Global Carbon Data Management and Synthesis Project

Christopher L. Sabine[1], Richard A. Feely[1], Steve Hankin[1], Rik Wanninkhof[2], Tsung-Hung Peng[2], Alex Kozyr[3], Robert Key[4], Frank Millero[5] and Andrew Dickson[6]
[1]NOAA Pacific Marine Environmental Laboratory, Seattle WA
[2]NOAA Atlantic Oceanographic and Meteorological Laboratory, Miami FL
[3]Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge TN
[4]Princeton University, Princeton, NJ
[5]University of Miami, Miami FL
[6]University of California San Diego, Scripps Institution of Oceanography, La Jolla CA

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1. Abstract

The Global Carbon Data Management and Synthesis Project takes the raw data generated by the three primary OCO carbon observing networks (CLIVAR/CO_2 Repeat Hydrography, Underway CO_2, and Moored CO_2) and processes these data into meaningful products that can be used by other researchers and the public. We are also working with the international research community to assemble high-quality ocean carbon data that has not been previously accessible to the public. By developing sophisticated web-based tools, we hope to make these products easy for non-specialists to examine and understand. The data products are focused on two complimentary approaches for studying the role of the oceans in the global carbon cycle: surface ocean carbon changes (ocean carbon uptake) and interior ocean carbon changes (ocean carbon storage). We are also working to understand the impact of the additional carbon stored in the ocean on marine ecosystems (ocean acidification).

2. 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 CO_2 budget for 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 CO_2 for the anthropocene and to provide a baseline for future estimates of oceanic CO_2 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). These data have greatly improved our understanding of the spatial distributions of natural and anthropogenic carbon in the ocean and are being used to examine the mechanistic controls on ocean carbon distributions.

The single snapshot of the ocean provided by the GLODAP data set is not ideal for understanding the temporal patterns of variability in ocean uptake and storage. 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, but many other useful data sets exist or are being collected which have not been analyzed in such a context 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. For example, the NOAA Ocean Climate Observation's Carbon Network (hydrographic sections, underway pCO_2, and CO_2 moorings) is a valuable contribution to the Global Ocean Observing System (GOOS) and Global Climate Observing System (GCOS). 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. Carbon scientists are the primary users of ocean carbon data. We must not only collect the data, but also turn them into meaningful products that decision makers and the public can use to make informed decisions about current and future CO_2 emissions.

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

3. Scientific Accomplishments

The OCO ocean carbon network makes two basic types of observations: surface CO_2 observations (with ships of opportunity and moorings) and water column carbon observations (with repeat hydrography cruises). The surface observations are aimed at understanding the exchange of CO_2 across the air-sea interface (i.e. ocean carbon uptake). 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.

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 FY09 are discussed below.

While the OCO ocean carbon network is primarily aimed at understanding the uptake and storage of ocean carbon, it also provides information on the consequences of that carbon on the chemistry of the oceans. When anthropogenic CO_2 is absorbed by seawater chemical reactions occur that reduce both seawater pH and the concentration of carbonate ions in a process known as “ocean acidification”. The pH of ocean surface waters has already decreased by about 0.1 units since the beginning of the industrial revolution (Caldeira and Wickett, 2003; Caldeira and Wickett, 2005), with a decrease of ~0.0018 yr^{-1} observed over the last quarter century at several open ocean time-series sites (Bates, 2007; Bates and Peters, 2007; Santana-Casiano et al., 2007).

The OCO ocean carbon observations and subsequent synthesis efforts through this project have played a significant role in highlighting to the scientific community and the general public the importance of ocean acidification and its consequences on marine life. The advancements in our understanding in ocean acidification made through this project are discussed in a section 3.3 below.

3.1. Surface Ocean CO_2

The surface ocean component of the Global Carbon Data Management and Synthesis Project involves continued processing of the carbon data generated from the OCO volunteer observing ships and moorings, working with Taro Takahashi (LDEO) to generate updates to his CO_2 flux climatology, developing the algorithms to make seasonal CO_2 flux maps using satellite

observations, and working with the international ocean carbon community on the Surface Ocean CO_2 Atlas (SOCAT) project. Each of these is very briefly discussed below.

Processing of New Data

To conform to internationally agreed standards for the reporting of surface CO_2 data, all of the historical AOML and PMEL CO_2 data were reprocessed last year and resubmitted in the agreed upon format. As part of this effort AOML reanalyzed 4 year's worth of *Skogafoss* data accounting for temperature biases in the intake temperature of the ship, and have created annual files of 4 years of *Explorer of the Seas*, and 3 years of *Ronald Brown* data. The annual files are mutually consistent and have data quality flags and metadata as recommended by the IOCCP. PMEL has also processed and submitted the data from their VOS and mooring instruments. During the 2009 fiscal year, PMEL received daily underway pCO_2 data files via iridium satellite or e-mail from the following ships: *Ka'imimoana, McArthur II, Miller Freeman, RV Revelle, RV Wecoma, RV Thompson, OOCL Tianjin*, and *Cap Van Diemen*. Improvements were made to diagnostic software written to create plots of fCO_2, 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 fCO_2 data. Data processing software has been streamlined and updated. During the time in review, data from 19 cruises were processed and submitted to CDIAC. For more information see the underway carbon and moored CO_2 OCO reports.

Takahashi Climatology

Synthesis Project investigators have been closely involved in the latest update of the Takahashi CO_2 climatology which was published this year (Takahashi et al., 2009). The climatology gives the mean surface water pCO_2 distribution over the global oceans in non-El Nino 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.

CO_2 Flux Maps

A new means of determining seasonal air-sea CO_2 fluxes was developed as part of a NOAA Global Carbon Cycle project, but directly contributes to the OCO surface CO_2 project. The flux map approach was developed to determine fluxes in near real-time (≈3-month lag) utilizing remotely sensed SST and wind products. An interactive data and graphics retrieval system can be found at: http://cwcgom.aoml.noaa.gov/erddap/griddap/aomlcarbonfluxes.graph. It provides monthly fluxes from 1988 through 2009. An example of a flux map is shown in figure 1. These maps represent a regular product that contributes to the annual reporting of the essential climate variables.

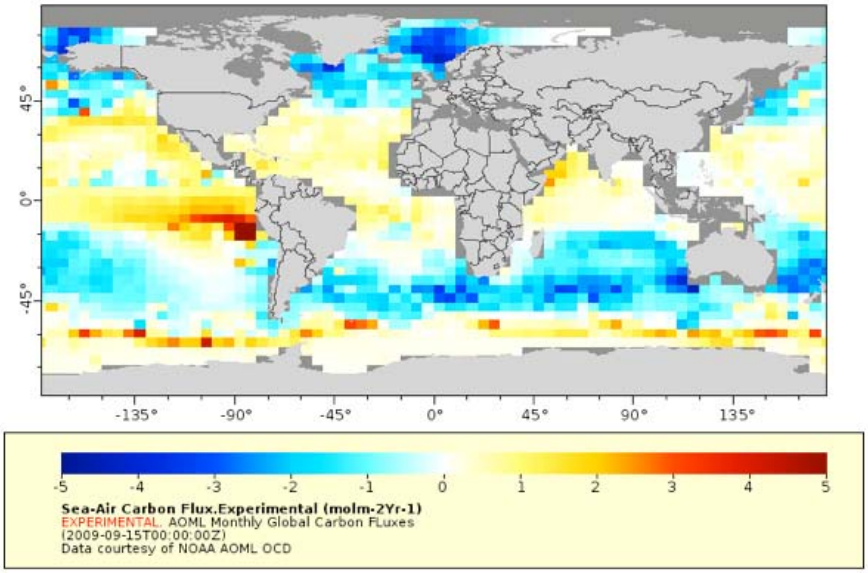

Fig 1. An air-sea CO_2 flux map for September 2009.

Surface Ocean CO_2 Atlas

A significant effort for the Synthesis Project investigators over the last year has involved the Surface Ocean CO_2 Atlas (SOCAT) project. This is an international effort to establish a global surface CO_2 data set that would bring together, in a common format, all publicly available surface CO_2 data for the surface oceans. This activity has been requested by many international groups for a number of years, and has now become a priority effort for the marine carbon community. The SOCAT data set already contains over 2100 cruises and over 9 million data points from 1968-2007. This data set will serve as a foundation upon which the community will evaluate the controls on air-sea CO_2 fluxes and will continue to be a resource as the data base continues to grow in the future.

The SOCAT data set is meant to serve a wide range of user communities and it is envisaged that, in the future, 2 distinct SOCAT data products will be made available: 1) a 2nd-level quality controlled, global surface ocean fCO_2 (fugacity of CO_2) data set following agreed procedures and regional review, and 2) a gridded product of mean monthly surface water fCO_2 concentrations on a 1° x 1° grid with no temporal or spatial interpolation.

In FY2009 PMEL launched a special web portal to support the SOCAT project. The goal of the system is to facilitate the process of determining and applying 2nd level quality control ratings. Since March 2008, Jeremy Malczyk at PMEL has been working closely with SOCAT's primary data manager, Benjamin Pfeil of the Bjerknes Centre for Climate Research, Bergen, Norway, to create the SOCAT web portal. This portal provides a centralized storage repository for SOCAT data files, visualization / analysis tools, and a logging system to collaboratively quality control the data. Access to the SOCAT site is currently restricted to contributing members, with the goal of fully open access when 2nd order quality control is completed and the dataset has been published at CDIAC.

In order to keep track of changes to the SOCAT collection in a multi-user environment, a special repository is used to store the data files, metadata files, and auxiliary QC documents. This system automatically tracks changes to all data, metadata, and QC document files stored in the system, and ensures that nothing can be lost, overwritten, or deleted as multiple users contribute to and alter the repository. The state of the dataset at any earlier point can be recalled, allowing the evolution of SOCAT to be completely transparent once the dataset is publicly available.

A Live Access Server (LAS) provides visualization and analysis tools for SOCAT. The main interface consists of an interactive (click and drag) map of all variables in the dataset with controls that allow scientists to constrain data selections by various parameters. From the map, users can access fine grained analysis tools such as the property/property plot shown in figure 2. Data and metadata can be downloaded in user specified subsets, and links to external metadata are provided. Additionally, the system manages quality control flags and comments set by scientists as they QC the data.

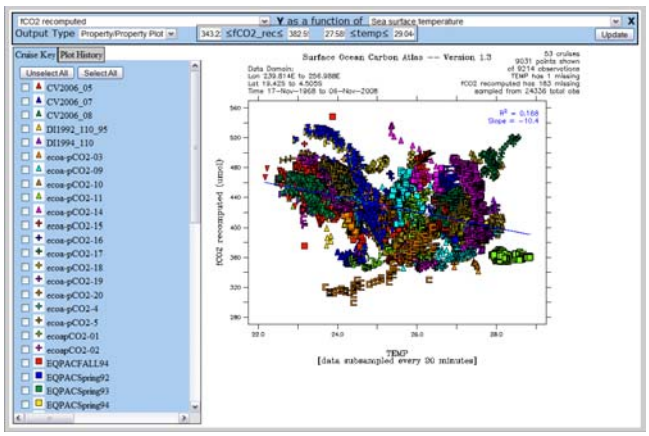

Fig. 2 Property / property plot of fCO_2 vs sea surface temperature.

In March 2009, the SOCAT Pacific regional group held a meeting and workshop in Tsukuba, Japan. The group was split into several subgroups and worked through a prepared exercise indentifying suspected duplicate data in the collection. This proved to be an instructive activity for all concerned – scientists (data reviewers), data managers, and the system developers. The group provided useful feedback that was immediately used to improve the usability of the system. A key lesson learned at Tsukuba was that some cruise data would require a significant level of level 1 clean-up before it would be possible to begin level 2 QC. A final report for the Tsukuba meeting is available at http://ioc3.unesco.org/ioccp/FinalRpts/WR221_eo.pdf

In late June 2009, a similar workshop was held at the University of East Anglia in Norwich, UK. Based upon feedback from Tsukuba many enhancements were added to the system to improve the user experience. In parallel the SOCAT data collection, itself, was updated by Benjamin Pfeil based upon problems identified in Tsukuba. Version 1.3 was released and further QC resumed at this meeting. A dynamic (click a column to sort) table of likely cruise "crossovers", points where cruises came close to one another in location and time, was included with links to dynamic maps showing those cruises in LAS (Fig 3). The final report for the Norwich meeting is available at http://ioc3.unesco.org/ioccp/FinalRpts/WR222_eo.pdf

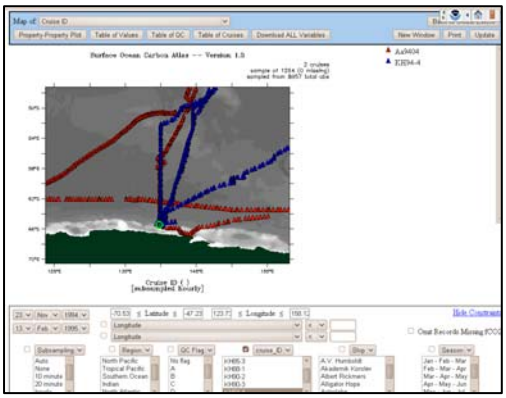

Fig 3. Interactive cruise crossover plot.

We are now in the process of developing a set of standard protocols that each of the regional groups should use to do their 2nd level QC checks. Once the protocols are established the regional groups will begin working through their analyses of the data. The International Ocean Carbon Coordination Project (IOCCP), chaired by C. Sabine (one of the Synthesis Project investigators), will continue to coordinate this activity and sponsor regional group meetings as necessary to complete the data evaluation. The goal is to develop a quality controlled data set that can be used for scientific analysis of surface ocean carbon variability and ocean carbon uptake. Once the initial synthesis is completed, additional data sets can be added and QCed on a regular basis so the data base is always current.

3.2. Ocean Interior Carbon

The ocean interior component of the Global Carbon Data Management and Synthesis Project involves continued processing and assessment of the CLIVAR/CO_2 Repeat Hydrography data, an international synthesis of high-quality carbon data for the period from GEOSECS to CLIVAR, and a global assessment of decadal changes in ocean carbon inventories. Each of these is discussed very briefly below.

Processing Repeat Hydrography Data

In FY2009 the data from the 2008 I6S cruise was processed for its post cruise quality assessment and submitted to CDIAC. The data from this year's cruise, I5, have gone through their initial quality assessment checks and are currently being finalized. For more information see the Repeat Hydrography OCO report.

Several of the recent Repeat Hydrography cruises have been examined for evidence of carbon inventory changes using either the multiple linear regression or isopycnal analysis approaches. For example, during the WOCE program, a north-south cruise line P18 in the eastern Pacific Ocean along 103°W– 110°W was occupied in January-April 1994. This cruise line was reoccupied during the CLIVAR/CO_2 Repeat Hydrography program in December 2007- February 2008. To investigate the temporal changes in DIC from 1994 to 2007 along this cruise line, we analyzed the data obtained during these two time periods along the isopycnal surfaces with sigma-theta of 26.0, 26.2, 26.4, 26.6, 26.8, 27.0, 27.2, and 27.4. The results show insignificant changes in DIC in the equatorial region north of 15°S. In contrast, higher DIC increases are

evident in the temperate region south of 15°S. The extra DIC has penetrated along isopycnal 27.0 in the southern temperate region, while there is negligible penetration below 27.2 isopycnal surfaces. The estimated DIC increases vary for each isopycnal intervals, with increases from 6.9 μmol kg^{-1} along the 27.0 isopycnal and 22.8 μmol kg^{-1} along the 26.0 isopycnal in this region. Using the mean depth of isopycnal surfaces between 20^oS and 40^oS, a mean DIC inventory change of 0.68 mol m^{-2} yr^{-1} is obtained for the south temperate region south of 15^oS from 1994-2007, which is equivalent to a CO_2 increase rate of 1.12 μmol kg^{-1} yr^{-1}.

Global Synthesis of Interior Ocean Carbon Data

For the last several years the Synthesis Project investigators have been actively involved in an international effort called CARINA to synthesize previously unavailable carbon data from the Atlantic, Arctic and Southern Oceans. The CARINA project officially ended this fiscal year and the parent program from the E.U., CarboOcean, is also over at the end of this year. This was an extremely important activity for the ocean carbon community with many scientific benefits such as:

- Rescue of approximately 50 million Euro (estimate by A. Olsen) of European cruise data that would potentially have been lost otherwise. A large fraction of these data were in private holdings and the odds of public release without this effort are small. Equally important for the future, the quality of record keeping was significantly improved and many of the PIs involved now recognize the value obtained by early release. Since no one country can currently make measure the volume of data required for climate change science this paradigm shift is critical. We also have reason to believe that the current "data holding time" for Europe will soon match that of the U.S. and other CLIVAR participants.
- Production of 3 large calibrated data products for the ocean community. The CARINA AMS product provides the community with the first high quality data set for the Arctic and Arctic marginal seas (Nordic Seas). These regions were almost totally unrepresented in GLODAP. Given the rate of change being reported for the Arctic, this data product will be extremely valuable as a baseline even though the data coverage for the Arctic-proper is still too sparse to accurately map. The CARINA ATL product more than doubles the number of data for the Atlantic over what is in GLODAP and extends the GLODAP coverage from 1996 up to ~2003. The data density for the North Atlantic when GLODAP and CARINA-ATL are combined will allow significant improvement in the GLODAP property distribution maps for this area. The CARINA-SO data product approximately doubles the data available in GLODAP and extends the temporal coverage. We now have the beginning time series for several locations and much better coverage for the Weddell Sea and other critical regions. Each of the data products has been assigned a DOI via CDIAC with the entire CARINA team listed as author. CDIAC is also producing a numeric data package (NDP) with the same authorship that gives a very basic introduction to the data products.
- The details of the CARINA work have been thoroughly documented in series of about 20 papers which are being assembled for a special issue of *Earth System Science Data* (ESSD). R. Key, X.Lin and/or other members of this project (R. Wanninkhof, C. Sabine, D. Pierrot) are lead or co-authors on 13 of these papers. NOAA support is acknowledged in these documents. A couple of the papers are "published" and the remaining ones are in various stages of the review/publication sequence.

- Other CARINA participants (primarily T. Tanhua, C. Schirnick and S. van Heuven) developed software which allows semi-automation of the various secondary QC procedures developed in GLODAP and honed during CARINA. This technology has been transferred to Princeton (and implemented), to Japanese collaborators working on PICES and published on the CARINA web site. In addition, the web site development tools that made the CARINA collaboration possible are also now public. These "tools" will be used for the PICES project and, with minor or no adaptation should greatly facilitate any similar future project.

An example of the CARINA quality assessment and subsequently the proposed data adjustments is shown in figure 4. The Atlantic synthesis involved 98 cruises in the area from Greenland-Iceland-Scotland Ridge to north of about 30°S. The analysis resulted in corrections in DIC data of 17 cruises.

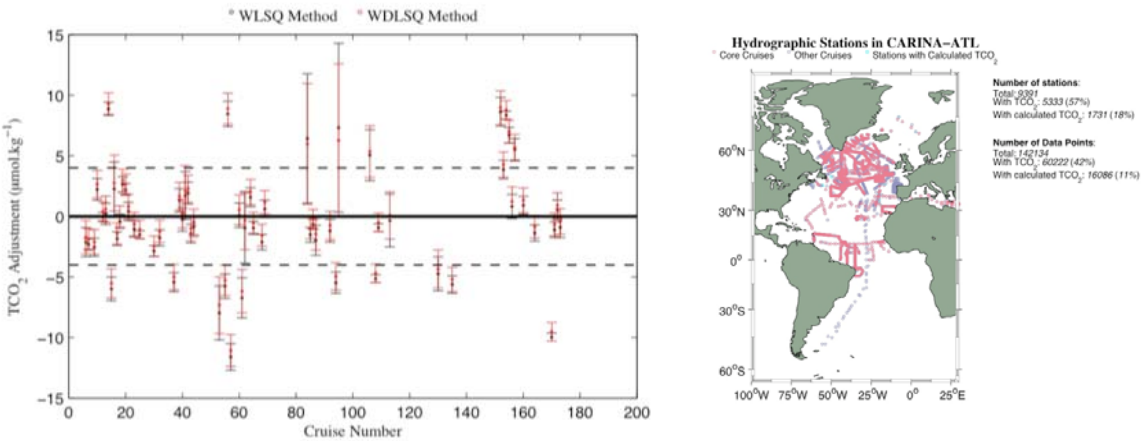

Fig 4. Adjustment values obtained from the two inversion methods used in the CARINA analyses as a function of an arbitrary cruise number. The cruise tracks of the data compared is shown on the map to the right. No corrections were applied if the adjustments were less than 4 μmol kg^{-1}.

With the completion of the Atlantic, Arctic and Southern Ocean synthesis, our efforts are now moving into the Pacific. We have been working with the members of the North Pacific Marine Science Organization (PICES) to gather new data sets from the Pacific. At a recent PICES meeting in Jeju, South Korea more than 150 previously unreleased data sets, primarily from Japan, had been gathered in the data base. A decision was made to continue to look for additional data from the U.S., Canada, Korea and perhaps China and Russia to fill out the new data collection. Once the data have been assembled, the quality assessment will begin using techniques based on the latest CARINA synthesis. In the end, we expect to produce a global data set of quality controlled carbon data that is several times larger than the original GLODAP synthesis.

Global Assessment of Decadal Changes in Ocean Carbon Storage

This past summer a meeting was organized in Ascona, Switzerland by IMBER and SOLAS, two international ocean research programs, to assess "where we stand" and "what can we do" with respect to assessments of the ocean carbon storage changes over the last decade. The first global repeat hydrography decadal survey will be completed in 2012 and input will be needed within a

year for the next IPCC assessment report. The primary outcome was an agreement to try to work together to develop one coordinated assessment of the change in the global anthropogenic ocean carbon inventory since the WOCE/JGOFS synthesis. Change estimates would be "uniformly" calculated using the e-MLR method and based on comparison between recent CLIVAR and CARINA cruises relative to earlier cruises from GLODAP. This effort is just starting but will become increasingly important over the next year.

3.3. Ocean Acidification

The uptake of anthropogenic CO_2 by the global ocean induces fundamental changes in seawater chemistry that could have dramatic impacts on biological ecosystems in the upper ocean. Estimates based on the Intergovernmental Panel on Climate Change (IPCC) "business as usual" emission scenarios suggest that atmospheric CO_2 levels could approach 800 ppm near the end of the century. A component of the surface ocean and ocean interior studies described in the previous sections is an assessment of how ocean carbon changes are resulting in the acidification of the ocean. While this project does not replace the need for a comprehensive ocean acidification program, we are working to provide guidance on the potential magnitude of the expected chemical changes in the global ocean.

For example, recent estimates from observational data and biogeochemical models for the ocean indicate that surface water pH will drop from a preindustrial value of about 8.2 to about 7.8 in the IPCC A2 scenario by the end of this century, increasing the ocean's acidity by about 150% relative to the beginning of the industrial era (Feely et al., 2009). In contemporary ocean water, elevated CO_2 will also cause substantial reductions in surface water carbonate ion concentrations, in terms of either absolute changes or fractional changes relative to pre-industrial levels. For most open-ocean surface waters, aragonite undersaturation occurs when carbonate ion concentrations drop below approximately 66 μmol kg^{-1}. The model projections indicate that aragonite undersaturation will start to occur by about 2020 in the Arctic Ocean and 2050 in the Southern Ocean (Figure 5). By 2050 all of the Arctic is undersaturated with respect to aragonite, and by 2095 all of the Southern Ocean and parts of the North Pacific would become undersaturated. For calcite, undersaturation occurs when carbonate ion drops below 42 μmol kg^{-1}. By 2095 most of the Arctic and some parts of the Bering and Chukchi Seas would become undersaturated with respect to calcite. However, in most of the other ocean basins the surface waters will still be saturated with respect to calcite, but at a level greatly reduced from the present.

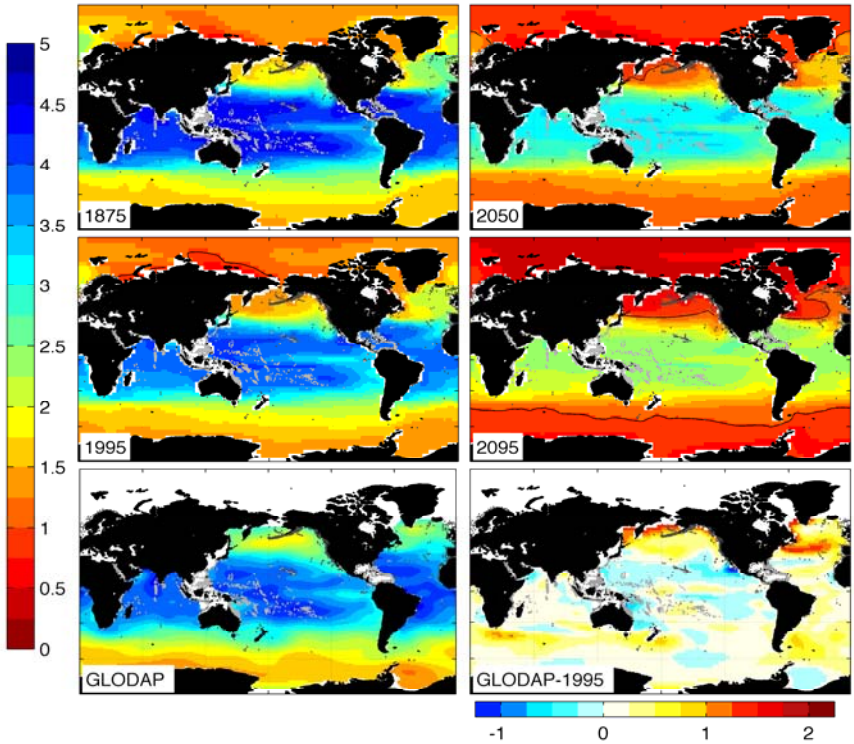

Fig 5. Modeled decadal mean Ω_{arg} at the sea surface (top, middle rows), centered around 1875, 1995, 2050, and 2095. The solid black contour line indicates where $\Omega_{arg} = 1$. On (bottom left) data-based Ω_{arg} at the sea surface, nominally for 1995, and (bottom right) the difference between the data-based and model-based 1995 fields. Note the different range of the difference plot in bottom right. Deep coral reefs are indicated by darker gray dots; shallow-water coral reefs are indicated with lighter gray dots. White areas indicate regions with no data.

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4. Education and Outreach

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

The R/V *Walton Smith* is used by the University of Miami Department of Marine Science to provide undergraduate students with at sea experience in marine chemistry. The pCO_2 data collected during these cruises are used by the students in exercises designed to introduce them to the collection and analysis of oceanographic data, and the preparation of a cruise data report.

5. Publications and Reports

5.1. Publications with Principal Investigators as First Author

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