2006 R&D 100 AWARDS ENTRY FORM

1. Submitting Organization

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AFFIRMATION: I affirm that all information submitted as a part of, or supplemental to, this entry is a fair and accurate representation of this product.

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2a. Joint entry with:

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3. Product name:

Carbon Explorer

4. Briefly describe (25 words or less) what the entry is (e.g., balance, camera, nuclear assay, etc.)

The Carbon Explorer is a smart, robotic, sensor- and telemetry-enhanced ocean float with advanced optical sensors for characterizing carbon in the ocean.

5. When was this product first marketed or available for order? (Must have been first available in 2005.)

The Carbon Explorer was first made publicly available for purchase in 2005.

6. Inventor or Principal Developer (List all developers from all companies)

Developer Name	James K. Bishop
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Developer Name	Scripps (Russ Davis, Jeffrey Sherman) and WET Labs (Casey Moore) See section 2 above.

7. Product price

Approximate cost of Carbon Explorer with depth, temperature, and salinity sensors, telemetry enhancements, and optical particulate organic carbon detector is $24 k.

8. Do you hold any patents or patents pending on this product?

No.

9. Describe your product's primary function as clearly as possible. What does it do? How does it do it? What theories, if any, are involved?

The oceans play a critical role in the global carbon cycle and in the regulation of atmospheric CO_2 levels. Half (50 billion metric tons of carbon per year) of global carbon photosynthesis occurs in the ocean. This photosynthesis, performed by microscopic phytoplankton—the small marine plants that are the foundation of the ocean food chain—is the first stage of the ocean's carbon pump, the sedimentation of carbon from the ocean's surface to its depths, which acts as the ocean's natural carbon sequestration mechanism (Figure 1). However, the biological and physical processes of the carbon pump remain poorly understood because of the incomplete, fragmentary nature of ship-based or moored observation studies. Such studies are far too costly to do on a significant scale, impossible under extreme weather and oceanic conditions, and, critically, cannot observe the extremely rapid life cycles of ocean phytoplankton, the microscopic plants that are the foundation of the biological pump that sequesters atmospheric carbon. Thus, global warming is changing ocean temperatures, acidity, currents, and ecosystems, in ways that are not understood or predictable due to the inadequacy of current data.

The Carbon Explorer (Figure 2), conceived by Berkeley Lab's James K. Bishop in collaboration with Scripps Institution of Oceanography (La Jolla, California) and WET labs, Inc. (Philomath, Oregon), is a low-cost, solution to the observational gap left by shipboard or moored oceanic observation systems. With its system of carbon sensors, advanced communications devices, and remote operating capacity, the Carbon Explorer enables, for the first time, the continuous tracking of the biological processes of the carbon cycle in the ocean. It can stay in the ocean year-round

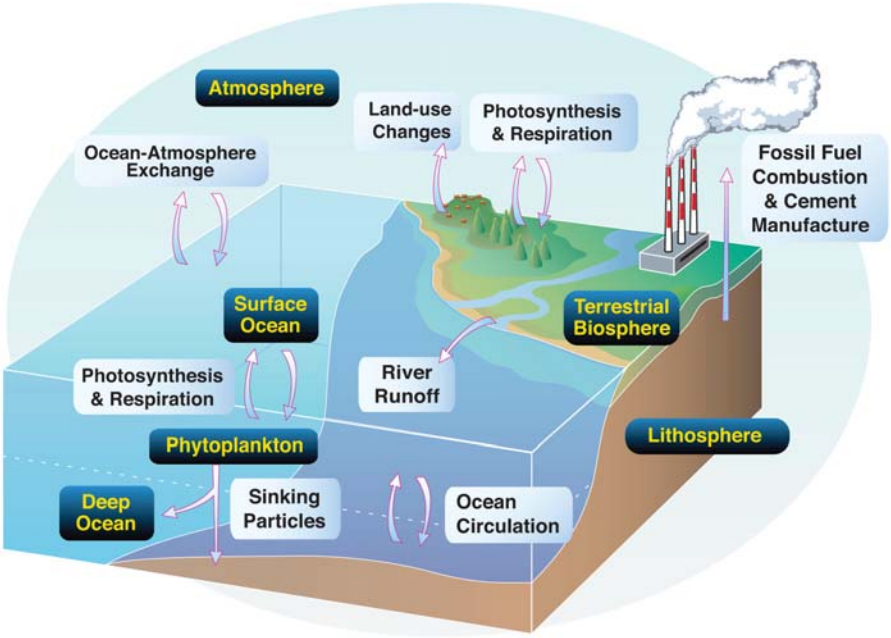

Figure 1. The oceans are the largest reservoir of carbon in fast interaction with the atmosphere. Marine phytoplankton that live only for days convert ~50 Pg C year $^{-1}$ from inorganic to organic form and approximately 10 Pg C year $^{-1}$ of organic matter sinks into the deep sea. This fast process of the biological ocean carbon pump is what the Carbon Explorer is designed to observe.

to observe the annual variations in levels of particulate organic carbon (POC) to several kilometer depths in the ocean. The Carbon Explorer measures POC at a level of accuracy, precision, and frequency previously unachieved, and it does so in real time. Moreover, Carbon Explorers have been deployed to date in some of the world's most remote and extreme ocean environments (where ships could not safely operate), consistently yielding data that had never before been generated and resulting in two publications in *Science*.

Imagine waking up each morning and discovering that 20% of all plants in your garden had disappeared over night. They had been eaten. Equally astonishing would be the discovery in the afternoon that new plants had taken their place. This is the norm of life in the ocean. Without the ability to accurately observe these daily changes in ocean life cycles, over vast spatial scales, we lack the ability to predict how the ocean will respond to rising CO_2 levels, crippling our ability to develop accurate models of global warming or devise strategies to prevent it. The Carbon Explorer meets this need by gathering groundbreaking amounts and types of data to improve our modeling abilities in this critical scientific area.

WHAT IS THE CARBON EXPLORER?

The Carbon Explorer is a smart, fully autonomous robotic "float"—a device that can set its density to the density of seawater at a particular depth in the ocean and thus "float" or maintain neutral buoyancy at any depth below the ocean's surface without expending any energy. (Its movement is LaGrangian, meaning that it follows water currents just as a hot air balloon would follow air currents, as opposed to being "fixed."). In appearance and size rather like a compressed gas cylinder, the Carbon Explorer "profiles" temperature, salinity, and particulate carbon at various ocean depths. ("Profiling," in this case, involves moving from a set depth to the ocean surface, or the reverse, collecting data along the way.) Upon surfacing, the Carbon Explorer sends that data to satellites overhead.

Figure 2. Carbon Explorer prior to deployment from the NOAA research vessel *Ron Brown.* The Explorer is held horizontally by Lt. Cdr. M. Hoshlyk. Its top is to the left, where the black ORBCOMM/GPS antenna system and light-colored CTD are located. The black sensor (affixed to its center) is the WETLABS, Inc. transmissometer.

The Carbon Explorer is based on the Sounding Oceanographic Lagrangian Observer (SOLO) floats originally designed by Scripps. (Thousands of SOLO floats and clones of the SOLO, which measure temperature and salinity at various depths, are now adrift in deep ocean currents around the world [see Figure 3], as part of the international Project Argo to study ocean climate variability.)

The partnership led by Bishop involving Scripps and WET Labs integrated optical sensors that measure particulate organic carbon (POC) concentrations and carbon sedimentation in the ocean. Following Bishop's lead, this partnership engineered and built sensor interfaces and data protocols, bidirectional satellite (ORBCOMM) communications, and remote programming capacity. WET Labs fabricated a neutrally buoyant and stabilized version of the transmissometer (a device that measures the transmission of light through seawater) that Bishop's research had shown to be a reliable and accurate sensor for POC concentration in most ocean regions.

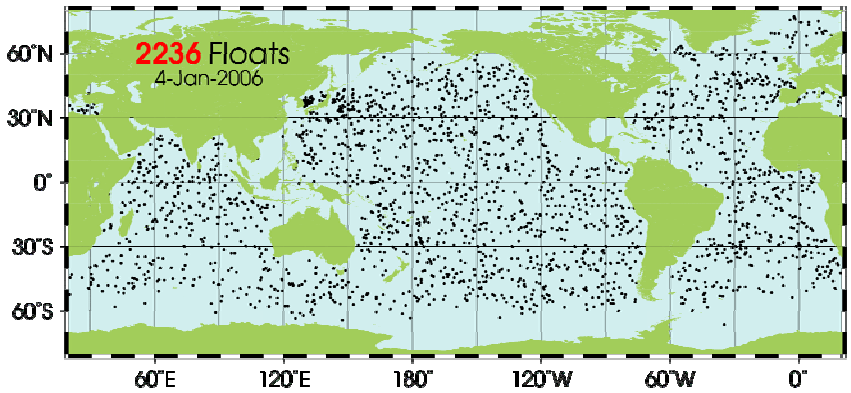

Figure 3. Argo float array status as of January 2006. These floats measure profiles of temperature, salinity, and deep ocean currents. Our Carbon Explorer has advanced upon Argo technology to enable real-time quantification of CO_2 uptake by the ocean and gain information critical to CO_2 management and prediction.

By pairing a transmissometer with this proven float technology, Bishop has accomplished the first-ever practical and affordable means of following ocean carbon pump processes, demonstrating the ability to monitor, in real-time, important ocean carbon cycle processes on a global scale.

CARBON EXPLORER OPERATION

Once placed in the water (via research vessel, small boat, or aircraft), the Carbon Explorer activates and locates itself in space and time using signals from Global Positioning System (GPS) satellites, and then begins a mission based on a set of preprogrammed instructions, adjusting its buoyancy by pumping hydraulic fluid between a reservoir within its pressure case and an external inflatable bladder. (Typical profiling speeds are 10 meters per minute.) The Carbon Explorer can be programmed to operate on a customized time schedule. For example, a repeating 1-day cycle is used to quantify the magnitude of net daily production of carbon in the water (as shown in the profiling time

graph of Figure 4). Data is transmitted to overhead satellites when the Carbon Explorer surfaces, in a matter of minutes (weather permitting; should weather not permit, the data is retained for later transmission). In addition, the Carbon Explorer can be reprogrammed remotely.

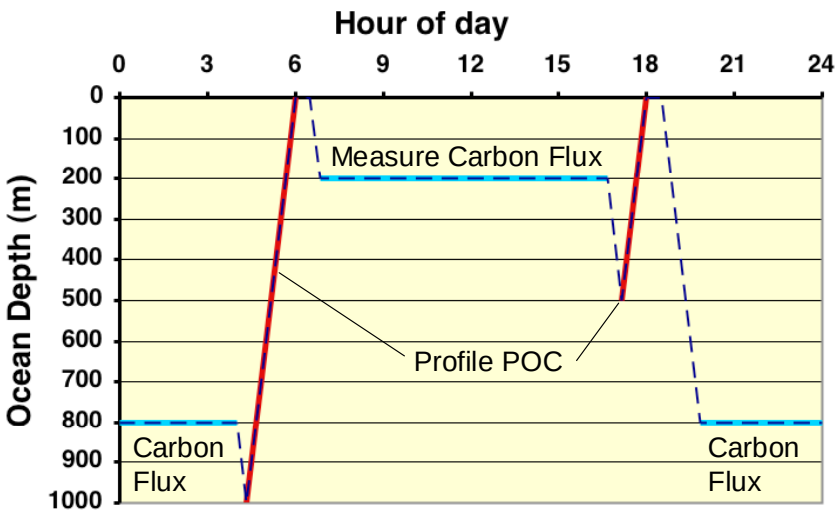

Figure 4. A day in the life of the Carbon Explorer. In this scenario, the programming would be: "Profile up from 1,000 m below the surface to the surface at 0600 hours local time (near dawn), return to 200 m below surface and "sleep" (i.e., maintain a certain depth in the water without profiling), profile up from 200 m depth to the surface at 1800 hours local time (near dusk), return to 1,000 m and sleep."

The Carbon Explorer's telemetry and operational capabilities are also novel and represent orders-of-magnitude improvement over previous systems in some cases. We have replaced the older SOLO float's slow, unidirectional satellite communication system with much faster and bidirectional ORBCOMM telemetry. ORBCOMM transmits data at a rate of 2400 bits per second, 20 times faster than the communications system it replaced. This enables substantially more data to be relayed and reduces the energy spent on communication considerably. It also has the effect of reducing biofouling (the process of attachment and growth of marine organisms on instrument surfaces, which can cause such instruments to become nonfunctional and even unrecognizable within weeks of deployment) by reducing the time spent at the surface to tens of minutes instead of days. Improved interfaces for sensors, onboard computer, and new data compression and telemetry logic schemes have also been implemented.

CARBON EXPLORER MEASUREMENT OF CARBON FLUX

One extremely important measurement for understanding the ocean's carbon sequestration capacity is the rate at which carbon moves downward in the water

(called carbon flux or sedimentation). This is a critical Carbon Explorer measurement, one that is unprecedented in oceanic exploration. The Carbon Explorer determines the carbon flux index (CFI) by again using the transmissometer (Figure 5)—the same instrument that measures concentrations of particulate organic carbon—but in a novel way. Taking advantage of an idea by Bishop, the transmissometer performs a POC reading at the end of a Carbon Explorer sleep cycle (before another session of profiling is to begin). The organic particles accumulated on the sensor over that sleep period are washed off, and then the transmissometer takes another POC reading. The CFI is the difference between the two readings, divided by the time that the CE was "sleeping" at a particular depth. Along with temperature and salinity data from the conductivity (salinity), temperature, and depth (CTD) sensor, these POC and carbon flux measurements can tell us how effective the carbon pump—the biological mechanism of ocean carbon sequestration—is working at a given location in the water, through data no previous technology could provide.

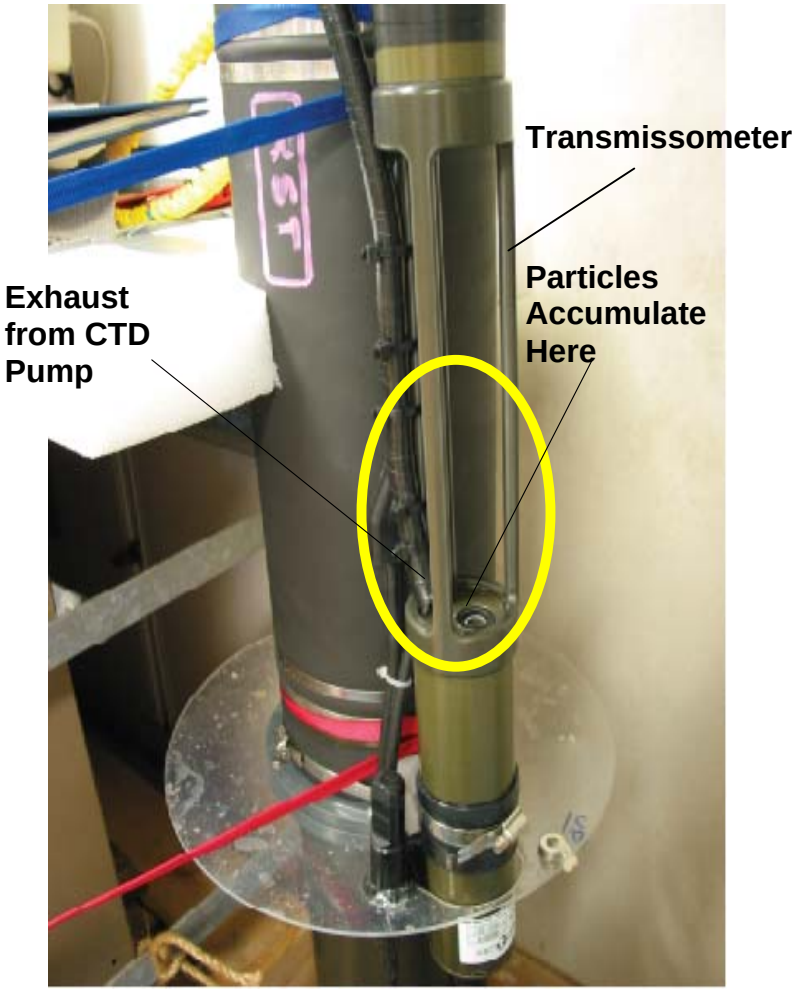

Figure 5. Sinking particles accumulate on the upward looking transmissomteer window while the CE is sleeping between profiles. The transmissometer is read before and after a stream of water is used to wash the particles away. This measurement is called the carbon flux index.

CARBON EXPLORER CONTRIBUTIONS TO UNDERSTANDING THE OCEAN'S CARBON CYCLE

At present, model simulations of the ocean carbon cycle, carried out using the world's fastest and most advanced computers, are the only way to "look" into the future of the ocean's impact on climate change. The current generation of models includes biological processes, but only in a very simplistic way. The observations guiding model predictions are largely based on data collected from ships—which, as mentioned above, cannot work safely in bad weather or in remote ocean locations for very long. **The Carbon Explorer's new and unprecedented wealth of observational data has already led to new insights (and shown some weaknesses in our current understanding) that will enable better model-simulation accuracy.**

This wealth of data and new insights is demonstrated in two papers published in *Science*. The first paper describes how Carbon Explorers deployed in the waters of the subarctic North Pacific captured the first record of the ocean's response to iron deposition during the passage of an intense storm laden with Gobi Desert dust in 2001. Ships have gone out to this location for 50 years without observation of a single dust-storm event, even though such dust storms occur on average once every three years. With the Carbon Explorer constantly "being there," we observed the fast biological response to short-lived and episodic events (such as dust storms) that are important to understanding the ocean carbon cycle.

The second paper describes how two Carbon Explorers captured the first complete and controlled record of iron-stimulated plankton growth and carbon sedimentation during the 2002 Southern Ocean Iron Experiment (SOFeX). SOFeX investigated the role of iron-stimulated photosynthesis in explaining the observed fluctuations of atmospheric CO_2 between glacial and pre-industrial modern times. A dozen similar iron fertilization experiments have been performed in the oceans, but this Explorer expedition is the only one that followed a fertilization experiment from beginning to end. Previously, we had a

few partial answers to how the Southern Ocean works; now we have a first complete answer.

In the last four years, a dozen Carbon Explorers have racked up a total of *7 years' worth* of observations, many times more than an oceanographer might record in over two decades of research. The same pair of SOFeX Explorers deployed north of the polar front went on to observe natural carbon processes in these waters for another year. One SOFeX Explorer deployed south of the Antarctic polar front survived two Antarctic winters, in total absence of sunlight, in the presence of ice—and yet reliably relayed data to satellites above. Data collection under these conditions had never happened before—and since these conditions exist more or less year-round (or for long stretches of time) at some locations, how the ocean's carbon pump worked at those locations had been entirely unknown.

10A. List your product's competitors by manufacturer, brand name and model number.

The Carbon Explorer (CE) can be compared with other ocean-observation methods. All methods listed below are able to use the same kinds of sensors we have deployed. The difference is that the Carbon Explorer allows cost-effective observations of carbon cycle processes *on the time and space scales of these processes*—and at global scales not obtainable with any previous ocean profiling systems.

1. Ship-lowered systems: Oceanographic research vessels are routinely outfitted with winch-lowered conductivity, temperature, and depth (CTD)-rosette water sampling systems. The CTD instrument package can accommodate the same transmissometer sensor used on the Carbon Explorer. Under operator control, this CTD-rosette system collects one continuous real-time profile of salinity, temperature, and depth each time it is deployed. Shipboard packages have to be manually deployed and recovered every time they are used and have to be heavy enough so that the wire they are attached to does not become slack as the ship rolls in surging waves.

Sea-Bird Electronics, Inc., Seattle, WA (Model SBE-32) and General Oceanics Inc., Miami, FL (Model 1018) are examples of such systems.

2. Moored systems: Mooring systems with capabilities to operate year round are anchored to the ocean bottom. Multiple optical logging instrument packages are attached using chains, clamps, and shackles along the length of the mooring wire and are capable of rapid observations. A skilled team of half a dozen individuals working in close communication with ship's personnel controlling heavy winches is required to deploy and recover such moorings.

These systems are constructed from component parts, many of which are available from manufacturers such as Sea Bird, WET Labs, and General Oceanics.

3. Moored profiling systems: A new development for moored observations is the advent of wire-crawling instrument packages that can carry sensors similar to those used on the Carbon Explorer. This eliminates the need for multiple instrument packages as deployed on standard moorings. The system is optimized for measurement of water currents, temperature, and salinity, but no information on the optical sensor performance of such systems is available. Given the necessity to avoid the effects of storm-induced waves, this system must be operated at depths greater than 50 m, which generally is below the euphotic zone—the ocean's uppermost (~100 m) layer, which receives enough sunlight to permit phytoplanktonic photosynthesis)

The McLean Moored Profiler (MMP; McLean Research Laboratories, Falmouth, MA) is an example of such a profiling system.

10B. Supply a matrix or table showing how the key features of your product compare to existing products or technologies. Include both numerical and descriptive comparisons

Competitive Matrix

System → / Feature ↓	*Berkeley Labs / Scripps / Wet Lab's Carbon Explorer (CE)*	*Ship-Lowered Systems (such as Sea-Bird Electronics, Inc., Model SBE-32)*	*Moored Systems (constructed from various manufacturer's components)*	*Moored Profiling Systems (such as McLean Research Laboratories McLean Moored Profiler)*	**Competitive Advantage of Berkeley Lab Technology**
Observation Frequency	Captures diurnal variations from surface to up to 1,000 m.	Capable of profiling daily, but profiling is frequently disrupted by storms and other ship conditions.	Tens of minutes at a set depth.	Similar to CE. Optical sensors have not been used with this platform since it is optimized for ocean current profiling.	**Captures the day-night cycle of biological processes to kilometer depths in a way not matched by any other system.**
Time Frame of Mission	Seasons to years.	Days to weeks.	Seasons. Biofouling of instruments rapidly degrades their performance.	Seasons to year or more—could operate with CE's sensor suite.	**We have deployed 12 CE's to date and now have 7 float years of high-quality POC data.**
Scalability	Thousands of CE's can operate simultaneously. Each operates independently. Can be deployed from small boats, research vessels, or aircraft.	Operational costs and availability of ships limit studies using multiple ships.	Cost, and the need for large research vessels to deploy and recover mooring, limit worldwide deployments of moorings to less than 100.	Similar to moored systems.	**The international project Argo has deployed over 2,000 profiling floats worldwide. Berkeley Lab's CE, with its similar scaling abilities, can easily achieve a similar worldwide deployment.**
Accuracy of Transmiss-ometer (POC sensor)	Beam attenuation coefficient, derived from light transmission measurements, is proportional to POC concentration. CE drift in beam attenuation coefficient is less than 0.0015 (per meter) per month. This is far better than any competing methods.	POC sensor easily contaminated when CTD-rosette system is on deck.	Fixed depth monitoring of POC is difficult due to lack of known reference and strong biofouling effects.	No data are available.	**The POC sensor accuracy is far superior when operated from a CE, due to much-reduced biofouling effects.**

System → / Feature ↓	*Berkeley Labs / Scripps / Wet Lab's Carbon Explorer (CE)*	*Ship-Lowered Systems (such as Sea-Bird Electronics, Inc., Model SBE-32)*	*Moored Systems (constructed from various manufacturer's components)*	*Moored Profiling Systems (such as McLean Research Laboratories McLean Moored Profiler)*	**Competitive Advantage of Berkeley Lab Technology**
Carbon Flux Measurement	Rapid changes in carbon sedimentation can be determined optically using carbon flux index.	Not possible.	Carbon- flux systems have been successfully deployed at depths below 1,000 m. Sample collection at a rate of one per 14 days is typical.	Not possible. These systems are moving when they make measurements; lateral currents flowing across the unit prevents carbon flux measurement, because sensors in motion will not give accurate readings of flux.	**The CE is the only technology to achieve direct and frequent real-time monitoring of particulate carbon sedimentation on a global scale.**
Reliability	Biofouling is minimal due to CE being parked at great depth below euphotic layer (the sunlit oceanic layer within 100 m of the surface).	Optics must be cleaned prior to each lowering because of exposure to shipboard contamination	Biofouling is a major issue with all instruments held at one depth.	Biofouling has not been characterized. Profiling requires complex infrastructure. Moving parts may fail due to biofouling.	**Biofouling affects reliability. The CE, by virtue of how it is operated, greatly minimizes these effects. There are no external moving parts to the CE at risk of failure.**
Cost	~$24k	~$50k for CTD and optics. Ship operations cost $20k per day.	>$500k. The numbers of instrument packages needed to achieve a profile and the infrastructure to deploy them is costly.	>$150–$200k . Profiling instrument package with sensors costs $60k. The infrastructure adds ~$100k	**One CE costs about the same as a day or two of ship time. Yet it can operate for seasons to years. Less costly by an order of magnitude than moored systems.**
Weight	40 kg	1,000 kg—in non-CE technologies, the infrastructure needed to support the sensors is what makes them so heavy.	> 5,000 kg.	>2,000 kg.	**CE's are easily handled by a single person and can be deployed without mechanical aid. All others require teams of personnel and heavy winch systems.**
Size	The size of a gas cylinder. Easily carried by one person. Easily deployed from small boats.	Typical units lowered by ships are 2 m in diameter and 2 m tall. Must be raised and lowered using a winch system and minimum of three people .	Moorings must extend to the ocean bottom (mean depth is 4 km) The basic system includes wire that weighs at least a ton, acoustic releases, clamps, anchor, etc.	Moorings must extend to the bottom (mean depth is 4 km.) Slightly less complex than fixed moored systems, but still uses 4,000 m of wire weighing at least a ton.	**The CE is small enough that it is easily deployed without winches.**

System → / Feature ↓	*Berkeley Labs / Scripps / Wet Lab's Carbon Explorer (CE)*	*Ship-Lowered Systems (such as Sea-Bird Electronics, Inc., Model SBE-32)*	*Moored Systems (constructed from various manufacturer's components)*	*Moored Profiling Systems (such as McLean Research Laboratories McLean Moored Profiler)*	**Competitive Advantage of Berkeley Lab Technology**
Data Reproduc-ability	The first 2 CE's deployed returned virtually identical records of POC over eight months (Bishop et al. 2002, *Science*).	Reproducibility is frequently foiled because of contamination (rust-laden water, evaporated salt, etc.) aboard a ship.	Biofouling makes data hard to reproduce reliably.	No data—no optical observations have been reported.	**The CE data have surpassed any other study to date in reproducibility.**
Power Needs	Low. CE's will operate on year-long time scales with only 14 D-sized lithium batteries.	Requires a ship plus the energy required to raise and lower a 1,000 kg package over 1 km.	CE power consumption multiplied by the number of sensor packages (6–10) needed to define POC levels in the upper ocean.	High, due to wire crawler needed to achieve profiling	**The CE's power advantage is many orders of magnitude superior.**
Operating Limitations	Demonstrated to operate through intense storms, high seas, and even in the presence of 50% ice cover.	Limited to wind conditions <40 knots and waves <6 m.	Cannot operate near surface in strong currents or in presence of ice.	Strong currents degrade profiling success. Cannot operate near ice.	**The CE has minimal operating limitations for observing carbon cycle processes in the deep sea.**

10C. Describe how your product improves upon competitive products or technologies.

Carbon Explorer technology is unique in its ability to gather copious amounts of data over many geographical areas in a cost effective manner. It revolutionizes ocean-research technologies in the following ways:

- **Only method for obtaining reliable, direct, frequent particulate organic carbon and carbon sedimentation measurement**—It is the only way to achieve accurate, direct, and frequent real-time monitoring of the rapid changes in particulate carbon and carbon sedimentation on a global scale. Ships can profile daily or even more frequently, but such profiling can easily be disrupted by storms and other ship conditions. Moreover, season-long observations are impossible because of the practical limitations of human endurance, safety, and cost. For carbon sedimentation, all other systems deployed for a seasonal or multi-month period must collect samples that average carbon flux variations for periods of one

week or longer, because of limits on equipment operation. These samples all must be recovered and returned to shore for analysis. Thus, no technology other than the Carbon Explorer's has transmitted its observations in real time.

- **Superior data accuracy, reliability, and reproducibility**—The CE avoids the biofouling problems of other technologies by resting at depths in the ocean below the euphotic (synthesizing) zone, where plant and animal life is most abundant. Specifically because of its reduced biofouling problems, its data have surpassed any other study to date in reproducibility: The first two Carbon Explorers deployed in the North Pacific returned virtually identical records of POC over eight months.
- **Greater geographical coverage (even in severe, icy weather)—**Unlike other technologies, it can operate under almost any conditions in the deep sea. Thousands of CE's can operate simultaneously and independently in the ocean, whereas other technologies are restricted by the operational and availability limitations of ships. Moored systems allow sustained presence at a fixed geographic location and more complex sensor suites, but require expensive ship time to deploy and maintain. Moorings with "profiling" capabilities are expensive and cannot profile near the surface layer in areas with strong currents.
- **Lower size and weight—**The approximate size and weight of a gas cylinder, it can be carried by one person and easily deployed from small boats, without mechanical aids (such as winches). All other technologies are considerably bigger and physically harder to manage.
- **Lower cost enables far more data gathering and greater scalability—**One Carbon Explorer, which may continuously generate data for a year or longer, costs the equivalent of operating a typical deep-sea oceanographic vessel for a single day. Yet the Explorer can operate for seasons to years, thereby being orders of magnitude more cost-efficient than other technologies. Moreover, a conservative cost estimate (exclusive of ship time) for deployment of 20 deep-sea moorings for

one year is approximately $5–$10 million, which would enable deployment of 200–400 Carbon Explorers. Power consumption costs are low: the Explorer requires a handful of batteries to run; other technologies take on the typical fuel-burning costs of ships.

- **Larger Data Capacity/Less Taxing on Scientists—**Bishop has been on 30 ocean expeditions over 25 years. In that time he has collected approximately 1.5 years worth of data—typical for an active oceanographer of his experience. As mentioned earlier, in four years, a dozen Carbon Explorers have racked up a total of *7 years' worth* of observations, all in real time.

11A. Describe the principal applications of this product.

Real-Time Global Carbon Assessment, Monitoring, and Verification

The Carbon Explorer provides a precise measure of particulate organic carbon (POC) concentration from ocean surface to several-kilometer depths. We are able to track these POC measurements and how they vary on a day-to-day basis over a year or longer. The POC sensor can also be used to monitor the sedimentation of particulate carbon material. This carbon flux index developed from POC measurements has allowed a first-ever view of the daily changes in particulate carbon sedimentation. The two carbon measurements provide critical data for understanding what happens to carbon in the ocean. We have proven the ability to monitor these changes in real time.

In these ways, the Carbon Explorer technology addresses the overwhelming lack of data in ocean carbon observations and contributes to a fuller understanding of how the ocean's biological systems are responding to increasing levels of CO_2 in the atmosphere.

11B. List all other applications for which your product can now be used.

Calcium-Carbonate (Particulate Inorganic Carbon) Sensor

Under Bishop's direction, Berkeley Lab has developed a first-ever optical sensor specific for particulate inorganic carbon (PIC) particles. PIC forms the mineral ballast that accelerates aggregated organic carbon sinking into the deep sea. The formation of

PIC is poorly understood; the growing acidification of the ocean will likely impact calcareous organisms, and we need to quantify this impact. The PIC sensor will be a pioneer in closing this knowledge gap. One prototype of this sensor has already been deployed on the U.S. National Oceanic and Atmospheric (NOAA) ship surveys of the Atlantic Ocean. The PIC sensor is expected to be part of the Carbon Explorer suite of sensors in the near future. (The Carbon Explorer's demonstrated ability to carry an expanding suite of sensors is one of its decisive advantages over other technologies.)

Carbon Explorer Technology Combined with Ship-Lowered Optical Systems

All sensors capable of being deployed on a Carbon Explorer can be deployed across all platforms—including ship-lowered systems (Figure 6). For example, we have operationally deployed the PIC and POC sensors on such systems for the U.S. NOAA surveys mentioned above.

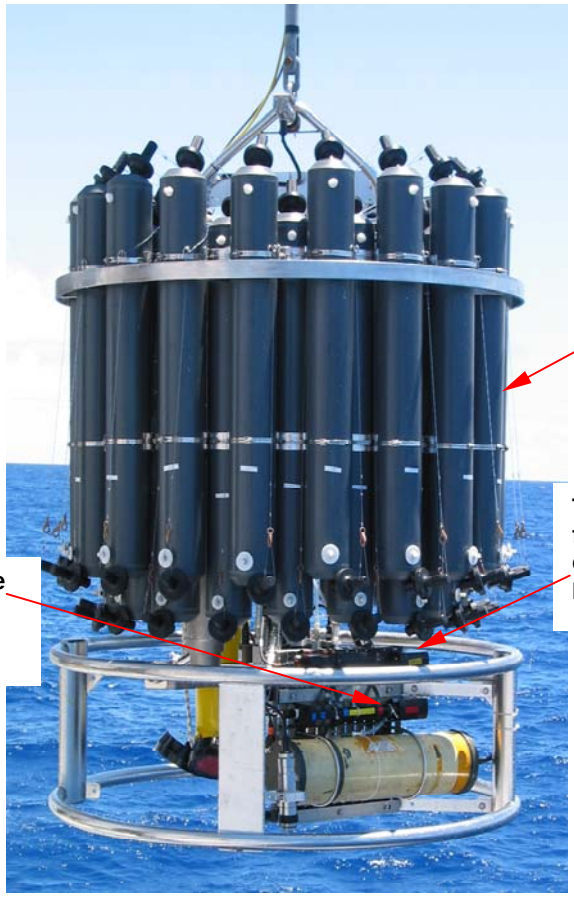

Figure 6. Ship lowered CTD–water sampling rosette system being deployed from the research vessel *Ron Brown*. The instrument package includes sensors for POC and Berkeley Lab's new sensor for particulate inorganic carbon (PIC). WET Labs manufactured both sensors.

Imaging Optical Carbon Recorder

The carbon flux index is (at present) a very powerful measure of POC sedimentation. At Berkeley Lab, we would like to know still more about this

process. We are perfecting a new instrument that can ride aboard a carbon explorer and accurately and distinctly quantify the rapid changes in POC and PIC sedimentation with an imaging system (Figure 7). There is currently no sensor that can do this. We aim to obtain specific detail on the kinds of carbon-carrying particles raining into the deep sea, telling us more about the ocean's carbon pump.

Figure 7. Berkeley Lab's prototype Imaging Optical Carbon "Flux" Instrument. The instrument at the right of the float is designed to record daily variations of particulate organic and inorganic sedimentation for seasons.

12. Summary. State in layman's terms why you feel your product should receive an R&D 100 Award. Why is it important to have this product? What benefits will it provide?

Quite simply, the Carbon Explorer, with its system of carbon sensors, advanced communications capabilities, and remote programming capacity, offers a tremendous breakthrough in how we explore the oceans. Unlike any previous technology, it allows scientists studying the ocean to "be there," both in space and time, to perform carbon observations under virtually all oceanic conditions (except permanent ice cover) for seasons to years—and it permits such observations at very low cost, far lower than any alternative technology.

Carbon Explorers operating in remote and stormy seas, under conditions too severe for any ships, have returned real-time, year-long records of carbon change and sequestration to kilometer depths. In one example, operating far from any manned vessel, under the extreme weather and rough-ocean conditions of the Southern Ocean's "Furious 50's" (a latitude belt famous for high sustained winds and virtually continuous storms), these Carbon Explorers

recorded the first evidence of carbon exported to the ocean depths by iron-fertilized plankton. Such observations are critical to the comprehensive picture of how the ocean works to sequester carbon and its possible role in mitigating global warming.

Expanding our understanding of global warming requires research in a wide range of fields. The development of the Carbon Explorer is only one piece in this quest. The success of this technology has already energized efforts throughout the world to develop increasingly accurate observations of, and generate new insights about, the ocean carbon cycle. In the not-to-distant future, Carbon Explorer technology will form the basis for a global carbon observing system capable of real-time assessment of atmosphere-to-ocean exchanges of CO_2. Equally important, this technology will provide the observational basis for accurate models of the carbon cycle and thus guide human efforts to control the release of CO_2 to the atmosphere.

ORGANIZATION DATA

13. Contact person to handle all arrangements on exhibits, banquet, and publicity.

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Appendix
List of Attachments
2006 R&D 100 AWARDS
ENTRY—Carbon Explorer (Berkeley Lab)

A. Letters of Support

- Woods Hole Oceanographic Institution
- Department of Global Ecology at the Carnegie Institution
- U.S. Department of Commerce—National Oceanic and Atmospheric Administration
- Department of Atmospheric and Oceanic Sciences at the University of California Los Angeles

B. Scientific Publications

- Bishop, J.K.B., R.E. Davis, and J.T. Sherman, Robotic Observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific, *Science*, **298**, pp. 817–821, October 2002.
- Bishop, J.K.B., T.J. Wood, R.E. Davis, and J.T. Sherman, Robotic Observations of Enhanced Carbon Biomass and Export at 55°S During SOFeX, *Science*, **304**, pp. 417–420, April 2004.

C. Selected Press Coverage

- "Climate Change Scenarios Compel Studies of Ocean Carbon Storage," LBNL Science Beat, February 1, 2001.
- "Robotic Floats for Monitoring Ocean Carbon Launched in Pacific," LBNL Science Beat, April 24, 2001.
- "Where in the Ocean is that Float from San Diego?" LBNL Science Beat, October 1, 2001.
- "A 'Little Robot that Could' Tracks Plankton Growth in Stormy Antarctic Waters," LBNL Research News, February 15, 2002.
- "Asian Dust Storm Causes Plankton to Bloom in the North Pacific," October 24, 2002.

- “Adrift in the Southern Ocean: Tracking Plankton through Storms and Ice,” Berkeley Lab Highlights, 2002–2003.
- “Robotic Floats Shed New Light on the Iron Hypothesis,” LBNL Research News, April 15, 2004.
- “Going Deep to Study Ocean Carbon,” LBNL Science Beat, April 30, 2004.
- “Sampling the South Atlantic,” Science@Berkeley Lab, May 13, 2005.

2006 R&D 100 AWARDS
ENTRY—Carbon Explorer (Berkeley Lab)

Appendix A

Letters of Support

WOODS HOLE OCEANOGRAPHIC INSTITUTION

Dr. Scott C. Doney, Senior Scientist, Marine Chemistry and Geochemistry Department

R&D 100 Award Selection Committee

Dear Committee Members, February 15th, 2006

It is my great pleasure to write this letter in support of Dr. Jim Bishop's nomination for the R&D100 Award. Jim is a world leader in chemical oceanography, and he is one of those rare individuals who combines both the excellent technical and analytical abilities required for making new and difficult measurements in the ocean with the keen insight and scientific perspective to appreciate the broad implications of those data. Presently, he is revolutionizing oceanography through his pioneering work on the development of the *Carbon Explorers*, which combine state of the art, *in situ* bio-optical sensors with autonomous profiling floats to independently sample the harsh, open-ocean environment for months to a year at a time.

Marine ecosystems were once thought to be too vast and remote to be strongly impacted by human activities. But growing evidence shows that these environments, too are threatened by human-induced pressures from over fishing to climate change and ocean acidification. Our understanding of ocean dynamics and long-term trends is severely hampered by lack of data. The *Carbon Explorers* are thus a transformational technological advance in the history of ocean carbon observations, greatly expanding our ability to measure the ocean and opening up new vistas for scientific exploration and environmental monitoring.

Prior to the *Carbon Explorers*, observations of marine biomass variations with depth and of biological processes that control biomass and productivity relied on labor-intensive and very expensive, ship-based measurements. Because of their very nature, such observations are limited in time as well as space. Jim's *Carbon Explorers* can be dropped from a ship, and as they drift with the currents, yo-yo up and down the water column making measurements and transmitting data back shore via satellite. And the cost of one such instrument (whose batteries last for year) is equivalent to one day of ship time. The limitation of making measurements primarily from ships has dramatically constrained the type of phenomenon and time/space scales studied by ocean biogeochemists and ecologists. Jim's work overcomes many of these limitations and is fundamentally altering the field, much in the way that the development of continuous measurements of temperature, salinity and pressure from profiling CTDs and moorings did for physical oceanography in the 1970's.

The central piece of the first *Carbon Explorers* is the use of optical measurements to measure biomass. The concentration of biomass and other suspended particulates in the water column is extremely low, and such measurements are exceedingly difficult even by traditional methods. The translation of the optical measurements into biomass comes from Jim's decades of ocean observations using the several generations of huge and labor-intensive large-volume *in-situ* filtration systems that Jim has developed during and since his

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PhD thesis. That the first deployment of the *Carbon Explorers* worked beautifully (a technical marvel) and delivered new insights – Jim's research has already demonstrated important scientific as well as technical findings. For example, on one of the early float deployments, he observed a large ocean plankton bloom associated with a dust storm that injected iron into the surfaces waters of the North Pacific. Such behavior had been hypothesized to occur but would be very difficult to capture using a traditional ship-based campaign because dust storms are short-lived and episodic. Many of outstanding science questions in oceanography will be answered only through a network of extend, continuous *in situ* measurements. Therefore it is not an overstatement to say that Jim's work is laying the ground-work for the next generation of ocean scientists.

Jim has not rested on his successes, and has continued to develop new instruments to attach to the *Carbon Explorers* – for measuring particulate inorganic carbon concentrations, particulate carbon fluxes, and other parameters of the carbon system. As chair of the Ocean Carbon and Climate Change Scientific Steering Group, part of the US Climate Change Science Program, I can unequivocally state that the *Carbon Explorers* are a critical piece of the emerging US and international ocean carbon observing program. The oceanographic community is extremely excited about the new window hat Jim's *Carbon Explorers* have opened into the biological processes in the ocean. The Explorers yielded, for the first time, the opportunity for routine, long time series about marine biological processes at great depths in the remote oceans and can operate in hostile seas where no ships and humans have been.

The success of the *Carbon Explorers* is a testament to Jim's comprehensive understanding of what is important to measure regarding the ocean carbon cycle and of what could be measured with great precision and accuracy, his attention to details, his tenacity and dedication, and above all his ingenuity and intuition. He is truly deserving of the R&D100 award.

Scott C. Doney

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CARNEGIE INSTITUTION
DEPARTMENT OF GLOBAL ECOLOGY

Extending the Frontiers of Science

16 February 2006

RE: R&D 100 Award Nomination

Dr. James K. Bishop and his coworkers have developed the first robotic device that can autonomously measure particles of organic carbon in the deep ocean. Carbon Explorer can be programmed to rise and fall in the water column, measuring particles at different depths, and then rise to the surface briefly to communicate the data to a satellite.

The invention of Dr. Bishop represents the future of oceanography in understanding the role of marine biology and its relation to large-scale ocean chemistry and physics.

Carbon Explorer advances the state of the art

Dr. Bishop develops instruments that can be put on deep-sea gliders and floats to measure biologically important quantities. The instruments need to be small enough to be housed in a small glider or float and low-enough power demand to run for a long time on batteries. They need to be reliable enough to work repeatedly for long periods of time at sea. They need to be accurate enough to provide a basis for our understanding and they need to be cheap enough to be affordable.

The Carbon Explorer does more than advance the field of robotic carbon measurement; it is the field of robotic carbon measurement. The state of the art before the work of Dr Bishop and colleagues was not much more advanced than throwing a bucket off the side of a ship. Now the way is open for a vast array of robotic devices, reporting on biological, chemical, and physical changes throughout the ocean volume.

Carbon Explorer helps solve a technological and social problem

Mankind is affecting the biology, chemistry, and physics of the ocean, but we do not yet understand the dynamical relationships among these processes, especially at large spatial scales and over long time periods.

Any hope of understanding the complex dynamical interactions among ocean biology, chemistry, and physics depends on having a good set of observations. But all we have today is little bits of isolated data collected almost anecdotally.

Even looking at the complete numerical output from computer simulations of the ocean, it is very difficult to develop a dynamical understanding of the interactions between biology, chemistry, and physics even in the model. So, we need a reasonably complete set of biologically important measurements in the ocean, with good spatial and temporal coverage, if we are to have any hope of getting a real understanding of how marine biology and physics interact. The only possible affordable way of doing this is with automated observation systems that are able to make accurate measures of biological and physical properties, with good spatial and temporal coverage.

Carbon Explorer shows that it will be possible to develop instruments that can be used affordably to report on the biological and physical state of the ocean. This data can form the basis for a much richer understanding of how our ocean works.

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My impressions of the Carbon Explorer based on its use

Carbon Explorer proved itself in the field.

The Carbon Explorer played a leading role in two recent papers in the prestigious *Science* magazine. The Carbon Explorer proved itself in operation. It witnessed the biological effects of Asian dust landing on the North Pacific Ocean. It also observed an experiment in which the ocean was fertilized near Antarctica. Both of these events were "first time ever" type observations. Again,

We "end users" will benefit from Carbon Explorer

The ultimate end user of this technology is society at large. We collectively are gaining an understanding of how our planet works.

The short term benefits to society are the advances in knowledge – as exemplified by two different papers in the prestigious *Science* magazine in the first year.

Robotic observations are the only hope for affordably getting enough observations of the oceans so that we can have some hope of actually understanding how the ocean works, and how, therefore, humanity might one day live in way such that both we and the ocean flourish.

Carbon Explorer is worthy of an RD100 Award because …

With the Carbon Explorer, a new window is opened up into the ocean interior.

The short term importance is shown in that two different uses of Carbon Explorer in the first year were "first of their kind" observations leading to two different papers in the prestigious *Science* magazine.

As great as those accomplishments are, the real importance of Carbon Explorer is that it points to the future of oceanography. The Carbon Explorer may be like Babbage's computer. Someday, we will look back to the Carbon Explorer as the beginning of the modern age of oceanography, when we finally developed the tools needed to develop a real understanding of ocean biology, chemistry, and physics.

Sincerely,

Ken Caldeira
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February 13, 2006 R/PMEL

R&D 100 Award Selection Committee

Dear Committee Members:

This letter is in behalf of Dr. Jim Bishop, who is being considered for the RD100 Award for development of the "Carbon Explorer." Over the past three decades, Jim has demonstrated a extraordinary capability for developing highly creative oceanographic instruments for studying dissolved and particulate biogenic matter distributions and fluxes in the oceans. This work has culminated with his development of the highly innovative Carbon Explorer, which provided the oceanographic community with its first new autonomous in-situ instrumentation for studying biogenic carbon flux processes using autonomous sensors. His scientific leadership is clearly demonstrated in development of particulate organic and inorganic sensors that have been modified for deployment on Argo-style floats to determine real-time changes in carbon biomass distributions and fluxes in the open-ocean. This research represents a major step forward in the way oceanographic research will be conducted over the next several decades.

The Carbon Explorer allows oceanographers to study the physical and biogeochemical processes controlling the transfer of biogenic carbon from the surface to the ocean interior under in-situ conditions with data transfer back to the laboratory in near real time for periods as long as a year or more. These high-frequency measurement systems have been used successfully to study carbon fluxes under a variety of different environmental and experimental conditions, from the impacts of storms and dust events on productivity in the North Pacific to the effects of Fe-fertilization on carbon sequestration processes in the Southern Ocean.

The Carbon Explorer has given the oceanographic community valuable new insights into the time and space scales of biogenic carbon fluxes in the oceans. This is of particular importance for society because the oceans are largest active reservoir for removing anthropogenically-derived carbon dioxide from the atmosphere. Because of this, there has been considerable discussion within the oceanographic community about expanding this new technology to include other important oceanographic parameters, such as pCO_2, oxygen, trace metals, etc., and the development of the Carbon Explorer will undoubtedly lead the way toward many new futuristic innovative sensors mounted on autonomous underwater vehicles (AUVs- propeller driven torpedo-like vehocles), buoyancy driven self-navigating gliders (CE's with wings), all the way to ship deployed packages and moored arrays.

In summary, I wholeheartedly support the nomination of Dr. Jim Bishop for this prestigious RD 100 Award for his innovative design, development and successful deployment of the Carbon Explorer for oceanographic research.

Sincerely,

Dennis W. Moore

for Richard A. Feely
Supervisory Oceanographer

UNIVERSITY OF CALIFORNIA, LOS ANGELES UCLA

BERKELEY DAVIS IRVINE LOS ANGELES RIVERSIDE SAN DIEGO SAN FRANCISCO SANTA BARBARA SANTA CRUZ

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February 17, 2006

R&D 100 Award Selection Committee

Re: Letter of support for the nomination of the Carbon Explorer

Dear Committee Members,

I hereby enthusiastically support the nomination of the Carbon Explorer for consideration of this year's R&D 100 Award. The Carbon Explorer is an ingenious new tool that will revolutionize the way we observe the ocean carbon cycle. Such observations are extremely crucial if we want to understand and predict how this cycle will respond to a changing world, brought about by the increase of carbon dioxide in the air from human-induced emissions of this greenhouse gas. The Carbon Explorer will open entirely new windows to studies of the ocean, perhaps in a way similar to how satellites have revolutionized the way we look at processes in the atmosphere and at the earth's surface. The Carbon Explorer will permit us to investigate processes and regions that were previously completely inaccessible to experimental studies, and is bound to add many new discoveries to the two major ones that were recently published in *Science*. Thus, the Carbon Explorer embodies all the characteristics expected from a newly developed system worthy considering for the R&D 100 Award: Ingenuity, importance, and readiness. I explain the reasons for my excitement in more detail below.

The ocean plays a very fundamental role in the global carbon cycle and our climate system, yet historically we have been severely challenged in our ability to observe it. This has resulted in the ocean being the least well observed "sphere" of our planet, and big holes in our understanding of how it works and how it may respond to a changing climate. So far, most of our oceanic observations, and particularly those pertaining to the ocean carbon cycle, stem from shipboard-based systems, where research ships that cost several tens of thousands of dollars per day to operate steam through the ocean and collect water samples along their way. Naturally, only a very tiny fraction of the time-space variability of the ocean can be captured this way.

However, a revolution is on its way. Autonomous sampling systems on floats that profile up and down through the water column are about to change forever the way we observe the ocean. In the last few years alone, the roughly 3000 floats that have been deployed in the ocean as part of the ARGO project have been collecting data that exceed the total number of oceanic observations made during the entire century before that. So far, these systems have been limited to the measurement of temperature and salinity, with the addition of other measurement systems facing a large number of challenges, such as lifetime, power consumption, long-term stability etc. The team around Jim Bishop from the Lawrence Berkeley Lab has ingeniously solved these challenges, added a suite of extremely important new sensors and communication technology to these floats, and thereby created a novel and exciting new tool: the Carbon Explorer.

The Carbon Explorer is bound to revolutionize ocean carbon cycle research, to the benefit not only of the oceanographic research community, but also to society as a whole. By measuring the flow of organic carbon from the surface where it is fixed by small plants down into the ocean's interior, the Carbon Explorer will provide constraints on a major, and hitherto not well quantified pathway of carbon around the globe. This biologically induced downward flux of carbon away from the surface tends to reduce the atmospheric CO_2 concentration. There exist great concerns that a changing climate and the acidification of the ocean in response to the uptake of CO_2 from the atmosphere will make this downward transport smaller, thereby leading to a release of CO_2 from the ocean into the atmosphere. This would further accelerate climate change with substantial potential impacts on humankind. The Carbon Explorer is a breakthrough development that will shed much light into these processes, permitting the scientists to detect such changes early, and to improve their ability to better predict the potential future development of Earth's climate.

For all these reasons, I enthusiastically support this nomination. Please don't hesitate to contact me if you have any further questions.

Sincerely yours,

Prof. Nicolas Gruber
UCLA Associate Professor of Geophysics
ETH Zürich Professor of Environmental Physics

2006 R&D 100 AWARDS
ENTRY—Carbon Explorer (Berkeley Lab)

Appendix B

Scientific Publications

Science Reprint

Robotic Observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific

James K. B. Bishop, Russ E. Davis, Jeffrey T. Sherman

25 October 2002, Volume 298, pp. 817-821

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Robotic Observations of Dust Storm Enhancement of Carbon Biomass in the North Pacific

James K. B. Bishop,[1]* Russ E. Davis,[2] Jeffrey T. Sherman[2]

Two autonomous robotic profiling floats deployed in the subarctic North Pacific on 10 April 2001 provided direct records of carbon biomass variability from surface to 1000 meters below surface at daily and diurnal time scales. Eight months of real-time data documented the marine biological response to natural events, including hydrographic changes, multiple storms, and the April 2001 dust event. High-frequency observations of upper ocean particulate organic carbon variability show a near doubling of biomass in the mixed layer over a 2-week period after the passage of a cloud of Gobi desert dust. The temporal evolution of particulate organic carbon enhancement and an increase in chlorophyll use efficiency after the dust storm suggest a biotic response to a natural iron fertilization by the dust.

Marine phytoplankton biomass is replaced, on average, once every 1 to 2 weeks (*1–3*). Carbon products of photosynthesis (*4*), i.e., particulate organic carbon (POC), particulate inorganic carbon (PIC), and dissolved organic carbon (DOC), are exported below 100 m at a rate of

~10 Pg C year^{-1}. This process, commonly referred to as the ocean's "biological pump" (*5*, *6*), is important to the regulation of atmospheric CO_2. The variability and linkages of the biological pump from surface to depth are poorly understood, because virtually all information on carbon dynamics within the upper kilometer of the ocean is derived from ship-dependent systems deployed for short periods of time (e.g., days to weeks).

Until recently, the use of optical instrumentation from drifting research platforms (*7*) and from deep ocean moorings (*8–14*) has been the only way to acquire long-term, uninterrupted high-frequency (hours or better), and depth-resolved time series measurements for detailed studies of biological and physical relations in the upper ocean on seasonal time scales. These observations provided clear documentation of a strong diurnal cycle in the abundance of particulate matter (*7*) and established the observational basis of an improved understanding of physical and biological process coupling in surface waters. Though ships and moorings are effective for deploying sophisticated instrumentation within regions or at individual sites, their costs limit their use for long-term monitoring on ocean basin or global scales.

The international program ARGO (*15*) has begun to seed the world's oceans with 3000 autonomous profiling floats to gather widespread temperature and salinity profiles and information on mid-depth circulation for investigation of the climate of the ocean. Such long-lived floats are designed to profile to the surface from kilometer depths once every 10 days over 5 years, and they have been already widely used to chart deep ocean circulation over basin scales (*16*). A faster derivative of the ARGO-style float (*17*) has been developed and equipped to measure POC (*18*, *19*). Here we present carbon biomass variability of the North Pacific ocean obtained from first deployment of these floats, which we call Carbon Explorers (*4*).

Two Carbon Explorers were deployed from the U.S. Coast Guard ice breaker *Polar Star* in the subarctic north Pacific near Ocean Station PAPA (OSP; 145°W, 50°N) on 10 April 2001 (Fig. 1). Each was programmed to surface from depth at dawn, dusk, and midday on a repeating 2-day cycle (*4*) to capture net dawn-to-dusk POC production as well as data coincident with overpass of the sea-viewing wide field-of-view sensor (SeaWiFS) ocean color satellite (*20*). PAPA was chosen because its high-nutrient low-chlorophyll (HNLC) waters have been well characterized for POC and beam attenuation coefficient (*c*) variability (*19*) as part of the Canadian Joint Global Ocean Flux Study (C-JGOFS) (*21*) and because PAPA is one of few sites in the world with a multi-decade–long time series of ocean observations relevant to the biological pump (*22–25*).

The two Carbon Explorers returned virtually unbroken data streams over 8 months of operation from April to December 2001 (*4*). Our longest-lived float completed nearly 400 profiles by 24 December 2001, at which time its batteries ran out. In this analysis, we focus on Carbon Explorer records from the first 50 days when the two profiling floats drifted within 40 km of each other and returned virtually identical records of POC variability (Fig. 2).

Throughout the first 50 days, the dawn mixed-layer depths ranged between <30 and 100 m (Fig. 2). There is a strong halocline at 100 m, suggesting isolation of the upper 100-m layer from beneath. POC is always highest in the surface mixed layer, and there is almost always a photosynthetic increase of POC in the mixed layer between dawn and dusk. The boundary between the particle-rich waters of the surface mixed layer and particle-poor waters below corresponds to the depth where the dawn profile potential density increases by 0.05 per mil (‰) relative to its surface value. This depth closely approximates the depth of greatest mixing during most days of the record and defines the "mixed layer" in discussions below.

A net photosynthetic production of POC in the mixed layer was recorded between dawn and dusk virtually every day throughout the observing period (Fig. 2, bottom). The frequent return of the dawn POC to the previous day's morning values during many days of the record confirms the generally close balance between daytime primary productivity and day-long grazing in the waters at PAPA on a daily basis (*24*). There were times when net POC production appeared to exceed grazing. Daily POC increases frequently reached values of ~0.5 μM between days 110 and 118 (a 15% increase relative to dawn POC values); net gain over the following 30 days record averaged ~0.2 μM (typically ~10% of dawn POC levels), exceeding 0.3 μM only three times. Using the POC levels and dawn-dusk changes, we estimate a fast turnover time of POC in the mixed layer of 7 to 10 days. A natural consequence of the enhancement of rates of net POC production during days 110 to 118 is the observed build up of biomass in the mixed layer during those days.

The Carbon Explorers encountered two major storms in the first 50 days, when the mixed layer deepened rapidly to 100 m (Fig. 3). Average POC concentrations in the mixed layer were ~2.1 μM at the beginning of the study in April, typical of shipboard observations in 1996 and 1997 (*19*). Within 5 to 6 days after passage of the first storm (days 101 to 102), with thermal stratification, mixing depth shoaled to 50 m and POC began a steady increase over 10 days reaching peak levels of ~3.5 μM by day 118. During the second storm (days 119 to 121), POC concentrations dropped again to ~ 2.1 μM due to progressive entrainment of POC-poor subsurface waters as the mixed layer deepened twofold to 100 m. Another brief 1-day wind event

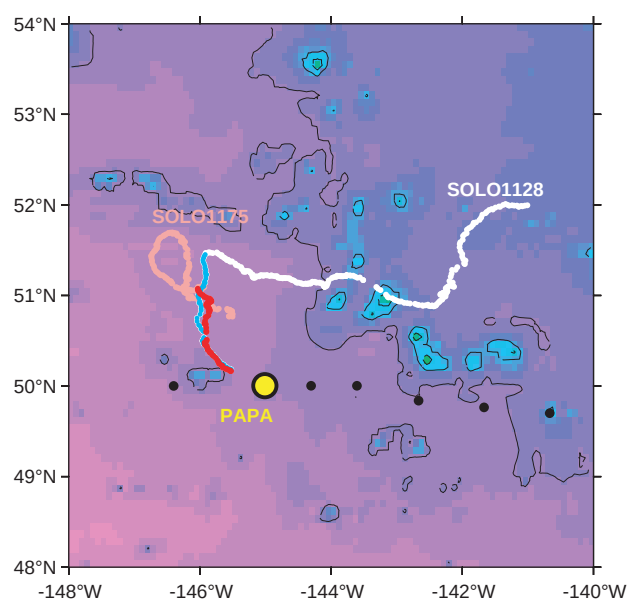

Fig. 1. Trajectories of SOLO Carbon Explorers over their lifetime (April to December 2001) superimposed over bathymetry (water depth near PAPA is greater than 4 km; black lines denote bathymetry contours at 1-km intervals). Cyan and red tracks denote trajectories for the first 50 days of deployment. White and pink tracks are trajectories of the floats from June to December 2001. The Carbon Explorers were deliberately placed to the northwest of OSP and were expected to drift eastward with the subarctic current. They drifted in the opposite direction from OSP for 3 weeks before turning northward and then finally turning east. Drift rates were 3 to 5 cm s^{-1} during most of their 8-month deployment. They remained within 2 to 3 km of each other for 20 days; one float and then the other encountered a subsurface warm feature, and float separation increased to 40 km by 50 days. Black symbols are "line P" station locations (*23*) occupied during the C-JGOFS cruises.

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occurred on day 127. With restratification after the second period of stormy weather, there was a weak increase of POC to levels of ~2.5 μM 10 days later (by day 136).

Photosynthetically active radiation (PAR) available for biological production in the water column varies with cloud cover, mixing depth, and particle concentration. Values fluctuating between 5 and 25 Wm^{-2} were calculated (*26*) for the mixed layer (Fig. 3B). We identified two 10-day-long periods between storm events, centered on days 115 and 135, which had similar mixed layer stratification, high PAR, and constant salinity (32.60 ± 0.005 ‰; Fig. 3C). Yet these time periods had very different averaged mixed layer POC maxima (~3.5 μM and ~2.5 μM), suggesting that hydrographic and insolation changes alone cannot explain the high POC after the first storm (at day 118).

The growth of phytoplankton in HNLC waters near PAPA is believed to be limited by the availability of iron for all or part of the time (*22*, *24*, *27*, *28*). Fe demand by phytoplankton near PAPA is estimated to be ~60 μM Fe m^{-2} on an annual basis (*28*). The total supply, 3 μM Fe m^{-2} from upwelling and 25 μM Fe m^{-2} from aeolian delivery (assuming an upper limit of 10% of the dust bourne Fe is biologically available), falls short of the demand by at least two times.

Correlative analysis of different but not temporally coincident biogeochemical time series observations near PAPA (*22*) suggest that dust from the atmosphere could be the major iron supply. Lateral iron delivery from the continental margin, generally a result of river runoff and redox processes in shallow marine sediments, could also be a source of Fe to PAPA. This was ruled out in the correlative analysis because drifters deployed with a drogue at 100 m moved from west to east consistent, with the general west-to-east flow of the subarctic current. Surface layer freshening is a mid- to late-summer occurrence at PAPA (*23*) and was evident also in C-JGOFS observations collected in 1996 (*19*) and in the Carbon Explorer records in late July–early August 2001. Of the two Carbon Explorers, SOLO1128, which traveled further east, observed a lower and earlier salinity decrease than SOLO1175. Mixed layer POC reached as high as 5.5 μM in both Carbon Explorer records (not shown) with the peak coincident with the July-August arrival of a shallow 10- to 20-m-thick fresher layer with salinity ~0.1‰ lower than found at any other time of year. These observations suggest a likely summertime POC enhancement in response to seasonal continental runoff penetrating southwestward from the continental margin, with possible delivery of iron and micronutrients. However, with the mixed layer salinity remaining constant (within 0.005‰) between days 110 and 145, we rule out continental runoff as a contributor to the POC maximum near day 118.

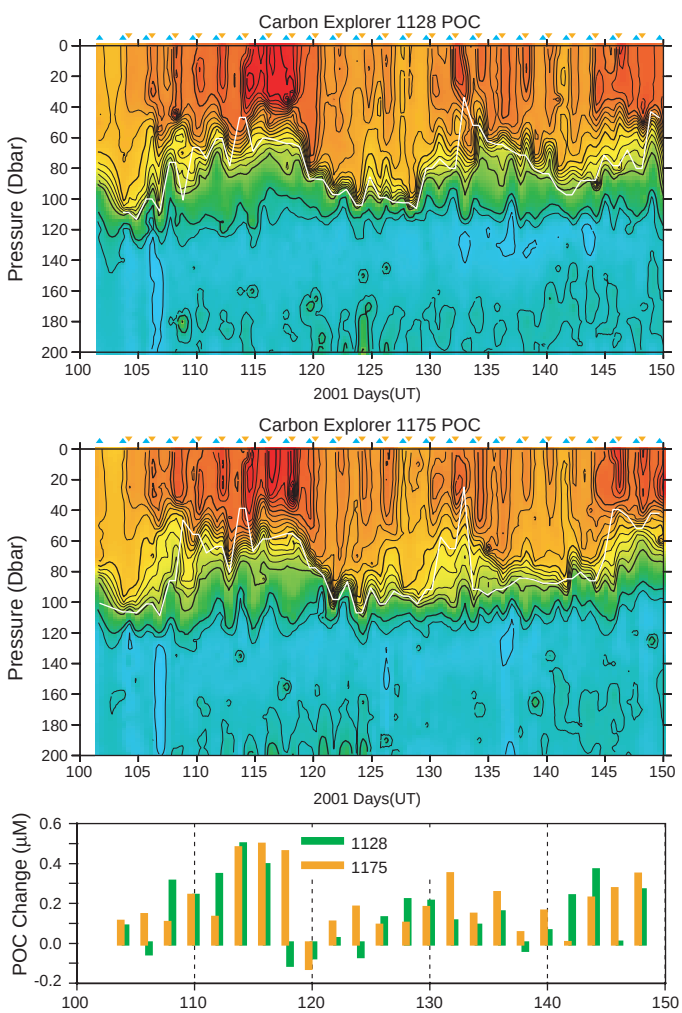

Fig. 2. (Top and **middle**) Time series of POC variability from SOLO1128 and SOLO1175 during the first 50 days of deployment. Cyan up-triangle and orange down-triangle at the top of each panel are plotted at the times of dawn and dusk profiles, respectively. On alternating days, a mid-day profile also contributes to the time series. Heavy black contours for cold to warm colors are drawn at 0.5, 1.0, 2.0, 3.0, and 4.0 μM POC levels. Light contours are at 0.2 μM spacing above 1.0 μM and at 0.1 μM spacing below 0.5 μM. White curve is mixed-layer depth calculated from the dawn Carbon Explorer profile using a potential density increase of 0.05 relative to the surface. Mixing variability was consistent with surface winds retrieved twice per day using the JPL/QUIKSCAT instrument. Storms with winds persistently exceeding 25 knots occurred on days 101 to 102 and on days 119 to 122 and on day 127. Data contoured using GRI software. The "lock-step" nature of both records indicates that observed POC variability is a response to large scale forcing. (**Bottom**) Daily net growth or loss of POC calculated as dusk minus dawn POC averaged between the surface and depth of the dawn "mixed layer." Enhanced net growth rates occurred on days 114 through 118 approximately 2 weeks after Gobi desert dust passed over PAPA.

The first storm (day 101 to 102) encountered by the Carbon Explorers was a dust storm from Asia. Many details of this event are similar to the dust storm events of April 1998 (*29*). On 7 April 2001, the NASA TOMS satellite sensor recorded a large dust storm originating near the Gobi desert in southern Mongolia–northern China. The cloud of dust passed over Japan on 10 April (day 100), over PAPA on 12 and 13 April, and reached North America on 14 April 2001. The eastward decline of the TOMS aerosol index averaged for latitudes 50° to 52°N and longitudinal bands 165° to 155°W, 150° to 140°W, and 135° to 125°W suggests dust deposition to the oceans (Fig. 3A). Deposition was further indicated by the apparent lack of spatial dispersion seen in composite satellite images of the dust cloud as it passed these longitudes.

Therefore, the major dust input was on days 101 and 102. The POC loading in the mixed layer started to increase 5 days later, and peaked after 2 weeks (Fig. 3D). POC almost doubled between days 108 and 118. These higher values exceed, by a factor of two to four, the POC levels observed from ships in February of 1996 and 1997 and in May of 1996 (Fig. 3D) (*19*). The timing of the POC increase is similar to that found in purposeful addition of iron to cold southern ocean waters (*30*).

Chlorophyll retreivals by SeaWiFS (*31*) were sparse near PAPA during April and May 2001 due to nearly complete (>92%) obscuration of the sea surface by clouds. The 11 usable images show a 25% chlorophyll enhancement between days 110 and 118 (Fig. 3D). Using Carbon Explorer and SeaWiFS observations, we estimate the POC/chlorophyll weight ratio for mixed layer particles to range between 60 and 80:1 (g C/g chlorophyll). The highest POC/chlorophyll ratio of 80 occurred during

the POC peak on days 116 to 118 and remained near 60 throughout the second storm and stratification period. The high ratio during the first stratification period is consistent with greater efficiency in nutrient utilization and biomass production as a result of reduced iron stress (*28*), analogous to observations of increased photosynthetic competency with the reduction of iron limitation (*32*).

The Carbon Explorer and SeaWiFS observations are, therefore, strongly supportive of the hypothesis of enhanced marine productivity, and enhanced carbon biomass in the euphotic zone, i.e., "fertilization," in response to inputs of iron and other micronutrients from the Asian dust storm. Without Carbon Explorer observations before day 100, we cannot rule out definitively a preconditioning of the upper ocean that led to the enhanced bloom. However the POC/chlorophyll systematics strongly support an iron fertilization effect. It is evident that effects of the added Fe did not persist past 2 weeks, because there was only a weak growth of POC during the second 10-day-long stratification period.

Our observations of increasing POC levels following the likely natural fertilization of HNLC waters near PAPA indicates net photosynthesis increased faster than grazing and settling losses. The POC concentrations in deeper waters near 200 m show an increase near days 120 to 125 after the first surface POC maximum (Fig. 2). However, we cannot attribute this to dust-induced enhancement of organic carbon export from the euphotic zone to the deep sea, because our Carbon Explorers were not equipped to measure particle fluxes and we cannot distinguish between grazing and particle loss in the existing data.

All previous reports of dust and biological enhancement have relied on opportunistic observations made from ships at sea for very short periods of time (*33–35*). Strong dust events are highly episodic and affect the HNLC waters of the North Pacific near PAPA for a few days once every several years (*22*). It was only through analysis of hundreds of weekly surface chlorophyll observations made from weather ships at PAPA from 1961 through 1976, statistical seasonal probability analysis of wind trajectories and probable dust source regions, and a correlative comparison with 1984–89 records of carbon sedimentation at 3800 m that a very loose "link" was established between delivery of dust from the atmosphere and enhanced carbon export to the deep sea (*22*). The two Carbon Explorers provided, for the very first time, direct continuous observations of the upper ocean biological response to episodic events such as dust inputs and ocean storms. They have proven to be capable of sustained, high-frequency observations of carbon biomass variability in the ocean for the greater part of 1 year, thus greatly increasing the probability of directly observing biological responses to such episodic events.

This observational study with two autonomous floats supporting physical sensors and two bio-optical sensors demonstrates a potential for studying the carbon cycle on basin scales and multi-year time scales as well as some of the difficulties. Because the main carbon-cycle variability occurs in depth and time and is markedly decreased at depth, a time series of profiles is both descriptive and helpful in removing sensor drifts such as those caused by biofouling. Low cost, year-round operation and an ability for proliferation make autonomous floats particularly well suited to augmenting satellite observations by working under cloud cover, describing vertical structure, colocating multiple measurements, and making measurements more accurately than is possible with remote sensors. In contrast, autonomous instruments are not suitable platforms for many sophisticated measurments that require tending, use large amounts of energy, or are subject to biofouling (even at reduced levels achieved in this study). Ultimately, the challenge of carbon-cycle study will be observing with acuity the broad range of interacting variables over large space and time scales. Extensions of the Carbon Explorer concept should contribute.

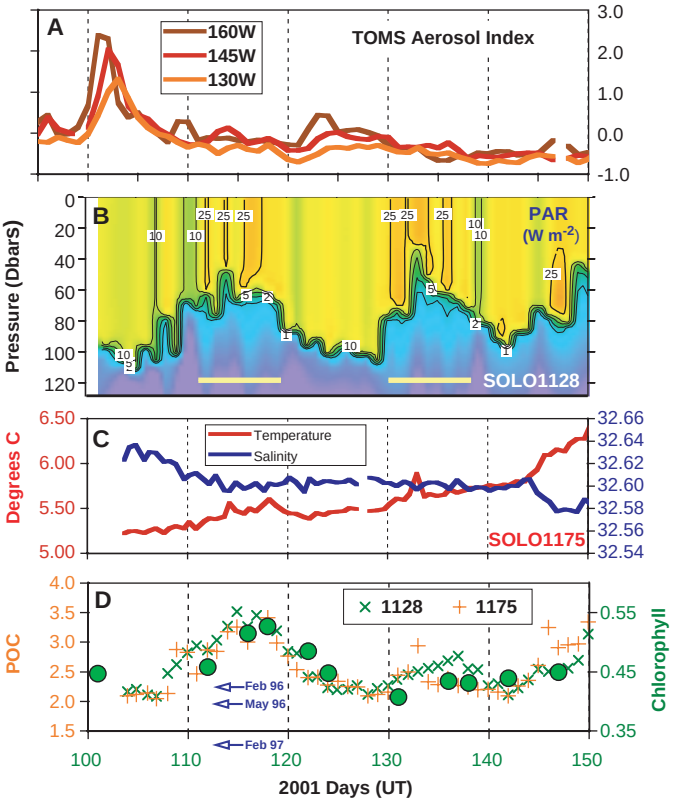

Fig. 3. (**A**) Time series of TOMS aerosol index data for 165° to 155°W, 150° to 140°W, and 135° to 125°W for 50° to 52°N. The decreasing atmosphere aerosol abundance from west to east indicates dust deposition near PAPA. (**B**) PAR distribution for the SOLO1128 record. PAR below the surface was computed using clear sky irradiance and TOMS surface reflectance. PAR at greater depth is computed using a POC-based estimate of depth-varying diffuse attenuation coefficient. PAR was averaged over the depth of the mixed layer. Subsurface maxima are a contouring software artifact. (**C**) Temperature and salinity averages for the "dawn" mixed layer. The sudden change in salinity and temperatue at day 145 was accompanied by a jump in POC. This is suggestive of lateral advection. Our analysis focuses on the first 45 days when the mixed layer appeared to be isolated as POC and temperature and salinity did not concurrently change. (**D**) Time series of mixed-layer "noon" POC variability for SOLO1128 and SOLO1175 and SeaWiFS chlorophyll retrievals for the first 50 days of record for a 200 km by 200 km region near PAPA. POC is in units of μM. Chlorophyll is in units of mg m^{-3}. Arrows denote POC levels from our C-JGOFS cruises from February 1996 and 1997 and from May 1996. The peaks in both POC and chlorophyll on days 116 to 118 (28 April 2001) are consistent with a biomass response to inputs of Asian dust and iron.

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Supporting Online Material
www.sciencemag.org/cgi/content/full/298/5594/817/DC1
Materials and Methods

11 June 2002; accepted 17 September 2002

Science Reprint

Robotic Observations of Enhanced Carbon Biomass and Export at 55°S During SOFeX

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16 April 2004, Volume 304, pp. 417-420

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Robotic Observations of Enhanced Carbon Biomass and Export at 55°S During SOFeX

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Autonomous floats profiling in high-nitrate low-silicate waters of the Southern Ocean observed carbon biomass variability and carbon exported to depths of 100 m during the 2002 Southern Ocean Iron Experiment (SOFeX) to detect the effects of iron fertilization of surface water there. Control and "in-patch" measurements documented a greater than fourfold enhancement of carbon biomass in the iron-amended waters. Carbon export through 100 m increased two- to sixfold as the patch subducted below a front. The molar ratio of iron added to carbon exported ranged between 10^4 and 10^5. The biomass buildup and export were much higher than expected for iron-amended low-silicate waters.

The Southern Ocean plays a critical role in the global carbon cycle and in the regulation of levels of atmospheric CO_2 (*1–3*), yet the biological and physical processes that sequester carbon remain poorly understood largely because of the difficulties in making observations in waters surrounding Antarctica. The January to February 2002 SOFeX (*4*) was designed to examine the biological and carbon system response to the effects of purposeful addition of iron to nitrate-rich waters north and south of the Polar Front Zone (PFZ). Iron was added to two ~225 km^2 regions near 55°S 172°W and 66°S 172°W to test the hypothesis that the lack of dissolved silicate would limit both biomass growth and carbon export. Waters north and south of the PFZ had dissolved nitrate:silicate concentrations of 22:2.5 μM and 27:60 μM, respectively. The "North Patch" at 55°S was considered to be silicate limiting.

Three free-profiling robotic Lagrangian Carbon Explorers (*5*) were deployed at 55°S from the research vessel (RV) *Roger Revelle* to provide high-frequency (three times per day) profile observations of particulate organic carbon (POC) (*6*), Temperature (T) and Salinity (S) in the upper 1000 m; a fourth was deployed at 66°S. Between profiles, the SOFeX Explorers were "parked" at 100-m depth to investigate the systematics of carbon export at 100 m with an optically derived carbon flux index (CFI) (*7*).

Our "control" Carbon Explorer 1177 (*8*) was deployed ~20 km north of the planned North Patch location on 11 January 2002; it drifted northeast parallel to bathymetry as expected for the Antarctic Circumpolar Current. Two Explorers were deployed "in the patch" (Fig. 1A). Explorer 2054 was deployed on 12 January in the planned center of the North Patch; the first infusion of iron immediately followed. Explorer 2054 immediately tracked to the northwest, reflecting a current shear that soon split the initial 15 km by 15 km iron-fertilized patch in two. The northwest segment of the iron-fertilized water was sampled by Explorer 2054, and enhanced biomass levels were traced for 14 days; subsequent biomass profiles were typical of those observed by the control float. This segment was never sampled by SOFeX ships again. Explorer 2104 was deployed on 19 January (patch day 7) just prior to a second Fe infusion to the other "half" of the North Patch (*9*). It advected to the northeast on a course that closely paralleled that of the control (Fig. 1A). We refer to Explorer 2104 as the "in-patch" Explorer.

Over the following three weeks, the control (1177) and in-patch (2104) Explorers tracked each other closely, while relaying their surfacing positions, hydrography, and carbon mea-

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surements in real time by satellite. Analysis of remotely sensed (QuikSCAT) winds and retrieved surface solar irradiance (*6*) indicated that both Explorers sampled biological systems that had experienced nearly identical surface physical forcing. Winds averaged 9 m/sec (range 4 to 16 m/sec). Virtually no difference in T and S structure of the euphotic zones was observed by the two floats (*6*).

The single cloud-free ocean color image of waters near 55°S showed that the North Patch had strung out into a 4-km-wide by 250-km-long filament by patch day 21 (*4*, *10*). Both the control and in-patch Explorers had drifted nearly 200 km with the Antarctic Circumpolar Current. One week later, RV *Revelle* returned to the North Patch on 8 February 2002 (patch day 27) with the aid of the in-patch Explorer Global Positioning System (GPS) positions. *Revelle* survey and conductivity-temperature-depth (CTD) data confirmed that the in-patch Explorer was "in," but not perfectly in, the southwest segment of the narrow filamentous North Patch (*6*) of iron-amended, low-silica, high-nitrate water.

The in-patch Explorer recorded a greater than fourfold increase in POC concentration in the upper 50 m from ~2 μM to ~9 μM over 4 weeks, whereas records from the control Explorer showed little change (Figs. 1 and 2) (*11*). From patch days 29 to 31, the POC maximum abruptly shifted from the surface layer to below 30 m, so that surface biomass actually decreased 2 days after the third iron amendment. In deeper waters at about the same time, the 1-μM POC isoline began a stepwise deepening, going from ~120 m to ~180 m by patch day 41; the control Explorer's record showed little evidence of change in POC.

The subduction of POC began with a change in surface stratification, which coincided with the appearance of a layer of ~0.3 degree warmer water near the surface (little salinity difference was observed). The particle-rich waters were extruded into a much thinned ~20-m layer. The warm layer thus became the "mixed layer" (*12*), and the iron-stimulated biomass was suddenly isolated from the surface in an environment with less than 10% of previously available photosynthetically active radiation and very much reduced levels of turbulence (*6*). The POC enhancement near 50 m was last observed on UTC day 65 (patch day 53), almost 2 months after the experiment began.

The time series of CFI showed little difference between control and in-patch observations before patch day 26. One day later and 21 days after the second iron infusion (and just before a third infusion of Fe), the in-patch CFI observations at 100 m began to show indications of an export event in progress (Fig. 2) that was not mirrored by the control. High-CFI events were observed episodically at an interval of 2 to 3 days and peaked 2 weeks later on patch day 41. The shift in upper water column stratification and the subduction of POC-rich waters began on patch day 29. It appeared that each high-CFI event was coincident with or preceded the stepwise deepening of POC isolines. Such POC isoline deepening and high-CFI events are indications of rapidly sinking particles and, hence, carbon export.

Because of the complicated dynamics of the patch and the Lagrangian nature of the Explorer sampling, either temporal or spatial variability in carbon flux could lead to observations of episodic high carbon flux. A hypothesis that the rain of particles was episodic and that the in-patch Explorer was sampling all the episodes would yield a lower limit on the integrated carbon flux. A hypothesis that the Explorer was having "transient encounters" with a continuous rain of particles from the narrow filamentous patch would require interpolation of the CFI between encounters and yield an upper limit for the carbon flux in the filamentous patch. There is some merit to considering this latter view, because the settling velocity of exported particles (100 to 200 m d^{-1}) is small compared with expected horizontal motions as the patch was subducted; thus, it is unlikely that such particles would take a purely vertical trajectory between 50 m and 100 m (*13*). Integration over 50 days of CFI data for control and in-patch Explorers using these assumptions show a twofold and a five- to sixfold enhancement of sedimentation below iron-amended waters for the lower and upper limits, respectively.

Carbon export estimates from shallow sediment traps or thorium methods are not available at 55°S for a direct calibration of the CFI. However, a calibration of the CFI was possible using thorium-based carbon export rates at 66°S (*14*). CFI to carbon export factors of 89 to 58 counts d^{-1} (mmol C m^{-2} $d^{-1})^{-1}$ were derived (*15*). Extrapolations of previous sediment trap data (*16*) to 100 m (*17*) and comparison with control Explorer's CFI record at 55°S yielded similar results (*18*). Directly applying the two possible 66°S CFI calibration factors to the 55°S CFI records between days 39 and 55 yields a lower limit on net export enhancement of 120 to 190 mmol C m^{-2} for the "episodic rain" hypothesis and an upper limit of 760 to 1170 mmol C m^{-2} for the "transient encounter" hypothesis. POC standing stock changes, if translated into export, indicate loss rates of 280 to 340 mmol C m^{-2} (*19*), but this estimate is also a lower limit.

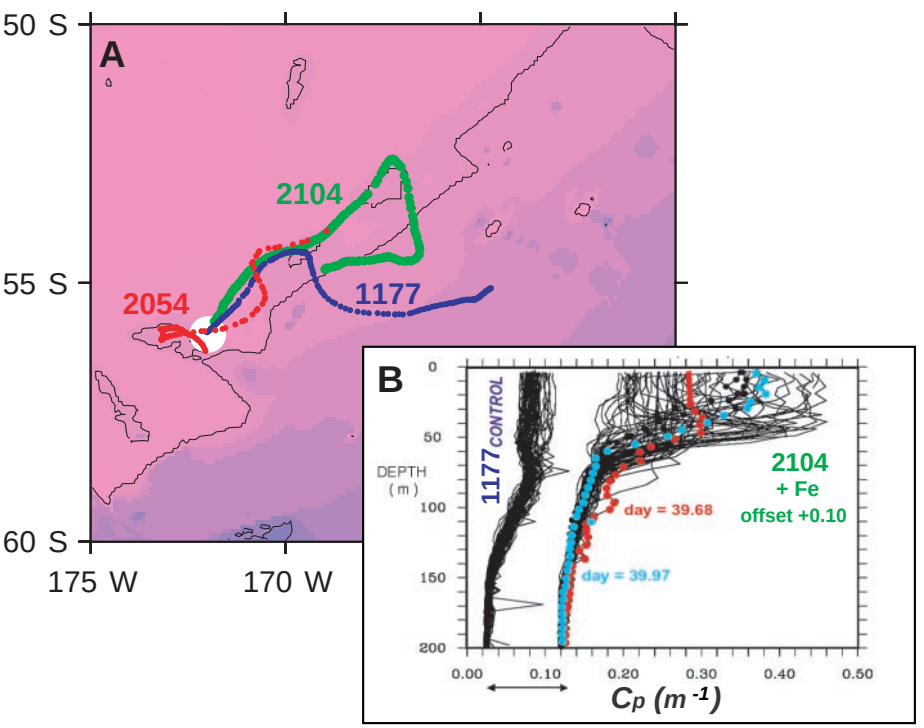

Fig. 1. (**A**) Trajectories of Carbon Explorers for the first 60 days of deployment superimposed over bathymetry of the Southern Ocean. Blue, red, and green tracks denote trajectories for Explorers 1177 (control), 2054 (in-patch #1), and 2104 (in-patch #2), respectively. (**B**) Carbon Explorer POC sensor data (beam attenuation coefficient) from the control (1177) and in-patch (2104) Explorers during the first month of observations of the North Patch. Three profiles per day were transmitted in real time. The highlighted profiles from the in-patch Explorer on universal time coordinated (UTC) day 39 were collected 6 hours apart at the time of the RV *Revelle* survey and indicate variable sampling of waters below 80 m that were enriched in POC. Both 1177 and 2104 went on to operate for another year in the Southern Ocean.

The Explorer data allows a first particle-based estimate of the ratio of Fe-added to POC-exported, as illustrated below. The original patch area was ~225 km², and the three amendments totaled ~1700 kg of Fe (*4*). The initial iron-fertilized patch (650 kg of Fe added) split in two, and half was lost from the experiment; thus, there was a net Fe amendment of ~1400 kg. From the only clear-sky satellite image available, the amended patch was approximately 1000 km² on patch day 21 (*4*, *10*), 6 days before the start of the sedimentation event and 10 days before the subduction event. During this subduction process, the layer containing the iron-enhanced biomass, between potential density surfaces of 26.6 and 26.5, decreased from a thickness of 40 m to approximately 20 m (Fig. 2 and fig. S11). We therefore hypothesize that the patch area doubled early during the sedimentation event, as required by water mass conservation. Applying the Explorer observations to a 2000-km² area yields an iron-added:POC-exported ratio (in moles) ranging from a lower limit of $\sim 1:1\times10^4$ to $\sim 1:1\times10^5$ at 55°S. These export estimates could increase by 40% if the third (450 kg) Fe addition (patch day 28) had no effect.

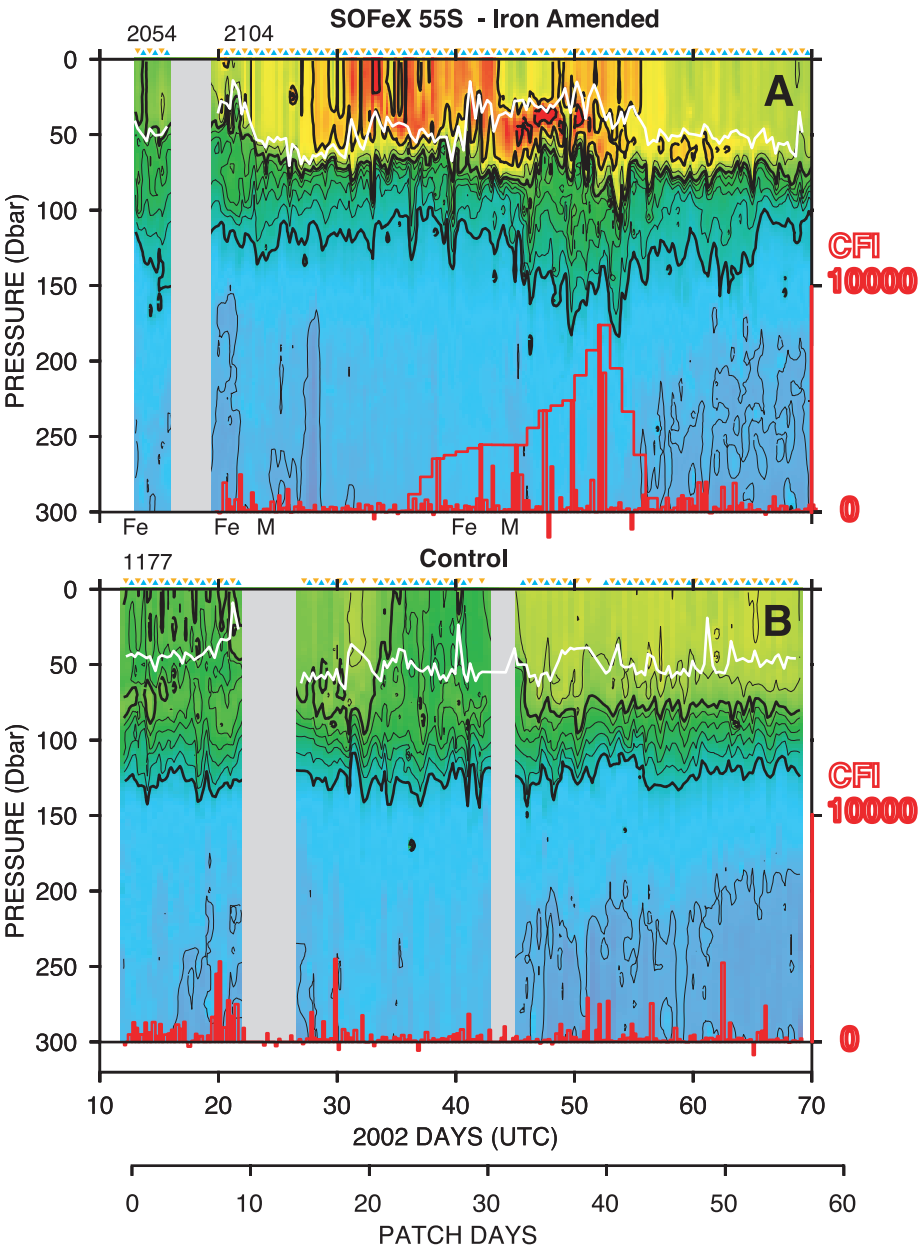

Fig. 2. Time series of POC variability from (**A**) Carbon Explorer 2104 (in iron-amended waters) and (**B**) Explorer 1177 (control) during the first 60 days of deployment. Patch day 0, the start of iron addition, corresponds to UTC day 12.5. The first week of data from Explorer 2054 is included in (A). Cyan up-triangle and orange down-triangle at the top of each panel are plotted at the times of dawn and dusk profiles, respectively. Heavy black contours for cold to warm colors are drawn at 1.0, 2.0, 4.0, and 8.0 μM POC levels. Light contours are at 0.5 μM intervals up to 2.5 μM (except between 1.0 μM and 2.0 μM, where they are drawn at 0.2 μM intervals). Near-surface lows in POC concentration recorded by the "in-patch" Explorer (e.g., UTC days 30 and 34) indicated that it was not always "in" the patch. The white curve is the mixed-layer depth, calculated from the dawn Carbon Explorer profile with potential density data (*12*). The red line plotted relative to the scale to the right of the figure is the carbon flux index (CFI) (counts d^{-1}) at 100 m. CFI values peaked UTC day 53 (patch day 41). About 150 POC profiles are represented in each of the time series shown. Gray bars are due to loss of profile data caused by transmit buffer overflow on the Explorer as a result of prolonged stormy conditions. CFI data are more frequent because they are transmitted at higher priority. *Revelle* was present at 55°S from 10 to 20 January and for a brief 2-day period in early February 2002. Times of Fe addition by RV *Revelle* are indicated by Fe. RV *Melville* (M) was present for several days during late January 2002 and again briefly in the third week of February 2002.

Phytoplankton present in the waters of the Southern Ocean have the highest iron stress in the world (*20*) and thus are most likely to respond to added iron (*21*). Iron fertilization experiments in the Southern Ocean have previously documented the stimulation of phytoplankton biomass after the addition of iron (*22*, *23*), but none of the experiments observed the end of the iron-stimulated blooms. SOFeX is the first experiment where the study of carbon export has been attempted on a sustained basis. Buesseler *et al.* (*14*) followed the export from the 66°S patch over 30 days. The Carbon Explorers at 55°S recorded patch events for ~50 days.

The SOFeX "ensemble" experiment tested the hypothesis that silica limitation would result in much less biomass enhancement and carbon export at 55°S compared with the silica-rich waters at 66°S. Our finding of a strong biomass increase in low-silicate, high-nitrate waters at 55°S contradicts the hypothesis and is confirmed by other shipboard data (*4*). We believe that the enhanced carbon export at 55°S was due to physical triggering (suddenly changed light/turbulence regimes), but we cannot rule out a natural progression of biogeochemical processes brought on by the third addition of iron and caution that extrapolation of these first results to greater depths or larger scales is premature.

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then, the exhaust from the Explorer's pumped CTD removes settled particles and the transmission counts are read again. The difference between "after" and "before" readings divided by the time that the Explorer was parked at depth gives the CFI (counts/day). More detail, including pictures of instrument setup, is found in (*6*).

8. The serial numbers of the Explorers are assigned by the Scripps Instrument Development Group; we retain these identities because they uniquely identify the data sets underlying this paper. For simplicity, we refer to Explorer 1177 as the "control" Explorer and Explorer 2104 as the "in-patch" Explorer. Explorers 2054 and 2103 were also deployed "in patch" at 55°S and 66°S, respectively. The POC sensor on Explorer 2054 had a start-up problem that precluded CFI results; poor data transmission success resulted in only sporadic profile data (29 profiles in 2 months). The first week of 2054's profile data is combined with the time series from 2104 in Fig. 2A. Data from 2054 beginning 2 weeks after its deployment no longer showed evidence of the iron-enhanced biomass. Explorers 1177 and 2104 operated for more than 14 months; Explorer 2103, deployed at 66°S, last communicated on 23 July 2003, 18 months after deployment.
9. Retrospective analysis shows that Explorer 2104 was deployed 8 km north of the Monterey Bay Aquarium Research Institute's "center" drifter and near the north edge of the second patch laid down by R/V Revelle. In the coordinate system of Explorer 2104, it was deployed approximately 7 km west of the second Fe patch and ~8 km north of the drifter. The float, however, was deployed in waters containing SF6 and immediately registered higher POC levels. During Revelle's second visit to the North Patch in early February 2002, the float was "in" the narrow feature (*6*).
10. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite image of surface chlorophyll was provided by F. Chavez and is described in (*4*).
11. Two pairs of Carbon Explorers operating in high-nutrient, low chlorophyll waters of the subarctic North Pacific in 2001 and 2003 yielded virtually identical biomass records over much longer periods (*5*, *24*) and thus provide confidence in the differences described here.
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19. Standing stocks of POC changed from about 9 to 2 mmol C m^{-3} over the export period. Assuming that the layer originally was ~40 m thick, we get a net loss of POC = 7 mmol m^{-3} × 40 m = 280 mmol C m^{-2}. POC loss estimated using profile data reported by Coale *et al.* (North patch RV *Revelle* station 32; rosette-collected water samples filtered through Whatman GFF filters) yields a difference of 8.5 mmol m^{-3} × 40 m = 340 mmol C m^{-2}. These calculations assume no net production of POC over the 2-week period of the loss and thus represent lowest estimates.
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Supporting Online Material
www.sciencemag.org/cgi/content/full/304/5669/417/DC1
Materials and Methods
Figs. S1 to S11
References

6 June 2003; accepted 26 February 2004

2006 R&D 100 AWARDS
ENTRY—Carbon Explorer (Berkeley Lab)

Appendix C

Selected Press Coverage

SCIENCE BEAT
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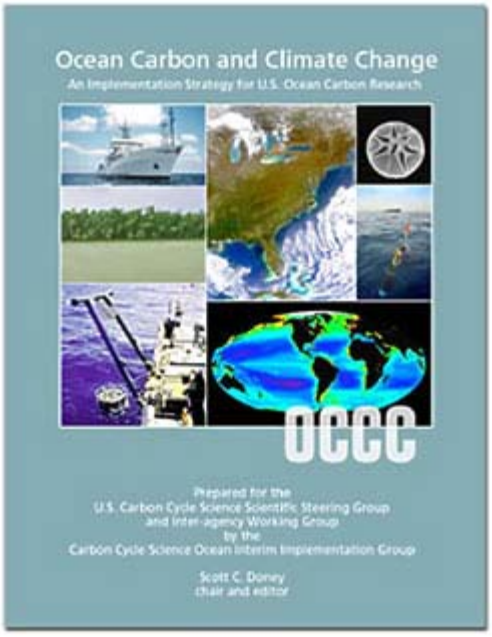
April 30, 2004

Going Deep to Study Ocean Carbon

Contact: Paul Preuss, paul_preuss@lbl.gov



Currently a third of the carbon humans put into the atmosphere — most of it from fossil fuels — goes into the world's oceans. But this situation may not last. A research plan recently issued by a group of scientists representing seven U.S. government agencies, titled *Ocean Carbon and Climate Change*, warns that "feedbacks among climate change, ocean circulation, marine biota, and ocean carbon dynamics" make the future of the ocean's carbon sink impossible to predict.

Or as oceanographer Jim Bishop of the Earth Sciences Division (ESD) puts it, "We don't know how the carbon cycle will respond to CO_2 in the atmosphere. We don't even know if the feedback will be positive or negative."

That's because, while some pieces of the puzzle are relatively clear-cut — physics and chemistry, for example, can explain why cold ocean waters absorb atmospheric CO_2 and warm waters emit it — "we lack a clear understanding of the solar-powered biology of the oceans," Bishop says. "Without rules for carbon transformation and sedimentation by marine life, we're flying in the dark."

If Bishop has his way, we won't be in the dark for long. Because of continual satellite monitoring and the remote sensing capabilities of autonomous instruments like Carbon Explorer SOLO floats, "we're on the cusp of a huge explosion in our ability to follow important and very fast processes in the ocean carbon cycle."

SOLO floats were originally developed by Russ Davis at the Scripps Institution of Oceanography to measure and report on salinity, temperature, and currents at depths of up to two kilometers. Bishop has led the effort to instrument SOLOs for monitoring carbon biomass and carbon flux as well. "Since 2001 we've deployed 12 Carbon Explorers around the world, racking up a total of eight float-years so far, and several are still going strong."

The research payoff has been momentous. In the spring of 2001, Carbon Explorer floats observed the first natural fertilization of a plankton bloom in the North Pacific by iron-rich, wind-blown dust from a storm in Central Asia — a phenomenon predicted but never seen before.

For several months early in 2002, Carbon Explorers tracked a plankton bloom created by artificial iron fertilization during SOFeX, the 17-institution Southern Ocean Iron Experiment. Operating far from any manned vessel, the floats recorded the first evidence of carbon exported to the ocean depths by artificially fertilized plankton — and kept reporting data for over a year, long after the plankton bloom had dissipated.

In 2003 Bishop and UC Berkeley graduate student Phoebe Lam launched Carbon Explorers from the National Oceanographic and Atmospheric Administration's Research Vessel *Ronald H. Brown* in the North Atlantic. One was instrumented with a new sensor equipped with polarizing filters to identify the phytoplankton known as coccolithophores (from the birefringent optical signatures of their microscopic calcite plates), the Carbon Explorers are

still operating. The Berkeley Lab group in addition collected an unprecedented set of optical observations along an 8,000-kilometer track, from west of Iceland to the tropical island of Madeira, and on to Natal, Brazil.

In the North Atlantic west of Iceland, Phoebe Lam and Jim Bishop launch a SOLO Carbon Explorer from the National Oceanic and Atmospheric Agency's research vessel *Ronald H. Brown*. [Photo courtesy Alexey Mishonov, Texas A&M University]

Coccolithophores form milky blooms tens of thousands of square kilometers in area. "Such prolific blooms can change the upper ocean heat balance," says Bishop, "by reflecting sunlight and shading organisms lower down. No one has observed such a bloom form or dissipate — they've only been seen by satellites when the clouds part," so more information is badly needed. In 2004, in the South Atlantic, Berkeley Lab researchers are scheduled for another 8,000-kilometer shipboard journey, timed to pass right through the southern coccolithophores' spring bloom (autumn in the north).

Seen from a SeaWiFS satellite, coccolithophores bloom near Newfoundland. [Photo NASA]

Thus squadrons of Carbon Explorers have repeatedly gathered data inaccessible to other techniques. Unlike shipboard expeditions, which are very efficient at sampling spatially, the floats are relatively inexpensive, can be widely deployed, and operate continuously for long periods of time to provide unprecedented temporal information. And unlike satellites, they see beneath clouds and plunge deep beneath the surface of the water.

Development and field validation of autonomous instruments is a key element in the research strategy outlined by *Ocean Carbon and Climate Change*. Says Bishop, "We're working as hard as we can on this."

Having dramatically demonstrated the worth of Carbon Explorers, Bishop and his colleagues are hard at work improving them. "When I came to Berkeley Lab I said, 'Wow, this place has infrastructure,'" Bishop remarks. "'How can I apply the same talent that built detectors like the SNO neutrino detector to ocean carbon measurement?'"

Carbon Explorers were a first step, adding two-way communications to SOLO floats and equipping them with instruments to measure how much light is blocked by accumulated carbon particles. But these simple measurements of carbon flux say nothing about which particles are involved, whether "dead plankton or the leavings of larger animals," as Bishop puts it.

With funding from the Office of Science, Bishop has recently enlisted the Engineering Division's Zach Radding and Derek Yegian in the design, construction, and sea-testing of a sophisticated Optical Sediment Trap that makes use of "better optics, a little CPU, and a four-gigabyte flash memory — the kind of components you can find in hand-held computers and consumer digital cameras these days." The sample chamber was fabricated at the Design Center's Rapid Prototyping facility, which uses computer drawings to turn out

precisely crafted, one-of-kind, free-form parts.

The new optical system, which Bishop says is designed to "bolt onto a SOLO after we've lopped its head off," concentrates naturally settling particles using a funnel and photographs the collected plants, animals, and waste particles on a clear flat surface as they accumulate — then reports the results every 20 minutes. Periodically the system cleans out the sample chamber, and repeats the process of watching the stepwise accumulation of particles. "This will help us understand the food web in the deep sea — the missing piece of the carbon-export process — in real time and on a better-than-hourly time scale."

Jim Bishop, Derek Yegian, and Todd Wood test the Optical Sediment Trap on land before sending it to Hawaii for sea trials.

Earlier this year, Yegian and ESD's Todd Wood tested the Optical Sediment Trap during a 10-day voyage to Station ALOHA, 100 kilometers north of Oahu, aboard the University of Hawaii's Research Vessel *Kilo Moana*. On the last of its eight deployments the float spent 36 hours at depth with no problems, heralding a new generation of sophisticated Carbon (Flux) Explorers.

Bishop confesses "I love to build instruments — but I'm driven by the fact that this is the only way to learn the answers to some fundamental questions." These include the consequences of various carbon sequestration schemes "or the consequences of doing nothing."

Bishop adds, "I'm optimistic that the oceans are resilient. But we'd better find out fast, or we may be in for some nasty surprises."

The research vessel *Kilo Moana* tested a Carbon Explorer float equipped with the new Optical Sediment Trap at sea. The float is now helping to study vertical transport of carbon particles in the Pacific Ocean near Hawaii.

Additional information

- More information about the first observation of natural iron fertilization of plankton in the North Pacific
- More information about Carbon Explorers in SOFeX
- Read *Ocean Carbon and Climate Change*, a strategy for U.S. ocean carbon research

Top

April 15, 2004

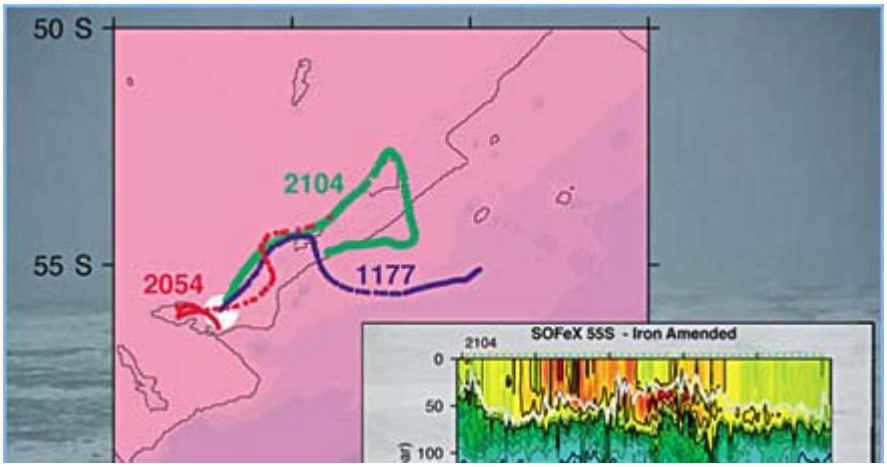
research news

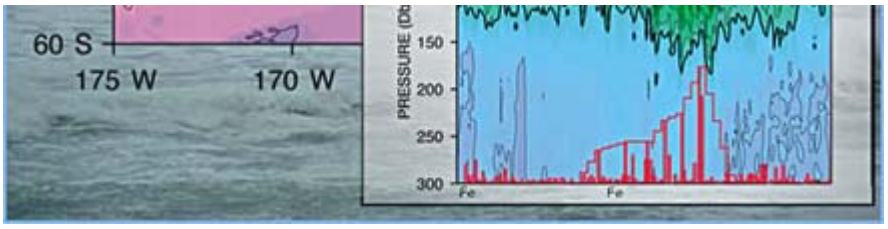
Robotic Floats Shed New Light on the Iron Hypothesis

Contact: Paul Preuss, paul_preuss@lbl.gov

BERKELEY, CA — Three robotic Carbon Explorer floats, launched by scientists from Lawrence Berkeley National Laboratory during the Southern Ocean Iron Experiment (SOFeX) in January and February of 2002, successfully tracked a patch of iron-fertilized plankton for many weeks through the storm-tossed waters between 50 and 60 degrees south latitude, gathering new evidence for the so-called "iron hypothesis." Research results are reported in the 16 April 2004 issue of the journal *Science*.

The iron hypothesis holds that by adding small amounts of iron, an essential micronutrient, to ocean waters rich in other nutrients, aquatic plants can be made to bloom vigorously, thus removing enough carbon dioxide from the atmosphere to offset the greenhouse effect.





Upper panel: Three Carbon Explorers were launched near 55 degrees south. Control float 1177 (blue) tracked outside the iron-fertilized patch. Currents carried float 2054 (red) on an erratic path. Float 2104 (green), the "hero" of the experiment, was launched inside the patch and tracked it faithfully for months. Lower panel: float 2104 recorded plankton blooming near the surface after iron fertilization (yellow and orange), followed by particulate carbon sedimentation below 100 meters (red graph).

"This was the first experiment to test the iron hypothesis by comparing observations of iron-amended waters with control observations—on the fast, hourly-to-daily time scales of marine biological processes," says oceanographer Jim Bishop of Berkeley Lab's Earth Sciences Division, who directed the Carbon Explorer studies, "and it was the first to follow such an experiment for months."

A pair of robotic Carbon Explorers recorded and regularly reported, via satellite, more than a four-fold growth of plankton in a fertilized patch of nitrate-rich but silicate-poor waters, measurements that contradicted the expectation that lack of dissolved silicates would limit plankton growth.

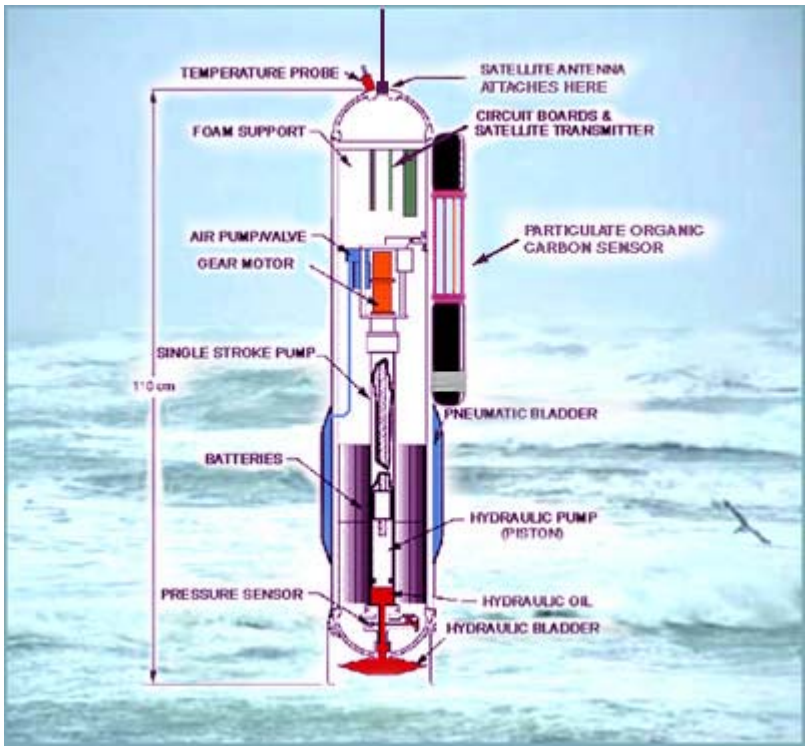
Programmed to descend to depths of up to one kilometer several times a day, the floats measured concentrations of particulate organic carbon and documented its export, within and outside the fertilized area, below 100 meters. They showed that for every atom of iron added to the water, the plankton carried between 10,000 and 100,000 atoms of fixed carbon below 100 meters upon sinking, well beneath the zone of light-stimulated plant growth.

"From previous experiments we knew that adding iron turns the water green," says Bishop — in other words, makes phytoplankton bloom. "What we didn't know was what happened to the carbon." He notes three possible fates: that "the plants just dissolve in the surface waters and the carbon recirculates into the atmosphere. Or the phytoplankton could be eaten by small microbes and zooplankton living in the upper ocean, which would have no impact on atmospheric CO_2 because of their respiration."

However, the Carbon Explorer results strongly support the third alternative: "The only way iron fertilization can have an impact on atmospheric carbon is if the plants fix the carbon, and a major fraction of that carbon settles out of the surface layer into the deep sea"—either as waste from grazing zooplankton or other aggregate particles, or as the plants themselves sink.

"The results of the SOFeX experiment demonstrate an important role for the SOLO-based Carbon Explorers, which were developed at Berkeley Lab with the support of DOE's Office of Science," said Dr. Raymond L. Orbach, Office of Science director. "The new, cost-effective Carbon Explorer technology makes an important contribution to understanding what happens to the carbon dioxide that enters the ocean from the atmosphere."

Carbon Explorers are based on SOLO floats, Sounding Oceanographic Lagrangian Observers, designed by Russ Davis of the Scripps Institution of Oceanography to measure temperature and salinity at various depths. ("Lagrangian" refers to the fact that the floats drift freely with the currents, which determine their speed, direction, and position.)



A Carbon Explorer is a SOLO float modified by the addition of a particulate organic carbon sensor, enhanced communications, and remote programming capacity. The floats can be programmed to park below the surface, descend to a depth of over a kilometer, and resurface several times a day. Carbon flux is measured by a transmissometer that counts particles settling on a window in the particulate organic carbon sensor.

Bishop and his colleagues equipped SOLOs with particulate organic carbon detectors and global-positioning and rapid communications systems. The floats' stored data can be recovered and their diving profiles altered via satellite link from almost anywhere on the globe.

As part of SOFeX, a multiship project led by the Moss Landing Marine Laboratory and the Monterey Bay Aquarium Research Institute, Berkeley Lab researchers Todd Wood, Christopher Guay, and Phoebe Lam joined the research vessel *Revelle* in the fall of 2001. Among other projects, the researchers launched four Carbon Explorers. Bishop monitored and communicated with the Explorers over a computer link from Berkeley.

Two of the Explorers—one a control float outside the fertilized North Patch, the other inside the patch—were originally planned for placement in the silicate-poor waters of the "Furious 50s," where plankton was expected to bloom sluggishly even after iron fertilization. The other two were to be launched in the silicate-rich waters farther south in the 60s, where a more vigorous bloom was expected after fertilization.

A control float, number 1177, was launched 20 kilometers north of the planned North Patch on January 11, 2002. An intended "in-patch" float was launched just before the iron was added to the patch the next day, but the current sheared and the float was swept away to the northwest, along with some of the fertilized water.

In a change of plan, the third float, number 2104, was deployed a week later, January 19, in the middle of the remaining segment of the patch. Bishop calls this float "the hero of the experiment"—not least because it documented quite unexpected results.

Revelle then traveled south to fertilize the South Patch in the 60s, where the final float was deployed. The ship stayed in this area for several weeks. The fourth float, which would encounter communications difficulties due to lack of satellite coverage, was deployed "in the patch" at 66 degrees south just before *Revelle* returned northward.

Meanwhile Carbon Explorer 2104 faithfully tracked the fertilized North Patch for three weeks, paralleled most of the time by control float 1177 outside the patch. Because of bad weather only one satellite picture of the green fertilized patch of water could be taken, just a day before *Revelle* returned to the scene on February 7—finding its way to the patch because of "hero float" 2104's position reports.

"Everyone believed that the lack of silicates in these waters would limit phytoplankton growth and thus carbon export," says Bishop. Because of this expectation, *Revelle* and SOFeX's two other ships were scheduled to spend only a little time in the North Patch. "Meanwhile our Carbon Explorers were left as sentinels in the North Patch. As it happened, they turned the tables on the hypothesis that silicates would limit growth."

Plankton known as diatoms use silicates to build their delicate supporting skeletons. But work by Phoebe Lam during SOFeX suggests that the siliceous plankton of the South Patch were too buoyant to sink, while the denser calcium-carbonate "ballast" of the calcareous plankton farther north allowed them to carry the carbon they had fixed below 100 meters.

Thus, says Bishop, while "the SOFeX ships certainly did everything they were funded to do, a couple of 25-thousand-dollar floats enhanced the shipboard experiments considerably."

Bishop notes that the Carbon Explorer results have implications beyond their bearing on the iron hypothesis, offering a new way to explore the oceans. "They allowed a ship that had been gone three weeks to steam right back to the North Patch with no delay; given the paucity of satellite images, that might not have been so easy otherwise. And they filled in the time series when ships weren't in the area."

Indeed, the two North Patch floats operated in the world's stormiest waters for over 14 months, diving, measuring, recording, and reporting their data while following the circumpolar currents from near New Zealand almost to South America before finally falling silent.

In conclusion, says Bishop, "the SOFeX Carbon Explorers showed that we can use autonomous technology to understand many physical, chemical, and biological processes important to the way carbon is sequestered in the oceans. Their success has energized efforts, both at Berkeley Lab and across the country, to develop a whole new generation of sensors."

SOFeX Carbon Explorer studies were supported by the Department of Energy's Office of Science through the Office of Biological and Environmental Research. Carbon flux measurement instrumentation for the floats was supported by the National Oceanographic Partnership Program.

The Berkeley Lab is a U.S. Department of Energy national laboratory located in Berkeley, California. It conducts unclassified scientific research and is managed by the University of California.

Additional information

- Robotic observations of enhanced carbon biomass and export at 55S during SOFeX," by James K. B. Bishop, Todd J. Wood, Russ E. Davis, and Jeffrey T. Sherman, appears in the 16 April 2004 issue of *Science*. Subscribers can access the article at http://www.sciencemag.org/, or reporters can contact the AAAS Office of Public Programs at (202) 326-6440 or email scipak@aaas.org.
- More about Berkeley Lab's Ocean Biogeochemical Processes Group, with links to the basic design of SOLO floats and their modification as Carbon Explorers
- More about DOE's Ocean Science program within the Office of Biological and Environmental Research, Office of Science
- More about SOFeX

Top

A Special Issue of
BERKELEY LAB research review
Berkeley Lab 2002-2003 HIGHLIGHTS

ENERGY AND THE ENVIRONMENT

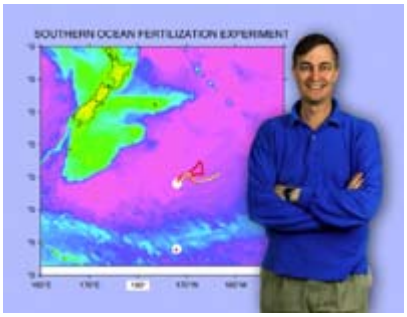
Adrift in the Southern Ocean: tracking plankton through storms and ice

Launched in January 2002, four deep-diving Carbon Explorers, designed by oceanographers in Berkeley Lab's Earth Sciences Division to report on biological activity in the sea, tracked the growth of phytoplankton for many months and thousands of kilometers through storms and ice in the Southern Ocean.

This is the cloudiest and windiest place on the planet," said oceanographer Jim Bishop, after the robotic floats were deployed from the research vessel *Revelle* as part of SOFeX, the Southern Ocean Iron Experiment. "The float in the center of the fertilized patch just keeps sending--its antenna is spectacular. I call it 'the little float that could.'"

SOFeX, a multi-ship project led by Moss Landing Marine Laboratory and the Monterey Bay Aquarium Research Institute, fertilized plankton by adding scarce iron to otherwise nutrient-rich waters. Because phytoplankton grow using carbon dioxide, ocean fertilization has been touted as a way to control global warming.

Berkeley Lab researchers had earlier led a collaboration to equip SOLO floats (Sounding Oceanic Lagrangian Observers), designed at the Scripps Institution of Oceanography to measure temperature and salinity at various depths, with particulate organic carbon detectors plus global positioning and fast communications systems. Remotely programmable Carbon Explorers were the result.



Jim Bishop and his colleagues devised instruments that SOLOs could use to measure both organic carbon particles, like plankton, and inorganic, like calcite, the most common carbon mineral in seawater. The map shows SOLO following the iron-fertilized water.

During SOFeX the *Revelle*, with Berkeley Lab researchers Todd Wood, Christopher Guay, and Phoebe Lam aboard, pumped iron into two areas along 170 degrees west longitude. In the "howling 50s" of seagoing lore, the ocean is poor in the silicates some phytoplankton need to form shells, so plankton was expected to bloom sluggishly there even after fertilization. A more

vigorous bloom was expected after fertilization of the silicate-rich waters farther south in the 60s.

The northern fertilized region promptly divided into two patches. *Revelle* launched three floats, the last programmed to stay in the center of the main patch. While the research vessel *Melville* and the U.S. Coast Guard icebreaker *Polar Star* later performed follow-up studies, the Carbon Explorers operated continuously and independently, diving and resurfacing each day to report. When high winds interfered with communication, data were saved and played back later.

"The floats were diving to depths as great as 1,000 meters every day, but we programmed them to 'sleep' at 100 meters so that they would follow surface waters best," Bishop explains. There was a risk, however: "By staying shallow in the middle of the plankton bloom, the instruments--which measure particulate matter by how much light is transmitted through the water--might become fouled."

Revelle headed south to fertilize the second patch of ocean; there the final Carbon Explorer experienced similar storms but much-reduced satellite coverage. Heard from only once in the next three weeks, it finally reestablished contact and played back most of its data.

Meanwhile Bishop, using his laptop back in Berkeley, was in daily contact with the northern floats. "Our guess at how to program the floats to stay with the patch, plus a simple change in configuration to reduce biofouling, paid off in a big way," says Bishop. The two floats stayed with the patch, one near its center, the other just outside, serving as a control.

Just before *Revelle* returned to the northern patch in early February, guided by the floats' accurate GPS positions, the skies cleared and the ship received the first color image of the area in over three weeks from NASA's SeaWIFs satellite. Despite expectations that growth would be poor, Bishop reported, "we can confidently say that particulate organic carbon in the patch has grown to be four or five times that outside the patch."

Revelle returned to port, but the northern Carbon Explorers kept reporting, despite days when winds exceeded 50 miles per hour and swells

averaged 40 feet from trough to peak. By June all three northern floats had traveled over a thousand kilometers.

The lone Carbon Explorer in the south reported periodically until late in the Antarctic autumn, when it was overtaken by advancing pack ice. Its data allowed glimpses of life at 1.5 degrees Celsius below zero. "That's about as cold as the ocean can get, and now it's almost perpetually dark," Bishop remarked.

Deep-diving SOLO floats like the one shown here have been specially equipped to report on biological activity in the sea.
A flotilla of SOLOs faithfully tracked a plankton bloom through the stormy Southern Ocean as part of SOFeX, an experiment to test the "iron hypothesis," the proposal that phytoplankton blooms can lower global temperature by removing carbon from the atmosphere.

In mid-June, Bishop reported that after a month of repeated "bonkings" under the ice, the indomitable Explorer reappeared, probably surfacing through leads in the ice. It reported its position and transmitted data stored from over two weeks of diving in the freezing dark.

Long after all SOFeX ships had returned to port, the Carbon Explorers were still on the job, more than half a year since their launch. In July, 2002, Bishop reported "We still have direct control of the Explorers, even though they are half a world away and operating in conditions akin to those experienced by Shackleton and his men." No other approach to investigating the ocean's carbon budget could have matched the performance of these intrepid robots.

The Carbon Explorers were developed with support from the National Oceanographic Partnership Program. Their deployment during SOFeX was supported by the Department of Energy's Office of Science, Ocean Carbon Sequestration Program.

-- Paul Preuss

< Highlights Top ^ Next >

October 24, 2002

research news

Asian dust storm causes plankton to bloom in the North Pacific

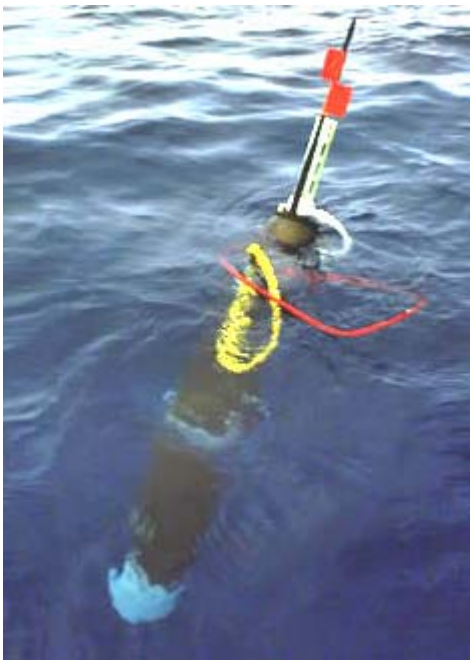
Robotic Carbon Explorers test the "iron hypothesis" in nature

Contact: Paul Preuss, paul_preuss@lbl.gov

BERKELEY, CA — In the spring of 2001, two robotic Carbon Explorer floats recorded the rapid growth of phytoplankton in the upper layers of the North Pacific Ocean after a passing storm had deposited iron-rich dust from the Gobi Desert. The carbon measurements, reported in the October 25 issue of *Science*, are the first direct observation of wind-blown terrestrial dust fertilizing the growth of aquatic plant life.

A group of scientists led by oceanographer James K. Bishop of Lawrence Berkeley National Laboratory's Earth Sciences Division engineered the deep-diving Carbon Explorers to measure particulate carbon in the upper thousand meters of the ocean. The Carbon Explorers are modified SOLO floats (Sounding Oceanographic Lagrangian Observers), originally designed by Russ Davis of the Scripps Institution of Oceanography to measure temperature and salinity at various depths. A growing number of SOLOs are now adrift in ocean currents around the world, as part of the international Project Argo to study ocean climate variability.

Two of the specially modified Carbon Explorers were launched April 10, 2001, from the U.S. Coast Guard's icebreaker *Polar Star* near Ocean Station PAPA, in subarctic waters a thousand miles west of Vancouver Island. The Carbon Observers were programmed to sample the depths and return to the surface three times every two days, regularly sending data to satellites overhead. The two floats, controlled from shore, returned a virtually unbroken stream of information for the next eight months, through December, 2001.



Carbon Explorers are SOLO floats, originally designed to measure temperature and salinity at depth, which have been modified to measure particulate carbon and also equipped with increased data capacity and remote programming capability.

Ocean Station PAPA, at 50 degrees north latitude, 145 degrees west longitude, is one of the few sites in the world whose waters have been studied for decades using shipboard instruments.

PAPA thus provides an excellent baseline for observing variations in the carbon products of photosynthesis at different depths.

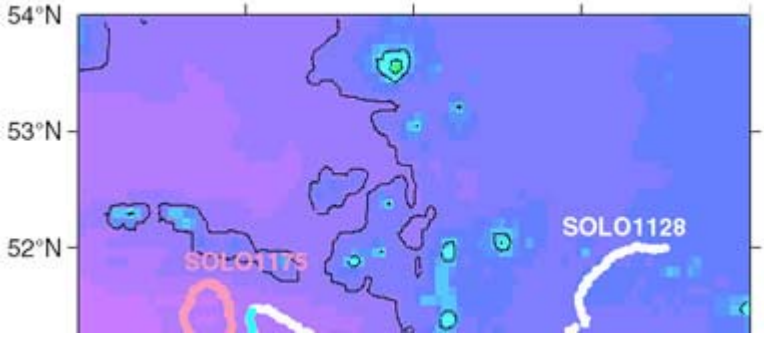
"The plants that fix carbon in the ocean typically live, reproduce, and die on day-to-week time scales," Bishop says. "The beauty of the Carbon Observers is that they keep on working day in and day out, for seasons at a time, matching the biological rhythms of the sea in a way that ships and other systems cannot."

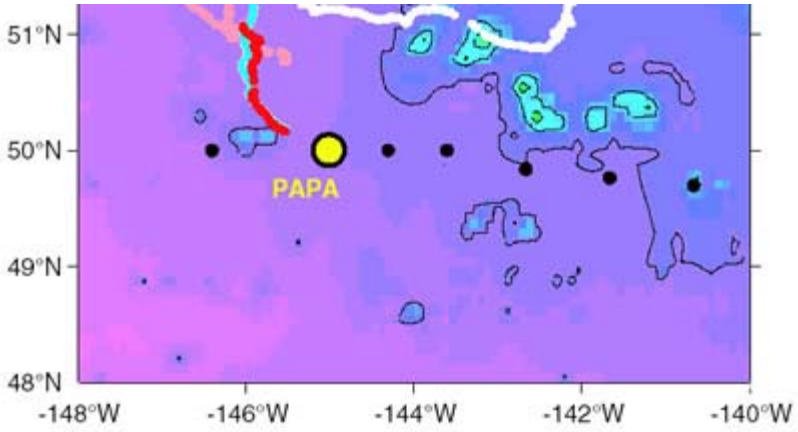
Phytoplankton growth is affected by factors like nutrient concentrations, light, temperature, salinity, and the way the sea water mixes. Earlier studies at PAPA suggested that growth in the region was also limited by a lack of dissolved iron in the water. The Carbon Observers would soon put that assumption to the test.

Testing the iron hypothesis

In the 1930s oceanographers first began to suspect that terrestrial dust storms play a key role in phytoplankton growth in the so-called high nutrient, low chlorophyl (HNLC) areas of the ocean, whose concentrations of dissolved iron, an essential micronutrient, are much lower than in other regions. By dissolving carbon in seawater and by fixing it as biomass or inorganic particulate matter, phytoplankton regulates carbon dioxide in the atmosphere and thus helps regulate global climate.

In the 1980s, oceanographer John Martin gathered these facts in his "iron hypothesis," which proposed that by fertilizing plankton growth with iron, global warming could be offset. Iron fertilization can indeed cause plankton "blooms" in HNLC waters, as several expeditions including Soiree (the Southern Ocean Iron Enrichment Experiment) in February 1999 and SOFeX (the Southern Ocean Iron [Fe] Experiment) in January and February 2002 have proved by pouring dissolved iron into HNLC areas in the Southern Hemisphere. But prior to the spring of 2001, fertilization by iron transported in terrestrial dust storms had never been observed directly.





Launched in April 2001, the two Carbon Explorers first traveled westward from Ocean Station PAPA, then turned north and eventually east, gradually drifting apart. Although frequently interrupted by high winds, they transmitted ocean carbon data regularly until their batteries gave out in December, 2001.

Three days before the launch of the Carbon Observers on April 10, a NASA satellite recorded a large dust storm originating near the Gobi Desert in China and Mongolia; on the day of the launch, the dust cloud was over Japan and heading for the North Pacific. It reached Ocean Station PAPA on April 12, where it kicked up the waves and deposited a large amount of dust.

Although high waves temporarily kept the Carbon Observers from reporting by satellite, data collection continued uninterrupted through the storm. Five days after the storm passed, the floats reported rising concentrations of particulate organic carbon; the concentration almost doubled in the next two weeks.

Bishop notes that "the timing of this natural increase matched the timing of plankton growth after iron was artificially added to Southern Ocean waters during Soiree and SOFeX, a good indication that iron fertilization was the cause in the North Pacific as well."

Plankton growth following the storm over Ocean Station PAPA was confirmed when NASA's SeaWiFS satellite got a glimpse through the clouds and saw the sea surface turning greener with chlorophyll. These satellite observations further supported the supposition that iron and other micronutrients from the Asian dust storm had fertilized the phytoplankton.

For the first time, one of the key assumptions of the iron hypothesis had been observed in nature: wind-blown dust does stimulate plankton growth in otherwise unproductive waters. But how long is

the atmospheric carbon thus taken up by phytoplankton sequestered in the ocean?

Jim Bishop and his colleagues hope Carbon Explorers and other instruments can soon find out what proportion of particulate organic carbon sinks all the way to the deep ocean. "Until we can answer that question with some precision, whether or not large scale iron fertilization of the ocean would be useful in slowing global warming will also remain unanswered. There's a huge amount of science left to be done in the next decade to assess the ecological changes and the downstream effects of the technique. We've only scratched the surface."

The National Oceanographic Partnership Program supported the development of the Carbon Explorers in a collaborative project including Berkeley Lab's Earth Sciences Division, the Instrument Design Group at Scripps, and WETLabs, Inc. of Philomath, Oregon. Other agencies that supported the Carbon Explorer program at Ocean Station PAPA include the National Oceanic and Atmospheric Administration's Office of Global Programs, the U.S. Coast Guard, and the U.S. Department of Energy's Office of Science, Ocean Carbon Sequestration Program. For more on ocean carbon research at Berkeley Lab, visit http://www-ocean.lbl.gov.

"Robotic observations of dust storm enhancement of carbon biomass in the North Pacific," by James K. B. Bishop, Russ E. Davis, and Jeffrey T. Sherman, appears in the 25 October, 2002, issue of *Science*.

The Berkeley Lab is a U.S. Department of Energy national laboratory located in Berkeley, California. It conducts unclassified scientific research and is managed by the University of California.

February 1, 2001

science beat

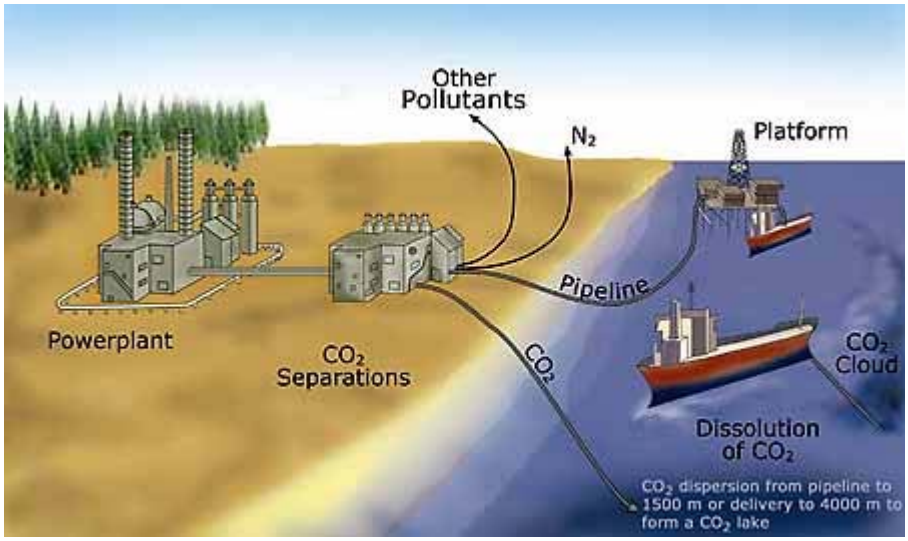
BERKELEY LAB

Climate Change Scenarios Compel Studies of Ocean Carbon Storage

Paul Preuss, paul_preuss@lbl.gov

One of the most promising places to sequester carbon is in the oceans, which currently take up a third of the carbon emitted by human activity, roughly two billion metric tons each year. The amount of carbon that would double the load in the atmosphere would increase the concentration in the deep ocean by only two percent.

Two sequestration strategies are under intense study at the Department of Energy's Center for Research on Ocean Carbon Sequestration (DOCS), where Jim Bishop of Berkeley Lab's Earth Sciences Division is codirector with Livermore Lab's Ken Caldeira. One is direct injection, which would pump liquefied carbon dioxide a thousand meters deep or deeper, either directly from shore stations or from tankers trailing long pipes at sea.



DIRECT INJECTION INVOLVES THE CAPTURE, SEPARATION, TRANSPORT, AND INJECTION OF CARBON DIOXIDE INTO THE DEEP SEA

"At great depths, CO2 is denser than sea water, and it may be possible to store it on the bottom as liquid or deposits of icy hydrates," Bishop explains. "At depths easy to reach with pipes, CO2 is buoyant; it has to

be diluted and dispersed so it will dissolve."

What happens to carbon dioxide introduced into the ocean in this way may soon be field-tested in Hawaii. Over a two-week period researchers plan to inject 40 to 60 metric tons of pure liquid CO2 over 2,500 feet deep in the ocean near the Big Island.

One variable they will be measuring is acidity. Water and carbon dioxide form carbonic acid, "but once diluted in sea water, carbonic acid is not the dominant chemical species," Bishop says, "because of seawater's high alkalinity and buffering capacity." If calcium carbonate sediments are involved, acidity is even less. "Think of Tums," he suggests.

Fertilizing the ocean

The other major approach to sequestration is to "prime the biological pump" by fertilizing the ocean. Near the surface, carbon is fixed by plant-like phytoplankton, which are eaten by sea animals; some eventually rains down as waste and dead organisms. Bacteria feed on this particulate organic carbon and produce CO2, which dissolves, while the rest of the detritus ends on the sea floor.

"There are areas of the ocean that are rich in nutrients like nitrogen and phosphorus but poor in phytoplankton," says Bishop. "Adding a little iron to the mix allows the plankton to use the nutrients and bloom. The energy for the process is supplied by sunlight. Already commercial outfits are dropping iron filings overboard, hoping to increase fisheries -- meanwhile claiming they are helping to prevent global warming."

In fact, Bishop explains, "if the excess fixed carbon in plants is eaten by fish near the ocean surface, the net effect is no gain. And in every part of the ocean there are open mouths."

THE GLOBAL CARBON CYCLE AND THE ROLE OF THE OCEAN

No one really knows where the carbon trapped by fertilization ends up. In one iron-fertilization experiment in warm equatorial waters, chlorophyll increased 30-fold in a week, and there was increased carbon sedimentation down through 100 meters. But the bloom shortly dissipated, the fate of the carbon in deeper waters wasn't followed, and long-term effects weren't measured.

In a more recent experiment in cold Antarctic Ocean waters the plankton bloom persisted much longer. Seven weeks after the experiment ended a distinct pattern of iron-fertilized plankton was still visible from space -- "which means the fixed carbon was still at the surface."

Bishop says that "people who want to add iron think the particulate matter will fall straight to the bottom; I have sampled natural plankton blooms, and I have not seen that happen. These guys have a potentially effective method of sequestering carbon, but as yet there is no scientific basis for their claims."

Fishing for data

One of Bishop's specialties is measuring the ocean's particulate organic and inorganic matter at different depths to determine variations with ocean circulation patterns and biological regimes. He and his colleagues lower units overboard that pump and filter thousands of liters of seawater through meshes of different size, trapping biological products and dissolved minerals. "In my former life I was a garbage collector," he jokes. "But this way we can tell how the ecosystem functions."

Because ships are expensive, carbon data is sparse. Much more data is needed to calibrate ocean circulation models such as those developed by Livermore's Ken Caldeira, who uses computers to visualize the possible consequences of both major strategies of sequestration.

Of these circulation models Bishop remarks that "any oceanographer would say, 'that looks like the ocean' -- because decades of ship observations has given us knowledge of how the ocean circulates." But representations of how fast things are happening at middle depths could be off by a factor of four, he says, "and we have no way of knowing unless we get more data. We can't afford enough ships, but we can do the job with floats."

Flying and gliding through the depths

Project Argo, a consortium of scientists from a dozen countries, is now deploying some 3,000 floats around the globe to measure the temperature and salinity of the upper 2,000 meters of the ocean. "They sink, stay down for two weeks, come up and send their position and data to a satellite," says Bishop. "They're like 3,000 points of light. They'll give us the mid-depth circulation."

Bishop and colleagues at the Scripps Institution of Oceanography and from private industry have developed a modified float dubbed SOLO, supported by the National Oceanographic Partnership Program (a consortium of

RESEARCHERS LAUNCH SOLO, A ROBOTIC SENSOR ABLE TO MEASURE CARBON CONCENTRATIONS

universities and other research organizations) and the National Oceanic and Atmospheric Administration. SOLO is equipped with instruments for measuring organic and inorganic carbon, both in solution and tied up in particles -- a "robotic carbon observer" with more sophisticated timing and positioning systems and faster data transfer than the Argo floats.

Four SOLOs will be launched this year in well-studied areas of the northern Atlantic and Pacific, where weather ships were once located. "Weather ships gave us more than just weather. When satellites came in, we lost an important source of time-dependent measurements of how ocean chemistry changes, seasonally and day- to-day."

Unlike trees, Bishop notes, the plants that fix carbon in the ocean typically live and die in a single day. "This makes it really hard and expensive to follow the variability of plants using a ship. When the weather gets bad all work on the ship stops -- yet biology goes on unobserved." But after floats are placed in currents from ships or planes, they "fly as balloons do, for seasons."

A more versatile platform is a robotic "glider" that can be launched from a harbor. Bishop says that a miniature submarine glider dubbed Spray, developed at Scripps and Woods Hole, "is an exciting new vehicle that we are learning how to use this year. You tell it where to go, what to do, and to come back when it's done."

Equipped with big batteries and a Global Positioning System receiver, Spray can be programmed by satellite to maintain a heading or adjust course and depth. Thus, Bishop says, "Gliders can effectively monitor what happens after ocean fertilization, swimming back and forth through the fertilized patch, measuring biomass and iron concentration at various depths."

Assessing change

DOCS is working to develop new platforms and instruments to gather sufficient data on fertilization, direct CO2 injection, and other methods for ocean carbon sequestration, data that will help researchers understand the implications for the oceans and the global environment. The most important questions are possible changes in biogeochemical processes -- and how the public responds to them.

"We need to define the sequestration strategies and find out if they can really work, and if there are problems associated with them," says Bishop. "One of our most important tasks is to establish DOCS as a consistent, unbiased voice on the scientific issues. We want to be an educational center, not an engineering center."

Additional information:

- Department of Energy Center for Research on Ocean Carbon Sequestration
- DOE Office of Fossil Energy Carbon Sequestration program

October 1, 2001

science beat

BERKELEY LAB

Part 2: After the Float

Paul Preuss, paul_preuss@lbl.gov

Although they didn't have a position, "we knew where we put it, we knew the currents in the region, and we had the data on temperature and salinity it was sending back," Bishop says.

Temperatures were useful because, for example, upwelling waters near shore are colder than offshore waters. At Bishop's instigation the New Horizon had been equipped to measure temperature and salinity; this data could be compared with what SOLO was reporting as the ship closed on the float.

Currents were trickier. Although the California Current moves southward on the surface, at mid-depths there is a "poleward countercurrent." With SOLO spending so much time below, the float might well be drifting in different directions at different times of day.

An unexpected clue came on a 1,000-meter dive when SOLO reported reaching a depth of only 706 meters: it had hit the bottom.

BERKELEY LAB'S CHRIS GUAY MONITORS DATA FROM A NEW OPTICAL SENSOR HE PIONEERED AT THE LAB TO MEASURE INORGANIC FORMS OF PARTICULATE CARBON IN THE OCEAN.

On August 27, an exhausted Jim Bishop wrote up his weekly Chief Scientist report as a debate among a group of fictional puzzle-solvers: playing himself, the Chief Scientist claims "I can find SOLO with a thermometer," while a Dynamicist claims "I can find SOLO with a basic understanding of the dynamics of the

California Current," and another researcher claims "I can find SOLO with a bathymetric map" (that is, a depth chart). The sailors in the galley got into the act and began practicing to retrieve the float with rod and reel; any albacore snagged during this exercise were purely fortuitous.

Bishop's fiction imagined the "shore-based SOLOists" simply waiting for the SOLO to "tell us where it is," and on August 23 it did just that. Apparently carried poleward by mid-depth currents, SOLO reported a position north-northeast of where it had been launched. Then the GPS "clammed up" again.

When the float hit bottom a second time, Bishop claimed that this event was welcomed by one of the researchers who was out to get core samples.

A dark and stormy night

Captain Murray Stein of the New Horizon laid out a search plan that brought the ship ever closer to its quarry, employing his own knowledge of the area. The ship arrived near Point Conception on Saturday, August 25, in 12-foot seas and 35-knot winds, with only three hours of daylight remaining.

While researchers aboard plotted temperature gradients and depth soundings, scientists onshore had ordered SOLO to abort its dive program and stay on the surface. The first signal to abort was not received. Did the second get through? Unless they found the float, the searchers would never know.

At last SOLO sent one more position report. Remarkably, the captain's search plan already had the ship heading straight for it, but another anxious hour went by before the searchlight caught the gleam of reflective tape on SOLO's antenna, bobbing in the rough seas. The captain eased the ship alongside, and at 11:30 p.m. Berkeley Lab's Todd Wood made the critical snatch. The SOLO was lifted aboard without a scratch.

Bishop concluded his log entry by noting that, despite the wayward SOLO, the mission's science was "a 200 percent success" —but oddly, he remarked, "the rod and reel club" from the galley was still angling off the stern days after the float had been recovered.

Lessons learned from the SOLO's "torture test" will be put to good use, Bishop says, when four more floats are launched in the raging waters of the Antarctic this coming

January.

Additional Information:

- Return to part 1 of this article
- For more about the DOE's Center for Research on Ocean Carbon Sequestration, visit http://www-esd.lbl.gov/DOCS/index2.html.

October 1, 2001

science beat

BERKELEY LAB

Where in the Ocean is that Float from San Diego?

Paul Preuss, paul_preuss@lbl.gov

On August 15, 2001, the Scripps Institution of Oceanography's 170-foot Research Vessel New Horizon left port in San Diego laden with equipment and researchers from Berkeley Lab and other organizations, its primary mission to calibrate and test new instruments for measuring the carbon dynamics of the ocean. But within days one important device, a new SOLO float, had gone missing.

SOLO stands for Sounding Oceanographic Lagrangian Observer, a float programmed to rise and sink to measure ocean water temperature and salinity. Jim Bishop of the Earth Sciences Division, co-director of DOE's Center for Research on Ocean Carbon Sequestration, worked with colleagues to augment the basic SOLO design with instruments to monitor concentrations and sizes of particulate matter and equip SOLOs for satellite telemetry.

"I torture-test this stuff," says Jim Bishop, chief scientist on the voyage, "and for the trial of the SOLO, I picked the worst place I knew."

Two such "robotic carbon observers," launched in the North Pacific in April, are still operating, beyond their expected lifetimes [see *Currents*, April 20, 2001]. The similar float launched off the California coast would test a simple method of estimating carbon sedimentation

The worst place I knew

"I torture-test this stuff," says Bishop, chief scientist on the voyage, "and for the trial of the SOLO, I picked the worst place I knew."

Point Conception, west and north of Santa Barbara, is a good place to test a depth-diving carbon sensor because of the rich biology of its coastal waters. But the swift California Current that flows down

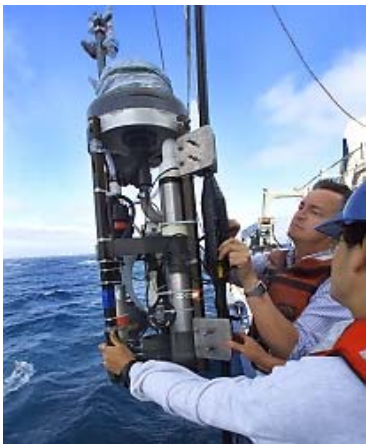
the coast has been infamous since the days of Sir Francis Drake, and the Point's high winds frequently turn the sea surface to chop.

The newly launched SOLO sent plenty of information as the New Horizon continued north to Monterey Bay. Mornings and afternoons the float dove to 300 meters and at night to 1,000 meters, resurfacing, as programmed, to send its accumulated data to ORBCOMM satellites overhead.

But it wasn't sending its positions, which it should have been able to determine using an onboard global position system (GPS). Perhaps rough seas prevented a good satellite fix.

The forensic science of the sea

Meanwhile, in course of developing "a forensic science to detect biological activity in the deep sea," the New Horizon's crew worked their way farther into the Pacific. They tested a new kind of optical instrument that exploits the polarization of calcium carbonate crystals to measure particulate inorganic carbon in the water. They also calibrated results from two quite different instrument systems.



(LEFT) JIM BISHOP GIVES A FINAL CHECK TO ONE OF THE 12 LARGE-VOLUME FILTRATION UNITS BEFORE DEPLOYMENT ON A 1,000-METER LONG POWER CABLE.

(RIGHT) UC BERKELEY GRADUATE STUDENT PHOEBE LAM PREPARES FILTRATION SAMPLES FOR MICROBEAM X-RAY ANALYSIS, TO INVESTIGATE THE FATE OF IRON IN SEAWATER.

One, the Multiple Unit Large Volume Filtration System (MULVFS), collects particulate matter in sizes from micrometers to millimeters. The other, the CTD — for conductivity, temperature, and depth — makes measurements similar to the SOLO carbon observers. By operating the two instruments side by side, says Bishop, "we could look at the signals we were getting from the

CTD, then look at what the MULVFS brought up and say, 'My gosh, here's what we saw.'"

Everybody in the 13-member scientific crew worked long and hard. Berkeley Lab photographer Roy Kaltschmidt did double duty, helping deploy and retrieve the massive instruments and analyze the results.

All the while the mystery of the hide-and-seek SOLO was deepening. The float wasn't hiding intentionally, but because it was submerged for all but a couple of hours a day, it might as well have been a submarine with orders to run silent, run deep.

THE CONDUCTIVITY, TEMPERATURE, AND DEPTH (CTD) "ROSETTE" GOES OVER THE SIDE.

Next page: After the Float

April 24, 2001

science beat

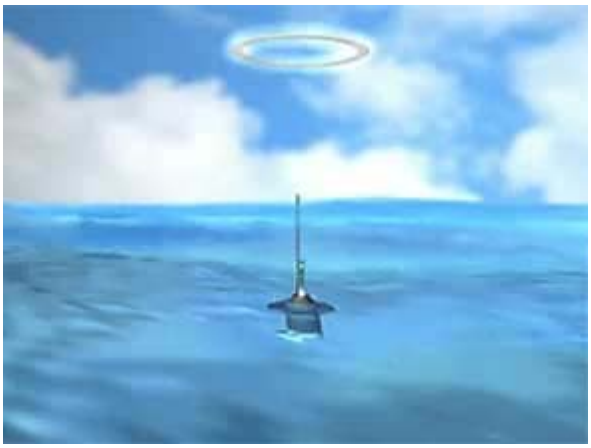
BERKELEY LAB

Robotic Floats For Monitoring Ocean Carbon Launched In Pacific

Paul Preuss, paul_preuss@lbl.gov

BERKELEY, CA -- Two SOLO floats, the nation's first "robotic carbon observers" -- designed to descend to kilometer depths and collect information on the role of plankton and other living things in the ocean's carbon cycle -- were launched Tuesday morning, April 10, from the Coast Guard icebreaker Polar Star in the northern Pacific Ocean. Both have been transmitting regularly despite temporary interruption by storms at sea.

Todd Wood of the Department of Energy's Lawrence Berkeley National Laboratory carried the SOLOs to the Polar Star by helicopter from Dutch Harbor in the Aleutian Islands. At 3:00 a.m. Tuesday Wood deployed the floats at Ocean Station PAPA, 1,000 miles west of Vancouver Island, British Columbia, with the help of US Coast Guard personnel.



AS DEPICTED IN THIS GRAPHIC, WHEN THE ROBOTIC FLOAT ASCENDS TO THE SEA SURFACE, IT TRANSMITS ITS DATA TO A SATELLITE

On Wednesday morning, April 11, they had resurfaced and began returning data by satellite link. Contact was interrupted by high waves during North Pacific storms later in the week, but no data was lost, and transmissions from both floats are now being received regularly.

SOLOs were invented by Russ Davis of the Scripps Institution of Oceanography in La Jolla, Calif., who dubbed them SOLO for "Sounding Oceanographic Lagrangian Observer." The floats measure temperature, salinity and mid-depth currents; those launched in April incorporate new carbon biomass sensors. From the surface they descend a thousand meters (a quarter of the way to the sea floor) and

resurface at dawn and dusk each day.

Each time they surface the floats communicate their collected data, along with their positions, by two-way telemetry link to ORBCOMM satellites. For optimal data collection, a new bidirectional telemetry system allows land-based scientists to control the up and down motion of the floats anywhere in the remote ocean.

"This concept experiment will pave the way for a fully instrumented SOLO-carbon observer, able to measure all components of carbon in seawater," says Jim Bishop, director of the Ocean Biogeochemical Processes Group in Berkeley Lab's Earth Sciences Division. Bishop spearheaded the concept of robotic profiling carbon sensors and leads the collaboration that built and instrumented the floats and is collecting their data.

THE GLOBAL CARBON CYCLE AND THE ROLE OF THE OCEAN

"We chose to deploy the floats at Ocean Station PAPA," he explains, "because our group has worked there extensively and because our colleagues at the Institute of Ocean Sciences in British Columbia regularly visit PAPA by ship. This way we can make sure we get consistent answers, in a place we understand."

A third of the carbon currently emitted by human activity -- roughly two billion metric tons each year -- is absorbed in the oceans, but the process is not well understood. The SOLO floats are vital, says Bishop, "because the plants that fix carbon in the ocean typically live and die in a single day. This makes it really hard and expensive to follow their variability using a ship. When the weather gets bad all work on a ship has to stop, yet biology goes on unobserved."

And the weather does get bad. The week before the carbon-observer SOLOs were launched, in the aftermath of the worst storm in the North Pacific in decades, the Polar Star was involved in the search for the fishing boat Arctic Rose that went down in the Bering Sea with the loss of all 15 aboard. "This tragedy," says Bishop, "underscores the difficulty and danger inherent in making observations at sea." SOLO floats are designed to operate in all weather conditions, however, and "they fly in the ocean as balloons fly in the air, for seasons at a time, tracking the daily rhythm of the plankton."

Partners in the SOLO-carbon venture include the Instrument Design Group at Scripps and WET Labs, Inc., of Philomath, Oregon, a private instrument firm. Support for the collaboration is provided by the National Oceanographic Partnership Program (NOPP), the Department of Energy, and the National Oceanic and Atmospheric Administration's Office of Global Programs. There are plans to launch two more

SOLO-carbon observers in the North Atlantic later this year.

Additional information:

- Ocean Biogeochemical Processes Group
- Video (3.5 MB avi file; right click after movie loads)

February 15, 2002

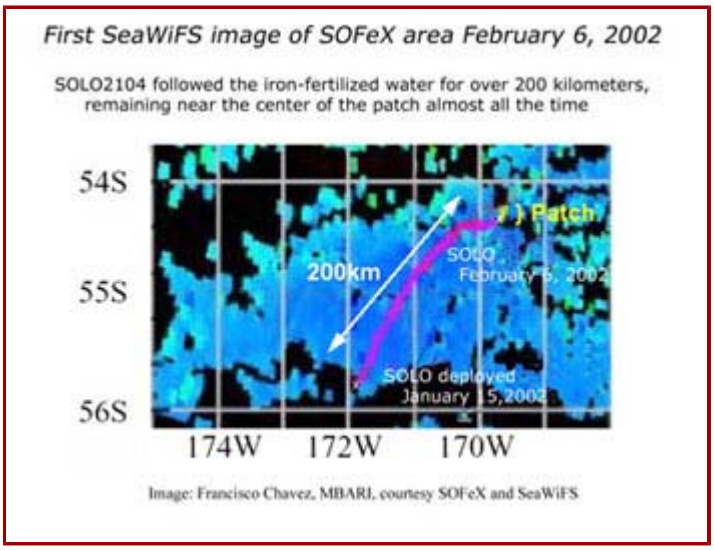
research news

A "LITTLE ROBOT THAT COULD" TRACKS PLANKTON GROWTH IN STORMY ANTARCTIC WATERS

Contact: Paul Preuss, (510) 486-6249, paul_preuss@lbl.gov

BERKELEY, CA — A deep-diving SOLO float, specially equipped by scientists at Lawrence Berkeley National Laboratory to report on biological activity in the sea, has faithfully tracked a plankton bloom for over 200 kilometers through the stormy Southern Ocean — even helping the ship that fertilized the plankton growth with iron relocate the same watery patch three weeks later.

"This is the cloudiest place on the planet, and the winds have been awful," says oceanographer Jim Bishop, whose group in Berkeley Lab's Earth Sciences Division designed and equipped the SOLO floats, originally created by the instrument development group at the Scripps Institute of Oceanography, as special "robotic carbon explorers." "But the float in the center of the fertilized patch just keeps sending — its antenna is spectacular. I call it 'the little float that could.'"



Click image to enlarge.

Three times each day two of the SOLO floats, the one inside the patch and another outside, acting as a control, dive up and down several hundred meters to measure particulate carbon — most of it in the form of phytoplankton, or single-celled algae. The floats return to the surface daily and, weather permitting, report their Global Positioning System (GPS) positions and data to satellites overhead.

SOFeX: making the Southern Ocean bloom

The floats were launched in mid-January from the research vessel Revelle, as part of the SOFeX experiment led by Moss Landing Marine Laboratory (MLML) and the Monterey Bay Aquarium

Research Institute (MBARI). Three ships are involved, R/V Revelle and R/V Melville, both operated by Scripps, and the United States Coast Guard's research icebreaker Polar Star.

The purpose of SOFeX, the Southern Ocean iron (Fe) experiment, is to test the late John Martin's "iron hypothesis." While director of MLML, Martin proposed that phytoplankton blooms can lower global temperature by removing carbon from the atmosphere. Since phytoplankton needs iron from sources like windblown dust to grow, Martin famously remarked "Give me half a tanker of iron, and I will give you an Ice Age."

The prospect of controlling atmospheric carbon through ocean fertilization and perhaps offsetting global warming are matters of intense interest to the Department of Energy and the other agencies and institutions participating in SOFeX. Consequently, under the scientific direction of MBARI's Ken Johnson, R/V Revelle pumped an iron solution (somewhat less than half a tankerful) overboard in two regions of the Southern Ocean along 170 degrees west longitude.

The waters of the more northerly region, at about 55 degrees south latitude — the "howling 50s" of seagoing lore — are poor in the silicate that some phytoplankton need to form a shell. Thus plankton in that patch were expected to bloom sluggishly even after iron fertilization, while a more vigorous bloom was expected after fertilization of the silicate-rich (and iceberg-crowded) waters of the southern patch, at about 66 degrees south.

After Revelle "pumped iron" into these regions, Melville, led by principal SOFeX investigator Kenneth Coale of MLML, followed to measure changes in phytoplankton growth. Soon the Polar Star, under the scientific direction of Ken Buesseler of the Woods Hole Oceanographic Institution, will visit the southern patch to begin assessing long-term carbon uptake.

Testing the waters

Most methods of testing the waters require towing instruments behind the ship or lowering them over the side, like the Multiple Unit Large Volume Filtration System (MULVFS) that Berkeley Lab researchers aboard Revelle used to trap particulate matter and haul it aboard ship. But the autonomous SOLO carbon explorers are unique.

An artist's impression of a SOLO float diving.

To measure particulate carbon the robotic floats follow depth profiles that can be programmed and reprogrammed via satellite from virtually anywhere in the world. The floats surface daily to signal their positions and send data, saving up to 11 depth profiles if high winds interfere with transmission.

Revelle started its voyage with our SOLO floats. One of the first two in the northern patch, designated SOLO2054, promptly drifted west when the fertilized water mixed and divided. The center of the main patch was recalculated and a third float, SOLO2104, was launched.

"We had programmed the depth profiles to keep the floats at a depth of 100 meters most of the time, instead of periodically 'resting' them at depth," Bishop explains. "We were a bit apprehensive, however, that by staying in the middle of the plankton bloom, the instruments — which measure particulate matter by how much light is transmitted through the water — might become fouled."

Revelle headed south to fertilize a second patch of ocean. Fair skies there soon turned stormy. Because of its far-south location in the southern patch, the fourth and final SOLO float suffered raging storms and reduced satellite coverage. Heard from only once before February 14, that float reestablished contact and played back all its past profiles when the winds finally moderated.

The Southern Ocean has some of the world's worst weather. (Image: SOFeX)

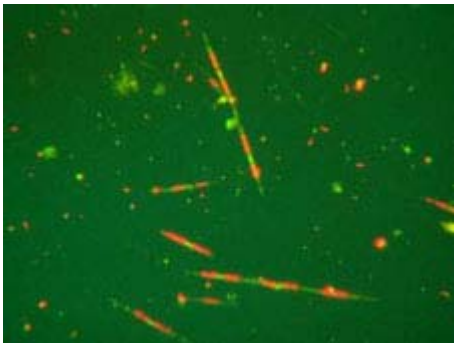
Programming pays off

While Berkeley Lab researchers Todd Wood, Christopher Guay, and Phoebe Lam were busy aboard Revelle, Bishop — using his laptop computer in Berkeley — was in daily contact with the floats tracking the northern patch. Although most of the time they were in relatively

shallow waters rich in plankton, their instruments escaped biofouling.

"Our guess at how to program SOLO to stay with the patch seems to have paid off in a big way," Bishop says. "SOLO2104 has remained at or very near the center of the patch since it was deployed, and the control SOLO has maintained position nearby."

Revelle returned to the northern patch on February 7, guided by SOLO2104's accurate GPs coordinates. Just before arrival, the ship finally received the first color image of the area in over three weeks, from NASA's SeaWIFs satellite. The highest concentration of plankton was found near the float's position, saving the ship enough search time, Bishop estimates, "to more than pay for the floats."



Plankton bloomed vigorously, even in the silicate-poor waters of the "howling 50s." (Image: SOFeX)

Although winds throughout the region had exceeded 20 knots most of the time, and SOLO2104 was unable to transmit during the worst storms, "it played back its data faithfully afterwards," Bishop says. "We also have an almost unbroken record from the control SOLO, to make this part of the experiment a major success." Despite expectations that growth in the northern patch would be poor, "We can confidently say that particulate organic carbon in the patch has grown to be four or five times that outside the patch."

Revelle returned to dock in New Zealand on February 14, but the SOLO floats have enough power to continue profiling for at least three or four more months, long after ships have left the region. The information they report will play a crucial role in assessing the possible role of ocean fertilization in regulating carbon in the atmosphere through ocean carbon sequestration.

Berkeley Lab is a U.S. Department of Energy national laboratory located in Berkeley, California. It conducts unclassified scientific research and is managed by the University of California.

Additional information:

- More about the SOFeX project (logbooks of the three participating ships are available by pressing "Logbooks" on the navigation bar at this website)
- More about the iron hypothesis
- More about DOE research into ocean carbon sequestration