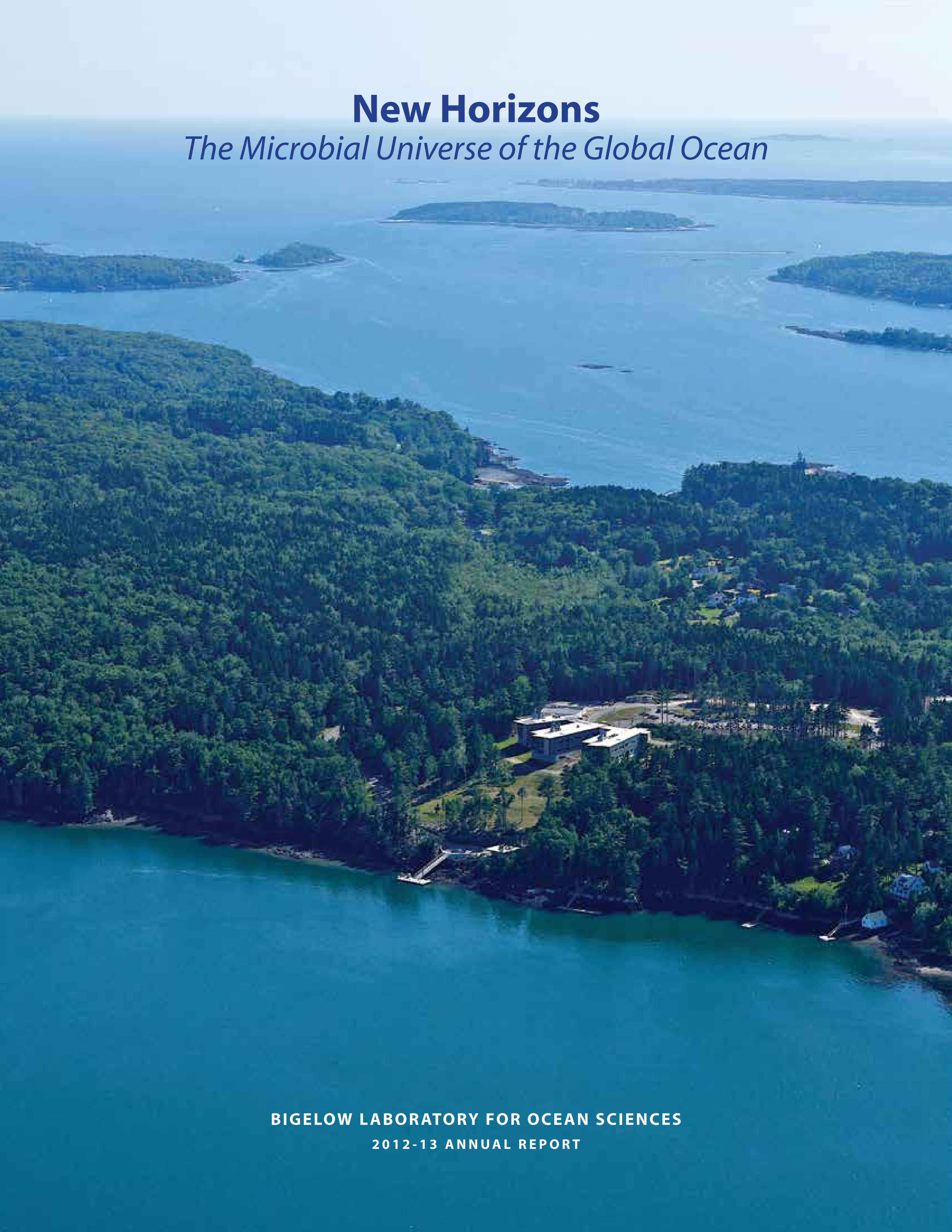
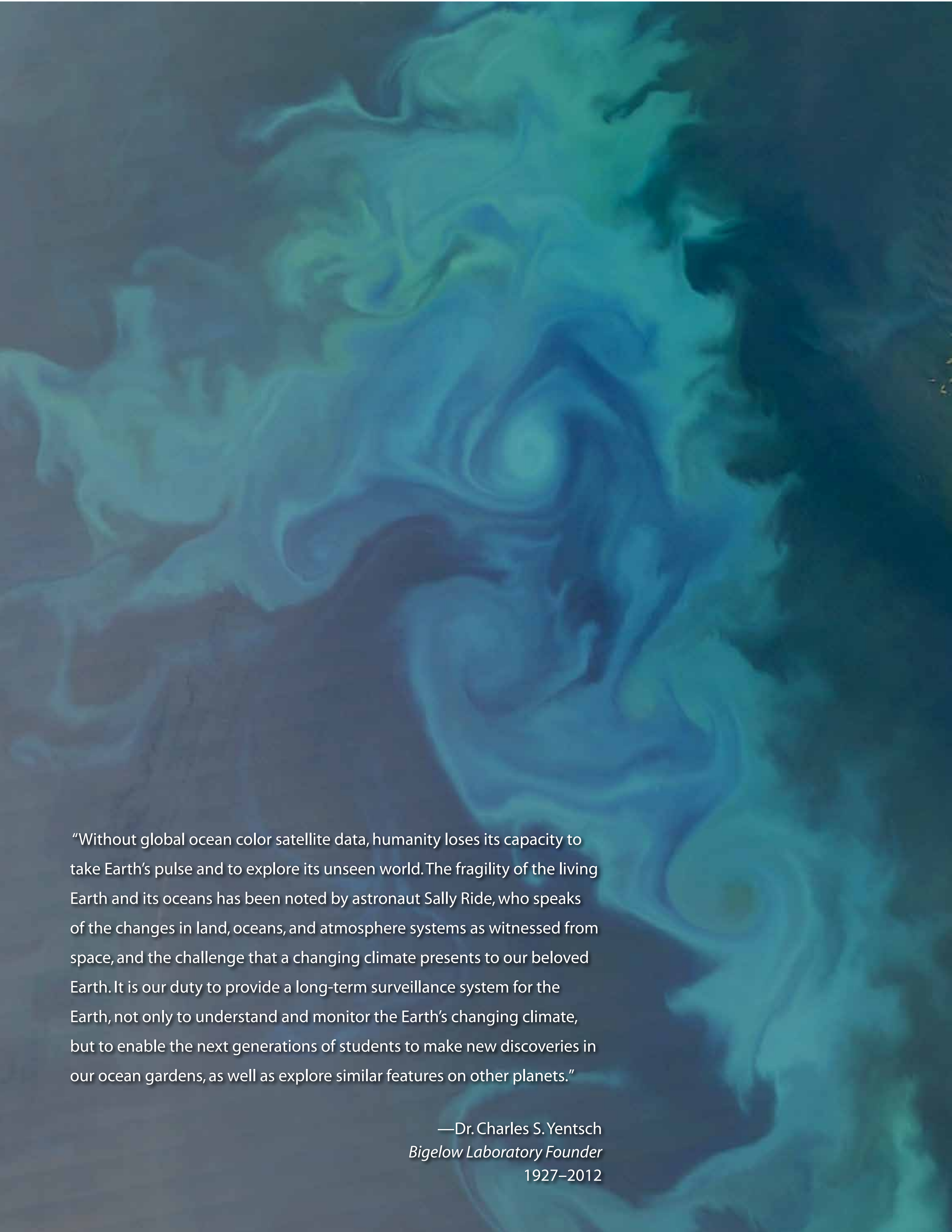
# New Horizons

*The Microbial Universe of the Global Ocean*



**BIGELOW LABORATORY FOR OCEAN SCIENCES**

**2012-13 ANNUAL REPORT**



"Without global ocean color satellite data, humanity loses its capacity to take Earth's pulse and to explore its unseen world. The fragility of the living Earth and its oceans has been noted by astronaut Sally Ride, who speaks of the changes in land, oceans, and atmosphere systems as witnessed from space, and the challenge that a changing climate presents to our beloved Earth. It is our duty to provide a long-term surveillance system for the Earth, not only to understand and monitor the Earth's changing climate, but to enable the next generations of students to make new discoveries in our ocean gardens, as well as explore similar features on other planets."

—Dr. Charles S. Yentsch
*Bigelow Laboratory Founder*
1927–2012

# Welcoming the Future

*A Message from the Chairman of the Board*

Photo by Greg Bernard.

David Coit

Bigelow Laboratory has just finished an exceptional and transformative period, a time that has witnessed the accomplishment of an array of projects that will take the organization to new levels of achievement.

The most obvious of these has been the completion of the $32 million Bigelow Ocean Science and Education Campus in East Boothbay. Shortly following the dedication of the new facilities in December, all of Bigelow Laboratory's management, scientists, and staff were on board and operational on the new site, enabling a higher level of scientific and operational efficiency and effectiveness than ever before.

Less visible to the outside world, but equally as important to the organization's ultimate success, has been the establishment of the Bigelow Laboratory *Five Year Business Plan, 2013-2017*. This detailed planning document was the product of many, many hours of intense collaborative effort by the Bigelow Board of Trustees, senior management, scientists, and staff, guided by the Laboratory's visionary *Strategic Plan*, which was first developed in 2008.

Bigelow Laboratory also received two prestigious awards over the past year, providing early markers of progress on the organization's path toward achieving its ambitious long-term goals. The Maine State Council of the Society for Human Resources Management named Bigelow Laboratory as one of the "top ten best places" to work in the state in 2012; it was the only non-profit organization to receive the award. More recently, the Laboratory received the "Innovator of the Year" award from the Maine International Trade Center, in recognition of the global reach of its oceanographic research and technical services. As this report goes to press, we have just learned that the Laboratory has been named one the Best Places to Work in Maine in 2013, as well.

I would also like to recognize another achievement that has transformed the governance of Bigelow Laboratory over the past several years. As a result of a concerted effort begun several years ago by the Governance Committee, Bigelow Laboratory has attracted a significant number of excellent new members to its Board of Trustees and to its newly constituted Advisory Board.

I am particularly pleased with the leadership and membership of each of the Laboratory's Trustee committees, which are populated by talented, experienced, dedicated, and very active members, both from the Board itself and the Advisory Board. Meeting often and working in close collaboration with the senior scientists, these committees guide the various strategic initiatives that are central to the organization's *Strategic Plan* and *Five Year Business Plan.*

Photo by Greg Bernard.

View of the Bigelow Ocean Science and Education Campus from the Damariscotta River.

Few of us who have been involved with the transformation of Bigelow Laboratory over the past several years can deny that we have stretched the boundaries of growth and change that an institution of our size can reasonably assume. However, the one central resource that has given me confidence that we will succeed has been the talented and dedicated team of individuals involved at all levels of this dynamic organization.

We have a great deal to be thankful for and to celebrate with the opening of the new Bigelow Ocean Science and Education Campus on the banks of the Damariscotta River. At the same time, we have also assumed significant financial and programmatic obligations and are now beholden to significant new stakeholders and supporters—foundations and individuals who have made our new home a reality.

But we have really just laid the foundation for what is possible, and we have considerable work ahead of us before we can declare victory in meeting our planned objectives. I encourage you to be involved in this very exciting venture as we enter into the next phase of Bigelow Laboratory's evolution, when new ideas and additional resources will be critical ingredients for our continuing voyage together.

David M. Coit
*Chairman of the Board of Trustees*

Bigelow Dock.

# In 85 Words . . .

*Bigelow Laboratory for Ocean Sciences conducts research ranging from microbial oceanography at the molecular level to global ocean processes. Our mission is to understand the key processes driving the world's ocean ecosystems, their evolution, and their fundamental relationship to all life on Earth through interrelated programs of research, education, and technology transfer. Our process of discovery is organized around three integrated areas of scientific inquiry—the Norton Center for Blue Biotechnology, the Center for Ocean Biogeochemistry and Climate Change, and the Center for Ocean Health.*

# Exploring the Microbial Universe of the Global Ocean

Photo by G.reg Bernard.

Graham Shimmield

Ocean waters are literally teeming with life. Any one drop (1 $mm^3$) of seawater contains 10,000 viruses, a thousand bacteria, and tens to hundreds of eukaryotic algae and animals. Diving to the ocean floor and into the sediment and crust provides no respite from the omnipresent microbes – over 100,000 microbes per $cm^3$ up to 1,000m below the seafloor, making up about a third of the living biomass on the planet. With oceans covering 71% of the Earth's surface and providing over 95% of the living space, it is no wonder that the ubiquitous microbe has found an ideal location to live and reproduce. Using the term "microbe" is actually rather generalist—life in the microbial ocean represents all three primary domains of life: Bacteria, Archaea, and Eukarya, as well as microscopic viruses. The most abundant "plants" on Earth are the microscopic cyanobacteria, *Prochlorococcus* and *Synechococcus.* All these tiny organisms contribute to a carbon biomass on the planet of close to 0.6-1.9 x $10^{15}$ g carbon, which is over a billion metric tons.

However, all this living matter is locked up in cells 1/100th the diameter of a human hair (and smaller). These microscopic particles of life drive the planetary engines of major biogeochemical cycles and energy flow. Blueprints for the individual roles of these microbes are locked inside their DNA and can be discovered only by mapping their genes—genes that contain keys to evolutionary history, ecological function, and novel metabolic pathways that may be valuable in future industrial and commercial processes. Bigelow scientists collect these microbes throughout the world's ocean, from the tropics to the poles, and from the surface to the geological abyss, striving to unlock the information they contain with state-of-the-art technologies and revealing complexity that is truly astounding.

This Annual Report highlights projects that include the latest sampling of the ocean depths using remotely operated vehicles (ROVs) and scientific drilling operations. From new ocean crust being formed at mid ocean ridges, to submarine volcanoes off Hawaii, what we once thought was an inhospitable part of the ocean actually supports significant microbial diversity.

Microbes with specific molecular machinery that allows them to fix carbon into biomass as an energy source live in the depths of the totally dark ocean water column.

Microbial populations have significantly altered the chemistry of the troposphere (the part of the atmosphere immediately overlying the ocean) at the Polar Regions.

Such insights could only be realized with advanced research vessels and sampling platforms employing innovative technology capable of operating under extreme conditions. But such innovation is not limited to the challenges of "working in the field." Back in the laboratory setting, our new East Boothbay campus, officially opened by U. S. Senator Susan Collins in December 2012, provides a fabulous new working environment. From the unique seawater experimental facilities, to the custom-built culture rooms for the National Collection for Marine Algae and Microbiota, to the ultraclean and one-of-a-kind home of the Single Cell Genomics Center, we have been pushing the envelope for our experimental and analytical facilities.

Analytical instrumentation and computing power are now outstanding; examples include our ability to measure nanogram quantities of biogenic toxins in our samples, and to match millions of gene sequences against international databases. In the world of microbial oceanography, this synergy between accessing the remotest environments on the planet and the power of the most advanced biogeochemical and molecular analytical tools provides a unique and powerful capability for Bigelow Laboratory of which we are enormously proud.

Plankton diversity. Image courtesy of NOAA.

This technology will come to nothing, however, if we are not able to accurately explain and pass on the knowledge we acquire to the decision-makers, stakeholders, and the next generation of scientists, as well as to industries that can develop these ideas into marketable products, thereby benefitting society and supporting the Laboratory. We have been working hard on transforming our education strategy, particularly the vibrant relationship with Colby College and our summer Research Experience for Undergraduates program.

Alongside the growing Education Program, our Corporate Alliances and Technology Transfer (CATT) Program is seeking to market our outstanding laboratory and experimental facilities for use by the private sector and fellow academics. We are also developing examples of joint commissioned research programs that allow our experience and knowledge to be used to address some of the potential commercial opportunities that working with industry can provide.

All these developments might be seen as spreading our expertise and focus too thinly. I would argue that in the uncertain world of research funding that exists today, and the extremely high cost of operating modern infrastructure, we would be foolish not to diversify our partnerships and funding base. We are doing this strategically, and with good advice from our excellent Board and Advisory Board. Bigelow Laboratory is well placed to make the concepts and discoveries within the field of microbial oceanography lead to practical and beneficial outcomes for the next generation. I am extremely proud that we are helping to forge this field as the Laboratory enters the fifth decade in its history.

Graham Shimmield, Ph.D., FRSE
*Executive Director and President*


*As sea ice melts, what other processes will become a part of the broader, changing global system?*

Dr. Paty Matrai
Photo by Robert Mitchell

# *MELTING ICE*
# A Silver Lining in Arctic Clouds?

Arctic sea ice is melting, allowing the surface ocean waters to absorb more solar radiation. Climate change models tell us the seas release this excess heat, further contributing to global warming. But is that the whole story? As the sea ice melts, what other processes will become a part of the broader, changing global system? Might these processes in themselves help to slow down — or even reverse — some of the changes resulting from the loss of Arctic sea ice?


Melting ice in the Arctic Ocean. Photo by Thorsten Mauritsen.

Senior Research Scientist Dr. Paty Matrai is investigating these questions as part of the O-Buoy Project (www.o-buoy.org) currently underway in the Beaufort and East Siberian Seas. The multi-year project — a collaboration between Bigelow Laboratory and six other research organizations — has deployed a network of ice-tethered chemical sensors in order to understand the behavior of greenhouse gases in the northernmost climates. Ten O-Buoy monitoring systems have been deployed since 2009, allowing scientists to measure not just carbon dioxide, but also bromine oxide and ozone, as well as collect a wide range of meteorological information.

Matrai is studying the chemical composition of the atmosphere over the Arctic Ocean to understand the changes that have already occurred there and help anticipate further changes ahead. As part of this research, she is also investigating what may happen as the Arctic sea ice itself disappears.

Previous work has shown that melting ice may allow communities of marine microorganisms to thrive in places where they were not previously able to access enough sunlight for photosynthesis. Some of these marine microbial communities produce dimethyl sulphide gas (DMS), which enters the atmosphere and is oxidized into tiny aerosol particles that, along with directly emitted organic aerosols, help to form water droplets. This condensation, in turn, helps form clouds. In the Arctic, an increase in DMS and organic particle emissions may result in more low-level clouds, which would help to reflect some of the solar radiation and possibly mitigate some of the regional effects of climate change.

Other factors are at play here, however. Diminishing levels of sea ice will allow winds to stir up the surface layer of the Arctic Ocean, further increasing the flow of ocean aerosols to the atmosphere. But, as sea ice melts, the habitat of ice algae will decrease, potentially changing the overall composition and ecological roles of microalgal species in Arctic waters.

The processes connecting the physics, chemistry — and now — the biology of the atmosphere with the underlying surfaces of ocean water and sea ice are at the core of Matrai's Arctic research. This area of investigation is making an important contribution to knowledge about how climate change will impact the physics of the atmosphere, beyond the more thoroughly studied climate change "fields" of radiation and meteorology.

*TRACE GASES, AEROSOLS, AND PHYTOPLANKTON*

# Where the Ocean and Atmosphere Meet

*Increasing levels of atmospheric carbon dioxide are turning the oceans more acidic, changing plankton composition and physiology and, consequently, the emission rates of the trace gases that help seed clouds.*

Dr. Steve Archer

Photo by Robert Mitchell

The ocean plays a major role in the atmospheric chemistry and climate of our planet. Constantly exchanging a variety of atmospherically important volatile gases such as sulfur, nitrogen, and halogens, the ocean and the atmosphere have an ongoing and significant impact on the global climate system.

The exchange of gases influences stratospheric and ground level ozone concentrations, atmospheric aerosols, and cloud formation. Ground-level ozone has a direct impact on our health and climate, while biogenic iodine in the atmosphere shapes our climate indirectly, and provides an essential source of iodine to terrestrial species, including humans. The sulfur gas dimethyl sulfide (DMS) — the smell of the sea — produced by many species of phytoplankton contributes to the composition of atmospheric aerosols that seed clouds and, consequently, affects Earth's ability to reflect the sun's heat back into space.

At the same time, increasing levels of atmospheric carbon dioxide are turning the oceans more acidic, changing plankton composition and physiology and, consequently, the emission rates of the trace gases that help seed clouds.

Led by Dr. Steve Archer, researchers in the Air-Sea Interactions Laboratory are investigating the processes that influence concentration of trace gases in the surface ocean and the biogeochemistry of their interaction with the atmosphere.

Their goal is to understand which of these gases are most important to climate change, how they act and react collectively, and how climate change will alter their production in the ocean and their collective exchange. Their findings can then be incorporated into the global circulation models used to predict climate change and potential feedbacks.

Setting up a mesocosm during the EPOCA ocean acidification experiment. Photo by Ulf Riebesell.

Archer is investigating how the response of natural planktonic populations to increasing carbon dioxide influences trace gas exchange. The goal is to understand this at varying levels, ranging from alteration in species composition in the ocean, to the molecular control and enzyme activity governing key biochemical processes.

Understanding how the exchange of DMS and other trace gases will alter in the face of increasing levels of atmospheric carbon dioxide and ocean acidity is complex challenge. The ability to predict the magnitude of the influence that trace gases such as DMS may have on climate change requires knowledge of both the atmosphere's and the ocean's response to changes in the chemical and physical forces operating in biogeochemical cycles.

Archer was recently part of a research expedition — the European Project on Ocean Acidification (EPOCA) — examining the impact that changes in the marine microbial community have on atmospheric systems off the coast of Spitzbergen Island in the Arctic Ocean.

The research team sealed off 50 tons of oceanic water inside each of nine mesocosms — imagine giant socks, 20 meters deep and 3 meters wide —and then changed the acidity inside each structure. Over the 30-day experiment, the microbial communities in the most acidic mesocosms — which matched projections for ocean pH in the year 2100 — produced DMS at rates between 35% and 60% lower than they do under present day conditions.

The experiment showed how planktonic ecosystems in the Arctic will respond to acidification, and how this may affect trace-gas exchange, atmospheric chemistry, and global climate conditions. The results from this study have appeared in three scientific publications (Archer et al, *Biogeosciences* 2013; Hopkins et al, *Biogeosciences* 2013; and Six et al, *Nature Climate Change*, 2013).

*New information demonstrates that icebergs are catalyzing phytoplankton growth, further influencing the exchange of carbon dioxide between the atmosphere and the ocean.*

Dr. Ben Twining
Photo by Robert Mitchell

### *FEEDING THE SEA*
# Iron and Icebergs

In recent years, ships traveling through the Southern Ocean have noticed an unusual phenomenon — an increase in the abundance of phytoplankton visible in the paths of massive icebergs. Now new research by Senior Scientist Dr. Benjamin Twining and a team of colleagues has revealed that these icebergs are, indeed, affecting marine ecosystems as they drift through the ocean.

Icebergs form when pieces of ice break off, or "calve," from glaciers or ice shelves. Photograph courtesy Patrick Rowe, NSF Antarctic Photo Library.

Phytoplankton cells need iron to thrive, iron that is normally in short supply in the Southern Ocean. In other parts of the world ocean, iron arrives in the form of dust from nearby land masses. Most of the land near the Southern Ocean, however, is covered by ice, limiting the amount of dust and iron that enter the water. With few available iron sources, phytoplankton and other algae are unable get the nutrients they need to grow. This, in turn, limits the amount of phytoplankton available for other species to consume.

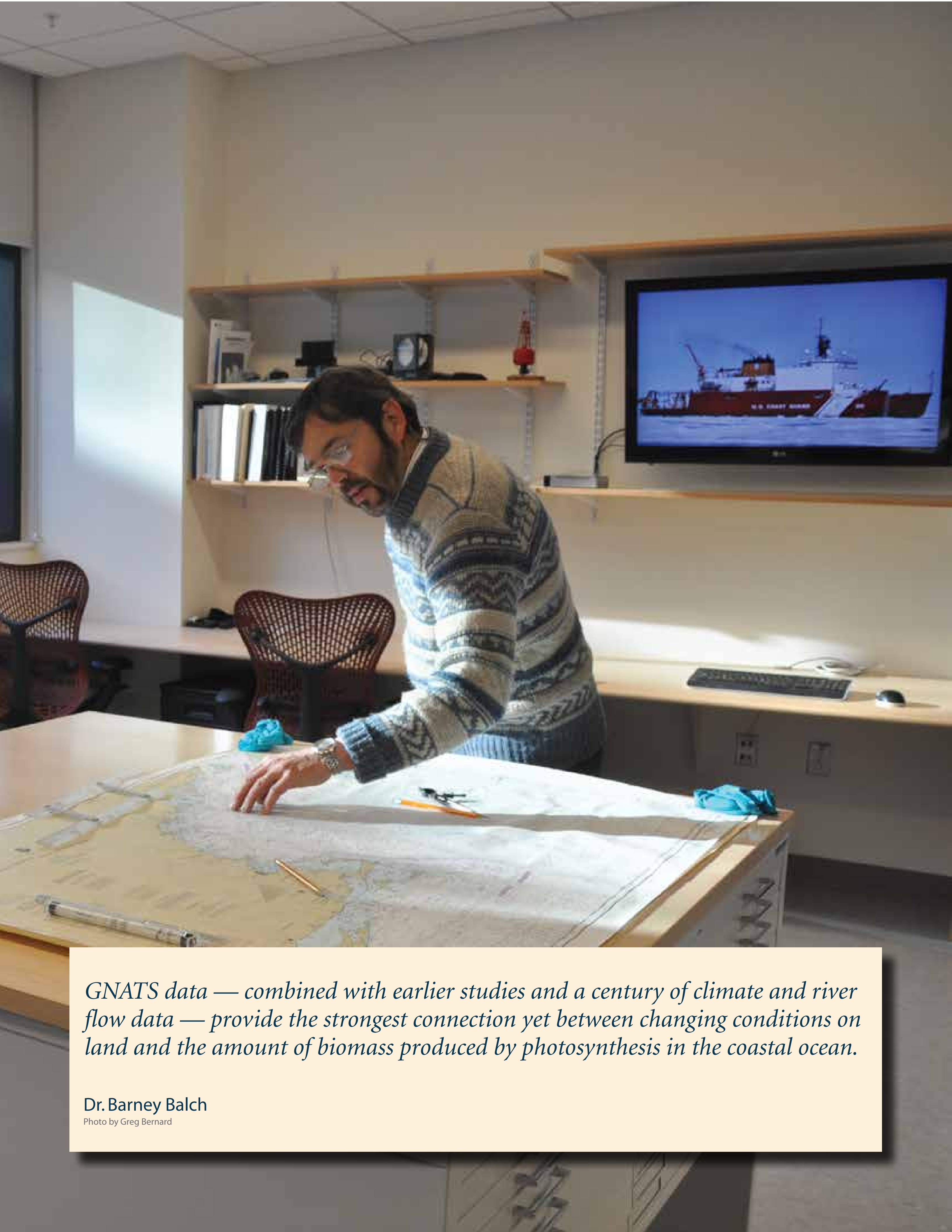
This all changes when icebergs break off the Antarctic Peninsula and enter the ocean. These enormous ice formations originally scraped their way over the Antarctic continent before breaking off and falling into the sea, taking dirt and soil from the land with them. As the icebergs drift and melt, this dirt is slowly released into the water, feeding the ecosystem in the process by introducing nutrients that nourish phytoplankton.

Twining and researchers from eight other institutions traveled to the Southern Ocean in 2005, 2008, and 2009 to learn more about this phenomenon. Using remotely operated vehicles (ROVs), they were able to get closer to the moving icebergs than was possible in the past. The ROVs even traveled underneath the icebergs, allowing the researchers to collect water and biological samples, along with video footage and other information.

The research team studied multiple aspects of the marine ecology around the icebergs, including phytoplankton, local fish and bird populations, and water chemistry. Twining found that iron was accompanied by naturally occurring radium, which could only have entered the ocean water by way of dirt or soil. This linked the iron in the water to Antarctic soil, and thus directly to the icebergs themselves.

Dissolved iron was not present at very high concentrations right at the face of the icebergs themselves. Instead, it appears that the iron is released as particles, some of which sink down toward the ocean floor. Others dissolved and formed the food base for new populations of phytoplankton.

The research — which yielded papers about the influence of free-drifting Antarctic icebergs on pelagic marine ecosystems in *Oceanography*, V. 25(3), pp. 38-39) and a special issue of the journal *Deep Sea Research* — shows increase in plant abundance in the wake of icebergs as they travel and melt. The Southern Ocean was already known to have an important role in the global climate system as the point of origin for much of the world's deep water and a source of heat and carbon dioxide transport. This new information demonstrates that icebergs are catalyzing phytoplankton growth, further influencing the exchange of carbon dioxide between the atmosphere and the ocean.



*GNATS data — combined with earlier studies and a century of climate and river flow data — provide the strongest connection yet between changing conditions on land and the amount of biomass produced by photosynthesis in the coastal ocean.*

Dr. Barney Balch

Photo by Greg Bernard

## *TRACKING THE EVIDENCE IN THE GULF OF MAINE*

# Climate Change on the Doorstep

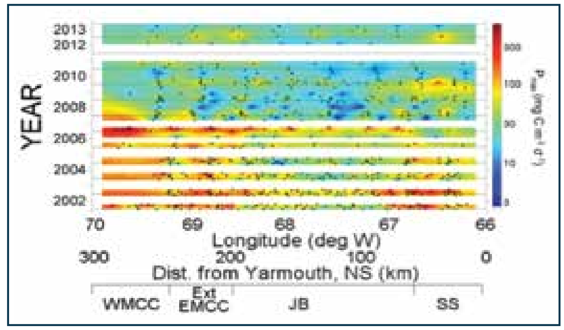
Systematic, long-term monitoring of the ocean environment is essential to understand how global climate change is affecting ecosystem processes. Led by Senior Research Scientist Dr. Barney Balch, the Bigelow Ocean Observing and Optics Team's NASA-funded Gulf of Maine North Atlantic Time Series (GNATS) is a 34+year field program that crosses the Gulf of Maine from Portland, Maine to Yarmouth, Nova Scotia to collect information as an ongoing, long-term transect time series.

The GNATS is the longest transect time series in the Gulf of Maine and is currently tracking environmental changes resulting from multiple years of extreme freshwater discharge from rivers in the Gulf's twenty-five surrounding watersheds, as well as providing critical ocean color calibration and validation data for NASA satellites and the first comprehensive regional assessment of carbon fixation in this large ocean ecosystem.

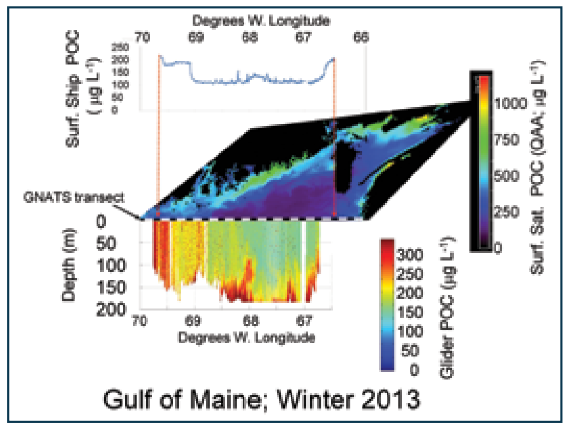
Half of Maine's largest rainfall events in the century have occurred in the past seven years. Working in collaboration with the U. S. Geological Survey, the GNATS team has documented evidence that a 500% drop in the growth rate of phytoplankton in the Gulf of Maine has direct ties to this period of increased rainfall and volumes of river discharge. The GNATS data — combined with earlier studies and a hundred years of climate and river flow data — provide the strongest connection yet between changing conditions on land and primary productivity (the amount of biomass produced by photosynthesis) in the coastal ocean.

The team's findings were first published in *Marine Ecology Progress Series* (Vol. 450:11-25, 2012).

The data suggest that increased river discharge is preventing deep, North Atlantic water — which carries nutrients essential for phytoplankton growth — from entering the Gulf of Maine through the Northeast Channel, causing significant changes in the Gulf's biogeochemistry. At the same time, greater runoff from rivers has led to increased amounts of detritus and colored dissolved organic matter in the water, reducing the amount of light available for phytoplankton photosynthesis and growth.




Time-space diagram for primary productivity from the GNATS, showing that primary production dropped precipitously (500%) in 2007 and Gulf-wide primary production still has not recovered to pre-2007 levels as of 2013.

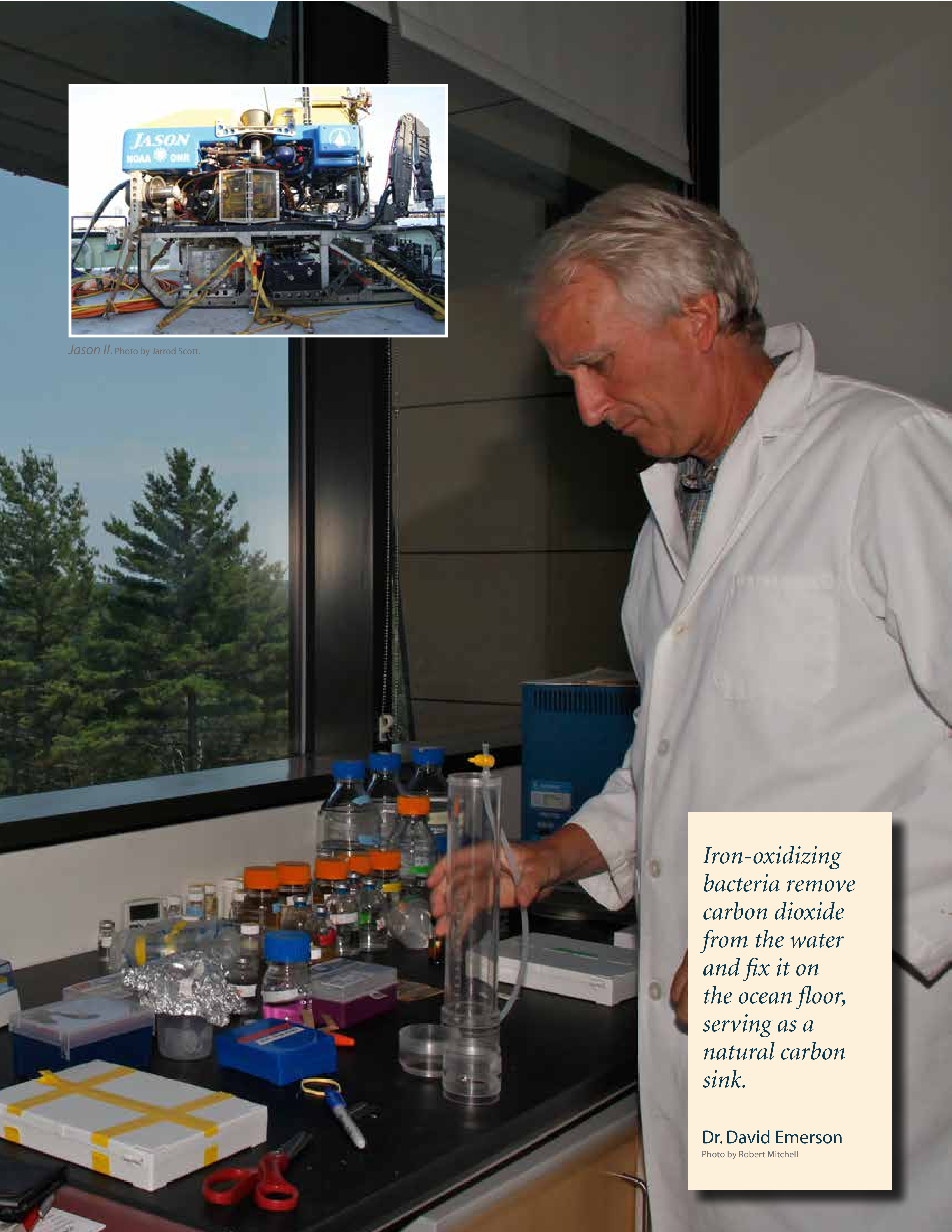



3-D view of particulate organic carbon (POC) in the Gulf of Maine, estimated from satellite, surface ship, and glider data during winter 2013.

The impact of a five-fold decline in the growth rate of phytoplankton — the microscopic, single-celled plants that form the foundation of the marine food web and ultimately support the Gulf's fish and lobster populations — could take several years to affect the food supply of commercial fish species, however, since phytoplankton are food for larval fish, several years in advance of their capture as adults.

The GNATS study also collected temperature and salinity data, which were compared to measurements taken along the same transect begun 35 years ago by scientists including Bigelow Laboratory founding director Dr. Charles Yentsch. These data show increases in surface temperature in the Gulf, as well as decreases in salinity.

The increase in temperature is consistent with global increases in ocean temperature that have been reported by other researchers. The decrease in salinity, however, is greater than changes observed further out in the mid-Atlantic, and is likely attributable to the Gulf's proximity to freshwater rivers. Long-term salinity decreases can be caused by a number of factors, including changes in the Earth's water cycle and the melting of the polar ice cap.




*Jason II.* Photo by Jarrod Scott.

*Iron-oxidizing bacteria remove carbon dioxide from the water and fix it on the ocean floor, serving as a natural carbon sink.*

Dr. David Emerson

Photo by Robert Mitchell

## *EXPEDITION TO THE MID-ATLANTIC RIDGE*

# Hunting Iron-eating Bacteria in the Depths

Iron-oxidizing bacteria (FeOB) live by consuming iron in environments as varied as the deep-sea hydrothermal vents of undersea volcanoes, shipwrecks, and the root systems of wetland plants. They grow by oxidizing iron, converting it into rust, and using it as their energy source. In the ocean, FeOB remove carbon dioxide from the water and fix it on the ocean floor, serving as a natural carbon sink. FeOB may have influenced the biogeochemistry of early Earth through precipitation of iron oxides and the formation of banded iron formations (the world's primary source of iron ore), and likely continue to play a significant role in geological and geochemical processes today.

Many FeOB species produce billowy, rust-colored mats consisting of unique microstructures made of filamentous sheaths or stalks. A recently discovered class of FeOB, the *Zetaproteobacteria*, has been associated with the microbial mats found at iron rich hydrothermal vents of submarine volcanoes deep in the ocean. With funding from the National Science Foundation, Senior Research Scientist Dr. David Emerson and his geomicrobiology research team have begun investigating the ecology of these microbial mats to learn what is driving the structure of microbial communities, how microstructures influence the way FeOB function, and how FeOB evolved within this extreme hydrothermal vent environment.

In October 2012, while Hurricane Sandy made landfall on the east coast of the United States, Emerson and members of his team were hundreds of miles away at the Mid-Atlantic Ridge (MAR), part of a multi-institutional expedition aboard the *R/V Knorr* to study the microbial community of the deep-sea hydrothermal vents associated with the ridge. The team used Woods Hole Oceanographic Institution's robotically operated deep sea vehicle (ROV) *Jason II* to collect samples from three and half kilometers below the sea surface.

The MAR expedition sampled three different hydrothermal sites on the ridge, focusing on the meters-high "black smoker" chimneys on the ocean floor that emit hydrothermal vent fluids at temperatures close to 400°C (750°F).

Although they had not been observed at the Mid-Atlantic Ridge in the past, Emerson's team found active *Zetaproteobacteria* communities in the lower temperature vents associated with the black smokers, where iron alone was the dominant constituent of the vent fluid, providing ideal conditions for their growth.

By combining high precision structured seafloor sampling techniques developed by Emerson with modern single-cell genomics methods and geochemical measurements of vent fluid, the team has begun to link the evolution of physiological diversity of these microbes with the functional diversity of their microbial communities.

Research suggests that *Zetaproteobacteria* may be functioning as a keystone species within the microbial mat ecosystem by oxidizing iron, converting it to energy, and producing microstructures — effectively "engineering" a structured, delicate, microbial environment that fosters growth of other bacterial populations by influencing water and nutrient flow through the mat.

As ancient life forms with unique metabolic and morphological characteristics and well-defined habitats, *Zetaproteobacteria* offer an important model for understanding fundamental ecological concepts that drive microbial diversity and evolution, and illustrate how microbes can fundamentally influence geochemical cycling and mineral deposition.

Structures similar to those produced by *Zetaproteobacteria* can be found hundreds of millions (and possibly billions) of years back in the geological record, making them important both in terms of the history of life on Earth and in the search for life beyond our planet.

## FeOB:

### Microstructures with Big Potential

FeOB play both nuisance and beneficial roles in human activities—although they are major agents of biofouling and biocorrosion in industrial and domestic water distribution systems, they can also aid in the removal of harmful metals and organics in water treatment systems. Potential biotechnology applications include using the microstructures these bacteria form to capture specific chemicals or substances from the aquatic environment.

*L. ochracea* sheaths. Photo by Joyce McBeth.

*Relative abundances of different phytoplankton groups...may be impacting biogeochemical cycling and affecting how different species react and adapt to seasonal change, climate variability, and increasing levels of carbon in what is currently a warming ocean.*

Dr. Mike Lomas
Photo by Dennis Griggs

*RECONSIDERING THE REDFIELD RATIO*

# Phytoplankton Ecology on a Global Scale

Focusing on the physiology and ecology of natural marine phytoplankton populations, and the interactions between the two, Senior Research Scientist Dr. Mike Lomas uses a comparative ecosystem approach to understand the impacts of climate change on marine phytoplankton diversity and subsequent impacts on ocean biogeochemical cycles.

He is investigating the role of phytoplankton diversity in the global carbon cycle in terms phytoplankton elemental stoichiometry (the relative proportion of elements within phytoplankton cells) for carbon, nitrogen, and phosphorus. This research focuses on how the metabolism and physiology of phytoplankton cells—particularly the tiny, single-cell cyanobacteria and picoeukaryotes, which now dominate in 60% of the world's surface ocean—respond to nutritional and environmental stress, and how these responses, in turn, affect ocean biogeochemistry.

Lomas's recent findings are challenging a central principle that has been the basis of scientists' understanding of productivity in the surface ocean of the world for over 75 years, including the amount of carbon dioxide that is consumed by marine plankton.

Lomas is co-author of a study published in *Nature Geoscience* (Strong latitudinal patterns in elemental composition of marine plankton and organic matter. DOI: 10.1038/NGEO1757), showing that elemental ratios of marine plankton and organic matter follow a clear latitudinal trend, with large spatial differences and a global average that can vary substantially from the standard formula, known as the Redfield Ratio, that has traditionally described the relative proportions of carbon, nitrogen, and phosphorus in plankton.


An assortment of phytoplankton. Image courtesy of NOAA.

Although the Redfield concept remains a central tenet in ocean biology and chemistry, the team's research shows that elemental ratios in plankton follow a strong latitudinal pattern that differs from the Redfield Ratio. The findings suggest that the coupling between oceanic carbon, nitrogen, and phosphorus cycles via plankton varies systematically by ecosystem.

Working with colleagues from the University of California-Irvine and Princeton University, Lomas collected and analyzed the chemical composition of marine plankton from thousands of ocean samples across the globe, including the waters of the North Atlantic, the Caribbean, and the Bering Sea. The team, whose work was funded by the National Science Foundation, found that the chemical composition in marine plankton communities was significantly influenced by latitude and temperature, and was also related to changes in the abundance of different plankton groups.

Using flow cytometry and at-sea cell sorting technology in the field, Lomas is documenting the relative abundances of different phytoplankton groups across ocean gradients from the equator to the poles. His research suggests that the different physiologies of these varying groups may be impacting biogeochemical cycling—including the ocean's biological carbon pump—in distinct and significant ways, and affecting how different phytoplankton species react and adapt to seasonal changes, climate variability, and increasing levels of carbon in what is currently a warming ocean.

*Single cell genomics… is beginning to reveal how previously unrecognized types of microscopic life forms in the deep ocean are helping to balance the global cycles of matter and energy that sustain our planet.*

Dr. Ramunas Stepanauskas

Photo by Dennis Griggs

# Revelations from the Deep

Bigelow scientists have discovered that there are bacteria throughout the ocean able to harness chemical reactions instead of relying on sunlight to produce the energy they need to live. This research, published in *Science* (Potential for chemolithoautotrophy among ubiquitous bacteria lineages in the dark ocean. *Science*, vol 333, issue 6047, pp. 1296-1300), is essential to understanding the extent to which vast populations of microorganisms in the deep ocean are impacting the global carbon cycle.

In one of the first demonstrations of the power of high-throughput single cell genomics to decipher ecological roles of microorganisms in the environment, the researchers, led by Senior Research Scientist and Bigelow Laboratory Single Cell Genomics Center Director Dr. Ramunas Stepanauskas, were able to read genetic information from marine microbes that were previously inaccessible to investigation, ushering in a new chapter in the exploration of the microbial life that dominates marine ecosystems.

Funded by grants from the National Science Foundation, the Department of Energy, and other agencies, the project included collaborations with scientists from the U.S. Department of Energy Joint Genome Institute, the University of Vienna, the Massachusetts Institute of Technology, and the Monterey Bay Aquarium Research Institute.

The team combined a series of cutting-edge research techniques, including cultivation-independent single cell genomics and analyses of the physiology of individual microbial cells. They discovered that

Photo by Dennis Griggs.

many of the myriads of bacteria living in the deep ocean are able to use carbon dioxide to build their bodies in a process similar to plant photosynthesis, which is limited to the top 50-200 meters of the water column. Unlike plants, however, these bacteria convert carbon dioxide to organic compounds in complete darkness, producing biomass without energy from the sun.

This process is called chemolithoautotrophy, previously thought to occur only in extreme ocean environments, such as hydrothermal vents. The team's findings indicate that dark carbon fixation is also taking place in the deep, dark oxygenated water throughout the world's ocean — one of the most expansive habitats on the planet — with oxidation of reduced sulfur compounds, methane, and carbon monoxide likely replacing sunlight as energy sources.

Microbes drive most global biogeochemical processes, yet nearly 99% of them have resisted scientists' attempts to grow them in cultures, rendering them inaccessible to studies using classical microbiology techniques. Culture-independent research tools, such as metagenomics, have provided initial insights into the gene composition of microbial communities, but have seldom been able to identify the specific organism to which a particular gene belongs. Single cell genomics is bridging this gap, enabling the recovery of entire genomes from individual microbial cells without the need for cultivation, facilitating the search for new natural products and bioenergy sources, and beginning to reveal how previously unrecognized types of microscopic life forms in the deep ocean are helping to balance the global cycles of matter and energy that sustain our planet.


*Copepods act as microscopic bioreactors that affect ocean processes on a global scale.*

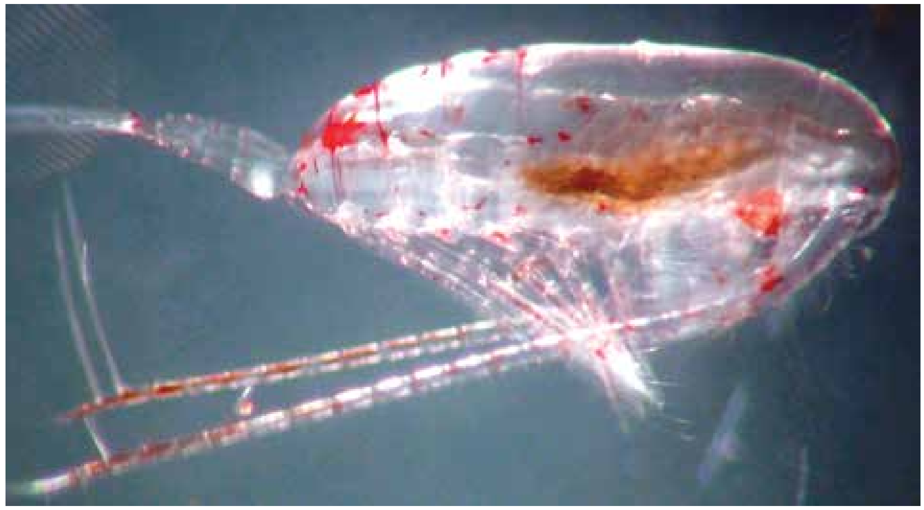
Dr. David Fields
Photo by Robert Mitchell

# Microbioreactors at Sea

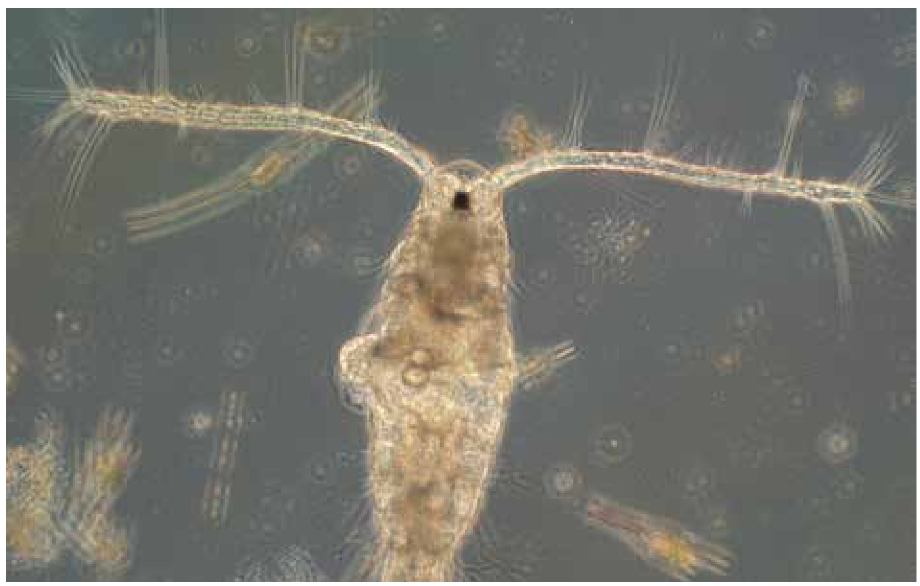
The tiny crustaceans known as copepods may not look like much individually, but together they have an enormous role in ocean ecosystems. That's because there are more copepods than any other kind of animal — $10^{21}$ individuals, or 1 sextillion. New research from Senior Researcher Scientists Drs. David Fields and Benjamin Twining, with Dr. Howard Browman from the Institute of Marine Research, shows how all of those copepods act as microscopic bioreactors that affect ocean processes on a global scale.

The impact comes from the copepods' digestive systems. Although the crustaceans are only about 1 or 2 millimeters long, collectively they pass a significant portion of the living material in the ocean through their intestines every year. As they digest this material, it interacts with the enzymes in their guts, changing methane levels in the waters around them, along with the availability of calcium carbonate and iron, which might otherwise sink to the ocean floor.

The researchers studied this phenomenon in adult *Calanus finmarchicus*, a zooplankton species found throughout the northern Atlantic Ocean, including the Gulf of Maine. They were investigating whether the pH and oxygen levels within the copepods' guts were consistent, whether they were stable, whether they varied according to diet, and whether any portions of the guts were depleted of oxygen. They found that the pH varied from 5.3 to 8.8 — an important issue, since calcium carbonate dissolves at pH levels below 7.5.



*Calanus finmarchicus*, after a big meal of *E. huxleyi*. Photo by David Fields.



A copepod (aka a microbioreactor) from Boothbay Harbor, Maine. Photo by Pete Countway.

Their research suggests that more than six percent of the calcium carbonate ingested by a grazing copepod will be dissolved in its guts and released back into the water. They also found low levels of oxygen saturation within the gut, facilitating the release of a large amount of methane (a significant greenhouse gas) while feeding.

This research, which calls copepod intestines "microbioreactors of global ocean processes," helps scientists to understand the role of these tiny creatures in regulating the levels of oxygen, methane, and calcium carbonate in the ocean waters, and helps predict how changes in copepod populations will alter global processes.

*The study of these extreme organisms may yield enzymes or other products important for nutrition, the development of new energy sources, and a variety of biotechnology applications.*

Dr. Pete Countway

Photo by Robert Mitchell

# *DEEP-SEA HYDROTHERMAL VENTS* Incubators for Biodiversity

Dr. Pete Countway with colleagues on *Alvin*. Photo courtesy of Pete Countway.

Deep-sea hydrothermal vents represent some of the most extreme environments on Earth, with heat and pressure inhospitable to most organisms, yet new research by Senior Research Scientist Dr. Peter Countway shows that these areas are overflowing with microbial life.

Countway and his fellow researchers have made four missions to deep-sea vents in the North Pacific on board the submersible vehicle *Alvin.* Two of the trips took them to the Guaymas Basin hydrothermal vent field in the Gulf of California, about halfway between Baja and mainland Mexico. Covered by a kilometer of sediment, the vent system there percolates a steady stream of hydrothermal fluids into the surrounding waters. The hydrocarbons in these fluids feed a microbial mat of sulfur-oxidizing bacteria around the seep, making the area extremely rich in microbial eukaryotes that feed on these bacteria.

Photo by Robert Mitchell.

Until recently, it was assumed that many single-celled eukaryotes (known as protists) in the deep-sea environment actually originated at shallower depths, eventually sinking to the deep sea. Previous research by Countway and his colleagues in the North Atlantic showed that this is likely not the whole story in explaining deep-sea protist distributions, given evidence for distinct assemblages of deep-sea protists that are not observed higher in the sunlit euphotic zone. In fact, only about 25% of the DNA sequences from deep-sea collections matched sequences from overlying shallow-water habitats.

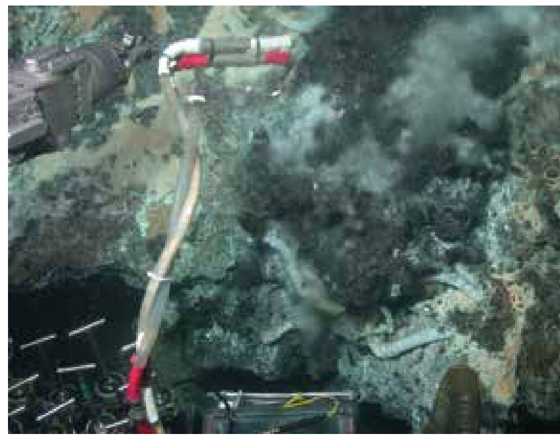
To study the life at these deep-sea vents, Countway and his colleagues deployed a series of microbial colonizers comprised of open-cell sponges inside acrylic tubes, which provided a colonization surface — first for bacteria and then for eukaryotic microbes that consume the bacteria. The samples — containing ciliates and other microbial eukaryotes — were brought back the surface, re-pressurized to mimic the conditions in the deep sea, and inoculated with green-fluorescent bacteria. The eukaryotic microbes ingested the bacteria, demonstrating that these organisms were indeed active at deep-sea vents and providing evidence for previously unknown food-web dynamics in this environment.

By using single-cell genomic techniques, further investigation of these protists is beginning to provide a wealth of information on what has been a poorly-studied class of organisms.

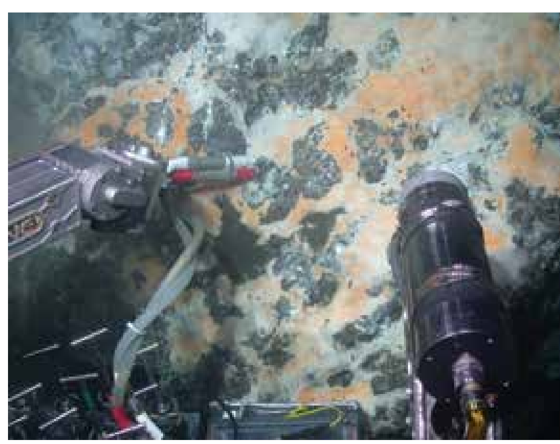
This research not only contributes to our knowledge of the distribution of species across the planet — even in these inhospitable extreme environments — it also provides more clues about the trophic dynamics of microbial communities, and how energy moves through deep-sea vent ecosystems. It may also eventually give us greater understanding about how life evolved on Earth and inform our search for life on other planets.

Countway's Microbial Ecology Laboratory plans to use the study of these extreme organisms to search for enzymes or other products that may be important for nutrition; the development of new energy sources; and the ability to withstand extremes of temperature, acidity, or radioactivity for use in a variety of biotechnology applications.

Above: A colony of the giant tubeworms, *Riftia pachyptila*, growing in front of an orange and white mat of sulfur-oxidizing bacteria at the Guaymas Basin deep-sea hydrothermal vent system in 2000 m of water.



Above: The port side robotic arm of the submersible *Alvin* (top left) is shown deploying a vacuum sampling device to collect microbial mat material from the surface of a hydrothermal "flange" structure. "Shimmering" water is shown in the top and central portion of the image, and is escaping from a pool of hot hydrothermal fluid that had accumulated on the underside of the flange.



Right: Additional samples were collected on different flange structures at Guaymas Basin. Temperatures on the topside of the flange were characteristic of temperate habitats, ranging from ~15-25 C, and providing an ideal habitat for microbial eukaryotes.

Photos and captions by Pete Countway.

Satellite image of *The Deepwater Horizon* oil spill taken from the International SpacTe Station, May 4, 2010. Photo by JAXA astronaut S. Noguchi. Courtesy NASA.

*The full effect of the* [Deepwater Horizon] *spill may not be known for years, so researchers have pioneered a new method to study methane and other hydrocarbons on the ocean floor over long periods of time.*

Dr. Beth Orcutt

Photo by Dennis Griggs

*ECOGIG*

# Deepwater Impact

How did the 2010 *Deepwater Horizon* oil spill affect the microbial ecosystem in the Gulf of Mexico? Senior Research Scientist Dr. Beth Orcutt is providing some of the answers to that question. Her research is part of the Gulf of Mexico Research Initiative's ECOGIG (Ecosystem Impacts of Oil and Gas Inputs to the Gulf), a research project established after the spill and funded by the British Petroleum-sponsored Gulf of Mexico Research Initiative.

The *Deepwater Horizon* spill resulted in the release of more than 200 million gallons of crude oil, a third of which is estimated to have remained on the bottom of the ocean, where it joined natural seeps of methane and oil from the ocean floor. In addition to the oil itself, millions of gallons of chemical dispersants were used in attempting to break up the oil, more than has ever been used in this context before.

The full effect of the spill may not be known for years, so ECOGIG researchers have developed a pioneering new method to study methane and other hydrocarbons on the ocean floor over long periods of time. In April 2012, the ECOGIG team deployed seafloor "landers" — six-by-six-by-nine-foot packages of sensors, instruments, and sample collectors. The landers sit on the ocean floor for months at a time, enabling long-term studies of the microbial degradation of oil and monitoring of the flow of methane gas from the seafloor.

After the first deployment, the landers were picked up in November 2012 with the aid of the RV *Falkor* — a research vessel provided to researchers free of charge by the Schmidt Ocean Institute — making it the longest record of seafloor hydrocarbon analysis to date. Two more lander deployments and recoveries have already occurred, with more scheduled in the near future.

The landers are being sent down each time with samples of tar balls or other hydrocarbons from the *Deepwater Horizon* spill, allowing *in situ* incubation of microbes on the oil, so that researchers can observe how long it takes the oil to degrade. The lander also pulls fluid from the sediment and collects samples of the microbes that are present. Once the samples are brought back to the surface, they are examined for biosignatures of the methane they consumed on the ocean floor, which provides a fingerprint of the activity they are conducting in the natural environment. The lander also collects water temperature, current, and oxygen and methane content data, developing a picture of the dynamics of the ocean system over time.

With the first chemistry data collected, the next task will be to extract DNA from the sampled microbes, allowing researchers to identify exactly which microbe species are present in the Gulf and what processes are occurring there.

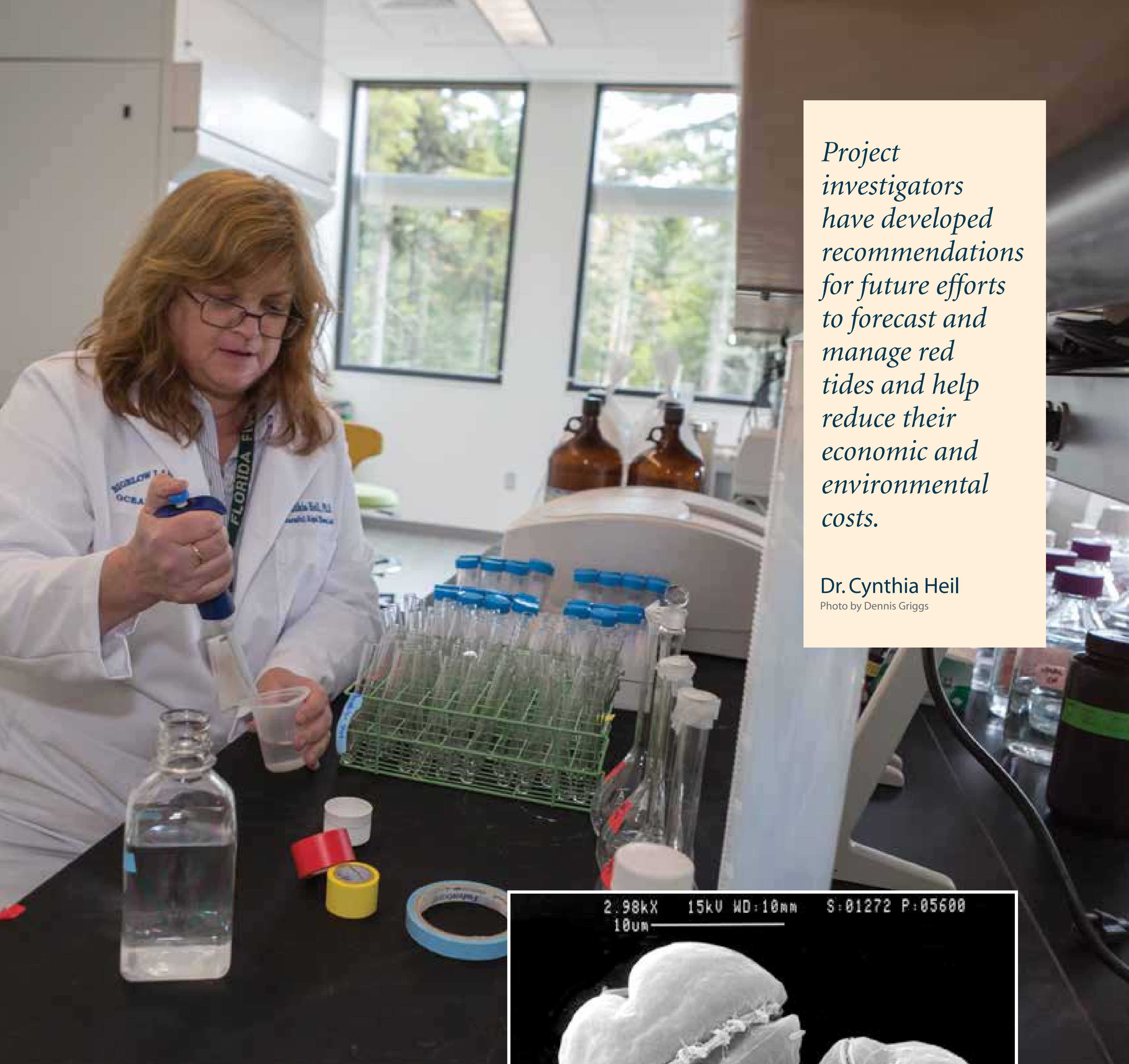
These long-term studies will allow Orcutt and other researchers to determine how much time it takes microbes to consume methane and observe the changes to the microbial community that have been created by the addition of spilled hydrocarbons to the Gulf of Mexico.

More information about this project can be found at www.ecogig.org

Borehole CORK observatory instruments on the sea floor. Photo courtesy of Woods Hole Oceanographic Institution and Beth Orcutt.

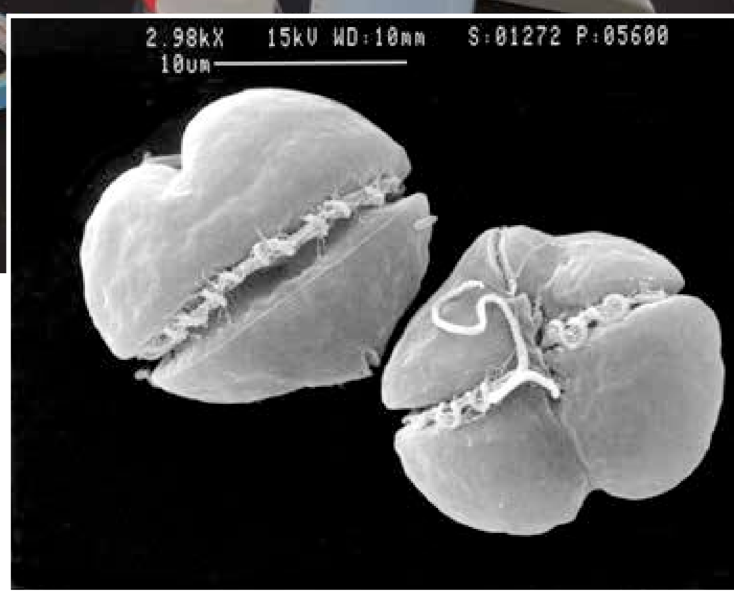
## The Deep Biosphere

Considering how important surface marine microbes are to global biogeochemical cycles—including the production of oxygen and the regulation of carbon dioxide—marine microbes living deep in marine sediments in oceanic crust and in hydrothermal vents may also be playing important roles in the cycling of elements and the flux of energy on Earth. Scientists currently estimate that there may be between 30 and 70 times more microbes living beneath the seafloor than in the ocean itself or in the soil on land. By combining state-of-the-art molecular biology and geochemistry techniques with observatory science, researchers in the Bigelow Deep Biosphere Laboratory advance our collective understanding of the form, function, and importance of the ocean's deep biosphere, and its relationship to a changing global ocean.



*Project investigators have developed recommendations for future efforts to forecast and manage red tides and help reduce their economic and environmental costs.*

Dr. Cynthia Heil
Photo by Dennis Griggs




Scanning electron microscope image of two *Karenia* cells. Courtesy of Cynthia Heil.

## *ECOHAB*
# Monitoring Florida's Red Tides

Much like Maine, the economy of Florida is highly dependent upon tourism. But Florida has something that Maine does not — frequent, toxic blooms of the algae *Karenia brevis*. The red tides in the Gulf of Mexico can affect not just the natural resources of western Florida, but also the local economies and human health. Understanding the dynamics of these *K. brevis* blooms is essential in order to forecast, monitor, and manage these dangerous events.

To better understand Florida's toxic red tides, Senior Research Scientist Dr. Cynthia Heil has spent the past five years as the lead investigator on a project studying the nutrient dynamics of *K. brevis* blooms in the Gulf of Mexico. The project — funded by NOAA's Ecology and Oceanography of Harmful Algal Blooms (ECOHAB) Program — involved nine biologists, chemists, physicists, and modelers from seven research institutes.

The ECOHAB: *Karenia* Project had two main goals — to find out what nutrient sources were fueling the massive blooms and to identify where those nutrients originated. The researchers started with a not-so-simple hypothesis: that there would be no "smoking gun" singular nutrient source contributing to the algal blooms, despite the public perception that the blooms were caused by coastal runoff and pollution. Over the course of the project, the team conducted four two-week cruises, as well as numerous field, retrospective, and laboratory studies in order to increase the body of knowledge about these algal blooms.

The hypothesis proved to be quite true — the research team found a complex system of a dozen different nutrient sources for *K. brevis*

*Karenia brevis* bloom approaching the Jacksonville, Florida shore in 2007. Photo courtesy of Cynthia Heil.

blooms. These included everything from sunlight interacting with dissolved organic matter, estuarine runoff, and the upwelling of deep, nutrient-rich waters, to the interaction with several other microscopic organisms. For example, the researchers found that *K. brevis* feeds on several species of single-celled cyanobacteria, while the algae itself is fed upon by macrozooplankton, which in turn excrete more nutrients for *K. brevis* to once again take up. Even the toxins produced by the algae had a role, as the fish killed during red tide blooms provided a supply of nutrients back to the bloom when they decayed, a process called algal cell "fish farming."

Project investigators have developed several conclusions and recommendations for future efforts to forecast and manage red tides and help reduce their economic and environmental costs.

First, they recommend finding ways to reduce some of the controllable nutrient sources through best management practices, although they caution that the complex nutrient system supporting *K. brevis* blooms means reducing any one nutrient source may not have a visible direct impact on bloom frequency or severity.

Second, they recommend developing further short-term forecasting and "now-casting" capabilities to monitor and predict short-term impacts (such as which communities will experience respiratory irritation or fish kills and when they will experience them).

Finally, they suggest adapting and utilizing new and existing educational outreach programs in order to reduce the vulnerability of West Florida residents to red tides as they occur.

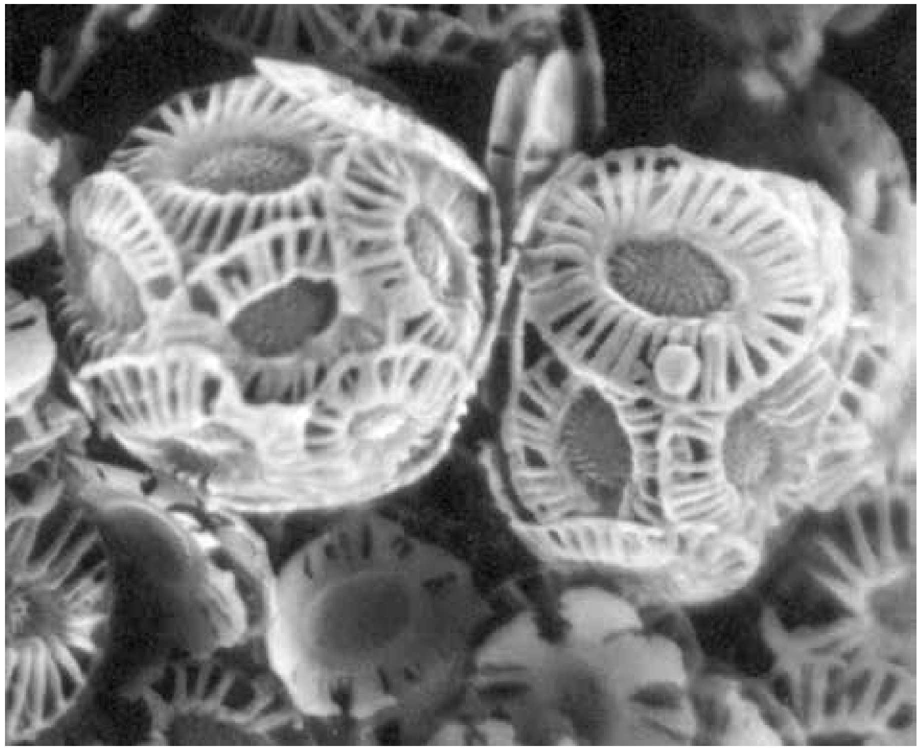
The result of this research promises to be far reaching. It has already led to testimony at two Senate hearings, 112 scientific publications, and more than 200 presentations, as well as meetings with stakeholders in government, tourism, and industry, all of which will have a key role in the future of Florida's red tides.

*The techniques used in this research may be transferable to virus-host systems in other environments, allowing easier and earlier identification, and a better understanding of the genetic basis of viral infection.*

Dr. Willie Wilson
Photo by Dennis Griggs

# Targeting Viruses in Phytoplankton

Even phytoplankton can get viruses. Infected algae quickly die, affecting ocean biodiversity, releasing a cocktail of different chemicals, and changing the flow of nutrients and carbon in the water. But when a virus arrives in a phytoplankton community, only some cells become infected. Why do some cells die while others resist the infection? The first step toward understanding the ecological implications of viruses that infect phytoplankton is coming up with the ability to determine which, and how many, cells are infected and which are not. Dr. Willie Wilson, Dr. Joaquín Martínez-Martínez, and other scientists at Bigelow Laboratory have developed a method to separate and investigate virus-infected and healthy cells within a phytoplankton community.



Virus attached to *E. huxleyi* coccolithophore cell (on the right). Scanning electron microscope image courtesy of K. Ryan, Marine Biological Association, Plymouth, UK.

Their study "Targeted Sorting of Single Virus-Infected Cells of the Coccolithophore *Emiliania huxleyi*," published in *PLoS One,* examined virus-infected cells of the coccolithophore *Emiliania huxleyi.* One of the most abundant and widespread phytoplankton species, *E. huxleyi* cells play an important role in the chemistry of the ocean, because they cover themselves with calcium carbonate (chalk) plates. When they die, that calcium carbonate sinks to the bottom of the ocean, forming sediment and sequestering carbon from the atmosphere.

The researchers developed a system to sort infected cells from non-infected cells by inoculating a culture of *E. huxleyi* cells with a virus strain called EhV-86. After the virus had time to incubate, the researchers added a fluorescent dye, FM 1-43, which attached to irregular bulges, known as blebs, in the membranes of cells. Blebbing was caused by an increased production of dense lipid, which was the cell's physiological response to the virus infection. Use of the dye made it possible to identify virus-infected cells at earlier stages of infection than was the case in previous studies.

Once the infected cells were identified, the researchers used the MoFlo™ flow cytometer at the Laboratory's J.J. MacIsaac Facility for Aquatic Cytometry to sort them according to levels of natural fluorescence and fluorescence caused by the dye. Once the separation was complete, they were able to compare the DNA of the infected and non-infected cells. Further research will examine genetics of individual phytoplankton cells to investigate why some cells become infected, while others do not.

Understanding how viruses infect and kill *E. huxleyi* cells is providing important insights about the chemical systems at work in the ocean. The techniques used in this research may be transferable to virus-host systems in other environments as well, allowing easier and earlier identification and a better understanding of the genetic basis of viral infection.

“PARASITE-OMICS”

# Fighting Oyster Disease with Malaria Weapons… and Malaria with Oysters


*In collaboration with the U.S. Military Malaria Vaccine Program, this research is exploring use of the oyster parasite as a platform to deliver vaccines against malaria.*

Dr. José Antonio Fernández-Robledo

Photo by Dennis Griggs

Oysters and malaria may not come up in the same sentence very often, but there is reason they should. Oyster beds around the world have been devastated by the protozoan parasite *Perkinsus marinus*, which is genetically closely related to the agents that cause malaria, toxoplasmosis, and other diseases that can threaten both humans and livestock.

Malaria alone is one of the most costly diseases on the planet: More than 200 million people contract the disease every year, resulting in hundreds of thousands of annual fatalities, mostly children under the age of five. Developing a better understanding of these parasites and how they affect their hosts could result in new ways to fight them and save lives.

Senior Research Scientist Dr. José Antonio Fernández-Robledo has turned to the marine environment to look for answers. He has employed cutting-edge DNA- and RNA-sequencing techniques and genetic engineering to help provide clues regarding the mechanisms of parasite virulence. He calls his research "parasite-omics."

Two of the major diseases that impact the oyster production in North America are "Dermo" disease caused by *Perkinsus marinus* and "MSX" (multinucleated sphere X) disease caused by *Haplosporidium nelsoni*. These protozoan parasites have devastated natural and farmed oyster populations in the United States, significantly affecting the shellfish industry and the estuarine environment. In some cases, the gradual expansion of their geographic distribution has been associated with global warming and shellfish trade.

Because traditional techniques for identifying parasites in oysters are neither species-specific nor as sensitive as molecular techniques, Fernández-Robledo uses PCR-based diagnostic technology to identify the parasite's unique genetic signature, which makes it possible to detect a single individual parasite cell in a 100 mg tissue sample.

A key aspect of Fernández-Robledo's research involves the search for compounds that can inhibit the proliferation of the *Perkinsus* parasite. About 20 such compounds were previously known to exist; Fernández-Robledo has now identified close to 300 by using the "Malaria Box," an open access library of compounds developed to combat malaria.

His research will now focus on the mechanics of how these compounds affect the parasites, as well as the health of infected oysters. The compounds can also be tested against other protozoan parasites including *Haplosporidium nelsoni*, the recent cause of mass mortalities in Maine oysters.

A related aspect of Fernández-Robledo's research approaches the problem from a different direction. In collaboration with the U. S. Military Malaria Vaccine Program, he is exploring the use of the oyster parasite as a platform to deliver vaccines against malaria.

The research group has shown that laboratory mice fed *Perkinsus* — which shares about 50% of the genes with the protists that cause malaria — do not experience any organ or tissue damage from the parasite. An even more interesting finding was that the oyster parasite, unlike most parasites that enter the body orally, induced an active and specific immune-response in the mice.

*Crassostrea virginica*. Image courtesy of Woods Hole Oceanographic Institution.

An oyster farm in the Damariscotta River, Maine. Photo courtesy of NOAA News Archive.

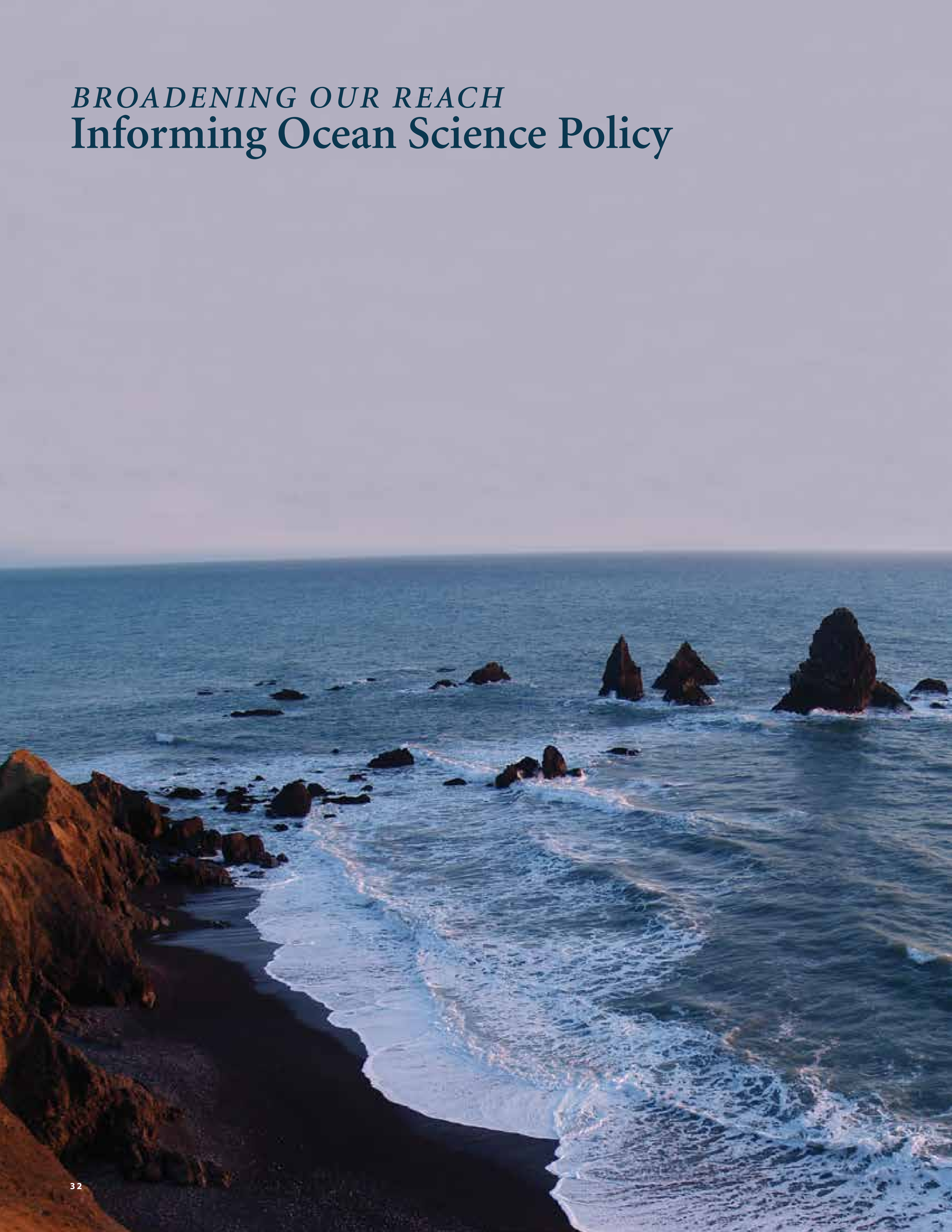
This suggests it may be possible to create an oral malaria vaccine that would be easier to transport, deliver, and preserve than current injected vaccines, which require refrigeration, can be hard to give to children, and often lead to infections at injection sites.

The next step is to replicate the experiment to evaluate the protection against malaria in mice — a first step to what could ultimately lead to a human vaccine against malaria.

Fernández-Robledo's work adds a new biotechnology and biomedical dimension to the Laboratory's research. It is a clear illustration that the world's ocean systems may hold answers to questions we are only beginning to ask.

*BROADENING OUR REACH*

# Informing Ocean Science Policy



Conducted across multiple interfaces — atmosphere, ocean, and sediments — and over scales spanning many orders of magnitude, from individual microbial cells in the laboratory to fieldwork on the open seas and across entire ocean basins, research at Bigelow Laboratory focuses on the microbial life and biogeochemical dynamics of the world's ocean, and on the interactions between ocean ecosystems, global processes, and the terrestrial environment. The Laboratory is known throughout the scientific community for its contributions to ocean science, and for its unique culture of scientific freedom, open interdisciplinary collaboration, mentorship, and entrepreneurship.

The Consortium for Ocean Leadership describes the United States as "an ocean nation," with more than 90,000 miles of shoreline, over half of the population living in coastal communities, and 95% of the nation's commerce moving through U.S. ports.

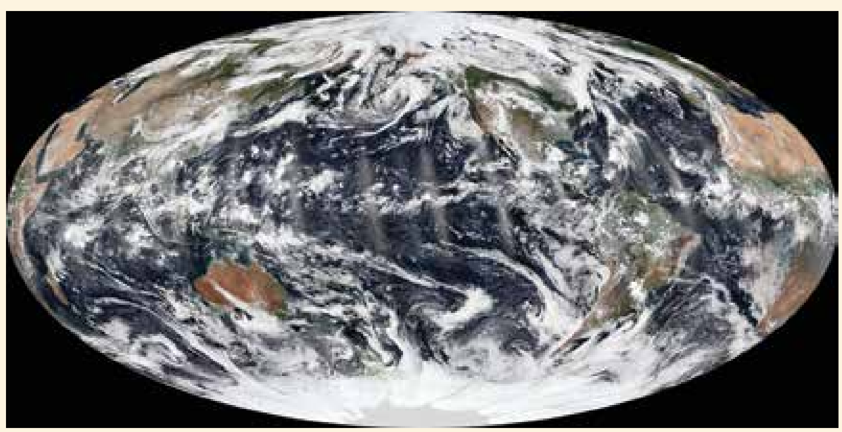
More globally, the ocean, besides providing 99% of the habitat on the planet, contains all but 3% of the water on Earth, drives major climate and weather patterns, and shelters an immense reservoir of as yet unexplored biological diversity.

It is well known that ocean ecosystems have played critical roles in the changing environment of the planet, such as modulating the long term, predictable cycle of ice ages over millions of years. Human intervention is increasingly dominating the natural world, however, and the consequences of these interventions on ocean ecosystems are not clear. The interaction between the human population and the marine world will have increasing significance in the decades ahead.

Fundamental discovery science at Bigelow Laboratory addresses these and other priority objectives in the U. S. National Ocean Policy by crossing frontiers in our understanding of the ocean's role in the global environment. In so doing, we are also advancing the human potential to create a sustainable future by informing policies that shape the stewardship, management, and use of the ocean and its resources.

Photo by Robert Healing

Photo by Greg Bernard



***"Three Oceans, No Cyclones"***

A composite of natural color images from fourteen polar satellite passes on September 8, 2013, acquired by the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi National Polar-orbiting Partnership satellite. At the time of those near-midday passes, there were no hurricanes, cyclones, or tropical storms in the Atlantic, Pacific, or Indian Ocean basins—a relatively rare occurrence at the height of the hurricane/cyclone season in the northern hemisphere. There was plenty of cloud cover, of course, and smaller storm systems. In the eastern Pacific, remnants of tropical storm Lorena were breaking up near the Baja Peninsula. In the eastern Atlantic, the pieces of tropical depression #9 were starting to gather near the islands of Cape Verde; by the next day, tropical storm Humberto would form. Image Courtesy of NASA.

*—NASA Earth Observatory*


Photo by Dennis Griggs

## *BUILDING A BRIDGE*

# Between discovery science and commercialization partners

Discoveries at Bigelow Laboratory are also creating new opportunities for economic growth across a broad array of human enterprises in multiple large markets, including energy, food, and medicine.

Advanced technology transfer requires strategic stewardship and effective commercialization of the Laboratory's growing storehouse of specialized knowledge. The Office of Corporate Alliances and Technology Transfer (CATT) works with the Laboratory's Core Facilities and Senior Research Scientists in establishing relationships with private sector partners to bring new discoveries and technologies to the marketplace.

The transfer of technology and expertise adds to the universal body of knowledge, is of direct benefit to society, and brings revenue back to the Laboratory, while at the same time industry partners profit financially from access to new technologies.

# *Partnerships, Agreements, and Awards*

CATT Director Mark Bloom. Photo by Tatiana Brailovskaya.

Through a growing network of partnerships with private sector businesses and industries, the Laboratory has begun to channel its intellectual capacity to solve problems and directly benefit society. Given the tremendous potential for new products and technologies within the vast reserves of undiscovered organisms and compounds in the world's ocean, the Laboratory is establishing relationships with other research institutions and with private technology companies to put intellectual property to work for commercial purposes.

**Recent Highlights**

- The Laboratory has entered into a five-year Strategic Inter-Institutional Partnership Agreement with the University of Mississippi, establishing a framework that facilitates joint R&D activities between the two institutions to advance biopharmaceutical sciences and develop transformative new approaches to marine natural products research and development. Specific areas of collaboration include molecular exploration of natural products as potential new sources of pharmaceuticals, nutraceuticals, and cosmeceuticals; research and development of prototype anti-infective and anti-cancer agents from aquatic sources; and development of new techniques for evaluating the potential research and commercial applications of aquatic algae, bacteria, viruses, and invertebrates.
- Bigelow Analytical Services (see p. 38) has entered into an agreement with the Maine Department of Marine Resources to perform shellfish toxin testing for the State of Maine. The Agreement involved purchase of state-of-the-art analytical equipment and staff training, as well as basic research.
- The Laboratory was among twenty institutions chosen to participate in the Global Academic Innovation Network (GAIN)/U. S. State Department/U. S. Chamber of Commerce Colombia Free Trade Initiative. The Laboratory's focus will be on marine science programs at four Colombian universities. The goal of the Initiative is to establish research connections between U. S. and Colombian scientists, as well as to foster and enhance the academic technology transfer capabilities of Colombian universities in partnership with U. S. academic institutions.
- The World Intellectual Property Organization (WIPO) awarded Bigelow Laboratory's Provasoli-Guillard National Center for Marine Algae and Microbiota (NCMA) the designation of International Depository Authority (IDA) under the "Budapest Treaty on the International Recognition of the Deposit of Microorganisms for the Purposes of Patent Procedure."

Other milestones include an Exclusive Biological Materials Commercial License with Wake Forest University Health Services for CCMP757 (*Rhodomonas* sp. Cryptophyceae (class), Strain EPB14) and the Laboratory's receipt of the 2012 Innovator of the Year Award from the Maine International Trade Center in recognition of our work in bringing the results of scientific discoveries from the ocean to society as a whole.

Photo by Dennis Griggs.

# *Core Facilities*

Bigelow Core Facilities represent concentrations of world-class expertise, underpinned by advanced technologies and designed to deliver scientific outcomes both for the Laboratory's scientists and its collaborators and partners worldwide. Each of the facilities is directed by a Senior Research Scientist to ensure that it is at the cutting edge of technology and scientific discovery. An individual model has been created for each facility to define the price of the service/sample to the customer (whether internal or external, academic or corporate), taking into account the direct costs of the service; the indirect costs, including utilities and space allocation; and provision for replacing equipment when needed to ensure future sustainability.

**Provasoli-Guillard National Center for Marine Algae and Microbiota (NCMA)**

***Cultivating diversity***

The official U. S. collection of marine phytoplankton, the NCMA is a repository for thousands of strains of living marine and freshwater algae, and is expanding to include bacteria and viruses.

The goals of the facility are to maintain a diverse culture collection for future biotechnology research; serve as a bioresource center to receive, maintain, and distribute living cultures of marine and freshwater algae, bacteria, and viruses; provide technical expertise and services to scientists and businesses worldwide; and continuously develop a comprehensive database available for public use.

The NCMA offers

- Sales of algae and algal growth media worldwide
- Mass algal culture production
- Algal characterization
- Culturing methods courses
- Screening for natural products
- International Depository Authority for the World Intellectual Property Organization

**Single Cell Genomics Center (SCGC)**

***Reading nature's genetic tales, one cell at a time***

Over 99% of the world's microbial species, constituting most of the life on Earth, remain uncultured, making them inaccessible to classical microbiology research methods. Single cell DNA sequencing, pioneered by SCGC scientists, reads the genomic blueprints of life without the need for cultivation. During its first four years in operation (2009-2013), the Single Cell Genomics Center (SCGC) established partnerships and supported research projects at over 60 universities, research institutes and companies in six continents.

Over 600,000 individual microbial cells — originating from the marine environment and soils to mammalian gut content — have been processed through the facility's high-throughput pipeline. The SCGC serves as a global engine of discovery, providing unique genomic data from major evolutionary branches and making a significant impact on scientific understanding of microbial life on the planet.

The SCGC is the first facility of its kind to make single cell genomics accessible to external users for research in

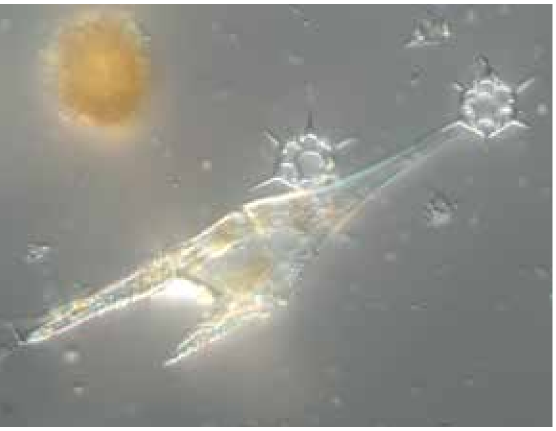
- Microbial ecology, biogeochemistry, and evolution
- Bioprospecting
- Human health
- High throughput pipeline for individual cell analysis
- Environmental sample preparation and single cell whole genome amplification
- PCR and amplicon sequencing

**Jane J. MacIsaac Facility for Aquatic Cytometry**

***The power of fluid and light***

Flow cytometry is a technique that uses laser light to rapidly detect particles, such as phytoplankton, in a water sample. The Jane J. MacIsaac Facility for Aquatic Cytometry in the Norton Center for Blue Biotechnology serves as a multi-user resource for scientists seeking to apply new technologies to the study of algae and aquatic microbes from marine and freshwater ecosystems.

The facility is available to scientists from around the world for



*Ceratium sp.,* with Silicoflagellates. Photo by Pete Countway.

development of new applications and stains; routine cell counting; cell sorting, isolation, and cultivation; biochemical analysis; culture purification; and aquatic flow cytometric training.

The Jane J. MacIsaac Facility for Aquatic Cytometry includes

- two state-of-the-art cell sorters
- a FACScan desktop analyzer
- microscopy and imaging systems
- a FlowCAM® imaging-in-flow analyzer (an instrument invented at Bigelow Laboratory and manufactured and distributed worldwide by Fluid Imaging Technologies in Yarmouth, Maine)
- a portable laboratory van with a cell sorter for researchers interested in sorting cells from fresh "field" samples for many applications.

**Bigelow Analytical Services**

***Providing a high quality service to academic research, industry, and the state***

Closely linked to the J. J. MacIsaac Facility for Aquatic Cytometry and the National Center for Marine Algae and Microbiota, Bigelow Analytical Services (BAS) offers access to the latest instrumentation, services, and training in analytical techniques for research and development in high technology fields — from nutrients and nutritional value to taste components and toxins — including modern quantitative approaches to:

Fundamental composition
- inorganic nutrients in seawater
- chlorophylls
- total lipids, protein, carbohydrates
- elemental composition

Detailed chemical composition
- algal and shellfish biotoxins
- lipid profiles (PUFAs)
- pigments / antioxidants
- amino acids and carbohydrate profiles

Chemical rate measurements
- isotope tracer approaches
- primary production and trophic transfer
- compound-specific production

Analytical capabilities at BAS include an Elemental Analyzer coupled to an IRMS, HPLC, LC-QQQMS, LC-TOF-MS, GC-MS, SEM, and Fluorescence and Confocal Microscopy.

**The Seawater Suite**

***Algal production and experimental aquaria***

The Laboratory's Center for Ocean Health (COH) is home to a state-of-the-art, continuously flowing seawater system, with taps in each of the Laboratory's three science wings. Photovoltaic cells on the roof of the COH supply up to 20kW of the power needed to operate the system. Designed to be expandable for future research needs, the system has the capability to provide 50- to 2,460-liter vessels for experimental use, with a temperature variability from 4° to 37° C.

Photo by Cheryl Rau.

Photo by Tim Pinkham.

Features of the seawater suite include

- Shore facility with equipment to hold and pump raw seawater from the Damariscotta River to the main buildings.
- 3,000-gallon seawater tank with bag filters to minimize particulate matter.
- Redundant pumps to ensure a continuous supply of seawater.
- Variable frequency drive (VFD) raw and filtered seawater pumps that can change GPM (gallons/minute) on demand, as needed
- Seawater pasteurizer and steam sterilizer
- Six 2,460-liter mesocosms, six bag continuous culture systems for large volume growing, and Kalwall tubes for smaller scale cultures

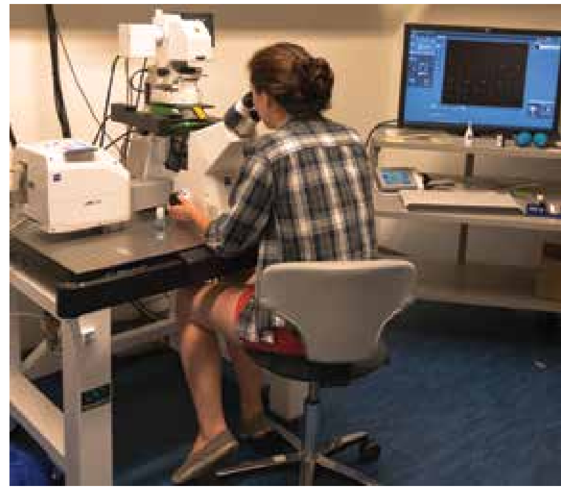
Photo by Dennis Griggs.

## The Industrial Collaboration Laboratory

### *Room to discover*

The Industrial Collaboration Laboratory (ICL) is a publicly accessible area in the Norton Center for Blue Biotechnology and available for entrepreneurial activities both within and outside Bigelow Laboratory. Advanced facilities in the ICL are designed to foster entrepreneurial activities and facilitate partnerships with the aquaculture, pharmaceutical, environmental/bioremediation, analytical instrument, and biofuels industries, among many others.

The ICL can be rented on a "pay for space and services" basis and offers private companies and businesses 550 square feet of laboratory space, with 180 square feet of adjacent office space.



Courtesy of Carlton Rauschenberg.

## High Performance Computing Center

### *Serving a diverse range of data processing needs*

The Laboratory's High Performance Computing Center is positioned to handle a diverse range of scientific data processing needs.

The Center features

- A "compute cluster" comprised of an SGI UV 2000 shared memory super computer configured with 160 CPU cores and 1.28TB of RAM. The cluster is scalable to 4096 CPU cores and 64TB of RAM and supports both native Windows and Linux applications.
- A data warehouse comprised of a NetApp FAS 3250 Clustered SAN/NAS currently configured with 300TB of raw storage and dual head units for high performance and high availability. The system is non-disruptively scalable to over 2PB in size and supports a wide variety of SAN and NAS protocols for utmost flexibility.
- 100Mbps Internet connectivity to facilitate fast transfers of large datasets. Connectivity is scalable to 1Gbps on both the public Internet and Internet2.

Photo by Robert Mitchell.

# Scientists-in-Training

Training and mentoring the next generation of ocean scientists is integral to Bigelow Laboratory's mission. The Laboratory's education portfolio includes high school, undergraduate, and professional training programs; postdoctoral training and mentoring; an active program of public presentations; and online resources for teachers and students.

Photo by Dennis Griggs.

## *Postdoctoral Education and Ethics Training Program*

The Laboratory is committed to helping its postdoctoral researchers acquire and refine the knowledge and crucial skills necessary to develop and sustain a successful research career in ocean sciences. Bigelow postdocs meet as a group to address a variety of topics, including responsible conduct of research; professional development, such as writing grant proposals and peer-reviewed papers; and skill-related topics, including bioinformatics and data analysis techniques, electron and confocal microscopy, and flow cytometry. Postdocs are also asked to mentor, provide lectures, and help guide students in the Laboratory's other education programs. Senior Research Scientist Dr. David McClellan was coordinator of the postdoctoral education program in 2012-13.

**Bigelow Postdoctoral Researchers, 2012–13**

*Geomicrobiology*
Erin Field
Emily Fleming
Adam Mumford
Jarrod Scott

*Single Cell Genomics*
Jessica Labonte
Brandon Swan

*Trace Metal Biogeochemistry*
Jochen Nuester

*Ocean Observing and Optics*
Meredith White

*Phytoplankton Ecology and Biogeochemistry*
LeAnn Whitney

## *Gulf of Maine and the World Ocean REU Program*


REU Class of 2012. Photo by Nicole Poulton.

The Laboratory's National Science Foundation-funded Research Experience for Undergraduates (REU) Program brings students from across the United States to spend ten weeks working on an independent research project with Bigelow scientist mentors. Ten students were selected for the 2012 program. Each student identified a research question; developed a proposal; conducted research; and prepared an abstract, poster, and formal presentation given during the science symposium at the end of the program.

The program is directed by Senior Research Scientist Dr. David Fields and is designed to give undergraduates an opportunity to become part of the Bigelow community and experience laboratory-based research with an emphasis on hands-on, state-of-the-art methods and technologies.

**REU Class of 2012**

**Marie Neidig**
*University of Southern Maine*
Production and Assimilation of Demethylsulfonionproprionate (DMSP) by Marine Phytoplankton
MENTORS: Matrai and Archer

**James (Nick) Hunt**
*Texas A&M University-Corpus Christi*
Enhancement of Lipid Production in Microalgae by Dodecane Addition and Nitrate Limitation
MENTORS: Wilson and Countway

**Cynthia Liles**
*University of California-Riverside*
The Relationship between Microalgae Growth Phase and Lipid Content
MENTORS: Countway and Wilson

**Emily Bell-Hoerth**
*Earlham College*
Variations in Phytoplankton Communities Associated with Bivalve Aquaculture in Coastal Maine
MENTORS: Poulton and Heil

**Zakary Jaques**
*Colby College*
Effects of Dissolved Humic Compounds from the Damariscotta and Kennebec Rivers on Marine Microbial Communities
MENTORS: Poulton and Heil

**Andrew Burchill**
*University of Chicago*
Detecting Evolutionary Selection in Highly Conserved Proteins: Physiochemical Shifts in the Mammalian Cytochrome *b*
MENTOR: McClellan

**Ashley Poehls**
*Lake Superior State University*
Effects of Ocean Acidification on Growth Rate, Biomass, and Coccolith Morphology of the Coccolithophore *Pleurochrysis*
MENTORS: Balch and Fields

**Melanie Ross**
*Colby College*
Indirect Effects of Ocean Acidification on *Acartia tonsa*
MENTORS: Balch and Fields

**Alyson Lowell**
*University of Maine*
Experimental Techniques for Characterizing Sheath-forming *Zetaproteobacteria*: A Methodological Approach
MENTORS: Fields and Emerson

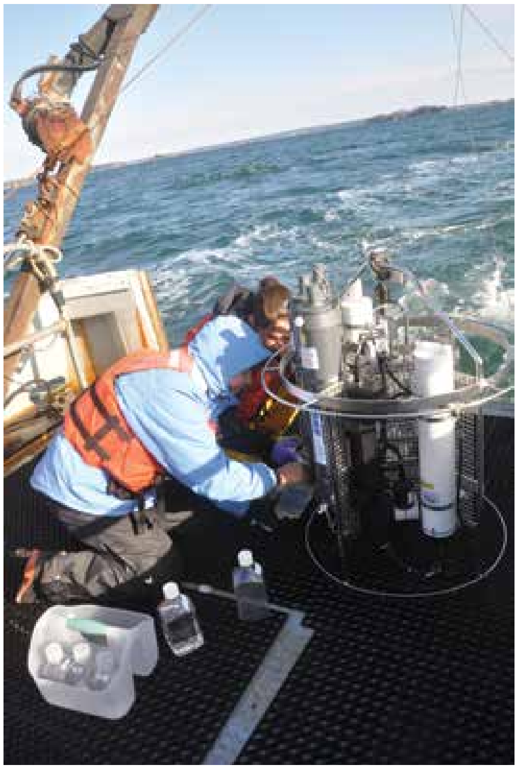
**Kaitlyn Pritchard**
*Northeastern University*
Examining the Grazing Preferences and Digestive Processes of *Oxyrrhis marina* Using a Ratiometric Fluorescent Dye
MENTORS: Nuester and Twining

# *Changing Oceans: The Colby Semester*

In 2009, Bigelow Laboratory and Colby College in Waterville, Maine, entered a formal partnership agreement to explore potential collaboration on academic and research programs of mutual interest. For the past three years, Bigelow scientists have taught courses during the College's January Program "semester," a five-week period of intensive course offerings between the fall and spring academic terms. The success of that program subsequently led to the development of a full semester-in-residence program for Colby students. The first Colby semester at the Laboratory, now part of the College's off-campus study program, began in the fall of 2012.

Working in collaboration with Colby faculty, Bigelow scientists designed a curriculum for undergraduates interested in an in-depth understanding of ocean science and a three-month, hands-on opportunity to work side by side with scientists conducting advanced research, in what was essentially a three-to-one Ph.D.-to-student ratio.

The students studied with Bigelow scientists Drs. Paty Matrai, Pete Countway, Ben Twining, David Fields, and Nicole Poulton, who taught four courses — The Ocean Environment, Diversity and Function of Life in the Oceans, Ocean Biogeochemistry on a Changing Planet, and Oceanographic Field Methods: Life on the Ocean Wave, which included daylong research cruises from the Damariscotta River estuary to the open ocean. Each student received 16 Colby College credits upon completion of coursework and an independent study project.



Life on the ocean wave. Photos by Greg Bernard.


Shaklee

# *BLOOM: The Bigelow Laboratory Orders of Magnitude Program*

Bigelow Laboratory's education program recognizes the importance of fostering ocean literacy among high school students and their teachers in Maine. A thriving education program also benefits the continuing professional development of our scientists, and creates a pool of alumni who are conversant in ocean sciences, with the potential to help support scientific discovery in the future.

Photo by Tatiana Brailovskaya.

Each May for the past 24 years, the Laboratory has hosted the BLOOM (Bigelow Laboratory Orders Of Magnitude) Program for Maine high school juniors, now augmented by a weeklong professional development workshop for Maine educators, designed to develop methods to bring ocean science into the classroom. Both programs provide hands-on experience with ocean research that includes fieldwork, data analysis, and discussion of emerging directions and issues in ocean sciences.

**2012 BLOOM Students**

Briar Bragdon, *Hall-Dale High School*
Sarah Caron, *Boothbay Region High School*
Taylor Church, *Catherine McAuley High School*
Sadia Crosby, *Morse High School*
Sarah Finnemore, *Skowhegan Area High School*
Michael Frazier, *Lewiston High School*
Brandon Howlett, *Presque Isle High School*
Chelsea Hunter, *Camden Hills Regional High School*
Kaleija Inniss, *Brunswick High School*
Leah Jones, *Bangor High School*
Jacob Leeman, *Oxford Hills Comprehensive High School*
Abigail Onos, *South Portland High School*
Kalista Rattray, *Houlton Junior/Senior High School*
Raina Rauch, *Erskine Academy*
Allison Scully, *Waterville Senior High School*
Mylie Warlick, *Kennebunk High School*

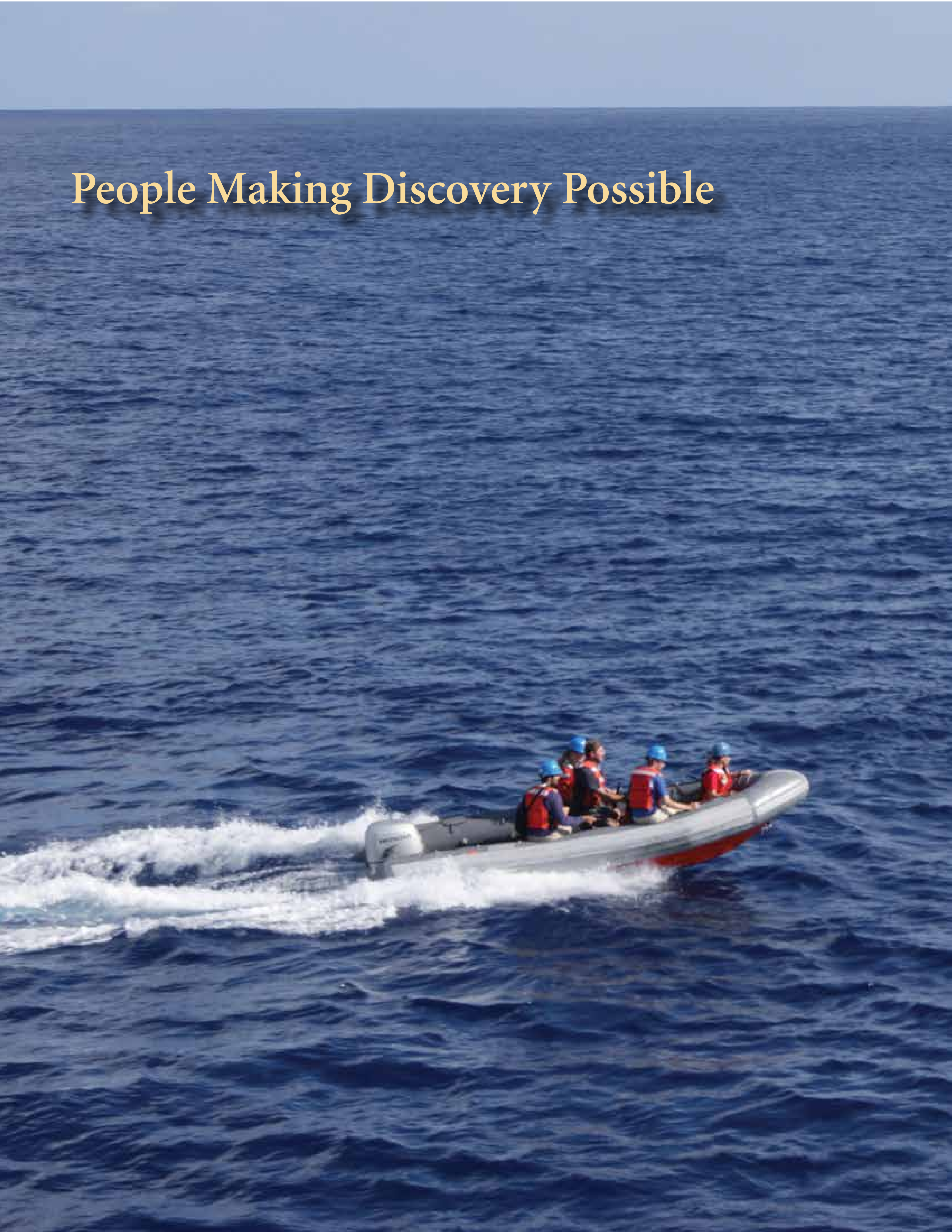

Photo by Nicole Poulton.


Photo by Nicole Poulton.

**2012 BLOOM Educators**

Cathy Woodbury, *Noble High School*
Maureen Edgerton, *Edward Little High School*
Kristen McGovern, *North Haven Community School*
Kathy Floyd, *RSU14 (Windham Raymond Adult Ed)*
Sue Lamdin, *Brunswick Junior High School*
Judd Thompson, *Warsaw Middle School*
Michelle Miclette, *Boothbay Region Elementary School*

# People Making Discovery Possible



With the effects of federal funding cutbacks rippling through the whole scientific community, philanthropic support of discovery research is critical. Our donors have risen to the challenge and are making it possible for Bigelow Laboratory to not only remain steadfast in its mission, but to grow and thrive through the expansion of research and education programs. From cutting-edge genetic research that is helping to advance the medical community's understanding of disease and search for medicines, to the discovery of new biofuels, each and every donor listed on the following pages is a pioneer contributing to a sustainable future.

Eleven generous visionaries are now participating in our Founders Campaign by pledging $250,000 or more in unrestricted support to help fund the Laboratory's transformational growth:

**Louise and Robert Bowditch**

**David and Margaret Coit**

**Paul and Giselaine Coulombe**

**Robert and Margery Healing**

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**Jane C. MacElree**

**Admiral Kinnaird McKee**

**Richard and Eleanor Morrell**

**Walter and Helen Norton**

**Richard and Denise Rubin**

**Cyrus and Barbara Sweet**

In 2012–13, Trustee Louise Bowditch and her family also hosted the Sea Steward Challenge to match new and increased gifts to our Annual Fund. In response, more than 175 Sea Stewards stepped up to qualify for the match and help us not only to meet, but to exceed, our goal.

The work at Bigelow Laboratory is so exciting because our world's oceans hold tremendous possibilities for new medicines, jobs, alternative energy, and food. By helping our research scientists to understand this last frontier, our donors are investing in our health, economy, and environment. Whether sequencing genes at our state-of-the-art facilities in Maine or studying samples at sea — from the Arctic to the Antarctic and from surface waters to the deep ocean crust — our research team is providing the best possible return on this investment.

The scientific accomplishments highlighted in this report would not be possible without philanthropic support. I want to extend my thanks to everyone listed here for being part of the outstanding legacy we are leaving for future generations by helping to shape the future of ocean science, and thus, the future health of our planet.

— Robert Healing
*Chair of the Board of Trustees*
*Development Committee*

# Annual Fund and Comprehensive Campaign Gifts

Bigelow Laboratory is extremely grateful to the donors listed below. The list represents cumulative contributions made from July 1, 2011 to December 31, 2012. Gifts matched by the Healing Challenge and the Bowditch Family Sea Steward Challenge are designated by an asterisk (*).

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Joseph and Marjorie Graham
Wayne and Deborah Hawkins and family
Mr. and Mrs. Howard V. Hennigar
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Thomas E. Keller
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Marlon and Trudy Lewis
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Kathy and Alan Muirhead
Pat and Charlie Parker
Esther Perkins
Victoria W. Reinecke
Clare B. and Darlene Conner Sampley
Fran Scannell
Drs. Stephanie and Craig Shipp
Joyce Sirois
Colin and Christina Strutt
Jill Kaplan Tupper
Nadia L. Woodman
Dr. and Mrs. W. Redwood Wright
The Yentsch Family

### Gifts in Kind

Chris and Deezie Flower
Knickerbocker Group, Inc.
John C. Laird
Rupert Neily
North Atlantic Capital Corporation
Laurence and Judy Sisson
Dr. Magdalena T. Tosteson

# Scientific Publications

*(2011–2012)*


Li, W.K.W. , **R.A. Andersen**, D.J. Gifford, L.S. Incze, J.L. Martin, C.H. Pilskaln, J.N. Rooney-Varga, **M.E. Sieracki**, **W.H. Wilson**, N.H. Wolff. 2011. Planktonic microbes in the Gulf of Maine area. PLoS ONE, V. 6(6), e20981.

Yang, E.C., G.H. Boo, H.J. Kim, S.M. Cho, S.M. Boo, **R.A.Andersen, H.S. Yoon**. 2012. Supermatrix data highlight the phylogenetic relationships of photosynthetic stramenopiles. Protist, V. 163, pp. 217-231.

Carpenter, L.J., **S.D. Archer**, R. Beale. 2012. Ocean-atmosphere trace gas exchange. Critical Review. Chemical Society Reviews, V.41, pp. 6473-6506.

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Hopkins, F.E. S.A. Kimmance, J. Stephens, R.G.J. Bellerby, C.P.D. Brussard, J.Czerny, K.G.Schultz, **S.D. Archer**. 2012. Response of halocarbons to ocean acidification in the Arctic. Biogeosciences Discussions ,V. 9, pp. 8199-8239.

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**Balch, W.M.**, **D.T. Drapeau**, **B.C. Bowler.**, T.G. Huntington. 2012. Step-changes in the physical, chemical and biological characteristics of the Gulf of Maine, as documented by the GNATS time series. Marine Ecology Progress Series, V. 450, pp. 11-35.

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Howard, M.D.A., A.C. Jones, A. Schnetzer, **P.D.Countway**, C. Tomas, R.M. Kudela, K. Hayashi, P. Chia, D.A. Caron. 2012. Quantitative real-time phlymerase chain reaction for Cochlodinium Fulvescens (Dinophyceae), a potentially harmful dinoflagellate from California coastal waters. Journal of Phycology, V. 48, pp. 384-393.

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Photo courtesy of Nicole Poulton

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# Active Grants and Contracts

*(July 1, 2011–June 30, 2012)*

**RESEARCH**

NSF / Fields / $ 322,532
*Collaborative Research*: From Structure to Information in Mechanosensory Systems: The Role of Sensor Morphology in Detecting Fluid Signals

NSF / Matrai / $ 498,722
*Collaborative Research*: Marine Microgels: A Microlayer Source of Summer CCN in High Arctic Ocean Leads

NSF / Balch / $ 495,729
*Patagonian Shelf Coccolithophore*: Ecological Factors Regulating the Southern Hemisphere's Largest Recurring Coccolithophore Bloom

NSF / Wilson/Stepanauskas / $ 808,750
Functional Genomics of Phosphate Acquisition during Virus Infection of *Emiliania huxleyi*

NSF / Matrai / $ 320,000
*Collaborative Research*: Biological and Physical Controls on DMS Production and Emission during VOCALS

NSF / Yoon/Andersen / $ 993,911
Unlocking the Mysteries of Plastid Origin through Comparative Genomic Analysis of Two *Paulinella* Species

NSF / Stepanauskas/McClellan/Sieracki / $ 976,747
Single Cell Genome Sequencing of Uncultured Prokaryotes from the South Atlantic Mesopelagic

NSF / Twining / $ 257,021
*Collaborative Research*: Iron Storage in Diatoms and N2 Fixing Cyanobacteria: Mechanisms, Regulation and Biogeochemical Significance

NSF / Stepanauskas / $ 650,000
Identification of Photoheterotrophic Microorganisms in Temperate Freshwater Lakes

NSF / Wilson / $ 549,105
Role of Latent Virus Infection in Marine Phytoplankton

NSF / Wilson/Stepanauskas / $ 338,950
*Collaborative Research*: Decoding Virus Leviathans

NSF-ARRA / Matrai / $ 104,337
*Collaborative Research*: Impacts of Changing Seasonality of Wind-driven Mixing on the Arctic System

NSF / Yoon/Fields / $ 1,360,652
*Collaborative Research*: RedToL — Phylogenetic and Genomic Approaches to Reconstructing the Red Algal (Rhodophyta) Tree of Life

NSF / Emerson / $ 115,372
*Collaborative Research*: High Resolution Bacterial Mat Sampler for Operation with Deep Submergence Vehicles

NSF/CCMP / Wilson / $ 1,807,672
*LSCBR*: The Provasoli-Guillard National Center for Culture of Marine Phytoplankton

NSF / Twining / $ 349,430
*GEOTRACES*: Atlantic Section: Characterization of Phytoplankton Trace Metal Quotas and Their Contribution to the Particulate Metal Pool in the Upper Ocean

NSF / Balch/Twining / $ 1,088,876
*Collaborative Research*: The Great Southern Coccolithophore Belt

NSF / Emerson / $ 635,893
Microbial Systems in the Biosphere: Unraveling the Lifestyles of Dominant Freshwater Fe-oxidizing Bacteria

NSF / Matrai / $ 1,075,619
*Collaborative Research*: The O-Buoy Network of Chemical Sensors in the Arctic Ocean

NSF / Yoon/Stepanauskas/Poulton / $ 331,607
Diversity of Marine Protists: Single Cell Genomics and Imaging for TARA Oceans

NSF / Twining/Fields / $ 519,331
Assessing the Chemical Speciation and Bioavailability of Iron Regenerated by Marine Zooplankton

NSF / Stepanauskas / $ 98,918
EAGER: Collaborative Research: Exploratory Application of Single Molecule Real Time (SMRT) DNA Sequencing in Microbial Ecology Research

NSF / Twining / $ 232,152
*Collaborative Research*: Understanding the Role of Picocyanobacteria in the Marine Silicate Cycle

NSF / Stepnauaskas / $ 411,652
Dimensions: An Integrated Study of Energy Metabolism, Carbon Fixation, and Colonization Mechanisms in Chemo Synthetic Microbial Communities at Deep-sea Vents

USC/NSF / Orcutt / $ 49,919
Primary Productivity in Young Oxic Ocean Crust: Rates of Activity and Autotrophic Groups in Subsurface and Seafloor-exposed Basalts from North Pond, Mid-Atlantic Ridge

UWA/NSF / Twining / $ 94,662
EAGER: Characterizing Biological Functions across a Persistent Oceanographic "Hotspot" in the NE Pacific Ocean

USC/NSF / Orcutt / $ 53,338
C-DEBI Theme Team Leader

NASA / Balch/Goés / $ 966,277
Climate Change and Its Impact on the Ecosystem of the Arabian Sea

NASA MODIS / Balch / $ 676,980
A Proposal for Refinement of the MODIS Calcite Algorithm and CAL/VAL Activities Towards Assembly of Earth System Data Records

UWA/NASA / Matrai / $ 445,171
The Autonomous Polar Productivity Sampling System (APPSS)

MSGC/NASA/EPSCoRD / Emerson/McClellan/Stepanauskas / $ 238,347
YEAR ONE Learning How to Breathe: What We Can Learn about Antiquity, Iron Oxidation, and Respiration of Oxygen from Modern Fe-oxidizing Bacteria

NASA / Balch / $ 685,001
Coccolithophores of the Beaufort and Chukchi Seas: Harbingers of a Polar Biogeochemical Province in Transition

NASA (workshop) / Sieracki/Stpeanauskas / $ 24,545
Workshop: Redefining Microbial Genomics: The Power of Sequencing Individual Cells

UCONN/NASA / Balch / $ 47,337
Differentiating Sources of Backscattering in the Southern Ocean: Calcite, Bubbles and Other Optical Constituents

NASA / Balch / $ 609,464
Generating Environmental Data Records of Ocean Particulate Carbon with NPP/NPOESS

NASA – MODIS / Balch / $ 649,998
Science data analysis for the MODIS ocean product for particulate inorganic carbon (PIC)

NASA GNATS '11 / Balch / $ 845,945
Land-to-Sea Carbon Export from the Northeast Watersheds of North America to the Northwest Atlantic Ocean

MSGC/NASA/EPSCoR / Emerson/McClellan/Stepanauskas
$ 243,012
YEAR TWO Learning How to Breathe: What We Can Learn about Antiquity, Iron Oxidation, and Respiration of Oxygen from Modern Fe-oxidizing Bacteria

UDEL/NASA / Emerson / $ 198,932
Development of Biogenicity Criteria and Paleoenvironmental Interpretations for Iron Microfossils Based on the Morphology, Physiology, and Behavior of Modern Iron-Oxidizing Bacteria

MSGC/NASA/EPSCOR / Emerson / $ 4,978
Travel to NASA Center w/Undergrad or Graduate Intern

ONR / Emerson / $ 955,602
Role of Fe-oxidizing Bacteria in Metal Biocorrosion in the Marine Environment

MT/NOAA / Wilson / $ 112,655
Development of a Technology Platform for the Assessment and Controlled Delivery of Therapeutic Bacteriophage in Aquaculture

UMiami/NOAA / Poulton / $ 14,286
Flow Cytometric Analysis Relating to the *Deepwater Horizon* Oil Spill—Nancy Foster Cruise

NOAA / Fields/Balch / $ 524,792
Implications of Ocean Acidification on Carbon Export in a Simplified Planktonic Food Chain: Experiments on *Arcatia pleurochrysis*

USFWF / Larsen / $ 15,000
Document Historical Distribution of Native Oysters

CPW / Matrai / $ 310,000
O-Buoy

ECU/Sloan / Stepanauskas / $ 148,960
Deep Life I: Microbial Carbon Transformations in Rock-Hosted Deep Subsurface Habitat

B&G Moore Fdn. / Wilson/Fields/Archer/Martínez-Martínez / $ 1,001,422
Gene Flow Mediated by Virus Life

## EDUCATION

UME/NSF / Sieracki/Goés/Roesler / $ 622,108
COSEE

NSF/REU / Wahle/Fields / $ 258,685
REU Site: Bigelow Laboratory for Ocean Sciences—Undergraduate Research Experience in the Gulf of Maine and the World Ocean

NSF/REU 2012-14 / Fields / $ 274,884
REU Site: Bigelow Laboratory for Ocean Sciences—Undergraduate Research Experience in the Gulf of Maine and the World Ocean

## PLANT AND EQUIPMENT

NSF/FSML / Emerson/Wilson / $335,341
Establishing Marine Archaeal, Bacterial and Viral Collections to Complement the CCMP at Bigelow Laboratory

NSF/FSML / Emerson/Twining/Fields/Yoon / $341,265
Acquisition of a Confocal Laser Scanning Microscope at the Bigelow Laboratory for Ocean Sciences

MTI/MTAF / Wilson/Shimmield / $4,528,971
Bigelow Center for Blue Technology

NSF ARRA / Shimmield/Matrai/Balch/Twining / $4,975,000
A Center for Ocean Biogeochemistry and Climate Change: Addressing the Role of Plankton in Ocean and Climate Change

NIST / Shimmield / $9,145,710
Bigelow Center for Ocean Health: Applying Systems Microbiology to Ocean Ecosystems

## TECH TRANSFER CONTRACTS

HEPI / Wilson / $33,000

CPW / Poulton / $83,059
Contract for FCM consultancy

B&G Moore Fdn. / Wilson / $40,000

ProDalG / Wilson / $500

# Summary Financial Statement

*(July 1, 2010–June 30, 2012)*

## Statement of Activities and Changes in Net Assets *(For fiscal years ended June 30)*

| | 2012 | 2011 | 2010 |
|---|---|---|---|
| **Operating Activities** | | | |
| Operating Revenue and Support | | | |
| Grants and contracts for research and education | $4,211,178 | $5,360,968 | $5,208,410 |
| Subawards | 60,241 | 364,950 | 932,646 |
| Contributions to Capital Campaign | 2,271,849 | 886,120 | 1,514,844 |
| Other revenue, including course fees | 921,820 | 958,296 | 662,180 |
| Contributions to Annual Fund | 326,616 | 356,138 | 338,326 |
| **Total Operating Revenue and Support** | $7,793,704 | 7,926,472 | 8,656,406 |
| **Operating Expenses** | | | |
| Research and Education | 5,992,042 | 7,046,983 | 7,084,982 |
| Unallocated management and general | 1,679,587 | 621,673 | 449,404 |
| Development | 770,571 | 722,512 | 368,396 |
| **Total Operating Expenses** | 8,442,200 | 8,391,168 | 7,902,782 |
| **Change in Net Assets from Operating Activities** | -648,496 | -464,696 | 753,624 |
| **Non-Operating Revenue and Support** | | | |
| Contributions and grants for equipment and construction | $10,855,498 | 4,836,557 | 788,806 |
| **Change in Net Assets from Non-Operating Activities** | 10,855,498 | 4,836,557 | 788,806 |
| **Total Change in Net Assets** | $10,207,002 | 4,371,861 | 1,542,430 |

## Statement of Financial Position *(At June 30)*

| | 2012 | 2011 | 2010 |
|---|---|---|---|
| **Assets** | | | |
| Cash | $678,002 | $747,540 | $350,481 |
| Cash restricted for Research | 751,294 | | |
| Cash restricted for construction | 1,137,595 | 859,086 | |
| Pledges receivable | 1,513,316 | 990,414 | 1,080,063 |
| Investments | 1,003,373 | 1,277,693 | 1,614,537 |
| Property and Equipment, Net | 33,803,853 | 15,261,099 | 6,542,677 |
| Other | 1,481,872 | 1,486,676 | 1,187,746 |
| **Total Assets** | $40,369,305 | $20,622,508 | $10,775,504 |
| **Liabilities and Net Assets** | | | |
| Short Term Liabilities | $2,106,850 | $1,040,973 | $1,094,214 |
| Short Term Liabilities for construction | 2,545,814 | 2,523,772 | |
| Long Term Liabilities | 11,456,488 | 3,004,612 | |
| Net Assets | | | |
| Unrestricted | 5,352,074 | 5,759,150 | 6,102,203 |
| Temporarily Restricted | 18,705,935 | 8,091,857 | 3,376,943 |
| Permanently Restricted | 202,144 | 202,144 | 202,144 |
| **Total Net Assets** | $24,260,153 | $14,053,151 | $9,681,290 |
| **Total Liabilities and Net Assets** | $40,369,305 | $20,622,508 | $10,775,504 |

Bigelow Laboratory for Ocean Sciences was formed in 1974. The Laboratory 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 2010, 2011, and 2012 were audited by Macdonald Page & Co. The summary financial statements shown here are derived from the audited financial statements. Copies of the audited financial statements are available on request from the Director of Finance, Bigelow Laboratory for Ocean Sciences, 60 Bigelow Drive, P.O. Box 380, East Boothbay, ME 04544; or by email to finance@bigelow.org. Bigelow Laboratory's IRS990 form is available at: www.bigelow.org/about-bigelow-laboratory/governance_administration/financial_statements/.

# Trustees, Scientists, and Staff



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Photo by Dennis Griggs

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Courtesy of Steve Archer.

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## CREDITS

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Inside front cover:
Phytoplankton bloom in the North Atlantic Ocean. Courtesy of NASA.

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Page 37: ©2011 Christopher Barnes

Page 40: Greg Bernard

Page 44: Nicole Poulton

Page 46: Jarrod Scott

Back cover: Micrograph of diatoms by Pete Countway.

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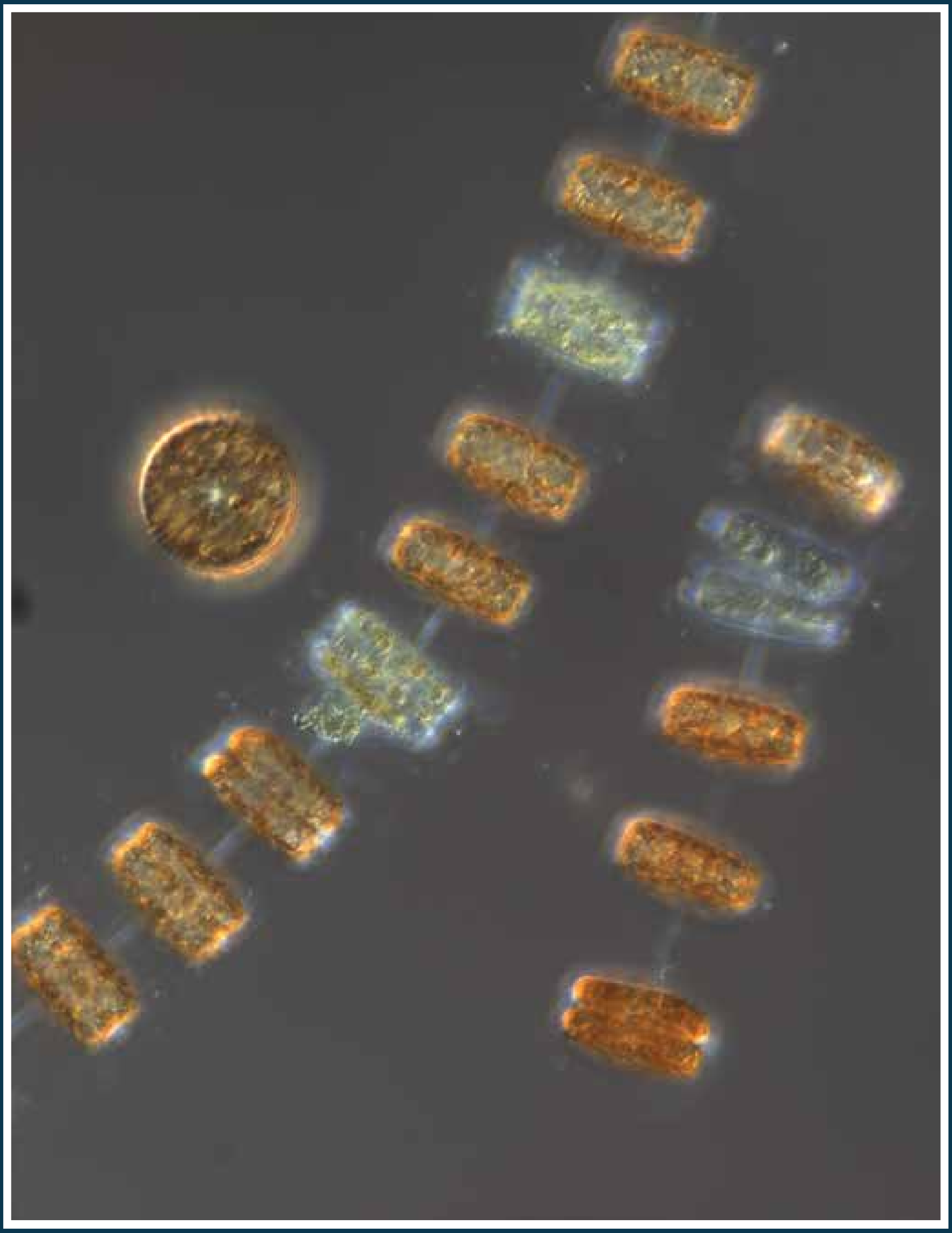

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