A New Wave of Ocean Science

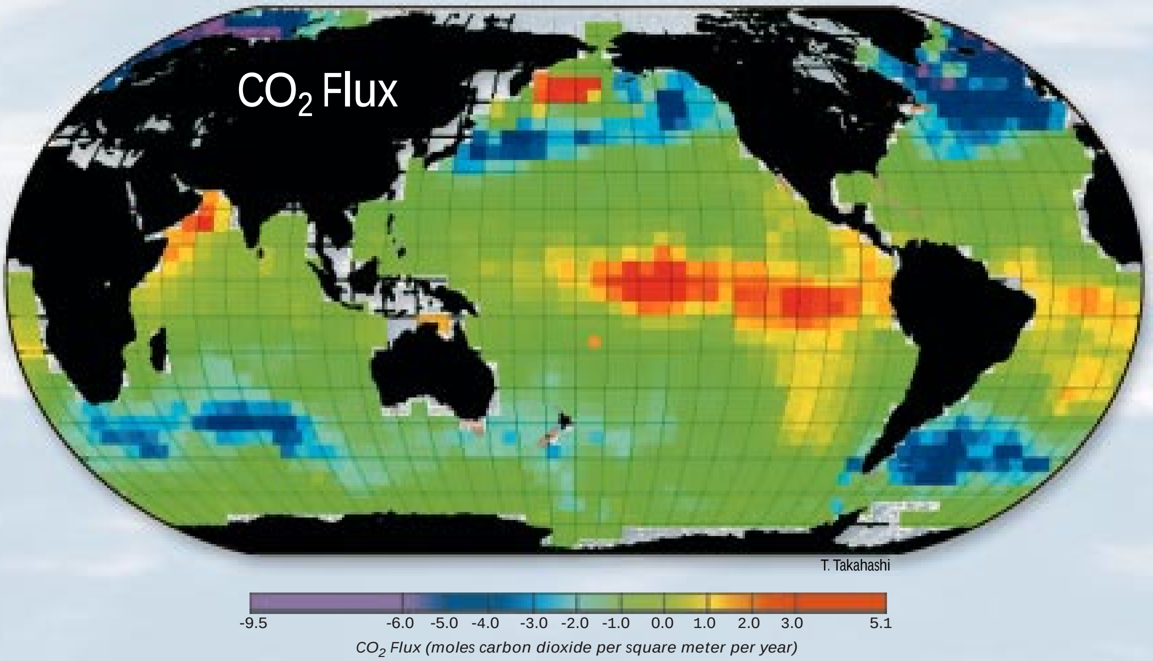
U.S. Joint Global Ocean Flux Study

Why Study the Ocean Carbon Cycle?

The ocean, which covers 71% of the surface of our planet, plays a major role in shaping the Earth's climate. One of the ways it does so is by regulating the global cycles of elements such as carbon, essential to life on Earth and an important player in the global climate system. Human activities, such as the burning of fossil fuels or the conversion of forests into pasture and farmland, currently release roughly 6.5 billion metric tons of carbon into the atmosphere each year in the form of carbon dioxide (CO_2). This increase in CO_2 and other trace gases in the atmosphere is contributing to rising temperatures by strengthening the "greenhouse" effect that prevents heat from escaping into space.

Only about half of the carbon released through human activities remains in the atmosphere. The rest ends up either in the ocean, which contains about 50 times more CO_2 than the atmosphere, or in plants and soils on land. How long carbon from the atmosphere is stored in these land and ocean reservoirs depends upon many factors.

Because the ocean and the atmosphere are tightly linked in the global climate system, changes in either can affect the other. Scientists study the cycling of carbon in the ocean to understand the natural processes that control the size and distribution of the ocean carbon reservoir. They also observe the effects that human activities are having on these processes. Our ability to predict and perhaps to alter the course of climate change requires a detailed understanding of the ways in which carbon in the ocean is transformed, transported, recycled or buried in the sediments of the sea floor.



T. Takahashi

This map, based upon more than 500,000 measurements of CO_2 in surface waters, allows us to see regional-scale patterns of the flux of CO_2 between the ocean and the atmosphere during an average year. Areas of the ocean that take up large amounts of CO_2 from the atmosphere are shown in blue and purple, while areas that release CO_2 into the atmosphere are shown in red and yellow.

S. Manganini

The U.S. Joint Global Ocean Flux Study

Launched more than a decade ago, the U.S. Joint Global Ocean Flux Study (U.S. JGOFS) is the most ambitious ocean biogeochemical research program ever mounted. The goal of this program is to understand the processes controlling the cycles of carbon and associated elements in the ocean. This knowledge is needed to predict the ocean's response to change and to appreciate its role in global climate cycles.

JGOFS, a component of the International Geosphere-Biosphere Programme, is a multinational and multidisciplinary program involving scientists from more than 30 countries. As part of this international program, U.S. JGOFS scientists established long-term time-series programs at sites near Hawaii and Bermuda, conducted detailed studies in critical ocean regions, and carried out a global survey of CO_2 in the ocean with another major ocean program, the World Ocean Circulation Experiment.

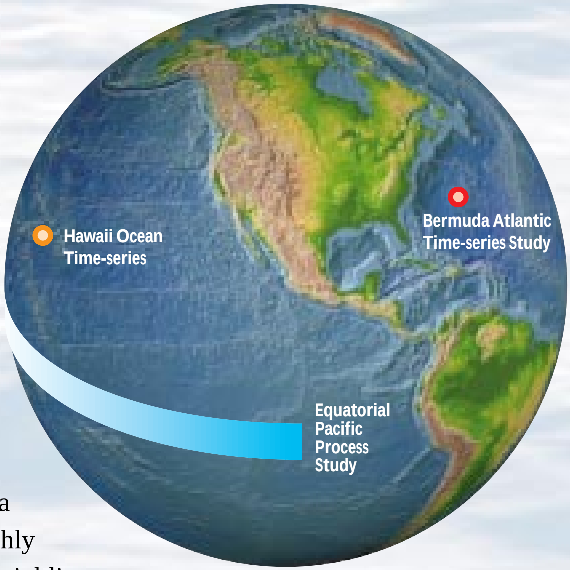
JGOFS has contributed to the emergence of ocean biogeochemistry as a discipline with a focus on the linkages among physical, chemical, and biological factors affecting the distribution of carbon and other biologically relevant elements. JGOFS investigators have begun to compile long-term evidence of links among climate patterns, ocean ecosystems, and the flux or movement of carbon between the ocean and its atmospheric and sedimentary boundaries. Older, simpler views of a stable, unchanging ocean are giving way to a new appreciation of the complexity of biogeochemical systems and their variability over time and space. A new wave in ocean science is emerging.

JGOFS Goals

- **to determine and understand on a global scale the processes controlling the time-varying fluxes of carbon and associated biogenic elements in the ocean, and to evaluate the related exchanges with the atmosphere, sea floor and continental boundaries**
- **to develop a capacity to predict on a global scale the response of oceanic biogeochemical processes to anthropogenic perturbations, in particular those related to climate change**

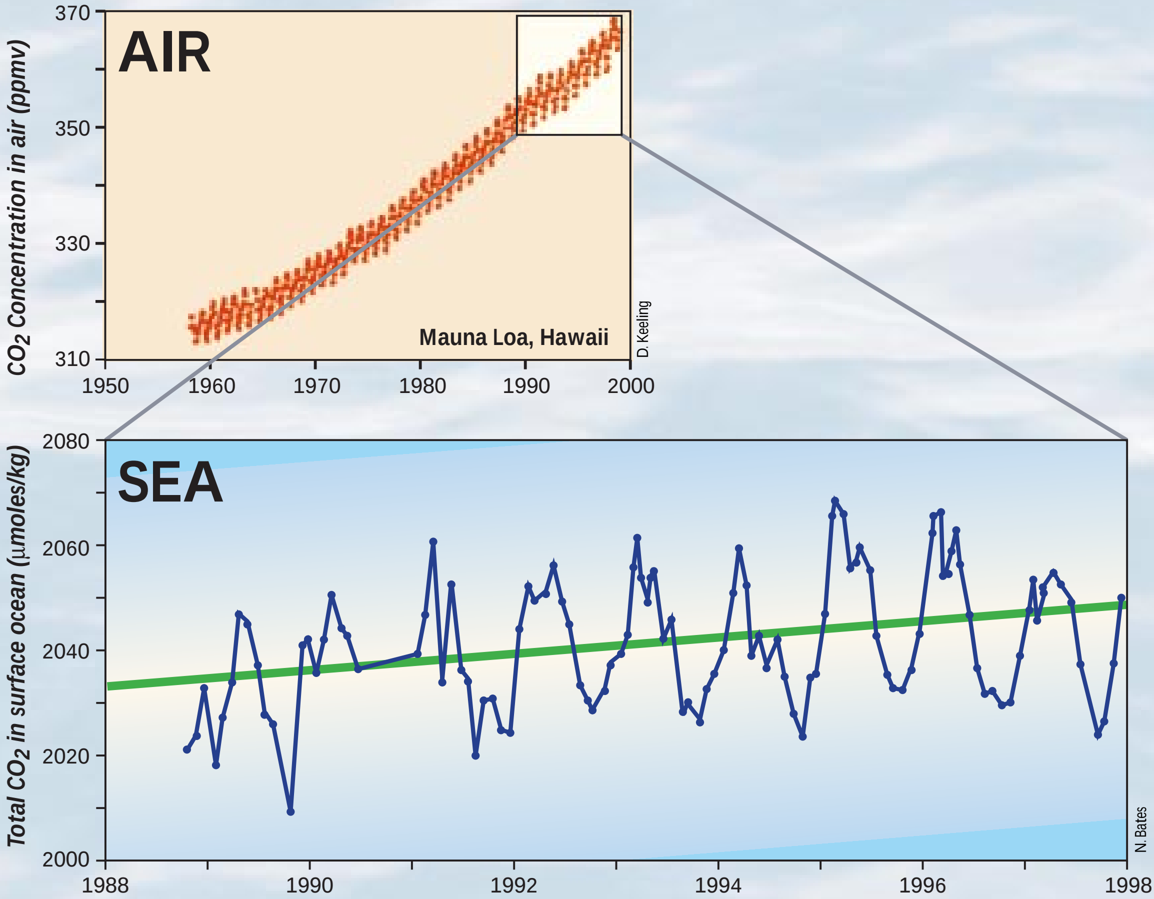
Changes in the Ocean Carbon Cycle:

The Value of Long-term Records



Observing changes as they occur over time helps scientists understand how systems work. Long-term observations have been a key part of the U.S. JGOFS research program since 1988, when time-series studies were launched at open-ocean sites near Hawaii in the Pacific and Bermuda in the Atlantic. The data sets amassed during monthly cruises to these sites over more than a decade are yielding a wealth of information on seasonal fluctuations, interannual variability and decadal changes in many oceanic properties, including components of the carbon system.

Measurements begun in 1958 at the summit of Mauna Loa in Hawaii have documented the rise in CO_2 levels in the atmosphere. As the accompanying figure shows, the data collected at the U.S. JGOFS time-series stations are allowing us to document for the first time a parallel increase in CO_2 in surface ocean waters.

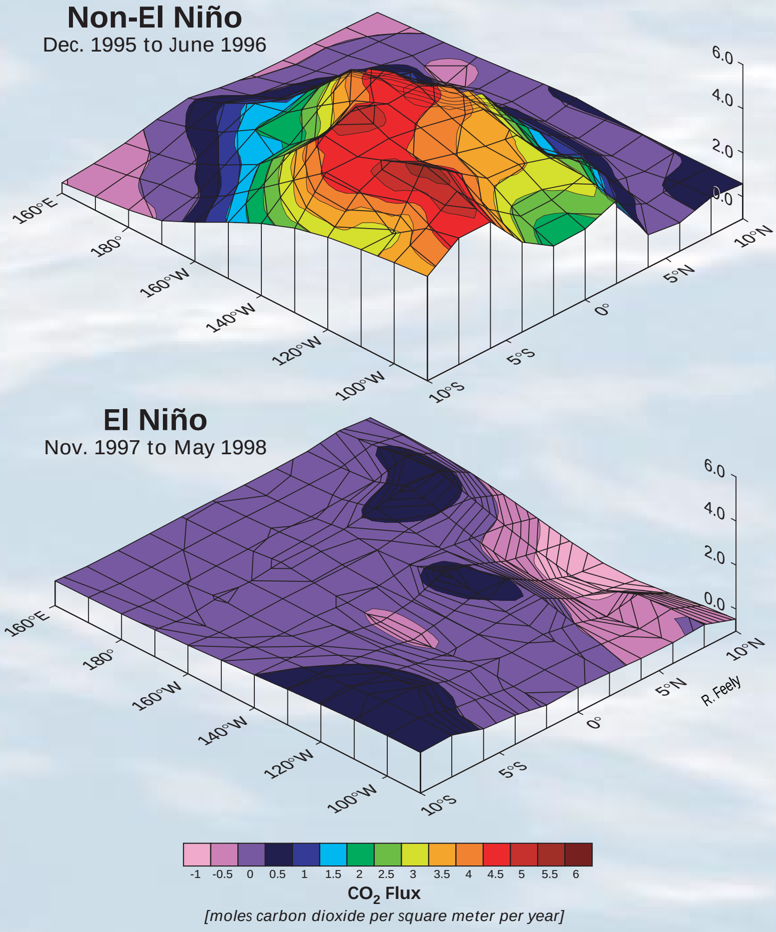


Ocean Variability

Cold surface waters in the polar regions sink to the ocean bottom, carrying with them CO_2 taken up from the atmosphere, and flow towards the equator. Upwelling brings cold water, rich in nutrients and dissolved inorganic carbon, to the surface in the equatorial ocean. During normal years, upwelling is particularly strong in the central and eastern Pacific, which releases four times more CO_2 into the atmosphere each year than all the other equatorial regions combined.

Episodic changes in atmospheric pressure, wind direction and sea-surface temperature that occur in the equatorial Pacific and beyond are a result of a recurring phenomenon referred to as the El Niño-Southern Oscillation (ENSO) cycle. U.S. JGOFS scientists working in the equatorial Pacific investigated the linkages between variations in the amount of CO_2 released in this region and the state of the ENSO cycle. They hypothesized that these variations play a major part in the global interannual variability in the exchange of CO_2 between the ocean and the atmosphere.

JGOFS field studies in the equatorial Pacific between 1995 and 1998 captured this interannual variability and its links to the state of the ENSO cycle. As this figure shows, the weaker winds and reduced upwelling that occur during El Niño conditions reduce the release of CO_2 from the surface waters of the equatorial Pacific by more than 75% (from roughly 0.9 to roughly 0.2 billion metric tons of carbon per year).

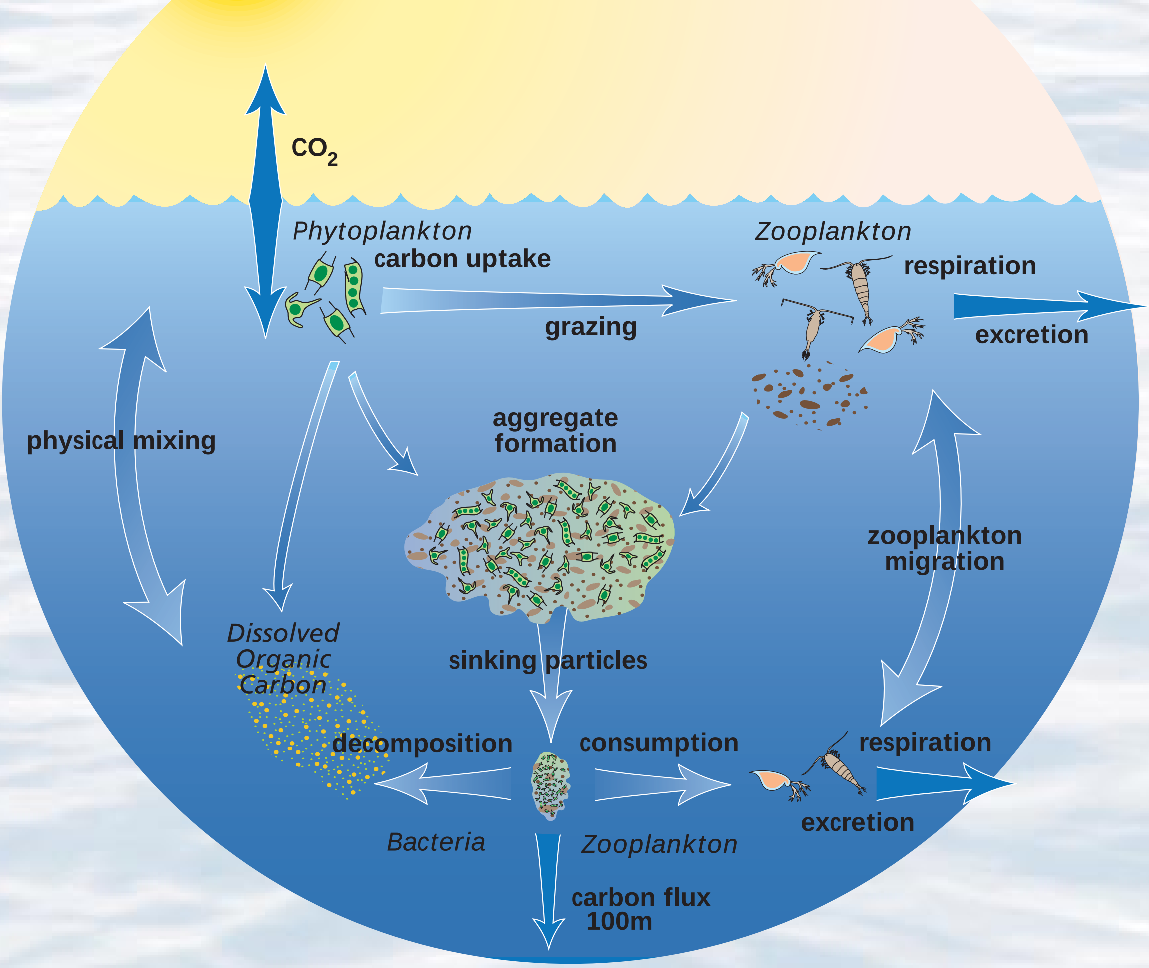

Non-El Niño
Dec. 1995 to June 1996

El Niño
Nov. 1997 to May 1998

Measuring CO_2 in Seawater

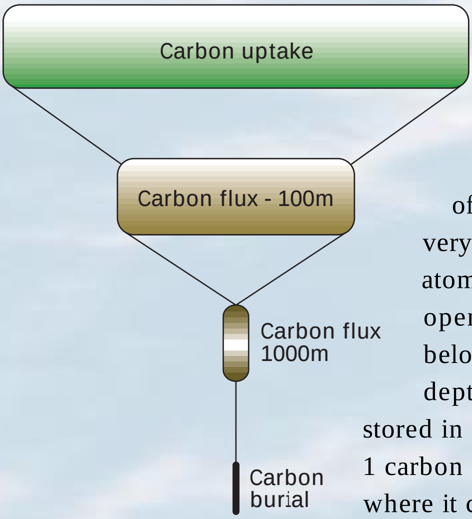
U.S. JGOFS supported the development, production and distribution of certified reference materials that can be used to calibrate instruments and validate processes for measuring CO_2 in ocean waters, thus assuring the reliability of the results. Over the JGOFS decade, more than 24,000 certified seawater samples in tightly sealed glass bottles, like the one shown here, have been distributed to scientists in 25 countries.


A. Dickson

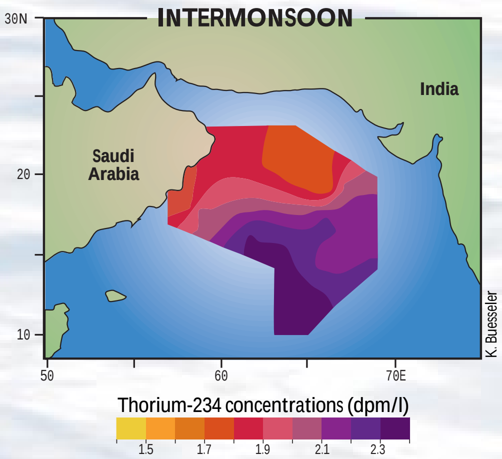


The Biological Pump

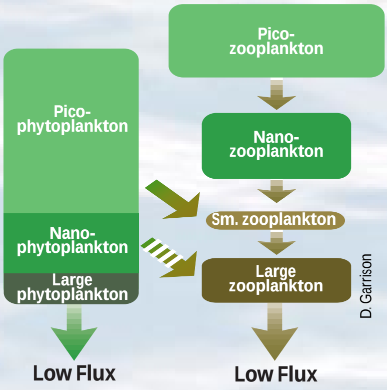
Most of the carbon in the ocean is stored in the deep waters and sediments of the sea floor. How much and how quickly carbon can be transferred from the atmosphere to the ocean depths is therefore important to the global carbon cycle. One route that carbon takes into the deep ocean is via what scientists call the “biological pump.” This pathway begins as phytoplankton, the single-celled organisms that form the base of the oceanic food web, take up CO_2 and nutrients through the process of photosynthesis and form organic matter. These organisms and the zooplankton that feed on them produce particles as they die, molt or excrete material. The particles containing organic material sink through the water column, carrying carbon into the ocean depths. During the days to weeks that it takes the particles to reach the sea floor, many are decomposed by bacteria or consumed by zooplankton and fish in the deep waters.



JGOFS scientists are interested in understanding what affects the efficiency of this biological pump, which is, in general, very low. On average, for every 1,000 carbon atoms taken up through primary productivity in open-ocean surface waters, only 50 to 100 sink below 100 meters, and only 10 are exported to depths below 1,000 meters, where carbon is stored in the deep ocean for millennia. Of these, only 1 carbon atom is buried in the deep ocean sediments, where it can be sequestered for eons.



K. Buesseler

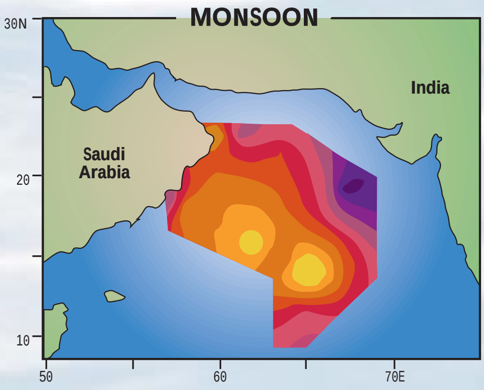


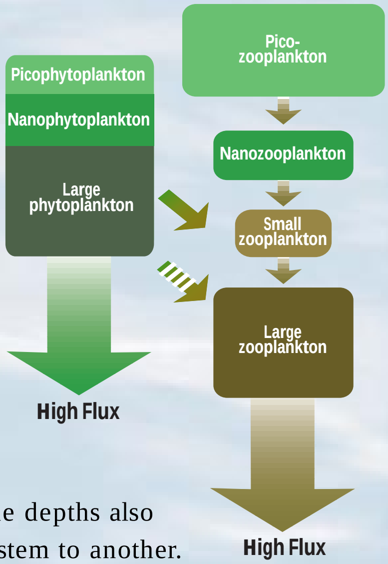
D. Garrison

The strength of the biological pump and the processes that regulate it are now better understood, thanks to advances made during JGOFS. For example, a new chemical method for measuring the rain of particles takes advantage of the properties of a naturally occurring element called thorium-234, a short-lived decay product of uranium-238 that sticks to particles. Because the thorium atoms hitch a ride on the particles that carry organic carbon into the depths, lower than normal levels of thorium in surface waters indicate a high particle flux.

JGOFS scientists working in the Arabian Sea measured lower thorium levels during the summer monsoon, indicating enhanced particle fluxes. This increase in flux is initiated by the strong monsoon winds which stir up the Arabian Sea and bring nutrients to the surface, stimulating blooms of larger phytoplankton. The shift from smaller to larger plankton, as depicted in these food web diagrams, changes the efficiency of the biological pump and swells the flux of particulate forms of carbon to the deep Arabian Sea.

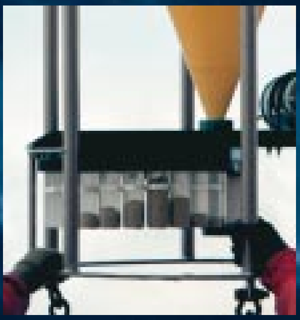
These measurements demonstrate that the efficiency of the biological pump varies dramatically from season to season. As we know from other JGOFS studies around the world, the strength of the biological pump and thus the amount of carbon transferred into the depths also varies greatly from one ocean ecosystem to another.





Moored Time-series Sediment Traps

Deep-ocean sediment traps catch the rain of particles in large funnels deployed at various depths in the ocean. An array of canisters positioned below the collection funnel rotates every couple of weeks. This system allows scientists to see the peaks and troughs of the particle flux cycle and provides valuable samples for analysis.



M. Bowles

What Controls Ocean Productivity?

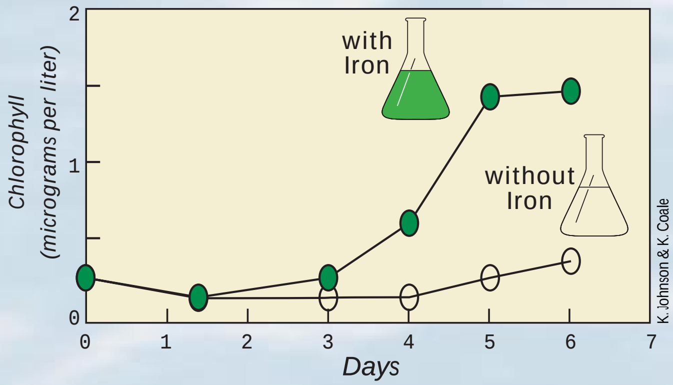
Physical factors, such as light level, temperature and the turbulence of the water, affect patterns of productivity in the surface ocean. But equally important are the nutrients that fuel the growth and reproduction of phytoplankton cells. Phytoplankton, such as the diatom on the top right page, take up inorganic nitrogen and phosphorus along with carbon during photosynthesis. These essential nutrients sustain the flux of carbon through marine ecosystems.

If these essential nutrients fuel production, why are there large regions of the ocean with low phytoplankton biomass, despite persistently high levels of nitrogen and phosphorus? The puzzle of these high nutrient-low chlorophyll (HNLC) regions has begun to be solved in recent years with a series of experiments designed to investigate the role of iron in ocean productivity.

Iron, which phytoplankton require in small amounts for growth, comes to the surface ocean primarily via wind-borne dust from the continents. Some ocean regions, such as the North Atlantic, receive an ample supply of iron dust, whereas the HNLC regions, such as the equatorial Pacific, generally receive little. Phytoplankton growth experiments, such as the one illustrated below, demonstrate conclusively that additional iron stimulates the growth of phytoplankton and, therefore, the uptake of inorganic carbon and the major nutrients.

Scientists and crew prepare to launch a net for plankton sampling.

D. Steinberg



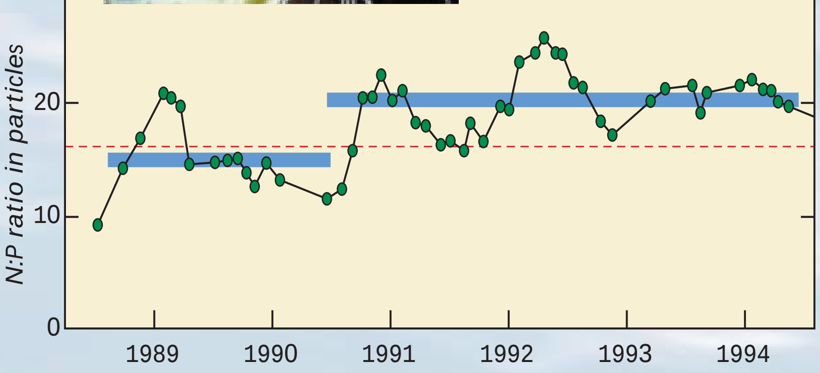
K. Johnson & K. Coale

Changes in the Nutrient Cycle


I. Kaczmarska & J. Ehrman

Data collected over the last decade at the JGOFS time-series stations near Hawaii and Bermuda have yielded further insights into the complex nature of the controls on ocean productivity. For example, U.S. JGOFS scientists have observed a long-term shift in the ratio of nitrogen (N) to phosphorus (P) in suspended particulate matter. They suggest that this is linked to the higher frequency of El Niño episodes during the 1990s, which bring warmer, calmer conditions to the oligotrophic (low nutrient) regions around Hawaii and Bermuda. These conditions favor the growth of large filamentous cyanobacteria, such as the *Trichodesmium* colonies shown below, that are able to use nitrogen gas dissolved in sea water rather than the less abundant nitrate, which is only supplied by upwelling of deeper, richer waters. These "nitrogen-fixing" bacteria thus shift the limitation on plankton growth to phosphorus, resulting in plankton that are rich in nitrogen, as evidenced by the elevated ratio of particulate nitrogen to phosphorus in the time-series record shown below.


P. Lundgren & B. Bergman



D. Karl

Dissolved Organic Carbon

Before JGOFS, scientists assumed that dissolved organic carbon (DOC) varied little from one ocean region to another. Thanks to new analytical tools developed during JGOFS, we now know that DOC levels vary over space and time because of the phytoplankton and zooplankton that produce DOC and the bacteria that consume it. Physical mixing transports the DOC that is not consumed into the depths. As much as 20% of the total carbon exported from the surface ocean is in the form of DOC.

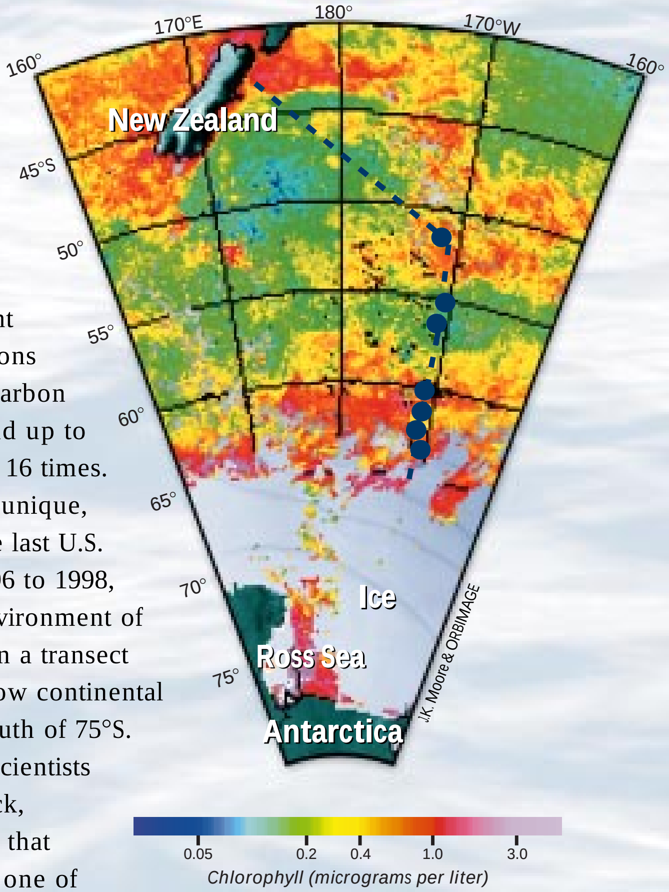
Collecting the Data: Anatomy of a Research Cruise

Over more than a decade, U.S. JGOFS scientists have spent the equivalent of eight years at sea in search of answers to questions about the role of the ocean in the global carbon cycle. The miles traveled in the process add up to the equivalent of circling the globe almost 16 times.

Although each ocean research cruise is unique, they have many elements in common. The last U.S. JGOFS process study, carried out from 1996 to 1998, took scientists to the remote and harsh environment of the Southern Ocean. Work concentrated on a transect south from New Zealand and on the shallow continental shelf waters of the Ross Sea, the region south of 75°S.

On 11 separate cruises, as many as 60 scientists and crew members worked round the clock, pausing only during the fury of the storms that sweep around Antarctica. The map shows one of these cruise tracks (dashed line) and the station locations (filled circles) where detailed studies were conducted. Water samples were collected from rosettes of bottles triggered to open at different depths, providing complete profiles of the physical, chemical and biological properties of the region. Nets were used to collect organisms for identification and study. Bio-optical instruments provided data on the amount of light available in the water at various depths.

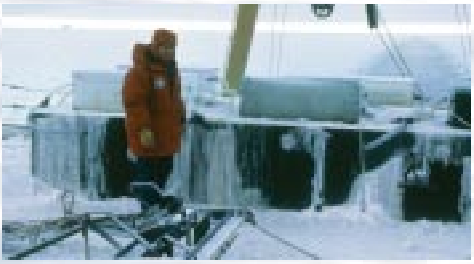
Sediment traps deployed over more than a year and pumps deployed during each cruise provided evidence of the quantity and quality of the flux of organic particles from the surface waters to the depths. Benthic samplers provided information on the transformations that occur at the sea floor and in the top layer of the sediments, while marine coring devices, like the one shown in the photo on the right page, provided data on the past history of carbon cycle changes recorded in the sediments.



J.K. Moore & ORBIMAGE

RVIB *Nathaniel B. Palmer* near McMurdo Station, Antarctica

M. Dennett



M. Dennett

Freezing conditions complicated experiments conducted in incubation chambers on deck, and often water samples froze in bottles as they came on deck.

M. Bowles

In addition to the data collected under often arduous conditions at sea, scientists can now use satellite images of ocean color to expand their knowledge about surface ocean productivity over space and time. The map on the left page shows regional variations in surface chlorophyll levels during a U.S. JGOFS cruise in December 1997 measured by a satellite. These data could not be obtained from ship observations alone.

While the phytoplankton blooms that occur in the Southern Ocean are not the world's largest, the region around the polar front, where cold Antarctic waters meet warmer waters from the north, has one of the most efficient biological pumps in the world. On an annual basis, up to 40% of the carbon taken up during primary production is exported below 100 meters in this region. These high particle fluxes are primarily associated with diatoms like the chain forming ones shown here, phytoplankton that use silica to form their shells.

K. Selph

ORBIMAGE

Satellites

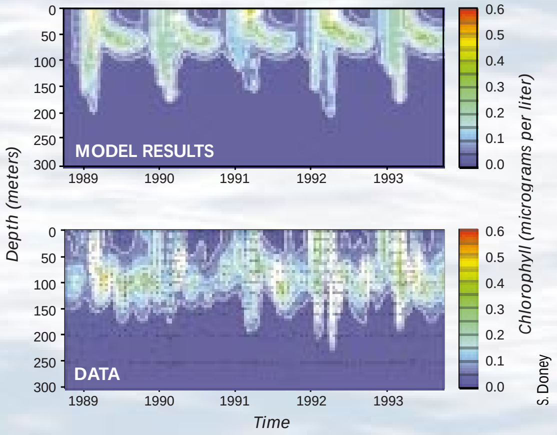
Satellites allow researchers to study the ocean year-round, providing a complete global view nearly every day. A new series of U.S. satellite-mounted instruments can be used to determine a wide variety of ocean properties, including sea-surface temperature, height and roughness, winds, and surface chlorophyll levels. These measurements are needed to improve our understanding of the global-scale processes that are important in the ocean carbon cycle and its interaction with climate.

From Description to Prediction:

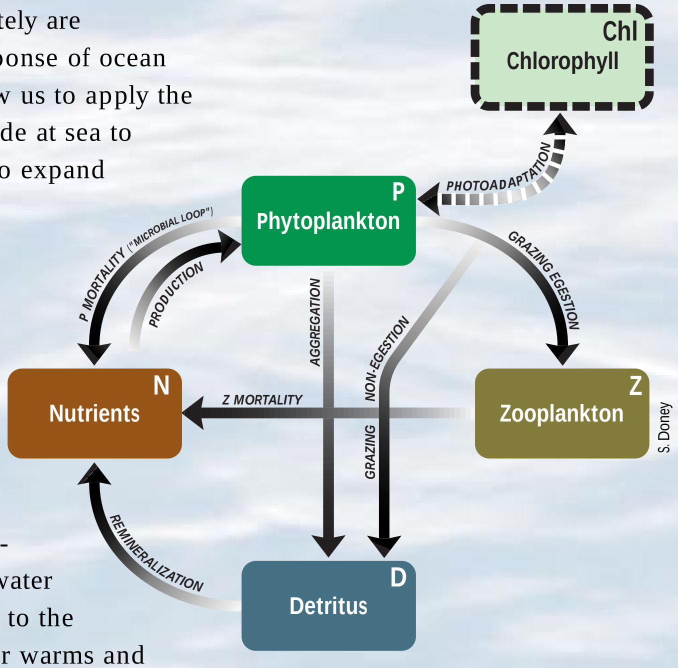
Modeling the Ocean Carbon Cycle

One of the goals of JGOFS is to synthesize the knowledge gained from field studies into a set of models that reflect our understanding of the ocean carbon cycle. Mathematical models that simulate real-world properties and processes accurately are critical tools in the effort to predict the response of ocean systems to changes in climate. Models allow us to apply the information gained from measurements made at sea to larger temporal and spatial scales. They also expand our ability to ask "what if" questions.

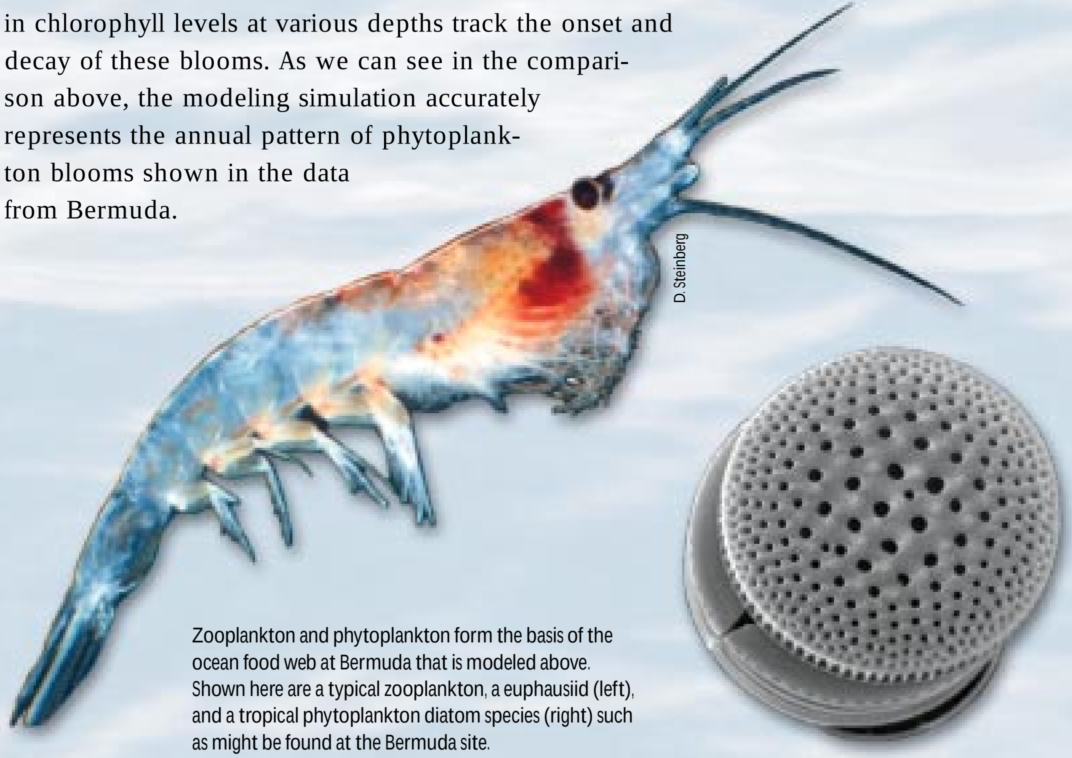
Merging models of the ocean food web, such as the one shown on the right, with models of the physical environment presents a formidable challenge. Fortunately we now have the chance to compare the results of modeling simulations with long time-series records of ocean properties. For example, at the U.S. JGOFS time-series site near Bermuda, wind-driven turbulence in the winter mixes the water column, bringing nutrients from the depths to the surface. With the arrival of spring, the water warms and becomes stratified, and the phytoplankton bloom. Changes in chlorophyll levels at various depths track the onset and decay of these blooms. As we can see in the comparison above, the modeling simulation accurately represents the annual pattern of phytoplankton blooms shown in the data from Bermuda.



S. Doney



S. Doney



D. Steinberg

I. Kaczmarska & J. Ehrman

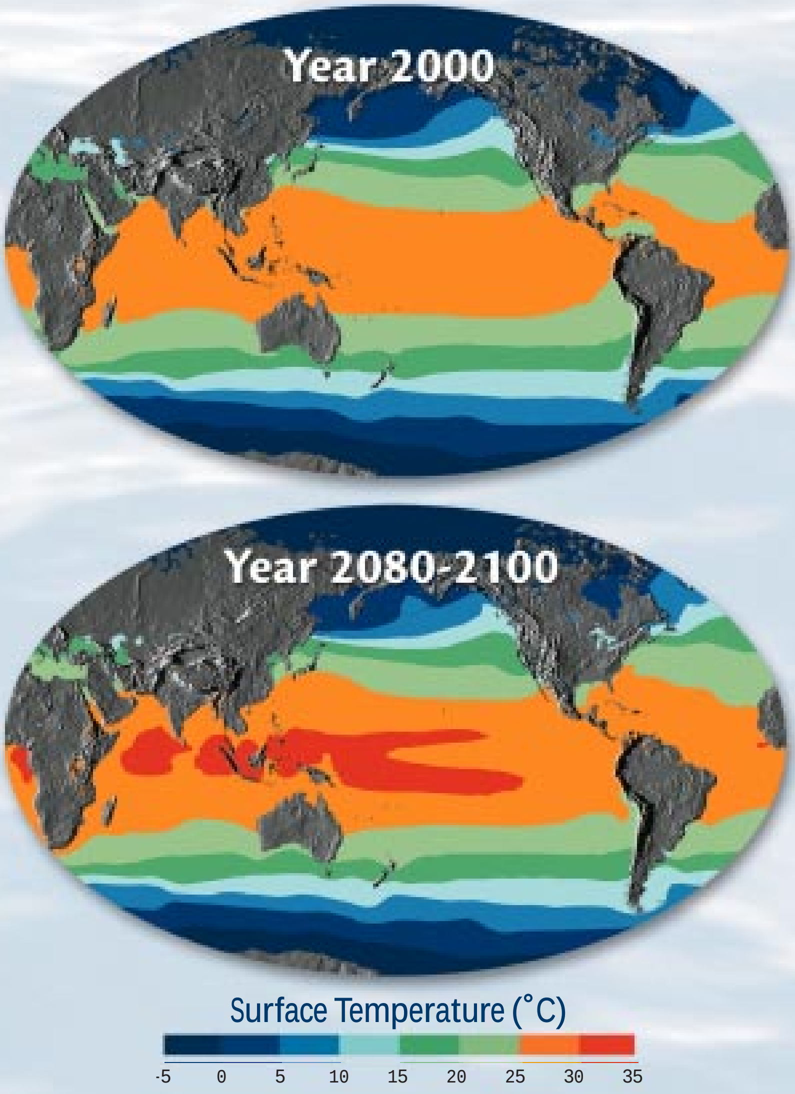
Zooplankton and phytoplankton form the basis of the ocean food web at Bermuda that is modeled above. Shown here are a typical zooplankton, a euphausiid (left), and a tropical phytoplankton diatom species (right) such as might be found at the Bermuda site.

Global Models

As we move into the post-JGOFS era, we are asking scientists to predict what will happen in various regions of the global ocean as CO_2 in the atmosphere continues to rise. As the atmosphere warms, so does the surface ocean. Shown below are the results of a global ocean model that predicts warming in surface ocean temperatures at the end of this century.

The predicted temperature changes would affect the solubility of CO_2 in ocean water. In addition, changes in temperature and winds could lead to alterations in ocean circulation patterns and the upwelling of nutrients into surface waters. These changes could affect the structure and functioning of ocean ecosystems and thus the way the biological pump operates in different regions of the ocean. Changes in the ocean's capacity to take up and store carbon could, in turn, affect the accumulation of CO_2 in the atmosphere.

U.S. JGOFS scientists are contributing to international efforts to model the global carbon cycle. The final step is to develop linked ocean-atmosphere models capable of predicting the complex interactions that shape the ocean's response to the rise in CO_2 and its effect on atmospheric CO_2 levels and climate.



J. Sarmiento & R. Slater

Developing the U.S. JGOFS Database

JGOFS was launched just as the Internet era was getting underway, and participants in the program recognized immediately the advantages of sharing data and information on-line via the World Wide Web. Close to 1,000 visitors are registered every day at the U.S. JGOFS web site. This web site provides program information and links to our government sponsors and other carbon cycle programs, as well as direct access to results from both field studies and modeling projects. Those interested in learning more can log on at http://usjgofs.whoi.edu

The Next Wave of Ocean Carbon Cycle Science

A number of measures attest to the success of U.S. JGOFS: the capability of its scientists, the multidisciplinary nature of its research projects and results, the volume of scientific publications and the wide range of ocean regimes explored during its field programs (*see statistics on back cover*). Over the last decade, JGOFS scientists have occupied the vanguard of a new wave of biogeochemical research that has changed both our understanding of the ocean carbon cycle and the way that investigations are carried out. The broad international participation in JGOFS has contributed to the emergence of new frameworks for thinking about the natural cycling of elements in the ocean and the impact of human activity on these cycles.

Reducing uncertainty about the role of the ocean in the global carbon cycle has required not only the diverse disciplinary perspectives and methods of chemical, biological, geological and physical oceanography, but also the development of improved measurement and quality-control standards, the deployment of new sensors on moorings, the use of satellite-mounted instruments to view the global ocean, and access to the World Wide Web for the exchange of data. Ocean and climate modelers can now take advantage of these advances to extrapolate and predict the effect of rising CO_2 levels in the atmosphere on the strength of the ocean carbon sink.

The post-JGOFS era will bring with it new tools for observing ocean phenomena. Shown below are examples of new platforms, instruments and approaches for studying the ocean and monitoring changes in the carbon cycle. JGOFS has set the stage for new biogeochemical programs in ocean science. The challenge for all of us is to use the scientific results to support sound policies for protecting environmental and human resources in a changing ocean.

E. Laws

The Next Generation

Over the last decade of ocean biogeochemistry, JGOFS has provided a fruitful context for training scores of future ocean scientists. Graduate and undergraduate students supported by JGOFS have participated actively in research cruises and laboratory investigations. These "graduates" of JGOFS have joined numerous new academic programs in the environmental sciences, making a strong contribution to research, education and policymaking at all levels.

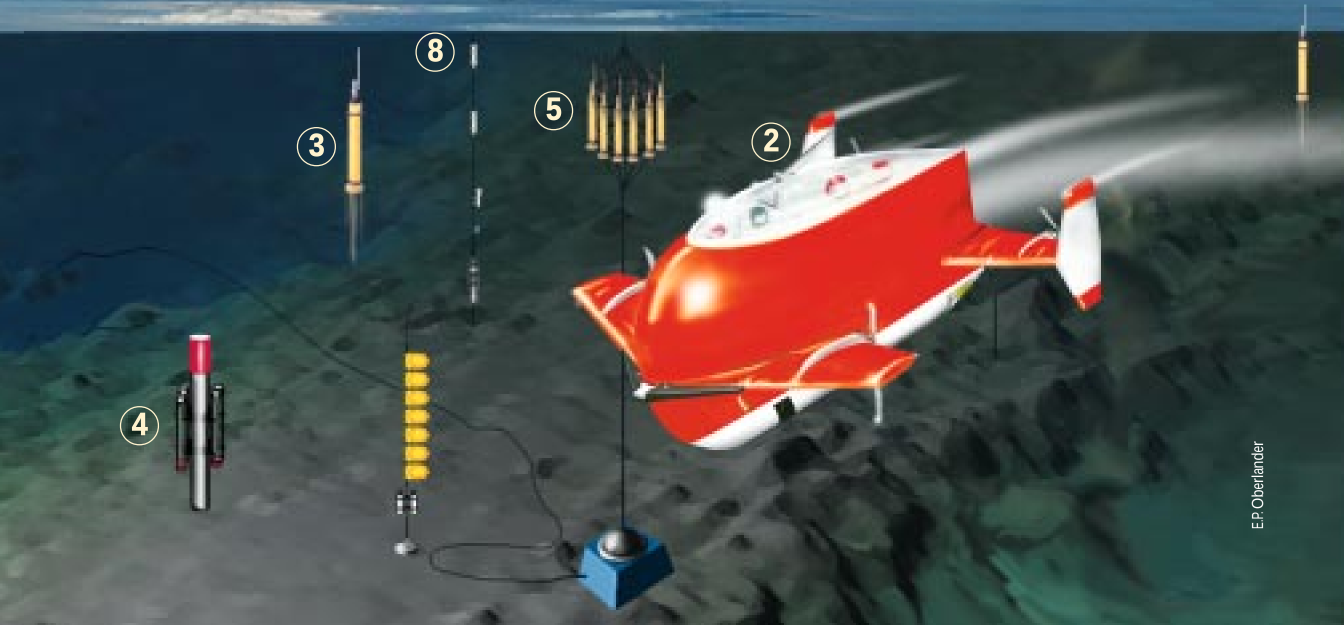
JGOFS has also provided unique opportunities for public outreach and education. For example, scientists at the Bermuda Biological Station for Research instituted a "crush a cup" program for elementary school classrooms. Students decorate styrofoam cups and mail them to Bermuda, where they are sent down with JGOFS sampling gear into the deep ocean. High pressures in the depths force out pockets of air and shrink the cups, as shown in the photo to the right. The students receive their cups back, a reminder of the forces at work in the ocean.

In the photo above, a scientist from the University of Hawaii explains how the ocean works to an attentive kindergarten class. One of these budding scientists may contribute to a future wave of ocean carbon science.

D. Steinberg

New Ocean Instruments

1. Ocean sensor and communications satellites
2. Autonomous underwater vehicle
3. Free-drifting ocean bio-optical sensor
4. Neutrally buoyant sediment trap
5. Time-series water sampler
6. Moored profiling chemical sensors
7. Benthic rover
8. Moored air-sea gas flux array
9. Time-series sediment traps



E.P. Oberlander

U.S. JGOFS Statistics

- 250 principal investigators
- Scientists at 73 institutions involved in U.S. JGOFS
- Grants to scientists in 26 states and the District of Columbia, plus Bermuda, Canada, the United Kingdom and France.
- Scientists in 22 countries collaborated on U.S. JGOFS projects
- More than 300 undergraduate and graduate students supported on U.S. JGOFS grants
- 657 scientific publications to date
- 10 special issues of the journal *Deep-Sea Research II* with several more underway
- 343,000 nautical miles of ocean explored on research cruises (almost 16 times around the globe)
- 3,040 days at sea (more than eight years) conducting U.S. JGOFS research
- Close to 1,000 visits recorded each day at the U.S. JGOFS World Wide Web site
- More than 14,000,000 bytes transmitted daily from the U.S. JGOFS World Wide Web site

Data collected by U.S. JGOFS Planning Office as of February 2001.

U.S. JGOFS has been supported primarily by the U.S. National Science Foundation in collaboration with the National Oceanic and Atmospheric Administration, the National Aeronautics and Space Administration, the Department of Energy and the Office of Naval Research.

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COVER PHOTO CREDITS: Top left: R. Weller; top right: C. Dickson; bottom left: R/V *Thomas G. Thompson*, courtesy of the University of Washington; bottom right: I. Kaczmarska & J. Ehrman