The Global Ocean Carbon Observing System – Connecting national programs and regional networks

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Introduction

Human activities such as fossil fuel burning and de-forestation have profoundly altered the Earth's global carbon cycle, and atmospheric concentrations of the greenhouse gas CO_2 are now higher than experienced on the planet for the past several million years. The ocean is the largest mobile reservoir of carbon on decadal-to-millennial time scales, and will ultimately absorb approximately 70-85% of the anthropogenic CO_2 released to the atmosphere. Observational and modelling estimates suggest that the ocean is presently taking up about 30-40% of fossil fuel CO_2 emissions, but the future behaviour of the oceanic sink is uncertain, depending upon possible carbon and climate feedbacks associated with changes in ocean chemistry, ocean circulation and marine biogeochemistry.

Ocean carbon scientists are faced with two different challenges in dealing with CO_2 in the ocean. One is how to understand, monitor, and predict the present and future ocean sink for CO_2. The other is how the CO_2 increase in the ocean will affect biogeochemistry and ecosystem functioning. The annual uptake of atmospheric CO_2 is much smaller than the spatial and seasonal variability of CO_2 in the ocean, and detecting the trend is a technical challenge. This "service" that the ocean provides of removing CO_2 from the radiative budget of the atmosphere, however, comes at a great cost. There is a strong possibility that by the middle of this century surface ocean pH changes resulting from increased dissolved CO_2 concentration (*e.g.*, acidification) may cause significant stress on calcifying plankton and coral reefs. While "dangerous anthropogenic interference with climate" has been widely discussed in the United Nations Framework Convention on Climate Change (UNFCCC), no scientific discussions have taken place to determine what oceanic CO_2 levels should be considered tolerable for marine life, or how proposed carbon management strategies might moderate or exacerbate effects on ocean chemistry and biology.

The vast scope of the ocean carbon problem can only be addressed through globally-coordinated research and observations. This issue has long been recognized at the highest levels of government, and numerous international conventions, such as the UNFCCC and the United Nations Conference on Environment and Development's "Agenda 21", have instructed IOC to develop the necessary coordination mechanisms to ensure that the combination of research and observations carried out by global and national research programs are coordinated, comprehensive and sustained. Over the last few years, the ocean carbon community has developed a collective vision for an ocean carbon observing system that would have significant scientific benefits. Along with this vision is the knowledge that implementing such a system will require international collaboration and coordination on an unprecedented scale. What we describe here are the first steps of our community to organize internationally to meet these challenges.

International Ocean Carbon Coordination Project

In response to these UN mandates, IOC, along with the International Council for Science's Scientific Committee on Oceanic Research (SCOR), established an Advisory Panel on Ocean CO_2 in 2000 to focus efforts on observation coordination. In 2003, the Panel initiated a pilot project with the Global Carbon Project (sponsored by the International Geosphere-Biosphere Program, the International Human Dimensions Program, and the World

Climate Research Program) called the International Ocean Carbon Coordination Project (IOCCP). IOCCP is working to develop a central information source of on-going and planned ocean carbon observations, and to establish international agreements on observation methods, best practices, data management, and data sharing that will lead to the joint development of global data products and synthesis activities documenting the ocean carbon cycle. IOCCP activities have been funded through grant OCE-0245278 from the U.S. National Science Foundation to SCOR, IOC, and the Japanese National Institute for Environmental Studies.

For several years, North Pacific research scientists have coordinated their efforts under the PICES framework and have begun Pacific CO_2 data integration. North Atlantic research scientists have also established a coordination mechanism to share ocean CO_2 observational data through the Carbon in the Atlantic (CARINA) activity of JGOFS. IOCCP is working to establish long-term relationships with PICES and other regional data synthesis groups to develop the collective capacity to produce data products such as annual basin- and global-scale air-sea CO_2 flux data sets and decadal basin- and global-scale data sets of carbon distributions in the water column.

The first workshop of the new IOCCP was held in January 2003, at the United Nations Educational, Scientific, and Cultural Organization (UNESCO) headquarters in Paris, and brought together 56 participants from 17 countries to discuss the current state of ocean carbon observation activities and the way forward for international coordination. The workshop produced compilations of on-going and planned ocean carbon measurements and outlined the scope for the project and working arrangements for the project office (to be managed through the CO_2 Panel Secretariat at IOC). These compilations are available at: http://ioc.unesco.org/ioccp. An observing system for ocean carbon builds on three basic elements: (1) repeat hydrographic sections, (2) time-series stations, and (3) underway measurements from research and volunteer observing ships. Each of these activities is at a different stage of development and is implemented with several partner programs.

Repeat sections – One of the key components of the initial ocean carbon observing system is the repeat hydrographic sections being conducted in collaboration with the Climate Variability and Predictability Program (CLIVAR). Observations of large-scale distributions of carbonate system variables provide important information on the patterns and rates of air-sea exchange, organic/inorganic matter export, subsurface re-mineralization, and anthropogenic carbon storage and transport. They also serve as key constraints on ocean biogeochemical numerical models. Transient tracer fields offer insight on physical mixing, circulation pathways and transport rates that have direct impact on the ocean's ability to absorb anthropogenic CO_2. The global survey lines of carbon and tracers carried out through the WOCE program are being re-occupied beginning in 2003. At present, there are 31 lines committed (funded) and another 6 awaiting funding approval (Fig. 1). In 2003, the CLIVAR Basin Panels included carbon and tracer experts as members of each of the Panels. The international community has been working together to determine the minimum set of core repeat sections required for a standard global survey of ocean carbon and tracers, and to establish international agreements on core and ancillary measurements for the survey. It is anticipated that an international strategy for the ocean carbon repeat hydrography program will be published by the end of 2004 as part of the IGBP - SCOR *Integrated Marine Biogeochemistry and Ecosystem Research* (IMBER) Program. IOCCP will be working with the international carbon and CLIVAR communities to develop this strategy into an implementation plan.

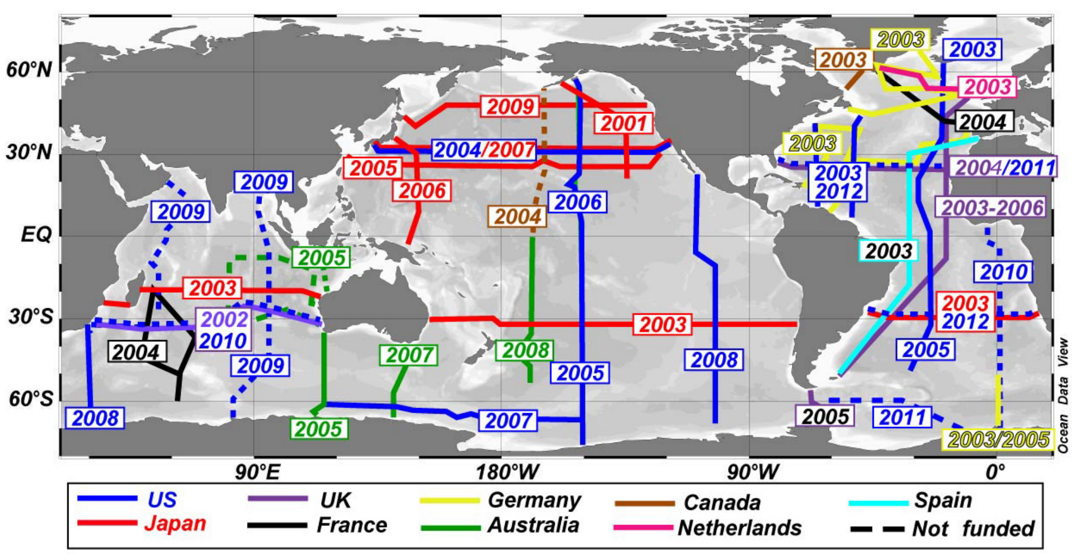

Fig. 1 Global repeat hydrography map.

Time series – Long-term time-series measurements are crucial for characterizing the natural variability and secular trends in the ocean carbon cycle, and for determining the physical and biological mechanisms controlling the system. In 2000, the Ocean Observations Panel for Climate (sponsored by the Global Climate Observing System (GCOS), the Global Ocean Observing System (GOOS), and the World Climate Research Program (WCRP)) joined with CLIVAR, and the Partnership for Observations of the Global Oceans (POGO) to develop an international science team to guide the development and implementation of a global network of time-series stations. IOCCP has been working with the carbon experts on this science team in the development of the design strategy for the network. A number of time-series stations measuring ocean carbon and related measurements will be developed as part of the global research programs such as SOLAS and IMBER. IOCCP and the SCOR-IOC Advisory Panel on Ocean CO_2 will be working closely with these groups to coordinate the research, observations, and data synthesis activities through regional groups including PICES.

Volunteer Observing Ship (VOS) surveys – One of the key products of a globally coordinated oceanic pCO_2 observation system is the development of global ΔpCO_2 maps. Taro Takahashi has already provided an initial global climatology for non-El Niño conditions (*Deep-Sea Res. II*, Vol. 49, pp. 1601-1622, 2002). His maps are the most significant product from the last several decades of ΔpCO_2 observations. This climatology plays a critical role in global carbon cycle model validation, and aids in improving the accuracy of climate change modelling. However, these climatological maps represent aggregated data for the last 40 years of observation projected to a single year: 1995. Surface ocean pCO_2 can be affected by short-term modes of climate variability (*e.g.*, El Niño events) and changes in biological productivity. Variability on time scales of 1 month or shorter can be significant for estimating annual air-sea CO_2 flux. It is clear that we must move beyond a pCO_2 climatology and develop time-resolved global pCO_2 maps in order to resolve temporal changes of the oceanic sinks and sources of CO_2. Such task truly requires extensive observation and data integration. At present, carbon VOS surveys (Fig. 2) are not coordinated through any global research activity, and the development of IOCCP has provided a forum for these scientists to address common issues and to develop joint plans. The two IOCCP-sponsored workshops in 2003 and 2004 have been focused on the VOS issues, and have been held in coordination with PICES scientists and programs.

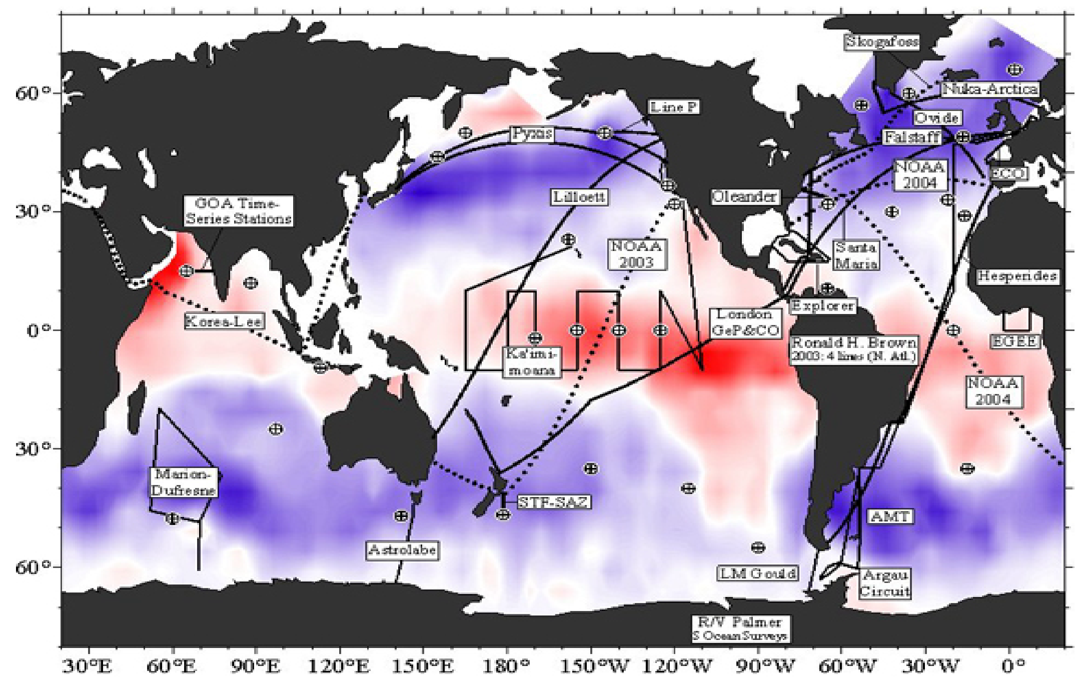

Fig. 2 Global underway pCO_2 map.

International pCO_2 system inter-comparison experiment

As one of the first contributions to this new coordination effort, Dr. Yukihiro Nojiri of the Japanese National Institute for Environmental Studies (NIES) organized an international pCO_2 inter-comparison experiment for underway pCO_2 systems in March 2003, with financial support from the Environmental Agency of Japan. Inter-comparison exercises are crucial to ensure the accuracy of pCO_2 observations. Previous pCO_2 inter-comparison experiments (in 1994 at the Scripps Institution of Oceanography, and in 1998 on board R/V *Meteor*) were useful, but the experimental set-up was not ideal in either case. The recent experiment, held March 10-14, 2003, at the National Research Institute of Fishery Engineering, Hazaki, Japan, used an indoor seawater pool under controlled laboratory conditions, which allowed very precise comparisons of the equilibrators and gas measurement systems. The pool contained 170,000 liters of coastal seawater adjusted to a salinity of 33 psu. Nine different underway systems, including 3 from Japan, 2 from the United States, 1 from the Republic of Korea, 1 from New Zealand, 1 from Germany and 1 from the United Kingdom, were plumbed in series into a water system that re-circulated saltwater from the pool at a rate of 300 L/min. In addition, three autonomous drifter-type systems (2 from the United States and 1 from France) were deployed in the pool. A series of experiments were run over five days to evaluate the response of the systems and potential biases over a range of temperatures and pCO_2 values observed in nature. A careful comparison of calibration approaches was also made by providing a common set of gas standards and a CO_2-free reference gas to all participants. The results of this experiment are currently being compiled, but the basic conclusion was that despite the wide variety of equilibrator and gas detection systems, the systems evaluated in this study agreed much more closely than observed in previous inter-comparison studies. However, a few sources of variability that could be attributed to specific design aspects were identified and will be discussed in the workshop report. In keeping with the goals of IOCCP, the workshop report will also include a set of "best practice" recommendations for those interested in making underway pCO_2 measurements.

Workshop on "Ocean surface pCO_2, data integration, and database development"

In January of 2004, IOCCP, NIES, and PICES co-sponsored a follow-up workshop to the inter-comparison experiment in Tsukuba, Japan, to address "Ocean surface pCO_2, data integration, and database development". This workshop, which brought together 44 participants from 12 countries, was carried out through three working groups focusing on:

- the results of the inter-comparison experiment for ocean pCO_2 systems,
- standardization of data and metadata formats, and
- data integration and networking.

Ocean pCO_2 systems – In order to combine the results of individual programs into a global observing network, it is first necessary to make measurements of known accuracy from a variety of different systems. It is unfortunately not practical to make liquid standards for pCO_2 measurements, and so we must have a detailed understanding of how different systems behave relative to each other under a variety of conditions, and compare with results from a laboratory-based system of known accuracy. At the workshop, Working Group 1 identified several key areas of errors and biases in the eight system designs, and outlined ways of resolving these discrepancies. In general, it was found that well-designed and operated systems agreed with each other to within ± 2 μatm, which is close to the estimated accuracy of the measurements from the at-sea systems. The goal is to be able to make an estimate of the annual mean uptake of ocean CO_2 with an uncertainty of about 10%, or ±0.2 Pg C yr^{-1}. Based on existing seasonal pCO_2 climatologies and wind speed distributions, basin average ΔpCO_2 must be resolved to 3-10 μatm. A full technical report of the experiment results will be published by the Carbon Dioxide Information and Analysis Center (CDIAC), following the outline and sensor designations used in the previous 1996 inter-comparison experiment (CDIAC Numerical Data Package 067). The goal is to have the first draft prepared by mid-April, with a final draft by June 2004 for a presentation at the PICES Thirteenth Annual Meeting in October 2004.

Standardization issues for data and metadata formats – Metadata and data file contents were developed by Working Group 2 and approved by the workshop. These are available on the IOCCP web site at: http://ioc.unesco.org/ioccp. These will be promoted as the IOCCP Recommended Format upon final revision. Alex Kozyr at CDIAC's Ocean CO_2 Project will create an easy-to-use web-based metadata reporting form to facilitate this uniform approach. Working Group 2 discussed the necessity of using a uniform approach to estimating overall uncertainty for CO_2 measurements, and recommended that a special working group be formed to develop and propose guidelines.

Data integration and data networking – While a mature observing system will have a network of operational data centers obtaining data in near-real time and producing regular data products, the first steps toward that goal involve making international agreements on data and metadata formats, and agreements on how to share these data among the existing data centers and data collectors. Because ocean CO_2 data are still very much in the research realm, where data collection is funded through research proposals and where the only "user" for the data products is the research community producing the data, it was felt that we still need to offer some "intellectual property" protection to those scientists who collect the data. This comes in two forms. One is in keeping with global research program policies, to allow scientists up to 2 years to make the data publicly available. The other is to pursue new innovations in electronic publishing, so that data sets housed at accredited data centers can be cited as peer-reviewed journal articles. Specific working arrangements discussed at the meeting are:

- <u>Data release / Data Center networking</u>
  Ocean CO_2 data sets (providing the IOCCP-recommended information) should be sent to the CDIAC World Data Center for Atmospheric Trace Gases (either directly or via other World, National or project Data Centers) no later than 2 years after the end of the cruise (current contact: Alex Kozyr, E-mail: kozyr@ornl.gov).

- Data citations and acknowledgements
  When data are submitted to a Data Center, the contributor should provide information on how the data set is to be cited or acknowledged in publications using the data. For data submitted <2 years before the end of a program, CDIAC can limit access to the data until the contributor has been contacted, if this is desired by the data contributor. As a courtesy to the original data contributors, it should become common practice for individuals who prepare scientific products based (even in part) on a particular dataset, to inform the contact person for that dataset of its use. IOCCP is investigating the American Geophysical Union protocol for citation of data sets in AGU journals and will encourage this practice where appropriate.

- Data integration and synthesis activities
  Surface pCO_2 data integration and synthesis activities (such as developing basin-scale and global data sets) undertaken in the next few years should be coordinated with activities of SOLAS Focus 3 (especially 3.1), with integration organized around regional (basin) groups. Integration should also cover coastal areas.

Workshop follow-up activities

The workshop reached a number of important agreements for the longer-term networking of data and synthesis activities, and produced the following action items for IOCCP for 2004:

- Development and publication of a CDIAC Technical Report on the ocean pCO_2 system inter-comparison experiment (first draft by mid-April 2004; final draft by June 2004);
- Development of the CDIAC Ocean CO_2 web-based metadata reporting form (first draft by mid-April 2004);
- Establishment of a small working group to develop and propose guidelines for a uniform approach to estimating overall uncertainty for CO_2 measurements;
- Final writing and publication of the "Guide of best practices for oceanic CO_2 measurements and data reporting", by Andrew Dickson, supported by PICES and the SCOR-IOC Advisory Panel on Ocean CO_2 (final draft by mid-2004 to incorporate international recommendations on data and metadata formats);
- The workshop participants also concluded that both individual scientists and national agencies need an internationally agreed upon implementation strategy, in order to evaluate national efforts in an international context, and to prioritize projects that contribute to the global network. We need both to sustain existing programs and to develop new programs based on the analysis of the spatial and temporal resolution of measurements needed to meet global data set goals. The workshop participants outlined the necessary elements for developing an implementation strategy of surface ocean CO_2 observations, and noted that many of the elements already exist, such as an inventory of on-going and planned activities, an initial analysis of the measurement resolution required, and a data management network. It was felt, however, that the initial sampling strategy analysis (see "Errors in the sea-air CO_2 flux due to time-space ocean sampling strategies for sea-air pCO_2 difference" by Takahashi and Sweeney, in "A large-scale CO_2 observing plan", Bender *et al.*, 2002.) should be re-evaluated considering issues like the time-space smoothing of the data sets. For 2004, IOCCP will seek funding support for the 2- to 3-month analysis project, and will prepare a first-draft of an implementation strategy by the end of the year, with the goal of having a full strategy ready for comments and publication by mid-2005.

Putting the pieces together

The coordination of national programs and regional networks is providing the foundation upon which we will build the ocean carbon observing system. While the calls for a coordinated system of observation come both from the highest levels of government as well as individual scientists, the resources for its development are almost entirely at the national level. This requires building the system from the ground up, where the international community of scientists must first develop joint implementation strategies (*e.g.*, for repeat sections, underway measurements from VOS, and time series stations), and then work closely with their national agencies to coordinate and implement their part of this network. At the international level, the ocean carbon observing system is connected to other global observing system elements through the GCOS-GOOS-WCRP Ocean Observations Panel for Climate (OOPC). IOCCP provides regular reports to OOPC, and contributes to the implementation strategy of the ocean observation system for climate being developed as part of the Global Climate Observing System for UNFCCC. While many national efforts in ocean carbon observation are well advanced, the international coordination of these efforts is at a very early stage, and our biggest challenges are still the basic building blocks of measurement technology, standardization, and data sharing. IOCCP will continue to rely on PICES for regional leadership in this global partnership.