The Global Reach of Microbial Oceanography

BIGELOW LABORATORY FOR OCEAN SCIENCES

2011 ANNUAL REPORT

The mission of Bigelow Laboratory for Ocean Sciences is to understand the key processes driving ocean ecosystems, their evolution, and their fundamental relationship to life on Earth through interrelated programs in research, education, and technology transfer. Our focus ranges from microbial oceanography to the large-scale dynamics of the global ocean.

The first two wings of the Bigelow Ocean Science and Education Campus.

In High Gear

A Message from the Chairman of the Board


Photo by Robert Mitchell.

David Coit

The excitement and promise of a new era for Bigelow Laboratory is growing by leaps and bounds at the site of our new, state-of-the-art Ocean Science and Education Campus in East Boothbay. Construction is in high gear, and the first research wing—the Bigelow Center for Blue Biotechnology—officially opened in mid-December. The second and third wings are on schedule for completion in June and November of 2012, when all of our science teams will be back together under one roof.

Equally important is the progress we are making in the three core sectors of the Laboratory's mission: leading edge ocean science research, education of the next generation of oceanographic researchers, and commercialization of the Laboratory's discoveries for the good of society.

The Laboratory's commitment to fundamental ocean research has never been stronger. Our scientists continue to win major research grants from the National Science Foundation and other research granting agencies. In the past months, we have hired two exceptional new Senior Research Scientists; three more will join the senior research team in the coming year. The results of the Laboratory's research have been published in prestigious, peer-reviewed journals—including *Science*, *Proceedings of the National Academy of Sciences of the United States*, *Microbial Ecology*, and *Journal of Geophysical Research*, among many others.

Our education programs have achieved new levels of success as well. Both the annual BLOOM residency program for Maine high school juniors and the summer Research Experience for Undergraduates program—which draws college students from across the United States—have attracted record numbers of applicants and high marks from attendees. Our partnership with Colby College is another highlight, as Colby students and faculty have been working with our scientists in classrooms, in our laboratories, and as active participants in research expeditions at sea. These programs bring new energy and enthusiasm to the Laboratory, as the next generation of ocean researchers interacts with Bigelow scientists.

The Laboratory's new Department of Corporate Alliances and Technology Transfer has been actively building partnerships with private companies to bring Bigelow discoveries into the marketplace. In addition to making the benefits of our federally funded research directly available to society, these partnerships contribute to the financial health of the Laboratory itself.

Photo by Dick Rollins.

View of the Bigelow Ocean Science and Education Campus from South Bristol, Maine.

Our ambitious plans require increasing financial support from a wide variety of sources. Competitively won state and federal grants have provided over $18.5 million toward the construction of the new campus. Financing from the First, N.A. completed the funding package for the current $33 million construction project. Significant additional support is needed for successful implementation of the Laboratory's *Strategic Plan*. In fiscal 2011, the Board of Trustees established the Office of Advancement to organize a full time fund raising effort to ensure the Laboratory's financial stability well into the future. This office has already made substantial strides toward expanding the community of donors who recognize and support the Laboratory's pioneering contributions to global ocean science.

Bigelow Laboratory is blessed with exceptional executive leadership and world-class scientists. This, together with the generosity of our donors and growing public awareness about the importance of our mission, has launched a transformative period in the Laboratory's history. Even with this wealth of resources, however, new challenges and opportunities lie ahead of us as we wrestle with the significant dynamics that come with rapid organizational growth and a more complex business model.

I encourage you to consider supporting Bigelow Laboratory and becoming a part of its exciting future. Our work is making a vital contribution to understanding the world's ocean and discovering the benefits that this last global frontier brings to all our lives.

David M. Coit
Chairman of the Board of Trustees

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The Global Reach of Microbial Oceanography

Photo by Richard G. Sandifer.

Graham Shimmield

Behind the stunning detail and perspective in the wonderful image by artist Glynn Gorick on our front cover, lies a profound message about the role of the ocean and the microbial life within it. Personally, I think of this artist's image as the oceanic equivalent of the Hubble telescope, which has revolutionized the way we have viewed our universe over the past two decades. The equivalent for the ocean is the massive power of genomics, advanced cellular biogeochemistry, and ultra high resolution microscopy performed on living cells—all of which is underway at Bigelow Laboratory and is described in the pages of this Annual Report.

Look carefully at the center of Glynn's image and you will recognize the familiar double helix of the DNA strand, the building block of life, but then also notice the geometric viruses that transfer genetic codes between their infected hosts in the marine phytoplankton community. A single teaspoon of seawater contains millions of these viruses, along with many tens of thousands microscopic marine phytoplankton, the single-celled plants at the foundation of ocean life.

By using sunlight (seen as the burst of rainbow light in the upper left quadrant of the image), myriads of phytoplankton take up the carbon dioxide (CO_2) that dissolves into the oceans from the atmosphere, producing oxygen and building tissue and skeletons made of chalk or silica. The magnitude of this process is almost incalculable. We know that its overall effect made the planet habitable by oxygenating the atmosphere 2.4 billion years ago, and created vast reserves of hydrocarbons in the underlying sediments through geologic time—but the key details of geographic variation in CO_2 uptake and decomposition of organic matter are among the essential scientific questions currently under investigation by Bigelow Laboratory scientists.

One underlying and chronic challenge facing the ocean is that the increase in CO_2 in the atmosphere, which dissolves into the ocean, is making ocean water more acidic. Consider a marine world where the skeletons and shells of corals, molluscs, bivalves, and even some of the phytoplankton themselves (e.g., *Emiliania huxleyi*, visible at "7 o'clock" in the image) begin to dissolve, or experience growth defects. Then consider the predators (the middle "ring" in the image) who need these plankton and shellfish to survive, and we start to understand the nature of interconnected ecosystems and the vital role that microbial life plays in fueling major protein sources for the fisheries that humans, along with our most valued charismatic species, depend upon.

Another surprising concept, but one with fundamental importance to the biogeochemical cycling described above, is the *rate* at which the ocean's microbes grow and die. Although the total biomass of phytoplankton in the ocean at any given time is enormous (around 1 billion tons), it is still significantly smaller than the combined biomass of all the land plants that we know (500 billion tons, much of which is wood). But if we consider that the average lifespan of our terrestrial plants is ten years, compared to one week for phytoplankton, we see that the rate of carbon fixation by microscopic plants in the ocean is over 500 times faster, making the total amount of carbon being fixed by marine phytoplankton in one year roughly equal to all the rainforests, boreal forests, and crops on land!

Now turn to the back cover. Using satellites to record the spectral quality of the reflected and adsorbed light in the surface ocean, we can see the majesty, scale, and detail in the distribution of these microorganisms in the waters off Patagonia in South America. Filaments of chalk-secreting *E. huxleyi* weave between ribbons of cyanobacteria and diatom blooms in response to a complex interplay of currents and nutrient sources. Our scientists work with NASA satellite scientists and brave the turbulent waters of the Southern Ocean to reveal the latest dynamics of ocean fertilization, ocean acidification, and cellular biochemistry in an ecosystem larger than the rainforests of South America.

As we learn more about the genetic, chemical, and ecological significance of the microbial ocean, we begin to appreciate its potential contribution to human enterprise. Novel sources of energy, pharmaceuticals, foodstuffs, waste remediation, and even biodegradable packaging are being identified among the vast diversity of microscopic marine life. The Laboratory is making rapid strides in collaborating with other research groups and local and regional industry partners, and is reaching out to some of the largest multinational corporations to bring our discoveries to the marketplace for economic and societal good.

The broader impacts of public-funded science are an imperative for all of us in the research community. Understanding the ecology of marine microbial communities and their response to the environmental stresses we impose on ocean ecosystems helps us to predict the benefits that could come from ocean stewardship, or the consequences of its lack. We intend to play a full part in communicating the wonder and benefit of our work, as well as firing-up the next generation of aspiring scientists and decision-makers to better understand the role and value of the ocean.

This year's Annual Report marks the true emergence of Bigelow Laboratory as a research institution dedicated to improving our understanding of the ocean's microbial world, and moving out from seclusion among scientific peers to become a full contributor to fundamental science, education, and technology transfer on the last major frontier for discovery on our planet. I commend to you the description of our endeavor—and its associated value to society—as a true and profound vision of our ocean world, illuminated with all the new tools at our disposal, and captured on our cover by Glynn Gorick.

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

Marine Microbiology

why it matters

Marine microbes and viruses represent one of the largest untapped biotechnological resources on the planet, offering the potential for new products and medicines of direct benefit to humans. Research on the contribution of the ocean's microbial life to ocean ecosystem resilience at the genetic level has begun to reveal the key role ocean microbes play in maintaining marine biodiversity.

Although invisible to human eyes without magnification, single-celled microorganisms are the oldest, most abundant, and most diverse forms of life on the planet. They are directly involved in the health of humans and other large organisms, and have a central role in global cycling of critically-important elements, including carbon, nitrogen, and other greenhouse gases. Ecological interactions in the microbial ocean have profound effects on natural selection, ocean chemistry, and the abundance and biological productivity of ocean life.

Until recently, however, the microscopic size of this vast reservoir of life has been a major stumbling block in oceanographic research.

The Laboratory's marine microbiology researchers are pioneering advanced technologies in molecular biology and microbial ecology that make it possible to investigate the viruses, bacteria, archaea, and algae living in diverse environments throughout the world's ocean.

Working both with the wealth of microbial organisms in the natural environment and with those preserved in cultures, the researchers' goal is to understand the genetic and chemical make-up of the ocean's microbial communities, how they adapt to environmental changes, and their function within the essential ocean processes that support life on our planet.

Life and Death in a Drop of Seawater

Bigelow scientists Dr. Hwan Su Yoon from the Algal Molecular Evolution Laboratory, Dr. Ramunas Stepanauskas from the Single Cell Genomics Center, Dr. Mike Sieracki from the J. J. MacIsaac Facility for Aquatic Cytometry, and Dr. Willie Wilson from the Marine Virology Research Laboratory have discovered that picobiliphytes, tiny marine microbes first believed to be single-celled plants when they were originally identified several years ago, are actually animals that use a range of feeding strategies to survive. The discovery has opened a new window onto the intricate ecological relationships within marine microbial ecosystems.

Working in collaboration with scientists from Rutgers University, the researchers studied a drop of seawater taken from Boothbay Harbor in Maine. They used cell sorting technology in the Laboratory's J. J. MacIsaac Facility to separate photosynthetic from non-photosynthetic cells, and were surprised to find that picobiliphytes lacked chlorophyll—*they were not plants at all, but animals*.

Single cell genomics technology pioneered at the Laboratory made it possible to analyze genomes of these microscopic animals directly from the environment, helping answer diverse ecological questions about the tiny animals' feeding behavior, their ecological status in the food web, and how diseased individuals differ from neighboring healthy ones.

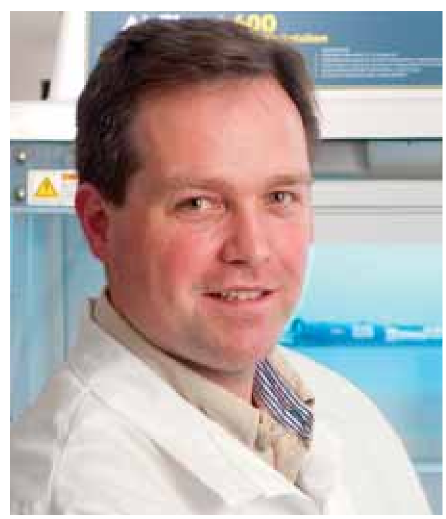
Less than 10 micrometers across, picobiliphytes are found throughout the ocean and are among the most miniscule forms of life on the planet. Despite their size, they adopt a range of feeding strategies similar to the

Dr. Hwan Su Yoon

Dr. Mike Sieracki

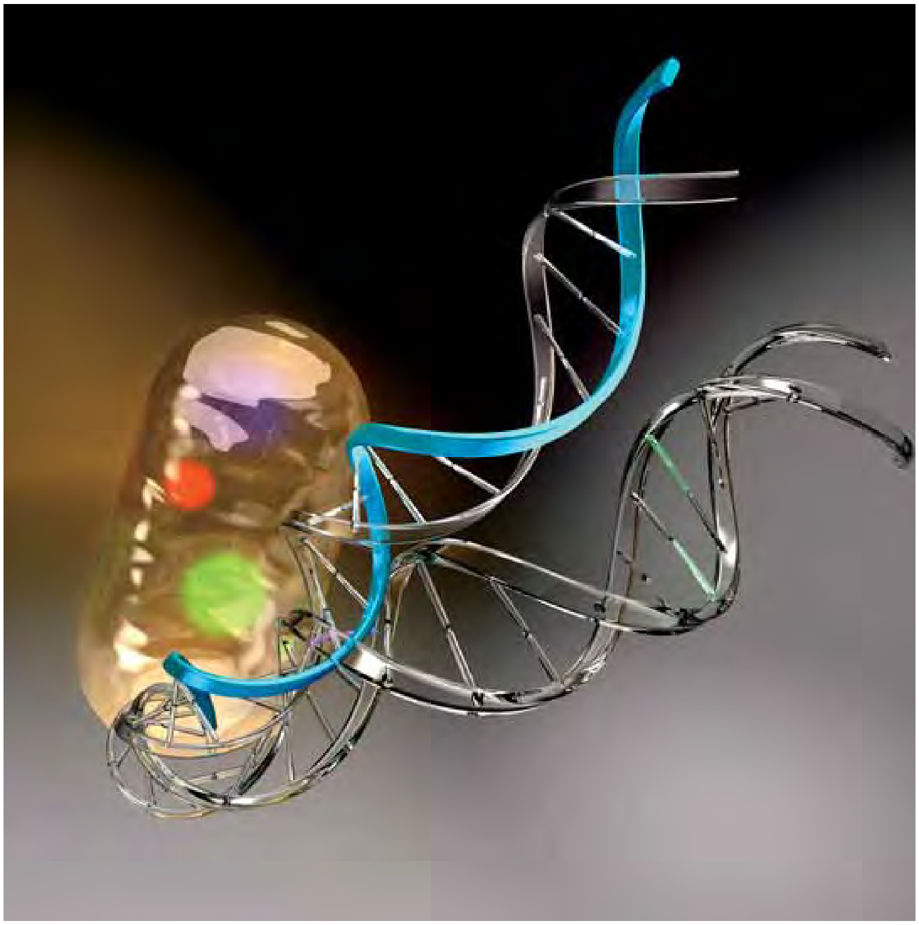
Photo by Buddy Doyle (2).

Dr. Ramunas Stepanauskas



Dr. Willie Wilson

Photo by Richard G. Sandifer (2).



A graphic artist's rendition of a single-cell organism in the ocean, trailing its sequenced DNA. *Illustration by: Susanne Ruemmele. Courtesy of Rutgers University.*

kind of complex interactions taking place among the much larger animals in, for instance, an African savannah ecosystem. The research team used single cell technology to explore the analogous drama underway within a single drop of ocean water—an ongoing drama featuring predation, viral infections, and the divergent fates of closely related species.

While sequencing the genomes of three individual picobiliphytes, the researchers found traces of entire microscopic food chains, including evidence that the tiny creatures were feasting on viruses and virus-infected bacteria. The team also found and reconstructed the genome of a previously unknown virus that was infecting one of the picobiliphytes.

The team's findings were published the journal *Science* (May 6, 2011). The tools developed for this project may also contribute to other kinds of biological research, helping, for example, to understand why different cancer cells from the same tumor grow at different rates.

The Evolving Mechanics of Life

Dr. David McClellan's research in the Bigelow Evolutionary Bioinformatics Laboratory applies the power of bioinformatics and evolutionary modeling—the science of collection and analysis of complex biological data—to understanding one of the most basic signatures of life.

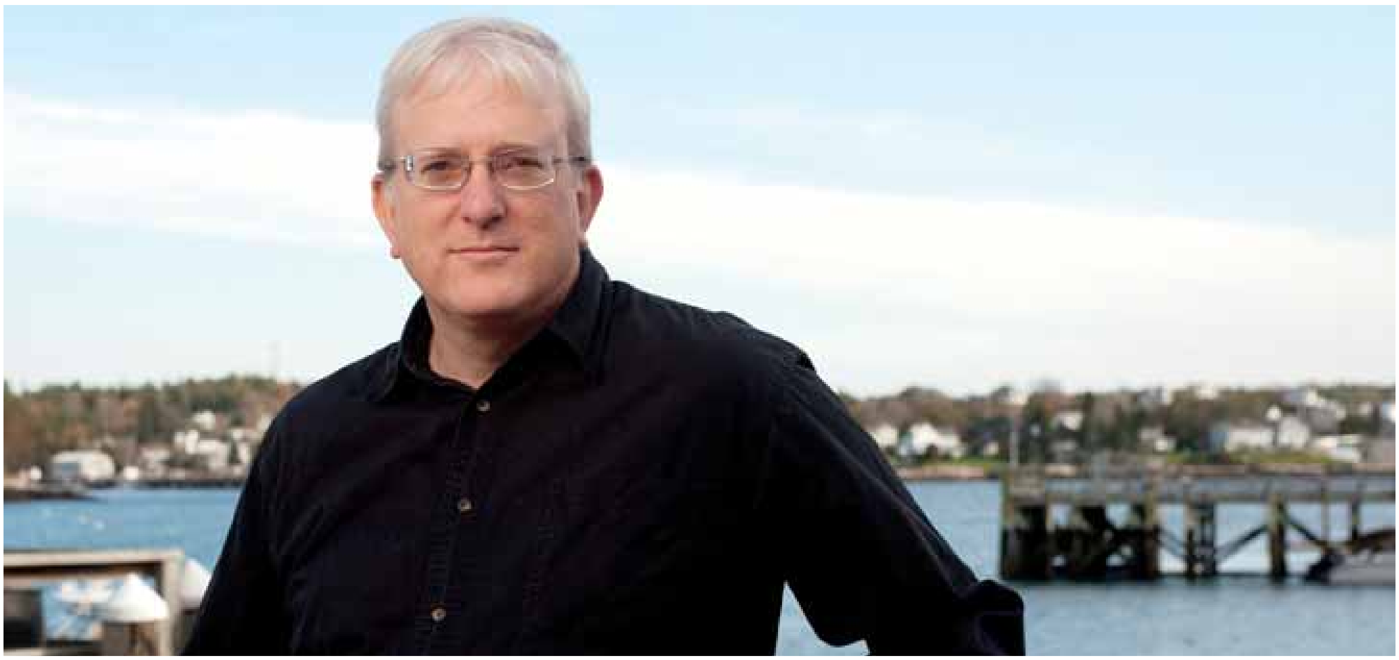


Photo by Richard G. Sandifer.

Breathing, or respiration, is a function shared by every living cell on the planet, from bacteria to trees, penguins, and people. Working with *Zetaproteobacteria*, an ancient life form discovered by Bigelow geomicrobiologists, McClellan is tracing the evolutionary history of the genes and proteins driving the physical process of cellular respiration at the molecular level. Using DNA isolated from *Zetaproteobacteria* and other organisms, he is examining the inner workings of molecular proton pumps and electron transport chains that fuel life, and how these cellular "nanomachines" adapt to changing environmental conditions in both marine and terrestrial ecosystems.

First originating in microbial life of the primeval ocean, the genes that encode these subatomic machines reveal how, over time, primitive proteins on the planet evolved to perform different roles in the cellular respiration of all living things, including the molecular mechanics by which electrons and protons regulate the underpinnings of human metabolism today.

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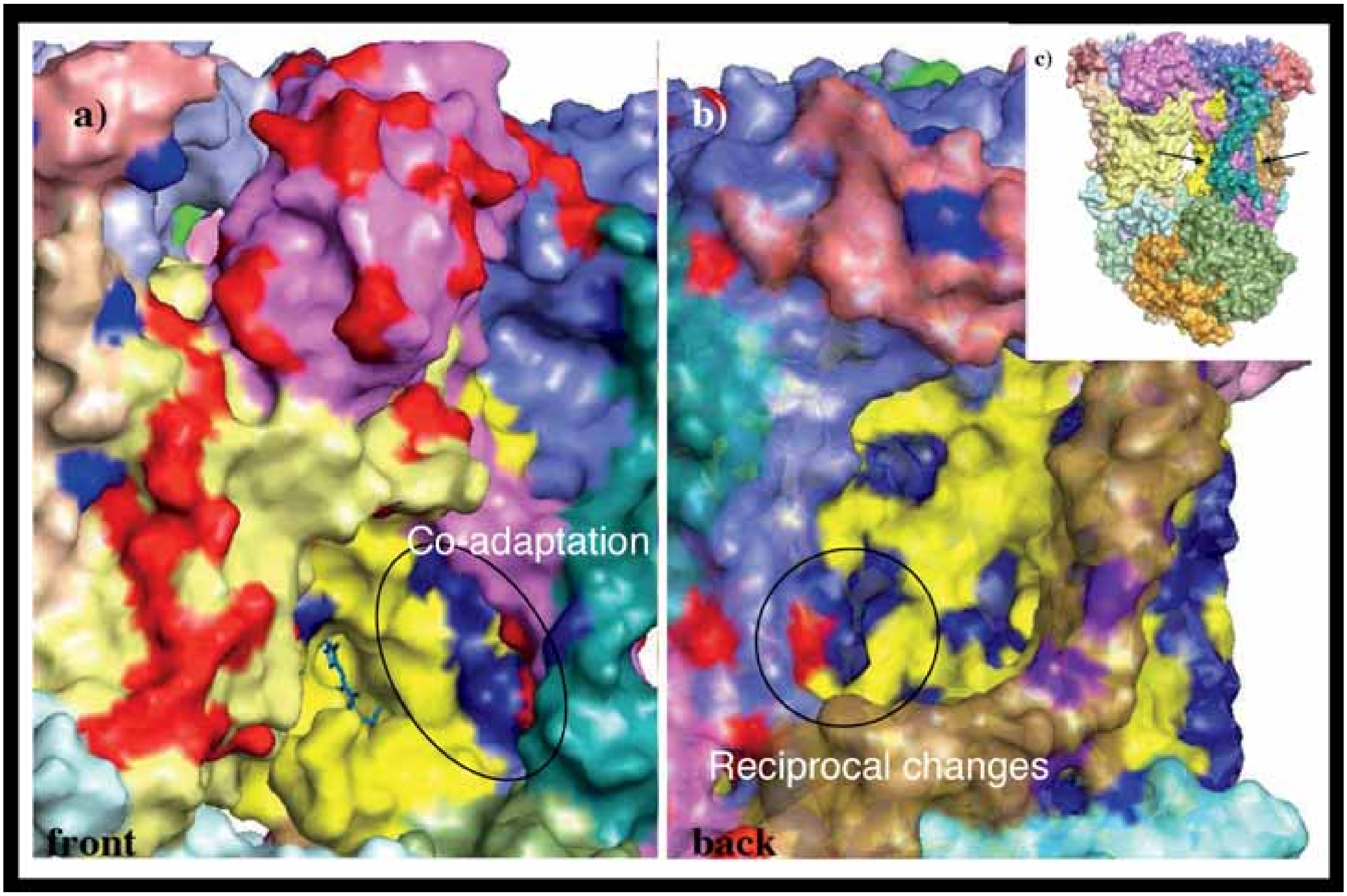


Illustration of the evolution of three functional proteins—cytochrome *b* (cyt-*b*), cytochrome c_1 (cyt-c_1), and the Rieske iron-sulfur protein (ISP)—in the vertebrate cytochrome bc1 complex in the electron transport chain of cellular respiration. Cyt-c_1 and ISP are encoded within a cell's nuclear genome (i.e., the chromosomes), while cyt-*b* is encoded by the circular genome in the cell's mitochondria. ***The proper function of this protein complex is critical to the survival of all vertebrate organisms and has been shown to be an important factor in obesity, Alzheimer's disease, and longevity in humans.*** Radical amino acid changes are highlighted in red and blue. **a)** The inner surface of cyt-b helix E (left arrow in **c**). **b)** The outer surface of cyt-b helix E (right arrow in **c**). Highlighted adjacent amino acid residues circled in **(a)** all have experienced radical changes in the way they attract protons by hydrogen bonding, while highlighted adjacent residues circled in **(b)** all have experienced changes that are effectively reciprocal to those in **(a)**. The coordinated evolution depicted in this figure allows the protein complex to functionally adapt, while preventing significant changes in the local biochemistry that would be detrimental for the organism. *Courtesy of David McClellan*.

The genetically driven changes taking place at these infinitesimal, sub-microscopic scales create the physical variations upon which natural selection works, making it possible to perpetuate in an ever-changing environment.

Knowledge about the mechanisms of life at this level is giving researchers a window onto the processes by which living cells adapt in a given direction and ultimately survive to reproduce.

McClellan's research for this project is part of a multi-year collaboration with the Single Cell Genomics Center and the Geomicrobiology Research Laboratory, as well as Colby College and federal scientists from the Maine Space Grant Consortium's Experimental Program to Stimulate Competitive Research.

Saltwater Microbial Rust Factories

Iron oxidation, familiar to most people as rust, is one of Earth's basic geological processes. It also is responsible for the widespread and expensive problem of steel corrosion, which results in major economic costs to governments and private industry every year.

By the mid-nineteenth century, scientists had already recognized that some types of bacteria around metal surfaces interact with the environment in ways that help start or accelerate chemical corrosion. Mild carbon steel—commonly used for construction of ship hulls, steel pilings, pipelines, and other structures—provides a substrate for these iron-oxidizing bacteria (FeOB), which consume iron and form rust as a by-product of their metabolism. Despite the fact these bacteria use iron as their primary food source, the role of marine FeOB in the process of steel corrosion remained unclear.

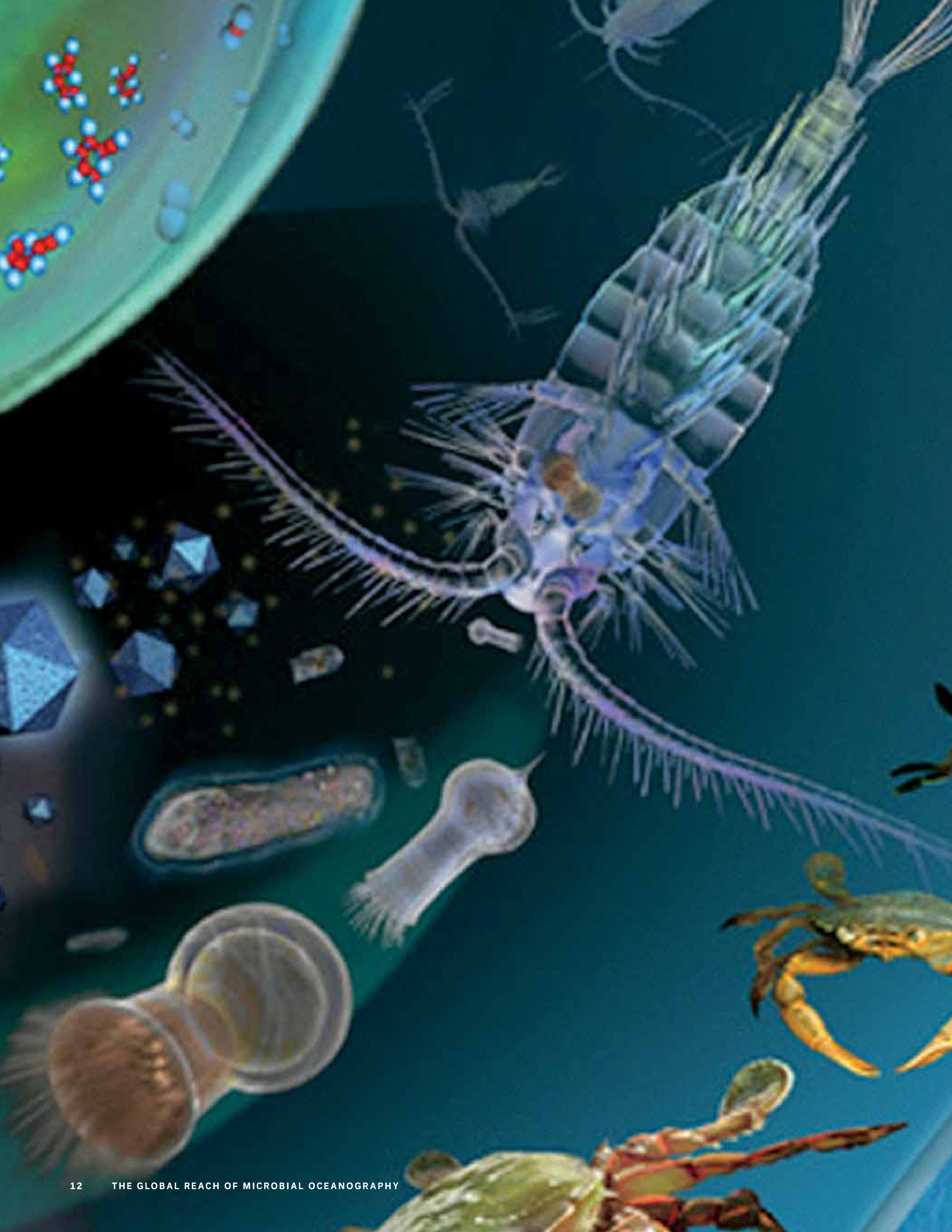
Working with researchers from the U.S. Naval Research Laboratory and an undergraduate from Bowdoin College, Dr. David Emerson and his team of scientists at the Bigelow Geomicrobiology Research Laboratory conducted field incubations and laboratory microcosm experiments to investigate this role. Using bacteria isolated from a microbial mat in a salt marsh in Maine, the team found that FeOB were able to rapidly colonize and speed corrosion of steel samples in temperate coastal waters.

Subsequent DNA extraction and genetic analysis of the thin layer of biofilm taken from the steel samples revealed that these microbes were *Zetaproteobacteria*, a class of marine FeOB discovered recently by Emerson and his co-workers, but previously thought to exist only in deep-sea hydrothermal vents associated with underwater volcanoes.

FeOB live in a diversity of places on the planet, including deep-sea hydrothermal vents, shipwrecks, and root systems of wetland plants. These ancient life forms may have helped shape the biogeochemistry early in our planet's history. It is possible they played an important role in the formation of the banded iron formations that are our primary source of iron ore today. *©2011 Applied Environmental Microbiology.*

The project's discovery of *Zetaproteobacteria* in the coastal ocean and their unequivocal involvement in steel corrosion have significantly advanced understanding of the influence that FeOB have in the biogeochemistry of iron and other elements. The team's findings were published as a cover story in *Applied and Environmental Microbiology* (February 15, 2011).

Photo by Richard G. Sandifer.



Ocean Health

why it matters

Ninety percent of the life in the world's ocean is microbial. With several billion cells in every gallon of seawater, marine microbial communities completely dominate the functioning and health of ocean ecosystems. The Laboratory's ocean health researchers use current discoveries in genomic research, microbiology, and bio-informatics to develop fundamental new research methods that go beyond traditional field-to-laboratory approaches in order to assess the health of the ocean at the cellular, community, and ecosystem levels.

Working at the critical interface linking the ocean's smallest living particles with major global ecosystems, our key areas of focus in ocean health include the contribution of microbial communities to the marine food web, to global biogeochemical cycles, and to the population dynamics of harmful algal blooms and marine pathogens that impact ocean health and productivity.

This research ranges from the individual marine microbe, or association of microbes and organisms, through a progression of ecosystems at local, regional, and global scales—from Boothbay Harbor, to the Gulf of Maine, to the global ocean. Increased understanding of the ocean's microbial systems and their interactions is advancing the knowledge needed to address rapidly emerging environmental challenges and inform effective, sustainable management and stewardship of global ocean resources.

Intertwining Branches on the Underwater Tree of Life

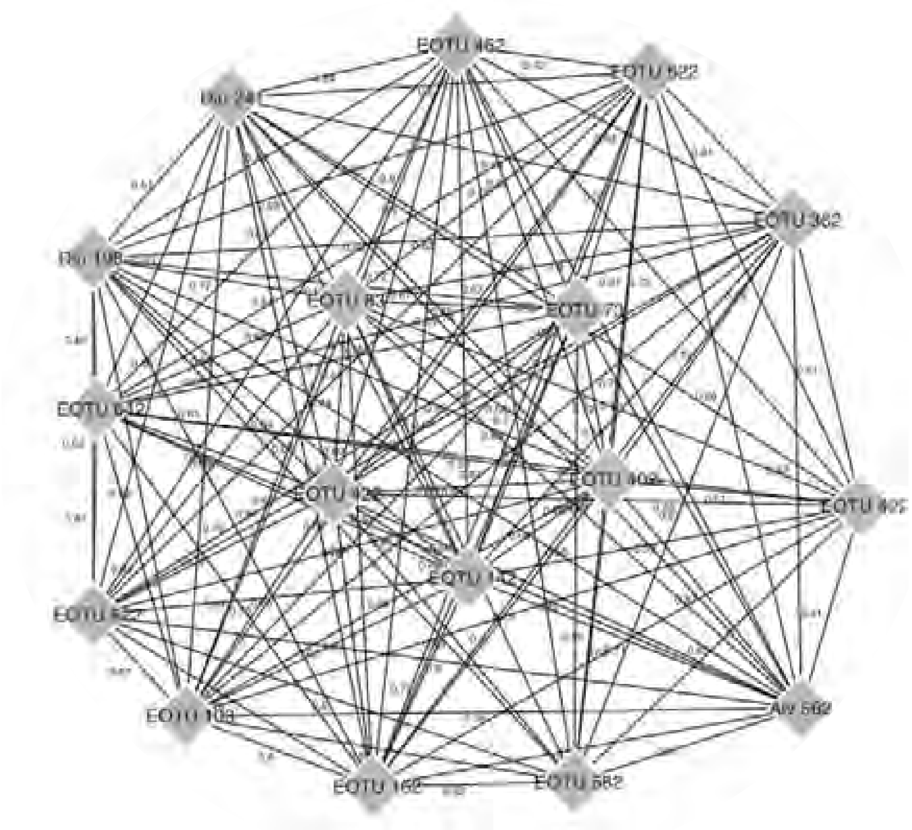
Microbial communities represent the majority of all global biomass and play central roles in the marine food web and global biogeochemical processes, but how do the microbes in these complex systems act and interact with each other? Until now, information about these microbial communities has been scarce, but new research by Bigelow marine microbial ecologist Dr. Peter Countway, working with California Institute of Technology's Dr. Joshua Steele and colleagues at the University of Southern California, has revealed a glimpse of possible interactive networks connecting hundreds of microbial species.

The presence of particular phylotypes, or species, in an ecosystem can be an important predictor about which other phylotypes will be present, or may soon appear. At the same time, it is possible that phylotypes with even a relatively low frequency of occurrence (e.g., members of what is called the "rare" microbial biosphere) can have a large effect on other components of the microbial assemblage. Research into the effects of various phylotypes on the microbial ecology of the ocean can provide greater understanding of the chemical and biological dynamics within the marine environment, and enhance future efforts to understand ecosystem function, stability, and resilience.

Over a period of 36 months, Countway studied the microorganisms known as protists—single-celled eukaryotes (organisms with a membrane-bound nucleus), such as microalgae and protozoa, off the coast of southern California, while Steele examined bacteria and archaea from the same water samples. Both researchers examined fragments of DNA that were extracted and amplified from seawater, comparing them to existing DNA databases to provide possible identification of phylotypes among many of the microbes from their study site. Countway's and Steele's data were combined and analyzed in a new way, revealing numerous potential interactive networks among different members of the microbial groups.

A central finding of their research was that the microbial phylotypes themselves—rather than ancillary environmental factors such as temperature, depth, or nutrients—seemed to be the best predictors of the occurrence of other microbial phylotypes.

Photo by Richard G. Sandifer.



When visualized separately, microbial operational taxonomic units (OTUs) formed a highly inter-connected cluster. (Adapted from J. A. Steele, Countway, P.D., Xia, L., Vigil, P.D., Beman, J. M, Diane Y Kim, D. Y., Chow, C-E. T., Sachdeva, R., Jones, A. C., Schwalbach, M. S., Rose, J. M., Ian Hewson, I., Patel, A., Sun, F., Caron, D. A., and Fuhrman, J. A. Marine bacterial, archaeal and protistan association networks reveal ecological linkages. *The ISME Journal* (2011), 1–12, Figure 2. © 2011 International Society for Microbial Ecology.

Over the course of the study, certain microbial phylotypes occurred in the ocean at the same time, or in sequence, showing patterns of co-occurrence in the microbial community. For example, the arrival of one phylotype during a given month appeared to affect the chances that other species would also be present. Conversely, some phylotypes were negatively correlated with one another, possibly indicating competition for similar resources.

Scientists are just beginning to ask questions about the possible roles of diverse microbial phylotypes in the marine environment, many of which are known only by their DNA sequences. While comparable patterns of competition and interaction have long been observed and understood in larger organisms, this is some of the earliest research showing similar relationships in the microbial world, and offers the advantage of being able to investigate hundreds of different possible interactions simultaneously.

The results of this research were published in *The ISME Journal* (September 2011), providing new insights into the natural history of microbes, a foundation for understanding the complexity of marine microbial interactions, and a first look at the mechanisms that may be responsible for resilience and maintenance of healthy marine ecosystems.

Diatom micrographs by Pete Countway.

Food, Seawater, and Sunlight

Reduction in global atmospheric ozone levels has led to rising ultraviolet radiation from the sun. UVB radiation (one of several kinds of ultraviolet radiation) has been shown to be harmful to certain aquatic organisms, and now new research shows that it has the potential to alter the rate at which organic matter flows through the marine ecosystem, impacting the ability of the ocean to sequester atmospheric carbon.

Abundant populations of algae-grazing copepods (microscopic crustaceans that form a significant fraction of the ocean's zooplankton) play an important role in the ocean's ability to remove carbon from the global atmosphere. Phytoplankton cells, which use carbon dioxide to grow, are ingested by copepods as food. The cells are digested and repackaged into fecal pellets that rapidly sink into the deep ocean, carrying carbon and other organic matter with them. Understanding the factors that affect the rate at which this happens is essential to our ability to predict the long-term environmental consequences of changes in this critically important process.

Dr. David Fields and his team in the Bigelow Sensory Ecology and Zooplankton Physiology Laboratory, collaborating with scientists from Norway's Institute of Marine Research, have examined how UVB radiation affects not only phytoplankton growth rates themselves, but also its secondary effect on the organisms that graze on phytoplankton. The researchers subjected

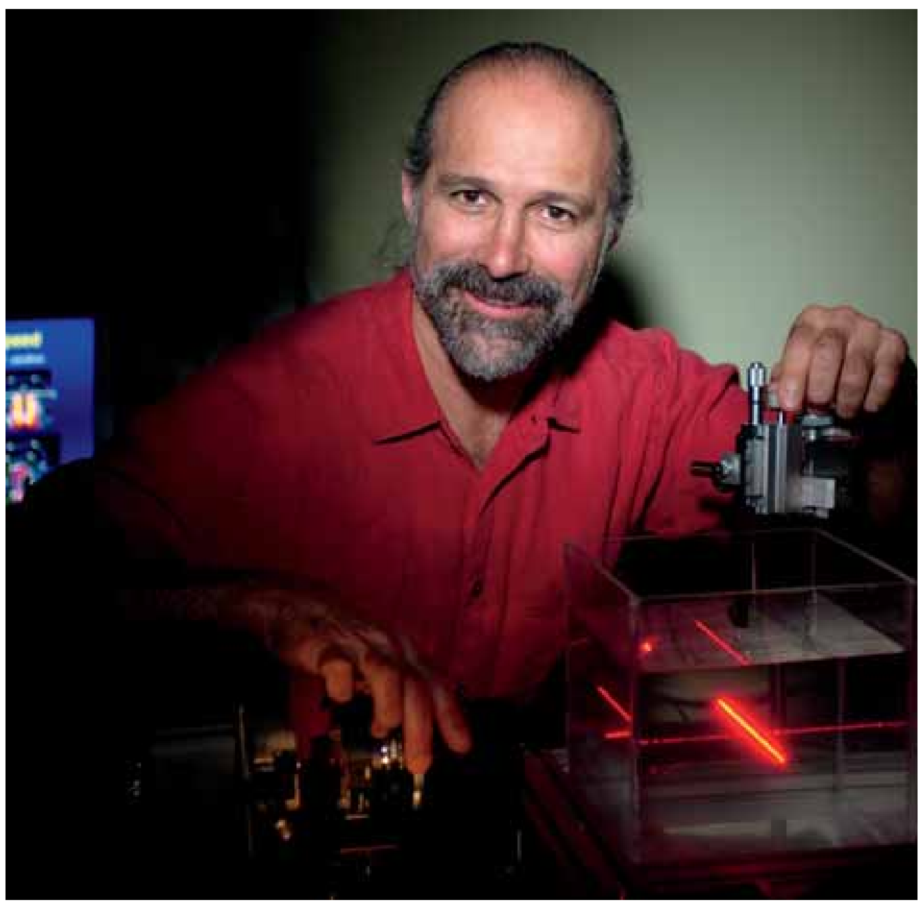


Photo by Richard G. Sandifer.

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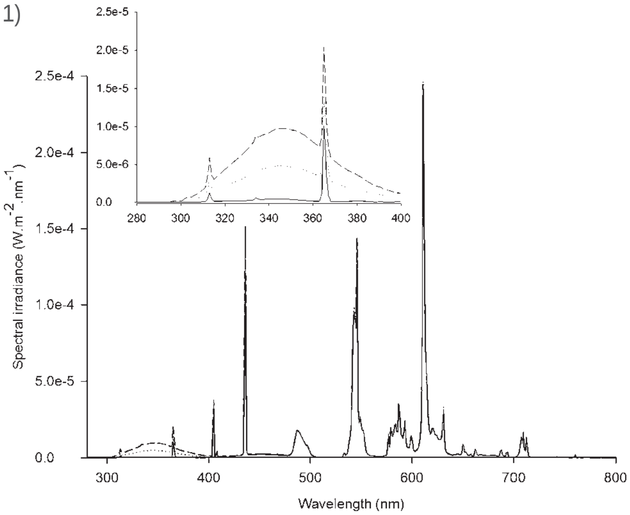

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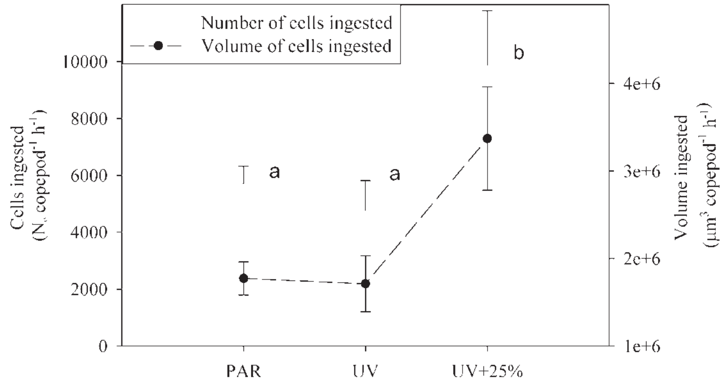


1) Spectral irradiance for UVB (280–320), UVA (320–400 nm): photosynthetically active radiation (PAR) (solid line), PAR plus ambient UVR (dotted line), and PAR plus enhanced UVR (dashed line) measured inside the Teflon bags that were used for culturing the algae. **2)** The number of cells (left axis) and volume of cells ingested by *Calanus finmarchicus* feeding on *Thalassiosira weissflogii*. *Courtesy of David Fields*.

the phytoplankton *Thalassiosira weissflogii*—a unicellular diatom found in both fresh and marine waters around the world—to varying levels of ultraviolet radiation. Increased exposure to UV radiation above the normal levels necessary for photosynthesis led to decreased growth rates and larger cell size.

Fields then studied the secondary impact of radiation exposure by observing the rate at which copepods ingested the UV-treated *T. weissflogii* cells. The team fed the *T. weissflogii* cells to *Calanus finmarchicus*—a copepod species largely found in the northern Atlantic, including the waters off the coast of Maine—and measured

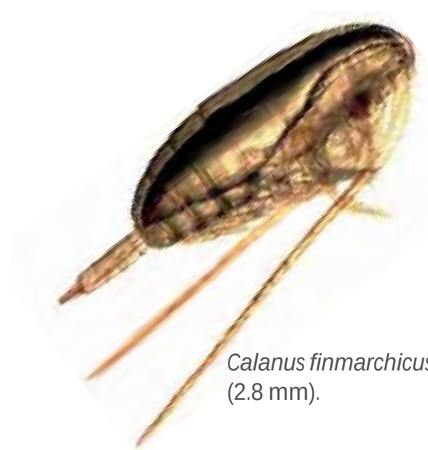
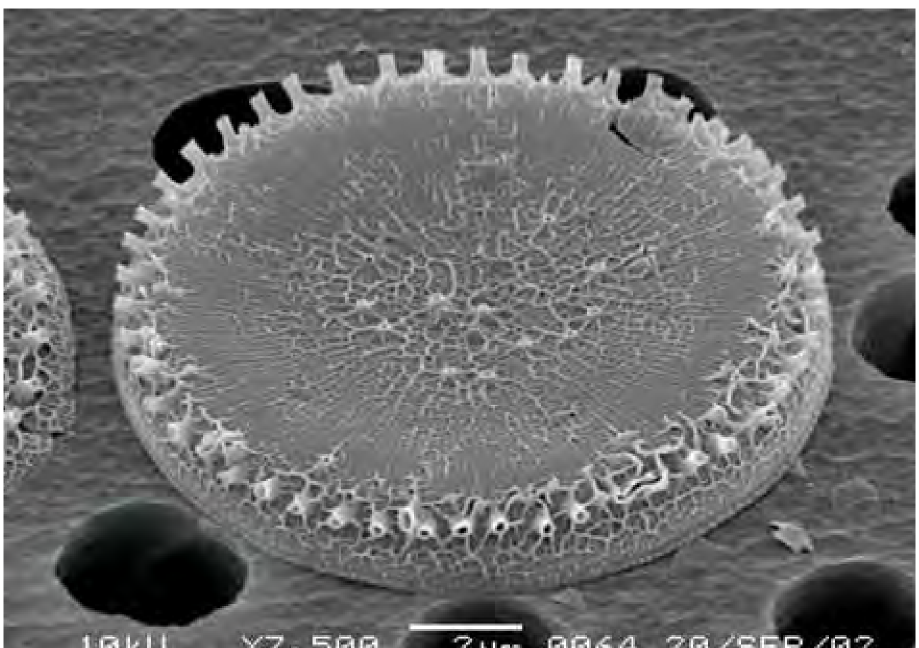


Photo by C.B. Miller/K. Tande.

Calanus finmarchicus (2.8 mm).

the speed at which the diatoms were ingested. Results showed that the copepods grazing on *T. weissflogii* treated with higher UV rates consumed 66% more than those grazing on algae raised under low UV radiation levels. In part, this may have been a result of the lowered nutritional value of the UV-treated algae.

Published in *PLoS ONE* (October 2011), these findings show that an increase in UV radiation levels can change the trophic (food) interactions between marine species, directly influencing the amount of organic material that passes through this major segment of the marine ecosystem.



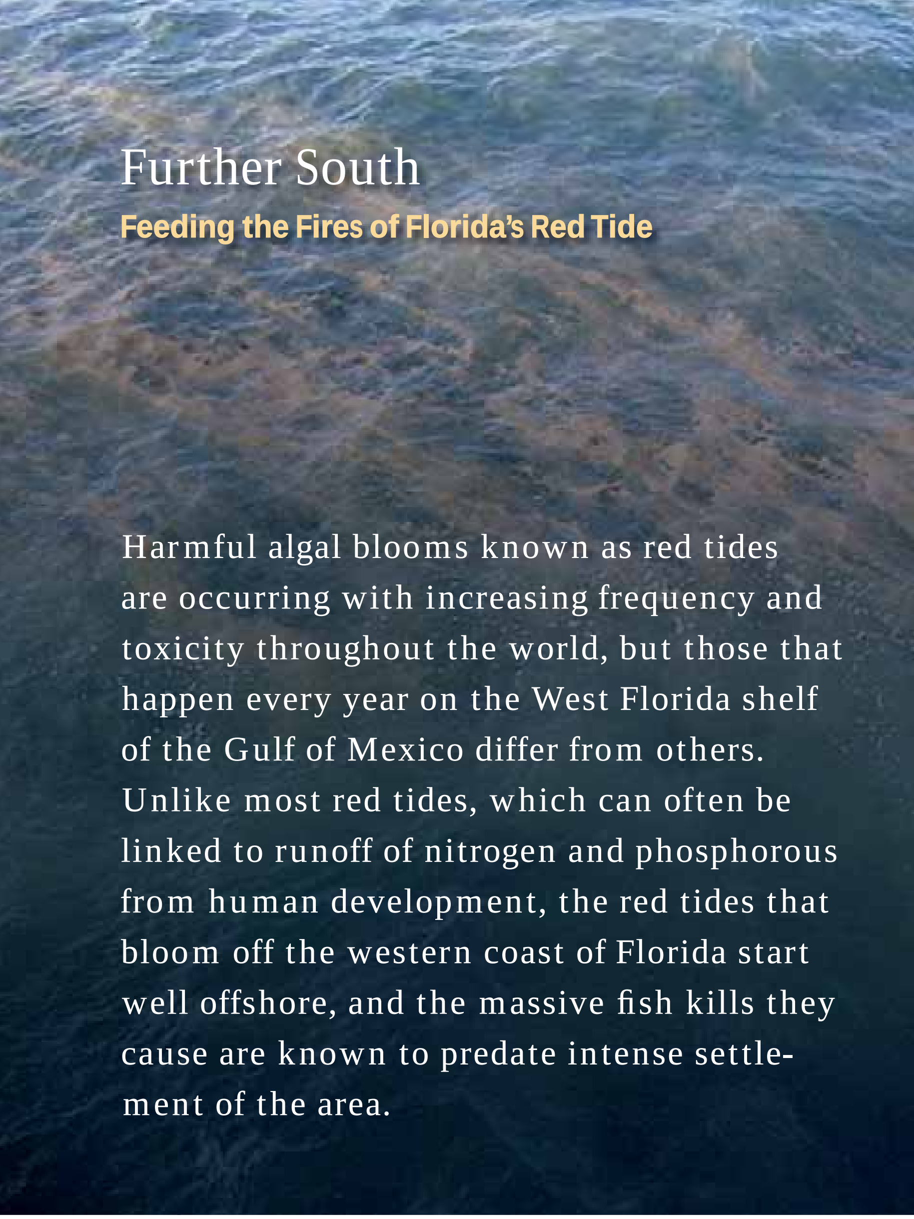
CCMP1336. *Thalassiosira weissflogii*. SEM by Irena Kaczmarska. *Courtesy of NCMA*.

Further South

Feeding the Fires of Florida's Red Tide

Harmful algal blooms known as red tides are occurring with increasing frequency and toxicity throughout the world, but those that happen every year on the West Florida shelf of the Gulf of Mexico differ from others. Unlike most red tides, which can often be linked to runoff of nitrogen and phosphorous from human development, the red tides that bloom off the western coast of Florida start well offshore, and the massive fish kills they cause are known to predate intense settlement of the area.

Photo by Richard G. Sandifer.



Trichodesmium bloom. *Courtesy of ASLO.*

CCMP 2229. *K. brevis* (~30 µm). *Courtesy of NCMA.*

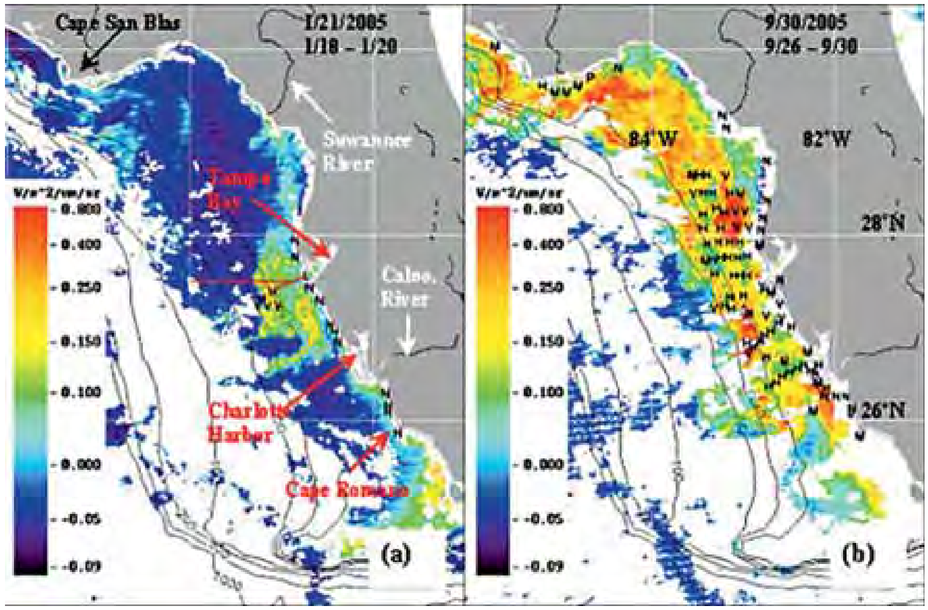
Karenia brevis is the toxic dinoflagellate species responsible for red tides in Florida, which lead to beaches awash with dead fish and respiratory irritation in beachgoers—serious problems for a region whose economy is almost entirely dependent upon tourism. Understanding the nutrient sources that cause *Karenia brevis* to bloom can help officials predict which beaches will be safe on given weekends and which should be avoided, and may also make it possible to help manage the size and scope of red tides in the future, before they become dangerous.

Recent research by Bigelow phytoplankton and harmful algal bloom ecologist Dr. Cynthia Heil, working in collaboration with the University of South Florida's Dr. Jason Lenes, has found that, rather than responding to runoff, *Karenia brevis* blooms are linked to blooms of another species, the marine cyanobacterium *Trichodesmium*.

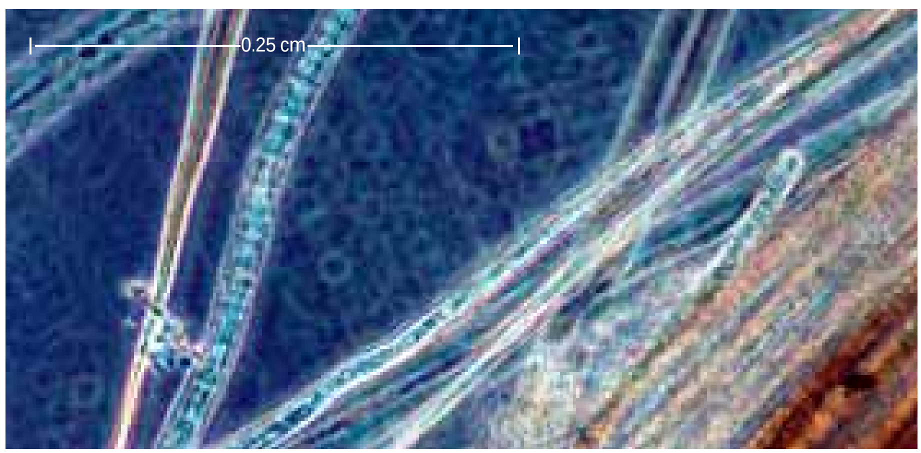
Known to sailors as "sea sawdust" because its colonies resemble sawdust on the ocean's surface, *Trichodesmium* is a nitrogen fixer. To satisfy its requirements for nitrogen, *Trichodesmium* takes up nitrogen gas and "fixes" it into ammonia (NH4+). The fixed nitrogen is released directly into the environment, where it becomes a nutrient source for *Karenia brevis*. Heil and Lenes examined historical records of *Trichodesmium* presence and abundance during red tides dating back to 1960 and discovered that cycles of *Trichodesmium* blooms correspond with development of *Karenia brevis* red tides.

But how does *Trichodesmium* itself grow in the largely nutrient-poor West Florida shelf? Saharan dust blown across the Atlantic Ocean and into the Gulf of Mexico fertilizes the water there with iron, leading to “pulses” of growth of *Trichodesmium* each spring. This, in turn, feeds the growth of subsequent *Karenia brevis* blooms.

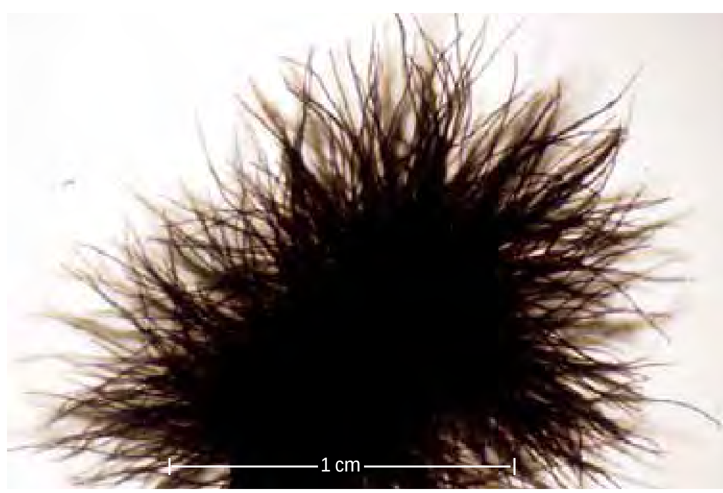
Although *Trichodesmium* is not the only nutrient source for *Karenia brevis*, Heil’s and Lenes’s research has shown that it may be one of the most important. Since *Trichodesmium* species can be found around the world, these findings may provide new insight into red tides in places such as Japan, New Zealand, and Europe, where they do not occur as predictably as those in Florida. Results of this research were published in the *Journal of Plankton Research* (vol. 32, number 10).



These MODIS satellite images show the *Karenia brevis* (red tide) algae in shallow (less than 164 feet) regions of the West Florida shelf. The colors of dark green, yellow, and red show high concentrations of the algae. The second date on each image indicates the water sample collection time by the Florida Fish and Wildlife Commission (FWC). Letters represent different red tide concentrations as follows: N –below detection limit; P – present; L – low; M – medium; H – high; V – very high. *Courtesy of USF/NASA/FWC.*



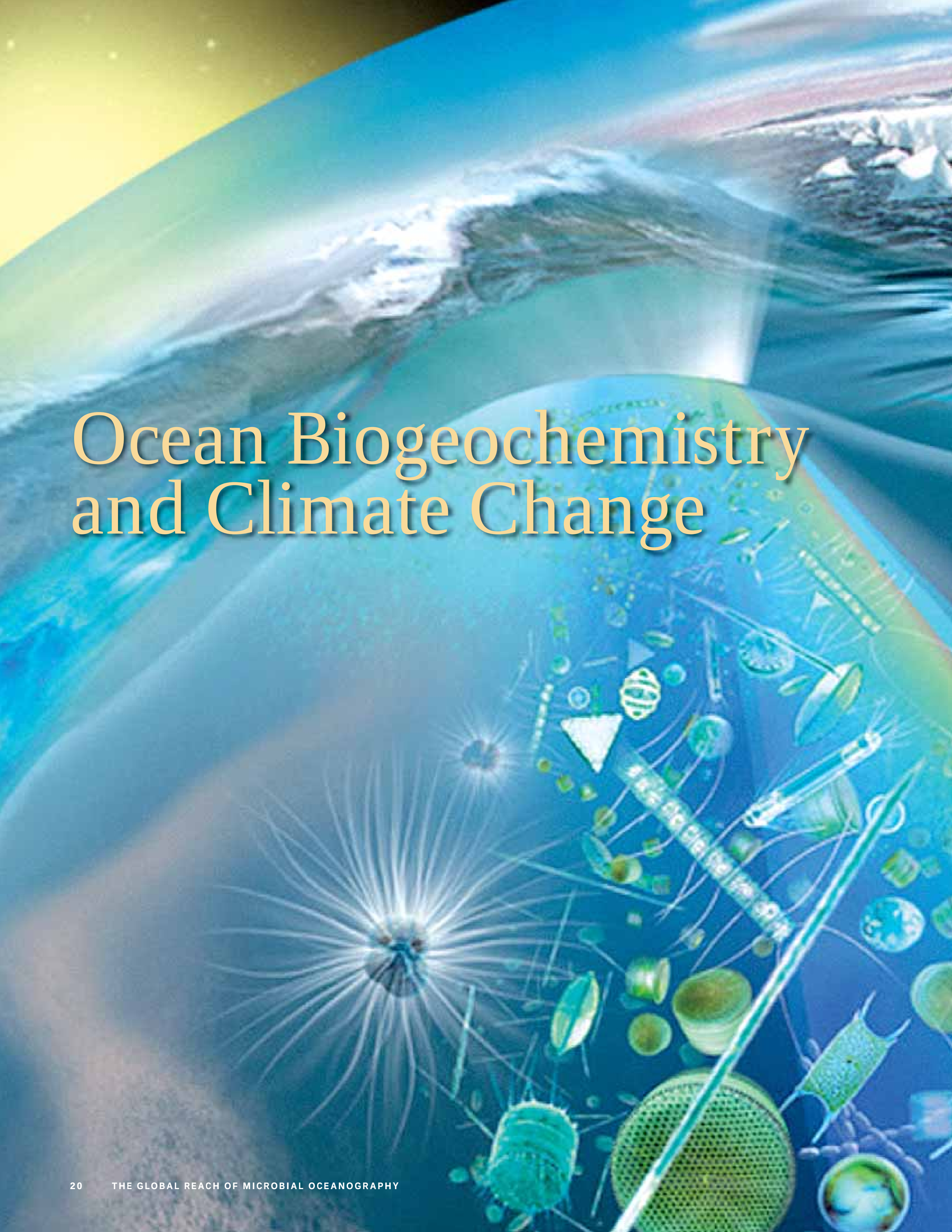
Trichodesmium trichomes forming tufts. *Courtesy of the Smithsonian Environmental Research Center.*



Trichodesmium puff.

Photo by Judy O’Neil.

Ocean Biogeochemistry and Climate Change



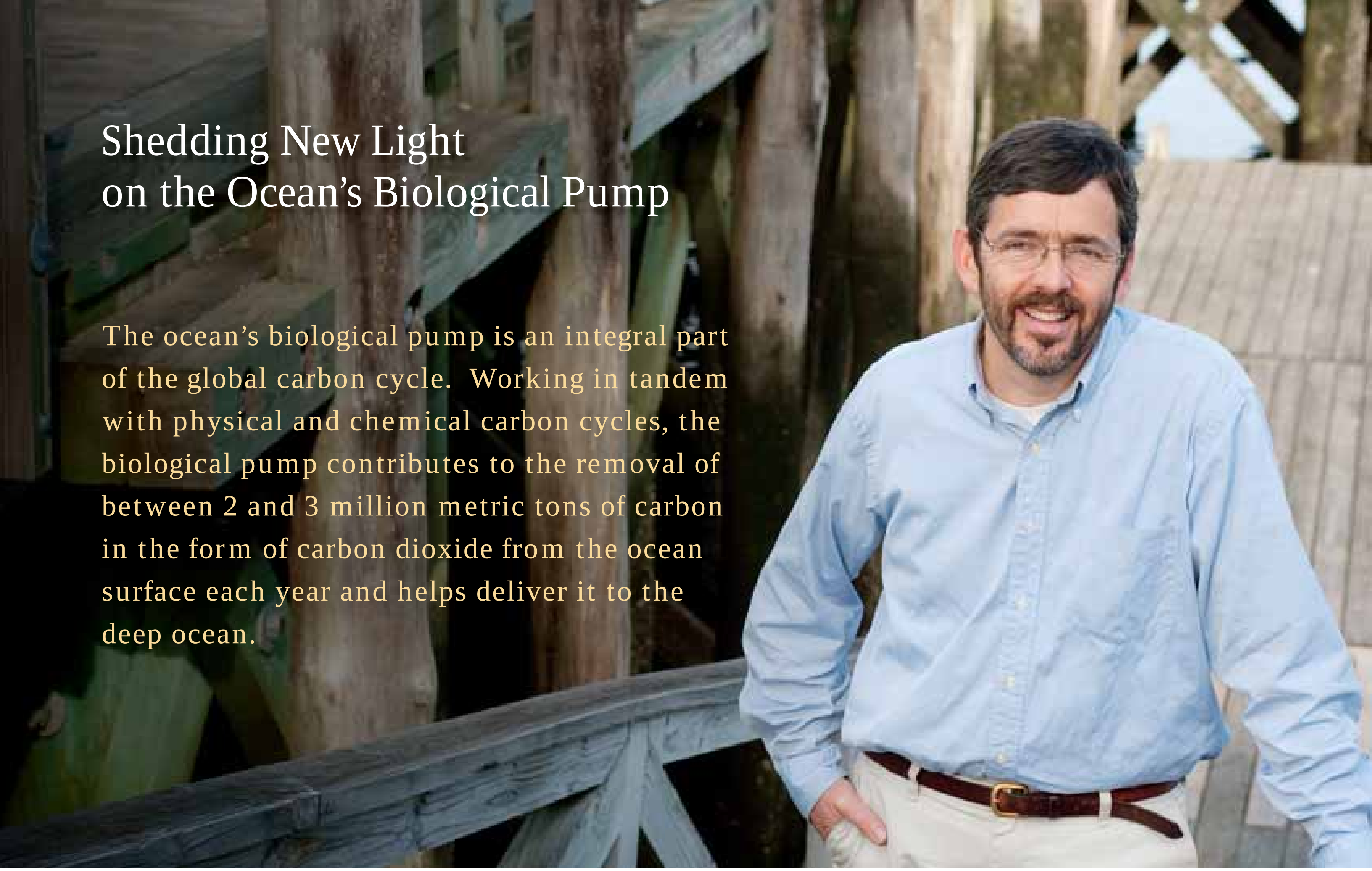
why it matters

As they photosynthesize and grow, microscopic marine phytoplankton continuously generate half the oxygen that all life on the planet needs to breathe. Along with phytoplankton, other marine microorganisms—including bacteria and viruses—affect global climate and weather patterns, and contribute significantly to the planet's essential biogeochemical cycles.

Ocean microbes are directly involved in transporting atmospheric carbon dioxide from the ocean's surface to deep waters, where carbon is slowly locked away in sediments beneath the ocean floor. As a result, the ocean has become the world's greatest carbon reservoir, storing 16 times more carbon than is held in terrestrial vegetation and soils, and 50 times more carbon than is contained in the atmosphere.

Changing climate conditions are altering the dynamics of the ocean's microbial populations, however, including the way they influence surface ocean chemistry and ecosystem productivity, with direct impacts on the dynamics, resilience, and survival of all levels of life in the ocean.

Bringing together research in ocean observing, air-sea interactions, cellular biogeochemistry, and land-sea interactions, the Laboratory's ocean biogeochemists, biological oceanographers, and ocean and atmospheric chemists are investigating these processes at multiple scales, from local to global, and from individual cells to entire ocean basins. By studying the interface between atmosphere, ocean, and sediments, their research is advancing our understanding of the connections between the complex interactions within marine microbial communities and the ocean's role in global climate variability.



Shedding New Light on the Ocean's Biological Pump

The ocean's biological pump is an integral part of the global carbon cycle. Working in tandem with physical and chemical carbon cycles, the biological pump contributes to the removal of between 2 and 3 million metric tons of carbon in the form of carbon dioxide from the ocean surface each year and helps deliver it to the deep ocean.

Photo by Richard G. Sandifer.

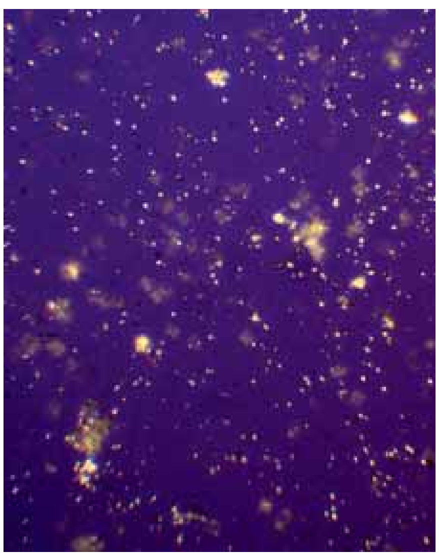


Photo by Barney Balch.

Light-scattering calcifying phytoplankton known as coccolithophores and their detached calcium carbonate shields (viewed under a microscope at 200x) glow in this epifluorescent image.

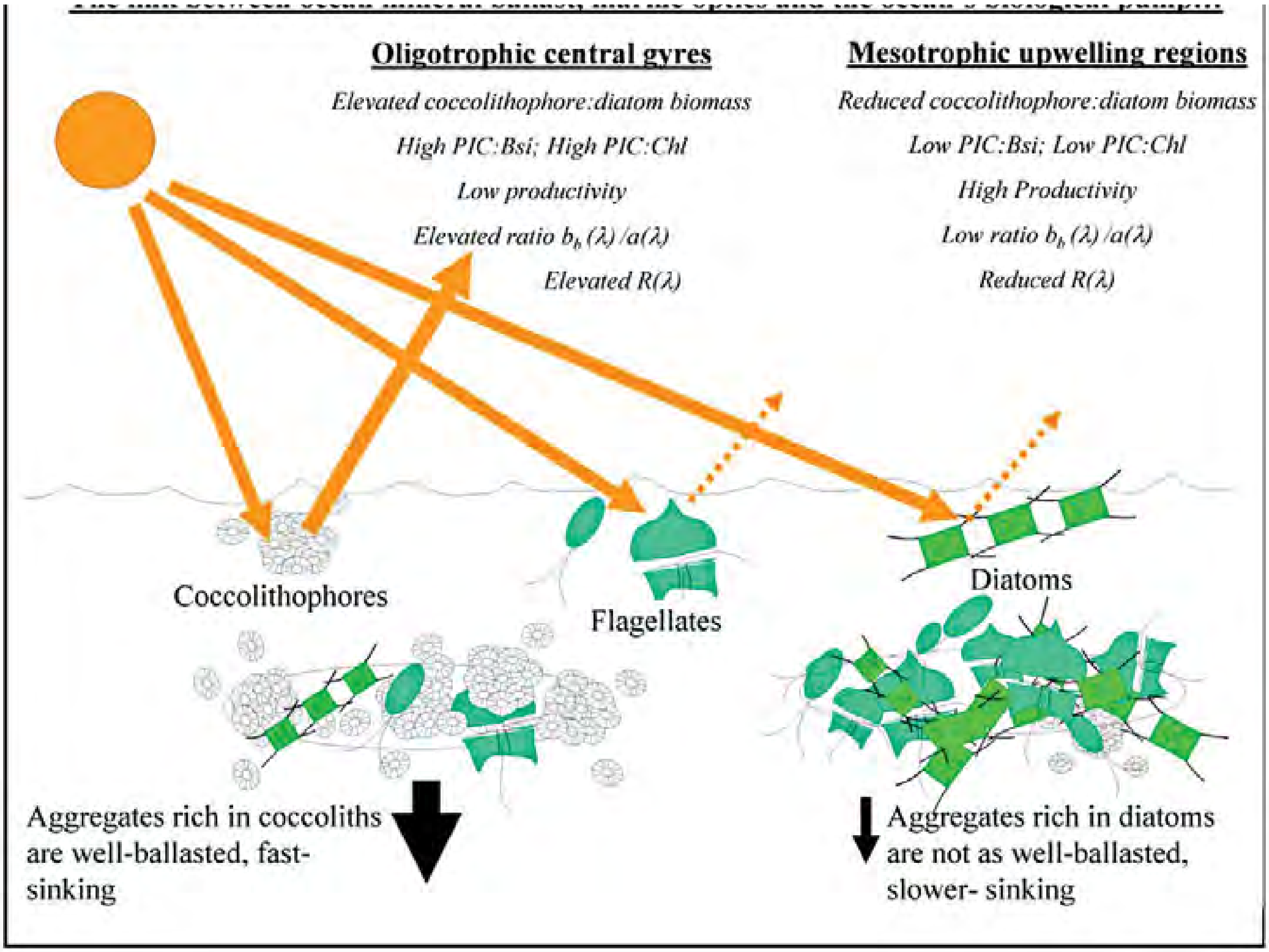
Calcium carbonate (known as particulate inorganic carbon, or PIC) is a key driver of the ocean's biological carbon pump, providing a significant portion of the ballast that allows particulate matter to aggregate and sink to the ocean floor. At the present time, the ocean is the largest active carbon sink on Earth—calcium carbonate makes up half of all the biologically-fixed carbon that sinks below 1000m depth in the ocean.

Dr. Barney Balch, his research team in the Ocean Observing and Optics Laboratory, and colleagues from the National Oceanography Centre in the United Kingdom have been the first to demonstrate that calcium carbonate is responsible for a major fraction of the light scattered throughout the vast subtropical gyres of the Atlantic Ocean.

The researchers examined the influence of calcium carbonate and biogenic silica (BSi), another source of ballast material, on both the optical properties of particles in the ocean and their effect on the rate at which particles sink. Differences in the way light is scattered by PIC, BSi, and particulate organic carbon from photosynthesis (POC) made it possible to compare surface inorganic to organic carbon ratios.

Their data show that calcium carbonate contributes up to a quarter of particle light scattering that occurs in nutrient-poor subtropical gyres and temperate waters, and that this relationship applies over most of the Atlantic Ocean.

They discovered a strong, inverse relationship between the ratio of calcium carbonate and biogenic silica to POC, with higher sink-



Optical connections to the two main types of ballast found in particulate matter from oceanic environments, calcium carbonate from coccolithophores, and biogenic silica from diatoms. Three algal functional groups are represented as contributing to the bulk of particulate organic matter (POM), coccolithophores, diatoms, and flagellates. The latter, on its own, has no minerogenic (inorganic) ballast. As the ratio of calcium carbonate to biogenic silica increases in ocean particulate matter, two things happen: 1) aggregates of sinking particles become denser, thus, all other things being equal, they will sink faster, and 2) optical backscattering and reflectance of ocean waters increases, and this is measurable using satellite remote sensing. *Courtesy of Barney Balch.*

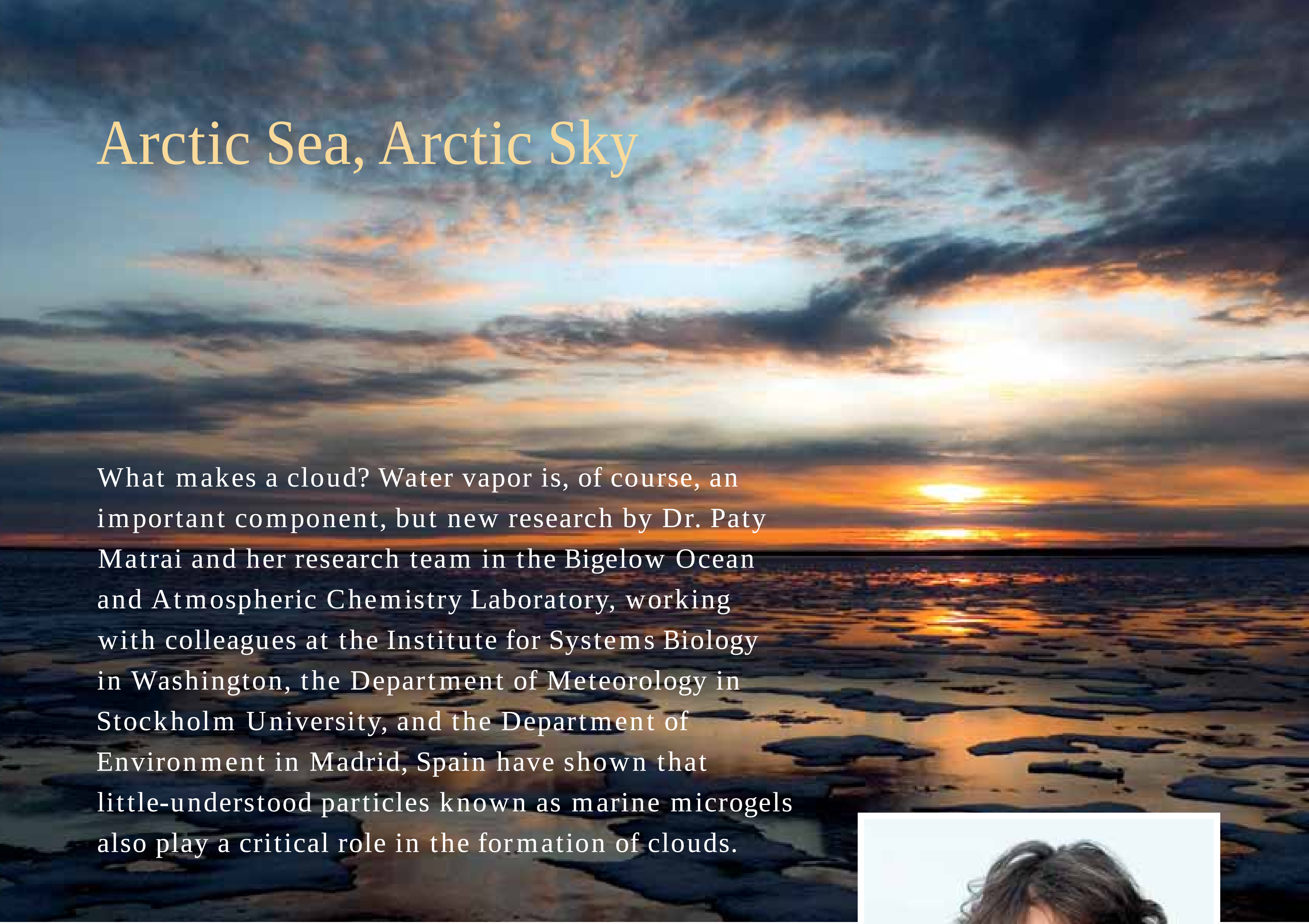
ing rates (meaning a more efficient biological pump) in those areas that had a greater relative abundance of calcium carbonate.

The researchers have combined these observations into a model that predicts carbon flux from the surface ocean by estimating PIC, POC, and BSi concentrations using satellite remote sensing images.

The team's findings have created a radical change in the assumptions used in ocean remote sensing because, until now, it was the chlorophyll found in the ocean's living phytoplankton cells that was thought to be the primary ingredient determining how light scatters in the ocean.

By accurately pinpointing the nature of bio-optical properties throughout vast regions of the Atlantic Ocean, the researchers have provided a basis for predicting the rate and efficiency of the ocean's biological pump as a whole.

Funded by grants from NASA (the National Aeronautics and Space Administration; Ocean Biology and Biogeochemistry Research Program) and NERC (the Natural Environment Research Council of the UK), their findings are the result of three trans-Atlantic research expeditions and have been published in *Geophysical Research Letters* (VOL. 37, L22605).



Arctic Sea, Arctic Sky

What makes a cloud? Water vapor is, of course, an important component, but new research by Dr. Paty Matrai and her research team in the Bigelow Ocean and Atmospheric Chemistry Laboratory, working with colleagues at the Institute for Systems Biology in Washington, the Department of Meteorology in Stockholm University, and the Department of Environment in Madrid, Spain have shown that little-understood particles known as marine microgels also play a critical role in the formation of clouds.


Photo by Richard G. Sandifer.

Marine microgels, discovered only about two decades ago, are three-dimensional polymer hydrogel networks formed from dissolved organic matter in the oceans. Although they exist on an infinitesimally small, nano scale, they are also extremely abundant, forming as much as ten percent of the dissolved organic material present in marine waters.

Using ocean samples collected at 87°N during the Arctic Summer Cloud Ocean Study expedition to the high Arctic, the multidisciplinary international team is investigating cloud formation over the Arctic Ocean and the role of these clouds in the Arctic climate system. The team has shown that marine microgels are an essential component of cloud condensation nuclei—the particles that, by their abundance and size, determine the heat distributing and light reflecting properties of clouds.

Matrai and her fellow researchers characterized and quantified the presence of marine microgels in sub-surface waters; at the interface between air and water; and in clouds, fog, and airborne aerosols. The dominance of marine microgels in cloud condensation nuclei was particularly striking north of 80˚N, where the presence of sea ice prevents wind from stirring up

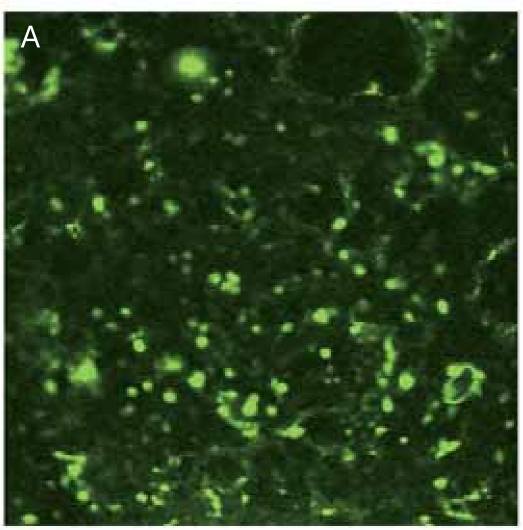
Photo by Carlton Rauschenberg. (2)

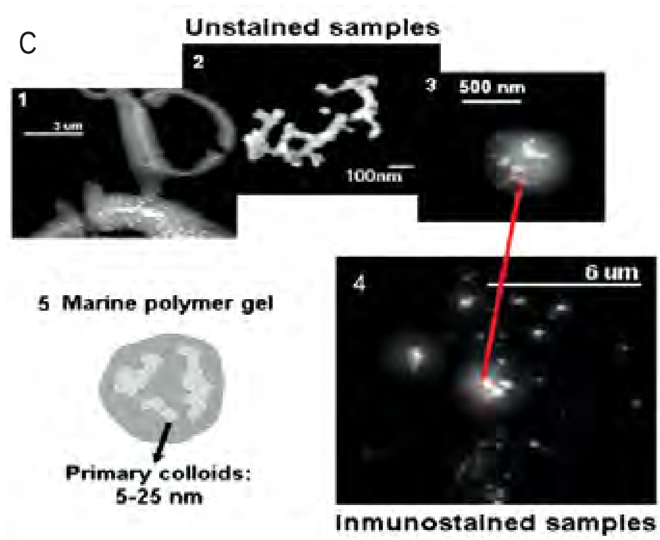
Photo by Thorsten Mauritsen.

sea spray. Even without the help of wind, microgels were still able to make the transition from sub-surface waters to the air/water interface through bubble bursting, ice degassing, and other particle ejection processes.

The results of this research, published in the *Proceedings of the National Academy of Sciences* (vol. 108, no. 33), link the biology at the ocean surface with cloud properties and climate over the central Arctic Ocean, and show, for the first time, that marine microgels affect the chemistry and physics of Earth's atmosphere.

Current climate models place little emphasis on sea ice extent and thickness, and even less on the porosity and permeability of sea ice, although both are important elements in the heat budget and the development of clouds in the high Arctic Ocean. Understanding how marine microgels seed clouds by becoming part of cloud condensation nuclei provides important new insights into the processes controlling cloud formation, and will help to improve the accuracy of future climate models.





Microgels in clouds. (A) Immunostained gels: Nanometer (nanogels)- and micrometer (microgels)-sized polymer gels. (C) Structure of nano and microgels. Adapted from M. Orellana, Matrai, P. A., Leck, C., Rauschenberg, C., Lee, A. M., and Coz, E. Marine microgels as a source of cloud condensation nuclei in the high Arctic. *PNAS* August 16, 2011 vol. 108 no. 33 13612-13617. ©*2011 National Academy of Sciences*.

Sink or Swim, A Question of Ballast

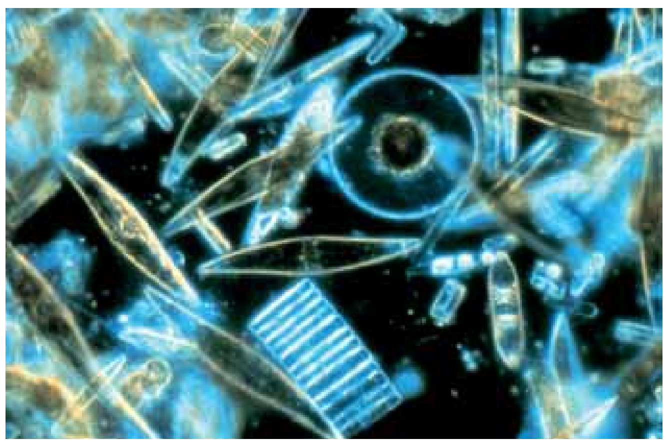
The ocean's smallest organisms have an immense impact on global cycles. Playing a major role in the global climate cycle, phytoplankton sink to the deep ocean as they die, carrying with them much of the carbon they absorbed during life. Diatoms—one of the most common types of phytoplankton—have an especially important part in this process, as their dense, opalescent silica shells are more likely to sink than species without these shells, which makes diatoms more likely to remove carbon from the atmosphere.

Until recently, scientists assumed that all diatoms around the world behaved in the same way. But new research from the Bigelow Trace Metal Biogeochemistry Laboratory, Stony Brook University, the University of California, and France's Institut Universitaire Européen de la Mer shows that this not the case.

Dr. Ben Twining and his research team collected diatom samples from the cold waters of the Antarctic Zone of the Southern Ocean (SOAZ), which contain high levels of the silicic acid used by diatoms to form the their intricate "glass" shells, and from the warmer waters of the eastern equatorial Pacific (EEP), which have lower levels of silicic acid. Examining the diatom cells with a synchrotron-based X-ray fluorescence microprobe at Argonne National Laboratory, they found that the diatoms from SOAZ contained six times more silicon per volume than those from the EEP.

Diatoms from both samples were fed varying levels of iron, phosphate, and silicon—the nutrients necessary for phytoplankton growth—with little effect on their silicification (the process by which organic matter becomes saturated with silica), indicating that, unlike previously assumed, diatoms in different regions do not behave in the same way, and that the degree of silicification differs from region to region.

Rather than being a function of their environment, it was found that the diatoms' silicon content was based on the type of diatoms found in each region, suggesting that diatom community composition is a primary determinant of the role of silicification in these areas.



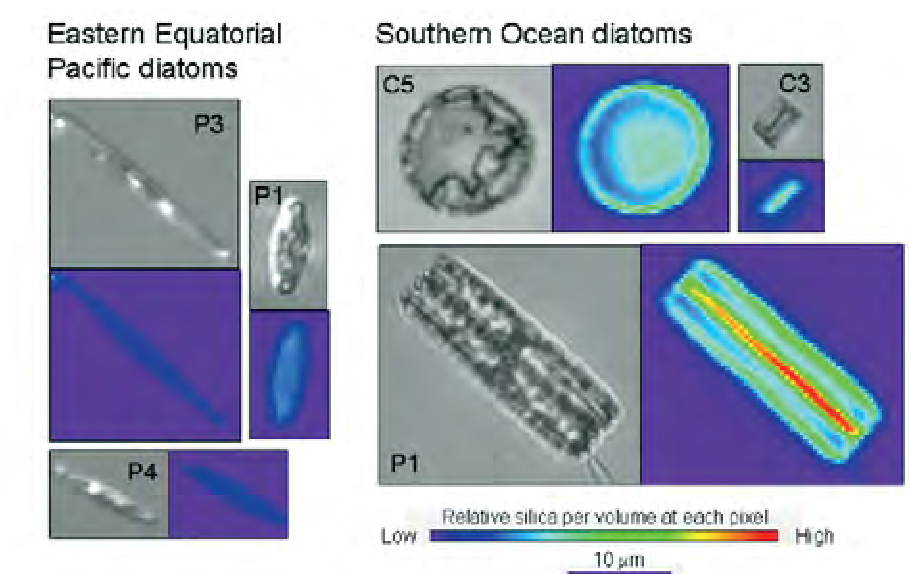
Assorted diatoms as seen through a microscope. These specimens are encased within a silicate cell wall and were living between crystals of annual sea ice in McMurdo Sound, Antarctica. *Photo courtesy of NOAA Corps Collection (corps2365). Image by Professor Gordon T. Taylor, Stony Brook University.*

...plankton communities must be considered and studied individually to understand their effect on the carbon cycle...

Finding varying levels of diatom silicification in different oceanic regions demonstrates the need to understand the biogeochemical implications of the life cycles of single-celled organisms at the community level. The dramatic difference between EEP and SOAZ diatoms shows that plankton communities must be considered and studied individually to understand their effect on the carbon cycle, as well as how climate change and changing ocean conditions will impact these species in the future.

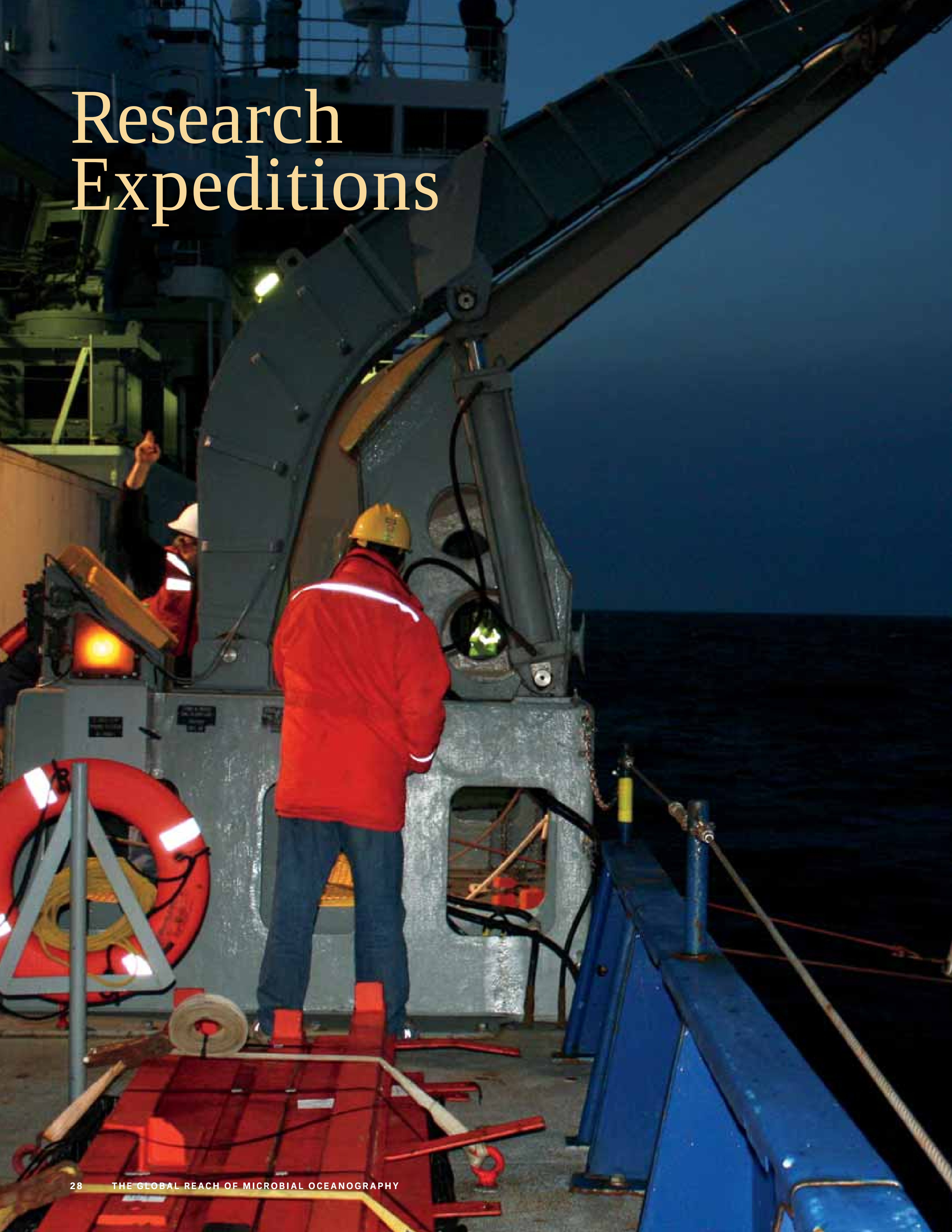
Information about how the diatoms in different regions function in their environments will allow scientists to build better models for predicting the role of ocean ecosystem processes in climate change. The paper based on this research has been published in the journal *Global Biogechemical Cycles* (Vol. 24, GB4031).

Photo by Richard G. Sandifer.



Differential interference contrast micrographs and false color maps of Si X-ray fluorescence for the three most common diatom taxa from the (left) eastern equatorial Pacific (EEP) and (right) Southern Ocean–Antarctic Zone (SOAZ). The fluorescence scale and linear dimensions are the same for all images to emphasize differences in size and Si content among taxa. *©2010 Global Biogeochemical Cycles.*

Research Expeditions



The Great Calcite Belt Expedition of 2011

In January 2011, Dr. Barney Balch mobilized a 23-member multi-institutional science team on the *R/V Melville* and set out from Punta Arenas, Chile on a 5,445-nautical mile transect across the South Atlantic to Cape Town, South Africa.

The scientists conducted sampling and shipboard experiments to determine how increasing ocean acidity from burning fossil fuels is affecting coccolithophores, highly abundant phytoplankton that mineralize calcium carbonate.

Coccolithophores play a major role in the carbon cycle by removing carbon dioxide from the atmosphere to form a protective calcium carbonate covering of microscopic plates, or coccoliths, around each cell. At the end of a coccolithophore bloom, the coccoliths, now aggregated with other organic debris, sink to the deep ocean, carrying carbon with them to the ocean floor, where it is buried in sediments.

The National Science Foundation sponsored the 36-day research expedition, which was planned to coincide with the largest recurring coccolithophore bloom in the South Atlantic, known as the Great Calcite Belt. At its full extent, the bloom extends over more than a quarter of the global ocean.

The expedition was the first systematic study of this massive annual phenomenon. Field observations and optical, chemical, and analytical data collection focused on factors influencing the abundance and distribution of coccolithophores, their role in global biogeochemistry, and the impacts of ocean acidification and climate change on the coccolithophores in the Great Calcite Belt.

Joining the Bigelow Ocean Observing and Optics research team were Dr. Ben Twining and members of his Trace Metal Biogeochemistry Laboratory, who examined the effect that trace metals such as iron, zinc, and cobalt are having on coccolithophore growth.

Members of the expedition team also included scientists from Bermuda Institute of Ocean Sciences; the National Oceanography Centre, Southampton; University of Miami; Woods Hole Oceanographic Institution; Colby College; and Scripps Institution of Oceanography.

Facing page: Night work in the South Atlantic. *Photo by Rebecca Fowler.*

GEOTRACES Expedition in the South Pacific

Research Associate David Drapeau, a member of Bigelow Laboratory's Ocean Observing and Optics Laboratory team, was part of the scientific crew aboard Australia's *R/V Southern Surveyor*, conducting trace metal sampling in the waters of the South Pacific as part of the 2011 GEOTRACES program. Scientists from thirty nations are participating in a ten-year program known as GEOTRACES, an international initiative to study the world's ocean basins through a series of expeditions to improve our understanding of the large-scale distribution of trace metals in the ocean and their part in global biogeochemical cycles.

R/V Southern Surveyor. © Commonwealth Scientific and Industrial Research Organisation, 2003–2011.

Trace elements in the marine environment are essential for ocean life and play key roles in both the global carbon cycle and in the way ocean ecosystems function. The mission of the GEOTRACES program is to identify and measure the factors influencing where trace elements are found in the ocean and to determine how these distributions are affected by changing environmental conditions. The program is contributing significant new data about sources, internal cycling, and chemical diversity of trace metals in the ocean; advancing understanding of current biogeochemical processes in the ocean; and providing insights about the ocean's role in past climate change.

Aboard *Tara Oceans*

Studying plankton is like taking the pulse of our planet.

—oceans.taraexpeditions.org

In late fall 2010, Bigelow phytoplankton ecologist Dr. Nicole Poulton joined the *Tara Oceans* expedition, a two-and-half-year circumnavigation of the world's ocean that is investigating the diversity of marine planktonic organisms across five orders of magnitude (marine viruses to small metazoans) and their response to climate change. The expedition is mapping the diversity and distribution of plankton populations and generating large datasets that will be used in ocean ecosystem models. As Chief Scientist on the Rio de Janeiro to Buenos Aires leg of the expedition, Poulton worked with an interdisciplinary team of oceanographers, ecologists, biologists, geneticists, and physicists aboard the 118-foot sailing research vessel for several weeks, training the crew in the use of at-sea instrumentation for flow cytometry and imaging.

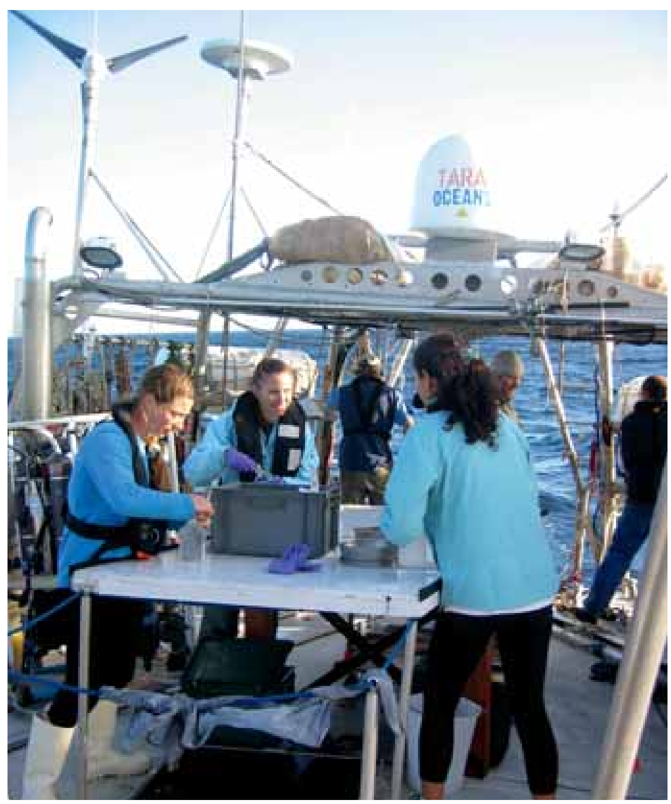


Photo by Danniel Bayley.

Chief Scientist Dr. Nicole Poulton (center) on *Tara*.

The Beaufort Gyre Expedition

Photo by Carlton Rauschenberg.

O-Buoy deployment on Arctic sea ice.

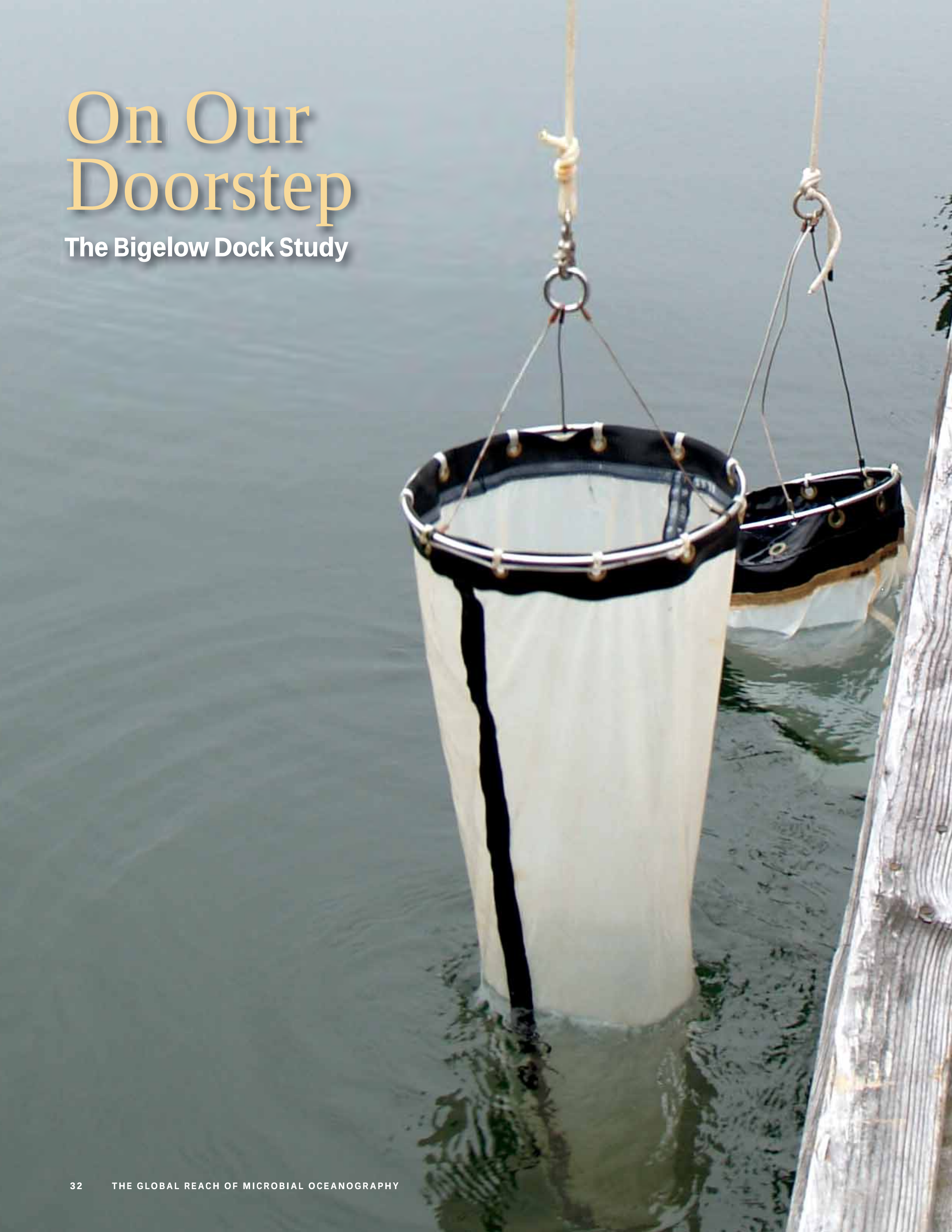
Climate conditions in the Arctic are changing more abruptly than anywhere else in the world, making it critically important to understand atmospheric chemistry over the Arctic Ocean and its influence on ecosystem productivity, ocean surface dynamics, cloud formation, air quality, and human health. The Beaufort Gyre, in the Arctic Ocean north of Alaska, is a massive, wind driven, rotating system that plays a key part in the climate of the entire Arctic region. Until recently, the physical and logistical challenges of collecting data in this remote region have meant that very few atmospheric measurements above the Arctic Ocean surfaces (open water and sea ice) have been possible.

To address this problem, Dr. Paty Matrai and her Ocean and Atmospheric Chemistry research team are leading a multi-institutional, National Science Foundation-funded initiative to construct, test, and deploy a system for year-round measurement of ozone, bromine monoxide, carbon dioxide, and meteorological conditions over Arctic sea ice. Known as the O-Buoy Network, the result is a buoy-based platform of instruments that, once installed, operates autonomously, using satellite communication to send daily data transmissions back to the mainland.

In late 2010, Ocean and Atmospheric Chemistry Research Associate Carlton Rauschenberg joined a 25-member team of scientists from the United States, Canada, and Japan on a 34-day expedition to the Beaufort Gyre. Working aboard the Canadian Coast Guard Icebreaker *Louis S. St. Laurent,* he assembled and deployed the third O-Buoy in the Beaufort Sea. This was the fourth successful installation of an O-Buoy in the Arctic Ocean in the past two years. Eleven additional O-Buoys are being deployed over the next four years to collect atmospheric data and investigate the behavior of ozone and carbon dioxide (two of the most important greenhouse gases) and their effect on climate in the Arctic.

On Our Doorstep

The Bigelow Dock Study



When Bigelow Laboratory established the first flow cytometry facility for ocean sciences in the 1980s, it put a sophisticated instrument for analyzing cells next to the pristine coastal bay just outside the door, creating a unique opportunity to use advanced methods to study the ocean on our doorstep. Every week since then, Bigelow researchers have collected water samples at high tide from the Laboratory's pier in Boothbay Harbor and run them through the cytometer, producing in a continuous, weekly flow of information for the past eleven years. The project has involved a growing team of scientists, community volunteers, and summer students.

The Dock Study is documenting physical and biological changes over time, focusing primarily on the distribution and population dynamics of microorganisms in the local waters of the Boothbay region. Studies such as this are an invaluable source of information about changing environmental conditions, providing a perspective that is only possible through painstaking, consistent collection of data over many years.

After the first several years, the team began to see a pattern of strong seasonal cycles in the microscopic populations in the water column; now it has become possible to see the natural variations from year to year. As the study's time frame continues to grow, long-term trends associated with climate oscillations and environmental changes will also become clearer. Results from the Bigelow Dock Study were recently presented at the Ocean Sciences Meeting, in Salt Lake City, Utah.

Photo by Cheryl Rau (2)

Terry Cucci (top), a key member of the weekly sampling team and a former longstanding Bigelow employee, processes and analyzes the dock water samples using flow cytometric techniques. He has been an active Bigelow volunteer since 2002 and has participated in the Bigelow Dock Study since it began. The study would not have been possible without his assistance. Other current and former participants in the Bigelow Dock Study project are Elin Haugen (above, left) and Nicole Poulton (above, right), Michael Sieracki, Edward Thier, Ilana Gilg, Brian Thompson, Ben Tupper, Peter Countway, David Fields, Steve Shema, Wendy Bellows, and undergraduate summer students Kate Hamre from Colby College and Ashley Couture from the University of Maine.

Facing page: Plankton tows from the dock. *Photo by Greg Bernard.*

Ocean Science
THE NEXT GENERATION

Photo by Rebecca Fowler.

REU
Class of 2011

Mark Chaffin
Colby College

Whole genome comparison of uncultured, ammonia-oxidizing marine group I archaea through single cell genomics. **Mentors:** Ramunas Stepanauskas, Brandon Swan

Kai Eldredge
University of Chicago

Urea in central Maine coastal waters: Concentrations and interactions with *Alexandrium fundyense* in natural microbial populations. **Mentor:** Cynthia Heil

Abigail Fuchsman
Bard College

Evolutionary pressure on cytochrome c oxidase I in copepods resulting in adaptation to new habitats. **Mentor:** David McClellan

Kate Hamre
Colby College

Predator-prey dynamics of *Dinophysis* spp., its prey *Myrionecta rubra*, and cryptophytes in West Boothbay Harbor, Maine. **Mentors:** Nicole Poulton, Elin Haugen, Kristen Reifel, Michael Sieracki

Alexandra Lopez
Interamerican University of Puerto Rico (San German)

Heterotrophic vs. autotrophic metabolism in iron oxidizing bacterium *Leptothrix ochracea*. **Mentors:** David Emerson, Emily Fleming, Joaquin Martínez, Ramunas Stepanauskas

Nicole Messerman
University of Maine-Orono

Ocean acidification and sperm motility in the giant sea scallop *Placopecten magellanicus*. **Mentor:** Rick Wahle

Helena Pound
University of Tennessee-Knoxville

Investigation of latent virus infections in marine phytoplankton. **Mentors:** Sheri Floge, Willie Wilson

Alexander Vermont
Northern Arizona University-Yuma

Dimethylsulfonioproprionate (DMSP) release during mesozooplankton grazing: A grazing deterrent? **Mentors:** David Fields, Paty Matrai, Steve Shema, Carlton Rauschenberg

Lousia Walker
Colby College

Diversity and gene expression of *Phaecystis*-associated DMSP degrading bacteria in cultures and coastal Gulf of Maine waters. **Mentor:** Pete Countway

Gulf of Maine and the World Ocean REU Program

The third year of the Laboratory's National Science Foundation-funded Research Experience for Undergraduates Program drew nearly 200 applicants from across the United States seeking an opportunity to spend ten weeks working on an independent research project with a Bigelow scientist. Eleven students were selected for the 2011 REU Program, and, based on mutual research interests, each was paired with one or more Bigelow mentors.

Over the following weeks, each student identified a research question; developed a proposal; conducted research; and prepared an abstract, poster, and formal presentation given during the student symposium at the end of the program.

Directed by Senior Research Scientist Dr. David Fields, the program is designed to give undergraduates a laboratory-based research experience with an emphasis on hands-on, state-of-the-art methods and technologies, as well as a chance to become part of the Bigelow community, including participation in seminars, field trips, outreach programs, and social events.

Each year since the program began, the quality of the Laboratory's REU student research has been recognized with awards and sponsorships, allowing many of these students to travel to professional conferences and scientific meetings to present their work to a broader audience. In 2011, four students received conference travel awards and three REU students attended the international ASLO (Association for the Sciences of Limnology and Oceanography) conference in Salt Lake City, Utah.


Photo by Bridget Besaw.

Dr. Pete Countway with Colby REU student Louisa Walker.


Photo by Rebecca Fowler. (2)

Dr. David Fields (left) in the field with members of the 2011 REU Class.

Colby College January Program

Bringing Ocean Science to Waterville, Maine

As part of the Laboratory's growing partnership with Colby College, Bigelow scientists again taught two intensive courses at the Waterville, Maine campus during the College's four-week 2011 January Program ("Jan Plan"). In keeping with the Jan Plan's mission "to broaden and extend the learning experience at Colby College by offering students distinctive opportunities not ordinarily available during the traditional academic semesters," the Laboratory's Jan Plan courses are designed to give students an opportunity to learn about and explore some of the most current topics in oceanography.

Dr. Pete Countway's course in *Diversity and Function of Life in Oceanic Realms* was a survey of the diversity of life in the oceans, with particular emphasis on microbial life forms. The course highlighted the revolutionary molecular tools (e.g., PCR, metagenomics, and genomics) researchers are using in oceanographic assessments of ocean life, and the potential role of biodiversity in maintaining healthy marine ecosystems.

Dr. David McClellan's *Marine Ecosystem Response to Climate Change* course focused on how marine ecosystems respond to changes in weather conditions over long periods of time, and examined how stresses that result from these changes can lead to adaptation or extinction of biological populations and communities.


Photo by Carlton Rauschenberg.

Broken ice in the Beaufort Sea.

BLOOM x 2

High School Students, High School Teachers

Hands-on research experience for sixteen of Maine's brightest high school juniors…

Photo by Rebecca Fowler.

The 22nd annual Keller BLOOM Program gave sixteen Maine high school juniors hands-on experience with ocean research, including a research cruise, sample collection, data analysis, and time to learn about life as a Bigelow scientist. This long-running residency program has included over 350 Maine students since it began in 1990.

BLOOM students spend four days with Bigelow scientists conducting and reporting about research on the phytoplankton and zooplankton that form the foundation of the marine food web. The students present their findings to a non-scientific audience at the end of the program. An independent assessment of the program completed in 2011 showed that 100% of all BLOOM students subsequently attend college, 70% major in science or mathematics, and half go on to pursue science careers. Many BLOOM alumni cite the program as a pivotal event in their lives and their first experience of academic success outside their local environment.

Ocean research, back at school…

An important expansion of the BLOOM experience was made possible last year by grants from the Horizon Foundation, Ingalls Foundation and the Betterment Fund, which provided support to launch a parallel program for Maine high school teachers interested in bringing ocean science to their classrooms. Ten teachers from high schools in Bangor, Belfast, Boothbay Region, Camden, Gardiner, Islesboro, Madawaska, and South Portland met at the Laboratory for an all-day workshop designed to help integrate ocean science principles into high school science curricula.

Led by Dr. David Fields, Dr. Nicole Poulton, NCMA Assistant Curator Carrie Schuman, and Education Director Rebecca Fowler, the day included an overview of current research directions in ocean science, hands-on laboratory activities, and a discussion about how scientists and teachers can collaborate to improve ocean science education. The group met again last summer for a four-day residential professional development workshop. Teachers created and tested lesson plans, conducted laboratory experiments, and received a toolkit of sampling equipment to use in the classroom. The BLOOM teacher program was certified by the University of Southern Maine to offer three Continuing Education Units to its participants.

2011 Keller BLOOM Program Sponsors*

A.R. & Marylouise Tandy Foundation Trust
The Betterment Fund
COSEE Ocean Systems/ National Science Foundation
The Dorr Foundation
The First, N.A.
First Federal Charitable Foundation
Horizon Foundation
The Ingalls Foundation
MetLife Foundation
National Girls Collaborative Project
Sylvester Foster Foundation
VWR Foundation
Drs. Charles and Clarice Yentsch

*Gifts of $1,000 or more

Blue Biotechnology

Private Sector Partnerships, Corporate Alliances, and Economic Growth

The Corporate Alliances and Technology Transfer Program

The ocean's scientific frontiers hold remarkable potential for commercialization of new discoveries and technologies in multiple large markets, including algae-based biofuels, pharmaceuticals, nutraceuticals, foodstuffs, and cosmeceuticals. The Laboratory's Office of Corporate Alliances and Technology Transfer (CATT) identifies opportunities and facilitates private sector partnerships that match the Laboratory's research results with corporations and venture capital firms. Introducing cutting-edge ocean science to the marketplace brings revenue back to the Laboratory, while at the same time industry partners profit financially from access to new technologies.

The Bigelow Center for Blue Biotechnology (BCBB), the first wing of the new Ocean Science and Education Campus to be completed, is designed to facilitate technology transfer projects that benefit society, help develop Maine's innovation economy and contribute to the Laboratory's own long-term strategy for financial stability. Construction of the BCBB was made possible in part by the Maine Technology Asset Fund and the people of Maine who voted to pass the Research and Development Bond in 2007.

Industry Agreements and Partnerships

Over the past year, the Laboratory established the following new relationships with private sector partners. These agreements streamline the process for corporate sponsorship of Laboratory-based research projects and facilitate the commercialization of Bigelow discoveries.

Long-term Master Professional Research Services Agreements

Fluid Imaging Technologies, Inc.
Yarmouth, Maine

BioProcess Algae, LLC
Portsmouth, Rhode Island

Health Enhancement Products, Inc.
Phoenix, Arizona

Exclusive Technology License Agreements

Satlantic, Inc., *Halifax, Nova Scotia*

Kennebec River Biosciences,
Richmond, Maine

Photo by Robert Mitchell.

Entering the Bigelow Center for Blue Biotechnology.

The BCBB houses three of the Laboratory's major service centers—the Provasoli-Guillard National Center for Marine Algae and Microbiota, the Jane J. MacIsaac Facility for Aquatic Cytometry, and the Single Cell Genomics Center. It also includes the Geomicrobiology Research Laboratory and a glass-enclosed, "showcase" Industrial Collaboration Laboratory available for collaborative research with companies in the pharmaceutical, aquaculture, environmental/bioremediation, analytical instrument, and biofuels industries. The CATT Program is working to develop a gateway for Bigelow research to help address current societal challenges, including the search for clean energy sources and the discovery of new products and medicines.

Program Director Mark Bloom participated in numerous corporate visits, trade meetings, and professional conferences throughout the year, and presented a talk about "The Intellectual Property and Commercialization Aspects of Algae in the Biofuel Industry" to attendees of the 2011 World Congress for Marine Biotechnology held in Dalian, China. He also served as a mentor to two summer undergraduate interns, Rebecca Stevenson, from North Yarmouth, Maine, who is attending the University of Oklahoma and Yale University student Thomas Winger, a native of Falmouth, Maine.

CATT's Corporate Affiliate Program (CAP) offers private companies an opportunity to establish working relationships with Bigelow researchers. The program provides each member company with a single interface and access to the resources at the Laboratory. CAP members receive advance information about research projects and new technologies developed at the Laboratory, including advance copies of working papers and articles produced by Laboratory researchers. The Founding Member of the CAP is BioProcess Algae, LLC.

Recent CATT Program Publications

Bloom, M.G. Overview of the regulatory aspects of pharmaceuticals, medical devices and biologicals. *AUTM Technology Transfer Practice Manual (TTPM)*—3rd Edition (2011). Association of University Technology Managers Press.

Bloom, M.G. The impact of Stanford v. Roche on the Bayh-Dole Act: A catastrophe for academic technology transfer or much ado about nothing? *The Licensing Journal,* September/October 2011 Issue. Aspen Publishers, Inc., Frederick, Maryland.

Bloom, M.G. Non-profit licensing: Past, present and future. *2011 Licensing Update.* Aspen Publishers, Inc. Frederick, Maryland.

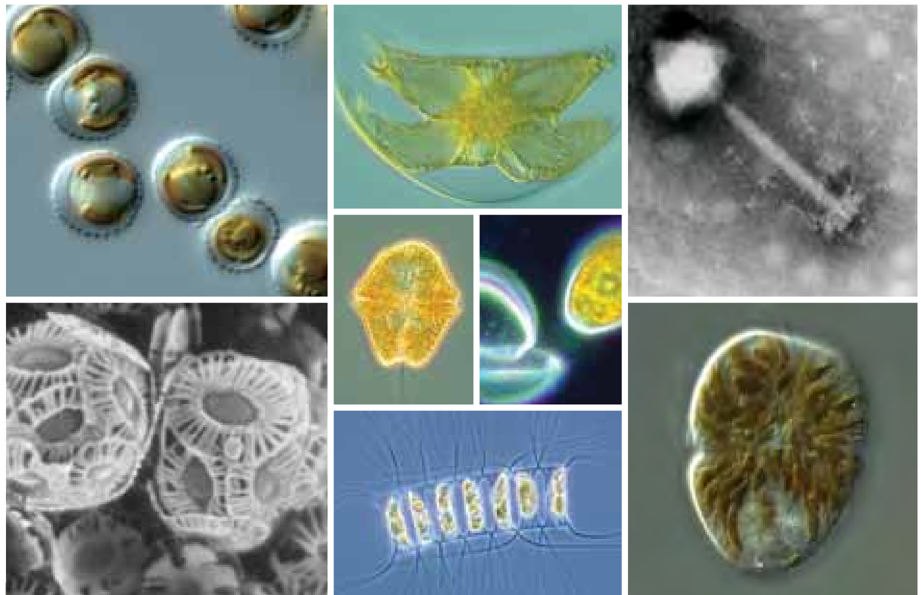
The Provasoli-Guillard National Center for Marine Algae and Microbiota

Thirty years in the algae business…

The National Center for Marine Algae and Microbiota (NCMA) is the nation's official collection of marine phytoplankton, and houses close to 3,000 strains of microscopic life from throughout the world's ocean. Most are marine phytoplankton (free-drifting, single-celled plants), but the facility also contains benthic, macrophytic, freshwater, and heterotrophic organisms. Phytoplankton specialist and algal culturing pioneer Dr. Robert Guillard established the center at the Laboratory in 1981. Originally known as the Center for the Culture of Marine Phytoplankton (CCMP), its name was changed to NCMA in 2011 to reflect the inclusion of marine bacteria and viruses that made it one of the world's first integrated collections of microbial ocean life.

NCMA curators maintain the collection in cultures at five temperatures (- 2°C, 4°C, 14°C, 20°C and 25°C), corresponding to the range of ocean temperatures at which the original samples were acquired. There are two culture chambers at each temperature, and three sets of cultures for each strain. A set of cryopreserved strains is also kept in separate storage tanks.

Part of the new Bigelow Center for Blue Biotechnology, NCMA has an international customer base, growing and shipping live cultures and products to scientists around the world. Under the leadership of NCMA Director Dr. Willie Wilson, its vision is to build upon three decades of experience in the algae business to become a one-stop service facility for the aquaculture, biomedical, and biofuels industries, offering culturing methods courses, opportunities for collaborative research, sales of algae and algal growth media, lipid profiling, molecular taxonomic identification, and screening for natural products.



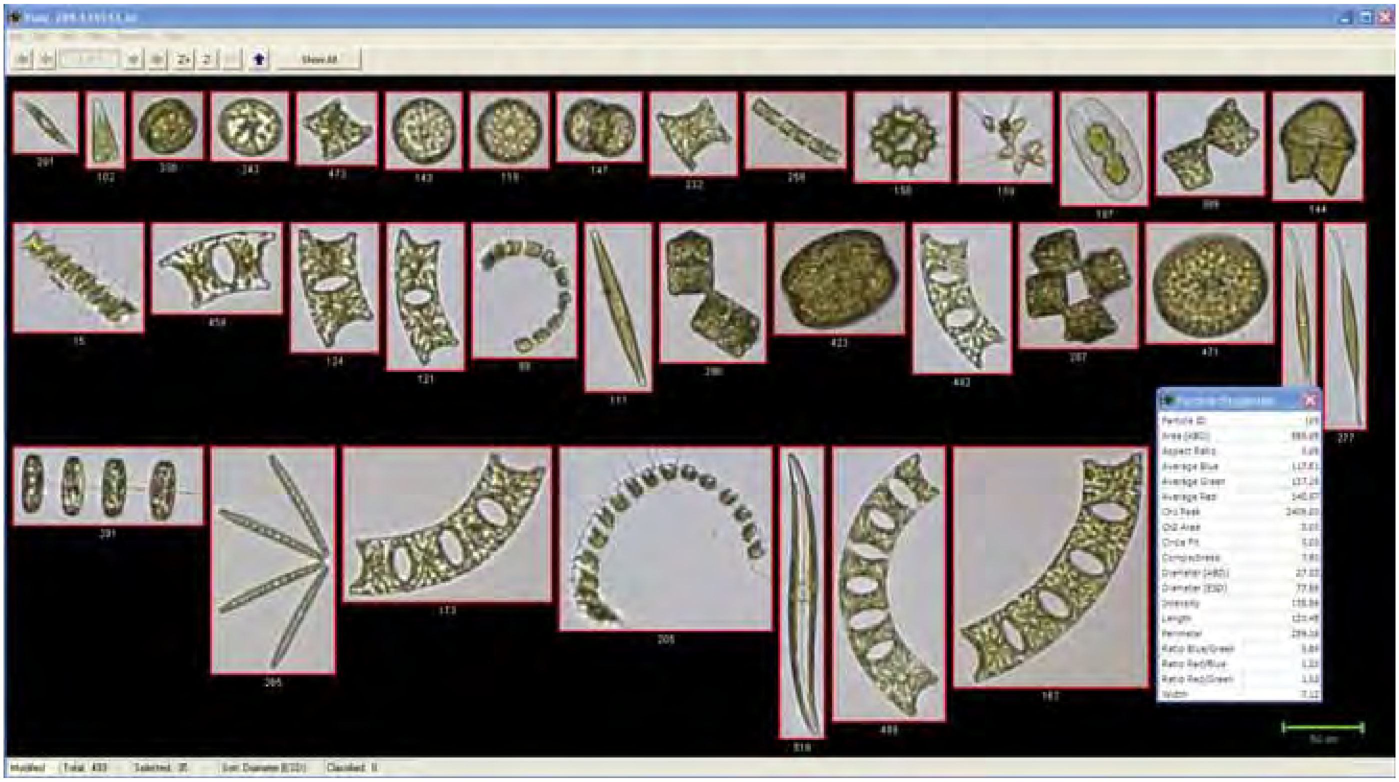
Micrographs courtesy of NCMA.

Photo by Cheryl Rau.

Dr. Willie Wilson at the NCMA.

The Jane J. MacIsaac Facility for Aquatic Cytometry

"Particle analysis with vision…"—Fluid Imaging Technologies, Inc.



Courtesy of Fluid Imaging Technologies, Inc.

Plankton images from the FlowCAM®.

Flow cytometry is a technology widely used in biomedical research for counting, examining, and sorting microscopic particles suspended in a stream of fluid. The first flow cytometer to be used in aquatic research was housed in the Jane J. MacIsaac Facility for Aquatic Cytometry, which began operations at the Laboratory in 1983. This multi-user facility continues to refine and adapt basic flow cytometry techniques to the study of algae and aquatic microbes from marine and freshwater ecosystems.

Using the latest cytometric methods to study planktonic viruses, bacteria, protozoa, and phytoplankton in natural systems, in laboratory experiments, and in cultures, scientists at the MacIsaac Facility have developed instruments, imaging technologies, and applications that allow them to investigate complex marine microbial ecosystems and global-scale phytoplankton blooms. Researchers from around the world use the facility for routine cell counting and sorting, biochemical analysis, culture purification, development of new applications and stains, and training in aquatic flow cytometry techniques.

The MacIsaac Facility contains several flow cytometers, cell sorters, and microscopy and imaging systems, including the FlowCAM® imaging-in-flow analyzer, an instrument invented at the Laboratory and now manufactured and marketed worldwide by Fluid Imaging Technologies in Yarmouth, Maine. The Facility is also able to operate off-site, using a portable laboratory van with a cell sorter to isolate cells from fresh samples at sea.

Headquartered in state-of-the-art space within the Bigelow Center for Blue Biotechnology on the Laboratory's new East Boothbay campus, the MacIsaac Facility's unique co-location with the National Center for Marine Algae and Microbiota and the Single Cell Genomics Center accelerates progress in algal cultivation, biochemical analysis, and single-cell genomics.

The Single Cell Genomics Center

Cutting-edge services for basic research and biotechnology applications…

Photo by Dennis Griggs.

Single-cell genomics, the technique of sequencing DNA from individual cells, allows researchers to analyze hereditary information at the most basic biological level. In the case of the billions of microbes inhabiting every gallon of seawater, each cell is an entirely separate organism. These single-cell life forms harbor enormous potential for discovery of new natural medicines and other products, bioenergy production, and bioremediation. However, scientists estimate that more than 99% of the world's microbial species remain uncultured, making it impossible to investigate them using classical microbiology methods.

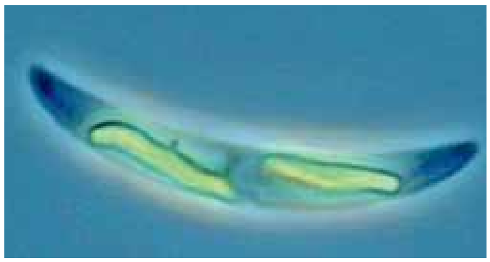
Single cell genomics technology allows researchers, for the first time, to study multiple genes and entire genomes of uncultured species directly from the ocean, as well as from a diversity of other natural environments. The key to this technology is physical separation of individual microbial cells, followed by amplification of DNA from each cell to make billions of identical DNA copies without first having to grow the cells in cultures.

…single-cell life forms harbor enormous potential for discovery…

This DNA can then be sequenced and assembled into genomes using conventional techniques. The Laboratory's Single Cell Genomics Center (SCGC), the only facility of its kind in the world, pioneered this new approach to genetic research.



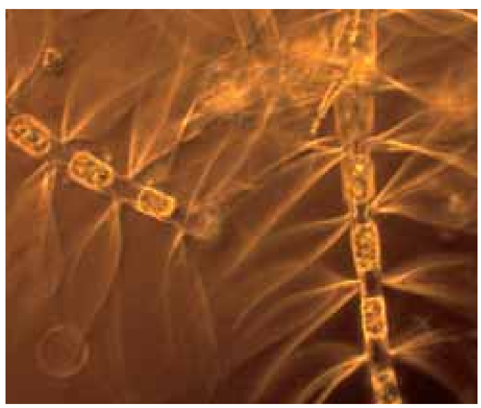



Micrographs courtesy of NCMA. Photo by Ramunas Stepanauskas.

Led by Director Dr. Ramunas Stepanauskas, the SCGC team has developed robust, high-throughput protocols for genomic DNA recovery from individual microbial cells and analyzed more than 300,000 of them, representing over 60 phyla of bacteria, archaea, and protists. Most of these microbes have never been cultivated, so this technology is providing the first view of their biological features.

The SCGC has provided services to over 30 organizations around the world, including research universities in North America, Europe, and Asia; federal agencies in the United States; and members of the international biotechnology industry. This work has enabled advanced research in microbial processes and carbon cycling in the ocean, renewable energy production, and human health. This, in turn, has led to recent discoveries about the detailed feeding strategies of single-celled marine life forms



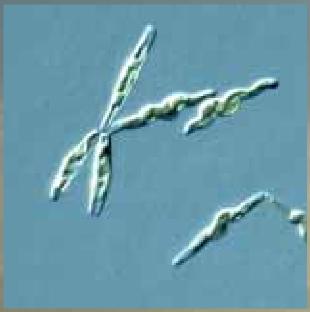
(see p. 7), the identities of microbes that can harvest sunlight, and the carbon biochemistry of microbial life in the deep ocean.

The SCGC's services include single cell sorting, whole genome amplification and DNA sequencing, and customized project support. Now located in the Bigelow Center for Blue Biotechnology, the SCGC makes single cell genomics accessible to the broad scientific community and serves as a leading engine of discoveries in the areas of microbial ecology, evolution, and bioprospecting.

Photo by Dennis Griggs.

Ocean Science Philanthropy

Helping to Make Our Discoveries Possible

A Report from the Development Committee of the Board of Trustees

In 1951, Rachel Carson dedicated *The Sea Around Us* to the Laboratory's namesake, Henry Bryant Bigelow, and what she said in the preface to that bestselling book is still true—"[t]he sea has always challenged the minds and imaginations of man and even today it remains the last great frontier of Earth." Private gifts to Bigelow Laboratory are essential in advancing our knowledge about this frontier, realizing its promise for new technologies and products, and preserving its resources for future generations.

Philanthropy is playing an increasingly important role in the Laboratory's work, and it is an integral component of the *Strategic Plan* adopted by the Board of Trustees in 2009. The Board established an Office of Advancement in 2010 to generate the private support that is critical to the Laboratory's future. The Founders Campaign, begun in 2010, is building significant new capacity to help the Laboratory achieve its strategic goals for advancing ocean science research, education, and technology transfer. Limited to the first 20 donors who contribute at least $250,000, the Founders Campaign goal is to attract early leadership support for the Laboratory's expanding operations and for the implementation of its *Strategic Plan*. To date, this campaign has attracted the early support of eight visionary Founders (see p. 53).

At the same time, the Laboratory's Annual Fund is growing steadily, helping to pay for essential programs not covered by research grants. In the last fiscal year, more than 250 donors gave over $355,000 in gifts to the Annual Fund. In the first half of this fiscal year, over 200 donors have contributed nearly $280,000. This includes over $66,000 in new or increased gifts from 117 donors in response to a year-end matching challenge. In addition, a special Bigelow "Pathfinder's Campaign" raised over $10,000 in gifts from the Laboratory's scientists and staff.

A complete list of our donors appears on pp. 53–56. We are immensely grateful to all of them for their generosity and their commitment to advancing understanding of the ocean and its importance to life on Earth.

Photo by Richard G. Sandifer.

Jennifer Cutshall joined Bigelow Laboratory as Director of Advancement in the fall of 2010. She is part of the senior management team and is leading the fundraising effort. With over 20 years of experience in both non-profit and for-profit management, she was most recently Director of Advancement at Maine Audubon and Senior Associate Director of Philanthropy at The Nature Conservancy in Maine. She was an award-winning development officer for New Hampshire Public Television, and worked in business development for Wheelabrator Environmental Systems, an environmental services company located in New Hampshire. She and her staff are responsible for the significant strengthening of the Laboratory's philanthropic program described here.

Ocean Literacy for All

Communications and Public Outreach

Thriving Science Conversations

Attendance at the Laboratory's regular series of Café Scientifique "science conversations" reached record levels over the past year, bringing over 900 people to the Opera House in Boothbay Harbor to talk with Bigelow scientists and special guests. Many of the talks were filmed and are available online at bigelow.org/news/cafe-scientifique. Guest speakers included Dr. Erik Zettler, Associate Dean at the Sea Education Association (SEA) in Woods Hole, Massachusetts; Dr. Richard Rockefeller, Steering Committee member of the Sargasso Sea Alliance; author and journalist Eric Lax; and Dr. Kevin Strange, Director and Professor, Mount Desert Island Biological Laboratory.

Bigelow scientists led 2011 Café Scientifique discussions about red tides and harmful algal bloom research, new discoveries about survival strategies of microscopic life in the ocean, radioactivity in the seas, trace metals in marine microbes, phytoplankton response to changing climate in the polar regions, DNA studies on endangered Hawaiian monk seals, and at-sea research about seasonal changes in North Atlantic phytoplankton communities.

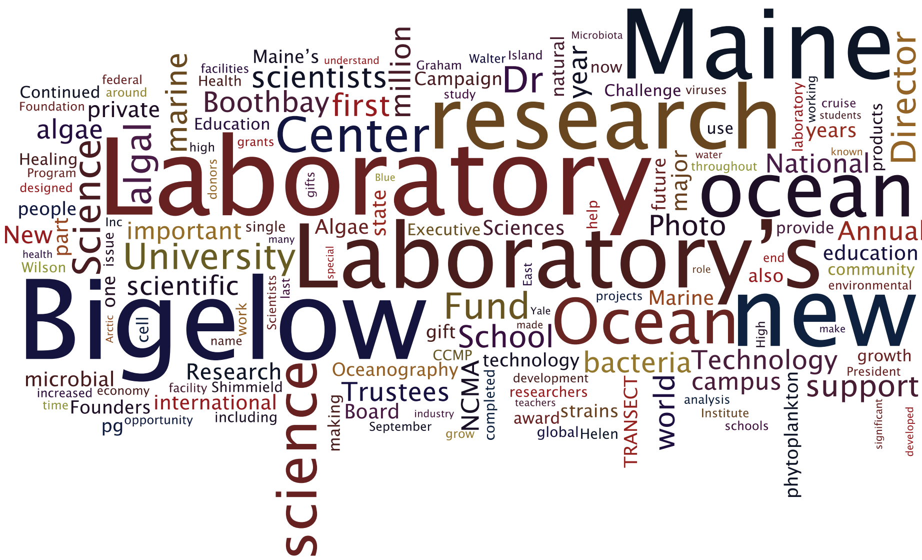
Photo by Pete Countway.

In Print, Online, and in Person

The Laboratory's *Transect* news magazine, published twice a year, provides an overview of recent developments in major program areas and service centers, and includes an "ocean science spotlight" that describes a special dimension of the Laboratory's research in each issue. In addition to *Transect*, over 2,400 individuals receive a monthly e-news bulletin, providing updates about current research grants and publications, expeditions, education programs, media coverage, technology transfer initiatives, and the latest progress in construction at the new Ocean Science and Education Campus in East Boothbay. The annual Open House brings neighbors and visitors to the Laboratory to meet scientists and students, tour individual laboratories, and have a first-hand look at ocean research in action.

Photo by Greg Bernard.

Photo by Rebecca Fowler.



Word "cloud" from *Transect*, Vol. 3, Issue 2. Word clouds are a visualization method for text that shows relative frequency and prominence of specific words by using different font sizes and colors. *Courtesy of Barney Balch.*

Library and Information Center

The Laboratory's Library and Information Center is a major resource for marine research. Founded with the Laboratory in 1974, it now includes 15,000 volumes, periodicals, DVDs, technical publications, and online resources that emphasize the biological and physical study of the world's oceans. A small special collection called the Fishermen's Library contains books, pamphlets, and other media resources about fishing gear and methods, fishery history, and Maine's fishing and aquaculture industries.

The Library and Information Center supports the research efforts of Laboratory scientists, visiting researchers, postdoctoral researchers, and students participating in the Laboratory's education programs. Sharing its collection with the Maine Department of Marine Resources, the Bigelow Library and Information Center is available to educators, fishermen, aquaculturists, and the general public.

A recent grant from the Stephen and Tabitha King Foundation initiated implementation of KOHA, a web-based open-source integrated library system that automates library management operations, making the collection more directly available to a broader clientele. This web-based system allows users access to the full contents of the collection directly from the Bigelow Laboratory Library web site (www.bigelow.org/research/facilities/library).

In order to meet growing demand and diverse research needs, the Library and Information Center is continuing its efforts to expand and enhance the online resources available to Bigelow researchers.

Active Grants and Contracts

(July 1, 2010–June 30, 2011)

No.	Funder	Principal Investigator(s)	Award Total
34101	NSF	Stepanauskas/Sieracki	$659,836
34103	NSF	Matrai	306,793
34105	NSF	Sieracki/Pilskaln/Balch	1,555,515
34113	NSF	Matrai	413,994
34114	NSF	Fields/Sieracki	462,847
34121	NSF	Fields	322,532
34124	NSF	Matrai	498,722
34125	NSF	Balch	495,729
34126	NSF	Wilson/Stepanauskas	808,750
34127	NSF	Emerson	114,695
34129	UME/NSF	Sieracki	40,000
34130	NSF	Matrai	320,000
34131	NSF	Twining	181,090
34132	NSF	Yoon/Andersen	993,911
34133	NSF	Stepanauskas/McClellan/Sieracki	976,747
34134	NSF	Goés	296,905
34135	NSF	Goés	139,819
34139	NSF	Wilson	69,523
34140	NSF	Twining	137,756
34141	NSF	Twining	257,021
34142	NSF	Stepanauskas	650,000
34143	NSF	Wilson	549,105
34144	NSF	Wilson/Stepanauskas	338,950
34145	NSF-ARRA	Matrai	104,337
34146	NSF	Yoon	1,360,652
34147	NSF	Goés	333,261
34149	NSF	Emerson	115,372
34150	NSF	Wilson	1,807,672
34152	NSF	Twining	349,430
34153	NSF	Balch/Twining	1,088,876
34155	NSF	Emerson	635,893
34157	NSF	Matrai	1,075,619
34158	NSF	Yoon/Stepanauskas/Poulton	331,607
34159	NSF	Twining/Fields	519,331
34304	NASA	Balch	800,386
34305	NASA	Balch/Goés	966,277
34311	NASA	Goés	745,316
34312	UCB/NASA	Emerson	217,845
34314	UCONN/NASA	Balch	389,688
34316	OSU/NASA	Sieracki	115,846
34317	NASA	Balch	676,980
34320	NASA	Goés	830,056
34321	UWA/NASA	Matrai	445,171
34322	MSGC/NASA DEBSCoR	Emerson/McClellan/Stepanauskas	724,799
34323	NASA	Balch	685,001
34324	NASA	Sieracki/Stepanauskas	24,545
34325	UCONN/NASA	Balch	47,337
34404	ONR	Emerson	955,602
34504	MT/NOAA	Wilson	112,655
34506	UMiami/NOAA	Poulton	14,286
34604	DOE	Stepanauskas/Poulton	15,000
34605	USFWF	Larsen	15,000
34804	CA DWR	Poulton	24,000
34903	CPW	Matrai	19,000

EDUCATION

34109	UME/NSF	Sieracki/Goés	622,108
34137	NSF	Wahle/Fields	258,685
34713	MSGC	Goés	9,000

PLANT AND EQUIPMENT

34136	NSF	Emerson/Wilson	335,341
34138	NSF	Stepanauskas/McClellan/Emerson	574,045
34148	NSF	Emerson/Twining/Fields/Yoon	341,265
34703	MTI	Balch	141,200
34706	MTI	Goés	346,000
34712	MTI	Shimmield, Wilson	4,528,971
34156	NSF	Shimmield/Matrai/Balch/Twining	4,975,000
34805	NIST	Shimmield	9,145,710

Scientific Publications

(July 1, 2010–June 30, 2011)

Baines, S.B., **Twining, B.S.**, Brzezinski, M.A., Nelson, D.M., Fisher, N.S. Causes and biogeochemical implications of regional differences in silicification of marine diatoms. (2010) *Global Biogeochemical Cycles*, 24 (4), art. no. GB4031.

Baines, S.B., **Twining, B.S.**, Vogt, S., **Balch, W.M.**, Fisher, N.S., Nelson, D.M. Elemental composition of equatorial Pacific diatoms exposed to additions of silicic acid and iron. (2011) *Deep-Sea Research Part II: Topical Studies in Oceanography*, 58 (3–4), pp. 512–523.

Balch, W.M., **Bowler, B.C.**, **Drapeau, D.T.**, Poulton, A.J., Holligan, P.M. Biominerals and the vertical flux of particulate organic carbon from the surface ocean. (2010) *Geophysical Research Letters*, 37 (22), art. no. L22605.

Balch, W.M., **Drapeau, D.T.**, **Bowler, B.C.**, Lyczskowski, E., Booth, E.S., **Alley, D**. The contribution of coccolithophores to the optical and inorganic carbon budgets during the Southern Ocean Gas Exchange Experiment: New evidence in support of the Great Calcite Belt hypothesis. (2011) *Journal of Geophysical Research C: Oceans*, 116 (8), art. no. C00F06.

Balch, W.M., Poulton, A.J., **Drapeau, D.T.**, **Bowler, B.C.**, Windecker, L.A., Booth, E.S. Zonal and meridional patterns of phytoplankton biomass and carbon fixation in the Equatorial Pacific Ocean, between 110°W and 140°W. (2011) *Deep-Sea Research Part II: Topical Studies in Oceanography*, 58 (3–4), pp. 400–416.

Baumgartner, M.F., Lysiak, N.S.J., **Schuman, C.**, Urban-Rich, J., Wenzel, F.W. Diel vertical migration behavior of *Calanus finmarchicus* and its influence on right and sei whale occurrence. (2011) *Marine Ecology Progress Series*, 423, pp. 167–184.

Boo, G.H., Lindstrom, S.C., Klochkova, N.G., Yotsukura, N., **Yang, E.C.**, Kim, H.G., Waaland, J.R., Cho, G.Y., Miller, K.A., Boo, S.M. Taxonomy and biogeography of *Agarum* and *Thalassiophyllum* (Laminariales, Phaeophyceae) based on sequences of nuclear, mitochondrial, and plastid markers. (2011) *Taxon*, 60 (3), pp. 831–840.

Borges A.V., Alin S.R., Chavez F.P., Vlahos P., Johnson K.S., Holt J.T., **Balch W.M.**, Bates N., Brainard R., Cai W.-J. and others. "A global sea surface carbon observing system: inorganic and organic carbon dynamics in coastal oceans," in *Proceedings of the OceanObs'09: Sustained Ocean Observations and Information for Society Conference* (Vol. 2) Venice, Italy, 21–25 September 2009. Hall, J., Harrison D.E. and Stammer, D., eds. ESA Publication WPP-306, 2010.

Browman, H.I., Yen, J., **Fields, D.M.**, St-Pierre, J.-F., Skiftesvik, A.B. Fine-scale observations of the predatory behavior of the carnivorous copepod *Paraeuchaeta norvegica* and the escape responses of their ichthyoplankton prey, Atlantic cod *(Gadus morhua)*. (2011) *Marine Biology*, 158 (12), pp. 2653–2660.

Brzezinski, M.A., Baines, S.B., **Balch, W.M.**, Beucher, C.P., Chai, F., Dugdale, R.C., Krause, J.W., Landry, M.R., Marchi, A., Measures, C.I., Nelson, D.M., Parker, A.E., Poulton, A.J., Selph, K.E., Strutton, P.G., Taylor, A.G., **Twining, B.S.** Co-limitation of diatoms by iron and silicic acid in the equatorial Pacific. (2011) *Deep-Sea Research Part II: Topical Studies in Oceanography*, 58 (3–4), pp. 493–511.

Chan, C.S., Fakra, S.C., **Emerson, D.**, **Fleming, E.J.**, Edwards, K.J. Lithotrophic iron-oxidizing bacteria produce organic stalks to control mineral growth: Implications for biosignature formation. (2011) *ISME Journal*, 5(4), pp. 717–727.

Chan, C.X., Gross, J., **Yoon, H.S.**, Bhattacharya, D. Plastid origin and evolution: New models provide insights into old problems. (2011) *Plant Physiology*, 155(4) pp. 1552–1560.

Chan, C.X., **Yang, E.C.**, Banerjee, T., **Yoon, H.S.**, Martone, P.T., Estevez, J.M., Bhattacharya, D. Red and green algal monophyly and extensive gene sharing found in a rich repertoire of red algal genes. (2011) *Current Biology*, 21(4), pp. 328–333.

De Jonge, M.D., Holzner, C., Baines, S.B., **Twining, B.S.**, Ignatyev, K., Diaz, J., Howard, D.L., Legnini, D., Miceli, A., McNulty, I., Jacobsen, C.J., Vogt, S. Quantitative 3D elemental microtomography of *Cyclotella meneghiniana* at 400-nm resolution. (2010) *Proceedings of the National Academy of Sciences of the United States of America*, 107 (36), pp. 15676–15680.

Dessimoz, C., Zoller, S., Manousaki, T., **Qiu, H.**, Meyer, A., Kuraku, S. Comparative genomics approach to detecting split-coding regions in a low-coverage genome: Lessons from the chimaera *Callorhinchus milii* (Holocephali, Chondrichthyes). (2011) *Briefings in Bioinformatics*, 12 (5), art. no. bbr038, pp. 474–484.

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Fields, D.M., Durif, C.M.F., Bjelland, R.M., **Shema, S.D.**, Skiftesvik, A.B., Browman, H.I. Grazing rates of *Calanus finmarchicus* on *Thalassiosira weissflogii* cultured under different levels of ultraviolet radiation. (2011) *PLoS ONE*, 6(10), art. no. e26333.

Fleming, E.J., Langdon, A.E., **Martinez-Garcia, M.**, **Stepanauskas, R.**, **Poulton, N.J.**, **Masland, E.D.P.**, **Emerson, D.** What's new is old: Resolving the identity of *Leptothrix ochracea* using single cell genomics, pyrosequencing, and FISH. (2011) *PLoS ONE*, 6 (3), art. no. e17769.

Heywood, J.L., **Sieracki, M.E.**, **Bellows, W.**, **Poulton, N.J.**, **Stepanauskas, R.** Capturing diversity of marine heterotrophic protists:

One cell at a time. (2011) *ISME Journal*, 5 (4), pp. 674-684.

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Summary Financial Statement

(July 1, 2010–June 30, 2011)

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

	2011	2010	2009
Operating Activities			
Operating Revenue and Support			
Grants and contracts for research and education	$5,360,968	$5,208,410	$4,700,215
Subawards	$364,950	$932,646	$580,444
Contributions to Capital Campaign	886,120	1,514,844	73,725
Other revenue, including course fees	958,296	662,180	577,186
Contributions to Annual Fund	356,138	338,326	304,509
Total Operating Revenue and Support	7,926,472	8,656,406	6,236,079
Operating Expenses			
Research and Education	7,046,983	7,084,982	6,630,744
Unallocated management and general	621,673	449,404	354,459
Development	722,512	368,396	377,245
Total Operating Expenses	8,391,168	7,902,782	7,362,447
Change in Net Assets from Operating Activities	-464,696	753,624	-1,126,368
Non-Operating Revenue and Support			
Contributions and grants for equipment and construction	4,836,557	788,806	362,730
Change in Net Assets from Non-Operating Activities	4,836,557	788,806	362,730
Total Change in Net Assets	4,371,861	1,542,430	-763,639

Statement of Financial Position *(At June 30)*

	2011	2010	2009
Assets			
Cash	$747,540	$350,481	$270,617
Cash restricted for construction	$859,086		
Pledges receivable	$990,414	$1,080,063	$436,935
Investments	1,277,693	1,614,537	1,687,413
Property and Equipment, Net	15,261,099	6,542,677	5,419,030
Other	1,486,676	1,187,746	1,171,743
Total Assets	20,622,508	10,775,504	8,985,738
Liabilities and Net Assets			
Short Term Liabilities	$1,040,973	$1,094,214	$846,864
Short Term Liabilities for construction	$2,523,772		
Long Term Liabilities	$3,004,612		
Net Assets			
Unrestricted	5,759,150	6,102,203	5,766,256
Temporarily Restricted	8,091,857	3,376,943	2,170,845
Permanently Restricted	202,144	202,144	201,769
Total Net Assets	14,053,151	9,681,290	8,138,870
Total Liabilities and Net Assets	20,622,508	10,775,504	8,985,734

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 2009, 2010, and 2011 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.

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Chip Davison, an accomplished world sailor, is a graduate of Yale University and was the co-founder and President of Great Eastern Mussel Farm. He serves on numerous boards of special relevance to the Laboratory, including the Maine Technology Institute, the Maine Aquaculture Association, and the Maine Department of Marine Resources Advisory Council.

Russell Jeppesen holds a B.A. and MBA from Bentley College in Waltham, Massachusetts. He has served on the Regional Board of Directors of BankBoston and is the owner of the Acadia Group in North Hampton, New Hampshire. He has been on the Board of Overseers of Berwick Academy and has served as President of the Sylvester M. Foster Foundation.

George Mitchell practiced law as a trial attorney, and was a U. S. Attorney, U. S. District Judge, and U. S. Senator. He served as Senate Majority Leader from 1989 to 1995, and was Special Advisor to the President and the Secretary of State for Economic Initiatives in Ireland. He is a recipient of the Presidential Medal of Freedom and was appointed as Special Envoy for Middle East Peace. His books include *Making Peace* and *Not for America Alone: The Triumph of Democracy and the Fall of Communism*. He is a graduate of Bowdoin College and Georgetown University Law Center.

Herb Paris is a graduate of Brandeis University and holds a Master of Hospital Administration degree from the Medical College of Virginia. He was Associate Director of the Yale New Haven Hospital before moving to Brunswick, Maine in 1987, where he served as President and CEO of Mid Coast Health Services until his retirement.

Randy Phelps, a graduate of Denver University and University of Colorado Law School, is a residential real estate developer and co-founder of the U.S. Energy Corporation. He serves on the boards of the Carpenter's Boat Shop in Pemaquid, the Genesis Community Loan Fund in Damariscotta, and the Family Planning Association of Maine in Augusta.

Jonathan Schaffer, a physician in The Cleveland Clinic Foundation's Department of Orthopaedic Surgery, is managing director of eCleveland Clinic and holds a joint appointment in the Department of Biomedical Engineering. A Fellow of the American College of Surgeons, he has been a visiting scientist at the Massachusetts Institute of Technology and was President of Harmonie Group, Inc., in Boston. He received a B.A. from Haverford College, an M.D. from Case Western Reserve University, and an MBA form Northwestern University.

Kevin Strange is a professor and the director of the Mount Desert Island Biological Laboratory (MDIBL). He came to Maine in 2009 from Vanderbilt Medical Center, becoming MDIBL's first full-time, on-site director. He holds a B.S. degree from the University of California at Davis and a Ph.D. from the University of British Columbia. His research focus is on environmental stress biology and membrane biology.

Michael Tetreault is the Executive Director of The Nature Conservancy in Maine. He taught wilderness leadership and environmental education at Teton Science School in Jackson Hole, Wyoming and worked as staff scientist at Appalachian Mountain Club. He holds an M.S. from the University of Vermont and a B.A. from Brown University.

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Photo by Rebecca Fowler.

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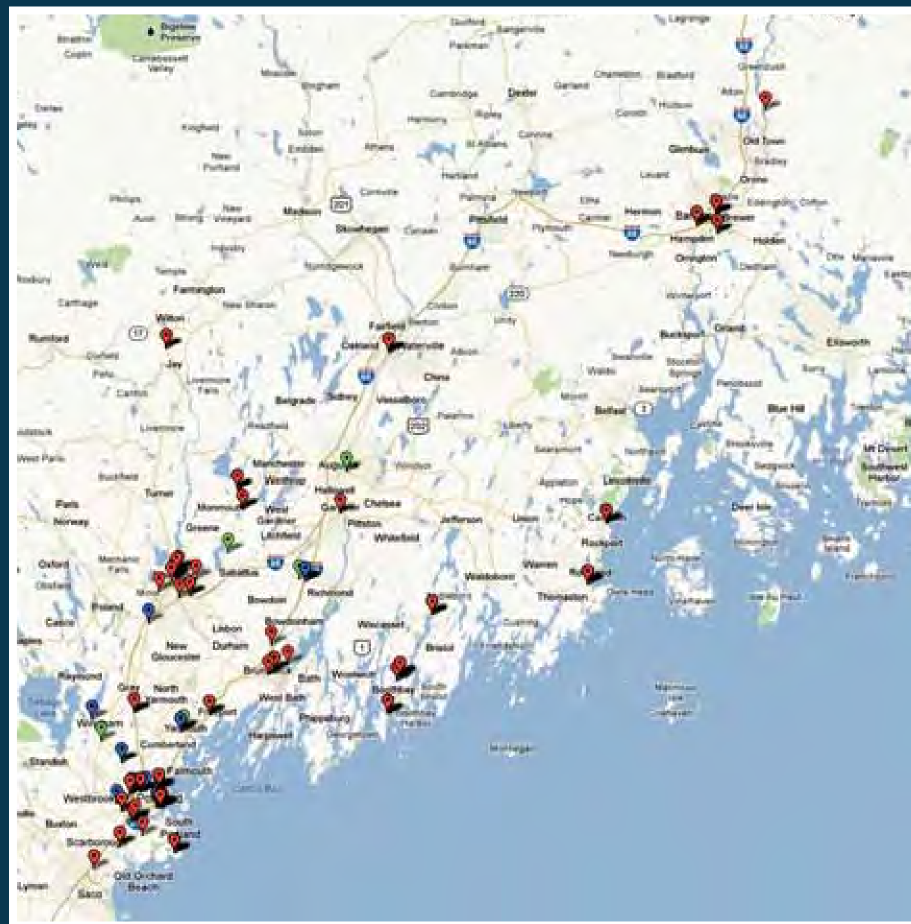
A recent independent economic analysis estimates that the statewide direct and indirect economic impact of the construction project will exceed $57 million and support over 250 full and part-time jobs.



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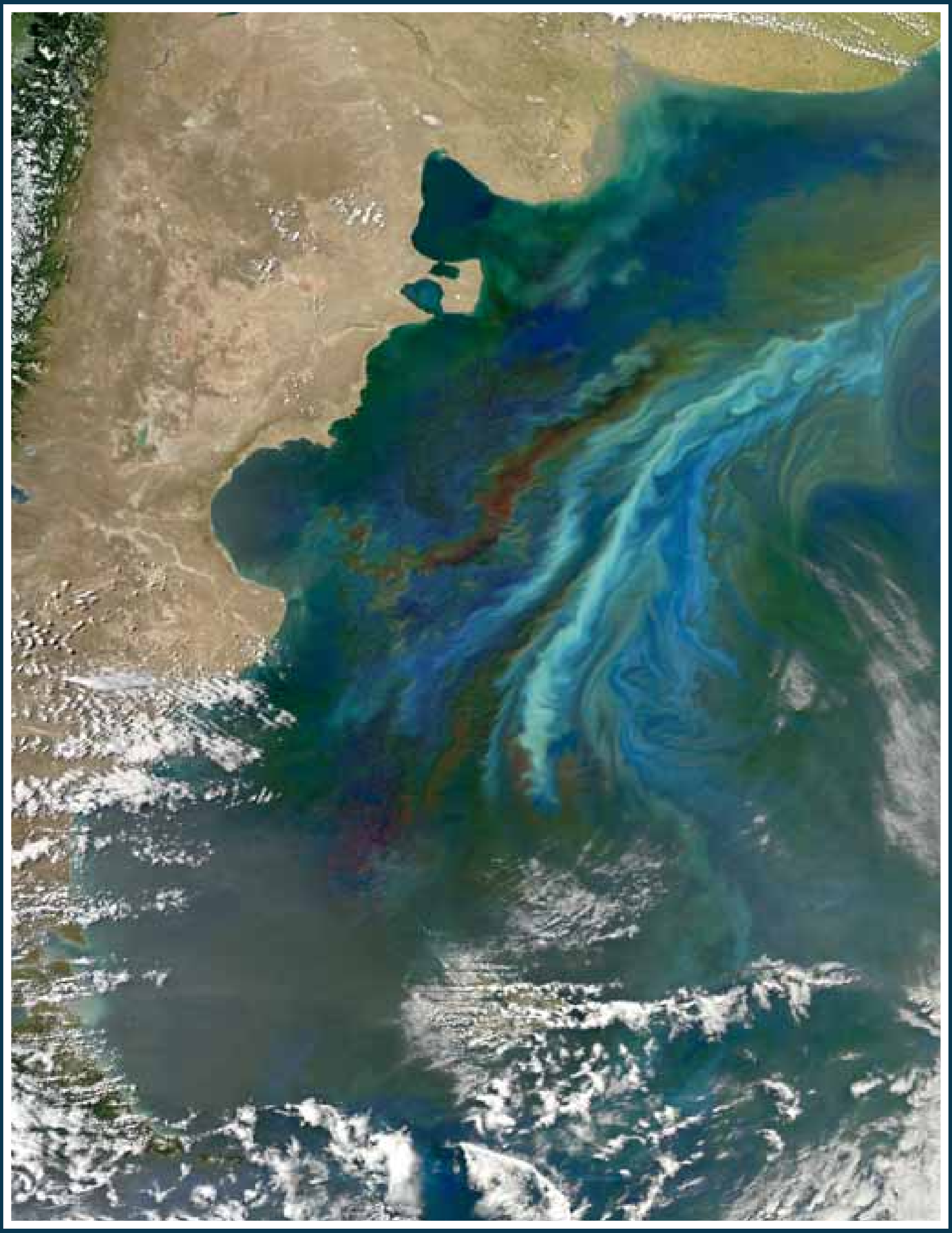

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