AN INTEGRATED OCEAN CARBON OBSERVING SYSTEM (IOCOS)

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Abstract

The global ocean is undergoing fundamental and rapid changes in response to warming, changes in wind stress, atmospheric CO_2 increases, and changes in the hydrologic cycle. Each of these factors has impacts on the ocean carbon cycle and the ability of the ocean to sequester CO_2 from the atmospheric. In turn, changes in the ocean carbon cycle, and ocean warming and stratification lead to changes in ocean biogeochemistry and ecology. Feedbacks and impacts are complex and not fully understood. However, rapid advances in observing system technology are occurring, along with improvements in models and understanding of the system. A comprehensive integrated ocean carbon observing system (IOCOS) to understand and monitor these changes is within reach in the next decade. Rather than relying on a single approach or parameter, the IOCOS will be composed of an integrated system of ongoing surface and sub-surface observations, modeling, and assessments. This observing element will also rely heavily other parts of the International Ocean Observing System (IOOS). It will include new technology and modeling approaches to quantify carbon fluxes, and inventories in the world's oceans.

Key words: global carbon cycle, operational oceanography, biogeochemistry, international coordination

1. INTRODUCTION, BACKGROUND, HISTORY, OR ACCOMPLISHMENTS

Carbon Cycle Science including observing system requirements is overseen in the USA by the United States Carbon Cycle Science Program[1]. The global nature of the issues is well recognized and goals in the USA match closely with international efforts. Moreover, the resources and intellect necessary to address the issues requires international collaboration. For IOCOS, international coordination occurs through the International Ocean Carbon Coordination Project (www.**ioccp**.org), which is part of the global climate observing system, and sponsored by UNESCO-IOC and SCOR.

The science rational and overarching goals of a global carbon observing system, including the ocean, are clearly articulated in the US Carbon Cycle Science plan[2] and its update in 2011[3]. The first steps towards a carbon observing system are described in the Large-Scale Carbon Observing Plan: in situ oceans and atmosphere (LSCOP) report[4]. The report outlines a step-wise strategy of implementation with regional foci and deliverables, as a means to complete a global ocean observing system. This implementation plan dovetails with the international Global Ocean Carbon Observation System plan[5].

The scientific goals of these plans are focused on quantifying the anthropogenic CO_2 uptake by the ocean on seasonal to decadal time scales, and regional to global space scales. Decadal scale estimates are based on changes in inorganic carbon content of the ocean interior with a goal of estimating changes over the decade to within 10 % (≈ 2 Pg C globally). Shorter-term estimates are based on sea-air CO_2 flux measurements with similar goals on accuracy of 0.2 Pg C yr^{-1} for a global sea-air CO_2 uptake of 2 Pg C yr^{-1}.

2. TECHNICAL AND USER REQUIREMENTS

The initial ocean carbon observing system is developed by adaptation and improvement of established platforms and technology. It is focused on quantification of sea-air CO_2 fluxes and ocean carbon inventories that rely on measurement of partial pressure of carbon (pCO_2) which is an Essential Climate Variable (ECV) defined by the Global Climate Observing System[29]; total dissolved inorganic carbon (DIC), and total alkalinity (TA). These quantities are used along with other pertinent parameters such as temperature, salinity, nutrients, oxygen and transients tracers to estimate the anthropogenic carbon fluxes and storage in the ocean.

Changes in anthropogenic carbon storage in the ocean are determined from long-line cruises under auspices of the CLIVAR project and other international entities. Approximately 20 transects in all major ocean basins are mapped out. Based on rudimentary estimates, decadal occupations of the lines shown in **Figure 1,** and skillful temporal and spatial interpolation the performance goals are accomplished. The measurements performed are categorized as level l, 2, or 3 relative to its needs to fulfill the objectives of the program with level 1 being critical[6]. The repeat hydrography cruises often have expanded and evolving scopes such as measurements of trace metal concentrations and their impact on biogeochemical cycling, and quantification of organic matter and its transformations.

Surface water measurements to determine sea-air CO_2 fluxes are performed from buoys and ships of opportunity to capture the significant spatial and temporal variability in the fluxes that are a function of the gradient of pCO_2 across the air-water interface (ΔpCO_2) and surface turbulence, often parameterized with wind speed. Best practices procedures and protocols are established to reach the accuracy goals[7]. For global scale fluxes, the pCO_2 climatology of Takahashi et al.[8] based on measurements over the past 5 decades performed by collaborators worldwide, is frequently used. A community-wide effort to quality control, systematically reduce and collate global ΔpCO_2 data has produced its first database, the Surface Ocean Carbon Atlas (SOCAT)[9] (Fig. 2). These data products have provided a wealth of societal relevant information used in global and regional assessments, and offer constraints or boundary conditions for numerical models.

Ship-based time series for ocean carbon observations have been augmented by autonomous pCO_2 measurements from moorings. These measurements often are done in tandem with ocean reference stations such as OceanSITES[10] (Fig 3). The stations have provided new information on seasonal and interannual variability of the fluxes within different regions.

3. STATE OF THE OBSERVING SYSTEM AND TECHNOLOGY

The repeat hydrography effort has completed its first re-occupation of the subset of WOCE/WHP lines to determine the changes in the global ocean carbon budget in 2011. Appropriate parameters and quality measurements were performed to meet the stated goals of constraining decadal changes in anthropogenic CO_2 inventory (Table 1). However, the repeat hydrography effort led to the discovery of appreciable greater natural and climate induced variability of carbon and related biochemical parameters in the interior of the world's oceans

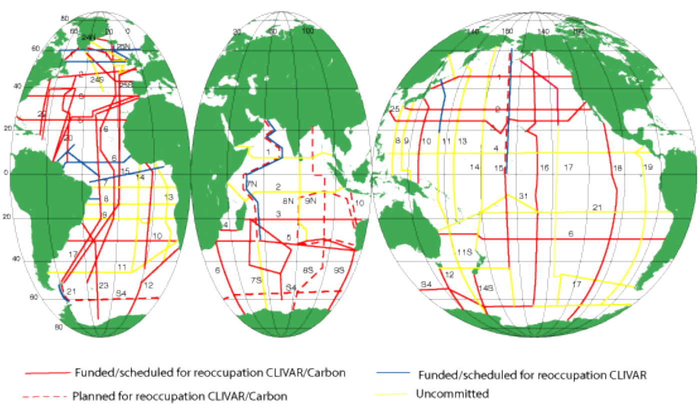

Figure 1: CLIVAR/Carbon Repeat hydrography lines from www.clivar.org/resources/data/clivar-carbon-and-hydrographic-sections

Moreover, penetration of anthropogenic CO_2 signal is deeper than previously estimated or modelled. Improved methodology, including numerical models have been developed utilizing transient tracers and known correlation between inorganic carbon, and physical and biogeochemical properties (nutrients and oxygen) and transient tracers to decrease the uncertainty in the anthropogenic carbon changes and transport, and has provided means to estimate inventory changes on an annual basis [11,12].

This observed variability and change in the ocean interior has led to a call for a reassessment of the observational strategy and an expanded observational suite [6].

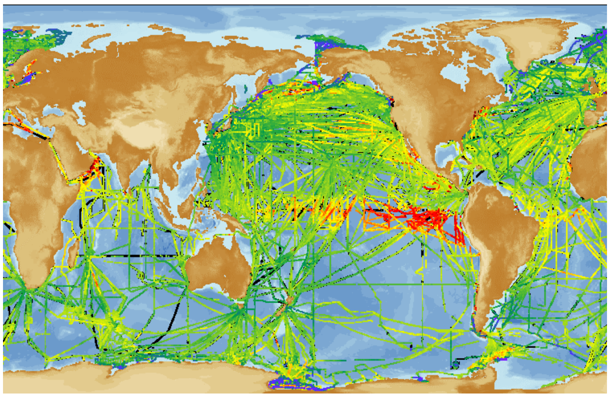

Figure 2. Map of cruise tracks of the data contained in SOCAT .The color coding indicates the surface water pCO_2 level with red and yellow indicating that CO_2 is released from the ocean while the green and blue are areas where CO_2 is taken up. The magnitude and locations of CO_2 sources and sinks depend on seasons and year and color-coding is illustrative of when the cruise took place. For a user-friendly query database see: (http://www.socat.info/)

Table 1. Estimates of ocean column inventory changes in anthropogenic carbon (mol C m^{-2} yr^{-1}) over the last decade along the cruise lines indicated[13].

Time interval	Basin (line)	N.Hemisphere	S.Hem.
1993-2005	Atlantic (25°W)	0.63	0.75
1991-2006	Pacific (152°W)	0.25	0.41
1995-2007	Indian (90°E)	0.63	0.83

The sea-air CO_2 flux network is based on ships of opportunity (SOOP) and moorings. Currently, about 3 dozen ships have autonomous instruments installed that meet the accuracy criteria required, and about 30 moorings have similar but less precise instrumentation than on ships to measure ΔpCO_2. The CO_2 flux observing network is meeting the specific criteria for the northern hemisphere and Equatorial Pacific[4] but rely on other observing approaches than originally envisioned.

As described in (4) an observational scheme of monthly measurements on an approximately 10-degree grid are necessary to constrain the fluxes from pCO_2 measurements alone. This spatial and temporal coverage has not been feasible except for the sub-polar and sub-tropical North Pacific and North Atlantic.

Global climatological estimates of sea-air CO_2 flux have been established with data holding over the past 4 decades[8] and methods are under development to interpolate data at high fidelity to quantify global and regional fluxes[14,15]. This is accomplished by utilizing high quality and high-resolution temperature, mixed layer, salinity and wind products, developed as part of the ocean observing system, and the relationship of the CO_2 flux to these parameters.

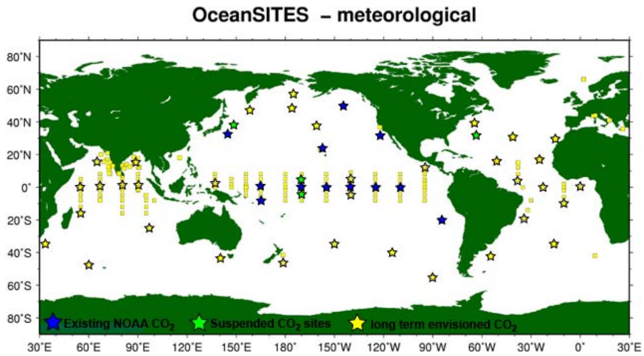

Figure 3. Map of the OceanSITES meteorological moorings with blue stars indicating moored pCO_2 systems. Yellow stars indicate the envisioned expansion. Additional coastal pCO_2 sites are addressed in a companion whitepaper on ocean acidification observing systems[27].

Taking full advantage of rapid advances in observing system technology, modelling, and basic research in process level understanding and inter-relationships of physical and biogeochemical parameters will facilitate implementation of the full IOCOS with fewer carbon system measurements than originally envisioned[4, 5].

4. INTEGRATION WITHIN IOOS, MODELING, AND DMAC

A key aspect of the IOCOS is adaptability and scalability. Adaptability includes using parts of the other observing systems to address the key aspects of the carbon observing system, and, in turn, providing data and infrastructure to new and evolving observing systems.

Carbon levels in the ocean are integrally tied to biogeochemical cycles of nutrients, and oxygen, and correlated with temperature and salinity. Techniques like multi-parameter regressions (MPR) provide means to extrapolate results in space and decrease uncertainty in findings. Novel aspects include using MPR in regions with a dearth of carbon measurements[26], such as the Southern Ocean to create the nature run for observing system simulation experiments (OSSEs) to establish an optimal IOCOS there. Profiling floats with oxygen, and other biogeochemical sensors, in addition to their regular thermistor conductivity payload will be of particular use for this application[18].

The requirements of high quality, accurate, and traceable measurements of temperature and salinity from surface to the deep ocean make the carbon observing platforms invaluable for other observing systems. High quality meteorological parameters are obtained from SOOP and Ocean reference sites and as such serve several observing system needs. The ocean acidification (OA) observing network has appreciable synergies with the carbon observing network and increasing CO_2 in the ocean is the cause of OA. As such, parts the carbon observing networks are being augmented to quantify OA and to determine the impact of OA on ecosystem health. The Integrated Ocean Observing System (IOOS) is also a key partner for incorporating ocean carbon observations into existing U.S. monitoring efforts. The established IOOS partnerships between federal, regional, and the private-sector can enhance our ability to collect, deliver, and use a wide variety of information, especially in the coastal ocean where sustained carbon observations are lacking. Because of the integral role of carbon in biogeochemical cycles, the IOCOS is the backbone for systematic and sustained observations of biogeochemical parameters[16].

Full implementation of the ocean carbon observing system will rely on many international partners whose contributions must meet the climate observing principles[17]. Procedures have been established that include creation of international program offices for coordination such as the IOCCP[20] and GOSHIP[21]; "best practices manuals"[22]; community training, and recommended instrumentation meeting clear standards.

Ongoing community data synthesis activities such as SOCAT[28] and GLODAP-2 are providing uniform high quality data products on regional and global scales. This includes "data mining" of historical datasets to improve knowledge of ocean carbon level and fluxes in the past to discern variability and trends.

Remotely sensed data have provided new opportunities to quantify fluxes but also changes in the interior. Table 2 provides a list of carbon products that rely, in part on satellite remote sensing.

Table 2. Essential Climate variables and satellite remote sensing products used

Carbon product	parameter	sensor
Sea-Air CO_2 flux	wind	several
Sea-Air CO_2 flux	temp	several
Sea-Air CO_2 flux	salinity	Aquarius
Inventories	salinity	Aquarius
Inventories	altimeter	JASON

5. THE WAY FORWARD FOR THE NEXT TEN YEARS

Full implementation of the ocean carbon observing system is both critical and feasible over the next decade. During this time we'll see unprecedented increases in atmospheric CO_2 levels. This will lead to corresponding changes in the ocean both due to increasing CO_2 levels and the response of the global oceans to climate change.

The objectives, deliverables, and infrastructure of the sea surface CO_2 observing system in the next decade include providing monthly flux maps, reduce uncertainties in regional fluxes to within 10-15 %, and include sensor and infrastructure development, as outlined in the community white paper of Ocean Obs.-09[24]. The subsurface measurements provided by the repeat hydrography program provide data and constraints for several essential climate variables. For carbon the main objectives for the next decade are to determine the distributions and controls of natural and anthropogenic carbon (both organic and inorganic), and augment the historical database of full water column observations necessary for the study of long timescale changes.[25]

5.1. Maintaining and augmenting current infrastructure: research ships, SOOP, and moorings

The IOCOS will rely on the research ships and core measurements of the repeat hydrography program under the auspices of GOSHIP. Recent enhancements of the core measurement suite include the transient tracer, sulfur hexafluoride, and pH. The current plans for repeat hydrography will meet the IOCOS requirements but will depend on:

- Securing the needed ship time on Class I ships
- Implementing a strategy of transparent international collaboration including exchange of scientific personnel and capabilities of core measurements
- Implementing international open data sharing and data synthesis arrangements

The SOOP effort will need an approximately 20 % increase in ships over the next decade with:

- An emphasis on the undersampled regions in the Southern Ocean
- Augmentation of sensors to include other biogeochemical parameters (O_2), physical and acoustic measurement[19]
- Continuation and formalization of international data collation and synthesis efforts as part of IOOS

Mooring based measurements are expected to increase by about 100 % in the next decade taking advantage of the infrastructure of OceanSITES and coastal moorings. These augmentations will be done in tandem with the ocean acidification observing system. Key points of a mooring based CO_2 measurement system is:

- An emphasis on the coastal regions with high spatial and temporal variability
- Augmentation of sensors to measure pH and oxygen at the surface and in the subsurface
- Incorporation of data and findings into the surface ocean CO_2 databases and data products

There is also a need to augment current monitoring and data synthesis activities to regions of future focus, including upwelling areas, the Arctic, inland seas Southern Ocean and coastal systems.

The activities are currently taken place in largely bottom up, community-organized fashion. They should be supported in a more sustained fashion including program offices for:

- IOCCP
- GOSHIP
- SOLAS/IMBER Surface Interior Carbon
- IOOS

5.2. New observing techniques: profiling floats autonomous surface vehicles and numerical models

The IOCOS cannot meet its goals in the next decade without adaptation of strategies that incorporate new technologies and modeling. The profiling float program should continue to augment its instruments with oxygen sensors for monitoring both the decreasing oxygen levels in the ocean and areas of hypoxia, and because change in oxygen are a prime indicator of changes in the natural carbon cycle. Following recommendation from the ocean-obs09 all ≈ 3000 floats should be equipped with O_2 [18]. Other sensors of benefit for IOCOS and in advanced stages of development include pH and nitrate sensors.

Autonomous surface vehicles such as the wave glider and OASIS can be readily adapted with sensors developed for moorings to reach areas that are inaccessible by ships. These include remote areas such as the Southern Ocean, and areas with navigational hazards such as regions with sea-ice and shallow bathymetry. The capabilities of these vehicles should be incorporated in observing system design.

Increasing computer power and better understanding of how to incorporate biogeochemical and biological parameters into numerical models have led to more robust forecasting and nowcasting capabilities that are important component of IOCOS. Improved data assimilation techniques of assimilating relatively small datasets such as produced in IOCOS will lead to increased utilization of models in assessments of ocean carbon cycle changes.

5.3 Coordination, and data distribution management and synthesis

The IOCOS will be a consolidated effort of partners worldwide with different agency and national funding avenues, which makes formal collaborations imperative. The successes over the past decade make it clear that this can be attained but sustained support is critical. The hierarchy of efforts is as follows:

- Individual groups performing measurements according to specified protocols and quality control
- Rapid submission of data to Global Data Management Centers
- Establishment of global synthesis groups with experienced leads to create synthesis products and documentation
- Distribution of products in user-friendly format through global data centers

Major updates of global interior ocean carbon products, including the necessary physical, biogeochemical and transient tracer measurements should be created on decadal scales. Interim products and assessments reflecting regional foci such as the Arctic and coastal ocean need to be created.

For surface water CO_2 measurements used to estimate fluxes and global data products need to be updated at bi-annual scales, and seasonal proxies need to be created. Within the USA, the Carbon Dioxide Information and Analysis Center (CDIAC) of DOE[23] serves the current IOCOS products such as GLODAP, the Takahashi et al., global pCO_2 climatology and SOCAT. Synthesis efforts are coordinated at international level with corporate knowledge and oversight provided by Princeton University.

6. CONCLUSIONS

The key developments over the past decade and lessons learned for the next 10 year of the IOCOS are:

- IOCOS has met the goals of quantifying decadal changes of ocean carbon inventory along the repeat hydrography tracks to within 10 %
- IOCOS has provided a climatological observation- based estimate of global sea-air CO_2 fluxes that agrees with global constraints
- The observing system requirements should be adjusted taking advantage of advanced knowledge of processes, modeling, remote sensing and new instruments and platforms
- New observing systems such as those addressing ocean acidification and hypoxia can be developed synergistically with IOCOS
- The IOCOS in the next decade will meet the needs of higher temporal and spatial information of carbon fluxes and inventories to gain better understanding of regional impacts.

IOOS will play a key role in facilitating seamless connection and interplay of the different observing system elements to address the key environmental issues and changes experienced by the ocean.

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