Bigelow Laboratory for Ocean Sciences

Annual Report 2007

More than two-thirds of our planet is blue ocean, a reality we see time and again in images taken from space. It should then be no surprise that the network of life in the oceans has great influence on the rest of the world, including the terrestrial ecosystems we ourselves inhabit and depend upon for survival. As a society, we have only just begun to understand the magnitude and scope of this influence. The biogeochemical cycles of the oceans, and the life they nurture, are inextricably linked; how and why they persist and change are key questions that ocean science seeks to answer.

The ocean holds tremendous possibilities for discovery—from new sources of energy to new genetic pathways to health. Advances in ocean research and technology are offering us ways to improve the quality of our lives at the same time that we build an environmentally responsible future.

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Bigelow Laboratory for Ocean Sciences is known throughout the international scientific community for its independence, its spirit of collaboration, its entrepreneurship, and its creative energy. I am committed to carrying forward the vision of the Laboratory's founders, Drs. Charles and Clarice Yentsch, by marshalling the outstanding multi-disciplinary talent, the resolve, and the resources to do the job. I would like to pay tribute to my predecessor, Dr. Sandy Sage, who enhanced the Laboratory's reputation over the past eleven years.

We must continue to explore the ocean from every conceivable perspective—from the genetic codes inside the smallest living cells that our novel molecular techniques reveal, to fieldwork in the extreme environments of the open ocean, to the analysis of detailed global images brought to us by remote sensing satellites—and we must tell people everywhere about the importance of what we are learning.

I am both honored and delighted to have this opportunity to introduce the 2007 Annual Report for Bigelow Laboratory for Ocean Sciences, and proud to join this exceptional team of researchers at so pivotal a time in our planet's environmental history.

Graham Shimmield, Ph.D.
Executive Director and President

May 20, 2008

Facing page: Photo courtesy of J. Goés.

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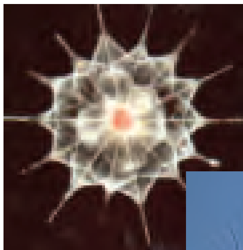

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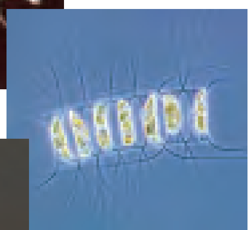

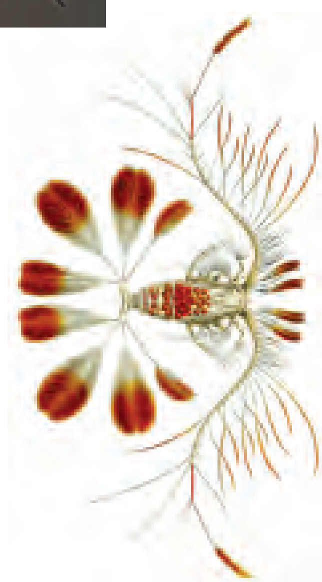

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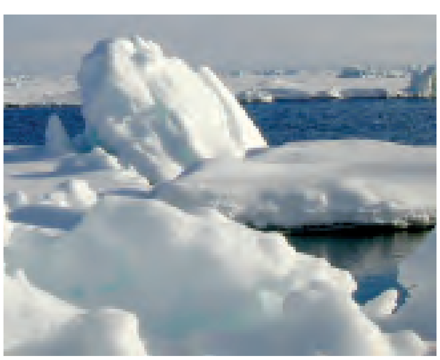

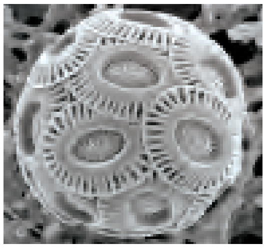

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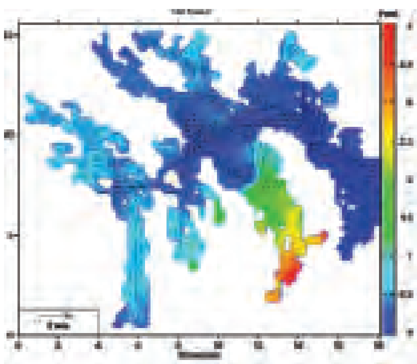
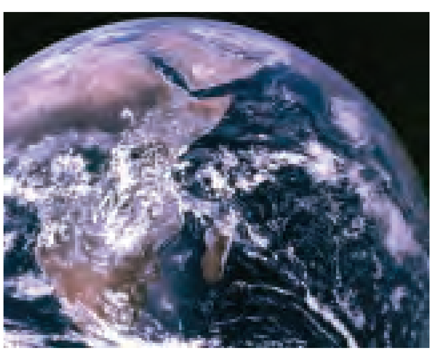




"How the Cause Works"

The Global Reach of Microbial Oceanography

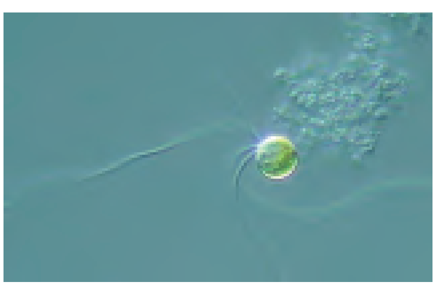
Henry Bigelow steering the U.S. Bureau of Fisheries vessel Grampus, 1914. Courtesy of Woods Hole Oceanographic Institution Archives.

The founder of modern ocean science, and the man after whom Bigelow Laboratory for Ocean Sciences was named, was early 20th-century oceanographer Henry Bryant Bigelow. He described the interconnected and largely undiscovered relationships between the biological, chemical, and physical systems in the world's oceans by saying that "nothing in the sea falls haphazard; if we cannot predict, it is because we do not know the cause, or how the cause works." Today, this visionary scientist is both an icon and inspiration for the 21st-century researchers at Bigelow Laboratory. His legacy is reflected in our focus on the dynamic biological, chemical, and physical relationships that sustain life in the oceans and their impact on the global environmental processes upon which all life depends.

The scope of research at Bigelow Laboratory ranges from study of the genetic structure of phytoplankton and other single-celled microbes to the relationship between ocean ecosystems and global climate change. Our scientists are exploring the biomolecular foundations of life in the world's oceans and discovering fundamental connections between the ***biological productivity*** of the planet's ocean ecosystems and changes in the global environment as a whole. This report focuses on Bigelow Laboratory's burgeoning research focus on microbial oceanography within the broad global context of our research programs.

Microbial oceanography is the study of microscopic marine life—single-celled marine organisms, bacteria, and viruses—that are essential to the functioning of the world's oceans. Although marine microbes exist in literally astronomical abundance throughout the world's oceans, the dynamics that drive this profusion of life take place on an infinitesimal biomolecular scale. But it is at this microscopic level that the vital global processes of photosynthesis, the global carbon cycle, and the flow of nutrients through the food web begin.

As a new and rapidly evolving scientific field, microbial oceanography is emerging from a synthesis of physical and chemical oceanography, marine ecology, physiology, and molecular genetics, offering scientists an unprecedented opportunity to understand the living world. Engineering advances in genetic research have made it possible to uncover the critical role that marine microbes have in biogeochemical processes that affect all life—from global climate



Marine Microbial Food Web

The "microbial food web" is the pathway in the marine food chain through which carbon is reintroduced to the marine ecosystem by bacteria that consume dissolved organic material. Microscopic marine organisms called protists consume the bacteria, which are then eaten by zooplankton. Since microbes are at the base of the marine food web, the microbial food web is vital to the total productivity of the oceans and plays a major role in how much organic carbon is transported to the sediments of the deep sea floor.

Note: Words in bold italic type are defined in the glossary on p. 42.

The Global Carbon Cycle

Carbon is one of the basic elements of living plants and animals and is also found in decaying organic matter, and in fossil fuel deposits. Atmospheric carbon dioxide gas (CO_2) traps a portion of the sun's heat, making the planet's atmosphere warmer than it would otherwise be. Emissions of carbon dioxide have caused CO_2 levels in the atmosphere to increase by approximately 30% since the beginning of the Industrial Revolution in the 18th century, a factor now recognized to be a major cause of current global climate change.

Scientists estimate that the amount of carbon in the world's oceans is at least ten times greater than on land, making the pathways within the marine carbon cycle critically important to all global ecosystems. There is a continuous exchange occurring between CO_2 in the atmosphere and the reservoirs of carbon in the oceans and on land. By far the largest carbon reservoir on the planet is the deep ocean, which has a much slower rate of exchange with the atmosphere, making it a net carbon "sink," where CO_2 fixed during photosynthesis is transferred into long-term storage. Understanding the biogeochemical role of marine microbes in the global carbon cycle is essential to addressing the challenge of climate change.

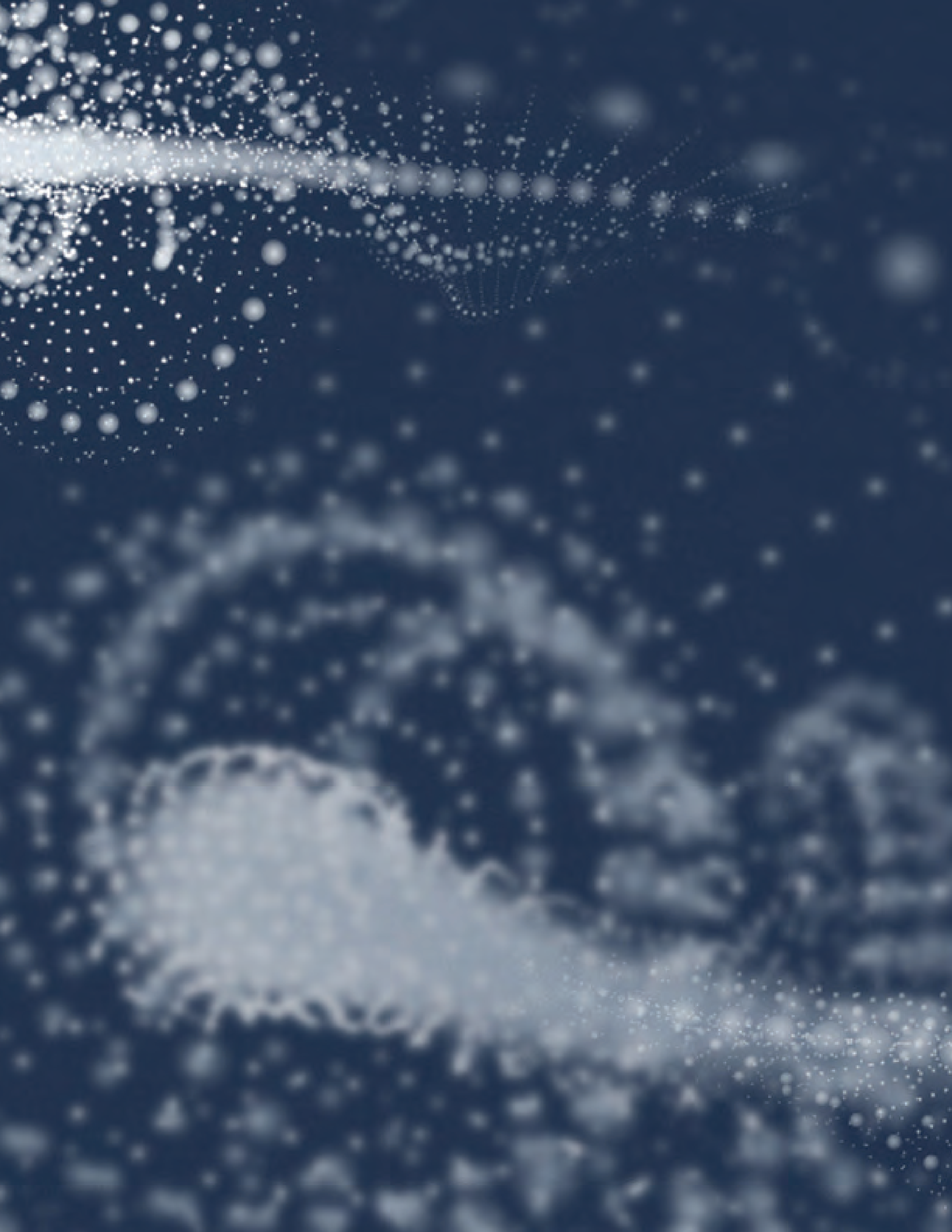
change, to the nature of the planet's food supply, to the future of evolution itself.

Natural ecosystems everywhere are responding to profound changes in the global environment. The role of the oceans in stabilizing and sustaining life on our planet is becoming increasingly clear, and this knowledge has direct bearing on our lives. As we come to understand the cause and how it works, we are empowered to face the environmental challenges and opportunities that will shape our future. In the years ahead, ocean research will continue to be at the forefront of discovery, and it is fair to say that the more we know, the more there is to know. At Bigelow, this serves both as a scientific mandate and as a source of hope—for our planet and for our ability to co-exist with the natural world.

Oceans cover 71% of the planet's surface, and contain all but 3% of the world's water. They provide the only source of protein for over a billion people, directly influence global weather patterns, and distribute solar energy throughout the world. Microscopic, single-celled marine phytoplankton generate over half of the oxygen we breathe, absorb half of the carbon dioxide in the atmosphere, and form the basis of the marine food web.

Photosynthesis

Photosynthesis is the process by which phytoplankton, algae, some types of bacteria, and higher plants use carbon dioxide (CO_2) and water to convert light energy from the sun into storable chemical energy, releasing oxygen as a by-product of the reaction. Researchers believe that photosynthesis is responsible for generating most of the oxygen in our atmosphere. As a result of photosynthesis, phytoplankton play a crucial role in the major global biogeochemical cycles that regulate the composition of the oceans and atmosphere, and thus directly influence the health of the entire planet. Photo courtesy of NOAA.

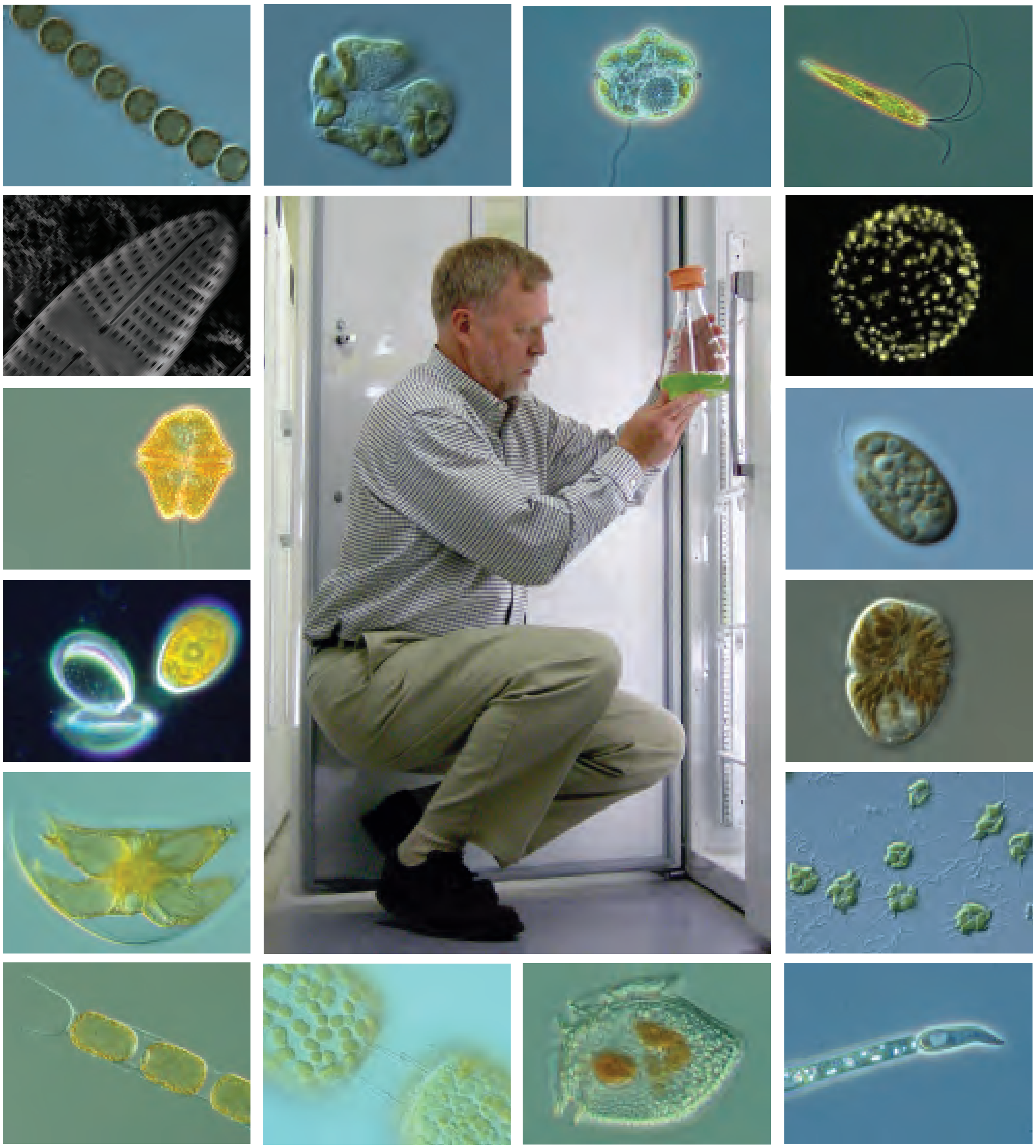


Bigelow Laboratory for Ocean Sciences

PART I

Molecular Biology and Marine Microbial Biodiversity

A LIVING LIBRARY



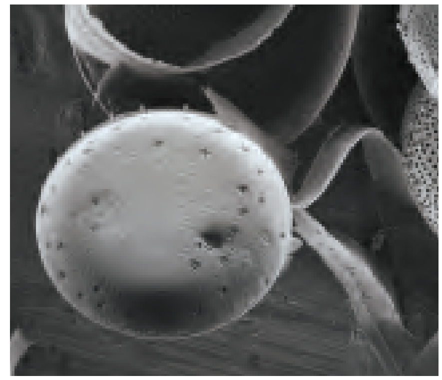
The Provasoli-Guillard National Center for Culture of Marine Phytoplankton

Exploring the abundance and diversity of the ocean's microbial universe has offered the researchers at Bigelow Laboratory a glimpse of frontiers and possibilities that, until recently, we hardly knew existed. Discoveries are everywhere; the challenge is to develop the tools and skills to know where to look, what to make of the wealth of information we are discovering, and how to understand the central role that ocean microbes play in the planet's biogeochemical processes.

An ever-growing sample of microbial ocean life is being collected, saved, and nurtured in The Provasoli-Guillard National Center for Culture of Marine Phytoplankton (CCMP) at Bigelow Laboratory.

The culture collection is literally a living library of resources available to scientists everywhere. The largest such collection in the world, the CCMP is providing living cells for researchers to investigate marine biodiversity's potential role in helping to address a range of issues, from developing new sources of bioenergy, to managing the harmful algal blooms that alter the dynamics of ocean ecosystems. Complemented by collections in several other universities and institutions, the CCMP is the central source of marine phytoplankton cultures for international scientific and commercial purposes.

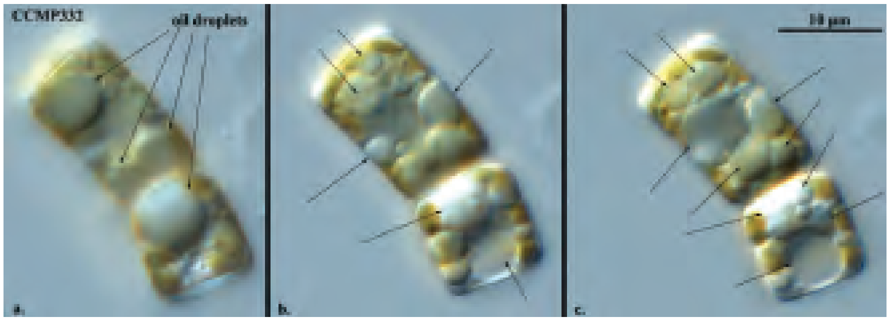
The CCMP is the official phytoplankton culture collection of the United States. As a public research asset and central repository for living cultures of marine phytoplankton, the collection is continually expanding. It currently holds more than 2,400 ***strains*** of phytoplankton from the world's oceans, and has supplied over 8,000 cultures to scientists from a variety of institutions and industries in the past five years alone. An average of ten cultures are shipped to researchers from the CCMP every day. Under the direction of Dr. Robert Andersen, the CCMP has isolated and successfully cultured new strains of marine phytoplankton for experimentation in the areas of biotechnology and nanofabrication. The Center's website (*ccmp.bigelow.org*) features images of many of the strains from its collection, and offers on-line



Above: Thalassiosira collected off the coast of Norway. Below: Odontella, resting on a Coscinodiscus cell. Scanning elecron microscope images by R. Andersen.

Inside the "Stacks"

The CCMP holds its cultures in a base of enriched seawater at five different temperatures (- 2°C, 4°C, 14°C, 20°C and 25°C) that represent a range of ocean environments ranging from polar to tropical regions. There are two culture chambers for each environment, and three sets of cultures are maintained for each phytoplankton strain. In addition, a complete fourth set of the entire collection is kept in a separate building, providing back-up cultures as a safeguard against the possibility of catastrophic loss. Strains are also maintained in frozen vials in two separate storage tanks.



Making biofuel from oil in phytoplankton cells on a scale that could replace conventional petroleum-based fuels is a growing focus of research in the development of environmentally sustainable energy sources. As the world's largest repository of living phytoplankton strains, Bigelow Laboratory is uniquely positioned to test and develop algal biofuel production technology. The photos above show two Cyclotella cryptica phytoplankton cells from the CCMP collection, taken at different focal planes. Arrows point to oil droplets inside each cell. Some algae strains are made up of as much as 50% oil.

ordering services and information about growing and preserving its cultures.

In addition to conducting research on the evolutionary history and structure of marine phytoplankton communities, Andersen teaches a professional summer training course in phytoplankton culturing techniques at the CCMP. The Center also provides isolation and purification services, starter cultures, strains with sequenced ***genomes***, kits with pre-mixed growth media and seawater, mass cultures, and DNA extracts.

The CCMP began as two private culture collections maintained by phytoplankton physiologists Dr. Luigi Provasoli at Yale University and Bigelow Laboratory's Dr. Robert R. L. Guillard, then at Woods Hole Oceanographic Institution. Their research on marine phytoplankton flourished as more strains were donated and collected, but by 1980, the task of maintaining and working with the growing collection became too large for a privately-based operation. The National Science Foundation provided support to establish a single, national collection for marine phytoplankton at Bigelow Laboratory and named Guillard as the collection's first director.

In 1992, the United States Congress formally recognized the CCMP as a National Center and Facility (Public Law 102-587, Oceans Act of 1992). The Center was named in honor of Provasoli and Guillard as a tribute to their pioneering contributions to marine phytoplankton research. Now Scientist Emeritus, Guillard has continued his work at the CCMP as it evolved to incorporate advances in electron microscopy and DNA analysis, further strengthening Bigelow Laboratory's research emphasis on marine microbial oceanography.

Robert A. Andersen, Ph.D., Botany/Phycology, University of Arkansas, 1981; M.A., Aquatic Biology, St.Cloud State College, 1972; B.S., Botany, North Dakota State University, 1970.

Robert R.L. Guillard, Scientist Emeritus, Ph.D., 1954 and M.S., Microbial Ecology, Yale University, 1951; B. S., Physics, City College of New York, 1941.

In 1992, the United States Congress formally recognized the CCMP as a National Center and Facility (Public Law 102-587, Oceans Act of 1992). The Center was named in honor of Provasoli and Guillard as a tribute to their pioneering contributions to marine phytoplankton research.

Marine Microbial DNA

One Cell at a Time

Marine microbes drive most of the biogeochemical cycles in the world's ocean, directly influencing the ocean's critical role in the global environment. However, the physiology and ecological roles of most marine microbes are still unknown. Genomic studies can greatly reduce this knowledge gap, but thus far they have mostly been limited to the roughly 1% of ocean microbes that can be cultured in the laboratory.

Single-cell DNA analysis is a major technological breakthrough in the study of microbial ecosystems in the ocean. Bigelow Laboratory has recently applied for a patent on this new method for genetic research.

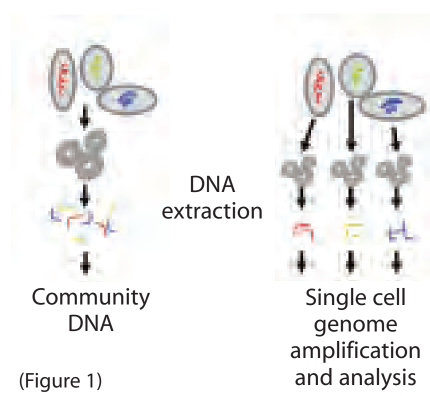
Piecing together the genetic "instructions" that drive marine microbial processes is essential to understanding the foundation and evolution of life in the ocean environment, as well as to discovering potential practical applications of marine microbes for human benefit.

Drs. Michael Sieracki and Ramunas Stepanauskas have developed a single-cell genomics (SCG) method, which, for the first time, allows researchers to obtain information about genes from individual microbial cells, without the need to grow them in cultures. Bigelow Laboratory has applied for a patent on this breakthrough in singe-cell DNA analysis, and in the future this technology may make it possible for microbiologists to rapidly and economically analyze the composition and biogeochemical functions of marine microbes throughout the world.

Sieracki and Stepanauskas study ***bacterioplankton***, the smallest organisms in the ocean (0.2–0.6 micrometers in diameter) and they have pioneered a way to combine the powerful capabilities of ***fluorescence-activated cell sorting*** with advanced molecular biology techniques to analyze ***genomes*** of individual uncultured microbial cells.

Until now, most molecular studies of uncultured marine microorganisms have relied on methods that contributed enormously to understanding the breadth of diversity among microorganisms on the planet. However, these methods did not allow researchers to see how various

Metagenomics vs. Single-cell genomics



(Figure 1)

Microbial Energy

Proteorhodopsins are light-sensitive proteins that convert sunlight into chemical energy, thought to provide a supplementary "charge" for as many as half of the bacteria living near the surface of the ocean. The Sieracki-Stepanauskas team discovered proteorhodopsin genes in two marine microbes in their pilot genetic library. It is still unclear which other types of bacteria carry proteorhodopsin genes, or whether all proteorhodopsins are involved in energy production. The team is currently collaborating with a group of molecular biologists at the U.S. Department of Energy Joint Genome Institute, using their new method to reconstruct the complete genomes of these bacteria. As more genomes of proteorhodopsin-containing microbes are sequenced, it may eventually become feasible to develop ways of harnessing proteorhodopsin's photometabolic activity in the production of bioenergy, thereby reducing our dependence on fossil fuels. Photo courtesy of NOAA.

genes interconnect to determine metabolic pathways, or to assemble complete genomes for individual microbes.

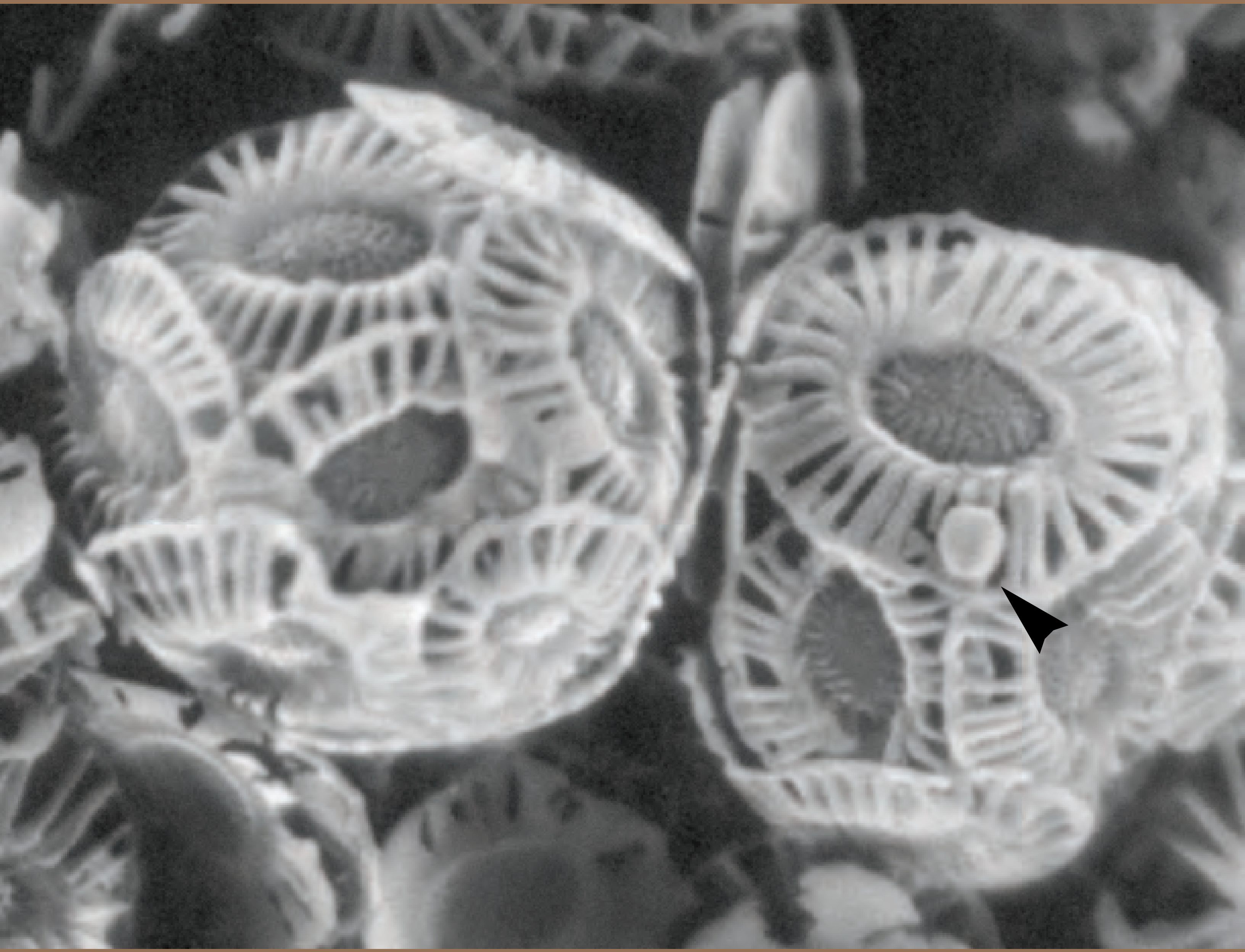
In the Human Genome Project of the 1990s, for example, J. C. Venter and his colleagues ***sequenced genes*** in millions of random, short DNA fragments and then assembled them, like a jigsaw puzzle, to recreate the genome. Venter's group subsequently used this "metagenomic" approach during a two-year ocean cruise to analyze DNA from marine microbes around the world. But the unanticipated magnitude of natural genetic diversity in marine microbial communities proved too high to assemble individual marine microbial genomes, apart from a handful of the most common types.

The SCG approach, on the other hand, allows researchers to isolate individual microbial cells directly from the environment and access their genetic information. SCG relies on the separation of individual microbial cells by fluorescence-activated cell sorting, followed by a reaction that copies the cell's genome to produce enough DNA for different genetic analyses *(see Fig.1, p.12).* Various DNA markers help determine a cell's identity and its biochemistry. SCG offers a practical alternative to metagenomics for examining DNA in marine microbes that cannot be grown in cultures.

Over the past year, Sieracki, Stepanauskas, and their research team have successfully completed this process for fifty marine bacteria and ***protists***, taking the first steps in creating a detailed genetic library for the marine environment.

Ramunas Stepanauskas, Ph.D., Limnology/Ecology, 2000, and M.A., Limnology, 1993, Lund University, Sweden; B.A., Limnology, Uppsala University, Sweden, 1993.

MARINE VIROLOGY
A New Universe of Possibilities



The arrow points to a virus attached to an Emiliana huxleyi coccolithophore cell on the right. The virus particle is approximately 190 nm (nanometers) in diameter. (There are 1 million nanometers in a millimeter.) Scanning electron microscope image courtesy of K. Ryan, MBA, Plymouth, UK.

Marine viruses are the most abundant biological particles in the ocean. With an estimated one million marine microbes in every teaspoon of seawater, the amount of microscopic life in the ocean can be overwhelming to imagine. There are a hundred million times more bacteria in the ocean than stars in the known universe, and ten- to a hundred- times more marine viruses than bacteria. On land, we usually associate viruses with damage and danger such as influenza epidemics, viral pneumonia, and HIV disease, among a host of other critical problems. But in the marine environment, scientists are finding that viruses are crucial to biogeochemical cycling in the sea.

Billions upon billions of mutations occur in marine viruses every hour, each of which has the potential to create still another new virus and affect the metabolic processes at the foundation of marine ecosystems.

As a leader in the rapidly expanding field of marine virology, Dr. Willie Wilson and a team of Bigelow Laboratory scientists are conducting research on the pathways by which viruses infect marine microbes and influence the dynamics of the marine environment and the global climate.

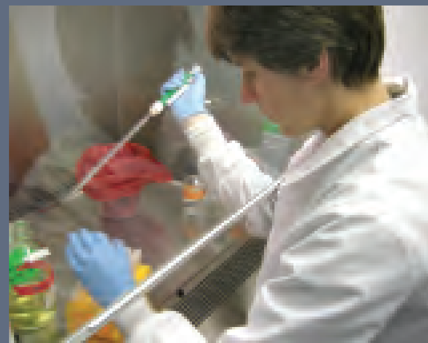
Marine viruses are key to breaking down phytoplankton and releasing organic carbon, acting as "lubricants" for the microbial loop at the base of the marine food web *(see p.4)*. Without marine viruses, there would be no rapid mechanism for decomposing organic matter in the ocean, and the seas would ultimately fill up with the same sort of organic sludge that waste treatment plants on land must process.

Viruses are instrumental in controlling the extent and duration of ***phytoplankton blooms***, influencing the ability of phytoplankton to act as important carbon sinks in the global carbon cycle *(see p.5)*. Up to a quarter of the carbon absorbed (or fixed) by phytoplankton is "shunted" into the dissolved organic carbon pool by viruses. There are also marine viruses that attack and eventually help to collapse harmful phytoplankton blooms such as red tide.

Marine viruses help determine nutrient content and species composition throughout the global ocean. Some marine viruses are believed to influence climate directly by causing the release of pulses of dimethyl sulfide gas, which contributes to cloud formation in the atmosphere.

Viruses exist in a multitude of shapes, sizes, and genetic types. Wilson and his fellow researchers are investigating a group of giant viruses, identifying them through individual DNA blueprints in their genes. By studying the diversity and distribution of viruses and their function in structuring microbial communities in different regions of the ocean, they are discovering how viruses adapt to rapid changes in

Blue Biotechnology



From the perspective of marine biotechnology, Dr. Susie Wharam sees the ocean as a largely untapped natural resource with the potential to solve a wide range of problems. Wilson's DNA analysis of the giant E. huxleyi virus (see below) produced a trove of novel genes for Wharam to explore. As a molecular biologist, Wharam uses advanced DNA analytical techniques to isolate and investigate genes from marine viruses and other marine organisms.

Researchers are discovering how to use viruses to kill harmful bacteria through an approach known as phage therapy, considered to be a key emerging technology because it avoids the need for antibiotics and the problems that result when bacteria develop antibiotic resistance.

Wharam and her research team are currently conducting tests on the use of marine viruses to fight specific disease-causing bacteria in lobster hatcheries. If these tests are successful, phage therapy in the future could benefit hatcheries and other aquaculture operations by preventing or controlling disease outbreaks.

Wharam is also interested in developing technologies and new diagnostic tools that will improve detection of marine bacteria and viruses that affect human health. One of her goals is to design hand-held virus detection kits that could be used for on-site testing of water available for recreation or shellfish harvesting.

the marine environment and how those changes affect ecosystem processes, natural selection, and species composition in the sea.

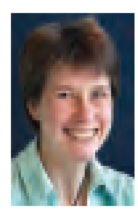
Wilson and his team are demonstrating that viruses have far-reaching effects on the structure of marine microbial communities, nutrient and energy flows, and global climate. Billions upon billions of mutations occur in marine viruses every hour, each of which has the potential to create still another new virus and affect the metabolic processes at the foundation of marine ecosystems.

Besides the importance of their role in the global carbon cycle, marine viruses themselves are a vast and constantly changing reservoir of unexplored and potentially beneficial genetic diversity. It is becoming clear that marine viruses are at the center of the interrelated dynamics of ocean life and are key to phytoplankton evolution, acting as vectors for gene transfer and fueling the evolutionary processes that maintain high levels of marine biodiversity on the planet.

Most viruses are genetic "minimalists," containing only a few genes, but Wilson and his colleagues have succeeded in unraveling the genetic code of the largest virus known to attack algae to date—the 472-gene virus that infects *Emiliana huxleyi*, a species of phytoplankton that is a major focus of current research on global climate and biogeochemical cycles. Over 400 of these genes have no database matches, making them completely new to science. Such degree of novelty provides a tantalizing glimpse of the potential benefits locked within, but many of the gene secrets still remain a mystery.

Of the genes that did have database matches there were several surprises, including compounds that could be developed for use in anti-aging and cancer-inhibiting therapies. These genes have never been found in a virus before—they are more commonly seen in animal and plant cells. Understanding these novel virus pathways will aid in the development of medicines that may help to limit life-threatening diseases and slow the aging process.

In the eye of a needle you could fit... 100,000 viruses, 10,000 bacteria, 1,000 phytoplankton, 100 amoeba, 10 copepod legs, and 1 human eyelash.



Susie Wharam, Ph.D., Molecular Biology of Plant/Pathogen Interactions, University of Warwick, UK, 1992; B.S., Molecular Biology and Biochemistry, Durham University, UK, 1988.

Willie Wilson, Ph.D., Marine Viruses, 1994 and M.S., Cyanobacteria Genetics, University of Warwick, UK, 1991; B.S., Marine Biology and Biochemistry, University College of North Wales, Bangor, UK, 1990.

Copepods and the Global Carbon Cycle

Copepods, a group of small aquatic microorganisms, have profound effects both on the ocean's fisheries and on the accumulation of greenhouse gases in the atmosphere. They consume approximately 80-90% of the organic carbon produced by marine algae, using some to grow and reproduce and packaging the remainder into pellets that sink to the bottom of the ocean.

Each year copepods provide food for commercially and ecologically important species such as fish and whales, and reduce atmospheric carbon dioxide by exporting carbon to the deep ocean.

Copepods are the most numerous multi-cellular ***invertebrate*** animals on the planet, with numbers approaching 10^{21} individuals. There are more copepods on the planet than there are insects, and they have roughly the same biomass as would 600 billion humans put together. They are found in both fresh and salt water systems, inhabiting waters from the poles to the equator and from the surface to the bottom of the ocean. Marine copepods primarily feed by grazing on ***phytoplankton*** and consuming several kinds of microscopic animals. Despite being tiny (between 0.1–10 mm in size), their numbers make them the dominant consumers of the ocean's biological production, fundamentally affecting the fate of the fixed organic carbon in the ocean and the global carbon cycle as a whole *(see p.5)*.

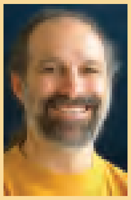
Dr. David Fields and his research team are investigating how copepods find their food and escape from potential predators. Combining small-scale fluid mechanics, neurophysiology, and animal behavior, much of this work has focused on how copepods are able to detect mechanical and chemical signals in their environment. Little is currently known about the sensory systems of copepods, but the enormous diversity of their sensory structures provides an ideal model system for understanding how these relatively simple, but important, marine invertebrates pick up and process sensory information.

A copepod is adorned with numerous sensors throughout its body. Fields's team is studying how the architecture of copepod sensory systems affects what these animals eat, what predators they can detect, and ultimately where they are found within the global ocean. In a recent joint project with the Massachusetts Institute of Technology, Fields and his colleagues modeled the fluid dynamics surrounding the individual sensory hairs that these animals use to perceive their environment.

Top: The female Temora longicornis (1.1 mm) swimming through the water column is searching for food (phytoplankton) and detecting predators using chemical and mechanical sensors on her antennae.

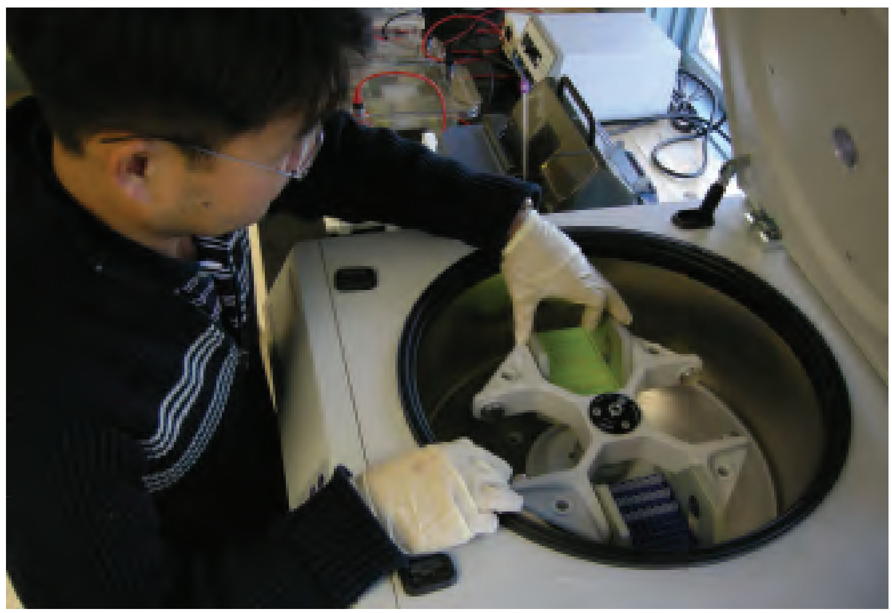
Bottom: A scanning electron microscope (SEM-800X) photograph of the antenule of Gaussia priceps. G. Priceps is a deep-sea copepod captured 2,100 feet below the ocean's surface off the coast of Hawaii. Photos by D. Fields.

Understanding the small-scale mechanics, structure, and "tuning" of these sensors may provide answers to how these organisms, and the marine life that depends on them for food, are distributed on a global scale.



David Fields, Ph.D., Oceanography 1996, and M.S., Coastal Oceanography 1991, State University of NY-Stony Brook; B.S., Biology, University of Utah, 1986.

Tracking Marine Life through Evolutionary Time



Often depicted as a vigorous ever-branching tree, life evolved through innumerable microscopic moments of genetic chance—each creating the possibility for a new way to go about living; for a different path to survival; for another branch. By deciphering the genetic signatures of marine microbes, researchers are discovering seismic moments in the history of nature that reach back to the roots of life itself.

The protist Paulinella chromatophora is a species of amoeba that has evolved the ability to use plastids for photosynthesis.

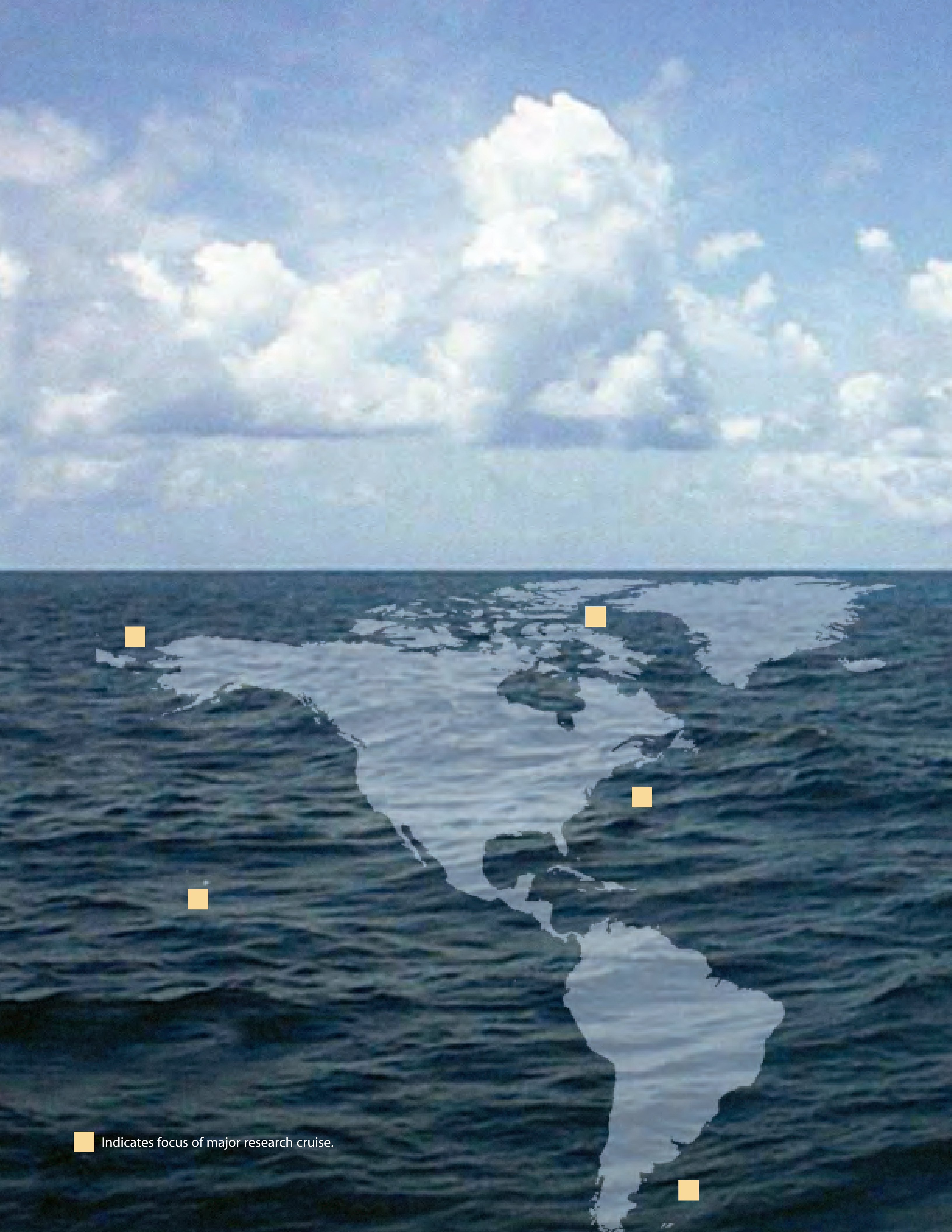
Dr. Hwan Su Yoon's research has uncovered one such moment over one and half billion years ago—the point at which bacteria took the first steps toward becoming plants, and photosynthesis began to fuel an explosion of new life on this planet. Yoon's work is central to the growing scientific focus on the evolutionary biology of marine life, and on what that history can teach us about biological processes at work in the ocean today.

The transition from the bacterial stage of life to more organized, single-celled life forms, and then on to the legions of complex multicellular organisms that include us, involved a biological process known as ***endosymbiosis***. This vital step consisted of the capture of one type of bacterial cell by another, but, rather than being consumed as food, the engulfed bacterium became a tiny organ, or ***organelle***, with a specialized function inside its "host" cell. One function, critically important for the rest of us, was harnessing the sun's energy through photosynthesis, and was performed by bacteria that had been engulfed by other bacteria, becoming a category of organelles called ***plastids***. Molecular biologists consider plastids to be "the powerhouses of primary productivity" in the plant kingdom.

The single-celled ***phytoplankton*** that drift in the open oceans and the more complex, multi-cellular marine algae we can see growing in coastal waters all contain plastids that are essential to their survival. Yoon is investigating the way photosynthesis first developed in marine algae by studying the evolution of plastids inside individual algal cells. He uses advanced gene sequencing techniques to identify the evolutionary connections among living cells, and analyzes the molecular structure of fossil cells to piece together information about how plastids originally evolved. His findings show that plastids were initially formed when a single-celled blue-green alga capable of bacterial photosynthesis was captured by another single-celled organism and became "enslaved" as a permanent organelle. By tracing thousands of genetic sequences found in algae backwards through time—a cellular forensics of sort—Yoon and fellow scientists have found evidence that photosynthesis by plastids began on the planet approximately 1.6 billion years ago.

As more and more genes are sequenced, researchers are discovering some of the pathways by which plastids diversified and diverged as different groups of algae evolved, eventually branching out to develop new and more specialized functions in the cells of higher plants. Yoon and his research team are creating an increasingly accurate evolutionary time-line connecting endosymbiosis and plastid evolution with the genetic diversity that continues to shape ocean ecosystems today.

Hwan Su Yoon, Ph.D., Botany, 1999; M.S., Biology, 1994; and B.S., Biology, Chungnam National University, Korea, 1992.


Indicates focus of major research cruise.

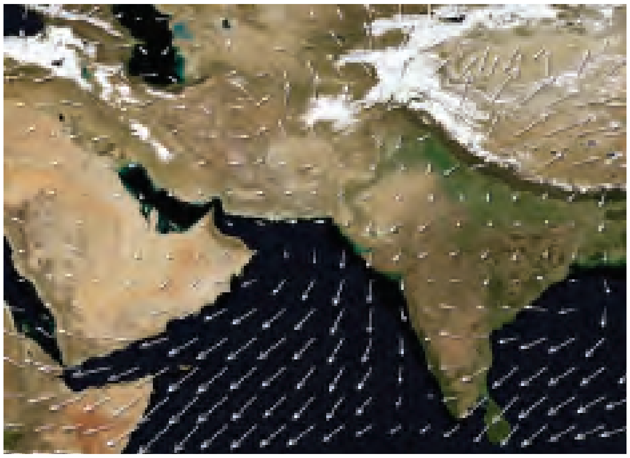
Bigelow Laboratory **PART II** for Ocean Sciences

Ship's Log, 2007
Research on the Open Seas

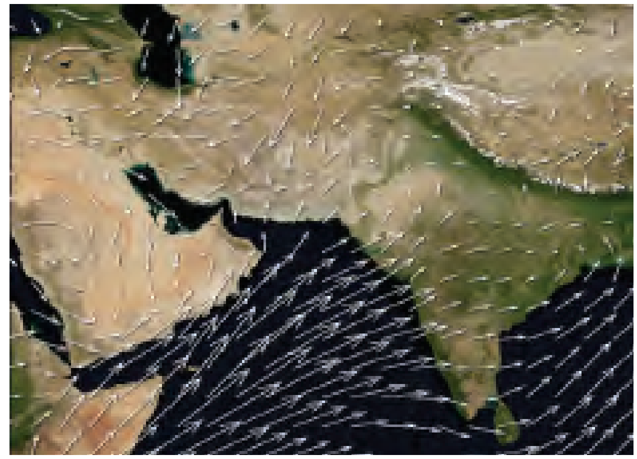
Abrupt Climate Change
Evidence in the Arabian Sea

In March 2007, Dr. Joaquim Goés and Dr. Helga Gomes received a three-year, $1.18 million National Aeronautics and Space Administration (NASA) grant, bringing an international team of atmospheric and ocean scientists together in the field to measure the effects of global climate change on phytoplankton blooms in the Arabian Sea. The team is using satellite imaging and direct sea sampling to investigate how global warming is affecting marine life in the Arabian Sea, increasing ***greenhouse gases*** in the atmosphere, and changing drought and flood patterns over southwestern Asia—an area that is home to more than a third of the world's human population.

(Figure 1)



Winter



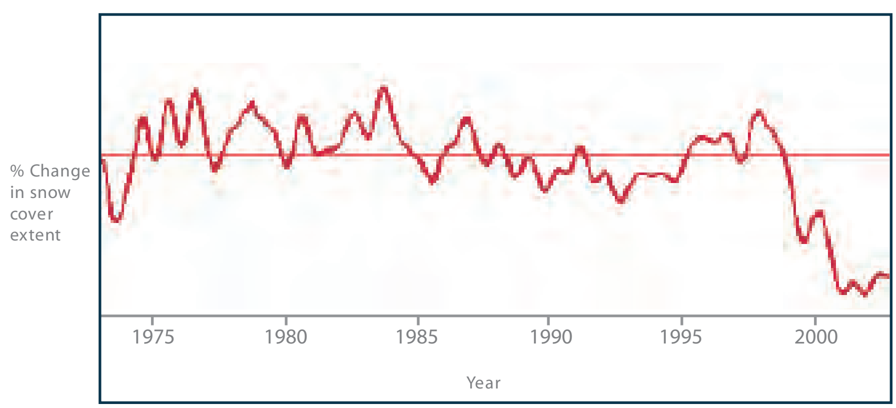
Summer

Differences in temperature between land and ocean drive the Asian monsoon. During the winter in South Asia (upper left), warm air over the Arabian Sea rises, drawing cold air from the land to the north. In summer (upper right), after much of the snow melts, the land warms more than the ocean, and the wind direction reverses. (Maps by Robert Simmon, based on data provided by Bigelow Laboratory.)

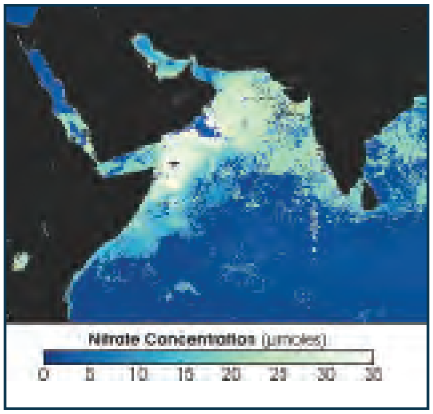
The Arabian Sea has given researchers at Bigelow Laboratory a window onto the dramatic consequences of global climate change for marine ecosystems. Over the past seven years, the western half of the Arabian Sea has witnessed record increases in phytoplankton blooms, triggered by the rapid decline and meltdown of winter snow over southwest Asia and the Himalayas. Goés and his research team are studying the connection between changing weather patterns and ocean processes in this 1.5 million square mile area of the Indian Ocean, amassing concrete evidence about the effects of abrupt climate change on ***phytoplankton blooms***. Goés began the study by using ***remote sensing*** data from NASA Earth Observing Satellites to measure chlorophyll, sea-surface temperatures, and nitrate concentrations throughout the Arabian Sea *(see Fig.3, p.24)*. He first observed signs of unusually high levels of nutrient upwelling in satellite images that showed massive increases in nitrate concentrations (a major nutrient source for phytoplankton).

Findings also showed a 350% increase in chlorophyll concentrations over the past seven years—reflecting an enormous increase in phytoplankton growth. Overall, the data show that phytoplankton blooms—once a healthy source of food for the area's fisheries—are occurring on such a scale and with such intensity, that upon death and decay, they are using up oxygen in the waters below the surface. This is causing a shift in species composition, and declining levels of phytoplankton biodiversity in the Arabian Sea ecosystem. Reports of fish kills from lack of dissolved oxygen in these waters are further

Across Eurasia, snow cover (red line) has dropped significantly since the late 1990s. Warming temperatures are most likely to blame. Lack of snow allows the land surface to heat up more in the summer, and the widening temperature contrast between land and ocean in the summer strengthens the monsoon. (Graph by Robert Simmon, based on data provided by Bigelow Laboratory.)



(Figure 2) Average snow cover, 1967–present.



(Figure 3)

Nitrate concentrations from August 2002, with blue indicating low levels and light green signifying high levels. (Map by Robert Simmon, based on data provided by H. Gomes, Bigelow Laboratory.)

evidence of a spreading "dead zone" in which biological productivity is virtually gone.

The problem is made worse by the fact that lack of dissolved oxygen in the water fosters the growth of a type of bacteria that releases nitrous oxide, a greenhouse gas that is a significantly greater contributor to atmospheric warming than carbon dioxide. Increasing levels of nitrous oxide are essentially adding "fuel to the fire" that has already warmed the Eurasian land mass 50% more than the average global temperature increase of 1.3°F. over the past century. (Since 1979, overall temperatures on land have been going up by nearly half a degree per decade, almost twice as fast as ocean temperatures have been rising.)

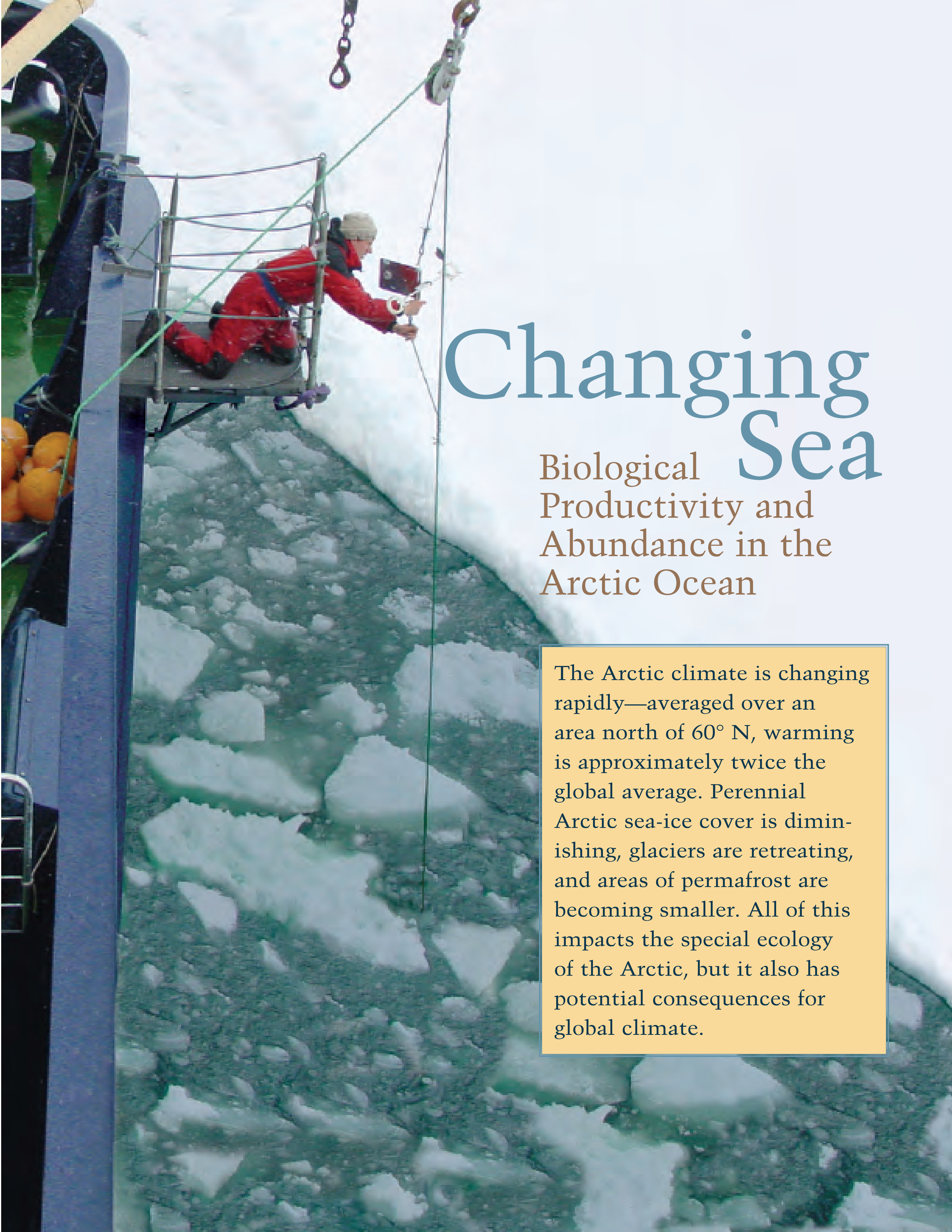
Located in the northwest part of the Indian Ocean between Arabia and western India, the Arabian Sea has historically had a unique ***monsoon*** cycle, with reversing winds that create both winter and summer monsoon seasons, causing a strong ***upwelling*** of nutrients that nourish seasonal phytoplankton blooms. The extent of winter and spring snow cover over the Eurasian land mass, and the heat released during spring, have a major impact on the land-sea ***thermal gradient*** that drives the monsoons. These yearly, seasonally reversing monsoons *(see Fig.1, p.23)* in turn drive one of the most energetic ocean current systems in the world, causing the greatest seasonal variability of phytoplankton observed in any ocean basin. The Arabian Sea is the only ocean system that fully reverses its circulation on a semi-annual basis.

The extreme seasonality of the Arabian Sea's circulation and its overlying wind field arise from the heating and cooling temperature contrasts between the Tibetan plateau of the Indian subcontinent and the large volume of ocean surrounding it. The plateau heats up in spring, producing low pressure over the region. Meanwhile, high pressure prevails over the ocean, causing winds to flow northwards. This strong surface wind reaches 36 knots (over 40 miles per hour) or more during July, pulling deep, nutrient rich waters to the surface to fuel phytoplankton growth. This water is then replaced by deeper, cold water welling up from below that is rich in dissolved nutrients, which nourish phytoplankton as they photosynthesize and grow.

The reverse is true in winter. Although these are regular and predictable events, monsoon intensity from year to year is governed by the amount of snow and ice on the plateau. In years of reduced snow and ice, heat in spring and summer warms the land faster, creating a large contrast between the pressure over land and ocean and resulting in a stronger summer monsoon.

Since 1999, there has been an abrupt decline in the amount of annual winter snowfall in the Himalayan-Tibetan mountains on the eastern side of the Arabian Sea *(see Fig.2, p.23)*, which has shifted weather patterns and intensified the monsoon winds in the western part of the sea. Year after year, rapidly declining snow cover in the mountains has led to ever-warmer conditions on land. This has strengthened the southwest monsoon winds and caused stronger nutrient upwelling from the cooler waters of the western coast, triggering increasingly massive phytoplankton blooms.

Joaquim I. Goés, Ph.D., Ocean Biochemistry, Nagoya University, Japan, 1996; M.S., Marine Microbiology, 1985 and B.S., Botany/Zoology, 1980, Bombay University, India.



Changing Sea

Biological Productivity and Abundance in the Arctic Ocean

The Arctic climate is changing rapidly—averaged over an area north of 60° N, warming is approximately twice the global average. Perennial Arctic sea-ice cover is diminishing, glaciers are retreating, and areas of permafrost are becoming smaller. All of this impacts the special ecology of the Arctic, but it also has potential consequences for global climate.

Curious visitors to the air and water sampling activities of Cruise AOE-01, Icebreaker Oden, 89° N. Photos on pp. 25–27 courtesy of P. Matrai.

Because the impact of global environmental changes is more extreme in the Arctic than anywhere else, the marine ecosystem of the Arctic Ocean, particularly the role of ***phytoplankton*** in the ***biological productivity*** of the region, has become a focus of research about changing conditions there and how they affect the rest of the planet.

The biological productivity of phytoplankton depends upon ongoing interactions between the biology and chemistry of the world's oceans. Phytoplankton bloom and thrive because of their ability to use sunlight for photosynthesis. As a consequence, they provide food for other forms of ocean life, fueling the vast, multi-dimensional predator-prey food web of the sea. Phytoplankton are directly involved in the cycling of chemical compounds through the marine environment and the exchange of gases at the interface between the ocean and the lower atmosphere. These processes are critical to the overall global ecosystem dynamics that regulate and sustain life.

Dr. Patricia Matrai is currently collaborating with a team of researchers on a multi-institutional project to synthesize existing knowledge about biological productivity in the Arctic Ocean. She and her colleagues are studying primary productivity through a combination

O(cean)-Buoy

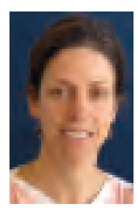
The International Polar Year (IPY) is a major scientific campaign focusing on the Arctic and the Antarctic. The largest polar research program in history, it is co-sponsored by the World Meteorological Organization and the International Council for Science. IPY is scheduled to run from March 2007 to March 2009, and is the beginning of a new era in polar science.

Dr. Matrai (right) is participating in the International Polar Year program through her work on O-Buoy, a three-year project with a team of scientists from the United States, Canada, and Germany. They will design and deploy a series of autonomous ice-tethered buoys with chemical sensors to monitor the atmospheric chemistry over the Arctic Ocean. Similar measurements have been made inland and along the coast, but O-Buoy is the first time scientists will continuously study the chemistry of the Arctic atmosphere by monitoring the frozen ocean surface. Each buoy will have an on-board computer controlling its instruments and sending data to satellites for transmission back to the lab. Researchers expect that the O-Buoy Project will begin years of measurements for ozone, carbon dioxide, and other atmospheric chemicals above the Arctic Ocean that are key indicators of pollution, mercury deposition, and greenhouse gas emissions.

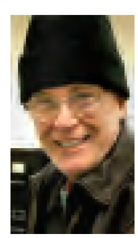
of historical direct measurements, ***nutrient budgets***, and ***remote sensing***. By looking at the biology of the Arctic Ocean from multiple dimensions they are modeling how climate change and its impact on sea-ice cover is affecting phyto-plankton populations in the region.

Nutrient Flow in Arctic Waters

The water that carries dissolved nutrients vital for phytoplankton growth through the central Arctic Ocean basin is influenced by two strong continental shelf currents along the Alaska coastline and the Bering Sea. Dr. John Christensen is project leader for two National Science Foundation-funded polar research teams compiling year-round baseline data about this bio-logically productive ocean area. The researchers are using nutrient analyzers on moorings positioned in ***shelf break*** regions to assess cycles of nitrate concentration and phyto-plankton abundance. Working at the North Pole Environmental Observatory, Christensen and his team are investigating whether the edges of the shelf break in the Arctic Ocean function as ***upwelling*** sites for nutrient-rich deeper waters from the surrounding Chukchi and Beaufort Seas. Helicopter surveys are helping to identify areas where strong currents influence tempera-ture, subsurface nutrient content, and phytoplankton abundance at different depths in advance of the spring ***phytoplankton bloom***. There is very little baseline biological data available from this region, and the results of this project are providing essential information about the Arctic Ocean ecosystem and how it is responding to changing climate conditions.



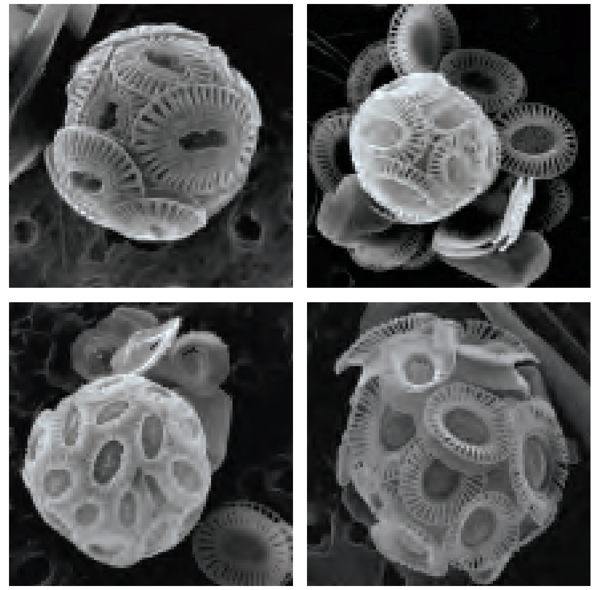
Patricia Matrai, Ph.D., Biological Oceanography, 1988, and M.S., Ocean-ography, 1984, Scripps Institution of Oceanography, University of California, San Diego; B.S., Marine Biology, 1981, Universidad de Concepción, Concepción, Chile.



John Christensen, Ph.D., Chemical Oceanography, 1981 and M.S., Chemical Oceanography, University of Washington, 1974; B.A., Chemistry, Northern Arizona University, 1971.

Following Tracks in the South Atlantic

Every year, the ocean over the Patagonian Shelf off the coast of Argentina turns brilliant turquoise as a teeming population of phytoplankton called ***coccolithophores*** creates one of the Southern Hemisphere's largest algal blooms. Dr. Barney Balch is the project leader of a major National Science Foundation grant to study the ecological factors regulating *Emiliana huxleyi*, the coccolithophore responsible for this massive bloom. His team is studying the role of coccolithophores in absorbing carbon from seawater and their significant impact on the global carbon cycle.



Microscopic Emiliana huxleyi coccolithophore cells cover themselves with highly-reflective limestone (calcium carbonate) platelets called coccoliths. When this single-celled phytoplankton species blooms, the coccoliths reflect sunlight back out to space, instead of absorbing light and raising the temperature of the water. Emiliana huxleyi blooms turn vast areas of the ocean a milky turquoise color that is clearly seen in satellite images from space. These images are scanning electron micrographs of Emiliana huxleyi cells taken by Dr. Dolors Blasco, Institute de Ciencias del Mar, Barcelona, Spain.

Since the beginning of the industrial revolution in the 18th century, the ocean has become about 26% more acidic (with more than half of that change in just the last decade).

Scientists have lacked even basic knowledge about the phytoplankton ecology of the Patagonian shelf and how environmental changes affect the blooms. Balch's project is the first multidisciplinary, ship-based investigation of these massive blooms, and it will allow researchers to build on information that, until now, has been based almost exclusively on bloom studies in the Northern Hemisphere.

Using a combination of underway, satellite, and direct sampling, the Patagonian expedition is documenting the factors regulating the distribution of the coccolithophore blooms. The results will be integrated with data that Balch and his research team have gathered over thousands of nautical miles on previous research cruises, refining estimates of phytoplankton productivity and other hydrographic, chemical, and optical properties of ocean ecosystems. By calibrating measurements at sea with satellite images of ocean reflectance, sea surface temperature, and light, Balch and his colleagues are able to interpret remote sensing satellite data about long-term changes in the ocean environment in the context of increasing levels of atmospheric carbon dioxide and associated global climate changes.

The coccolithophore *Emiliana huxleyi* belongs to a category of single-celled phytoplankton that take up dissolved carbon in the process of covering themselves with tiny plates or scales made from calcium carbonate ($CaCO_3$). The $CaCO_3$ plates create patches of color in the ocean that can extend 200,000 square miles or more and can be easily seen from satellites.

Facing page: Coccolithophore bloom (turquoise color) cradling the Falkland Islands, Patagonian Shelf. (NASA photo.)

Bigelow Laboratory's portable research unit is equipped for installation and use on oceanographic vessels and ships of opportunity (ferries, cargo ships, etc.) around the world.

Calcium carbonate is among the most common minerals found in the ocean and is the compound many marine organisms need to make shells. Coral reefs are made almost entirely from $CaCO_3$, as are the White Cliffs of Dover. The amount of $CaCO_3$ that can be found in ocean water is directly tied to the acidity of the marine environment.

Starting in 1994, researchers have documented a continuous increase in the acidity of ocean water. Since the beginning of the industrial revolution in the 18th century, the ocean has become about 26% more acidic (with more than half of that change occurring in just the last decade).

Balch and his colleagues are investigating the effect that this increasing ocean acidity is having on marine organisms' ability to make $CaCO_3$ shells. In sufficiently acidic conditions, $CaCO_3$ in shells may even dissolve, leaving organisms without their natural defense from predators.

Ocean acidification also has the potential to affect a much broader suite of physiological processes in plankton that are not directly tied to $CaCO_3$ production, such as photosynthesis and respiration. Increased acidity would also alter the natural chemical equilibrium that exists between CO_2 and other dissolved carbon forms in seawater, fundamentally changing the chemistry of the sea.

The information obtained on the Patagonian Shelf cruise is critical for modeling complex biogeochemical processes that regulate phytoplankton production and the global carbon cycle. This study will provide the first detailed analysis of the coccolithophores in this enormous area of the ocean.

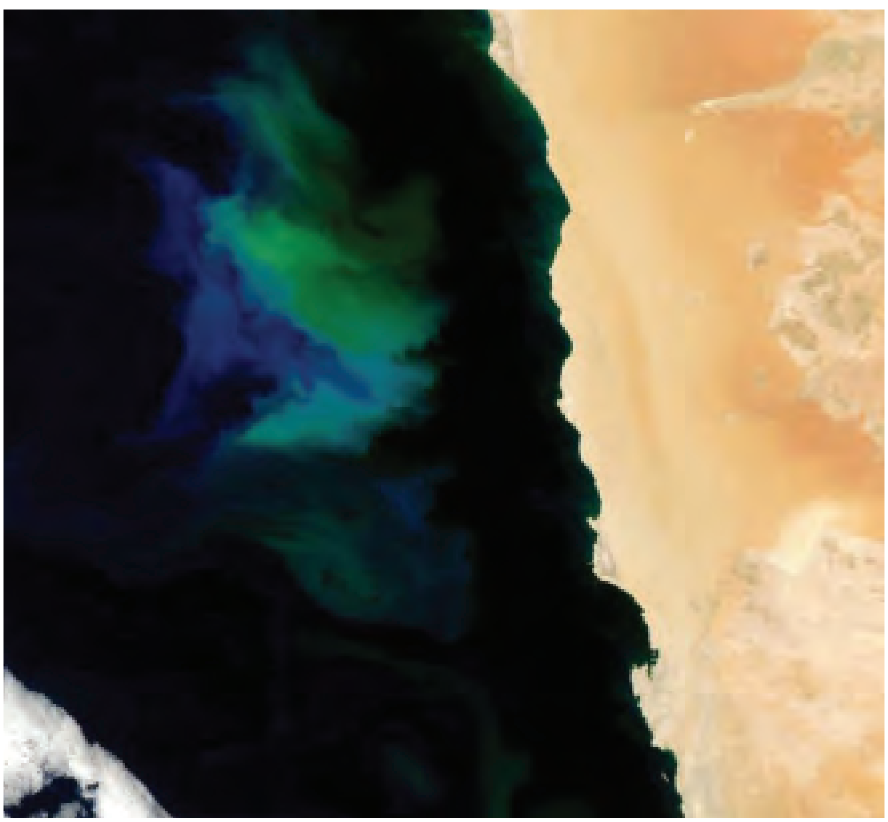
William "Barney" Balch, Ph.D., Scripps Institution of Oceanography, 1985; B.A. Biology, Cornell University, 1980.

Brazil to Namibia
The South Atlantic Transect

Scientists predict that "desert-like" areas of the ocean with relatively low biological productivity will expand as a result of the warming climate, particularly in the marine ecosystems of subtropical ***gyres*** such as the South Atlantic Ocean. Understanding the dynamics of phytoplankton communities and the biogeochemical processes at work in the huge physical expanse of these areas will help researchers assess the magnitude of their effect on global climate.

At the end of 2007, Dr. Michael Sieracki and a team of Bigelow researchers embarked on a four-week oceanographic research expedition between Brazil and Namibia to investigate the biochemistry and phytoplankton ecology of this vast and largely unexplored area of the South Atlantic. Taking 12-hour shifts to be able to work 24 hours of every day aboard ship, the team examined the structure, dynamics, and status of phytoplankton communities along a transect from the South Atlantic subtropical gyre to the biologically rich waters of the Benguela ***upwelling*** off the coast of Namibia on the African continent.

R/V Knorr. Owned by the U.S. Navy and operated by Woods Hole Oceanographic Institution for the ocean research community. Photo by M. Sieracki.



In December 2007, Dr. Sieracki led a team of scientists from Bigelow Laboratory on a research cruise to investigate the biological characteristics of these nutrient-rich waters as part of a month-long study of the largely unexplored South Atlantic Ocean between Brazil and Namibia.

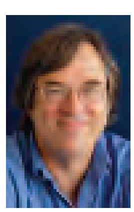
Phytoplankton bloom off Namibia, November 8, 2007. National Aeronautics and Space Administration (NASA), MODIS Image.

Along the South Atlantic transect, looking west. Photo by M. Sieracki.

Sieracki and his research team installed state-of-the art, high-speed ***fluorescence-activated cell sorting*** technology on board the R/V *Knorr* in order to analyze phytoplankton productivity and nutrient requirements for a myriad of phytoplankton species collected along the transect. Dozens of species were also collected for deposit in Bigelow Laboratory's growing phytoplankton culture collection *(see p. 9, Provasoli-Guillard National Center for the Culture of Marine Phytoplankton)*.

Comparing the measurements that Sieracki and his researchers made across the South Atlantic gyre with their subsequent analysis of the rich plankton community of the Benguela upwelling will strengthen our ability to evaluate phytoplankton productivity from remote sensing satellite images.

Marine sulfur compounds produced by phytoplankton eventually either enter the atmosphere as dimethylsufide gas, or are routed into the marine microbial food web *(see p.4)*. Results of the team's shipboard investigation of these compounds will allow climate modelers to more fully understand what the ocean's biogeochemical response to climate warming will be in the future.

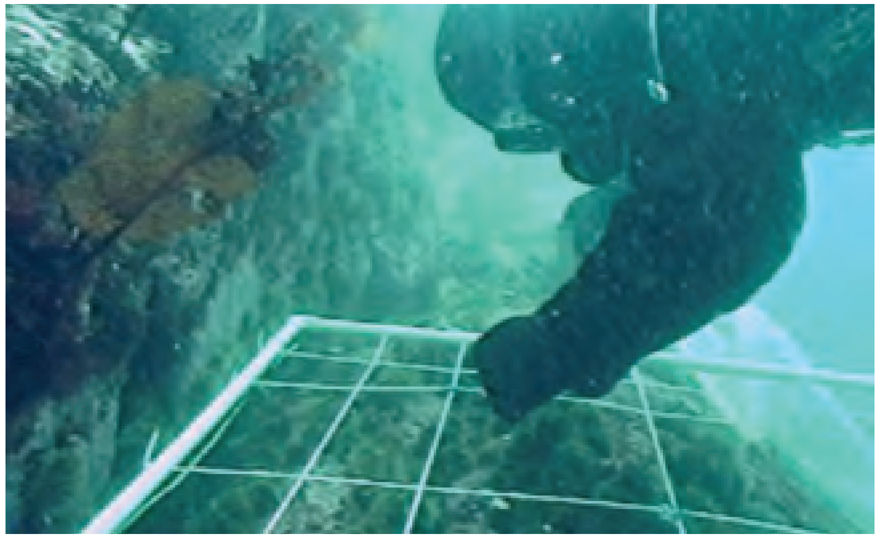


Michael Sieracki, Ph.D., Biological Oceanography, 1985 and M.S. 1980, Microbiology, University of Rhode Island; B.A. 1977, Biological Sciences, University of Delaware.

Forecasting Biological Productivity in the Northwest Atlantic

The Gulf Stream and the Labrador Current meet over the coastal shelf waters of New England and Atlantic Canada, resulting in the steepest north-south ***thermal gradient*** in ocean temperature in the world. Historically, the biological richness of this active mixing zone gave rise to some of the world's most productive fishing grounds. But the region's most iconic species, including lobster and cod, are increasingly threatened by human activity. Dr. Richard Wahle's research combines oceanography, experimental ecology, and fisheries science to evaluate and predict the consequences of natural processes and human impacts on the distribution and abundance of key species in the ***benthic*** communities of the Northwest Atlantic.

Dr. Wahle's research team with the benthic sled used in camera surveys of deep sea red crab off the southern New England shelf break. Photo by R. Wahle.



Rick Wahle conducting sea urchin population surveys in the Gulf of Maine. Photo by Hoyt Peckham.

Wahle and his research team study the critical links between life stages of ***benthic*** ocean species, from their beginnings as fertilized eggs, to initial days as free-floating planktonic larvae, to life as reproductive adults on the sea floor. A critical time for lobsters, for example, occurs just after the larval stage, when juveniles settle to nursery habitat on the bottom and begin to grow. The number of individuals that successfully makes this transition each year is vital to determining the number of adults entering the fishery between five and nine years later.

With initial funding from the National Science Foundation (NSF) and National Oceanic and Atmospheric Administration (NOAA), Wahle and his colleagues have developed techniques for settlement monitoring by diver-based suction sampling. Modeling larval transport and monitoring settlement success are essential tools in forecasting trends in lobster populations.

Much of this long-term monitoring is being continued by participating states and provinces from Rhode Island to Nova Scotia, with Bigelow Laboratory as the central clearinghouse for data and analysis.

Wahle's team has subsequently developed "passive post-larval collectors," making it possible for the first time to obtain lobster settlement data at depths beyond the limits of scuba diving. Funded by NOAA's Northeast Consortium, this deep-water project is opening a window on the poorly understood relationship between thermal stratification of the water column and benthic settlement patterns. The collaboration has widened to include several Canadian and European researchers, expanding the scope of study beyond lobster settlement to evaluate patterns of trans-Atlantic benthic biodiversity. Wahle's work is also providing a better understanding of how depletion of sea urchin and deep-sea red crab adults by harvesting may compromise individual spawning success and diminish the abundance of their larvae.

Results of the team's monitoring, modeling, and field experiments have allowed researchers to identify separate "geographies" for pre- and post-settlement processes, in which the role of ocean and atmosphere interactions on one hand, and disease, predation, and competition on the other, ultimately determine regional differences in population size. New funding from the National Aeronautics and Space Administration (NASA) is allowing Wahle and his collaborators to investigate how these patterns are being affected by changing climate conditions.

2007 Northeast Climate Impacts Assessment

Dr. Wahle was a contributing author on the Marine Sector Team of the Northeast Climate Impacts Assessment (NECIA) report, developed by fifty independent experts and the Union of Concerned Scientists, and released in the summer of 2007. The report was based on cumulative, multi-disciplinary research findings about the continuing effects of global warming on the northeastern region of the Western Hemisphere. Wahle's research is part of the NECIA's assessment of the impact of climate change on marine life.

Rick Wahle, Ph.D., Zoology, University of Maine, 1990; M. S., Biology, San Francisco State University, 1982; B. A., Zoology, University of New Hampshire, 1977.

Deep in the Pacific

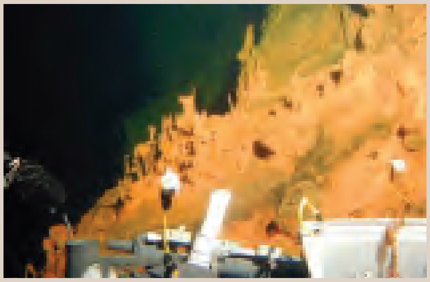
Extremes of Life on the Loihi Seamount

Biogeochemical interactions in the prehistoric seas were vastly different from the natural processes of life in most of the ocean today. Exploring deep reaches of the ocean floor, scientists have discovered hydrothermal vents and seeps in the Earth's crust where those ancient processes are still continuing.

The microbial life that flourishes in these extreme environments offers clues about the role of ocean microbes in the planet's early geochemistry. Microbes may have been directly involved in the creation of banded iron formations—the world's primary source of iron ore—as well as having had a central part in the evolution of the global ecosystem as a whole.

Compared to the abundant diversity of life in the ocean's water column, conditions at deep-sea vents tend to be quite extreme, favoring highly specialized microbes known as extremophiles. Vents where there is very little oxygen and lots of iron are an ideal habitat for a metabolically extreme group of iron-eating bacteria that are distinguished by their ability to convert iron molecules into food energy. These bacteria can live literally by eating nails and producing rust as by-product of their metabolism.

Microbial ecologist Dr. David Emerson has used deep-sea submersibles more than three miles below the surface of the Pacific Ocean to explore iron oxidation in biological systems associated with deep-sea venting and lava flows at the base of the Loihi Seamount,

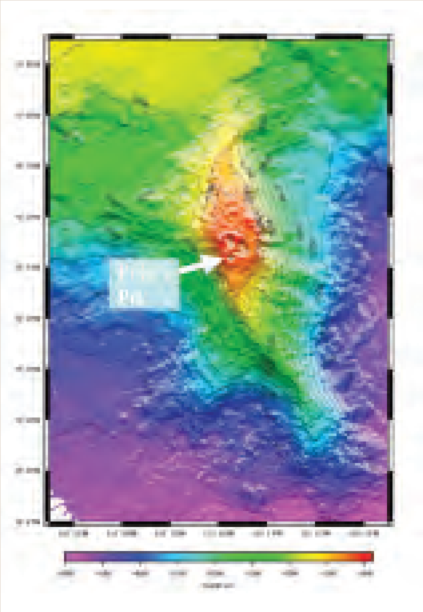


Iron-oxide structures at Loihi, 3,600 feet below the surface. Photo by D. Emerson.

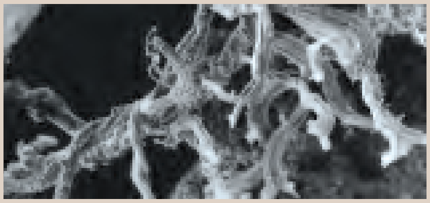
Hawaii's youngest underwater volcano. His expeditions are part of a novel deep-sea iron microbial observatory project, known as FeMO (Iron Microbial Observatory at Loihi Volcano).

Emerson and his research team have discovered an entirely new class of marine bacteria, including organisms called *Mariprofundus ferrooxydans*, which grow in thick filamentous mats around the volcano's caldera and hydrothermal vents. Investigation of the genetic structure and physiology of these life forms has begun to reveal the mechanisms by which they metabolize iron and survive where other microbes cannot exist.

Emerson and his colleagues are analyzing the genomes and physiology of these newly described microbes to determine their pos-



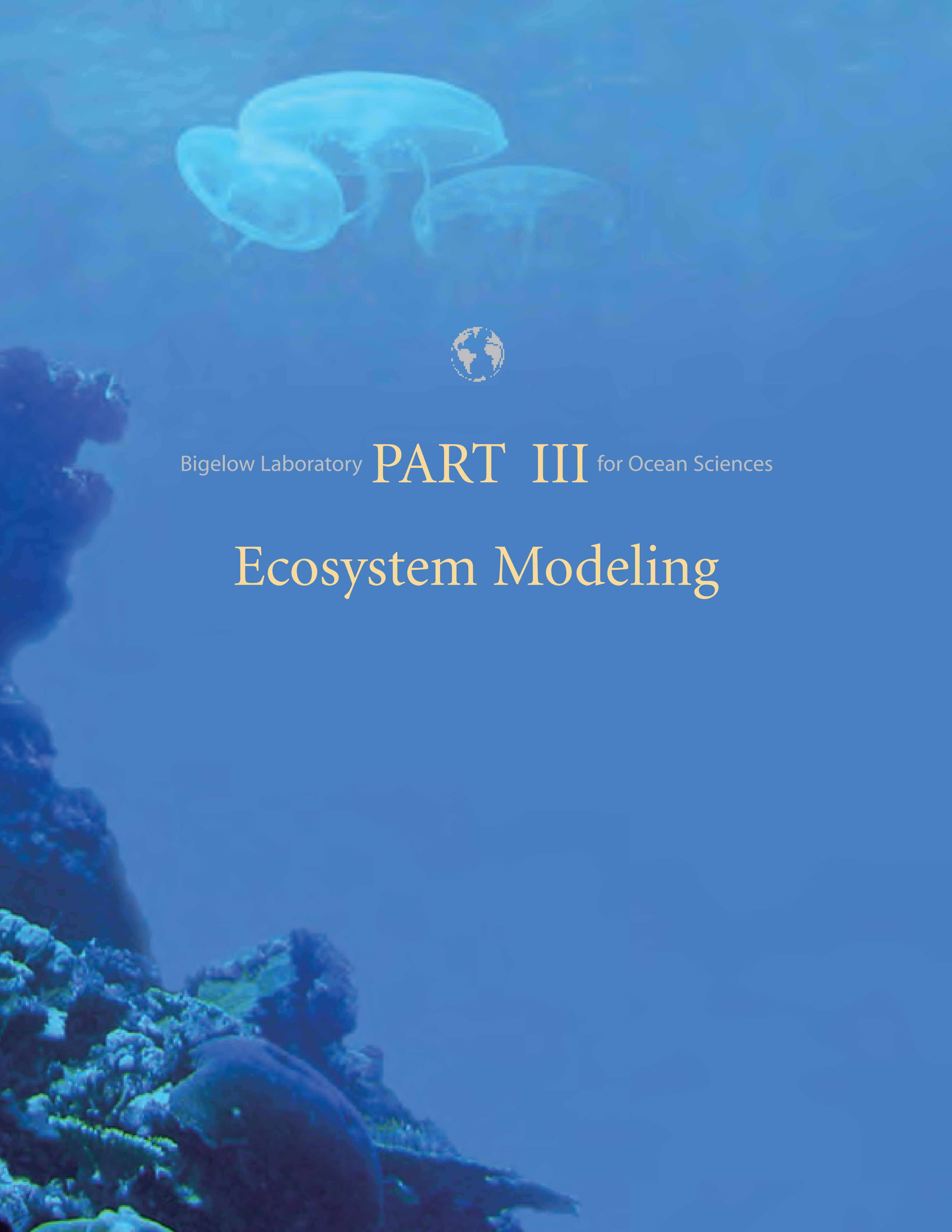
Bathymetry of the Loihi Seamount.



Close-up of filamentous bacterial mats. Courtesy of Clara Chan.

sible use in nanotechnology and other applications. For example, they may be quite effective at removal of both organic and inorganic pollutants for environmental clean-up. Other investigations are also underway to assess the role that iron-oxidizing bacteria may be able to play in climate change by acting as a potentially significant global carbon sink.

David Emerson, Ph.D., Microbiology, Cornell University, 1989; B.A., Human Ecology, College of the Atlantic, 1981.

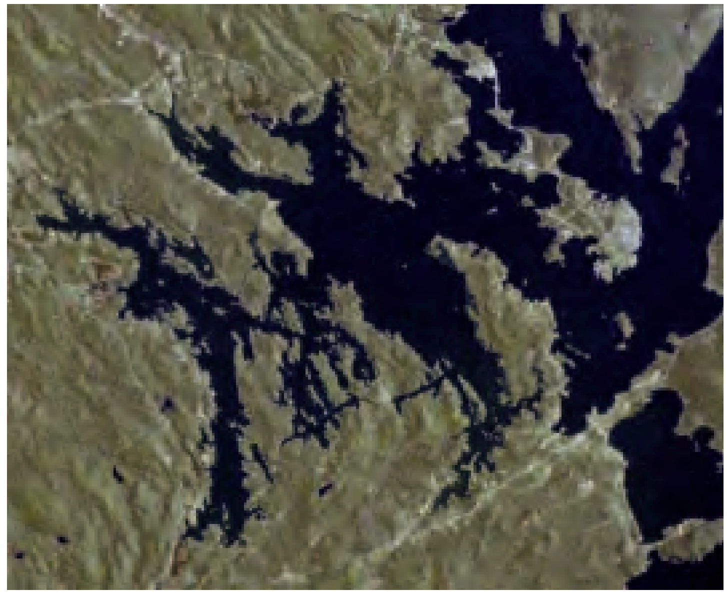


Bigelow Laboratory **PART III** for Ocean Sciences

Ecosystem Modeling

A Crucible for Multi-Disciplinary Ecosystem Modeling

Located on the international border between the United States and Canada at the mouth of the Bay of Fundy, Cobscook Bay has been the site of extraordinary biological richness for millennia, providing habitat for the highest level of biodiversity north of the tropics.



Cobscook Bay. Google Earth image.

The bay is a geologically complex estuary characterized by large tides and tidal pools, fog, and significant nutrient input. In recent decades, areas of the bay have been proposed for a series of industrial projects including sites for liquefied natural gas terminals, oil refineries, tidal power generation, and aquaculture.

Scientists have found 900 species of marine ***invertebrates*** living in the bay, and estimate a total species diversity of over 1,500. Funded by a major, multi-year grant to The Nature Conservancy from the Andrew W. Mellon Foundation, the Cobscook project brought together researchers from diverse ocean science disciplines to investigate how this spectacular combination of species richness and biological productivity developed and how it continues, in great part, to exist today.

An estuarine and coastal benthic ecologist at Bigelow Laboratory, Dr. Peter Larsen has been a member of the Cobscook research team since it began its work. More than two dozen scientists, Nature Conservancy staff, and Cobscook area community members synthesized what was already known about the bay and undertook new research to model the flow of energy and nutrients through the estuary. They studied physical, chemical, geological, and biological processes, including ***phytoplankton*** and macroalgal productivity, water quality, habitat characteristics, and hydrodynamics in order to describe the forces that drive and perpetuate the bay's biological productivity. Key among their findings is the fact that, when the myriad inputs into this unique biological system are translated into equivalent units of energy, tidal energy and circulation emerge as the dominant physical forces at work within the ecosystem.

Because of its unique convergence of natural features and processes, the bay has become an extremely valuable "proving ground" for modeling natural energy flows, as well as for evaluating the energy impacts of existing and proposed human activities, such as the potential environmental effects of tidal power development. Larsen is now expanding the Cobscook model to make this approach transferable to estuarine and marine ecosystem modeling in other coastal regions.

Peter F. Larsen, Ph.D., Marine Science, College of William and Mary, 1974; M.S., Zoology, 1969 and B.A., Zoology, University of Connecticut, 1967.

From Biomolecules to Ecosystems
Organizing the Genomic Revolution

A major research focus of marine evolutionary biology includes identifying the mechanisms by which adaptation takes place at the cellular level, the actual genetic pathways that create new approaches to survival in the face of environmental change. Bioinformatics is a computational approach to biology that combines molecular biology and mathematical modeling with computer software design to investigate this and other questions at the biomolecular level.

Bouquet of Corallium with deep purple Trachythela octocoral. Mountains in the Sea Expedition, 2004. Photo courtesy of NOAA Office of Ocean Exploration, Dr. Les Watling, Chief Scientist, University of Maine.

Dr. David McClellan is developing biological and computational approaches for the study of molecular adaptation, a field of research that investigates the molecular mechanisms behind a wide range of biological phenomena—from drug and vaccine resistance in viruses and bacteria, to the effects of global and local climate change on humans and other organisms. He is developing analytical methodology and computer software, and working in collaboration with other researchers at Bigelow Laboratory and around the world to characterize adaptation in a variety of organisms, including worms, copepods, wasps, agricultural crops, lizards, whales, and humans.

Molecular adaptation is usually a consequence of changes in genetic codes for proteins, which result in different levels of fitness in terms of an organism's chances to survive and reproduce. Bioinformatics provides a means for scientists to examine adaptation at the molecular level and uncover information about the molecular sequences within the specific amino acids that form the building blocks of proteins. For example, McClellan is currently using bioinformatics to study the molecular adaptations that allowed copepod species *(see p.17)* to make the evolutionary transition from fresh water to saltwater habitats.

The ability to find and use such data is helping researchers identify and categorize the causes of adaptation. This, in turn, is making it possible to visualize where and how evolution is occurring at the molecular level, determine the relative chronology of evolutionary changes in different species over time, and begin to model possible evolutionary changes in the future.

The emergence of bioinformatics as a new field of study was in large part a response to the flood of information from recent major advances in genomic research. By applying the power of database development and software design to the results of empirical research, bioinformatics is enabling scientists to understand and integrate biological systems at vastly different hierarchical levels, from molecules and microbes to entire ecosystems.

David McClellan, Ph.D., Biological Sciences, Louisiana State University, 1999; M. S., Zoology, 1994 and B.S., Zoology, Brigham Young University, 1992.

Ocean Literacy
Telling the Story

The research programs at Bigelow Laboratory continually expand our understanding of ocean systems and their importance to global environmental sustainability. Bigelow scientists are committed to sharing their discoveries with educators, students, and the public through a variety of programs. The need to communicate this knowledge to the wider world has never been greater.

Photo by Bruce Wood.

Foundations of Marine Science

A series of upper undergraduate and graduate level courses known as Foundations of Marine Science is taught at the Laboratory by Bigelow scientists, often in collaboration with guest lecturers from other institutions. Course content changes regularly and is based on current research projects, giving students the experience of directly contributing to ongoing investigations. Recent courses include:

Phytoplankton Culturing Techniques
Drs. Robert Andersen and Michael Sieracki teach at the Laboratory's Provasoli-Guillard National Center for Culture of Marine Phytoplankton. *(See p.9.)* Their phytoplankton culturing course is designed for graduate students, faculty members, and aquaculturists; and covers basic as well as advanced techniques for isolating, growing, and cryopreserving marine phytoplankton. Students use ***fluorescence-activated cell sorting*** to isolate and purify culture ***strains***, and conduct cryopreservation laboratory exercises.

Physical-Biological Interactions in the Plankton
Dr. David Fields and two colleagues from the Danish Fisheries Research Institute and Texas A&M University have collaborated to teach Physical-Biological Interactions in the Plankton—a small-scale fluid dynamics course that examines the miniature world of plankton and the physical and chemical characteristics that affect their feeding, encounter rates, and perception within the marine environment.

Agouron Hawaii Summer Course

In the summer of 2007, Dr. Michael Sieracki joined a team of international experts in marine microbiology, microbial ecology, and biogeochemistry who gathered at the University of Hawaii to teach an intensive eight-week graduate course on microbial oceanography. Sponsored by the Agouron Institute, the course brought students from seven countries together to explore the essential role of marine microbes in the ecology and biogeochemistry of ocean ecosystems. The course included a 10-day cruise with Sieracki aboard the 186-foot Navy catamaran R/V Kilo Moana, giving students hands-on experience with the research tools used to explore fundamental concepts in microbiology and oceanography.

Photo by M. Sieracki.

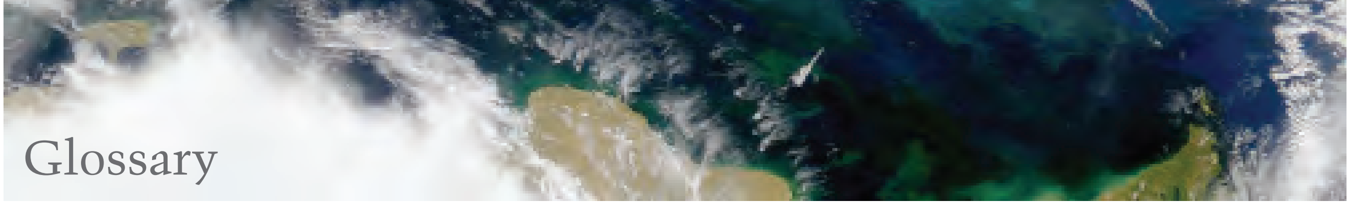
High School Research, for Real

Every year, Bigelow Laboratory brings sixteen high school juniors from Maine together for a week-long marine science research internship. The program was begun by Bigelow researcher Maureen Keller to provide a real-world ocean research experience for students who have demonstrated enthusiasm and aptitude for science. It is designed to encourage careers in ocean science and to further enhance young people's interest in science in general. The program combines laboratory workshops and field studies with a day-long research cruise. Working directly with scientists, students conduct field sampling in a variety of marine environments, and use state-of-the-art instrumentation for subsequent data analysis. The week includes discussion of science and public policy, scientific ethics, and career directions.


Photo by Bruce Wood.

Café Scientifique

Since the beginning of the Laboratory's residency on the Maine coast, Bigelow scientists have given talks for the general public, following the example of the Laboratory's founders Drs. Charles and Clarice Yentsch. Drawing an enthusiastic audience for many years, these have been informal gatherings and seminars to share scientific findings and the results of the latest ocean research projects with people of all backgrounds and professions. The Laboratory's summer lecture series recently took on the new title of *Café Scientifique*, based on the model of the international *Café Scientifique* movement begun in Great Britain in the mid-1990s. Over 150 cafés have been organized all over the world and are actively promoting public engagement with science. Recent Bigelow Laboratory *Café Scientifique* topics have included the connection between sea ice, clouds, and phytoplankton; ocean bacteria; the International Polar Year; red tides; and climate change.



Glossary

antibiotic resistance—a type of drug resistance in which a microbe has evolved the ability to withstand the effects of an antibiotic.

bacterioplankton—the bacterial portion of the plankton (see phytoplankton, below). Photosynthetic bacteria are major contributors to ocean's biological productivity.

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

benthic—living on or in the bottom of bodies of water.

coccolithophore—a type of phytoplankton (single-celled marine plant) that lives in large numbers throughout the upper layers of the ocean. Coccolithophores surround themselves with microscopic plates called coccoliths that are made of limestone (calcite). Individual coccolithophores are commonly smaller than 20 micrometers across and are often enclosed by over 30 plates.

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

fluorescence-activated cell sorting—a specialized type of flow cytometry, which is a technique for counting, examining, and sorting microscopic particles suspended in a stream of fluid. Fluorescence-activated cell sorting uses the light scattering and fluorescent characteristics of biological cells to sort them one cell at a time. This technique rapidly records fluorescent signals from individual cells, as well as making it possible to physically separate cells of particular research interest.

genome—a complete genetic sequence of an organism that is encoded in the DNA on one set of chromosomes.

greenhouse gas—any gas that absorbs infra-red radiation from the sun, trapping heat in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs), ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

gyre—a giant, circular, oceanic surface current.

invertebrate—an animal without an internal skeleton made of bone. More than 97% of the known animal species in the world are invertebrates.

monsoon—a seasonal prevailing wind that lasts for several months.

nutrient budget—a description of the measure of input and outflow of elements through various parts of an ecosystem.

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

phage therapy—the therapeutic use of viruses known to kill bacteria as a treatment for bacterial infections.

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

phytoplankton bloom—phytoplankton blooms occur when, under favorable conditions, phytoplankton rapidly increase in numbers. An example is the annual springtime bloom in the Northwest Atlantic that begins when sunlight and wind-mixed nutrients become readily available in the upper ocean.

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

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

remote sensing—the scientific technique or process of gathering data or images from a distance, as from satellites or aircraft.

sequencing genes—assembling a succession of letters representing the primary structure of a DNA molecule or strand, with the capacity to carry information.

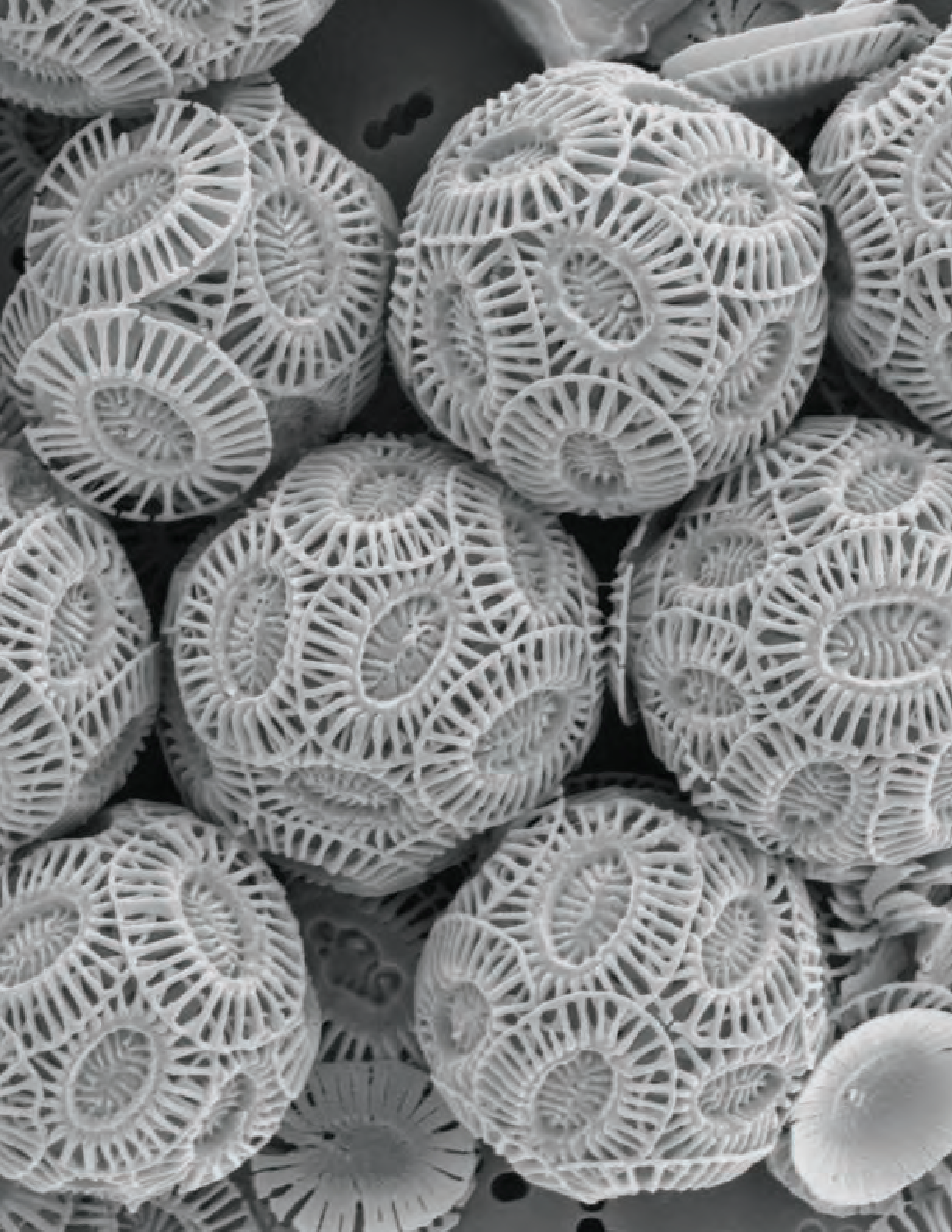
shelf break—the region of the ocean floor where the continental shelf and continental slope meet. This is where the more gently-shelving region of the sea bed adjacent to a land mass abruptly slopes more steeply down towards the ocean depths, commonly around 200 meters (approximately 656 feet).

strains—cell lines cloned from a single specimen in order to perpetuate it.

thermal gradient—the rate of temperature change with distance. For example, the ocean's layers of water have different temperatures, decreasing with depth from the warmer surface to the cold, deep regions near the ocean floor.

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

Facing page: Emiliana huxleyi coccolithophore cells. Scanning electron micrographs courtesy of the Belgian Federal Science Policy Office.



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This is a selected list of 2007 publications in which Bigelow scientists (in bold) are authors.

Understanding the ocean's role within the vast natural cycles that support the world's ecosystems is of paramount importance to the quality of our lives and to the generations who will live on this planet after us.

This is one of the most exciting periods in the thirty-four year history of Bigelow Laboratory for Ocean Sciences. Our researchers are working on the frontiers of scientific inquiry to develop, test, and patent new technologies to study microbial oceanography and global ocean systems in ways that have never been possible before.

Donna Cheney, Sandy Sage, and Graham Shimmield.

Bigelow Laboratory is drawing outstanding scientists from all over the world to study the global ocean. Five new senior researchers joined the science staff in 2007, further broadening our programs and strengthening opportunities for interdisciplinary collaboration. Their work and vision are an integral part of our plans for building the new, high technology center we will need to support global oceanographic research in the twenty-first century.

As this report goes to press, Bigelow Laboratory is welcoming Dr. Graham Shimmield as its new Executive Director. Dr. Shimmield is an international leader in ocean science, and part of a multi-disciplinary, collaborative research focus on oceans and global climate change. Dr. Shimmield has come to Bigelow Laboratory from the Scottish Association for Marine Sciences and the Dunstaffnage Marine Laboratory, which flourished under his direction by doubling its scientific staff, increasing annual research revenues six-fold, and building a major research facility.

In the past year, we have also celebrated the contributions of Dr. Louis "Sandy" Sage, who retired from his eleven-year tenure as Executive Director in July 2007. This report is a testament to his leadership in bringing Bigelow Laboratory into the vanguard of international ocean research.

Our society is becoming increasingly aware of the significant effect that climate change is having on the global processes that sustain life. Understanding the ocean's role within the vast natural cycles that support the world's ecosystems is of paramount importance to the quality of our lives and to the generations who will live on this planet after us. The scientific research underway at Bigelow Laboratory has direct bearing on the decisions, challenges, and opportunities that will determine our environmental future.

Donna Lee Cheney, *Chair*
Board of Trustees

May 20, 2008

Trustees and Scientists

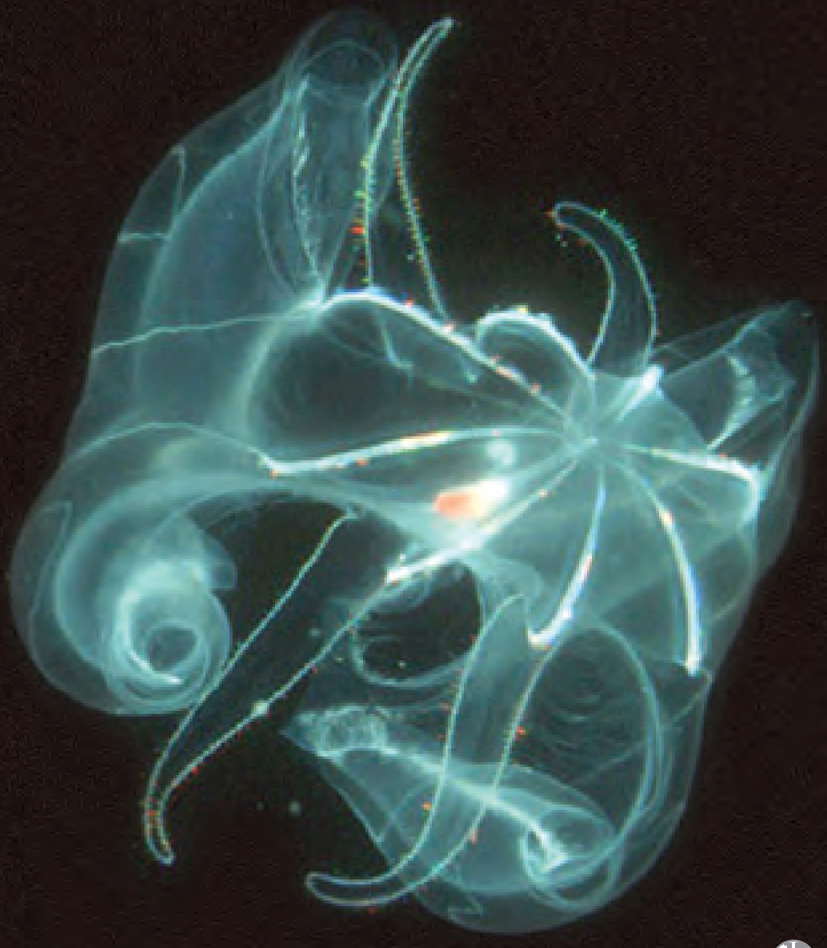

Photo courtesy of the Census of Marine Life.

Summary Financial Statements

Statement of Activities and Changes in Net Assets

(For fiscal years ended June 30)	2007	2006	2005
Operating Activities			
Operating Revenue and Support			
Grants and contracts for research and education	$ 4,317,915	$ 3,980,906	$ 3,614,363
Other revenue, including course fees	637,691	533,852	723,263
Growth fund assets released from restrictions	360,202	0	0
Contributions to annual fund	206,942	197,276	174,166
Total Operating Revenue and Support	5,522,750	4,712,034	4,511,792
Operating Expenses			
Research and education	5,005,089	4,594,254	4,508,603
Unallocated management and general	497,014	433,470	364,742
Development	90,553	71,185	90,150
Total Operating Expenses	5,592,656	5,098,909	4,963,495
Change in Net Assets from Operating Activities	(69,906)	(386,875)	(451,703)
Non-Operating Revenue and Support			
Contributions to growth fund	362,750	1,100,000	1,535,143
Gain on sale of land	0	0	1,554,151
Grants for purchase of equipment	239,290	992,191	477,529
Growth fund assets released from restrictions	(360,202)	0	0
Change in Net Assets from Non-Operating Activities	241,838	2,092,191	3,566,823
Total Change in Net Assets	171,932	1,705,316	3,115,120

Statement of Financial Position

(At June 30)	2007	2006	2005
Assets			
Cash	$ 254,395	$ 213,044	$ 448,674
Investments	2,599,931	2,933,632	1,736,786
Property and equipment, net	5,082,443	4,955,469	4,124,373
Other	1,620,585	1,140,107	1,282,088
Total Assets	9,557,354	9,242,249	7,591,921
Liabilities and Net Assets			
Liabilities	482,381	339,207	394,195
Net Assets			
Unrestricted	5,608,787	5,315,578	5,171,684
Temporarily restricted	3,267,231	3,390,816	1,831,415
Permanently restricted	198,944	196,639	194,627
Total Net Assets	9,074,962	8,903,042	7,197,726
Total Liabilities and Net Assets	9,557,343	9,242,249	7,591,921

Bigelow Laboratory for Ocean Sciences was formed in 1974. Bigelow is a Maine nonprofit public benefit corporation and is qualified as a tax exempt organization under Sec. 501(c)(3) of the Internal Revenue Code. The Laboratory's financial statements for fiscal years 2005, 2006, and 2007 were audited by Macdonald Page Schatz Fletcher & Co. The summary financial statements shown here are derived from the audited financial statements. Amounts shown in this summary as growth funds released from restrictions reflect contributions intended to support the recruitment and startup costs of new senior research scientists. Copies of the audited financial statements are available on request from: Director of Finance, Bigelow Laboratory for Ocean Sciences, P.O. Box 475, West Boothbay Harbor, ME 04575; or by email to: finance@bigelow.org

Satellite view of a phytoplankton bloom in the Black Sea. Photo courtesy of NASA.

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Unless otherwise noted, all photos are from Bigelow Laboratory for Ocean Sciences.

Bigelow scientist and on-site laboratory photographs by Buddy Doyle.

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