

A satellite image of the ocean showing complex swirling patterns of water in various shades of blue and teal. The top of the image shows white clouds. The bottom of the image shows a coastal area with brownish-green land and intricate waterways.

Oceans of Change

Bigelow Laboratory for Ocean Sciences

Annual Report 2008



“There is no finish line in the work of science.
The race is always with us—the urgent work
of giving substance to hope . . .”

~ President Barack Obama, March 9, 2009

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Cover: The bright waters of an *E. huxleyi* bloom off the northern coast of Norway in the Arctic Ocean's Barents Sea, as seen from an altitude of 438 miles by a MODIS polar orbiting satellite. Image courtesy of Jacques Desclotres, MODIS Land Rapid Response Team at NASA GSFC.

Facing page: *R/V Roger Revelle's* wake, South Atlantic Ocean off the coast of Patagonia. Photo by Jeff Lawrence.

Back cover: Instrument well on the *R/V Roger Revelle* in the midst of the 2008 coccolithophore bloom over the Patagonian shelf. The bright turquoise color is caused by the intense radiance of backscattered (indirect) light reflected upwards by coccolithophores in the water. Story on p. 43. Photo by Jeff Lawrence.



Why do we commit our time, our energy, and our treasure to basic scientific research? The answer, I believe, is our strong desire to challenge the frontiers of knowledge and make discoveries that will enhance the quality of our lives.

As I have observed Bigelow Laboratory advance our understanding of the oceans' microbial ecosystems, ocean processes, and global climate change, I have no doubt why the Laboratory is so successful. Our extraordinary team of scientists has demonstrated a record of winning competitive, peer-reviewed research grants from the National Science Foundation at a rate that is twice the national average. This does not happen by chance; it happens with impressive consistency because of the dedication and hard work of a team of highly talented, twenty-first century scientific explorers.

The foundation for Bigelow Laboratory's ability to attract world-class scientific talent lies in the unique culture of the organization and in its 35-year history of visionary leadership. In his first year as the Executive Director, Dr. Graham Shimmield has demonstrated why the Board of Trustees was so excited to attract him to the Laboratory. Graham has brought the Laboratory his wisdom and energy as a leader, and his global reputation as an ocean scientist.

Working with our senior research scientists, the staff, and the Board, Graham has charted an ambitious new course for the Laboratory. This new strategic plan builds upon the Laboratory's historic success in basic research, adding two important new elements to strengthen its resources and extend its goals through institutional partnerships. The first initiative contemplates partnering with one or more academic institutions to engage in joint research projects and further the Laboratory's commitment to educating the next generation of ocean scientists. The second involves building a technology transfer capability in partnership with commercial enterprises, enabling the translation of our scientific discoveries into applications in such fields as medicine and biofuels, among others.

As you read this Annual Report, I hope that you will come to appreciate the quality and relevance of the great work that goes on at Bigelow Laboratory. I hope you will also come away with a better understanding of the role that our planet's vast oceans play in our everyday lives, and of the potential for scientific discovery in areas that can enhance the quality of life for generations to come.

I welcome your interest in Bigelow Laboratory, and hope that you will become part of the Bigelow community.

David M. Coit
Chairman



The foundation for Bigelow Laboratory's ability to attract world-class scientific talent lies in the unique culture of the organization and in its 35-year history of visionary leadership.

Oceans of Change

From Microbial Evolution to Global Climate

In the year 2000, the Nobel Prize-winning atmospheric chemist Professor Paul Crutzen coined the term **Anthropocene**, to describe the influence of human activities on Earth as being sufficiently profound to have given birth to a new geological epoch. The imprint of these human activities can now be identified in the atmosphere, on land, and even in the deepest reaches of the ocean.

There have been momentous changes in the politics of science as well. Over the past several months, we have seen an unprecedented shift in the way science is viewed in the United States. President Obama has made it clear that his Administration will seek to resurrect the position of scientific research in the health, security, financial economy, and societal values of the nation.

Within the context of a changing world ocean, Bigelow Laboratory's mission is to understand the key processes driving the world's ocean ecosystems, their evolution, and their fundamental relationship to life on Earth. Collaborating with scientists and institutions from around the world, we work to

understand and predict the role of ocean ecosystems—from the scale of microbes and their evolution, to global biogeochemical cycles and Earth's climate. We investigate the molecular, microbial, organismal, and biogeochemical processes affecting the world's oceans, coastal seas, and estuaries, and the interactions between ocean ecosystems and the natural and anthropogenic variability of global climate.

The Laboratory's 2008 Annual Report reflects four overarching and interconnected themes that shape our research strategy, now and into the future:

Microbial evolution and genomics applies molecular biology and microbial ecology to the viruses, bacteria, and algae—the strands of life—that exist in diverse environments throughout the world's oceans. Working within the vast reservoir of microbial organisms in the marine environment that remain uncultured, we seek to understand their evolution, genetic and chemical make-up, and their potential application in human industry and enterprise.



Photo by Jane McLoughlin.

High Arctic landscape photo by Thorsten Mauritsen.

Ocean biogeochemistry research at the Laboratory examines the infinite networks within which essential elements such as carbon, nitrogen, phosphorus, silica, and micronutrients (e.g., iron, zinc) are cycled through the ocean, controlling phytoplankton and bacterial growth, often in the extreme environments of polar seas and submarine hydrothermal systems.

The impact of both natural and anthropogenic change—particularly on the underwater world of sensitive marine habitats and ***sentinel species***—is the unifying context of the Laboratory's focus on **ecosystem function and change**. Our research in this area examines the evolution and adaptation that is occurring throughout the world's oceans and coastal waters.

Key interactions between sunlight, water, atmosphere, and ice determine basin-wide plankton ecology and biogeochemistry at the interface of sea and sky. These processes and are the focus of observation, measurement, analysis and modeling within our **ocean systems science and climate change** theme.

Within these broad research themes, the Laboratory has identified key priority areas for contin-

Within the context of a changing world ocean, Bigelow Laboratory's mission is to understand the key processes driving the world's ocean ecosystems, their evolution, and their fundamental relationship to life on Earth.

ued development in the next five years. These are ocean remote sensing of microbial populations; ocean acidification; microbial ecosystem modeling; ocean energy and biotechnology, including biofuels and natural product chemistry; development of the combined culture collection for marine algae, bacteria, and viruses; and the ocean's role in human health.

Over this past year, we also have begun to define a future academic partnership that will allow significant educational and professional development at the Laboratory, and build a substantial and vital bridge to the future. Our new status as a National Science Foundation-sponsored institution under the Research Experience for Undergraduates program is the first, important step in this direction.

Finally, we have made a major commitment to developing significant technology transfer capability through innovation and carefully selected opportunities in order to

ensure that our research discoveries reach the private sector, helping to stimulate economic development in the State of Maine and in the nation.

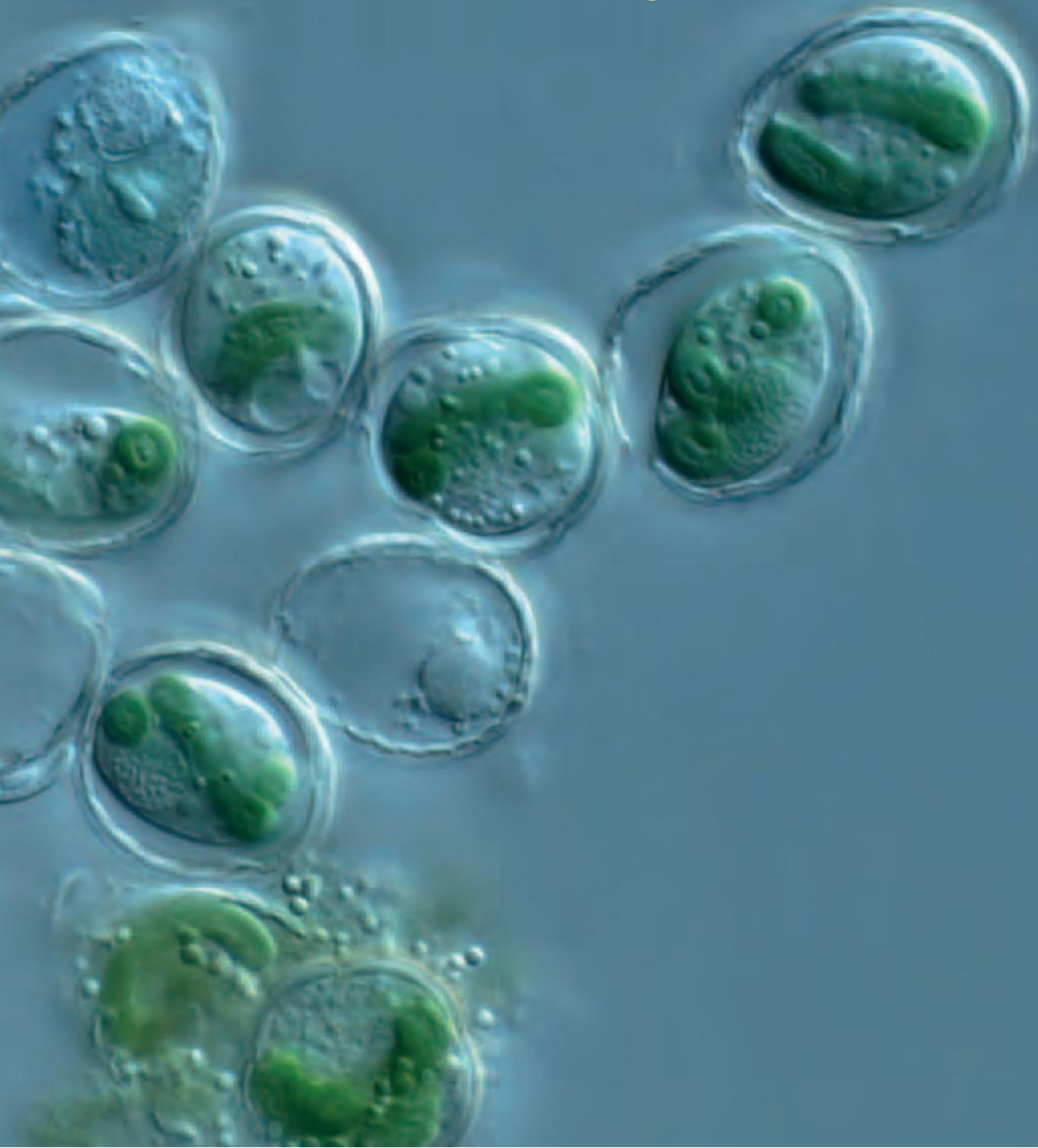
This Annual Report marks the end of my first year at Bigelow Laboratory for Ocean Sciences, and the 35th year since Drs. Charlie and Clarice Yentsch founded the Laboratory in 1974. It has been a huge honor and privilege to help set the course for the next decade, and to work with the depth of intellectual talent and commitment shown by our scientists, staff, and Board of Trustees. In this year of profound political and financial change, we will work to more fully recognize and understand the life support that the oceans provide for our planet—and to help predict what is ahead for all of us.

Graham B. Shimmield, Ph.D.
Executive Director

Note: Words in ***bold italic*** type are defined in the glossary on pp. 60-61.

STRANDS OF LIFE

Microbial evolution and genomics



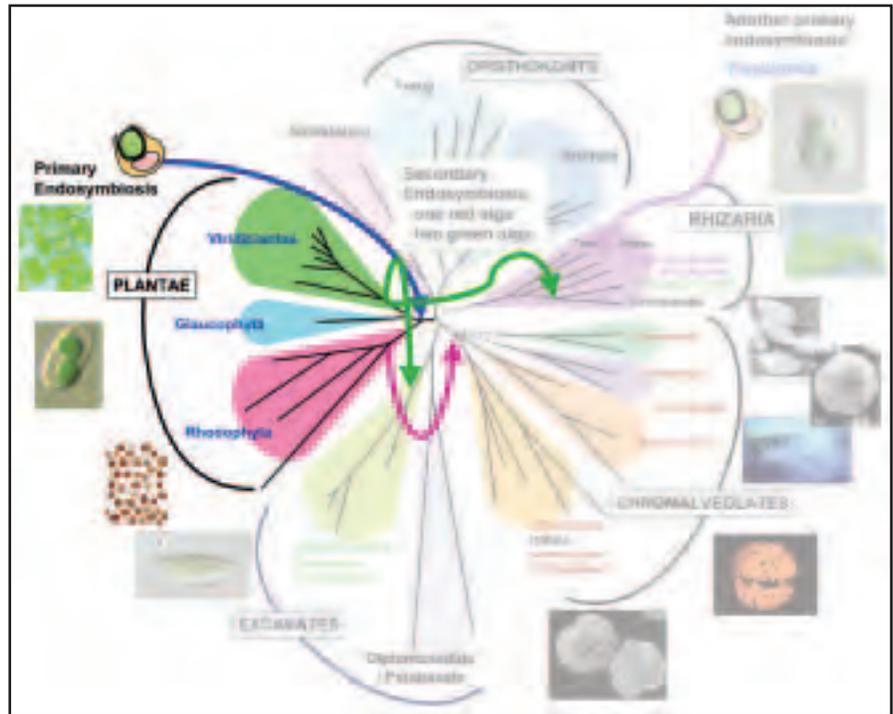
A Pivotal Moment in Evolutionary Time

There was a moment, a billion and a half years ago, when a few single-celled organisms developed the ability to photosynthesize—to convert sunlight, carbon dioxide, and water into energy for food. It was a moment that changed the world.

Photosynthesis became the basis of the planet’s food chain; the foundation upon which multicellular organisms, including human beings, depend for survival.

Photosynthesis takes place in specialized structures called **plastids**, found inside the cells of all plants—from giant trees in ancient, old growth forests to drifting blooms of innumerable phytoplankton cells that flourish and fade each year in the world’s oceans. The origin of plastids and their development as microscopic machines of photosynthesis are the focus of Dr. Hwan Su Yoon’s research on the genomes of two species of *Paulinella* amoebas.

About 60 million years ago, *Paulinella chromatophora* underwent the same plastid-acquiring process that transformed certain bacterial cells into single-celled plants more than a billion years



Summary of Plastid Evolution

The origin of the first plastid can be traced to a single primary **endosymbiosis** event (highlighted on the left, above), during which a non-photosynthetic **protist** engulfed a **cyanobacterium** and put it to work as an **organelle**. This proto-algae subsequently gave rise to red, green, and **glaucophyte** algae. Diagram courtesy of H. S. Yoon.



Dr. Hwan Su Yoon.

earlier. Instead of consuming bacteria as food, *P. chromatophora* began to capture and use them as engines for photosynthesis, generating its own supply of food. *P. chromatophora*’s relative *Paulinella ovalis* has not accomplished this, and continues life as a single-celled animal, feeding on bacteria for its food energy needs.

A grant from the National Science Foundation (NSF) is funding Yoon’s analysis of the genomes of both amoebas. Yoon and his collaborators, including co-principal investigator Dr. Robert Andersen, are using single-cell genomics technology first developed at Bigelow

Laboratory (see next page) to compare the genetic structure of these two plant and animal relatives, generating a precise gene profile of *Paulinella* evolution, before and after plastids entered the picture and changed everything. The researchers are investigating the genetic modifications that allowed plastids to form, and the genetic pathway by which the first animals became the first plants. Besides advancing scientific methods in the field of genetic engineering, this research has direct bearing on how scientists view critical genetic changes in the context of major transitions in evolutionary history.

Photo by Buddy Doyle.

Genetic Alphabets

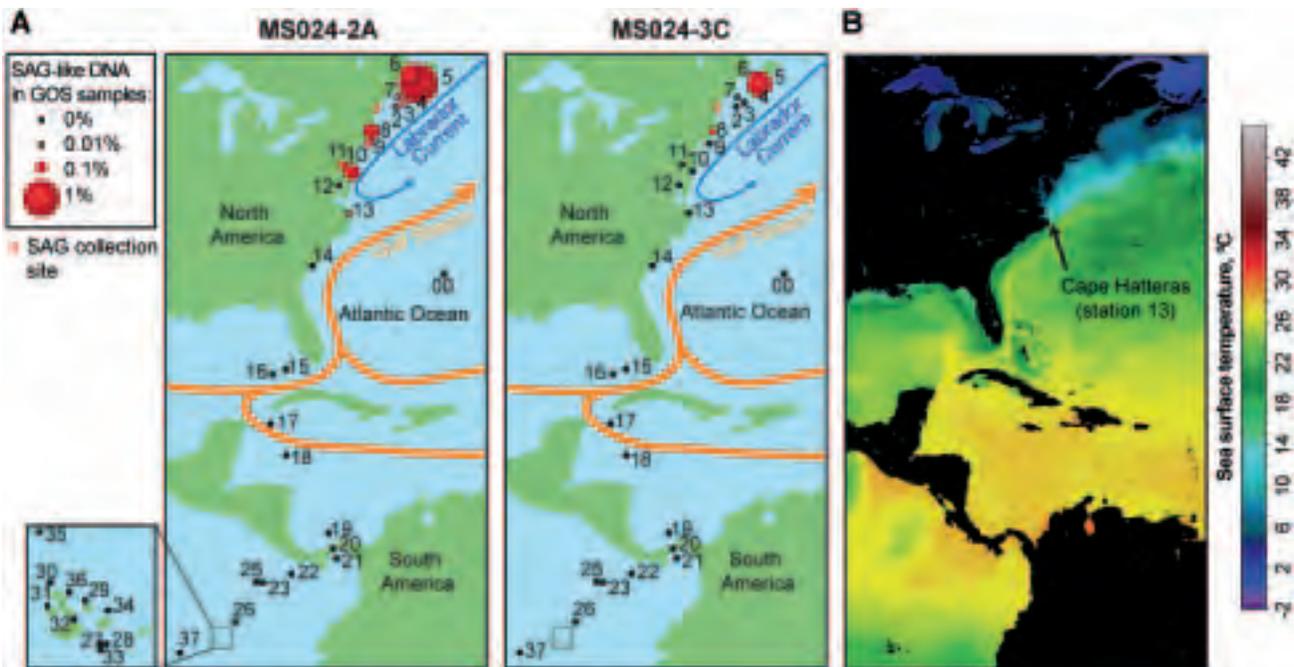
Sequencing Genomes, One Single Cell at a Time

Although they are invisible without strong magnification, millions of the microbes that support life in the ocean can be found in a single drop of seawater.

The ocean's microbes—microscopic bacteria, viruses, single-celled algae, and minuscule predators—collectively form the basic components of global ocean ecosystems, and are the initial links in the ocean's food chain. They drive the cycling of elements—such as nitrogen, phosphorus, iron, and sulfur—necessary for ecosystem processes, and recycle the nutrients essential for photosynthesis and

biological productivity. Responsible for half of the carbon dioxide (CO₂) that is removed from the atmosphere and most of the carbon exported to marine sediments, ocean microbes are a critical part of the global carbon cycle. Less than 1% of the ocean's microbial diversity has been cultured for study in laboratory settings, however, leaving a wealth of information untouched and unexplored.

Single cell genomics (SCG) technology was developed at Bigelow Laboratory over the past several years and represents a major breakthrough in the field of microbial research.



Geographic distribution of microorganisms related to two uncultured *flavobacteria*, known as MS024-2A and MS024-3C, containing genes for *proteorhodopsin* (figure from *PLoS ONE* 4:e5299). The geographic pattern shown here is inferred from DNA comparisons between the two single cell genomes (SAGs) and the Venter Institute's broad *Global Ocean Sampling (GOS) metagenome* (*PLoS Biology* 5:e77).

The National Science Foundation has awarded Bigelow Laboratory a Major Research Instrumentation grant for the equipment needed to begin establishing a national microbial single cell genomics center. Single cell genomics (SCG) technology was developed at Bigelow Laboratory over the past several years and represents a major breakthrough in the field of microbial research.

SCG bypasses the need to first grow a cell in culture before sequencing its genome, allowing scientists to isolate an individual cell from environmental samples that contain a multitude of microbial species, and then extract and duplicate that particular cell's genetic material in sufficient quantities for analysis and experimentation.

Examining the genetic structure of individual cells in the environment dramatically increases researchers' ability to understand microbial communities and unlocks a wealth of previously unavailable resources for bio-prospecting. The SCG center will offer scientists new laboratory and **bioinformatics** tools to investigate the diversity, ecological roles, evolution, and biotechnology potential of microorganisms from marine and other environments.

In 2008, scientists at Bigelow Laboratory received funding for several major research projects that use single cell genomics technology to study the genetic diversity of uncultured ocean microbes and how their genomes evolve in response to changing environmental conditions.



Photo by Dennis Griggs.

The ability to analyze multiple genetic segments in individual microbial cells allows scientists to understand how uncultured microbes function and interact in the environment. Drs. Ramunas Stepanauskas, Michael Sieracki, and Jane Heywood are using SCG to study food preferences of individual bacteria-eating microbes, whether these preferences are triggered by bacterial metabolism, and

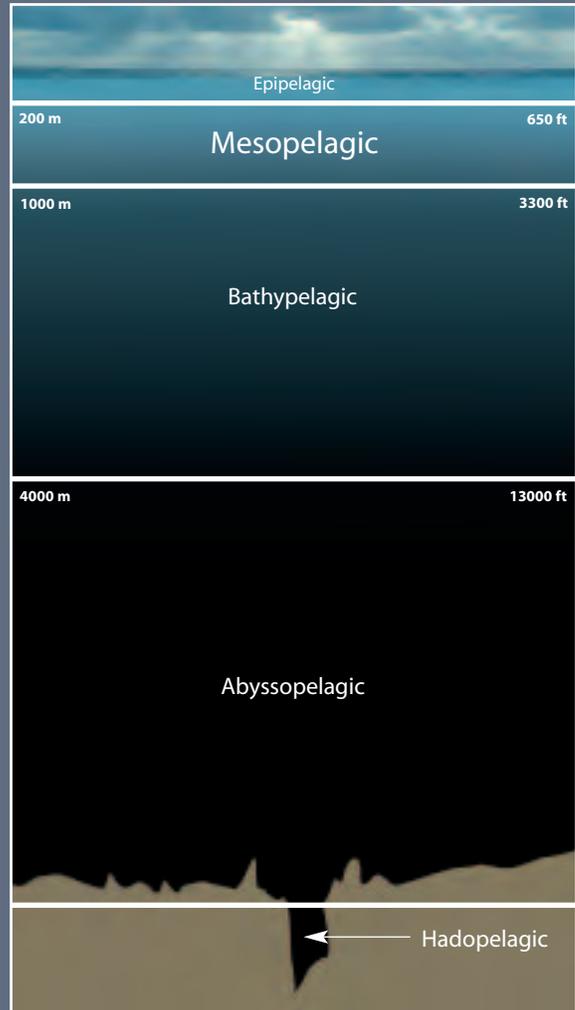
Drs. Michael Sieracki (seated) and Ramunas Stepanauskas.

The Twilight Zone

Microbes dominate a region between 650 feet and 3,300 feet below the ocean's surface known as the mesopelagic zone, which receives organic matter that rains down from the upper, sunlit photosynthetic zone. Containing approximately 25% of the ocean's volume, this vast environment is home to one of the largest and least understood ecosystems on Earth, and offers scientists a rich, untapped source of genetic and biomolecular resources.

Microorganisms in the mesopelagic zone play a major role in global ocean productivity and carbon cycling by regulating nutrient flow between the photosynthetically active, but nutrient-poor surface ocean, and the dark, nutrient-rich deep ocean.

Until recently, difficulties in cultivation of microorganisms from the mesopelagic zone prevented comprehensive studies of their diversity, biochemistry, physiology, and evolutionary history. As part of another NSF-funded research project at the Laboratory, Drs. Stepanauskas, Sieracki, and David McClellan are using SCG technology to read the genetic codes of mesopelagic microorganisms from the South Atlantic Gyre. This research will lead to a better understanding of the role of mesopelagic microbes in carbon and nitrogen cycling in the global ocean.



how such food preferences affect the reservoir of genetic diversity in the ocean's microbial communities.

Stepanauskas and Sieracki utilize SCG to identify uncultured microorganisms containing genetic codes for *proteorhodopsins*, a newly-discovered protein that allows a large fraction of marine bacteria to use light as a supplementary source of energy. In collaboration with researchers from the U.S. Department of Energy Joint Genome Institute and several other organizations, they have obtained the first near-complete genome sequences of two uncultured, proteorhodopsin-containing

marine bacteria from the Gulf of Maine.

The study demonstrates that, in contrast to cultivation, single cell genomics enables rapid genome recovery of those types of microbes that are dominant in the oceans and are therefore likely to play significant ecological roles. A new research grant from NSF will allow Stepanauskas and Sieracki to expand this research to freshwater ecosystems, where proteorhodopsins may be as plentiful as they are at sea.



Dr. Jane Heywood in the SCG Laboratory.

Photo by Dennis Griggs.

Survival Strategies

Emiliana huxleyi is one of the most abundant and widely distributed species of phytoplankton in the ocean. This tiny, single-celled plant belongs to a group of microscopic algae known as **coccolithophores**, and forms an outer shell of calcium carbonate plates called coccoliths.

Under the right environmental conditions in the ocean, *E. huxleyi* can grow in enormous numbers. At the height of a **phytoplankton bloom**, there can be over 10,000 *E. huxleyi* cells in a single teaspoonful of seawater. These immense turquoise blooms occur in vast stretches of ocean, offering dramatic evidence of the extent of the world's annual marine phytoplankton productivity. *E. huxleyi*'s life cycle directly affects the chemistry of the surrounding water, and has a major impact on the ocean's biogeochemical cycles.

Viruses that infect marine phytoplankton destroy individual cells, leading to the rapid disintegration of the massive seasonal blooms. Scientists estimate that by breaking down *E. huxleyi* and other phytoplankton cells, viruses have a direct influence in determining nutrient pathways in the ocean. Viruses recycle approximately 25% of the carbon captured by photosynthesis through a process termed the **viral shunt**, making them essential to the life-sustaining flow of nutrients and energy in the global ocean.

Marine virologist Dr. Willie Wilson has discovered a group of giant viruses that are responsible for the demise of oceanic *E. huxleyi* blooms. He termed this group the **coccolithoviruses**.

For successful infection of its host cells, marine viruses typically



True color satellite image of a milky *E. huxleyi* phytoplankton bloom in the English Channel south of Plymouth, UK.

Courtesy of the Plymouth Marine Laboratory Remote Sensing Group.



Research Associate Ilana Gilg and Postdoctoral Researcher Dr. Joaquin Martinez analyze the impact of marine viruses on phytoplankton growth in the Wilson laboratory.

Photo by Dennis Griggs.

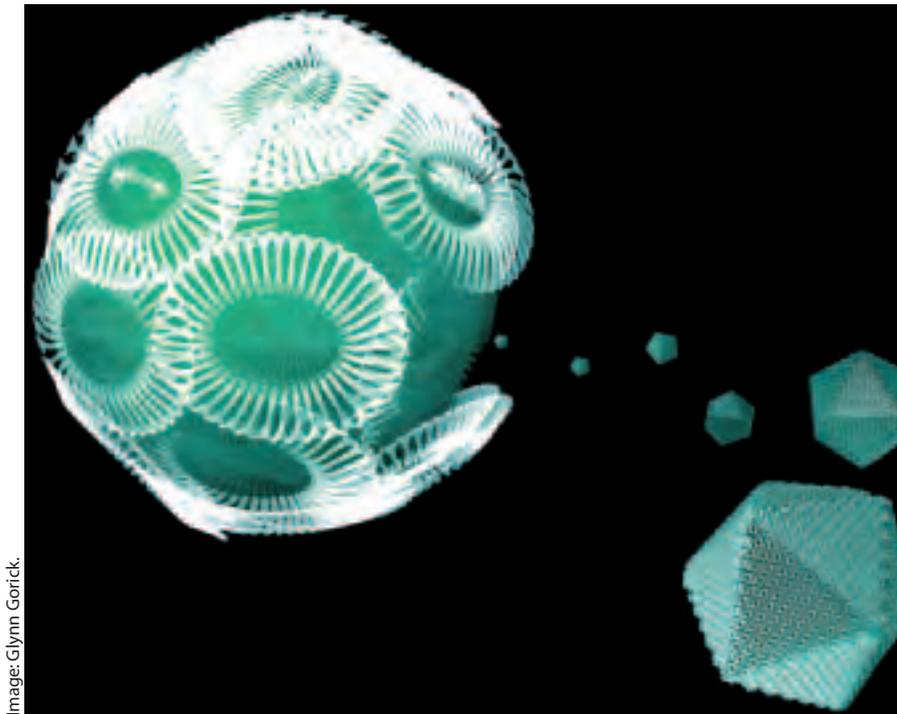


Image: Glynn Gorick.

Depiction of coccolithoviruses exiting an *E. huxleyi* cell.

require high levels of phosphorus as a nutrient in the water. *E. huxleyi*, however, prefers to grow in low phosphorus conditions. Using genetic analysis, Wilson and his colleagues have found that, as part of an endless predator-prey evolutionary “arms race,” coccolithoviruses have evolved a specific gene involved in phosphorus acquisition, gaining an advantage over its algal host during infection.

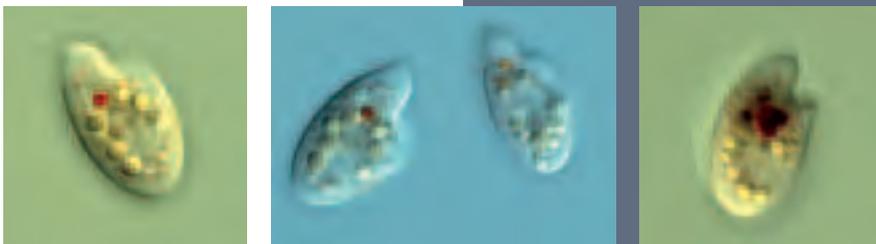
Wilson is now working with the Laboratory’s Senior Research Scientists Drs. Ramunas Stepanauskas and Susie Wharam on a new multi-year National Science Foundation project to determine

A Matter of Taste

Marine viruses have other means of influencing the pathways by which organic matter and energy cycle through ocean ecosystems. In a joint project with Dr. Claire Evans of the Royal Netherlands Institute for Sea Research, Wilson discovered that, given the choice, single-celled vegetarian grazers, in this case the **dinoflagellate** *Oxyrrhis marina*, prefer to graze on *E. huxleyi* cells that are infected with a virus, rather than uninfected cells. Chemical cues during the infection process may

make infected cells more palatable for grazers, or it may simply be that the increased size of these cells makes them a more appealing morsel.

As *O. marina* subsequently becomes food for other, larger forms of marine life, carbon that would otherwise have flowed back through the **microbial loop** as a nutrient after the *E. huxleyi* cell died is instead channeled further up the oceanic food chain. Wilson and his fellow researchers are continuing to investigate how profound an effect preferential grazing of this kind is having on both the flow of energy through the marine food web and on the overall ecology and biogeochemistry of the ocean.



Oxyrrhis marina. Photo by R. Anderson.



Photo by W. Wilson.

Mesocosm bags are emptied at the end of the month-long field study at the Espeland Marine Biological Station in Bergen, Norway. Note that the water is turning a milky color as *E. huxleyi* cells are returned to the adjacent fjord. Scientists (from left-to-right): Jan Finke, NIOZ Royal Netherlands Institute for Sea Research, the Netherlands; Dr. Susan Kimmanse, Plymouth Marine Laboratory, UK; Dr. Mike Allen, Plymouth Marine Laboratory, UK; Dr. Assaf Vardi, Rutgers University, USA.

how this gene helps its virus collect phosphorus from an otherwise low phosphorus environment.

Part of this study involved fieldwork at a seawater mesocosm site in Bergen, Norway during June 2008. A mesocosm is an enclosed experimental system that closely mimics real-life conditions—in this case a coccolithophore bloom—while allowing scientists to manipulate specific environmental factors. In the Bergen study, Wilson’s team examined how varying cellular, genomic, and environmental conditions in a series of (pseudo)natural bloom situations affected the virus’s phosphorus acquisition gene.

Hiding in Plain Sight

Working with an international team of colleagues, Wilson has also discovered that *E. huxleyi* has evolved an effective, “Cheshire Cat-like” strategy to help it escape viral infection. By switching from a growth to a reproductive stage in its life cycle, the coccolithophore is able to change its physical appearance to such an extent that it becomes essentially invisible to the attacking virus. Rather than using energy to fight infection, *E. huxleyi* cells can then reproduce, conserving their resources for growth until conditions in their environment improve. The researchers believe that *E. huxleyi*’s ability to respond to viral infection by switching to a reproductive stage may give it the genetic diversity and flexibility to adapt to rapid changes in climate and ocean conditions.



Photo by Dennis Griggs.

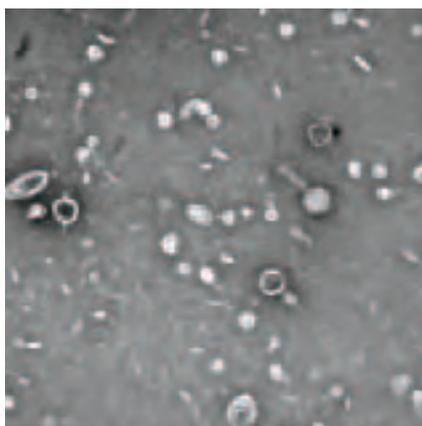
Dr. Wilson working with coccolithovirus sample in the marine virology laboratory.

Putting Viruses to Good Use

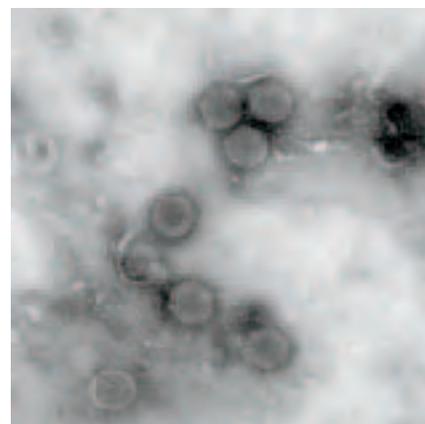
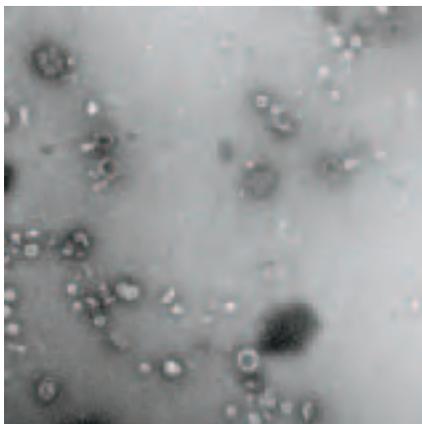
Marine viruses represent the largest unexploited biotechnological resource on the planet. They function as natural biological regulators in the environment, and have a global impact by controlling the ocean's phytoplankton blooms and bacterial populations. On average, there are 1 million to 100 million viruses in a single milliliter of seawater.

As infectious bacteria evolve ever-increasing resistance to antibiotics, scientists are turning to viruses as an alternative approach in the fight against bacterial infections. Known as phage therapy, this technique was first developed almost a century ago and has since been widely used in Eastern Europe. "Phage" (short for bacteriophage, meaning "bacteria-eater"), refers to a virus that infects specific bacteria. Most viruses in the ocean are bacteriophages.

With funding from the Maine Aquaculture Innovation Center, microbiologist Dr. Susie Wharam has worked in collaboration with an experimental lobster hatchery on an infection-fighting phage therapy initiative that has potentially far-reaching benefits—not only for the aquaculture industry, where disease causes the largest economic losses—but also for wider application of environmentally-friendly viruses to control harmful bacteria.



Vibriophages as seen by microscopy.
Direct magnification: 85000–14000X.
Microscopist: W. Wilson.



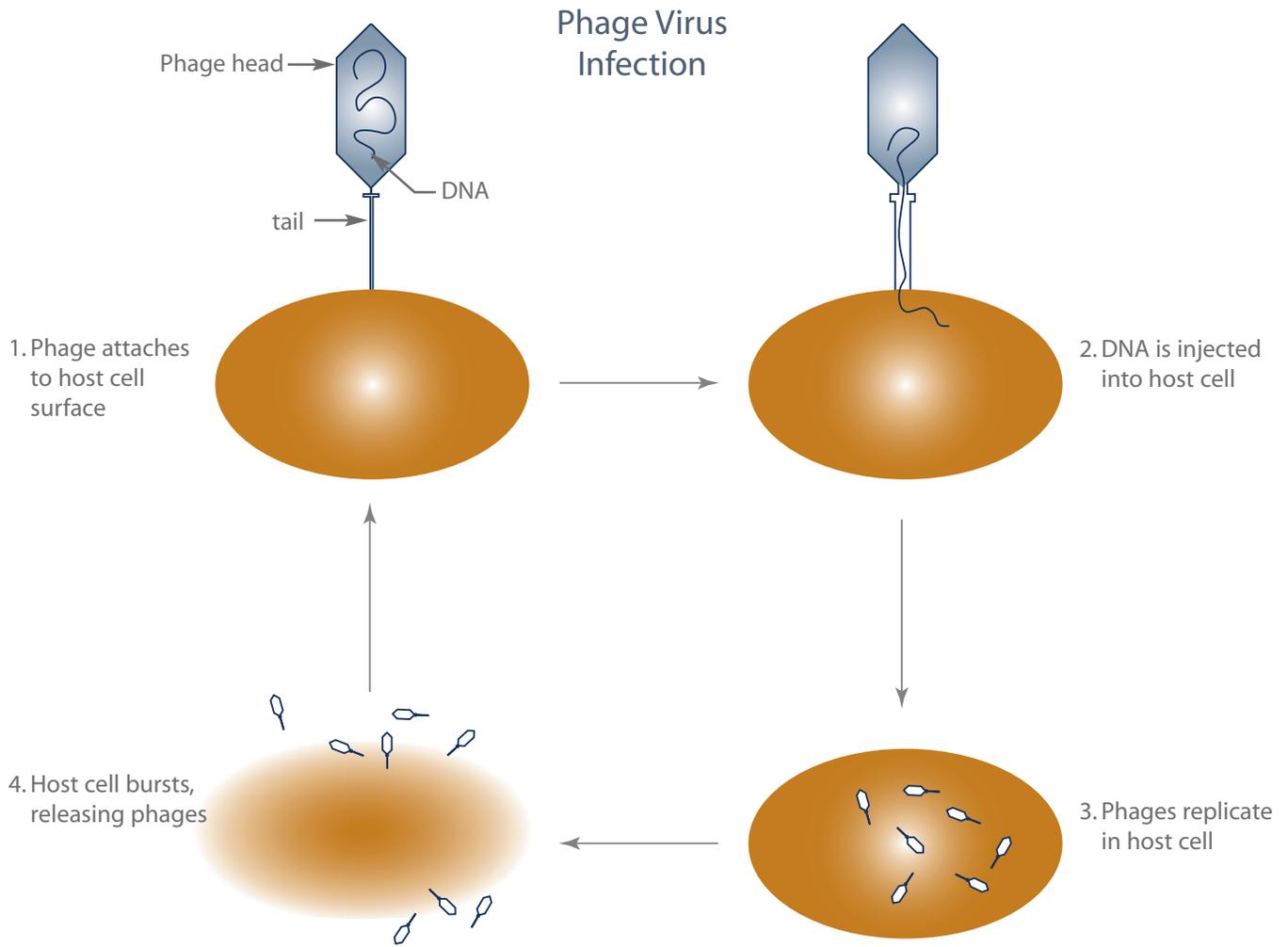


Illustration by David Perry.

A phage destroys an individual bacterial cell by attaching itself to a host cell and injecting its genetic material through the cell's outer membrane (see above). Replication within the cell leads to the formation of new phage particles. Ultimately, the infected cell bursts, spreading the newly replicated viruses to other host cells. This self-perpetuating process continues as long as there are host cells for the spreading virus to infect.

Phage therapy uses viruses as biological agents to fight disease

and infection, even antibiotic-resistant infections. Phages are very host-specific, thriving only in the presence of their target bacteria, without harming other organisms. Deploying them to attack particular disease-causing bacteria leaves others—such as potentially beneficial bacteria—intact and flourishing. Antibiotic treatment, on the other hand, does not discriminate, destroying good and bad bacteria alike.

Phage therapy uses viruses as biological agents to fight disease and infection, even antibiotic-resistant infections.

Fire with Fire: Fighting Vibrios with Vibriophages



Photo courtesy of the Zone C Lobster Hatchery.

Maine's Zone C Experimental Lobster Hatchery in Stonington was established to evaluate the feasibility of growing and releasing juvenile lobsters into the wild as a way to increase natural lobster populations in locally depleted areas. Although many thousands of lobsters have been successfully released since its work began three years ago, the hatchery has had to contend with vibriosis, an infectious disease caused by several species of naturally occurring, harmful *Vibrio* bacteria that can destroy entire aquaculture stocks.

In the past, many aquaculture facilities tried to control vibriosis by using large amounts of antibiotics, which often proved ineffective and, worse, led to the emergence of antibiotic-resistant *Vibrio* strains.

Wharam was looking for naturally occurring phages that could be used as an antibiotic-free way to prevent or control vibriosis out-



Photo by Buddy Doyle.

Dr. Susie Wharam.

breaks. In a one-year pilot study to assess phage therapy as a way to control disease in lobster hatcheries, she and her research staff took samples of water and larvae, then used filtration, microbial

culture techniques, and DNA sequence analysis to isolate and characterize 82 strains of *Vibrio* bacteria from the experimental hatchery. The bacterial strains were used to isolate five distinct marine phages from the hatchery samples. These phages, identified by electron microscopy and DNA analysis, could be deployed to attack specific *Vibrio*, while leaving other, beneficial bacteria unaffected.

Laboratory tests of various combinations of these five potential therapeutic phages on *Vibrio* cultures showed a promising initial drop in bacterial cell densities. Further study of phage-bacteria dynamics—at lower, “hatchery-level” population densities—will help refine phage therapy techniques and their potential applications—not only for a wide range of aquaculture settings, but also as a general approach to safe, effective treatment and prevention of bacterial disease.

Expanding the Collection

Bigelow Laboratory's Provasoli-Guillard National Center for the Culture of Marine Phytoplankton is a major international resource in the rapidly developing field of microbial oceanography.

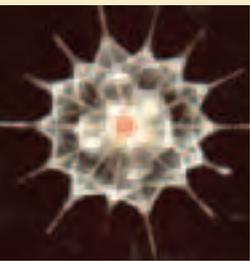
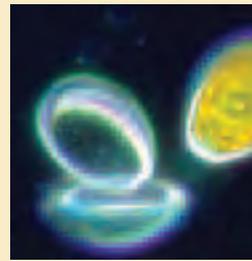
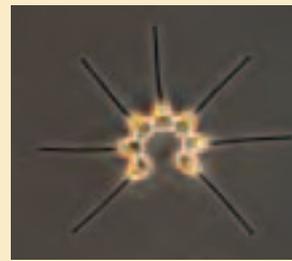


Photo by Buddy Doyle.

Dr. R. Andersen.



Phytoplankton physiologist Dr. Robert Guillard, working in collaboration with Yale University's Dr. Luigi Provasoli, began growing phytoplankton in cultures more than 60 years ago. Over time, the scientists' private collections were consolidated and moved to Bigelow Laboratory, where research continued in methods for collecting, growing, and preserving phytoplankton gathered from the world's oceans.

In 1985, the collection began to be called a "center" to reflect its broadening research mission, and was formally named in honor of Provasoli and Guillard as a tribute to their pioneering contributions to culturing marine phytoplankton. The United States Congress designated the Provasoli-Guillard Center as the nation's official marine phytoplankton culture collection in 1992. The Center began **cryopreserving** its strains and providing large-scale cultures and DNA to scientists worldwide in 1996.

Today, the Center annually supplies thousands of cultures to biochemists, cell and molecular biologists, biotechnologists, ecologists, oceanographers, and taxonomists, and conducts a professional training course in phytoplankton culturing techniques that draws an international cadre of scientists to the Laboratory each year.

The Center's collection has grown to more than 2,700 strains of algae living at temperatures ranging from tropical to polar ocean environments.

The Center is supported by grants from the National Science Foundation, National Oceanic and Atmospheric Association, and the Office of Naval Research. The Center's collection has grown to more than 2,700 strains of algae living at temperatures ranging from tropical to polar ocean environments. There are two culture chambers at each temperature, and three sets of cultures are maintained for each strain. A fourth set of cultures is housed in another building, as a fail-safe in case of catastrophic loss at the facility itself. Cryopreserved strains are maintained in storage tanks; each strain has frozen vials in at least two separate storage tanks.

In 2008, with funding from the National Science Foundation's Field Stations and Marine Laboratories program, the Laboratory began a major expansion of the Provasoli-Guillard National Center, which will add the world's first living collections of marine viruses and bacteria to what is now the largest living phytoplankton library in existence.

The new bacteria and virus collections will be organized within the framework of an expanded Center facility. The Laboratory's marine virologist Dr. Willie Wilson and microbiologist Dr. David Emerson are working to assemble the equipment necessary to house and maintain bacteria and virus collections, identify culture strains, and develop quality control policies that complement the Center's successful model for phytoplankton cultures.

Once established, the new cultures will also become available to scientists worldwide, further streamlining the research process by saving the time and expense of obtaining specific microbial samples from the world's oceans one project at a time.

INFINITE NETWORKS

Ocean biogeochemistry



Glass and Chalk

Global Biogeochemical Cycling

Many microscopic, single-celled species in the ocean cover themselves with hard cases, external latticework trellises, or coatings fashioned from even more microscopic plates and scales. The elements and minerals in these glass- and chalk-like coverings are essential components in the ocean's biogeochemical cycle.

Scientists have long believed that cellular "armor" evolved as a means of protecting cells from grazing by animals, but measuring grazing rates in relation to the amount of mineral in a cell's covering was not possible.

Recent technological advances in flow cytometry and micro-cinematography have improved the ability to identify and track specific elements in individual cells. This has allowed scientists to begin taking such measurements, and find out whether and to what extent armored cells are less vulnerable to predation than cells without a hard coat.

Drs. David Fields and Michael Sieracki are leading a project funded by the National Science Foundation to examine the relationship between concentrations of minerals found in several species of *diatoms* and the ingestion rates of the copepods that graze on them. Their research is leading to a greater understanding about varying pathways by which elements move through the ocean's biogeochemical cycle.

A primary focus of this study is *Thalassiosira weissflogii*, a relatively large diatom that is a favorite food for *copepods* and other microscopic crustaceans.

Fields and Sieracki are using controlled algal culturing techniques at the Laboratory's Provasoli-Guillard Center to grow *T. weissflogii* cells with different amounts of silica in their glassy armor (the more silica, the harder the armor). The researchers offer these cells to hungry copepods under controlled conditions, and examine the animals' grazing behavior to determine whether protection from grazing varies in relation to the hardness of the armor.

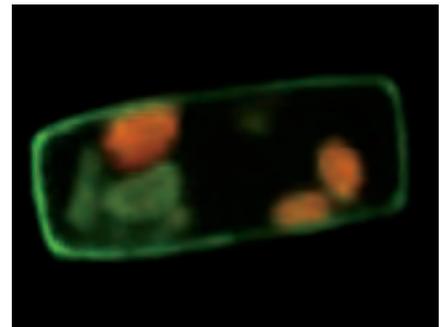
Preliminary experiments show that young copepods have a strong preference for softer cells with lower mineral content. Once ingested, the silica passes through the gut of the copepod relatively undigested, and is released back into the water column as pellets of silica and undigested carbon.

The amount of silica in a pellet affects its overall density (the armor is typically up to three times more dense than the rest of the cell). Pellet density determines the rate at which the carbon portion of the pellet sinks through the water column. Transporting carbon to the deep ocean (through the *biological pump*) is the principal mechanism by which the ocean *sequesters* carbon dioxide out of the atmosphere.



A female *Temora longicornis* copepod preparing to consume a *Brachionus rotifer*.

Photo by D. Fields.



Thalassiosira weissflogii diatom.

Confocal microscope image courtesy of D. Fields.

Recent technological advances in flow cytometry and micro-cinematography have improved the ability to identify and track specific elements in individual cells.



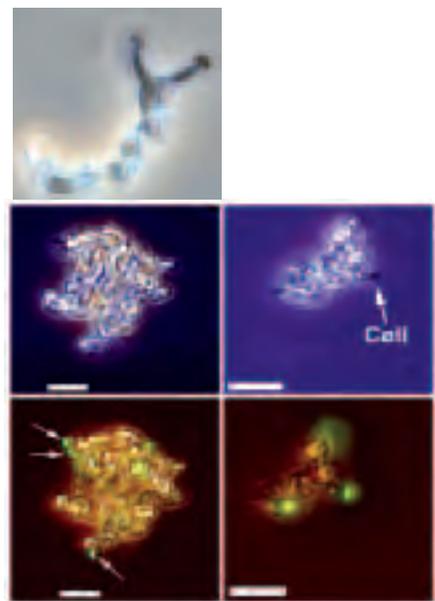
Dive JZ-366-VV4559. September 28, 2008.

Ancient Metabolism: Living on Iron

Iron is one of the most abundant elements on the planet, and in trace amounts, the metal is an essential nutrient for nearly all life forms. Surprisingly, the iron found in volcanic rocks and deep in the Earth is a rich source of food energy for an unusual type of rust-forming (*iron-oxidizing*) bacteria.

Several groups of microorganisms live entirely by chemically extracting all the energy they need to grow and reproduce from iron. These microbes are not only unique in how they grow and where they fit into the tree of life, but also in how they behave and the kinds of minerals they form. Scientists speculate that processing iron was one of the first, ancient forms of microbial metabolism.

With funding from the National Science Foundation, the National Aeronautics and Space Administration, and the Office of Naval Research, Dr. David Emerson and his research team are studying the physiology and behavior of iron-oxidizing bacteria by sampling them in the wild, then isolating, identifying, and growing them in laboratory cultures. In September 2008, working in collaboration with researchers



Photos by D. Emerson.

Images of iron-oxidizing *Mariprofundus ferrooxydans* bacteria. These panels show a composite of light microscope images showing the iron filaments with cells attached to the ends, denoted by arrows and green dots (these are stained cells). Top photo: Unstained *M. ferrooxydans* cells.

Photo by Shawn Doan.



The R/V Thomas G. Thompson.

“By virtue of their large numbers, unique metabolism, and perseverance over millions of years, iron-oxidizing bacteria could have produced the iron used in the hulls of today’s research vessels. It is a source of some humility to think that the iron our ship is made of, may have, at one time, been food for bacteria like the ones we are hunting at Loihi.”

~ David Emerson, aboard the R/V Thomas G. Thompson, 29 September, 2008

from Scripps Institution of Oceanography, Oregon Health and Sciences University, Western Washington University, and University of Southern California, Emerson’s team participated in the third major expedition of FeMO, the Iron-Oxidizing Microbial Observatory at Loihi Seamount. Loihi is a young, very active underwater volcano in the Hawaiian Islands. The FeMO project is investigating the diversity, evolution, physiology, and habitats of iron-oxidizing bacteria—from the extreme heat of **hydrothermal vents** to cold seeps and solid rock in the ocean depths.

Abundant populations of iron-oxidizing bacteria live in the deep water over and around Loihi, and in similar deepwater environments, where massive amounts of volcanic rock and associated vent fluids come in contact with seawater. The volcanic rocks, basalts, and the chemically altered water that flows from vents associated with these under-sea volcanoes are enriched with soluble iron. This makes an ideal habitat for iron-oxidizing bacteria.

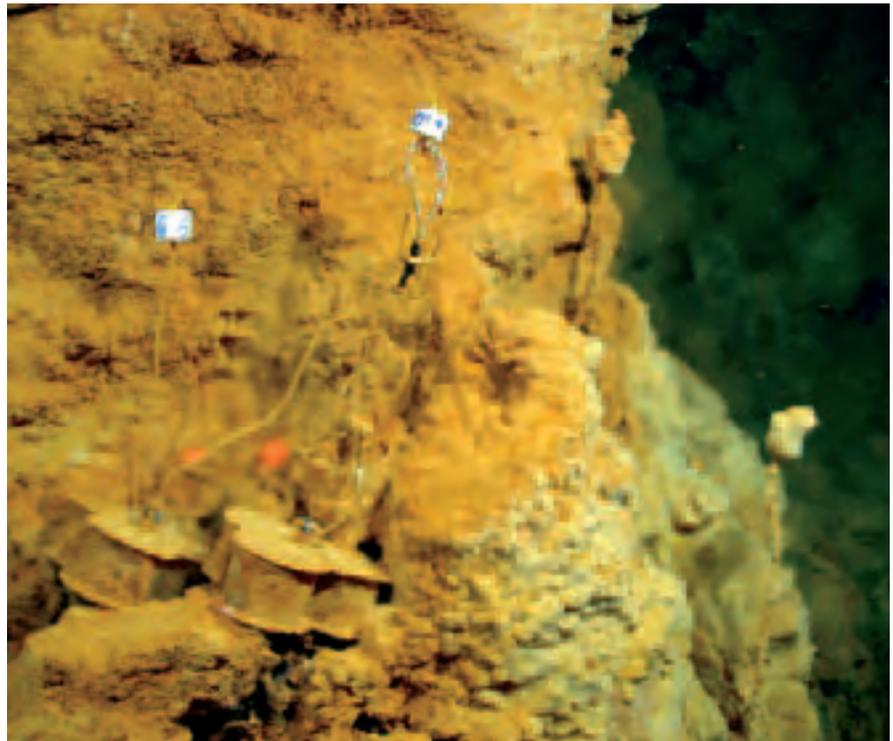


Photo by D. Emerson and the JASON II still camera.

Microbial mats formed by iron-oxidizing bacteria at an iron-rich hydrothermal vent at Loihi Seamount. The two small white floats are attached to short-term samplers that have been placed in the flow from the vent to investigate microbial colonization at the site. The two red laser dots (10 cm apart) are pointed at the vent orifice, which appears out of focus because hot water (55° C/131° F) from the vent is meeting the cold (4° C/39.2° F) ocean water, producing a “shimmer” known as the Schlieren effect. The rocks surrounding the vent are covered in a thick layer of rust-colored iron oxides made by bacteria that live off the ferrous iron in the vent fluid. Even the samplers, which had been deployed for 10 days when this photograph was taken, are becoming covered in these fast-growing microbial mats.

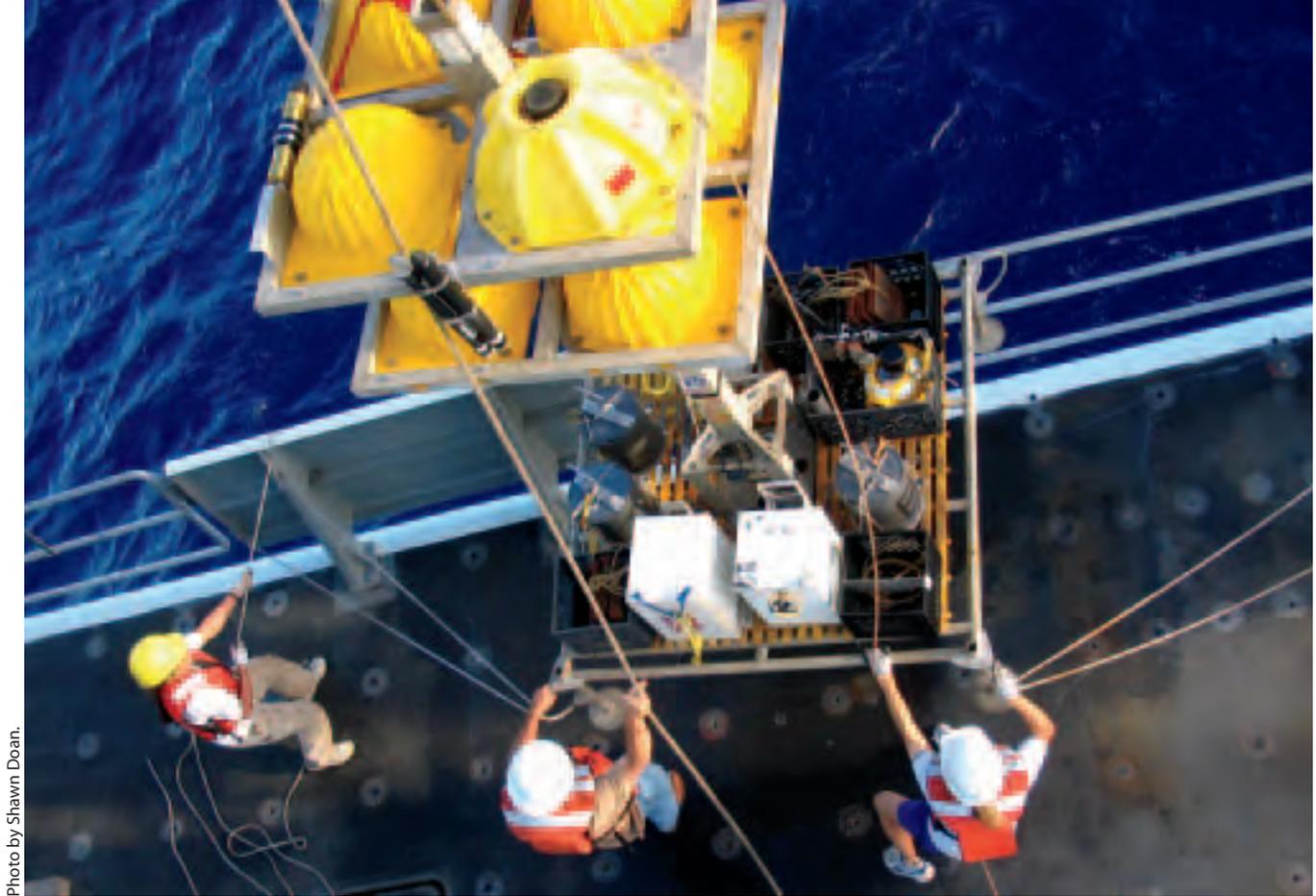


Photo by Shawn Doan.

Equipment elevator launch.



Photo by Jason Sylvan.

Drs. David Emerson (right) and the University of Hawaii's Brian Glazer removing a push core sample for fine-scale chemical analysis.

Using small amounts of oxygen, they consume soluble iron and precipitate rust (iron oxide) as a by-product. The bacteria create filamentous microbial mats that carpet large areas of rock, coating them in rusty deposits that can be more than a meter (over three feet) thick. The rust, in turn, impacts other microorganisms in the marine community and affects elemental geological processes on the planet. FeMO's goal is to understand the biochemical process by which iron-oxidizing bacteria form rust deposits, how they affect ocean chemistry, and their interaction with other bacteria in ocean ecosystems.

Scientists believe that early in Earth's history, iron-oxidizing bacteria may have helped create the massive deposits of iron ore in the banded iron formations that are

now mined to supply the steel industry. Today, these bacteria may be contributing to the ongoing undersea disintegration of the *Titanic* and other historic shipwrecks, literally eating away the iron hulls of those sunken ships. This kind of microbial bio-corrosion is also an important part of the larger industrial problem of metal corrosion. The economic toll from metal corrosion is enormous, costing industries as much as \$250 billion a year in the United States alone.

Emerson and his team are working to piece together the physiology and ecology of iron-oxidizing bacteria. This research will help scientists discover how these bacteria colonize steel surfaces and the part they play in bio-corrosion, their role in carbon fixation and the cycling of greenhouse gases, and whether these life forms may exist on other planets.



Chukchi Sea. Courtesy of NASA.

Nutrients in the Arctic Ring of Life

The continental shelf ecosystems of the Beaufort and Chukchi Seas in the western Arctic Ocean are among the most biologically abundant marine regions in the world.

The Chukchi is north of the Bering Strait, between Siberia and Alaska; the Beaufort Sea lies off northern Alaska, to the east of the Chukchi. Their combined area extends over 200,000 square miles (518,000 sq km), and sustains such a rich diversity and abundance of species that nearby Inupiat communities have named it the “Arctic Ring of Life.”

Chemical oceanographer Dr. John Christensen has been directing a multi-year research project to



Photo by J. Gardner.

Dr. John Christensen.

collect sediment cores along a series of four transects in the shelf and slope regions of the Chukchi and Beaufort Seas to measure sediment-water nutrient flows in different regions and at varying depths of the shelf basin. Because the continental shelf is generally more fertile and biologically diverse than the open ocean, measuring changes in how oxygen, carbon dioxide, nitrogen, and other nutrients cycle between the water and sediments of these areas is important in understanding patterns of global ocean productivity.

Christensen’s analysis shows that, for each transect, the highest levels of gas and nutrient flow occur in an eleven-mile wide band seaward of the continental **shelf break**, the area where the sea floor slopes abruptly down from the

shelf. When compared to flows in shallower areas closer to land, these results indicate that cold **upwelling** currents at the upper edges of the deep ocean play an essential role in supplying nutrients needed to nourish the highly productive ecosystems that exist on the border between these two underwater habitats.

Changes in global climate are likely to affect established patterns of nutrient flow in this region, either by altering upwelling and circulation patterns in nutrient rich water flowing in through the Bering Strait, or through ecosystem shifts resulting from changes in sea ice distribution. Christensen’s findings suggest a vital link between the biological abundance of this region and the currents that flow upward from the deep Pacific.



Dr. Ben Twining aboard the *R/V Nathaniel B. Palmer*, approaching one of the huge tabular icebergs, calved from the ice shelf in the Southern Ocean's Weddell Sea. Researchers estimate that large icebergs have a biochemical "zone of influence" around them approximately 20 miles in diameter. Tabular icebergs can stretch over 180 miles (300 km) in length.

Icebergs in Motion

Among the most dramatic effects of the planet's warming atmosphere are the disintegrating ice shelves of the western Antarctic Peninsula and the resulting increase in the number of free-drifting icebergs in the Antarctic Ocean, particularly in the Weddell Sea.

The icebergs continue to melt as they drift northward, adding freshwater and nutrients to the seawater around them, and creating hotspots of biological and chemical enrichment that vary substantially from the surrounding open ocean ecosystem. As they move, the icebergs become a focal point for the biological communities in the vicinity, and affect biogeochemical cycling within the ocean as a whole. As more icebergs are formed and join the "iceberg population," scientists estimate that these mobile **estuaries** will affect almost 40% of the surface ocean of the Antarctic region.

Dr. Benjamin Twining is part of a multi-year, collaborative field study of iceberg biogeochemistry that includes researchers from the Scripps Institution of Oceanography and the Monterey Bay Aquarium Research Institute (MBARI). In June 2008, Twining joined a 29-member NSF-funded expedition aboard the research ship and icebreaker *R/V Nathaniel B. Palmer*. The expedition, led by Dr. Ken Smith from MBARI, was organized to test the technology needed to track free-drifting icebergs in the northwest Weddell Sea and establish methods for analyzing their role in nutrient cycling—particularly iron enrichment, biological productivity, and **carbon export** in the Southern Ocean.

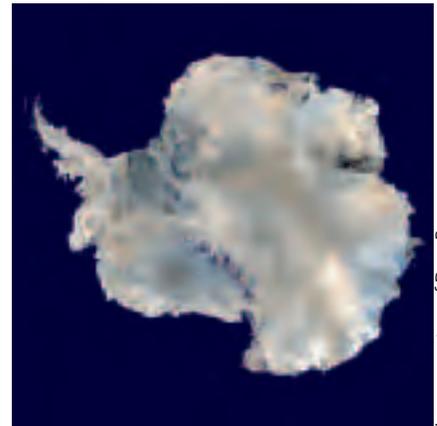
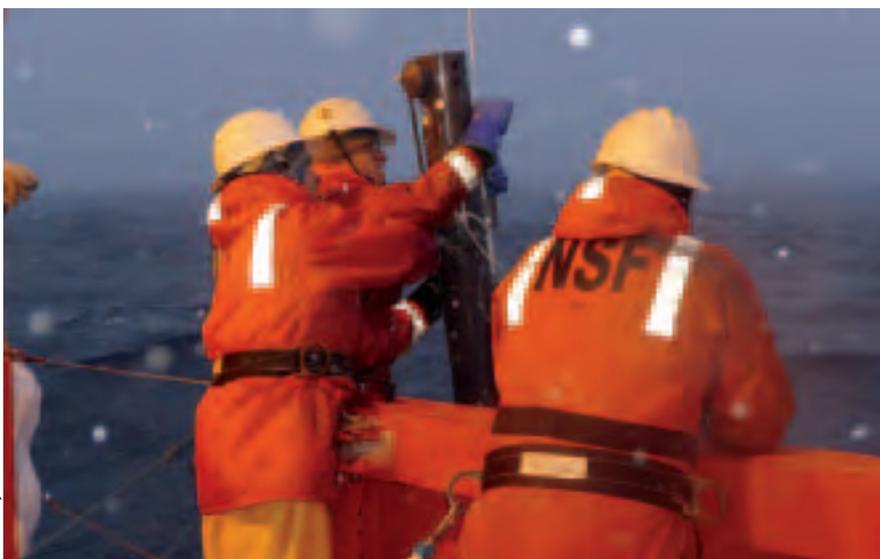


Image courtesy of Dave Pape.

An **orthographic projection** from NASA's Blue Marble data set of the continent of Antarctica. The Weddell Sea is the bay at the upper left.



Recovering seawater sampling instruments.

The 2008 cruise began a broad interdisciplinary research initiative involving everything from the engineering challenges of iceberg rotation and meltwater mechanics, to phytoplankton and zooplankton biology, to microbial oceanography and molecular study of bacterial processes. A primary goal of this first cruise was to devise methods of finding, tracking, and monitoring individual icebergs. Researchers chose likely candidates from satellite imagery, located them at sea, and used small remote-controlled planes to drop GPS units on them

for tracking. The team also deployed sediment traps designed to sink underneath icebergs and return with samples for analysis of carbon export and trace metals.

Research is focusing on the relationship between the physical structure and dynamics of free-drifting icebergs and the iron and nutrient distributions of the surrounding water column. The effects of iceberg processes on the surrounding *pelagic* communities, including microbes and zooplankton, and their impact on organic carbon transport to the deep ocean

are providing new evidence about the connection between climate change and carbon sequestration in the Southern Ocean.

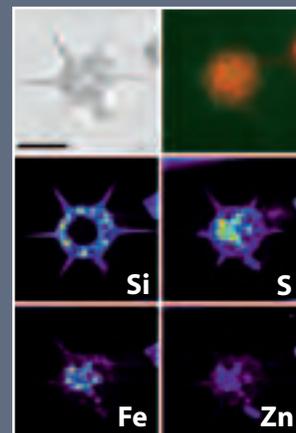
Iron is an essential, and often limiting, nutrient in ocean ecosystems. Twining is investigating total dissolved iron concentrations at various distances from the icebergs and examining changes in *iron oxidation* states and *chemical speciation* at different distances from the iceberg. He is looking for evidence that the iron entering the system from iceberg meltwater and particulate matter is providing a significant source of *bioavailable* iron as a nutrient in the surrounding biological community.

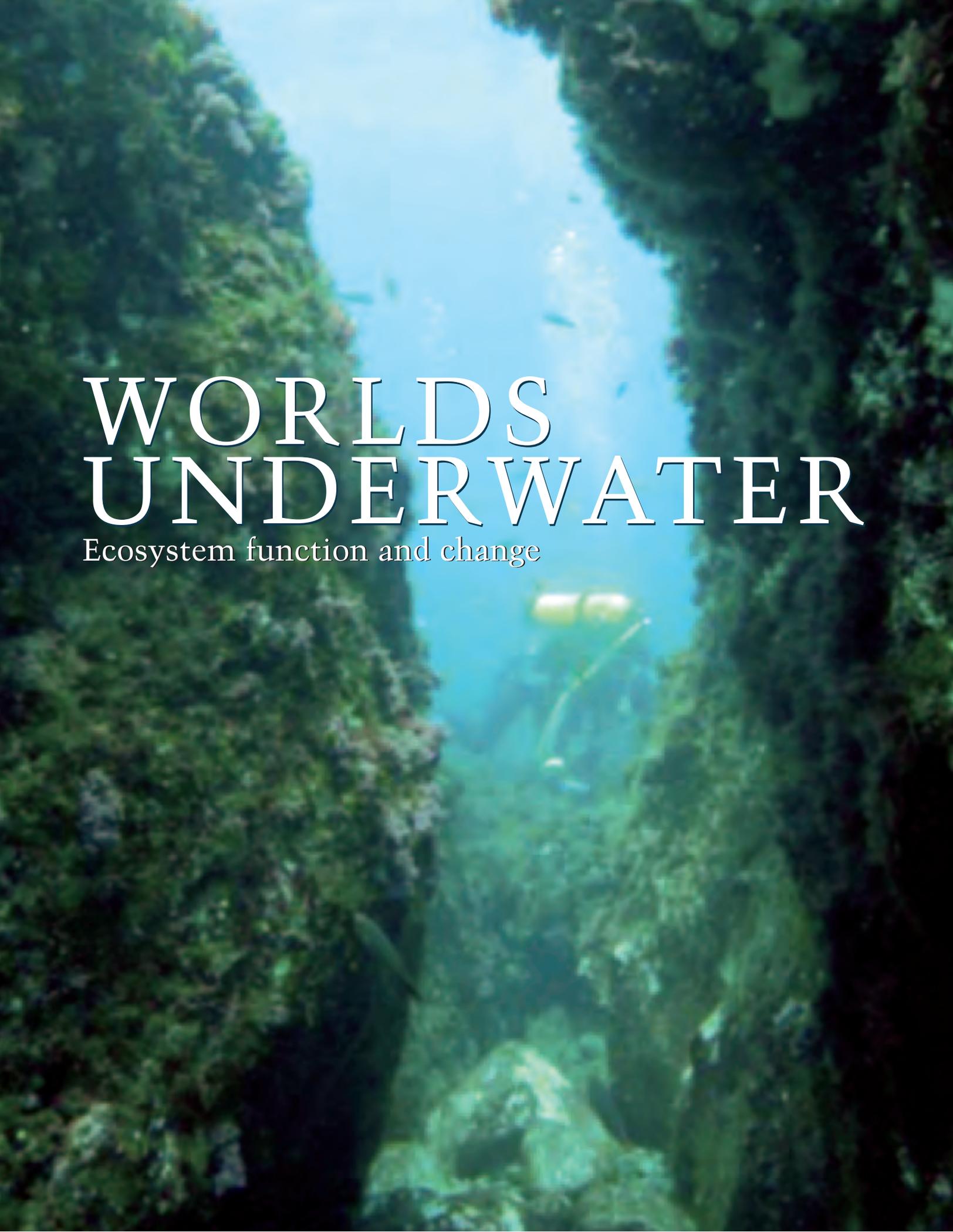
If this is the case, then free-drifting icebergs may be fertilizing an otherwise iron-limited biological community, spurring greater productivity and changing the way organic matter is cycled or sequestered. The more the icebergs melt, the more bioavailable iron enters the picture. Over the long term, as the climate warms and icebergs become more abundant, the effect of adding bioavailable iron to large areas of the ocean may trigger further changes in the biogeochemical process that regulate the global carbon cycle.

Synchrotron Time

Twining studies the distribution of iron molecules within a cell using a technology called synchrotron X-ray *fluorescence*, which uses a brilliant X-ray beam to view a single, intact cell (such as the silicoflagellate on the right). The beam causes electrons to eject, resulting in characteristic patterns of fluorescence for different elements (Si, S, Fe, Zn in this example). Since different elements fluoresce at different wavelengths, researchers are able to pinpoint specific elements present in a cell by “interrogating” it with the X-ray beam.

There are four Synchrotron X-ray fluorescence facilities in the United States operated by the U.S. Department of Energy. At any given time, there is room for 45 microscopes around the 1 km-wide ring of the machine, and, much like ship time, researchers apply for time and a seat around the ring.



An underwater photograph showing a diver in the distance, swimming towards a yellow buoy. The scene is framed by dark, rocky underwater structures on either side, creating a narrow passage. The water is clear and blue, with sunlight filtering through from above.

WORLDS UNDERWATER

Ecosystem function and change

Where Evolution Begins

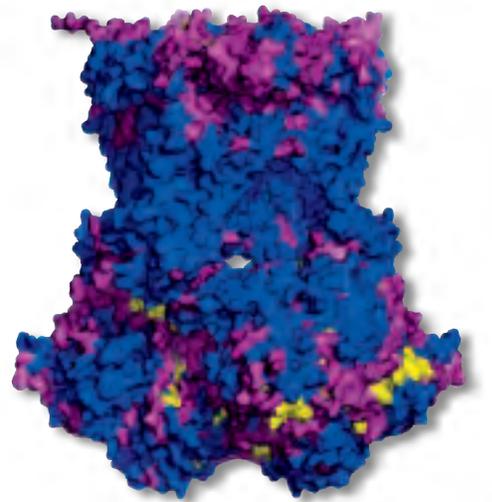
The physical processes that drive evolution begin at the molecular level, within the nuclei of billions of cells, where an organism's genetic instructions are encoded in DNA sequences for enzymes, proteins, growth, and reproduction.

DNA molecules and protein sequences in cells regulate the characteristics that determine how an individual will fare in the crucible of natural selection, the way it will adapt to its environment, and whether it will survive to pass its genetic codes on to future generations.

A host of factors determines how individual genes—and consequently the genome of a species as a whole—respond to shifting circumstances in the environment. Abrupt environmental changes can destroy or isolate large numbers of individuals in a population, causing a population bottleneck that results in less genetic variation in the remaining population.

With fewer genetic options, a population may not be able to adapt to new changes in climate conditions or resource availability. The smaller the population, the more vulnerable it becomes to extinction.

Phylogeneticists study evolution at the molecular level, uncovering the genetic connections and relationships among organisms, populations, and species. **Phylogenetics** is integral to our knowledge about adaptation at the molecular level and to our ability to predict the effects of environmental pressures on the network of biodiversity that sustains major ecosystem processes on the planet.



Evolution at the Biomolecular Scale The Cytochrome bc1 Protein Complex

This complex of proteins is part of the inner membrane of a cell's *mitochondria* and is responsible for an essential step in cellular metabolism. An organic compound called ubiquinone (Coenzyme Q₁₀) ushers electrons into the complex near the center, facilitating reactions that produce energy for the cell to live. Illustration by D. McClellan.

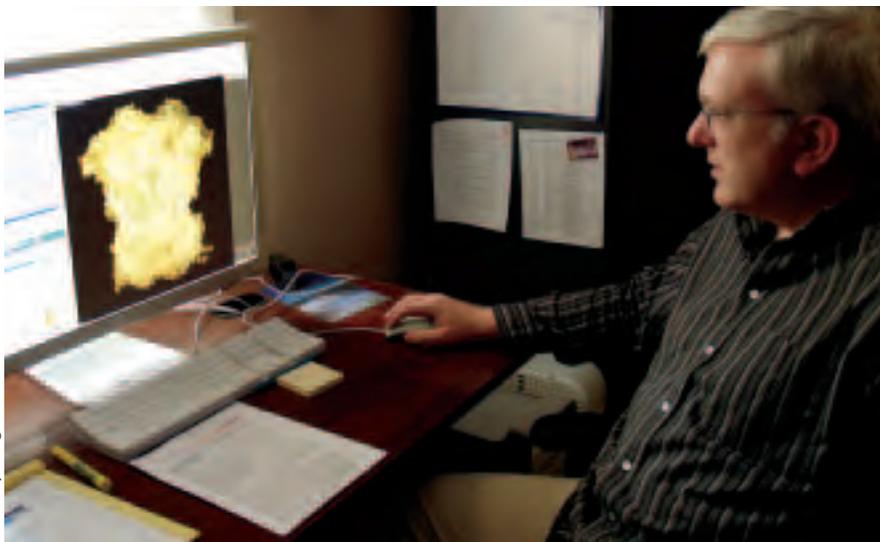


Photo by Greg Bernard.

Dr. David McClellan.

NATIVE HABITAT Evolutionary Transformations

Bigelow scientists are using phylogenetic analysis to study evolution at opposite ends of the world's ocean. Research on populations of native oysters in Maine and endemic lobsters in the South Pacific is opening new windows in our scientific understanding of the biochemical mechanism by which life adapts and survives, advancing our ability to identify and track the ongoing story of evolutionary change.

Phylogenetics is a key component of a collaborative project at the Laboratory to assess the feasibility of strengthening a **relict**

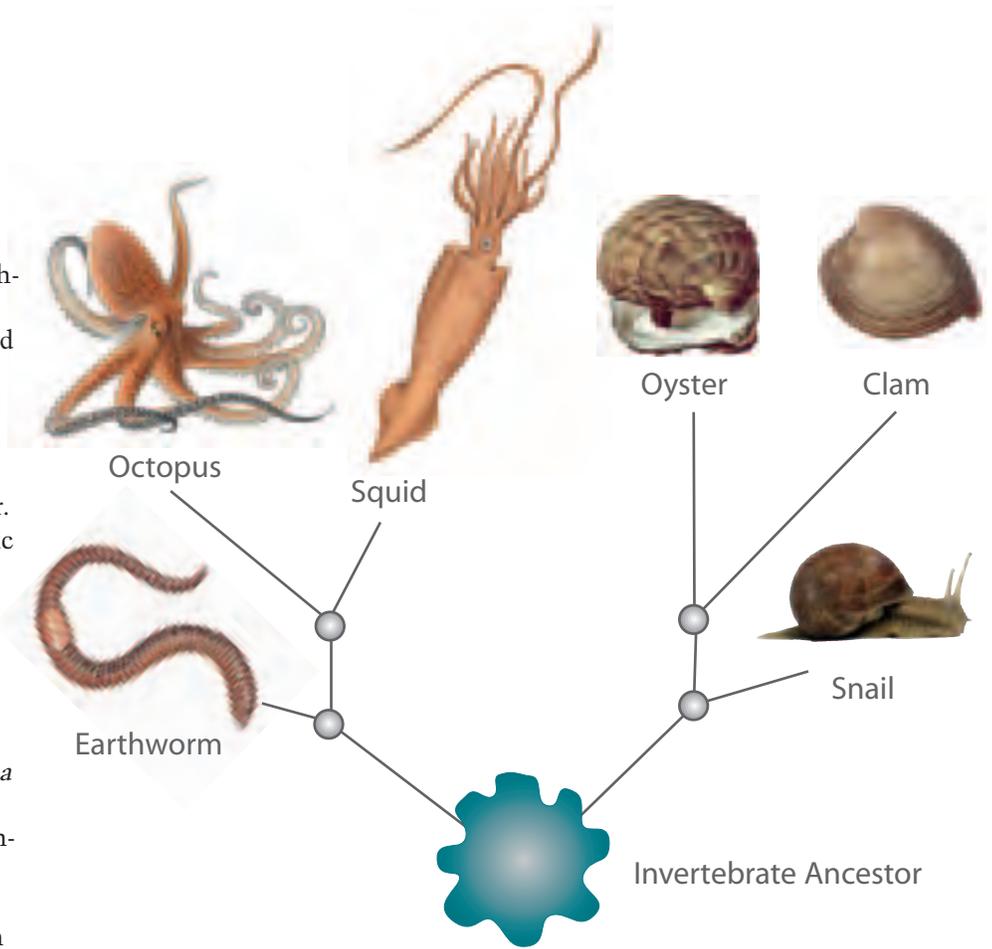
population of Eastern oysters (*Crassostrea virginica*) found in Maine. The population lives in a saltwater marsh creek at the northernmost limit of self-sustaining Eastern oysters in the country, and is one of only two known wild populations in the state.

Phylogeneticist and bioinformatician Dr. David McClellan is working with marine ecologist Dr. Peter Larsen to analyze the genetic structure of this isolated oyster population to determine how individual genes have adapted to changes in the local environment. They are studying how the population's genome compares to that of larger *Crassostrea virginica* populations to the south.

Maine's native wild oysters constitute a **population bottleneck**—their isolation and the limited extent of their habitat make them vulnerable to small-scale disturbances, disease, and pollution. Phylogenetic analysis of gene flow, or exchangeability, between different habitats and different oyster populations will allow McClellan and Larsen to gauge the effect that migrations between populations may have had on the relict gene pool—the less gene flow, the more profound the effects of the population bottleneck.

On the other hand, this isolated population of oysters may also have evolved genetic variation that could be vital to the species as a whole. Increasing the size of the relict population could strengthen the genetic reserve of resilience with which the species can confront environmental challenges such as changing climate conditions.

Previous attempts to enlarge the population by introducing oysters from southern waters have failed,



The Oyster Branch on the Tree of Life

Genetic analysis shows that oysters (Ostreidae), along with other **bivalve** mollusks such as clams (Veneridae), evolved from a common invertebrate ancestor, but separately from snails and other Gastropods. Different branches from the same ancestor eventually led to **invertebrates** such as Cephalopods (octopus and squid) and Annelids (worms). Snail photograph courtesy of Jürgen Schoner, Wikimedia Commons.

suggesting either that the **estuarine** habitat may have become unsuitable for new oysters to take hold, or that the genome of the relict population may have diverged too far to interbreed with its relatives.

Genetic analysis will test these two alternative hypotheses and help determine ways to restore the population. Deciphering the genome structure of the native oysters will allow researchers to see whether a prolonged bottleneck has caused sufficiently radical changes in key genes to prevent successful introduction of new individuals.



Dr. Peter Larsen.

Photo by Buddy Doyle.



Photo by R. Wahle.

THE RIDDLE OF ROBINSON CRUSOE ISLAND

At 33° South, Robinson Crusoe Island is almost literally at the other end of the world from the salt marshes of Maine. More than 250 miles off the coast of Chile, the island is the place where Scottish sailor Alexander Selkirk was marooned for four years. Robinson Crusoe remains a remote place, now inhabited by 500 people who live in the town of San Juan Batista, with one airstrip and one small fishing pier. At the end of 2008, benthic invertebrate ecologist Dr. Rick Wahle was invited to join a team of Chilean scientists in the first year of a multi-year project investigating the ecology and recent



Courtesy of Google Earth.

Robinson Crusoe Island.

*J. frontalis*, at home.

evolution of a virtually unstudied species of cool water spiny lobster. Called *Jasus frontalis*, the species is found nowhere else on the planet except in the waters around Robinson Crusoe and two other, smaller islands nearby that make up the tiny Juan Fernández archipelago.

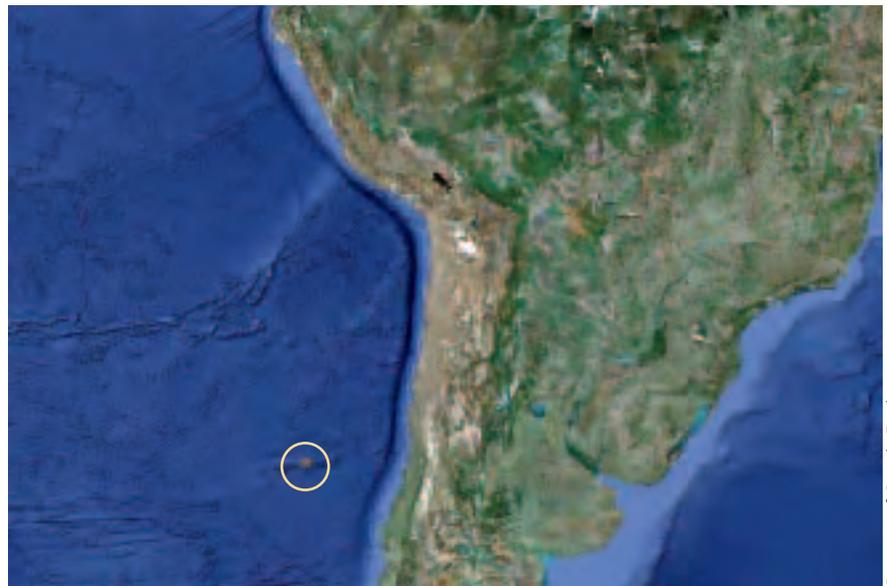
In addition to *J. frontalis*, several other marine species are **endemic** to the waters of this isolated archipelago, as are nearly twenty percent of the terrestrial plant species on the islands themselves. Although

J. frontalis is an economic mainstay of Robinson Crusoe's human population, virtually nothing is known about basic aspects of the lobster's ecology, biology, and evolutionary history. The nearest members of its same genus are found in New Zealand, Tasmania, Southern Australia, and South Africa, as well as in a few far-flung South Pacific Islands, but there are no close relatives on the South American coast. Why the species did not migrate any further to the coast of Chile is a mystery that makes *J. frontalis* an

ideal subject for evolutionary study.

At the beginning of the research project, Wahle's Chilean colleagues Drs. Alvaro T. Palma (Universidad Católica, Santiago) and Carlos Gaymer (Universidad Católica del Norte, Coquimbo) transported a complete field laboratory to Robinson Crusoe Island piece by piece. Wahle adds expertise to the project in methodology and instrumentation for sampling waterborne larvae, newly-settled juvenile lobsters, and other crustaceans.

Robinson Crusoe remains a remote place, now inhabited by 500 people who live in the town of San Juan Batista, with one airstrip and one small fishing pier. Over three million years old, the island is considered a geological youngster.



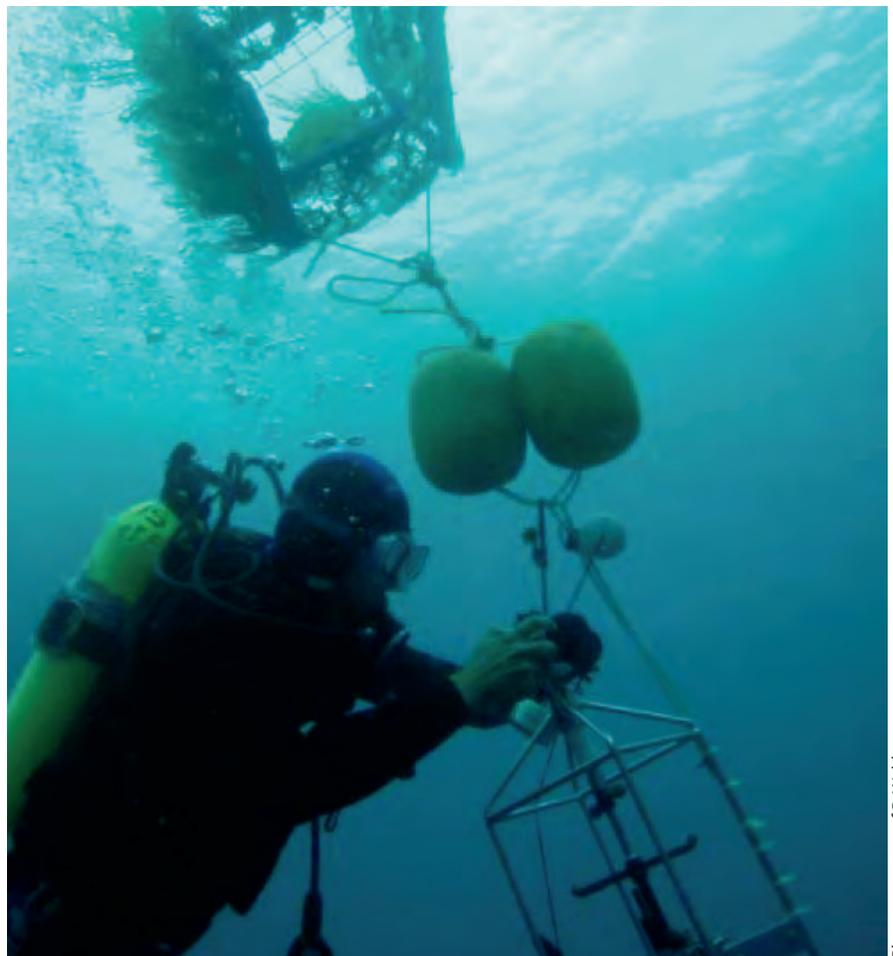
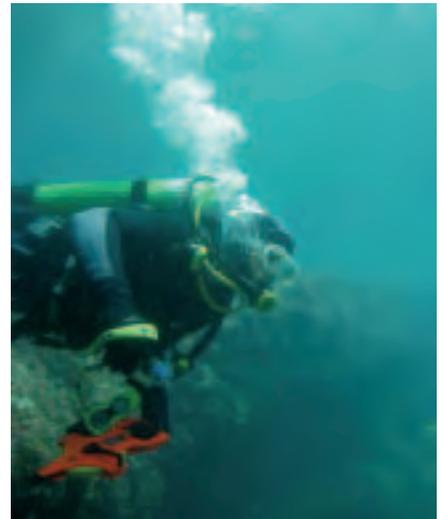
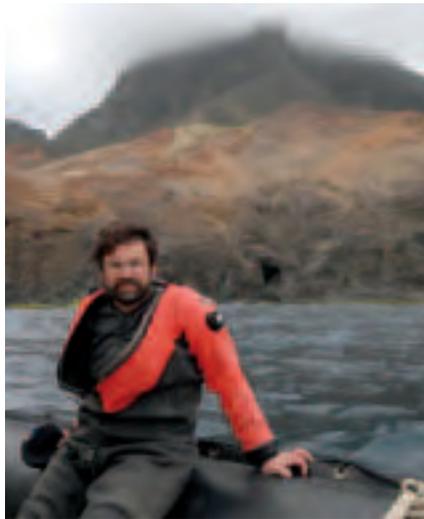
Robinson Crusoe Island, relative to the west coast of the South American continent.

Dr. Rick Wahle (top left) and divers on the *J. frontalis* research team.

Like most spiny lobsters, *J. frontalis* larvae spend close to a year in the water column—at the mercy of the currents and with a high risk of being cast away from their natal grounds. A major enigma surrounding *J. frontalis* is how enough larvae stay around Robinson Crusoe Island to repopulate the area. To begin answering this question, the research team has set up a battery of instruments to monitor atmospheric and oceanic conditions and larval distribution patterns.

Robinson Crusoe Island is three million years old, and is considered a geological youngster. Studying the genetic structure of *J. frontalis* and other benthic species—those shared between the island and the South American continent as well as those that are not—will allow scientists to reconstruct biogeographic histories and trace the emergence of new species around the archipelago.

Back in North America, Wahle and Dr. David McClellan are in the first stages of designing a method for the detailed phylogenetic analysis of *J. frontalis* that will examine whether cold **upwelling** currents off the South American coast form a barrier between the island and the continent and may be a reason why the species has evolved by itself, marooned for generations around Robinson Crusoe Island.



Photos courtesy of R. Wahle.

Why the species did not migrate any further to the coast of Chile is a mystery that makes *J. frontalis* an ideal subject for evolutionary study.

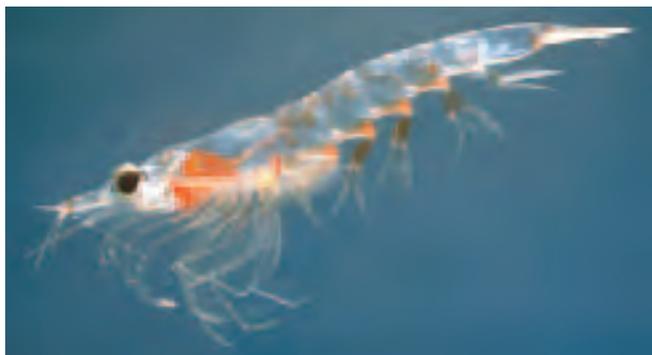
Underwater Pastures and Experimental Waves

Photo by Peter Stevick, University of Southern Maine.



Krill schooling in the Gulf of Maine. This image was part of a Census of Marine Life study of the biophysical mechanism underlying krill patch formation and upper trophic level feeding at offshore banks in the Gulf of Maine.

As ocean animals ingest smaller life forms, the food energy generated by phytoplankton photosynthesis moves higher and higher through the marine food chain. Areas where ocean life aggregates and thrives are determined by patterns of food distribution and abundance.



North Atlantic krill (*Meganyctiphanes norvegica*). Courtesy of MAR-ECO, Census of Marine Life.

Photo by Øystein Paulsen.

A multitude of physical factors affects these patterns and influences the feeding behavior and migration routes of a diversity of species.

Dr. David Fields and researchers from the University of Southern Maine and the New England Aquarium have received funding from the Office of Naval Research (ONR) for a collaborative interdisciplinary study of the relationship between the physical and biological processes in a particularly fertile region in the western Gulf of Maine. The ONR project uses field observations and laboratory experiments to examine the interaction between internal ocean waves and sea floor topography, and how these physical features affect the distribution of North Atlantic krill



Photo by Dennis Griggs.

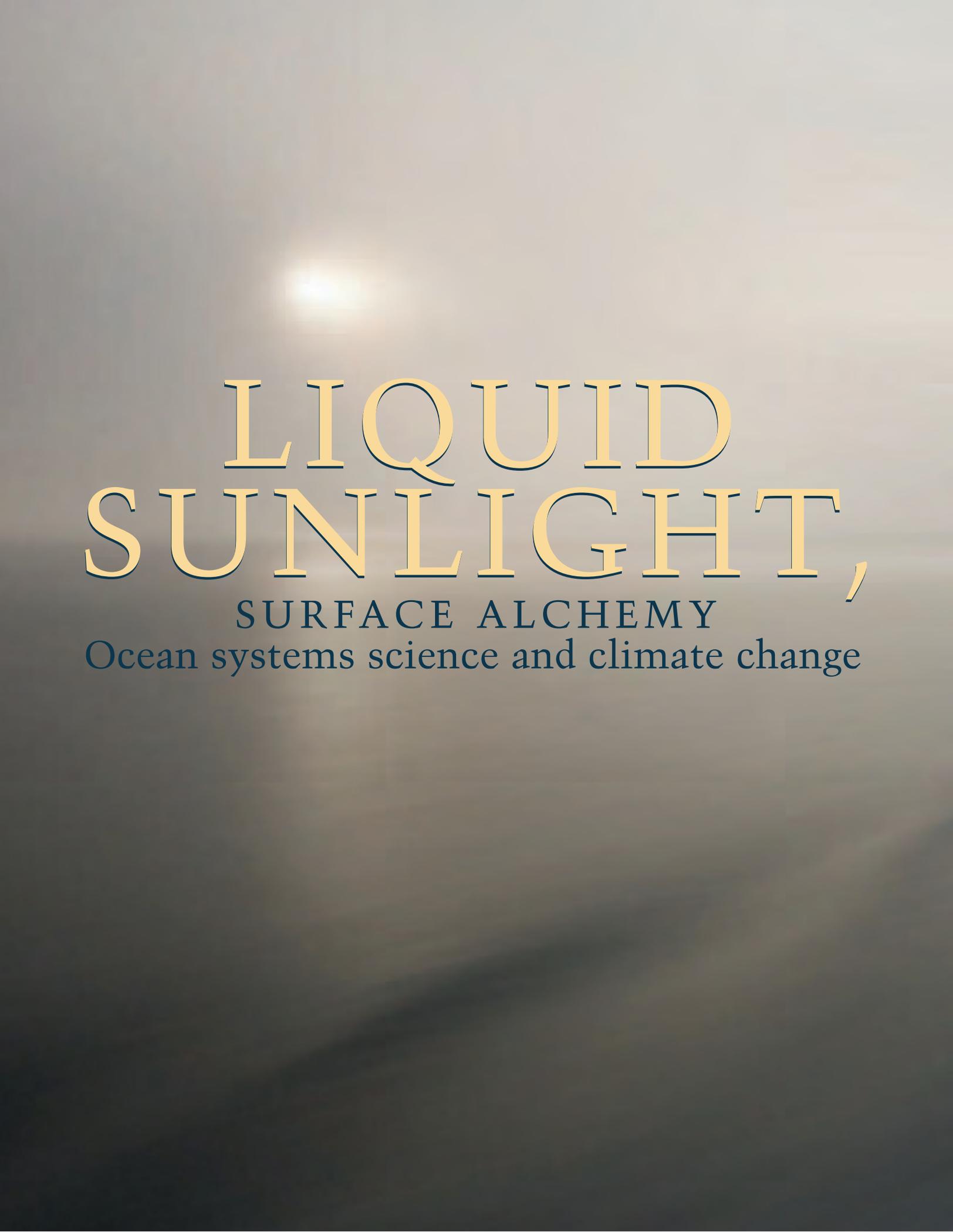
(*Meganyctiphanes norvegica*), a critical food source for baleen whales (including the endangered Northern Right Whale).

The research team is using acoustic and temperature profiles to investigate the possible role that local topography plays in creating both large- and centimeter-scale waves that affect krill behavior. Data collected in the field are used to calibrate small, propeller-driven **plumes** in a laboratory tank. This allows the scientists to measure the behavioral and neurophysiological responses of individual krill to changes in wave flows and internal wave structure. The team uses microscopic probes to tap into the krill's sensors and observe how the animal detects organisms and

responds to changing flows, varying light intensities, and other environmental perturbations. The data are providing information about how and where krill are likely to aggregate in the wild, and consequently about where species that feed on krill will go to look for them.

Understanding the relationship between offshore topographic features and ocean life is an important key to predicting feeding patterns of migratory ocean species. Results from this study can be used to help prevent negative impacts from non-combat naval activities, shipping, and fishing, as well as to provide information needed to sustain the diversity and function of large ocean ecosystems.

Dr. David Fields and Research Technician Steven Shema calibrating a small plume in the Fields laboratory.



LIQUID
SUNLIGHT,

SURFACE ALCHEMY

Ocean systems science and climate change

Summer Clouds over the High Arctic



Photo by Ake Wallin.

The icebreaker *Oden* with the science team's research helicopter.

The climate in the Arctic is changing more abruptly than anywhere else on the planet, a reality that is seen most visibly in the dramatic reduction of the extent of summer *sea ice* in the region.

Melting ice masses in the Arctic are considered a significant factor in global sea-level rise, and the influx of fresh water from melting ice may alter ocean circulation patterns the world over.

The physical processes of cloud formation over the Arctic Ocean are an important element of the region's overall influence on the global environment. As sea-ice cover on the Arctic Ocean diminishes, the solar radiation that would otherwise be reflected back into space by the ice is absorbed by the open water at the surface instead, further warming the water and causing still more ice to



Photo by Michael Tjernstrom.

Dr. Paty Matrai.



International collaboration at the “Bear Bay” research station. Photo by Michael Tjernstrom.

melt. Low-level cloud cover over the Arctic helps control the heat balance at the ocean’s surface. How this cloud shield forms, its characteristics, and the circumstances regulating its “life cycle” are directly relevant to the world’s climate future.

In August 2008, Dr. Paty Matrai was a team leader on a six-week scientific expedition on board the Swedish icebreaker *Oden* in the central Arctic Ocean. Called the Arctic Summer Cloud Ocean Study (ASCOS), the expedition was a multi-disciplinary collaboration

between biological and physical oceanographers, atmospheric chemists and physicists, and meteorologists. Matrai’s team investigated the effect that the biology of the ocean’s surface—the “microlayer” ecosystem of phytoplankton and microbes in open water leads between ice floes—has on the way summer clouds form in the atmosphere in the high Arctic.

ASCOS is part of a series of international research initiatives organized for the fourth International Polar Year, a far-ranging, interdisciplinary, multi-national mission to increase knowledge about polar regions and their role in the planet’s climate system. The ASCOS expedition was funded through the Swedish Research Council, the European Union, and the National Science Foundation and National Aeronautics and Space Administration in the United States, with additional support from private foundations.



Photo by Johan Knulst.

Research Associate Carlton Rauschenberg driving a remotely-operated surface microlayer sampler. Postdoctoral Researcher Andy Hind (in red) and University of Toronto doctoral student Rachel Chang preparing to deploy the team’s “bubble cat,” a small catamaran used to simulate and measure the effect of natural bubbles on the biochemistry of the water. A polar bear guard is standing watch in the background.

Using *Oden* as a base of operations, the research team established an atmospheric field camp directly on the surface of the ice near the North Pole to sample gases and aerosol particles in the atmosphere, measure biochemical and physical exchanges at the ocean-air interface, and track meteorological processes in the lower atmosphere. The ship was anchored to drifting sea ice at 87°N. Research was conducted on board and on the ice, augmented by a helicopter, a land-based research plane, and flights of a tethered weather balloon.

The biological activity of phytoplankton and ice algae creates microgels on the sea surface, consisting of organic matter, microbes, and insoluble particles. The researchers were investigating how these microaggregates, which form tiny particles in the air called aerosols, react with gases to catalyze cloud formation. The aerosol particles produced by surface microlayer biochemistry, along with subsurface mixing and winds, are playing a key role in global climate by “seeding” the atmosphere over the ocean, providing the building blocks of nuclei around which water vapor condenses to form fog



Photo by Thorsten Mauritsen.

Matrai's team used the ASCOS weather balloon to collect cloud water samples for analysis.



Photo by Johan Knulst.

Matrai, wearing a harness, prepares hanging bottles for an incubation experiment testing the effect of ultraviolet radiation on sea water conditions.

and cloud droplets. As the climate warms, the ice melts, creating more areas of open water, which affects the biological productivity and dynamics of the ocean's surface, and thus the size and number of aerosols that are released. This in turn, determines the nature and longevity of the clouds that influence the formation and melting of sea ice and the amount of incoming solar radiation that ultimately reaches phytoplankton, controlling their growth in surface waters.

Melting Ice

Climate Change in the Bering Sea

Photo courtesy of J. Goés.



Ice in the Bering Sea, July 2008.

Located in the northernmost part of the Pacific Ocean between Eurasia and North America, the Bering Sea is a critical link between the ecosystems of the North Pacific and Arctic Oceans. The region supports many of the world's major fisheries, and produces more than half of the fish and shellfish that are caught in the United States.

Relative to the rest of the world's oceans, the Bering Sea is experiencing one of the most rapid periods of climate change in recent history. Each year for the past decade, the region has witnessed a steady rise in temperature and a loss of *sea ice* over large areas. Since water from the North Pacific must pass through the Bering Sea before entering the Arctic Ocean, the extent and duration of the sea-ice sheet that forms in winter and retreats in summer has an enormous influence on the region.

Sea ice directly affects the flow of heat and dissolved nutrients in the Bering Sea, influencing the timing, intensity, and species composition of the spring phytoplankton bloom there. Recent changes in the Bering Sea's phytoplankton populations have had profound effects on the rest of the food chain—shifting periods of peak biological productivity, causing extensive die-offs of sea birds, reducing survival of commercially important larval fish populations, and altering migration patterns for several species of whales. Further



Photo by H. Gomes.

Dr. Joaquim Goés aboard the *USCG Healy*.



Research team deploying from the *USCG Healy*.

warming anticipated over the next several years is likely to become a major issue for the health of this vital ecosystem.

Ocean biogeochemists Drs. Joaquim Goés and Helga Gomes joined colleagues from Louisiana State University and Lamont Doherty Earth Observatory in July 2008 for a month-long research cruise to the Bering Sea on board the United States Coast Guard Icebreaker *Healy*. Their mission was to investigate a series of biological and ecological variables associated with sea ice, including its relationship to phytoplankton biodiversity and distribution, the carbon cycle, and other ecosystem processes in the region. This research is part of the National Aeronautics and Space Administration (NASA) contribution to the International Polar Year.

The NASA-funded expedition team examined the productivity and physiological status of phytoplankton populations over the Eastern Bering Sea shelf, together

with environmental conditions, in order to understand the likely response of the ecosystem to diminishing sea ice. In the course of the mission, the researchers also collected bio-optical data in that could be utilized for improving satellite observations of the oceans.

Satellite remote sensing technology has given scientists the opportunity to obtain environmental information over unprecedented time and space scales necessary for climate research.

Because of difficult working conditions, shipboard data collection in the Bering Sea is extremely challenging, so predicting long-term consequences of climate change must largely depend on satellite data. Through its observations at sea, the expedition team is ensuring that information from satellites is accurate. Combined with data about sea-ice cover, heat exchange, surface winds, and temperature, the Bering Sea project is contributing to increased knowledge about trends in physical, chemical, and biological processes of polar regions and allowing scientists to understand the connections between polar ecosystem processes and climate change occurring on the rest of our planet.



Dr. Helga do Rosario Gomes.

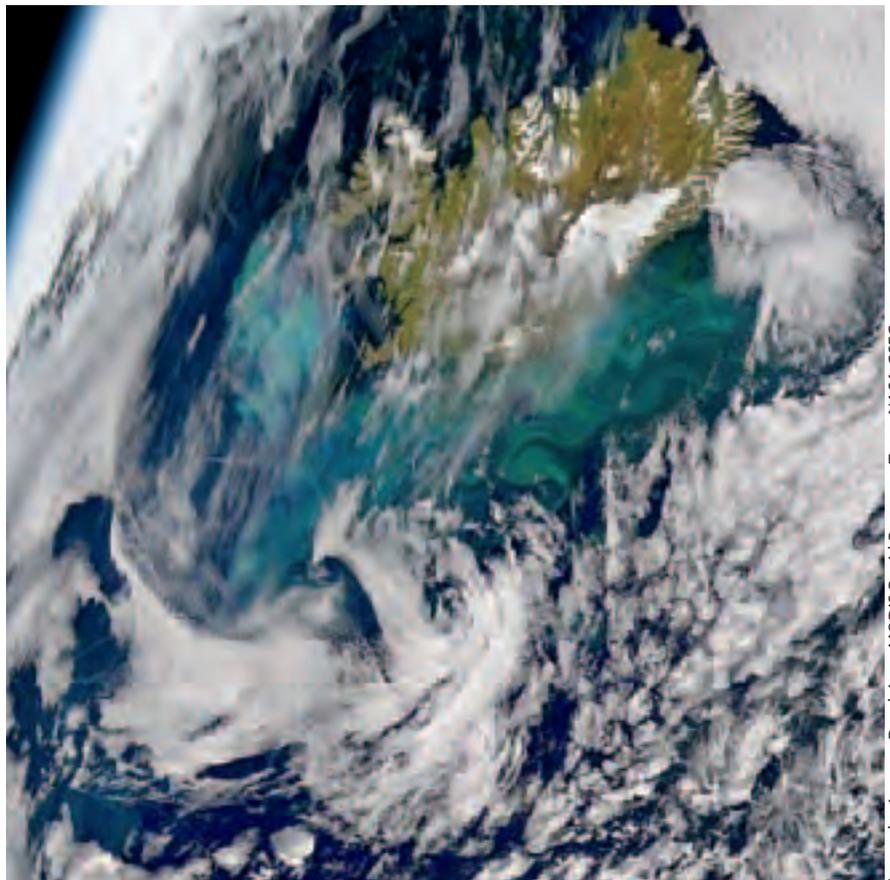
Sea Truth: The North Atlantic Bloom

More so than any other element, carbon forms the chemical basis of all known life on the planet. Carbon is essential to every plant and animal; it is a key component of the atmosphere and has supplied most of the power that fueled human industrial technology for the past three centuries.

There is a continuous exchange between carbon dioxide (CO₂) in the atmosphere and the reservoirs of carbon on land and in the oceans. The rate at which carbon is cycled through the Earth's biogeochemical system affects the biological productivity of the world's ecosystems, the amount of atmospheric CO₂ taken up by photosynthesis, and the pathways by which carbon is sequestered, on land and in the ocean. It is in the ocean, however, that biogeochemical processes generate an immense biological carbon transport pump, creating an oceanic carbon sink that holds ten times the amount of carbon found in terrestrial systems.

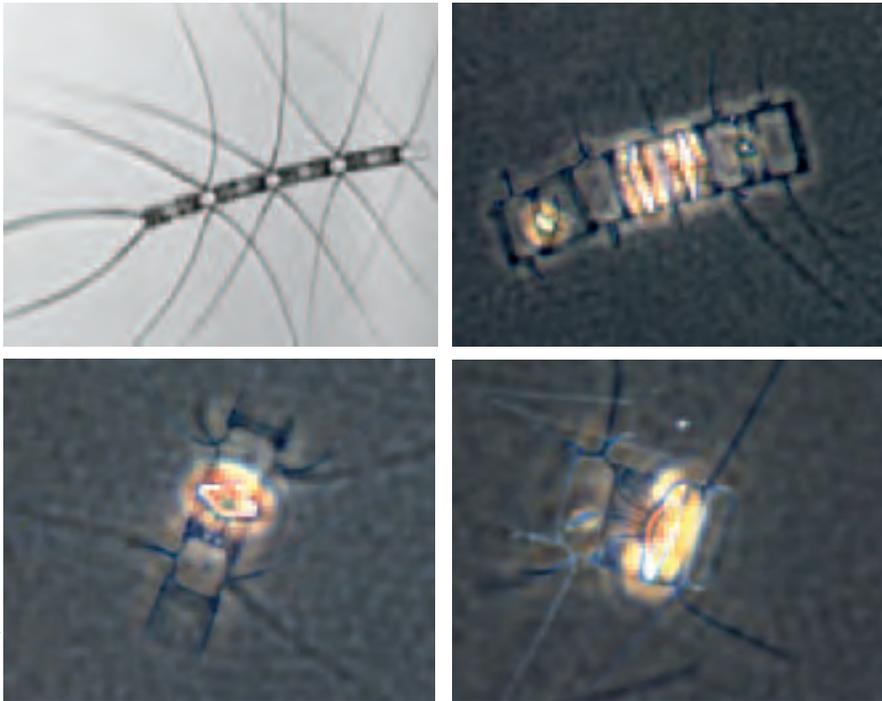
Over the past decade, researchers from Bigelow Laboratory have worked with a number of institutions and agencies to develop and test technologies for analyzing the ocean's carbon system and studying the dynamics of carbon flow during the North Atlantic Ocean's gigantic annual phytoplankton blooms. A primary goal of this research is to develop reliable methods to assess how changing environmental conditions—such as cloud cover, currents, winds, and waves—are affecting and altering these massive global events and their role in the global carbon cycle.

Nearly a quarter of global net CO₂ uptake by photosynthesis occurs in the North Atlantic Ocean, driven by the annual spring **phytoplankton bloom** north of 50°N.



Phytoplankton bloom (light blue colors) off Iceland.

Image by Jacques Descloitres, MODIS Rapid Response Team, NASA GSFC.



During the North Atlantic spring cruise, Drs. Sieracki and Poulton found that a species of the chain-forming *Chaetoceros* diatom (upper left) was predominant throughout the study area during the bloom. The single-cell alga went through a complete life cycle over three weeks, ending in a resting stage (bottom right) on the ocean floor, and possibly functioning as a “seed” for the next bloom.

Nearly a quarter of global net CO₂ uptake by photosynthesis occurs in the North Atlantic Ocean, driven by the annual spring phytoplankton bloom north of 50°N. Nourished by the winter accumulation of deep water nutrients, billions of phytoplankton cells respond to lengthening hours of daylight as the Northern Hemisphere moves into spring, triggering a dramatic global phenomenon. Many phytoplankton species flourish over thousands of square miles during the bloom, creating striking displays of swirling color, from the turquoise of chalk-covered coccolithophores to deep emerald greens from dense concentrations of chlorophyll pigments.

In May 2008, at the onset of the North Atlantic spring bloom, Drs.

Mike Sieracki and Nicole Poulton joined a collaborative, multi-disciplinary team of colleagues from the University of Washington, University of Maine, Dalhousie University, and University of California, San Diego Scripps Institution of Oceanography aboard the *R/V Knorr* for three weeks of shipboard research off the southern coast of Iceland. The *Knorr* was part of a research fleet for the project that also included vessels and scientists from Iceland and the United Kingdom.

As the bloom progressed, the researchers aboard the *Knorr* used Bigelow Laboratory’s **flow cytometry** technology to determine phytoplankton biomass and community structure from water samples. The team deployed programmed instru-

ment floats, autonomous underwater gliders, and sediment traps to document the growth, peak, and fallout of the bloom within specific water parcels and eddies—and to calculate the resulting flux of carbon to the deeper ocean. Sea-truth “inter-calibration” of data generated by this suite of robotic sensors—including optical measurements of vertical and horizontal mixing, patchiness and concentration of phytoplankton, organic carbon, nitrates, and oxygen—were used to model net carbon flow and predict changes in phytoplankton species composition through the fertile North Atlantic spring.

In the Long Run

Systematic, long-term monitoring of the ocean environment is essential to understand how global climate change is affecting ecosystem processes. The summer of 2008 marked the tenth consecutive year that Dr. William Balch and his research team at the Laboratory have been running the NASA-funded Gulf of Maine North Atlantic Time Series (GNATS) between Portland, Maine and Yarmouth, Nova Scotia, documenting changes in nutrient concentrations, phytoplankton biomass, and rates of **carbon fixation** by calcifying phytoplankton in the biologically productive ocean ecosystems of the Gulf of Maine. GNATS is the longest transect time series in the Gulf of Maine and reflects environmental changes in response to multiple years of extreme freshwater discharge from rivers in the Gulf of Maine watershed. These observations are making it possible to calibrate ocean color measurements from satellites and improve our large-scale interpretation of the biological oceanography of this large ocean ecosystem.

Balch and his team added an important new dimension to their GNATS program with the August 2008 launch of *Henry*, the Laboratory's first autonomous underwater Slocum glider, designed to collect data with a variety of customized sensors along the GNATS transect. The glider was funded by the State of Maine. This state-of-the-art, programmable, battery-powered instrument has significantly



Photo by Dennis Griggs.

augmented the team's research activities by allowing GNATS observations to proceed independently of traditional data collection from surface ships.

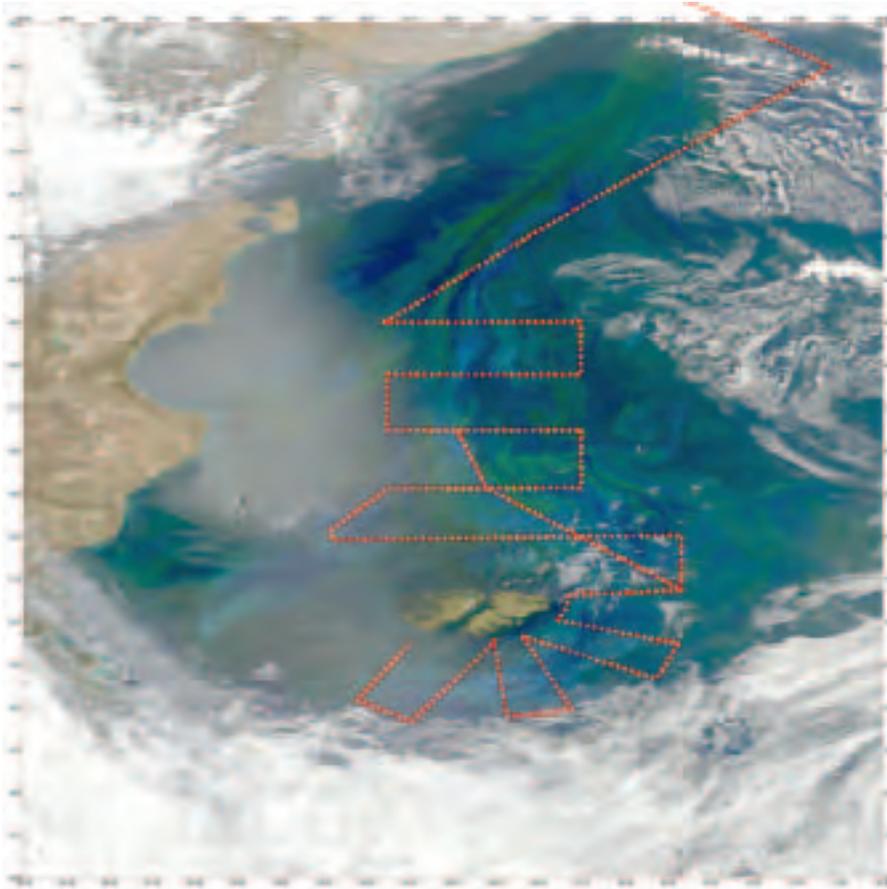
GNATS has provided one of the most recent comprehensive regional assessments of carbon fixation in the Gulf of Maine and Georges Bank. Together with only a few other long-term oceanic time series in the world—the Atlantic Meridional Transect (AMT), the Hawaii Ocean Time Series (HOTS), and the Bermuda Atlantic Time Series (BATS)—GNATS is providing a critical and ongoing perspective on changing conditions in coastal oceans not covered by the central ocean time series.

Balch research team member Bruce Bowler was aboard the British Antarctic research ship *RSS James Clark Ross* as part of the October 2008 Atlantic Meridional Transect time series, which measured changes in biodiversity and ecosystem processes over more than 7,200 nautical miles between the North and South Atlantic Oceans.

Left: *Henry* changes buoyancy to move up and down through the ocean at a horizontal speed of approximately half a knot. On board sensors can collect data on temperature, salinity, conductivity and a number of optical properties to a maximum depth of 200 meters for over three weeks at a time. Approximately four feet long, and weighing 114 pounds, the glider is programmed to surface at regular intervals to transmit data and receive further instructions.

Photo by Greg Bernard.

Bright Waters and Rough Seas



As of this writing, we are now in the “headwaters” of the coccolithophore bloom, south of the Falklands/Malvinas.

~ Chief Scientist William Balch, aboard the *R/V Roger Revelle*, December 10, 2008

True-color AQUA MODIS image of the Southwest Atlantic off of Argentina and the Falkland/ Malvinas Islands (10 December 2008; processed by Norman Kuring, NASA, Goddard Space Flight Center). The turquoise blooms consisted primarily of coccolithophores, which were so dense that objects could not be seen three feet (1m) below the surface. As the currents flowed northeast, the phytoplankton species composition in the bloom changed from coccolithophores to mixed dinoflagellates and flagellates (seen in the deeper green hues of the image). The cruise track of the *R/V Roger Revelle* through the bloom appears as a dotted red line.

Coccolithophores such as *Emiliana huxleyi* and its relatives are an extremely abundant, microscopic, calcifying phytoplankton species, that cover themselves with tiny limestone (calcium carbonate) scales during the course of their life cycle.

When coccolithophores shed their scales at the end of a seasonal bloom, these small particles act like billions of little mirrors, reflecting sunlight and turning the water a milky turquoise color, visible from space over thousands of square miles. The scales, or coccoliths, collectively contain vast amounts

of carbon, which is eventually buried in sediments on the ocean floor. Because calcium carbonate represents a vast storehouse of carbon on the planet, making up a quarter to a third of all marine sediments, the biogeochemistry of annual coccolithophore blooms has direct consequences for the global carbon cycle.



Photo by Jeff Lawrence.

Dr. William Balch (right) and Research Associate Bruce Bowler carry stand-alone pumps (SAPS) to filter cubic meters of water for molecular analysis.

Human use of fossil fuels and the resulting impact of carbon dioxide (CO₂) levels on global climate change have highlighted the importance of phytoplankton blooms in driving the carbon cycle. The ability of marine organisms to take up carbon in the form of CO₂ (or HCO₃ bicarbonate, in chemical equilibrium with CO₂) and convert it to organic matter or calcium carbonate for skeletons or coverings is a crucial step in this cycle, and any factors affecting this process have far-reaching implications for all global ecosystems.

Numerous models predict continued increases in atmospheric CO₂ as a result of burning fossil fuels. A large fraction of this anthropogenic CO₂ diffuses into seawater, combining with water to form carbonic acid, making large regions of the ocean more acidic. This ocean acidification is likely to have a significant negative impact on life in the sea, especially calcifying organisms' ability to function and survive (including a large range of organisms, not just coccolithophores).

Some of the most extensive coccolithophore phytoplankton blooms in the world occur every year on the Patagonian Shelf east of Argentina. Despite the importance of understanding the factors regulating these enormous natural blooms, the remoteness of this part of the Southern Ocean has been a major impediment for scientific research there.



Photo by Jeff Lawrence.

Research Technician Emily Lyczkowski in the Balch laboratory on board the *R/V Roger Revelle*.

In December 2008, Dr. William Balch was Chief Scientist aboard the *R/V Roger Revelle*, leading a 33-member research team on a five-week expedition to study the ecology, dynamics, and impacts of ocean acidification in the Southern Hemisphere's largest recurring coccolithophore bloom. In the expedition known as CoPaS'08 (Coccolithophores of the Patagonian Shelf), researchers aboard the *R/V Roger Revelle* examined the processes regulating the bloom and investigated the impact of increasing levels of ocean acidification on its dynamics.

A key goal for the ship's science team was to examine the effects of ocean acidification on changes in coccolithophore concentrations, growth and calcification rates, zooplankton grazing, and dissolution of calcium carbonate. This knowledge is critical to model complex biogeochemical processes that regulate phytoplankton production and the **biological pump** (the net process involved with biological fixation of CO₂ into organic matter) and the vertical sinking of this material to the sea floor. Prior to this expedi-

Despite weathering two intense ocean storms in the cold southwest Atlantic "summer," the researchers conducted underway sampling and deck experiments to allow real-time evaluation of phytoplankton species diversity and abundance in both bloom and surrounding non-bloom waters. Calibrating satellite observations is an essential tool in understanding the global carbon cycle, since satellite sensors provide a picture of bloom conditions in the world's oceans every two days.



Photo by Jeff Lawrence.



Photo by Jeff Lawrence.

Heavy weather during CoPas '08.

tion, which was one of the first multi-disciplinary, ship-based investigations of the Patagonian Shelf bloom, scientific knowledge about coccolithophore ecology was based almost exclusively on northern hemisphere bloom studies.

Combining satellite and underway observations with direct sampling, the expedition gathered basic information about the species composition and phytoplankton community structure of the bloom. Satellite measurements were used to estimate levels of particulate organic and inorganic carbon in the bloom.

Data analysis and shipboard experiments examined the relationship between coccolithophores and other species of phytoplankton, the impact of coccolithophores on the carbon cycle, and how changing environmental conditions might affect bloom dynamics.



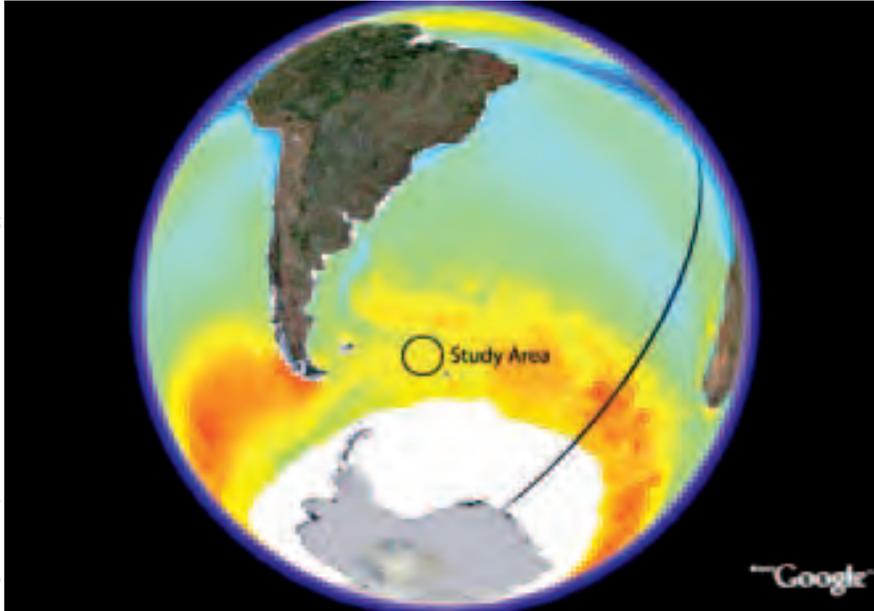
Photo by Jeff Lawrence.

The R/V Roger Revelle computer room.

A MOVING TARGET

Carbon Dioxide and the Southern Ocean

Image courtesy of NASA/Scatterometer Climatology of Ocean Winds.



The location of the expedition's study area in the Southern Ocean, showing mean wind speeds during March 2008. Hotter colors (brighter orange) denote higher winds.

Accurate assessment of the amount of CO₂ taken up by the world's oceans is essential to predicting future atmospheric levels of this potent greenhouse gas, and the amount of ocean acidification that it is likely to cause. Ability to measure the scale and rate of increase in CO₂ levels generated by fossil fuel emissions and the seasonal variations in the exchange of CO₂ between the ocean and the atmosphere requires coordination among a multitude of complex variables.

Between February and April 2008, Research Associate David Drapeau was part of a 30-person collaborative research expedition known as the Southern Ocean Gas Exchange (GasEx-III) experiment. Comprising 30 percent of

the total ocean surface area of world, the Southern Ocean has a profound influence on global CO₂ levels, but only limited research has been carried out there. This was the third large-scale ocean-CO₂ exchange study led by United States scientists in the past decade. GasEx-I took place in the North Atlantic in 1998; GasEx-II was in the Equatorial Pacific in 2001. The expeditions have been funded by the National Oceanic and Atmospheric Administration (NOAA), NASA, and the NSF.

The scientists spent 42 days aboard the NOAA ship, *R/V Ronald H. Brown*, amid the freezing winds and high waves 1,000 miles at sea in the western Atlantic sector of the Southern Ocean. They gathered data about the dynamics of CO₂ and other



ocean surface atmospheric gas exchange under varying physical conditions including wind velocity, fetch, and vertical and horizontal near-surface turbulence. The team also measured phytoplankton chlorophyll content at the surface and within the water column.

Differentiating among the optical properties responsible for light backscattering in the water, such as calcium carbonate concentrations and bubbles from turbulence, was a primary focus of Bigelow Laboratory's research during the cruise. In satellite studies of the Southern Ocean, Balch has observed what appear to be vast regions of elevated concentrations of calcium carbonate (limestone) stretching from the tip of South America over to the waters south of Tasmania.

Coccolithophores produce vast numbers of tiny coccoliths made of this highly reflective, light scattering mineral and may be responsible for increasing the ocean's reflectance. Alternatively, intense winds and associated bubble formation could explain this enormous region of high reflectance. Results of this work have clearly confirmed the presence of massive amounts of suspended calcium carbonate from coccolithophores. The expedition's findings will improve knowledge about the global distribution of coccolithophores and provide a much clearer understanding of CO₂ flux in large ocean ecosystems such as the Southern Ocean.

150 Scientists, 40 Institutions, 8 Nations

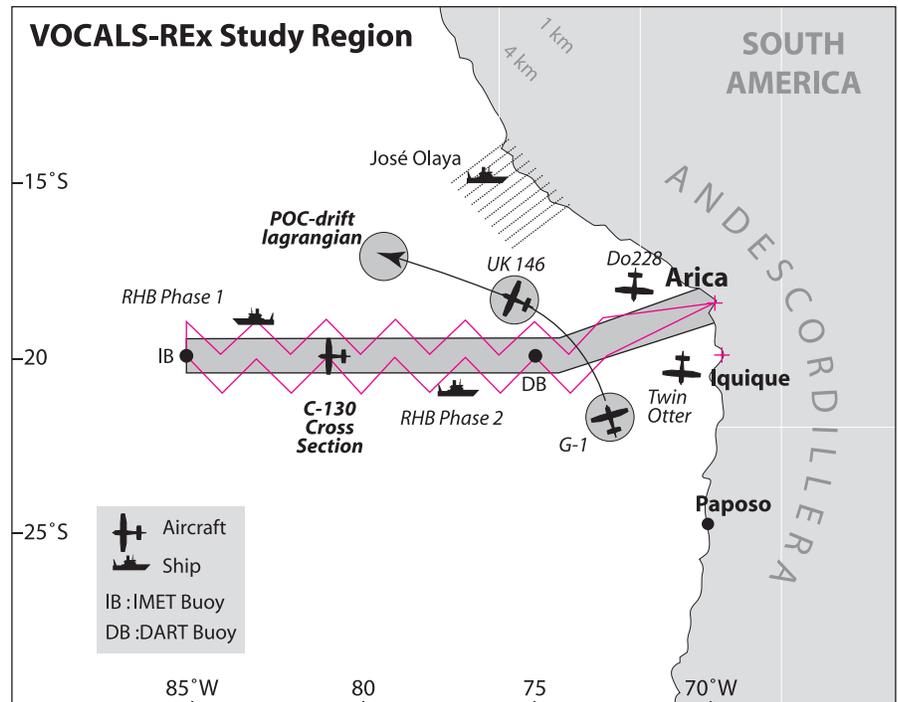
The Southeast Pacific Climate Field Experiment

On the other side of South America from Patagonia, the southeast Pacific Ocean is characterized by a strong coastal **upwelling** that carries cold water from the deep ocean toward the surface, creating cold surface temperatures over coastal areas.

The atmosphere above this region contains the largest subtropical deck of low-lying **stratocumulus** clouds on the planet. Compared to the North Pacific or Atlantic Oceans, the elements of this enormous climate system (defined as the land of sub-equatorial Peru down to approximately 35°S in Chile and the Southeast Pacific Ocean out to 110°W) have not been sufficiently studied to be adequately represented in global climate models.

During October 2008, Matrai research team members Andrew Hind and Carlton Rauschenberg, joined 150 other scientists from 40 institutions in eight nations to take part in VOCALS-REx, a multi-agency, international field program of the Variability of the American Monsoon Systems' (VAMOS) Ocean-Cloud-Atmosphere-Land Study. The goal of this program was to develop methods and collect data to improve scientific understanding, model simulation, and predictions about the southeastern Pacific ocean-atmosphere-land climate system for a range of timescales affecting global climate models.

VOCALS was scheduled for the month of October to allow scientists to conduct research at a time when stratocumulus cloud cover is greatest, the southeast trade winds are strongest, and the connections between the upper ocean and the lower atmosphere are most active.



Routes that the various aircraft and ships followed as they made observations of the ocean, clouds, and atmosphere in the Southeast Pacific region during the VOCALS field campaign.

The VOCALS-REx team used a NOAA research ship and five aircraft to sample the upper ocean and lower atmosphere during the course of the expedition. The team examined a range of environmental factors in the climate system, from processes that control the properties and formation of stratocumulus clouds—including the influence of microscopic aerosol particles emitted from volcanoes and human activities on the South American continent—to the mechanisms that control transport of cold water

through the ocean and the biochemical interactions between the lower atmosphere and upper ocean. The resulting real-time data about critical components of the atmosphere-ocean-land climate system of the southeastern Pacific region are adding much needed, missing information to climate models, increasing confidence in climate forecasts and predictions about future global climate change.



Photo by Bruce Wood.

Widening Circles of Scientific Understanding

Sharing knowledge about the ocean's importance to our environmental future is a growing priority in the Laboratory's education and outreach programs.

The Laboratory communicates about ocean science with researchers, educators, students, the media, and the public through a range of programs. Today's changing oceans make it imperative for us to work within an array of emerging scientific disciplines, train new oceanographers, and reach a wide audience, helping people to learn about the connections between the global ocean and the world that future generations will inherit, inhabit, and govern.

The Keller BLOOM Program: What Marine Invertebrate Do You Want to Be and Why?

High school juniors from across Maine responded to this question as part of their application to become one of sixteen students chosen for the May 2008 Keller-BLOOM Program. Bigelow Trustee Emeritus James McLoughlin and the late Dr. Maureen Keller began the BLOOM (Bigelow Laboratory Orders Of Magnitude) Program in 1990 as a way to provide young people with opportunities that foster scientific literacy and creativity. The program is an intensive, in-residence week of ocean science activities typical of the work and scope of the Laboratory's research. The program is sponsored by donations from individuals and businesses in Maine.



Photo by J. Gardner.

Open House: Up Close and Public



Photos by Greg Bernard.

For one day each summer, the Laboratory opens its doors to visitors of all ages, and invites the public to meet scientists, tour laboratory facilities, and acquire some hands-on experience with ocean sampling and analysis. The 2008 Open House drew people from our local community and the state, as well as summer tourists to the New England region. Left: Dr. Nicole Poulton helps Open House visitors on the Laboratory's dock collect samples from a plankton tow. Center: Guests in the conference room. Right: Glider pilot David Drapeau, with *Henry* and guests.

Phytoplankton Culturing Class



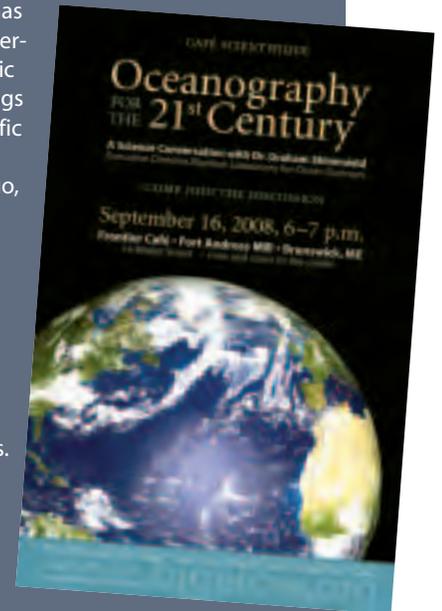
Photo by F. Scannell.

In October 2008, scientists from seven states, Pakistan, and Australia gathered at the Laboratory to participate in an intensive training course in phytoplankton culturing techniques. Taught annually by Drs. Robert Andersen and Michael Sieracki, the class is designed for graduate students, faculty members, and aquaculturists. It covers basic and advanced techniques for isolating, growing, and cryopreserving marine phytoplankton for use in environmental and biomedical research.

Café Scientifique in Maine Ocean Science Conversations

Bigelow Laboratory has hosted informal conversations with the public about research findings and emerging scientific issues for over three decades. Ten years ago, these gatherings became part of the international movement called Café Scientifique, which brings discussions about science to more than 150 "cafés" in 42 countries.

In 2008, the Laboratory's summer Boothbay Harbor Café Scientifique series expanded to add talks and events in the wider Maine community. Topics included the controversy around proposals to fertilize the oceans with iron to reduce global CO₂ levels, the challenges of ocean ecosystems science in the 21st century, the invisible jungle of marine microbes, use of phage therapy in lobster hatcheries, coastal ecosystem restoration, climate change and sea-level rise, and the discovery of new ocean microbial life forms.

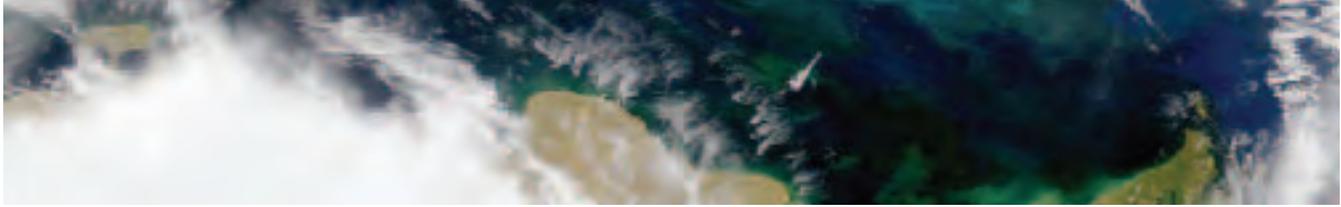


Active Grants

January–December, 2008

TITLE	FUNDING AGENCY	PRINCIPAL INVESTIGATOR(S)	AMOUNT
Bacterial dormancy, bacterivory, and bacterioplankton diversity in the ocean	NSF	Stepanaukas/Sieracki	659,836
Collaborative Research: Producing an updated synthesis of the Arctic's marine primary production regime and its controls	NSF	Matrai	306,793
Information Technology Research/Collaborative Research: Interactive software systems for expert-assisted analysis and classification of aquatic particles	NSF	Sieracki/Balch	1,555,515
Collaborative Research: ATOL: Deep Brown - A phylogenic and genomic investigation of the algal heterokont tree	NSF	Andersen	943,318
Small Grants for Exploratory Research: Single-cell genomics of marine bacterioplankton	NSF	Stepanaukas	147,412
COSEE: Centers for Ocean Science Education Excellence	UME/NSF	Sieracki/Goés	662,778
Annual cycles of nitrate and phytoplankton stocks using optics at the North Pole Environmental Observatory	NSF	Christensen	560,310
Plankton dynamics and carbon cycling in the equatorial Pacific Ocean: Control by Fe, Si, and grazing	OSU/NSF	Balch	305,657
Biocomplexity in the environment, coupled biogeochemical cycles, complex molecular to global interaction and feedbacks in the marine dimethylsulfide cycle	NSF	Matrai	1,716,238
The Collaborative O-Buoy Project: Development of a network of Arctic Ocean chemical sensors for the IPY and beyond	NSF	Matrai	413,994
Collaborative Research: The role of phytoplankton ballast material in deterring copepod grazing	NSF	Fields/Sieracki	462,847
Provasoli-Guillard National Center for Culture of Marine Phytoplankton	NSF	Andersen	1,915,968
Western Arctic Shelf Basin Interactions: SBI—Mesoscale nutrient structures in the Northern Chukchi and Beaufort Seas in several seasons	NSF	Christensen	299,999
Mechanoreception in Marine Copepods: Detecting complex fluid signals	NSF	Fields	201,148
Workshop: Single cell alternatives to metagenomics in environmental microbiology	NSF	Stepanaukas/Sieracki	44,856

CADWR	State of California Department of Water Resources	DUKE	Duke University	ONR	Office of Naval Research
CBEP	Casco Bay Estuary Project	FSML	Field Station and Marine Laboratory	OSU	Oregon State University
CIW	Carnegie Institute of Washington	IPY	International Polar Year	REU	Research Experience for Undergraduates
DEPSCOR	Department of Defense Experimental Program to Stimulate Competitive Research	MAIC	Maine Aquaculture Innovation Center	RSA	Research Set Aside
		MRI	Major Research Instrumentation	UCB	University of California-Berkeley
		MTI	Maine Technology Institute	UCONN	University of Connecticut
		NEC	Northeast Consortium	UME	University of Maine
		NSF	National Science Foundation		



TITLE	FUNDING AGENCY	PRINCIPAL INVESTIGATOR(S)	AMOUNT
Collaborative Research: From structure to information in mechanosensory systems: The role of sensor morphology in detecting fluid signals	NSF	Fields/Sieracki	322,532
Collaborative Research: Phytoplankton community dynamics and physiological status in the South Atlantic subtropical gyre and Benguela upwelling systems	NSF	Sieracki	228,646
MRI: Acquisition of new culture chambers for the Provasoli-Guillard National Center	NSF/MRI	Andersen	204,314
Collaborative Research: Marine Microgels: A microlayer source of summer cloud condensation nuclei in high Arctic ocean leads	NSF	Matrai	498,722
Patagonian Shelf Coccolithophores: Ecological factors regulating the Southern Hemisphere's largest recurring coccolithophore bloom	NSF	Balch	495,729
Functional genomics of phosphate acquisition during virus infection of <i>Emiliana huxleyi</i>	NSF	Wilson/Stepanuskas/Wharam	808,750
Collaborative Research: Loihi Seamount as an observatory for the study of neutrophilic iron-oxidizing bacteria and the microbial iron cycle	NSF	Emerson	114,695
Collaborative Research: Plant regulation of competition between methanogens and iron-reducing bacteria in freshwater wetlands	NSF	Emerson	100,721
Collaborative Research: Autonomous measurements of carbon fluxes in the North Atlantic bloom	UME/NSF	Sieracki	36,559
Collaborative Research: Biological and physical controls on DMS production and emission during VOCALS	NSF	Matrai	320,000
Collaborative Research: FeCycle II -- natural variability in plankton iron quotas during an unamended Lagrangian experiment	NSF	Twining	181,090
Unlocking the mysteries of plastid origin through comparative genomic analysis of two <i>Paulinella</i> species	NSF	Yoon/Andersen	818,006
Single cell genome sequencing of uncultured prokaryotes from the South Atlantic mesopelagic	NSF	Stepanuskas/McClellan/Sieracki	976,747
Collaborative Research: Quantitative importance and trophic role of <i>Nocticula</i> blooms in the Arabian Sea	NSF	Goés	296,905
Establishing marine archaeal, bacterial and viral collections to complement the Provasoli-Guillard National Center at Bigelow Laboratory	NSF/FSML	Andersen/Emerson/Wilson	335,341
REU Site: Bigelow Laboratory for Ocean Sciences — Undergraduate research experience in the Gulf of Maine and the world ocean	NSF/REU	Wahle/Fields	258,685

Active Grants

January–December, 2008

TITLE	FUNDING AGENCY	PRINCIPAL INVESTIGATOR(S)	AMOUNT
MRI: Acquisition of equipment for microbial single cell genomics research	NSF/MRI	Stepanauskas/McClellan/Emerson	494,045
Small Grants for Exploratory Research: Giant virus regulation of coccolithophorid dynamics	NSF	Wilson	69,523
Estimating nitrate in the world's oceans from space and its utility to study environmental regulation of nitrate-based NE WP production in the Arabian Sea	NASA	Goés	255,262
Using remote sensing to understand the consequences of climate, sea level changes, and increased human activities in the coastal Gulf of Maine: An interdisciplinary study of land-sea carbon coupling	NASA	Balch/Roesler	881,608
GNATS, The Gulf of Maine North Atlantic Time Series: Integrating terrestrial and ocean carbon cycles in a coastal shelf sea through coordinated ship and satellite observations	NASA	Balch	800,391
Climate change and its impact on the ecosystem of the Arabian Sea	NASA	Goés	966,277
Impact of Pacific climate variability on ocean circulation, marine ecosystems, and living resources	DUKE/NASA	Goés	114,186
Climate-related interannual variability of potential new production over the western North Atlantic Ocean	NASA	Goés	180,095
Organic matter metabolism in a coastal ocean ecosystem	NASA	Matrai/Sieracki	719,053
Spatial and temporal variability in chlorophyll, primary production, and carbon export in the Bering Sea linked to climate change (NSPIRES)	NASA	Goés	700,316
Biosphere of Mars: Ancient and recent studies	UCB/NASA	Emerson	217,845
Astrological Pathways: From the interstellar medium, through planetary systems, to the emergence and detection of life	CIW/NASA	Emerson	55,854
Differentiating sources of backscattering in the Southern Ocean: calcite, bubbles, and other optical constituents	UCONN/NASA	Balch	437,022
Using remote sensing to understand carbon flow and its transformations from upland ecosystems into the coastal ocean	NASA	Balch	524,795
Ecosystem carbon dynamics in high-latitude seasonal seas of the subarctic North Pacific and North Atlantic	OSU/NASA	Sieracki	115,846
A proposal for refinement of the MODIS calcite algorithm and CAL/VAL activities towards assembly of Earth System Data Records	NASA MODIS	Balch	676,980



TITLE	FUNDING AGENCY	PRINCIPAL INVESTIGATOR(S)	AMOUNT
Lobster settlement forecasting in the Gulf of Maine	UME/NASA	Wahle	66,535
Reducing uncertainty in the marine carbon cycle by coupling satellite and in-water robotic measurements	UME/NASA	Sieracki	86,455
Nanoparticles and ocean optics	ONR	Balch/Goés	622,336
DEPSCoR -- Energy transfer to upper trophic levels on a small offshore bank	USM/ONR DEPSCoR	Fields	136,513
Role of Fe-oxidizing bacteria in metal bio-corrosion in the marine environment	ONR	Emerson	418,877
Developing genetic fingerprinting techniques in lobster seeding trials	UMESeagrant/NOAA	Wahle	173,969
Developing tools to evaluate spawning and fertilization dynamics of the Giant Sea Scallop, <i>Placopecten magellanicus</i>	NOAA RSA	Wahle	183,270
Research on lobster age-size relationships: Developing regionally specific growth models from meta-analysis of existing data	DMR	Wahle	70,000
A proposal to add two Slocum Gliders to the Gulf of Maine North Atlantic Time Series (GNATS)	MTI	Balch	141,200
Facilities to catalyze a Center for Ocean Microbial Systems Science	MTI	Sieracki	160,000
Establishment of a LC-GC-MS Facility for research and education in marine science	MTI	Goés	346,000
Investigate effects of commercial rockweed harvesting on the associated macroinvertebrate community (Cobscook Bay)	DMR	Larsen	5,051
Coordinate the regional settlement survey	DMR	Wahle	3,000
Historical records of fouling organisms on the coast of Maine	ME DEP	Larsen	2,500
Historical records of fouling organisms on the coast of Maine	CBEP/USM	Larsen	500
Depth-related settlement patterns of the American Lobster in Southern New England and the Gulf of Maine	UNH/NEC/NOAA	Wahle	264,735
Workshop: Single-cell alternatives to metagenomics in environmental microbiology	Sloan	Stepanauskas/Sieracki	45,000
Assessment of phage therapy for the control of disease in lobster hatcheries	MAIC	Wharam	24,968
Using FlowCAM technology to measure high frequency spatial and temporal variations in phytoplankton and zooplankton species composition and develop state-of-the-art plankton monitoring	CA DWR	Poulton	24,000

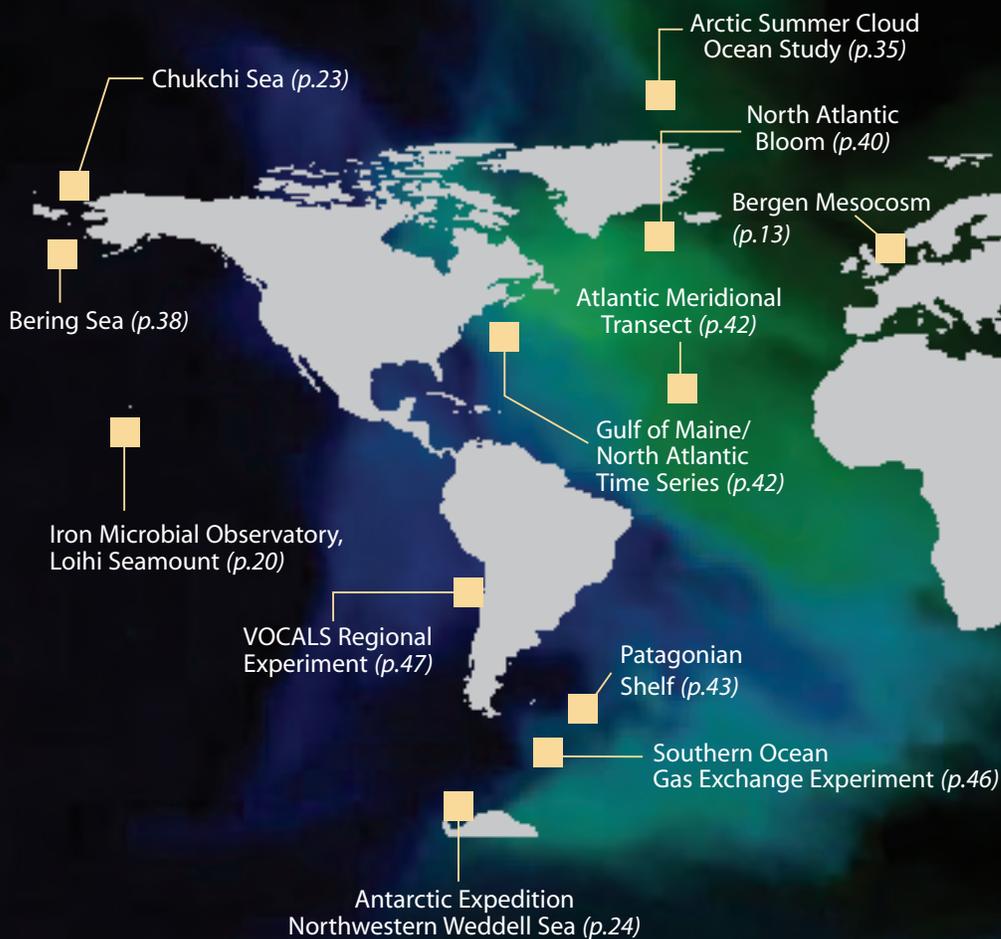
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Research Expeditions



Background photo of phytoplankton bloom off Namibia courtesy of NASA.

Antarctic research photo (left) courtesy of J. Goés. Arctic photo (above) by Michael Tjernstrom.

Summary Financial Statements

Statement of Activities and Changes in Net Assets

(For fiscal years ended June 30)

	2008	2007	2006
Operating Activities			
Operating Revenue and Support			
Grants and contracts for research and education	\$ 4,889,104	\$ 4,317,915	\$ 3,980,906
Other revenue, including course fees	324,064	637,691	533,852
Growth fund assets released from restrictions	698,672	360,202	0
Contributions to Annual Fund	268,641	206,942	197,276
Total Operating Revenue and Support	6,180,481	5,522,750	4,712,034
Operating Expenses			
Research and Education	5,733,334	5,005,089	4,594,254
Unallocated management and general	415,508	497,014	433,470
Development	248,629	90,553	71,185
Total Operating Expenses	6,397,471	5,592,656	5,098,909
Change in Net Assets from Operating Activities	(216,990)	(69,906)	(386,875)
Non-Operating Revenue and Support			
Contributions to growth fund	469,688	362,750	1,100,000
Grants for purchase of equipment	273,521	239,290	992,191
Growth fund assets released from restrictions	(698,672)	(360,202)	0
Change in Net Assets from Non-Operating Activities	44,537	241,838	2,092,191
Total Change in Net Assets	(172,453)	171,932	1,705,316

Statement of Financial Position

(At June 30)

	2008	2007	2006
Assets			
Cash	\$ 108,052	\$ 254,395	\$ 213,044
Investments	2,533,757	2,599,931	2,933,632
Property and Equipment, Net	5,459,860	5,082,443	4,955,469
Other	1,348,424	1,620,585	1,140,107
Total Assets	9,450,093	9,557,354	9,242,249
Liabilities and Net Assets			
Liabilities	547,584	482,381	339,207
Net Assets			
Unrestricted	5,882,690	5,608,787	5,315,578
Temporarily Restricted	2,818,775	3,267,231	3,390,816
Permanently Restricted	201,044	198,944	196,639
Total Net Assets	8,902,509	9,074,962	8,903,042
Total Liabilities and Net Assets	9,450,093	9,557,343	9,242,249

Bigelow Laboratory for Ocean Sciences was formed in 1974. Bigelow is a Maine nonprofit public benefit corporation and is qualified as a tax exempt organization under Sec. 501(c)(3) of the Internal Revenue Code. The Laboratory's financial statements for fiscal years 2006, 2007 and 2008 were audited by Macdonald Page Schatz Fletcher & Co. The summary financial statements shown here are derived from the audited financial statements. Amounts shown in this summary as growth funds released from restrictions reflect contributions intended to support the recruitment and startup costs of new senior research scientists. Copies of the audited financial statements are available on request from: Director of Finance, Bigelow Laboratory for Ocean Sciences, P.O. Box 475, West Boothbay Harbor, ME 04575; or by email to: finance@bigelow.org

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Glossary

Anthropocene epoch—the period (marked by a complex range of effects that are changing the physics, chemistry, and biology of the planet) when humans became the predominant force in Earth's environment. The Anthropocene epoch is often considered to have started 2,000 years ago, when the activities of humans first began to have significant impact on Earth's ecosystems and climate.

bioavailability—the degree to which, or the rate at which, a substance is absorbed or becomes available for use in an organism.

bioinformatics—an emerging area of biological research that combines molecular biology and mathematical modeling of biological phenomena with computer software design and implementation.

biological productivity—nature's ability to reproduce and regenerate living matter, defined as the rate at which organic matter is produced.

biological pump—the series of biological processes that transport organic carbon from the ocean's surface to its interior.

bivalve—an aquatic mollusk that is enclosed within two symmetrical, hinged shells, such as a scallop, clam, oyster, or mussel.

carbon export—the transfer of carbon out of the planet's atmosphere or surface into sediments on land or on the ocean floor.

carbon fixation—the process in plants and algae by which atmospheric carbon dioxide is converted into organic carbon compounds, usually by photosynthesis. Carbon fixation also takes place when calcifying phytoplankton such as *Emiliania huxleyi* form calcium carbonate shells.

chemical speciation—dissolved iron can occur in many chemical forms, or species, for example Fe^{2+} and $\text{Fe}(\text{OH})_3$, which are thought to vary in their bioavailability as nutrients.

coccolithophore—a type of phytoplankton (single-celled marine plant) that lives in large numbers throughout the upper layers of the ocean. Coccolithophores surround themselves with microscopic plates called coccoliths made of calcium carbonate.

coccolithoviruses—a recently discovered group of viruses that infect the globally important marine calcifying phytoplankton *Emiliania huxleyi*.

copepods—a group of tiny, shrimp-like crustaceans found throughout the world's oceans and in nearly every freshwater habitat. Most of the known copepod species are free-living marine forms and are a key part of the ocean's food chain.

cryopreservation—a process in which cells or whole tissues are preserved by cooling to low, sub-zero temperatures.

CTD rosette—A CTD is an electronic instrument that oceanographers use to record salinity, temperature, and depth. It is attached to a frame fitted with an array of water-collecting bottles called Niskins; the instrument, together with the bottles, is called a CTD rosette.

cyanobacteria—a category of bacteria that obtain their energy through photosynthesis. Also known as blue-green algae or blue-green bacteria, they are important primary producers in the ocean.

diatoms—single-celled algae with intricate glass-like cell walls made of silica. Diatoms can live in colonies that form a variety of shapes, and are one of the most common types of phytoplankton.

dinoflagellates—a large group of single-celled organisms, many of which are photosynthetic marine algae. Dinoflagellates have one or more whip-like organelles called flagella, used for locomotion.

endemic—native or restricted to a certain region.

endosymbiosis—a relationship between two organisms in which one (the endosymbiont) lives inside the body of the other (the host).

estuarine—characteristic of an **estuary**, an aquatic environment in which fresh and salt water mix, usually a semi-enclosed coastal water body with one or more rivers or streams flowing into it, and with a free connection to the open ocean. Estuarine habitats are characterized by a combination of marine (tides, waves, and influx of salt water) and freshwater (currents, sediment, runoff) conditions.

flavobacteria—a type of bacteria widely distributed in water and soil habitats around the world.

flow cytometry—a technique for counting, examining, and sorting microscopic particles suspended in a stream of fluid.

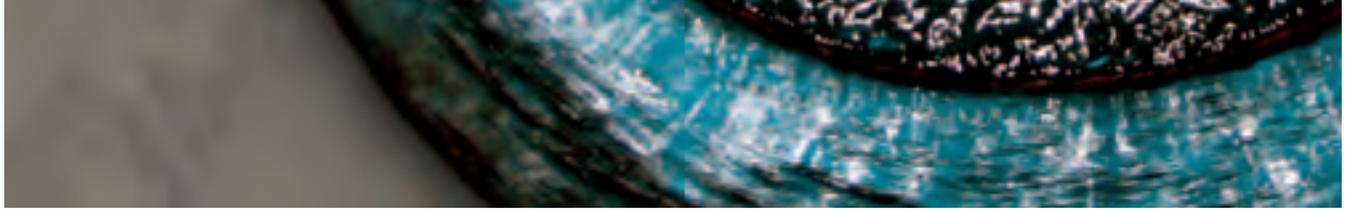
fluorescence—the property of absorbing light of short wavelengths and emitting light of longer wavelengths, allowing researchers to analyze the elements and chemicals present in an object.

glaucoophytes—a small group of freshwater microscopic algae that contain chlorophyll, the green pigment necessary for photosynthesis.

Global Ocean Sampling metagenome—the Craig Venter Institute's *Sorcerer II* Global Ocean Sampling expedition collected microbial DNA samples every few hundred miles around the globe, yielding an extensive dataset of DNA sequence fragments. This data provides an assessment of the overall gene composition, or the metagenome, within marine microbial assemblages.

hydrothermal vent—a fissure or crack in the planet's surface from which water that has been heated within Earth's interior is released. The areas around submarine hydrothermal vents host complex communities nourished by chemicals dissolved in the vent fluids.

invertebrate—an animal without an internal skeleton made of bone.



iron oxidation—the reaction of iron and oxygen in the presence of water or air moisture, resulting in rust.

microbial loop—the pathway in aquatic environments by which organic carbon is reintroduced into the food web by bacteria, which consume dissolved organic matter that cannot be directly ingested by larger organisms.

mitochondria—cellular organelles in which the biochemical processes of metabolism and energy production occur.

organelle—a specialized subunit inside a cell that performs a specific function and is separately enclosed within its own membrane.

orthographic projection—a map assembled from different angles to create a perspective that represents the planet's surface as it appears from space.

pelagic—part of the upper layers of the open ocean.

photosynthesis —a process that uses the energy from sunlight to convert carbon dioxide and water into organic compounds, producing oxygen as a by-product.

phylogenetics—the study of evolutionary history or development.

phytoplankton—the plant component of the suspended or floating microscopic animals, plants, and bacteria in the ocean, collectively known as plankton. Composed mostly of single-celled algae and bacteria, phytoplankton carry out photosynthesis and are at the base of the marine food chain. Most phytoplankton species are too small to be individually seen with the unaided eye.

phytoplankton bloom—phytoplankton blooms occur when, under favorable conditions, phytoplankton rapidly increase in numbers.

plastids—organelles that are found in the cells of plants and algae, and are the site of manufacture and storage of important chemical compounds used by the cell. Plastids often contain pigments used in photosynthesis, and the types of pigments present can change or determine the cell's color.

plume—in hydrodynamics, a plume is a column of one fluid moving through another; factors affecting the motion of this flow include the density, momentum, and diffusion of the liquid.

population bottleneck—the result of an event during the evolution of a species in which a significant percentage of its individuals are killed or otherwise prevented from reproducing.

primary productivity—the amount of biomass (organic compounds) produced from atmospheric or aquatic carbon dioxide, principally through photosynthesis. All life on Earth is directly or indirectly dependent on primary productivity.

proteorhodopsin—a light-sensitive protein found in marine bacterioplankton.

protists—a collective term for single-celled organisms, including single-celled algae, whose cells have a nucleus, but which are not considered animals, plants, or fungi.

relict population—the vestige of what was once a widespread natural population, now surviving only in isolated localities because of environmental changes.

rotifer—a microscopic, multicellular aquatic animal whose name is derived from a Latin word meaning “wheel-bearer,” referring to the rapid movement of the crown of cilia, or hairs, around its mouth, which make it appear to whirl like a wheel.

sea ice—frozen ocean water that forms, grows, and melts in the ocean; in contrast, icebergs, glaciers, ice sheets, and ice shelves all originate on land.

sentinel species—species that provide ecological information and give early warning signals about the ecosystem they inhabit because of their sensitivity to changing conditions.

sequestration—in chemistry, the creation and secure storage of a compound in a stable form, making it no longer available for reactions. The global carbon sink, which accumulates and stores carbon for an indefinite period, is a result of carbon sequestration.

shelf break—the region of the ocean floor where the continental shelf and continental slope meet, and where the gently-shelving region of the sea bed next to a land mass abruptly slopes more steeply down towards the ocean depths, commonly at around 200 meters (approximately 656 feet) in depth.

stratocumulus—a type of cloud that forms a low layer of rounded, dark gray masses, usually occurring in groups, lines, or waves.

upwelling—the transport of deep water to shallow levels of the ocean. The upwelling of nutrient-rich water is often responsible for driving biological productivity in the ocean, and is largely controlled by winds.

viral shunt—the process by which marine viruses move nutrients from organisms into pools of dissolved and non-living particulate organic matter.



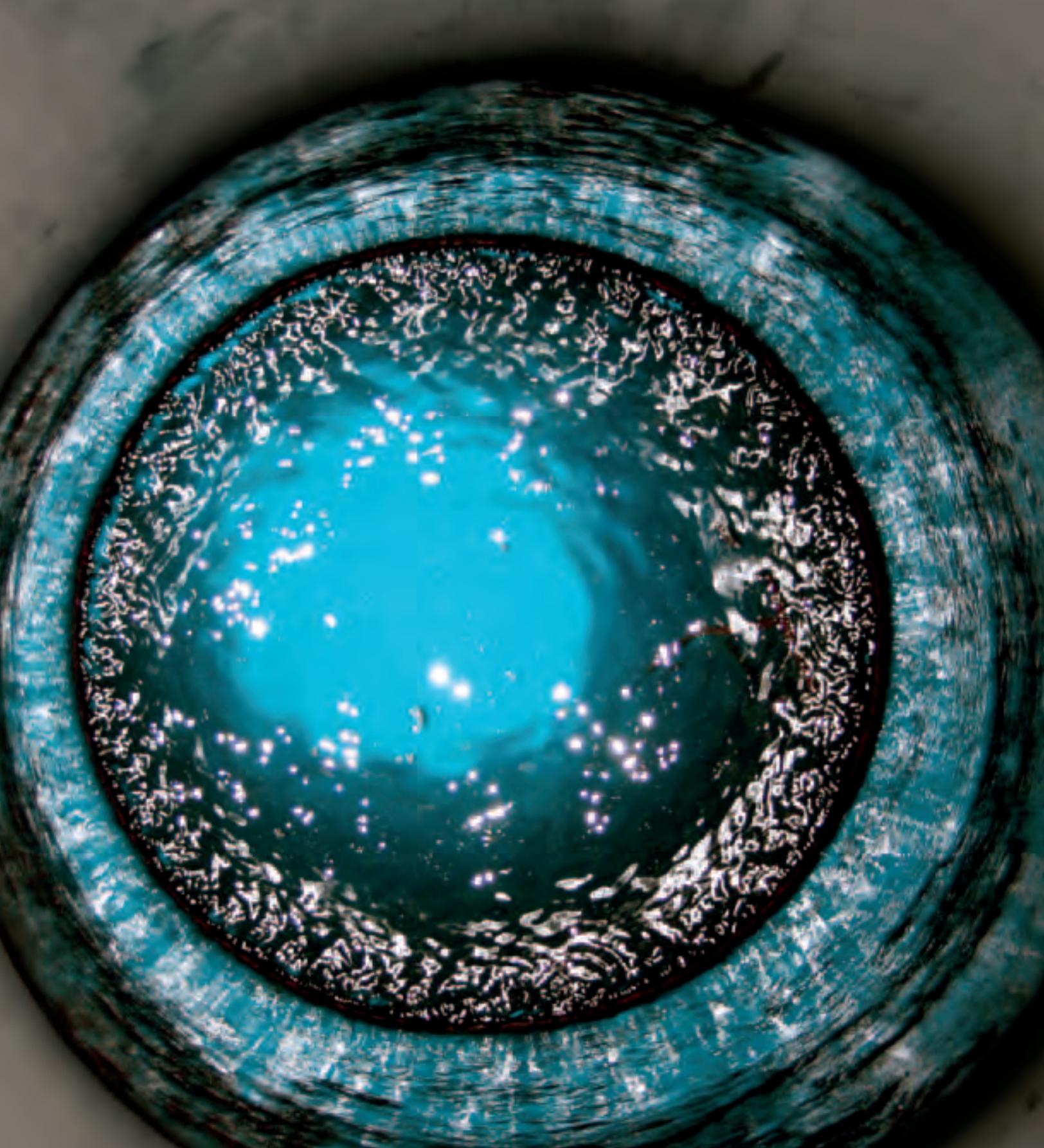
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