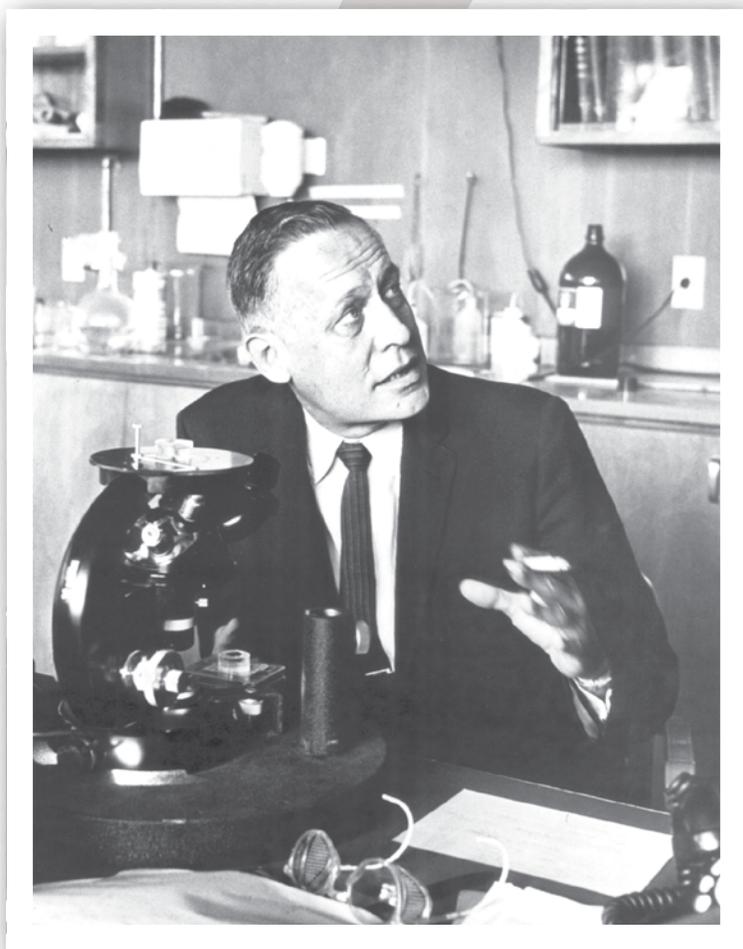


INTERNATIONAL CARBON COORDINATION



Roger Revelle in his lab circa 1958. Photo courtesy of
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*Roger Revelle's
Legacy in the
Intergovernmental
Oceanographic
Commission*

BY CHRISTOPHER L. SABINE,
HUGH DUCKLOW,
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ABSTRACT. Since its inception in 1960, the Intergovernmental Oceanographic Commission (IOC) has been responsible for organizing and coordinating the scientific investigation of ocean carbon. Roger Revelle (Scripps Institution of Oceanography) first articulated the principal need for international and intergovernmental coordination to address global-scale problems such as climate change when IOC was first developed. Regional to global-scale carbon studies started in earnest with the International Decade of Ocean Exploration (IDOE) and Geochemical Ocean Sections Study (GEOSECS) programs in the 1970s, but they were hampered by technological barriers that limited both the precision of carbon system measurements and the greater sampling frequency needed for a comprehensive global view. In 1979, IOC established the Committee on Climate Change and the Ocean (CCCCO) with Revelle as Chair. CCCC called for a carbon observation program and sampling strategy that could determine the global oceanic CO₂ inventory to an accuracy of 10–20 petagrams of carbon (Pg C). Perfection of the coulometric analysis technique of total dissolved inorganic carbon (DIC) in seawater by Ken Johnson (University of Rhode Island) and introduction of certified reference materials for DIC and alkalinity by Andrew Dickson (Scripps Institution of Oceanography) made such a study possible. The first global survey of ocean CO₂ was carried out under the joint sponsorship of IOC and the Scientific Committee on Oceanic Research (SCOR) in the Joint Global Ocean Flux Study (JGOFS) and the World Ocean Circulation Experiment (WOCE) in the 1990s. With these programs and underway pCO₂ measuring systems on research vessels and ships of opportunity, ocean carbon data grew exponentially, reaching about a million total measurements by 2002 when Taro Takahashi (Lamont-Doherty Earth Observatory) and others provided the first robust mapping of surface ocean CO₂. Using a new approach developed by Nicolas Gruber (ETH Zürich) and colleagues with JGOFS-WOCE and other synthesized data sets, one of this article's authors (Sabine) with a host of coauthors estimated that the total accumulation of anthropogenic CO₂ between 1800 and 1994 was 118 ± 19 Pg C, just within the uncertainty goals set by JGOFS and IOC prior to the global survey. Today, ocean carbon activities are coordinated through the International Ocean Carbon Coordination Project (IOCCP). Ocean carbon measurements now accumulate at a rate of over a million measurements per year—matching the total number achieved over the first three decades of ocean carbon studies. IOCCP is actively working to combine these data into uniform data sets that the community can use to better understand ocean carbon uptake and storage. The problem of ocean acidification caused by uptake of anthropogenic CO₂ is now a major target of IOC and IOCCP.

INTRODUCTION

Recognizing that global issues like climate change could only be addressed through international and intergovernmental cooperation, the Intergovernmental Conference on Oceanographic Research (also referred to as the “First Oceanographic Conference”) met in Copenhagen in 1960 to create the Intergovernmental Oceanographic Commission (IOC). From the beginning, the need to understand ocean carbon was seen as a major IOC driving force. During a Paris preparatory meeting for the Copenhagen conference in March 1960, Roger Revelle, then director of Scripps Institution of Oceanography, summarized the purposes of this new United Nations organization, citing the need for a better understanding of ocean carbon (Revelle, 1960):

In general, oceanographic research, like many other kinds of research, is best done by individuals or small groups working independently. However, there are some research problems that require international co-operation... Scientific problems that require nearly simultaneous observations over a wide area or over the entire ocean also demand international co-operation in taking the observations, and close co-ordination to ensure comparability of results. An example is the present

attempt to determine the total carbon dioxide content in the atmosphere and the change in this content with time as a result of the input from fossil fuel combustion and the loss to the ocean and biosphere. One of the questions we are asking is: Where is the carbon dioxide absorbed by the ocean? Does it remain in the surface layers or does it extend throughout the ocean volume?

At the time of this statement, it was assumed, based on fundamental thermodynamics, that the ocean was absorbing CO₂ from the atmosphere, but it was unclear how much was absorbed and how quickly it mixed throughout the ocean volume. There were relatively few high-quality inorganic carbon measurements in the ocean and no good techniques for isolating the anthropogenic component. The role of ocean biology in controlling carbon distributions in the ocean was also poorly understood from local to global scales. Revelle recognized the need for countries to work together to address these compelling global-scale questions.

Since its inception, IOC has been providing international coordination for ocean carbon and biogeochemical measurements, with its programs evolving to meet new challenges as the science progressed and coordination needs changed. As techniques develop

and more countries participate in large-scale field programs, the need for this type of coordination will become increasingly important. Through activities such as the International Ocean Carbon Coordination Project, IOC is

“**ROGER REVELLE WAS THE FIRST TO RECOGNIZE THAT UNDERSTANDING THE GIGANTIC GEOCHEMICAL EXPERIMENT BEING CONDUCTED BY ADDING FOSSIL FUEL CO₂ TO THE OCEAN REQUIRED AN INTERNATIONAL EFFORT OF UNPRECEDENTED SCALE, COMPLEXITY, AND INTEGRATION.**”

realizing the vision of coordination and cooperation envisioned by Revelle and the First Oceanographic Conference 50 years ago.

LONG-TERM AND EXPANDED PROGRAMME OF OCEAN EXPLORATION AND RESEARCH
IOC concentrated its early efforts in the 1960s on the International Indian Ocean Expedition, but there was little focus on ocean carbon, except for primary production measurements, until the 1970s when the United States initiated the International Decade of Ocean Exploration (IDOE). IOC

endorsed the US effort by initiating the Long-term and Expanded Programme of Ocean Exploration and Research (LEPOR), which highlighted the study of air-sea gas exchange and the effects of turbulence and breaking waves on

the exchange of elements such as halo-carbons and carbon dioxide (UNESCO, 1975). This new program also promoted the need for baseline geochemical surveys, including carbon dioxide, and studies of how climate variability impacts ocean biology.

The first high-quality, fully documented global inorganic ocean carbon measurements were carried out as part of the Geochemical Ocean Sections Study (GEOSECS) between 1971 and 1978. The GEOSECS program made roughly 6,000 measurements of dissolved inorganic carbon (DIC) and total alkalinity (TA) in the Atlantic, Pacific, and Indian oceans as well as the Mediterranean and Red seas (Figure 1).

Shortly after completion of the GEOSECS cruises, two publications independently proposed the first techniques for estimating anthropogenic CO₂ concentrations from ocean carbon measurements (Brewer, 1978; Chen and Millero, 1979). However,

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these approaches were criticized in the literature (e.g., Shiller, 1981; Broecker et al., 1985) and never found general acceptance in the community. Not only were there concerns about the calculation techniques, but there were also concerns about the magnitude of the anthropogenic signal relative to the large natural background of inorganic carbon in the ocean. The estimated accuracy of the GEOSECS measurements was $\sim \pm 20 \mu\text{mol kg}^{-1}$ (e.g., Takahashi et al., 1982). Although these measurements were state of the art at the time, Broecker et al. (1979) commented in an article in *Science* that "...unless [inorganic carbon] measurements that are more accurate by an order of magnitude can be made, at least a decade will pass before direct confirmation of the model-based [anthropogenic CO_2 uptake] estimates will be obtained." These words turned out to be prophetic, as it was more than a decade before another global carbon survey was attempted and nearly two decades before an improved technique for estimating anthropogenic CO_2 from DIC measurements was published.

Another notable achievement at the end of the 1970s was the development of the IOC/World Meteorological Organization (WMO)-Integrated Global Ocean Services System (IGOSS), which collected and exchanged data to produce ocean-related products and services. This program is the forerunner of today's IOC-WMO Joint Technical Commission on Oceanography and Marine Meteorology (JCOMM). The World Climate Programme was also developing the first Pilot Ocean Monitoring Study (POMS) as a precursor of a Global Ocean Observing System (GOOS), and was promoting the idea

of sustained global ocean observations. Initially, these programs focused their efforts on physical oceanographic observations. To complement these programs, the Scientific Committee on Oceanic Research (SCOR) teamed up with IOC to create the Committee on Climate Change and the Ocean (CCCCO), which included a strong biogeochemical component.

CCCCO CO_2 ADVISORY PANEL

Given the importance of understanding the connections between the ocean and climate change, Roger Revelle agreed to chair CCCCO when it was created in September 1979. As noted previously, there was concern that ocean CO_2 uptake estimates could not be properly constrained with the limited quality and number of observations available (Broecker et al., 1979; Brewer, 1986). In 1984, CCCCO established a CO_2 Advisory Panel, chaired by Revelle, which recommended the development of a carbon observation program and sampling strategy that could determine the global oceanic CO_2 inventory to an accuracy of 10–20 petagrams of carbon (Pg C).

This figure was at least twice as good as the best estimates at the time and would require a significant improvement in both measurement accuracy and data coverage relative to GEOSECS. The belief that this accuracy could be achieved was based on the development work of Johnson et al. (1985) to perfect the coulometric analysis of DIC, which provided a significant improvement in accuracy relative to the titrametric procedures used during GEOSECS.

In the early and mid 1980s, the US scientific community started developing a strategy for large-scale, coordinated biogeochemical process studies under the title Global Ocean Flux Study (GOFS). By 1987, several countries were planning similar carbon cycle and flux studies, so SCOR and the International Council of Scientific Unions (ICSU) gathered the leading experts in the ocean carbon cycle for a meeting in Paris to agree on the goals, scientific elements, topics of emphasis, and organizational structure for an internationally coordinated study known as the Joint Global Ocean Flux Study (SCOR, 1987).

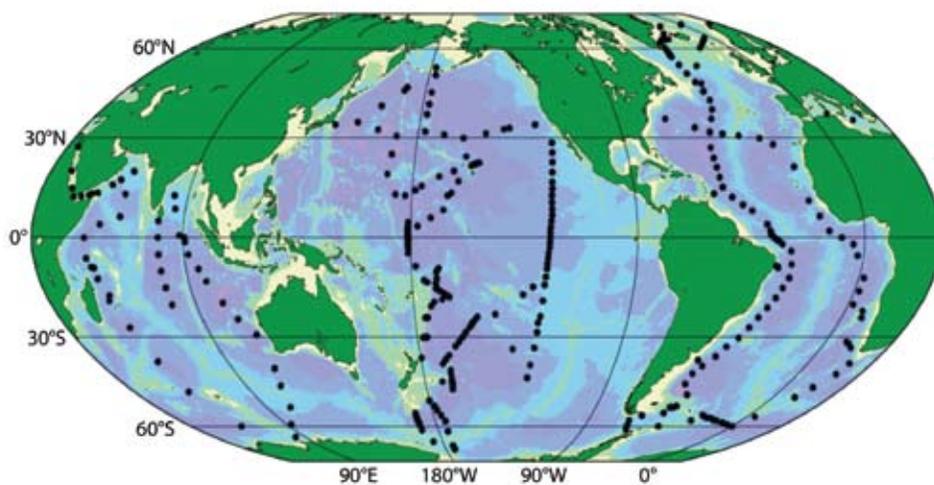


Figure 1. Map of station locations for the Geochemical Ocean Sections (GEOSECS) program (1972–1978).

Meeting participants recognized that understanding the carbon cycle would be central to JGOFS and that global oceanic CO₂ measurements would be critical to that understanding. JGOFS was developed under SCOR leadership in 1987, and the program was later accepted by the newly created International Geosphere-Biosphere Program (IGBP) in 1989 as its first ocean project, setting a precedent for wide support of international collaboration in the ocean sciences (JGOFS, 1990).

At the same time, the international physical oceanographic community was also organizing itself for a global study of ocean circulation called the World Ocean Circulation Experiment (WOCE). The intersection of the WOCE and JGOFS programs provided an opportunity for a comprehensive global survey of ocean carbon distributions that could accomplish the CO₂ inventory goal set by the CCCO CO₂ Advisory Panel and endorsed by JGOFS. After some negotiating, WOCE agreed to accommodate a small CO₂ contingent on the ships taking part in the WOCE Hydrographic Programme one-time global hydrographic survey.

JGOFS-CCCO ADVISORY PANEL ON OCEAN CO₂

Since the objectives of the SCOR-JGOFS and IOC-CCCO groups were congruent with respect to CO₂, it was agreed that JGOFS and CCCO should jointly assume responsibility for executing a global ocean CO₂ observation program. Accordingly, in September 1988 the CCCO panel was disbanded and the Joint JGOFS-CCCO Advisory Panel on Ocean CO₂ was created to provide the primary focal point for international

planning and commitments for implementing the carbon observations.

Although the carbon work had a purely research focus, CCCO was also promoting the establishment of a more operational sustained ocean observing system. Based on recommendations from the Technical Committee for Ocean Processes and Climate and the WMO Executive Council, the 15th IOC Assembly in July 1989 called for the design and implementation of a global operational observing system. Consequently, CCCO created an Ocean Observing System Development Panel (OOSDP) to specify the requirements for ocean measurements in support of climate observations. The first “official” use of the phrase Global Ocean Observing System (GOOS) to refer to this new system occurred during the 23rd IOC Executive Council meeting in March 1990. Later that year, endorsement of the GOOS concept widened further as the newly formed Intergovernmental Panel for Climate Change (IPCC) and the Second World Climate Conference both endorsed GOOS as a major component of the proposed Global Climate Observing System (GCOS).

The original US GOFS Program was conceived as “sediment traps and CO₂ measurements” (GOFS, 1984). In 1990, the international JGOFS program published a science plan that adopted an expanded ecological-biogeochemical focus, with a wide array of ecological measurements to undergird models relating ocean ecology (e.g., nitrogen cycling and new production) to the carbon cycle (JGOFS, 1990). One chapter of the 1990 science plan was devoted to large time/space surveys.

Components of this chapter included the global CO₂ survey in conjunction with WOCE, long time-series observations, and seasonal surveys of CO₂ partial pressure (*p*CO₂) in the surface ocean. The promotion of time series observations grew out of recognition that an understanding of variability over a range of time scales from seasonal to interannual was required to better understand the connection between climate and ocean biogeochemistry. Although a very few time series sites, such as the Canadian Station P time series in the North Pacific and the Icelandic time series in the Irminger and Iceland seas, were already making regular ocean observations, several large multidisciplinary time series sites were started around 1990. At that time, the United States had just started monthly shipboard time series sampling off Hawaii and Bermuda, including high-quality DIC analyses, sediment traps, and primary productivity measurements (Karl and Michaels, 1996). Other sites, including KERFIX (Kerguelen Fixed station) in the Southern Ocean, DYFAMED (DYNamique des Flux Atmosphériques en MEDiterranée) in the Mediterranean Sea, ESTOC (European Station for Time Series in the Ocean) near the Canary Islands, and CARIACO (Carbon Retention In A Colored Ocean) off Venezuela, were started as part of the international WOCE/JGOFS effort.

The seasonal *p*CO₂ surveys were prompted by the Tans et al. (1990) publication that combined 30 years worth of shipboard *p*CO₂ observations in an attempt to develop the first global estimates of air-sea CO₂ fluxes and examine the global carbon budget. This initial work suggested that the ocean

sink for CO₂ was only about half of the magnitude inferred from models (e.g., the first-generation, three-dimensional ocean carbon model of Maier-Reimer and Hasselmann [1987] or the ocean box model that used GEOSECS data by Bolin et al. [1983]). However, most of the high-latitude ocean was excluded because of lack of data. This work highlighted the need for a substantially increased surface observation program.

JGOFS-IOC ADVISORY PANEL ON OCEAN CO₂

Through the JGOFS program, the number of biogeochemical observations began to increase dramatically in the 1990s as did the need for coordination among groups and nations. A decision to phase out CCCO in December 1992 was followed by an agreement to continue the CO₂ Panel directly under IOC with joint sponsorship by JGOFS so the group could continue to facilitate international coordination and maintain active links to the ocean biogeochemistry community.

Some of the primary issues taken on by the CO₂ Panel were the need for standard analysis protocols and the utility of developing certified reference materials (CRMs) for the inorganic carbon measurements. Andrew Dickson (Scripps Institution of Oceanography) developed a technique for collecting and sterilizing large batches of seawater that were then bottled so they could be distributed to ocean carbon chemists to provide a secondary check on their instrument calibrations (see Dickson, 2010, in this issue). His first batch was bottled in January 1990 and was certified for DIC using coulometric and manometric analysis techniques. There were difficulties with some unstable batches during

the first year, but by 1992 production had stabilized and these CRMs were routinely being distributed to all of the US groups participating in the JGOFS/WOCE program as well as carbon chemists from several other countries. In 1994, CRMs were also certified for total alkalinity.

The CO₂ Advisory Panel facilitated the standardization of analyses by helping to organize instrument comparison exercises and establishing internationally agreed standard protocols. For example, a methods comparison exercise for DIC and total alkalinity organized by the CO₂ Advisory Panel clearly demonstrated the need for consistent methods and CRMs (Poisson et al., 1990a,b). By January 1994, the panel had helped produce the protocols for JGOFS core measurements (JGOFS, 1994) and the CO₂ Methods Handbook (DOE, 1994).

of macronutrients (e.g., nitrogen, phosphorus) but relatively little productivity as evidenced by low chlorophyll concentrations. From an ocean carbon standpoint, these high nutrient, low chlorophyll (HNLC) regions were also seen as a potential way of explaining the low ice age atmospheric CO₂ concentrations observed by Barnola et al. (1987) based on ice core data (i.e., increased iron dust stimulating ocean uptake of CO₂ during glacial periods) and as an opportunity for humans to increase modern ocean carbon uptake by fertilizing these HNLC regions with iron. John Martin (Moss Landing Marine Laboratories) is often quoted as having said at a seminar in Woods Hole, Massachusetts, “Give me a half tanker of iron, and I will give you an ice age.” Martin’s pioneering work on iron fertilization led to many in situ

“ THE CREATION OF IOC IN 1960 PROVIDED THE PLATFORM TO LAUNCH THIS EFFORT, WHICH GREW EVENTUALLY TO ENCOMPASS OVER A MILLION OCEAN CARBON SYSTEM MEASUREMENTS ANNUALLY, AND LAID THE GROUNDWORK FOR A GLOBAL OCEAN OBSERVING SYSTEM. ”

Another important development during the 1990s was introduction of the iron hypothesis—that primary productivity in some regions of the ocean is limited by the availability of certain micronutrients (Martin et al., 1994). A lack of available iron, an essential micronutrient for primary production, helped explain why there were large ocean regions with high concentrations

mesoscale iron fertilization process studies (see De Baar et al., 2005, and references therein) and investigations into the feasibility of purposeful ocean carbon sequestration. IOC, in collaboration with other UN organizations, addressed the issue of using the ocean to sequester excess atmospheric CO₂ with a comprehensive report highlighting the potential environmental

consequences and international legal questions surrounding this proposal (GESAMP, 1997).

The field portions of the WOCE and JGOFS programs ran for about a decade. In total, nearly 100 WOCE Hydrographic Programme cruises were run with CO₂ chemists aboard (Figure 2). Carbon measurements were a standard component of all JGOFS cruises. Iron fertilization studies were conducted in a variety of HNLC regions. Underway surface pCO₂ measurements became more frequently collected on research cruises and the JGOFS time-series sites were clearly showing variability over a range of time scales (e.g., Winn et al., 1994; Bates, 2002).

IOC-SCOR OCEAN CO₂ ADVISORY PANEL

With the completion of the JGOFS field components in the late 1990s and the emergence of GOOS, the CO₂ Advisory Panel was restructured as the joint IOC-SCOR Ocean CO₂ Advisory Panel with a focus on developing recommendations for an ocean carbon observing

system, including data management and synthesis activities, and on providing scientific and technical advice on ocean carbon sequestration. This new panel met for the first time in September 2000 under the chairmanship of Douglas Wallace (Leibniz Institute of Marine Sciences at the Christian-Albrechts Universität zu Kiel) and laid the foundations for the GOOS background report on establishing a global ocean carbon observation system (UNESCO, 2002). This report outlined ongoing ocean carbon observations as well as the many technical challenges that would need to be overcome to establish a system of ocean carbon measurements that could meet scientific goals. One of the biggest challenges to be tackled was how to appropriately and adequately measure the highly variable surface pCO₂.

The number of surface CO₂ observations grew exponentially through the 1960s, 1970s, and 1980s (Figure 3A), but with JGOFS, WOCE, and the strong focus on ocean carbon research in the 1990s, many more ships were instrumented with underway pCO₂ systems

during the last decade of the century (Figure 3B). Given the spatial and temporal variability of surface pCO₂, however, there were not enough global observations to develop robust surface pCO₂ maps until the late 1990s.

In 1997, Taro Takahashi (Lamont Doherty Earth Observatory) compiled 30 years worth of surface ocean CO₂ observations (~ 250,000 measurements) to produce the first monthly global surface pCO₂ maps (Takahashi et al., 1997). Although the number of research cruises dropped dramatically at the end of the WOCE/JGOFS program (Figure 4), the number of surface CO₂ observations continued to increase (Figure 3). Part of the reason for this change was the placement of underway CO₂ systems on research vessels and commercial ships of opportunity (SOOP). The IOC-SCOR Ocean CO₂ Advisory Panel was able to help facilitate the growth of SOOP carbon observations by promoting pCO₂ system comparison exercises (e.g., Koertzing et al., 2000) and through its IOC connection to the developing GOOS, which was also instrumenting commercial ships with physical oceanographic equipment. By the time Takahashi updated his climatology in 2002, the surface pCO₂ database had grown from approximately 250,000 measurements to more than 940,000 (Takahashi et al., 2002). Approximately three million measurements were included in his latest update (Takahashi et al., 2009).

In the years following the WOCE/JGOFS field programs, the number of ocean interior carbon observations dropped precipitously because the programs moved to synthesis and modeling (Figure 4). As part of the

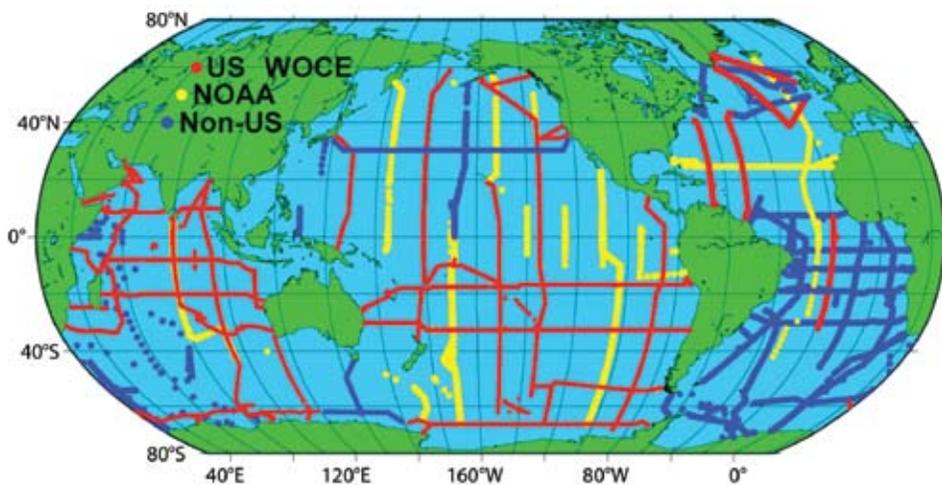


Figure 2. Map of station locations for the World Ocean Circulation Experiment/ Joint Global Ocean Flux Study (WOCE/JGOFS) surveys (1990–1998).

synthesis phase, the ocean carbon community began collecting and quality controlling the publicly available survey data through GLODAP (Global Ocean Data Analysis Project; http://cdiac.esd.ornl.gov/oceans/glodap/Glodap_home.htm). Complementary efforts through CARINA (Carbon Dioxide in the Atlantic Ocean; <http://store.pangaea.de/Projects/CARBOOCEAN/carina/index.htm>) and PICES (North Pacific Marine Science Organization; <http://www.pices.int>) were started to gather and archive data sets that were not publicly available so they would not be lost to the community.

The GLODAP synthesis accumulated approximately 72,000 observations collected by eight different countries over about a 10-year period. After going through an extensive quality assurance procedure, the DIC measurements were estimated to have an overall accuracy of $\sim \pm 2 \mu\text{mol kg}^{-1}$, finally achieving Broecker's prescription (Broecker, 1979; Sabine et al., 2005). However, the international community had yet to achieve the goal of estimating the ocean carbon inventory to $\pm 10\text{--}20 \text{ Pg C}$ that it had identified nearly two decades earlier.

Despite the questions raised by the Tans et al. (1990) paper over the ocean carbon sink and the increased emphasis on understanding the global carbon cycle for IPCC assessments, little progress was made on quantifying the ocean carbon inventory through most of the 1990s. Arthur Chen (National Sun Yat-sen University) and colleagues continued to publish regional anthropogenic carbon inventories based on the controversial Chen and Millero (1978) technique. By 1993, Chen had developed a DIC-based global anthropogenic CO_2

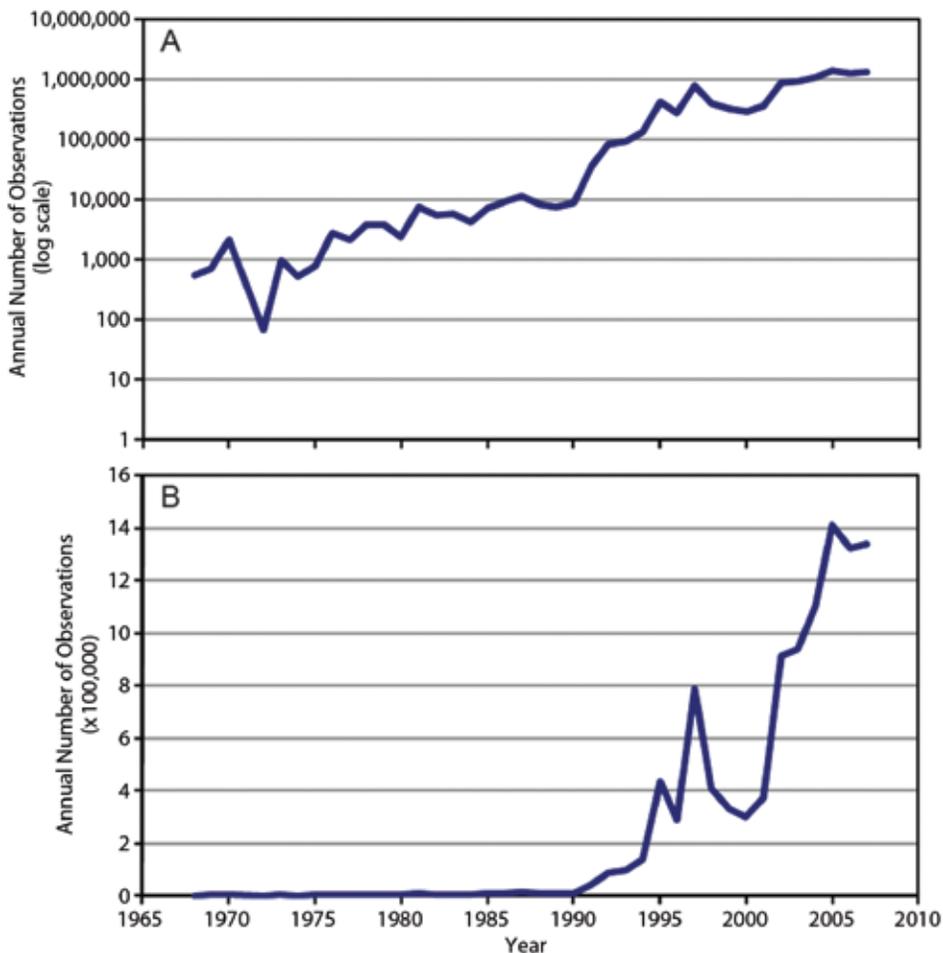


Figure 3. Plot of the annual number of surface CO_2 observations by year on a log scale (A) and on a linear scale (B).

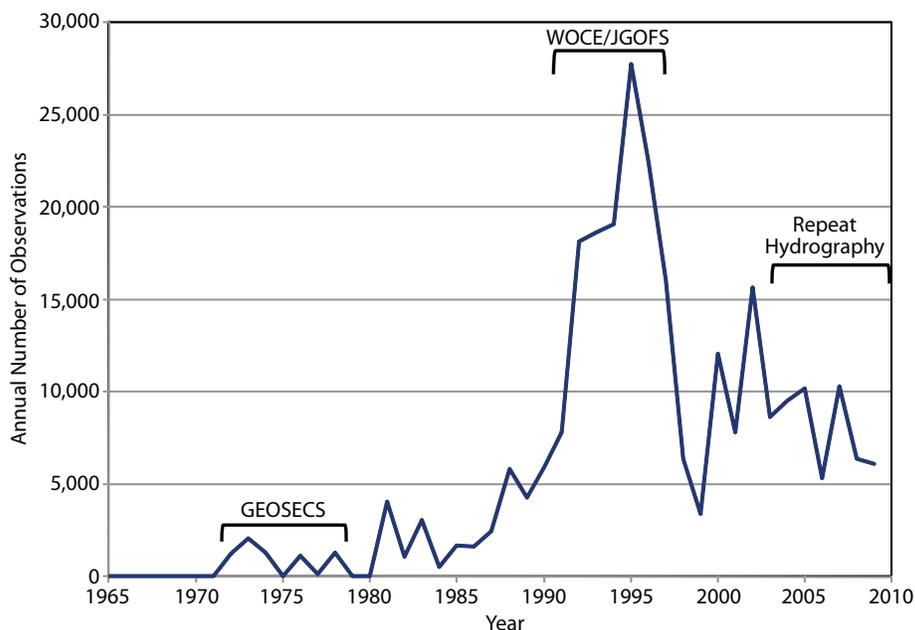


Figure 4. Plot of the annual number of ocean interior CO_2 observations by year.

estimate of 90 Pg C based primarily on the GEOSECS data (Chen, 1993). However, the large uncertainties associated with this work highlighted the need to improve the measurements and calculation techniques.

While some scientists focused on developing techniques for estimating ocean carbon uptake (e.g., Quay et al., 1992), it was not until nearly 20 years after the original inventory estimation techniques were introduced that a refinement of the anthropogenic CO₂ inventory approach was developed (Gruber et al., 1996; Gruber, 1998). This revised technique together with the newly developed GLODAP synthesized data set allowed Sabine et al. (2004) to estimate that the total accumulation of anthropogenic CO₂ between 1800 and 1994 was 118 ± 19 Pg C, just within the uncertainty goals set by JGOFS and IOC prior to the global survey (Figure 5).

THE INTERNATIONAL OCEAN CARBON COORDINATION PROJECT

In the early 2000s, global carbon cycle research again began to accelerate and more countries were becoming involved. The existing model of ocean carbon coordination through a small advisory panel that made recommendations to the community was not able to meet the coordination needs of the community. At one international meeting, some of the participants complained that the CO₂ Panel had been showing the same slide of recommended actions for nearly 15 years, but no international group existed to actually carry out the recommended coordination activities. With this incentive, the IOC-SCOR Ocean CO₂ Advisory Panel joined

with the newly formed Global Carbon Project (GCP, a joint effort under the International Geosphere-Biosphere Programme [IGBP], the World Climate Research Programme, and the International Human Dimensions Programme) to develop a pilot project called the International Ocean Carbon Coordination Project (IOCCP). A member of the GCP steering committee, author Christopher Sabine (NOAA/PMEL), agreed to chair the new pilot project to help develop a new approach to international coordination focused on implementing coordination actions rather than simply providing scientific and technical advice. IOCCP also began serving as a central communication and coordination forum to facilitate the development of ocean carbon data products that could be integrated with the terrestrial, atmospheric, and human dimension components of the

global carbon cycle.

GCP recognized that the best way to facilitate interactions and collaborations among scientists was to bring them together in workshops to share information and discuss ideas. To provide comprehensive and inclusive ocean carbon involvement in the new GCP, participation in IOCCP activities was opened to all ocean carbon scientists, led by a steering group of experts who took responsibility for coordinating key areas of ocean carbon observations. IOCCP also employed a bottom-up approach of providing communication and coordination services for all existing national, regional, and global ocean carbon observation programs without requiring adherence to or membership in any particular program or strategy. Coordination activities were built around bringing groups of experts together for focused workshops

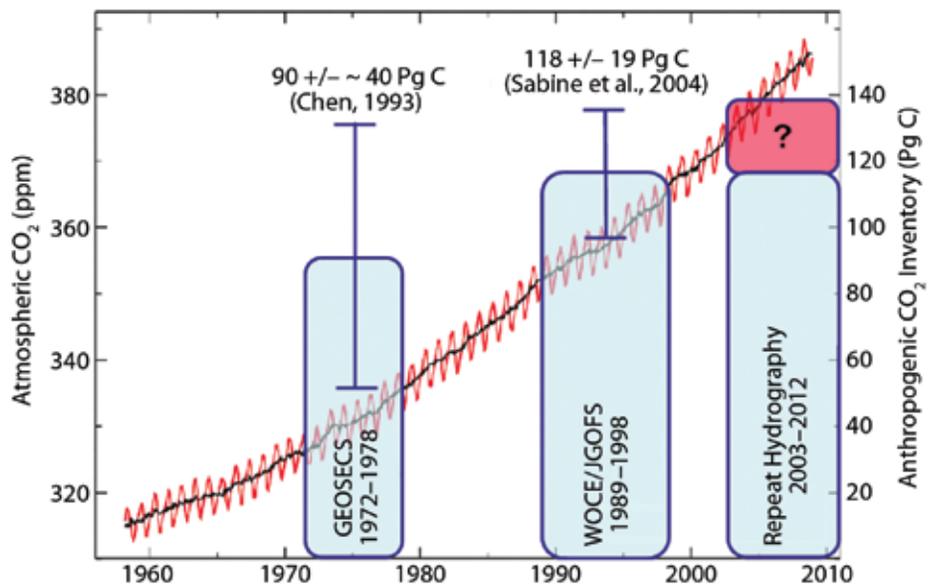


Figure 5. Plot of the monthly increase in atmospheric CO₂ at Mauna Loa, HI (left scale). Blue boxes show the time frame and global ocean anthropogenic CO₂ magnitude for the GEOSECS and WOCE/JGOFS global surveys (right scale). Data courtesy of Scripps Institution of Oceanography and NOAA Earth System Research Laboratory

to discuss technical coordination needs, to ensure the compatibility and comparability of results, and to identify the gaps, duplications, and requirements for meeting common global research and observational goals.

One of IOCCP's first activities was to organize the interior ocean carbon measurement groups to assess their current needs. The group recognized that one of the shortcomings of the back calculation approach is that it only provides a single snapshot of the ocean carbon inventory. It does not indicate how the ocean carbon storage is changing with time. Working with the new international research program, Climate Variability and Predictability (CLIVAR), IOCCP helped initiate an international effort to reoccupy a subset of the WOCE/JGOFS lines to evaluate decadal changes in ocean carbon storage (Figure 5). IOCCP also worked closely with the developing Surface Ocean-Lower Atmosphere Study (SOLAS) and the Integrated Marine Biogeochemistry and Ecosystem Research Program (IMBER), both of which include some aspects of ocean carbon in their strategies, requiring both technical and scientific coordination.

After two international stakeholders' meetings, IOCCP was recognized as a successful model for global-scale coordination and was requested to expand its mandate to include communication and coordination services for the full range of ocean carbon variables (not just CO₂) and to assist the global, regional, and national research programs as requested with coordination of research activities (not just large-scale observations). In 2005, IOC and SCOR agreed to make IOCCP a standing project,

replacing the CO₂ Panel, with new terms of reference approved by the SCOR Executive Council and the 23rd Session of the IOC Assembly.

COORDINATION OF TODAY'S OCEAN CARBON OBSERVATIONS

With the creation of IOCCP, IOC's ocean carbon programs have evolved from a 12-person advisory panel to a communication and coordination service for the ocean carbon community, with over 200 participants from 24 countries. Communication remains a core activity of IOCCP, with the belief that knowing "who is doing what and where" at any given time is crucial for coordination. To meet this goal, IOCCP compiles and maintains information about ocean carbon observations being carried out in national, regional, and global research programs and provides this information through maps, tables, news, and links published in an online Ocean Carbon Directory (<http://www.ioccp.org>). With this baseline information, IOCCP then brings together the community to analyze ongoing and planned activities, to ensure that the data from individual activities is comparable (e.g., through development and use of reference materials, quality control and quality assurance procedures, standard practices), and that the coverage from this combined network is sufficient to meet research needs for basin- and global-scale issues (and where it is inadequate, to identify and prioritize needs).

IOCCP works closely with numerous research and observation programs to maintain the most up-to-date and accurate information possible. IOCCP also works directly with the GOOS-GCOS-

WCRP Ocean Observations Panel for Climate (OOPC) and WMO-IOC JCOMM to integrate ocean carbon observation information into the plans of the Global Observing Systems for Climate in support of the United Nations Framework Convention on Climate Change, the World Summit on Sustainable Development, the Group on Earth Observations, and other international strategies on a regular basis.

In the seven years since its inception, IOCCP has held 18 workshops or meetings and has published and/or co-sponsored the publication of 16 reports, guides, and strategy documents. Through IOCCP, IOC is achieving the international cooperation in ocean carbon observations that Roger Revelle was promoting back in 1960.

Repeat Hydrography

Coordination of interior ocean carbon measurements has been a primary objective of IOC since its inception. Historically, large-scale survey cruises have been conducted as part of intensive field programs for a few years followed by periods with relatively few cruises. The GEOSECS program in the 1970s provided a first glimpse into the biogeochemical differences between the Atlantic, Pacific, and Indian oceans. The JGOFS and WOCE programs gave us the first large-scale examination of the physical and ecological mechanisms controlling the ocean carbon cycle in different regions and provided a detailed baseline assessment of ocean properties that will be used for decades to evaluate long-term changes in ocean physics and chemistry. The WOCE/JGOFS period was unprecedented in the level of support and number of observations

collected (Figure 4). This level of support, however, was not sustainable. The drastic decrease in cruises after the WOCE/JGOFS field program period forced a number of analytical labs to be shut down.

It is clear that the ocean is accumulating anthropogenic CO₂ (Figure 5). The number of new techniques proposed for estimating ocean inventories of anthropogenic CO₂ has increased substantially over the last decade (see Sabine and Tanhua, 2010, and references therein). Despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Ship-based hydrography is essential for documenting ocean changes throughout the water column, especially for the deep ocean below 2 km (52% of global ocean volume).

In collaboration with the international research programs, IOCCP is working to promote a sustained, repeat, ship-based hydrography program called the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP) that would be a component of the Global Ocean/Climate Observing System (<http://www.go-ship.org>). The principal scientific objectives for repeat hydrography have two closely linked components: (1) understanding and documenting large-scale ocean water property distributions, their changes, and drivers of those changes, and (2) addressing questions of a future ocean that will increase in DIC, become more acidic and more stratified, and experience changes in circulation and ventilation processes

due to global warming, an altered water cycle, and sea ice. A sustained observation program will help maintain a more consistent presence of research cruises that will be able to detect changes, both anticipated and unexpected, in the ocean carbon cycle.

Surface CO₂ Observations

Historically, surface CO₂ observations were made primarily on carbon and biogeochemistry cruises where the scientists for that expedition were interested in surface CO₂ variability. As the systems became more robust, they were frequently deployed on ships for extended periods and allowed to collect data even when the goals of the expedition did not directly involve CO₂. This change was made both because the large amount of overhead involved in setting up the instruments made it easier to just leave them installed on the ship, and because the systems could be run with minimal impact on the other ship operations. These systems did, however, generally require a scientist to spend some time each day maintaining them. As further development made the systems more autonomous and commercially available, scientists started installing the instruments on commercial ships. This strategy significantly increased the options for collecting data and began to provide better seasonal coverage as the commercial ships frequently transited back and forth along the same routes, while the research ships rarely reoccupied the same area on a regular basis.

Surface observations have become an important part of many national and regional research agendas. Today more than 1.3 million observations are made each year in all of the major ocean

basins, with operations involving more than a dozen countries (Figures 3 and 6). These data, however, still are not sufficient for directly constraining the net annual air-sea exchange globally. As a result, the community is exploring additional novel platforms for collecting data as well as empirical algorithms for extrapolating measurements using remotely sensed data (e.g., Watson et al., 2009). Autonomous CO₂ systems have been designed for moorings and drifters, so the expectation is that the data stream for surface observations will continue to grow.

The greatest value of these data is in the large-scale patterns they reveal, so international coordination and synthesis is becoming increasingly important. At a workshop co-sponsored by IOCCP in April 2007, participants agreed to establish a global surface CO₂ data set that would bring together, in a common format, all publicly available surface CO₂ data for the ocean. The Surface Ocean CO₂ Atlas (SOCAT) project, coordinated through IOCCP, has already compiled more than six million data points collected on 2171 cruises by 12 countries between 1968 and 2007 (<http://www.socat.info>). A quality-controlled data set should be released to the public in the summer of 2011.

Ocean Carbon Sequestration and Ocean Acidification

After the publication in 2001 of an Ocean Carbon Sequestration Watching Brief (ioc.unesco.org/iocweb/co2panel/Docs/WBprintfriendly.pdf), the IOC-SCOR Ocean CO₂ Advisory Panel discussed the need for an international symposium to examine all forms of ocean carbon sequestration being

proposed. During the initial planning for that meeting, it was suggested that a more in-depth look at the consequences of storing anthropogenic CO₂ in the ocean, including ocean acidification, should be examined. As discussions continued, it became clear that the issue of ocean acidification was in itself a subject that required immediate attention.

In May 2004, SCOR and IOC hosted an international symposium, The Ocean in a High CO₂ World, to evaluate what is known about how rising CO₂ levels in the ocean might impact marine ecosystems and services, as well as the possible benefits or impacts of ocean CO₂ mitigation strategies. This symposium brought together 120 of the world's leading scientists from 18 countries with expertise from different branches of marine biology, chemistry, and physics to identify urgent research priorities for

understanding the mechanisms, magnitude, and time scale of ocean acidification impacts. The journal *Nature* recently referred to this symposium as “a turning point in expanding awareness among scientists about acidification.” As of the end of 2009, approximately 60% of the peer-reviewed research on ocean acidification had been published following the 2004 symposium. IOC and SCOR, joined by IGBP and the Marine Environmental Laboratory of the International Atomic Energy Agency, hosted a second symposium on The Ocean in a High CO₂ World in 2008 at the Oceanographic Museum of Monaco under the High Patronage of His Serene Highness Prince Albert II, with 240 scientists from 32 countries attending. The symposium produced The Monaco Declaration with a foreword from Prince Albert II, which called for immediate action to lower CO₂ concentrations to avoid the worst of the impacts

expected from ocean acidification (<http://www.ocean-acidification.net>).

IOC is currently working with the European Project on Ocean Acidification (EPOCA; <http://www.epoca-project.eu>), the US Ocean Carbon and Biogeochemistry Program (<http://www.us-ocb.org>), and other national research groups to develop a Guide to Best Practices for Ocean Acidification Research and Data Reporting. IOC and its partners have also started planning for the 3rd Symposium on The Ocean in a High CO₂ World, scheduled for 2012. Although these meetings have developed a primary focus on ocean acidification, the debate on ocean fertilization and purposeful ocean carbon storage is far from over, and IOC also continues to address these scientific and technical issues in collaboration with the International Maritime Organization (IMO) and its London Convention.

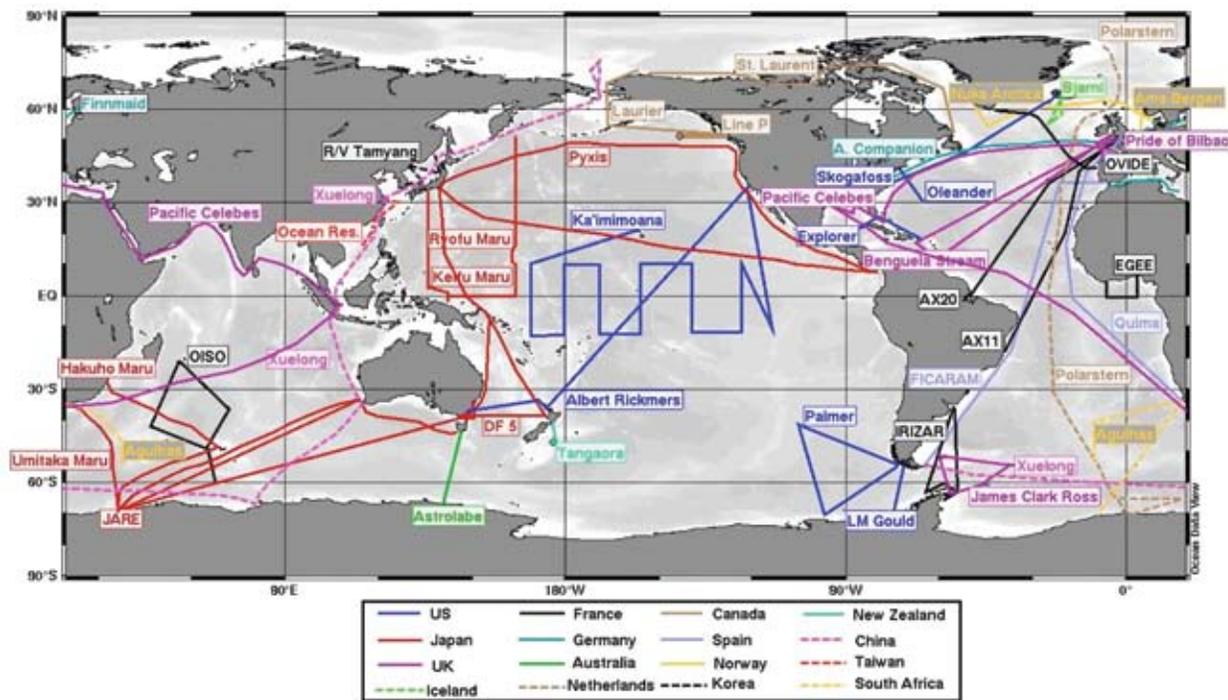


Figure 6. Map of repeated or one-time underway surface CO₂ measurements conducted during the period 2000–2009.

SUMMARY

Roger Revelle was the first to recognize that understanding the gigantic geochemical experiment being conducted by adding fossil fuel CO₂ to the ocean required an international effort of unprecedented scale, complexity, and integration. The creation of IOC in 1960 provided the platform to

were conducted is now being redirected toward large multinational studies of the mechanisms, pace, and consequences of ocean acidification resulting from anthropogenic CO₂ uptake, once again under IOC and SCOR leadership. Efforts to address the ocean carbon problem stand as the signature contribution of IOC's first 50 years.

“ UNDERSTANDING THE RESPECTIVE ROLES OF OCEAN PHYSICS, CHEMISTRY, AND BIOLOGY HAS BEEN A MAJOR FOCUS OF IOC AND SCOR-COORDINATED OCEAN RESEARCH SINCE THE 1980s. ”

launch this effort, which grew eventually to encompass over a million ocean carbon system measurements annually, and laid the groundwork for a global ocean observing system. Even with this huge enterprise, ocean scientists needed almost four decades to isolate and accurately quantify the anthropogenic component of CO₂ dissolved in the ocean water column.

Revelle had noted as early as 1960 that the ocean carbon problem had biological as well as geochemical dimensions. Understanding the respective roles of ocean physics, chemistry, and biology has been a major focus of IOC and SCOR-coordinated ocean research since the 1980s. The ocean science community has made great progress in understanding the biological processes responsible for the HNLC regions of the ocean through a series of international mesoscale iron addition experiments. The zeal with which these experiments

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