential alkalinity) which, when mixed – together with addition or removal of fresh water – comprise Antarctic Intermediate Water (AAIW). He has applied his model to the GLODAP data set for the southern Pacific Ocean, and it appears to adequately represent AAIW over a significant region. He is now using this data to characterize changes in AAIW composition (defined on a particular isopycnal) that occur with time. A draft manuscript has been prepared which he intends to submit to *Global Biogeochemical Cycles* by the end of the year.

The alkalinity data in the GLODAP data set is significantly noisier than that from the 2005 cruise, and from recent CLIVAR cruises: this limits the sensitivity of the end-member analysis. Brendan is now starting to look at the recent CLIVAR data from the Southern Ocean to see the effects of using higher-quality data, and is also extending his analysis into other ocean basins.

b) Surface CO₂

Global Carbon Data Management and Synthesis Project investigators were involved in two surface CO₂ synthesis efforts. First, we have continued to work with Dr. Taro Takahashi (LDEO) in his global CO₂ synthesis. During this past year Dr. Takahashi released the quality controlled data compilation that underlies his latest CO₂ climatology. These data are available from CDIAC. Second, at the “Surface Ocean CO₂ Variability and Vulnerability” (SOCOVV) workshop in April 2007, participants agreed to establish a global surface CO₂ data set that would bring together, in a common format, all publicly available CO₂ data for the surface oceans. This activity, named Surface Ocean Carbon Atlas (SOCAT), has been called for by many international groups for many years, and has now become a priority activity for the marine carbon community. This data set will serve as a foundation

upon which the community will continue to build in the future, based on agreed data and metadata formats and standard 1st level quality-control procedures.

An extended 1st level quality-controlled data set has been developed, building on the work started in 2001 as part of the EU ORFOIS project by Dorothee Bakker (UEA), which now continues as part of the EU CARBOOCEAN project, where Benjamin Pfeil and Are Olsen (Bjerknes Centre for Climate Research) have compiled the publicly-available surface CO₂ data held at CDIAC into a common format database based on the IOCCP recommended formats for metadata and data reporting. The community is in the process of forming regional groups to perform 2nd level quality control checks on the data.

In FY08 PMEL released the Ocean Carbon Data Management System (OCDMS -- <http://ferret.pmel.noaa.gov/OCDMS/>) – an operational Live Access Server (LAS) for the underway LDEO ocean carbon data collection from Taro Takahashi (NDP-88 at CDIAC). The Takahashi collection was selected as the initial target for this service, because at the time of planning the project it was the most complete collection of underway cruises that had been assembled. The tools and techniques developed for the OCDMS are being re-used and extended to support the Surface Ocean Carbon Atlas (SOCAT) effort.

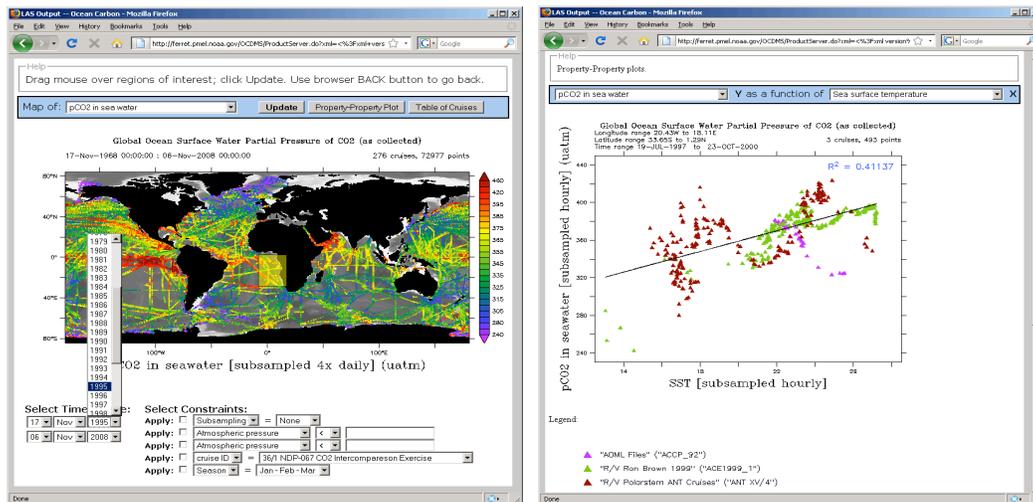


Figure 3. Web access to the Takahashi 2007 underway carbon collection.

The data base schema to accommodate the Takahashi collection was developed by Jon Callahan during FY06-07. In the course of that work hundreds of errors were discovered in the data and reported back to LDEO, ultimately to be incorporated into the official release of NDP-88. In February of 2008 Jon left the TMAP group and Jeremy Malczyk assumed responsibility for the ocean carbon data services. TMAP announced the operational release of the Takahashi OCDMS to the Carbon research community in March 2008. Figures 3a and b are screen snapshots of the server.

The server provides carbon researchers with the ability to select arbitrary regions in space and time; to click-and-drag/zoom into features of interest; to further constrain the selection based upon season, cruise ID, and the values of measured parameters; to examine the relationships between variables as property-property plots that are color-coded by cruise; and to download arbitrary subsets of data. This work was presented at the SOCAT 2nd level QC Technical Workshop in Paris in June 2008 and at the Office of Climate Observations annual review meeting in September 2008 in Silver Spring.

The OCDMS server made it possible for the first time to include historical ocean carbon observations in the OC Observing System Monitoring Center (OSMC) as we see in Figure 4. Due to

limitations in the metadata, the Takahashi collection in the OSMC appears as a single monolithic (virtual) cruise. The correct representation of the ocean carbon observing system will be achievable using the more complete metadata that will become available through the SOCAT collection during FY09.

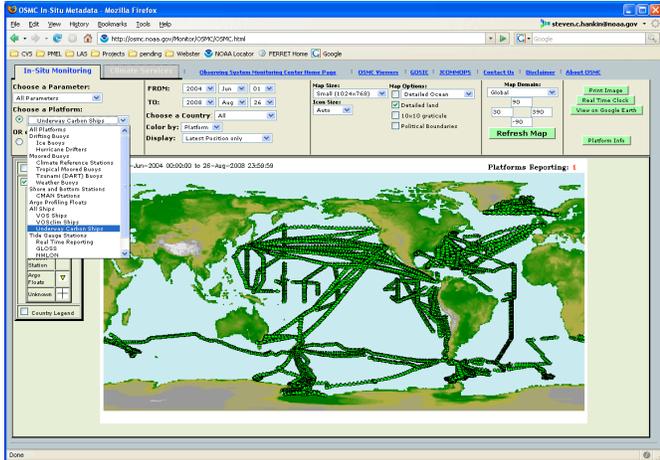


Figure 4. Underway carbon observing system seen through the OSMC.

From the middle of FY08 the focus of carbon data management work shifted to the community-sponsored SOCAT collection. The SOCAT data management effort is a close partnership between PMEL and the Bjerknes Centre for Climate Research, Bergen, Norway (Benjamin Pfeil). The initial SOCAT collection expands the scope of the data from 3.8 million observations in the Takahashi version 1.0 collection to 9.5 million observations expected in the January 2009 version of SOCAT. From the researcher's perspective the data management system appears to be very similar to the OCDMS. The underlying database design, however, has advanced significantly. Figure 5 shows one of the experimental products to emerge from this effort: an on-the-fly calculation produced by the server that shows SOCAT observation anomalies relative to climatology, based upon gridded climatology fields published by Takahashi in 2008. Such capabilities will be part of the system that will be provided to the SOCAT community in FY09 to support secondary quality control of the ocean carbon climate data record.

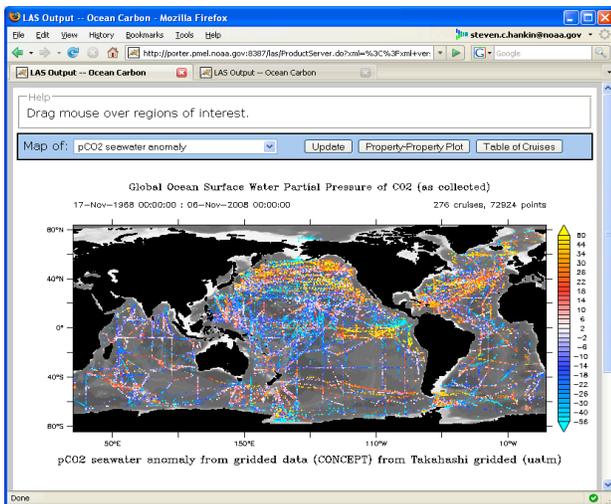


Figure 5. Underway pCO₂ anomalies from climatology generated on-the-fly by LAS.

3.3. Synthesis and Interpretation

a) Repeat Hydrography

Sabine et al. (2008) used the extended multiple linear regression (eMLR) technique to investigate changes over the last decade in DIC inventories on a meridional line (P16 along 152°W) up the central Pacific and on a zonal line (P02 along 30°N) across the North Pacific. Maximum changes in the total DIC concentrations along P02 are 15–20 $\mu\text{mol kg}^{-1}$ over 10 years, somewhat higher than the $\sim 1 \mu\text{mol kg}^{-1} \text{ yr}^{-1}$ increase in DIC expected based on the rate of atmospheric CO_2 increase. The maximum changes of 15–20 $\mu\text{mol kg}^{-1}$ along the P16 line over the 14/15-year time frame fit with the expected magnitude of the anthropogenic signal, but there is a deeper than expected penetration of the signal in the North Pacific compared to the South Pacific. The effect of varying circulation on the total DIC change, based on decadal alterations of the apparent oxygen utilization rate, is estimated to be greater than 10 $\mu\text{mol kg}^{-1}$ in the North Pacific, accounting for as much as 80% of the total DIC change in that region (Figure 6). The average anthropogenic CO_2 inventory increase along 30°N between 1994 and 2004 was 0.43 $\text{mol m}^{-2} \text{ yr}^{-1}$, with much higher inventories in the western Pacific. Along P16, the average Northern Hemisphere increase was 0.25 $\text{mol m}^{-2} \text{ yr}^{-1}$ between 1991/1992 and 2006 compared to an average Southern Hemisphere anthropogenic CO_2 inventory increase between 1991 and 2005 of 0.41 $\text{mol m}^{-2} \text{ yr}^{-1}$.

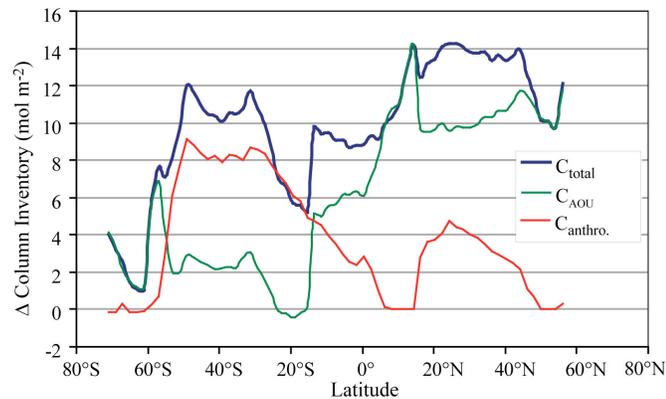


Figure 6. Column inventories of the change in anthropogenic CO_2 (solid black line), circulation carbon changes estimated from AOU (light gray dotted line), and the total DIC change (dark gray dashed line) along the P16 section.

Further analysis was performed on the A16 data by AOML investigators and publications that are in preparation have been revised based on refinements of the multi-linear regression techniques and other approaches to estimate anthropogenic CO_2 . Chanson et al (resubmitted, 2008) showed that the updated TROCA method yields unrealistic anthropogenic CO_2 values when applied to the Atlantic data. Wanninkhof et al. (in preparation, 2008) compared several methods of estimating decadal increases of anthropogenic CO_2 that suggest that on regional scale an extended multi-linear regression along density provides the most consistent estimate based on diagnostics with models and transient tracers.

During the WOCE program, the I08S cruise was carried out from 12/2/1994 (31.5°S, 110.2°E) to 12/28/1994 (63.3°S, 82°E), while I09N cruise was from 1/26/1995 (31.2°S, 106.3°E) to 3/3/1995 (2.7°N, 80°E). This north-south cruise line was re-occupied during the CLIVAR/ CO_2 Repeat Hydrographic program in March-April of 2007. To investigate the temporal changes in DIC from 1994 to 2007 along this cruise line, we have analyzed the data along the isopycnal surfaces. Comparisons of DIC along isopycnal surfaces with sigma-theta of 26.0, 26.2, 26.4, 26.6, 26.8, 27.0, and 27.2 for I09N and I09N/I08S are illustrated in Figures 7a,b. These DIC values are normalized to a salinity of 35 after

correcting for AOU. In Figure 7a, comparisons of $DIC_{n,AOU}$ values from I09N stations between 15°N and 12°S along isopycnal surfaces are shown. The figure shows small DIC increases in the equatorial region where the invasion of CO_2 is inhibited by the upwelling of subsurface water. The comparison of $DIC_{n,AOU}$ values in the temperate region between 12°S and 40°S is shown in Figure 7b. Higher DIC increases in the temperate region are observed as compared with those in equatorial region. The extra DIC has penetrated along isopycnal 27.2 in the temperate region while there is negligible penetration along isopycnal 26.8 in the equatorial region. The areas between two curves with solid and open circles in each isopycnal surfaces are integrated, and the mean changes in DIC are determined. The DIC increases vary for each isopycnal interval, with increases of 4.8 $\mu\text{mol/kg}$ along 26.8, and 7.0 $\mu\text{mol/kg}$ along 26.2 in the equatorial region, while in temperate region they change from 7.8 $\mu\text{mol/kg}$ along 27.2 to 15.2 $\mu\text{mol/kg}$ along 26.4 isopycnal. Using the estimated thickness of isopycnal horizons between 15°N and 12°S, we obtained a mean DIC inventory change of 0.43 $\mu\text{mol/kg/yr}$ in the Equatorial Indian Ocean between 1995 and 2007, which is equivalent to 0.16 $\text{mol/m}^2/\text{yr}$ CO_2 uptake rate. For the temperate Indian Ocean, the DIC increase is much faster. We have seen significant DIC increases along each isopycnal horizon. Based on the estimated thickness of isopycnal layers between 12°S and 40°S, that are much greater than in the equatorial region, the mean DIC inventory change is estimated to be 0.90 $\mu\text{mol/kg}$ from 1995 to 2007, which is equivalent to 0.82 $\text{mol/m}^2/\text{yr}$. The depth of isopycnal surfaces with sigma-theta ranging 26.0 to 26.6 shows that these density surfaces shallow starting from 25°S latitude. A separation of temperate region into subsections for analysis of DIC increase is necessary to improve quantification of DIC temporal increases in the Indian Ocean.

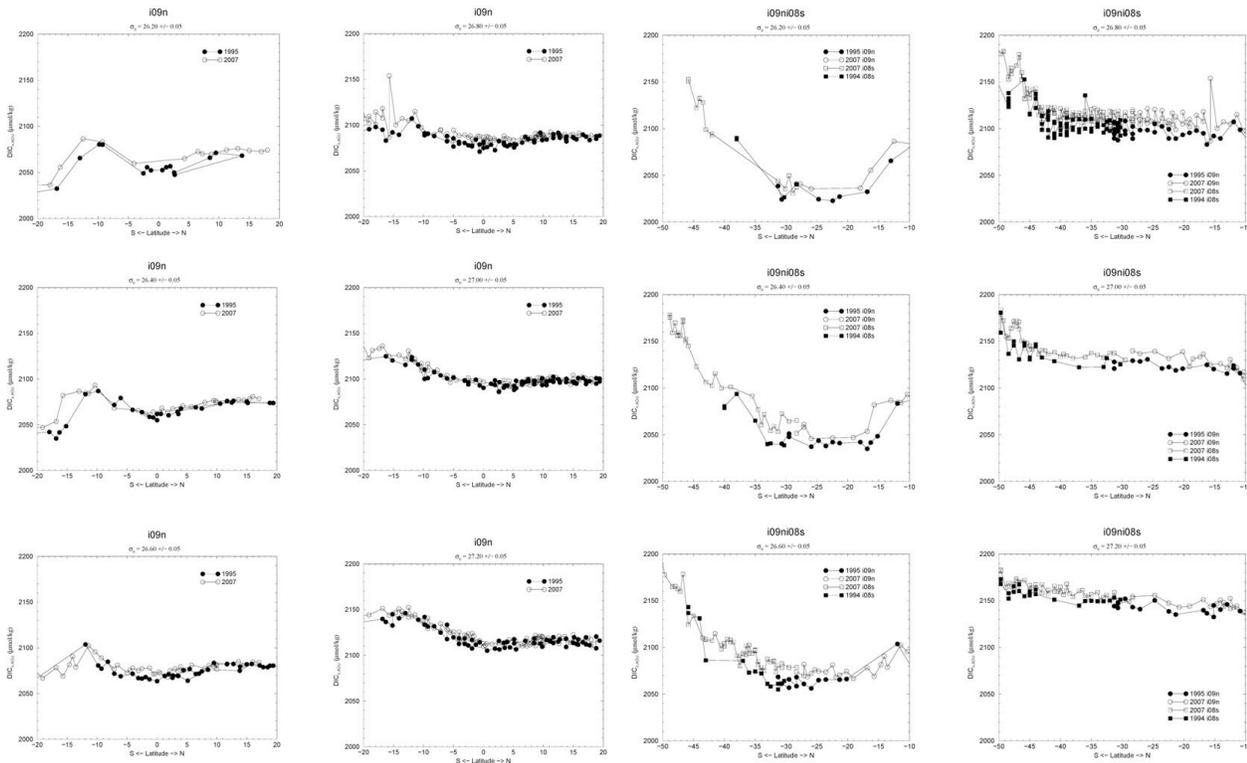


Figure 7. a) Comparison of DIC along isopycnal surfaces in the equatorial Indian Ocean for 1995 and 2007; b) Comparison of DIC along isopycnal surfaces in the temperate Indian Ocean for 1995 and 2007.

Frank Millero made an international presentation based on the repeat hydrography data in June 2008 in Trieste, Italy on the carbon dioxide system in the world oceans. Millero has been a part of two

papers published on the carbonate system this year based on the repeat hydrography data (Millero et al. 2008b; Sabine et al. 2008). Dr. Millero is working on the SCOR WG 127 committee and has published a number of papers on the reference salinity (S_R) of sea water and density methods of determining the absolute salinity of seawater (S_A) (Millero et al. 2008c).

b) Surface CO_2

AOML and PMEL investigators have been involved in the latest update of the Takahashi CO_2 climatology (Takahashi et al., 2008). The climatology gives the mean surface water pCO_2 distribution over the global oceans in non-El Niño conditions with a spatial resolution of 4° (latitude) x 5° (longitude) for a reference year 2000. It is based upon about 3 million measurements of surface water pCO_2 obtained from 1970 to 2006. The database used for this study is about 3 times as large as the 0.94 million used for our earlier paper (Takahashi et al., 2002). The net air-sea CO_2 flux is estimated using the sea-air pCO_2 difference and the air-sea gas transfer rate that is parameterized as a function of (wind speed)² with a scaling factor of 0.24. This is estimated by inverting the bomb ^{14}C data using Ocean General Circulation models and the 1979-2005 NCEP-DOE AMIP-II Reanalysis (R-2) wind speed data.

The equatorial Pacific ($14^\circ N$ - $14^\circ S$) is the major source for atmospheric CO_2 , emitting about $+0.44$ Pg-C yr^{-1} , and the temperate oceans between 14° and 50° in the both hemispheres are the major sink zones with an uptake flux of -0.63 Pg-C yr^{-1} for the northern and -0.91 Pg-C yr^{-1} for the southern zone. The high latitude North Atlantic, including the Nordic Seas and portion of the Arctic Sea, is the most intense CO_2 sink area on the basis of per unit area, with a mean of -2.3×10^6 gram-C $month^{-1} km^{-2}$. This is due to the combination of the low pCO_2 in seawater and high gas exchange rates. In the ice-free zone of the Southern Ocean ($50^\circ S$ - $62^\circ S$), the mean annual flux is small because of a cancellation of the summer uptake CO_2 flux with the winter release of CO_2 caused by deepwater upwelling. The annual mean for the net sea-air CO_2 flux over the global oceans is estimated to be 1.4 ± 0.7 Pg-C yr^{-1} . Taking the pre-industrial steady state ocean source of 0.4 ± 0.2 Pg-C yr^{-1} into account, the total ocean uptake flux including the anthropogenic CO_2 is estimated to be 1.8 ± 0.7 Pg-C yr^{-1} in 2000.

During the past fiscal year, final adjustments were made to the CO_2 climatology. Of particular note in this update is the large effect that the assumptions of increase in surface water pCO_2 have in determining the climatological fluxes. Based on the re-analysis and increased data coverage the global air-sea CO_2 flux was 0.2 Pg C/yr greater than the previous iteration. An error estimate of air-sea CO_2 flux was determined that breaks down the uncertainty in the different parameters in the estimate of the climatological flux. The net climatological global sea-air flux may be subject to random errors of (Takahashi et al., 2008):

± 0.18	Pg-C yr^{-1} ($\pm 13\%$)	from the ΔpCO_2 measurements,
± 0.42	Pg-C yr^{-1} ($\pm 30\%$)	in the scaling factor for the gas transfer velocity parameterization,
± 0.28	Pg-C yr^{-1} ($\pm 20\%$)	in wind speeds
± 0.5	Pg-C yr^{-1} ($\pm 35\%$)	for the mean rate of pCO_2 change in ocean water

The results indicate that the largest source of error in the climatological fluxes is the correction for the rate of change of surface water pCO_2 . This uncertainty will not impact the goal of the NOAA effort to determine the seasonal fluxes as the mean rate of change is measured. However, the uncertainty due to ΔpCO_2 measurements will be significantly greater due to a dearth of observations on such short timescales.

3.4. Ocean Acidification

Hydrographic surveys and modeling studies have revealed that the chemical changes in seawater resulting from the absorption of carbon dioxide are lowering seawater pH. For example, the time series data at Ocean Station Aloha shows an average pH decrease of approximate 0.02 units per decade in the Northeast Pacific (Figure 8; after Feely, 2008). The pH of ocean surface waters has already decreased by about 0.1 units from an average of about 8.21 to 8.10 since the beginning of the industrial revolution. Estimates of future atmospheric and oceanic carbon dioxide concentrations, based on the Intergovernmental Panel on Climate Change (IPCC) CO₂ emission scenarios and coupled ocean-atmosphere models, suggest that by the middle of this century atmospheric carbon dioxide levels could reach more than 500 ppm, and near the end of the century they could be over 800 ppm. This would result in an additional surface water pH decrease of approximately 0.3 pH units by 2100. Ocean acidification may be one of the most significant and far-reaching consequences of the increase of carbon dioxide in the atmosphere. Some call this the “other CO₂ problem” because, like global warming, it is driven by anthropogenic CO₂ (Doney et al., 2008). It is conceivable that the basic food-web structure of the ocean could change over the next 50 years. It is imperative that we rapidly improve our fundamental understanding of the impacts of ocean acidification on ocean chemistry and ocean biology. Because these changes are unprecedented in the modern era, we cannot predict with confidence how marine ecosystems will respond to this stress in the future. This rapidly emerging scientific issue and possible ecological impacts have raised serious concerns across the scientific and fisheries resource management communities. Though this is a global problem (Sabine et al., 2004), the North Pacific (Feely et al., 2004; Feely et al., 2008) has been shown to be one of the ocean regions most sensitive and vulnerable to ocean acidification. There is new evidence that corrosive “acidified” water is upwelling on the continental shelf of western North America (Feely et al., 2008).

The Global Carbon Data Management and Synthesis Project has been providing information directly related to better understanding the effects of ocean acidification. The data base of carbon measurements managed by this project is actively being utilized to initialize models of ocean acidification and Dr. Richard Feely, along with other project PIs, has been actively involved in developing the NOAA strategy for investigating and monitoring ocean acidification and its consequences. We have helped organize and participated in the Ocean Carbon and Biogeochemistry Scoping Workshop on Ocean Acidification at Scripps Institution of Oceanography in October 2007; <http://www.whoi.edu/sbl/liteSite.do?litesiteid=19977> and participated in the 2nd International Symposium on Oceans in a High CO₂ World in Monaco in October 2008; <http://www.highco2world-ii.org/main.cfm?cid=975>. This is an important scientific issue in the ocean community and will likely play a much more prominent role in our interpretation of ocean carbon data in FY09 and beyond.

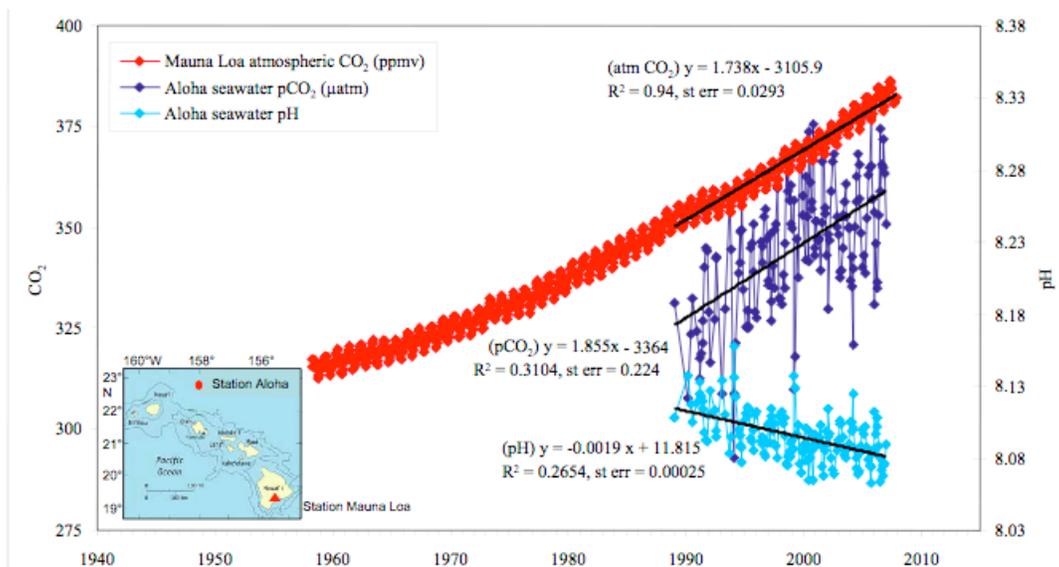


Figure 8. Time series of atmospheric CO₂ at Mauna Loa (ppmv) and surface ocean pH and pCO₂ (µatm) at Ocean Station Aloha in the subtropical North Pacific Ocean. Note that the increase in oceanic CO₂ over the last 17 years is consistent with the atmospheric increase within the statistical limits of the measurements (From Feely, 2008).

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