Searching for Systems in the Ever-Changing Sea

The First 25 Years of Bigelow Laboratory for Ocean Sciences 1974–1999

Compiled by Spencer Apollonio

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PREFACE

Since its founding in 1974, Bigelow Laboratory for Ocean Sciences has been involved in a broad range of investigations but focused primarily on the ecology and productivity of microscopic life in the sea—from the inshore waters of the Gulf of Maine, to the Arctic and Antarctic Oceans and the Arabian Sea, and into the deepest depths of the North Atlantic and the Pacific Oceans. These wide-ranging investigations were undertaken not so much for geographic reasons, but for the special characteristics found in those regions that contribute to the principal focus and investigations of the Laboratory. For example, expeditions to the ocean upwellings off Peru and Northwest Africa were carried out to shed light on the supply of deepwater nutrients essential to phytoplankton populations in the sunlit surface zones. As one reviews the record of the Laboratory, it becomes clear that the work arose from questions about the amount of basic or primary production of life in the sea, the minute organisms that contribute to or influence that production, and the ecological and interspecific interactions among those organisms and their environments. No matter where the fieldwork or the particular issue at hand, all these diverse investigations contributed to those questions. It is apparent that the researchers were aware that their work had profound implications for our knowledge of the processes contributing to and ameliorating the impacts of climate change—a growing concern and urgency during this period.

These field studies have been supported and complemented by laboratory research, some so sophisticated that it may challenge a layperson's comprehension or experience. Indeed, the Laboratory's annual report for 1979–1980 warns, "When we approach [some] areas of exploration we are in a realm where only the technical and abstruse terminology can be employed without gross inaccuracy." This historical review of that science, far-ranging geographically and intellectually, attempts to identify the essence and significance of that work but without becoming involved in the technical complexities of how the research is carried out. And, it will be understood that, unless attributed to other researchers or institutions, the work reviewed here is that of the staff of Bigelow Laboratory. The names are noted of principal investigators responsible for conceiving, finding funding for, directing, and completing the research projects and thereby making possible the Laboratory itself. But, the many trustees, volunteers, supporting staff, research associates, technicians, administrators, and maintenance staff, some of them with the Laboratory for 25 or more years, some longer than the senior scientists, should all be remembered and honored as essential for the work of the Laboratory.

It should also be remembered that science does not advance in a linear fashion. Hopefully, it progresses in the intended direction, but it may find itself in blind alleys or dead ends or suffer reversals from mistaken hypotheses or premises. That is the nature and unavoidable consequence of basic research that tries to identify, explore, and understand the *unknown*. Nor does science flourish in isolation; it builds upon the previous work of others, and its practitioners work best in collaboration with their peers either within their own laboratory or in research facilities throughout the world. Bigelow Laboratory has always operated on that basis. It has built formal relations with other institutions for strengthened research and educational capabilities, and its scientists have always joined with researchers of similar interests wherever they may be found. The Bigelow Laboratory annual reports have long lists of acknowledgements of collaborations, and, most commonly, its long lists of published scientific papers have multiple authors. This history cannot include all the collaborations with other institutions or scientists—such an attempt would produce an unwieldy volume—but, they should not be forgotten. This review does not attempt to include *all* the investigations of the Laboratory over 25 years; indeed, a number of its annual reports, upon which much of this review is based, confess that they cite only some of the research in those periods. However, this review does hope to suggest the diversity and range of Bigelow Laboratory's research and to include work that is innovative or unique and reflects the spirit of the Laboratory itself.

As the compiler of this record, I faced a dilemma: Some contributors believe that this text overemphasizes purely scientific endeavors of the Laboratory, thereby risking becoming tedious to a general reader, and neglected the *human* or *personal* dimensions of the experience of working at Bigelow Laboratory. Both views could not be accommodated while keeping the history a digestible length. I decided the focus of this history and believed those who choose to read this work will be most seriously interested in the accomplishments of the Laboratory, which are extensive, diverse, remarkable, and indeed interesting and even amazing. The founders and the entire staff of the first 25 years deserve such a comprehensive record of their accomplishments.

INTRODUCTION

Few naturalists have been as fortunate as were we . . . on our first oceanographic cruise in the Gulf of Maine . . . for a veritable mare incognitum *lay before us so far as its floating life was concerned . . . everything was yet to be learned as to . . . their relative importance in the natural economy of the Gulf . . . We even had no idea (incredible though it may seem at this place and day) what we should probably catch when we first lowered our tow nets into deeper strata of Massachusetts Bay, for so far as we could learn tows had never previously been tried more than a few fathoms below its surface.*[1]

So wrote Henry Bryant Bigelow, in whose honor the Laboratory was named, about his pioneering first exploration of the Gulf of Maine in 1912. Sixty years later, the same sense of intellectual good fortune and wonder about the unknown stimulated the group of co-founders and scientists who created Bigelow Laboratory for Ocean Sciences on the coast of Maine. In spite of 60 years of marine investigations, the Gulf of Maine and the world's ocean that lay beyond, were still very much a *mare incognitum* in the early 1970s. Three motives inspired all the Laboratory investigations into that unknown: fundamental curiosity about the nature of the ocean—ongoing discovery of the seas; productivity and ecological interactions among ocean components that evolved and preserve the stability of the benign life-supporting climate of our planet; and how rapidly changing conditions in the atmosphere and ocean may impact that essential stability. While it is said that Columbus and Magellan discovered the ocean some 500 years ago, they simply sailed over it. The ocean covers 70 percent of the surface of the planet and, because of its depth, provides 97 percent of the space on Earth for living organisms. Less than 5 percent of that space has been explored. The discovery of the ocean has barely begun.

The ocean holds realms of life that were hardly imagined in the 1970s, and the life of the sea survives and flourishes, we now know, by processes then completely unknown. In the years

1 Bigelow quote from the Foreword in Papers in Marine Biology and Oceanography, Dedicated to Henry Bryant Bigelow. 1955. Deep Sea Research, Supplement to Volume 3. London and New York. Pergamon Press.

since its founding, Bigelow Laboratory by itself and with national and international collaboration has developed and applied methods and techniques for marine investigations from outer space and in the deepest abyssal parts of the sea and at scales of minuteness beyond imagination that would have astounded and delighted Henry Bigelow—who at first worked alone and by necessity used the most primitive of sampling technologies. But his work was based upon a scientific philosophy that is the foundation of the work of Bigelow Laboratory: to study the sea as a unit, not simply to collect facts. But, as Henry Bigelow wrote, "to fit the facts together . . . in a way that would lift the veil that . . . obscured . . . understanding of the marvelously complex cycle of events that takes place within the sea." [2]

Bigelow Laboratory has held fast to that guiding principle—to study the ocean as a unit and to fit the facts from its various investigations together for a greater understanding of the whole. Rather than having a primary goal of creating a *laboratory*, the vision of founders Charlie and Clarice Yentsch was to bring together a group of like-minded researchers, with a diversity of points of view, to work collaboratively to find, understand, and relate the facts. *What are the critical interactions between microorganisms of the sea and their environment?*

From its beginning as a small group of people in a crowded, aging facility and to a great extent hidden within a larger scientific community, Bigelow Laboratory steadily grew and emerged into national and international prominence, with growing financial support from state and national sources, competitive research funding, increasing private and philanthropic contributions, and corporate support. Its rate of successful grant applications to the National Science Foundation (NSF) has been well above that of the national average. It sustained and justified that broadening support by publishing approximately one report every 10 days. It conceived, developed, and sustained formal research and educational programs for K–12 students, undergraduate and graduate students, and postdoctoral researchers. Its staff has grown from the original twelve to nearly a hundred.

2 Bigelow, H.B. 1930. A developing viewpoint in oceanography. Science 71 (1830):84-89.

The Laboratory realized such growth and development and achieved its international reputation by maintaining a non-bureaucratic philosophy that encourages interactions and cooperation among its staff, with freedom of intellectual and research choices and activities that emphasize innovation and exploration of new directions in marine microbial science. Its success came from collaboration among its own staff and with researchers throughout the world.

The primary focus of the Laboratory has always been *basic*, or pure, research as contrasted with *background* or *applied* or *practical* research. The differences among these forms of research are understood, although the lines between them are not absolute and distinct. Background research includes such activities as hydrographic or topographical surveys; collections and analyses of economic data; or the establishment of standards for hormones, drugs, or X-ray therapy. Applied research is directed toward the development or application of existing knowledge for particular purposes, decided upon and often carried on within a corporate, governmental, or institutional entity.

Basic research is different. It is a long-term process that ceases to be basic if immediate results are expected from short-term support. It is research without specific *practical* ends in view, and the objective is a general and fundamental understanding of nature and its laws. This general knowledge provides the means that may address a large number of important practical problems, or it may simply satisfy our fundamental and unending curiosity about the world we live in. The researcher may not be interested in the practical application of his or her work—they may be motivated simply by curiosity of how nature works. However, the development of important new industries depends primarily on a continuing rigorous progress of pure science, of basic research. To attain that end, the flow of new scientific knowledge must be both continuous and substantial. Each of the three general categories of research requires different institutional arrangements for maximum development. Basic scientific progress on a broad front results from the free play of free intellects so wrote Vannevar Bush in 1945: researchers working on subjects of their own choice, in the manner dictated by their curiosity for exploration of the unknown. The founders of

Bigelow Laboratory intended to create a non-hierarchical, non-departmentalized, non-bureaucratic environment to foster basic research as Bush described it.[3]

3 Bush, V. 1946. Science The Endless Frontier. A Report to the President by the, Director of the Office of Scientific Research and Development, July 1945.

ORIGINS AND PHILOSOPHY OF BIGELOW LABORATORY

Henry Bryant Bigelow (1879–1967)

After graduating from Harvard College in 1901, Henry Bigelow began working for Alexander Agassiz, a famed ichthyologist. He accompanied Agassiz on several major marine scientific expeditions, including the Maldives Islands in the Indian Ocean, the eastern tropical Pacific, and the West Indies.

Henry Bigelow enjoyed an accomplished 62-year career at Harvard University—the longest of any staff member in Harvard's history at the time. He was appointed to the position of Assistant Curator at Harvard's Museum of Comparative Zoology (1906), Lecturer in Zoology (1921), Curator of Oceanography (1927), and Professor of Zoology (1931). Henry Bigelow retired and was appointed Professor of Zoology Emeritus in 1950 and officially retired from the Museum of Comparative Zoology in 1962, but he continued to work there until his death in 1967.

Henry Bigelow began a study of the Gulf of Maine in 1912 which continued through 1924. It was a groundbreaking study because it included the whole gulf with its fishes, plankton, and physical oceanography. The study embodied his recognition of the value of encompassing the disciplines that comprise marine science. He wrote, "In the further development of sea science the keynote must be physical, chemical, and biological unity, not diversity. For everything that takes place in the sea within the realm of any one of these artificially divorced sciences impinges on all the rest of them."[4]

Nelson Marshall, an oceanographer, wrote:

> From his work, we think of Bigelow as the granddad of Gulf of Maine research as he laid the groundwork for a great deal of further study in the Gulf. Much of this later research was undertaken by scientists at the Woods Hole Oceanographic Institution, once it was

4 Bigelow, H.B. 1930. A developing view point in oceanography. Science 71(1830):84-89.

established, and later by the staff of the Bigelow Laboratory for Ocean Sciences located in West Boothbay Harbor, Maine, named in Bigelow's honor. [5]

Henry Bigelow was a member of many scientific societies in the United States and Europe, and he received many awards and recognitions for his work. In 1929, as Secretary of the Committee on Oceanography of the National Academy of Sciences, he wrote the report that led to the founding of Woods Hole Oceanographic Institution (WHOI) in 1930. He became its first director and remained so until 1939.

Henry Bigelow described 110 new species of marine life, and 26 species and 2 genera were named after him. He published more than 100 papers and several books; perhaps, the best known are his three volumes on the fishes, plankton, and physical oceanography of the Gulf of Maine. Michael Graham, an English oceanographer, wrote that his books give a better and more coherent account than that done by more hands in an area of comparable size. "For one man to have made such a clear and complete job of a relatively large area . . . was a monumental job of which any man could be proud even if he had done nothing else in his whole life."[6] Graham considered that Henry Bigelow might be called one of the founders of the *new* oceanography, which he described as, "oceanography with an ecological aim, so that instead of the mere description of what there was in the sea, there should be an explanation of the interconnections based on a full knowledge and the applications of the other sciences." Roger Revelle, director of Scripps Institution of Oceanography (SIO), wrote that Henry Bigelow was certainly one of the fathers of oceanography in the United States and of WHOI in particular.

The History Of The Mckown Point Facilities, The First Home Of Bigelow Laboratory[7]

In 1903, a federal government report warned that unless active management measures were taken, the declining lobster fishery of New England would eventually become commercially extinct.

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5 Marshall, N. 1999. In the Wake of a Great Yankee Oceanographer. The Anchorage Publisher.

6 Graham, M. Obituary of Henry Bryant Bigelow, Deep Sea Research, Vol.15, No.2, April 1968, The Pergamon Press.

7 Source: The Hatchery- an Eighty-Year Account of the Fishery Station on McKown Point from 1904 to 1984. By Alden P. Stickney. Boothbay Region Historical Society.

Congress, therefore, provided funds for construction of a lobster hatchery on 10 acres of land on McKown Point, Boothbay Harbor, Maine. Previously, lobster hatcheries had been tried in Norway and southern New England with results that justified their expense. The site in Maine was chosen because of its good water quality and proximity to the open sea and the center of the US lobster fishery. Construction began in 1903, and the new lobster hatchery began operating in 1905; shortly thereafter, finfish hatching was added to the program. In the second year of operation, 203 million lobster fry and 110 million codfish fry were released into the Gulf of Maine.

Beginning in 1910, fry from haddock, pollock, and flounder were produced and released. In subsequent years as many as 2 *billion* flounder fry were produced each year.[8] Production of lobster fry ended in 1919, but finfish fry production continued until 1944.

The State of Maine became involved in the hatchery in 1937 when, in cooperation with the federal government, it resumed lobster larvae production. The hatchery operation continued until 1945 when the entire hatchery program was discontinued, and the state–federal program at McKown Point was changed to conduct research into problems in the inshore softshell clam and herring (sardine) fisheries and the relations between inshore and offshore herring and lobster populations. But townspeople still asked researchers for 20, 40, even 60 years after the facility ceased hatchery operations if they worked at the hatchery.

Intensive foreign fishing on Georges Bank and in waters offshore from the mid-Atlantic states had developed in the 1960s and early 1970s. As a result, the federal government decided to focus its research on those offshore fisheries and consolidate that research in its laboratory at the Northeast Fisheries Science Center in Woods Hole, Massachusetts. It closed its laboratory on McKown Point in 1973.

The General Services Administration (GSA) notified the State of Maine that the federal property on McKown Point would be sold at auction. The state owned its research and hatchery building

8 In later years there was a story that the reported production had been inflated for political reasons.

on the property but did not own the land. The GSA decision thus produced a major problem for the state; what would become of its Department of Marine Resources' several research and public health programs if the land were sold?

Maine Senators Edmund Muskie and William Hathaway, Congressman Peter Kyros, and Maine's Commissioner of Marine Resources, Spencer Apollonio, met with the GSA administrator in Washington, D.C. Senator Muskie asked the administrator what would be done with the property and was told that it would be sold. The senator, in essence, said no. It was a short meeting. The GSA then advised the State of Maine that the state could lease the property for 30 years provided that it fully utilize the property. That presented a new problem. In 1971, the federal laboratory on McKown Point had a staff of 40 people. The state did not have any prospects for the financial or personnel capabilities needed to utilize the property fully.

At that time, Charlie Yentsch was director of a small marine research station on Cape Ann, Massachusetts, affiliated with the University of Massachusetts. Commissioner Apollonio had known Charlie Yentsch for 20 years, having carried out marine research with Charlie's active support, encouragement, and guidance from time to time from the 1950s through the mid-1980s. He wondered whether Charlie Yentsch might consider moving his laboratory to McKown Point, making full utilization of the facilities possible. However, after thinking about that possibility for some time and wishing it might be possible, he concluded that it might be awkward or inappropriate to ask and that Charlie Yentsch would not likely give up a secure, tenured, and beneficial relationship with the University of Massachusetts.

Late in 1973, Charlie and Clarice Yentsch called the commissioner and said they were coming to Maine to look for a wood stove. The commissioner looked forward to a pleasant social visit, not having seen them for some time. However, when they appeared at his office door, without saying hello, without mentioning wood stoves, without even sitting down Charlie asked, "What are you going to do with that property in Boothbay Harbor?" With that question, Maine's problem for maintaining its research activities on McKown Point was solved, and it acquired a partner for cooperative marine research in such areas as the marine biology of the Gulf of Maine, toxic algae, oil spill contamination, and larval fish recruitments. Charlie's question came at an opportune time within a narrow window of opportunity. The commissioner's predecessor a year before did not want the McKown Point property, and his successor 18 months later did not want Bigelow Laboratory.

With the full approval and support of Governor Kenneth M. Curtis and the Maine Legislature, a cooperative agreement was quickly arranged with Charlie Yentsch. Richard Morrell, then a member of the legislature and much later a trustee of Bigelow Laboratory, recalled that Governor Curtis and the chairman of the legislature's appropriations committee held several sessions to consider the proposal—both were very much for it. The legislature provided funds for initial partial support for the Laboratory, which upon relocating to Maine on July 1, 1974, became Bigelow Laboratory for Ocean Sciences.

Subsequently, the state acquired the closed Coast Guard property on McKown Point, known as the Welch House, through a contact of Linwood Palmer, a former legislator with Vice President George H.W. Bush. The Welch House was first a residence/dormitory and then became research and administrative offices for the staff of Bigelow Laboratory.

Hilary Glover wrote:

> I arrived at Bigelow Laboratory in the summer of 1975 on a Postdoctoral Fellowship from England. It was a memorable experience, housed with 18 college students in the Welch House on McKown Point with three beds to a room and only one bathroom. Coming from the University College London, with the zonal centrifuges and electron microscopes, the equipment at Bigelow Laboratory seemed marginal. Six months later things were looking up. An influx of new scientists had arrived, and Dick Dugdale's computer system took up almost 10 square feet—amazing when one thinks of the capacity of our modern handheld devices. What impressed me most as a young female was the large representation of women oceanographers at Bigelow Laboratory. There were no offices for junior staff, and initially, we had desks on the top floor of the biochemistry building. Young new arrivals invariably stayed at the commune in West Boothbay Harbor, which soon became party central.

On consideration, was Boothbay Harbor a good site for a new oceanographic laboratory? It was a good site for a lobster hatchery with good seawater in the heart of the nation's largest lobster fishery, but a laboratory committed to basic oceanographic research is quite a different affair. Looking landward from its location on the tip of McKown Point, one sees a small Maine village with a year-round population of 2,200 people. East Boothbay, the Laboratory's future home, is even smaller. Both villages are at the very end of a long peninsula and 12 miles from the main route along Maine's coast. The State of Maine as a whole was then only modestly engaged in and not renowned for marine research. People might wonder how the new laboratory could prosper in such a remote and unlikely location.

However, look seaward from McKown Point and one gazes out over the Gulf of Maine, that "very marked and peculiar piece of water" as it was described by nineteenth-century historian J.G. Kohl.[9] It took Kohl 20 pages, and with good reason, to explain that memorable characterization of the Gulf, even with the limited information available to him at that time. The Gulf of Maine is not the Atlantic Ocean; the ocean lies 200 miles beyond the seaward horizon. What one sees from McKown Point is a semi-enclosed, moderately large, and relatively shallow body of water with well-defined and distinctive characteristics of its own, quite different from the distant ocean. Its special nature lends itself to the kinds of studies that were the philosophy of Bigelow Laboratory—the assembly of a diversity of marine information into an understanding of the whole.

The Gulf of Maine has a well-defined hydrographic structure with surface circulation first outlined by Henry Bigelow. It has vertical structure subsequently clarified in part by researchers from Bigelow Laboratory. Its shores are remarkably endowed by a wealth of bays and estuaries and inlets that in places penetrate far into the coastal regions of Maine. Some of these, the Laboratory's staff learned, defy conventional wisdom of how such estuaries behave and interact with coastal waters. Some parts of Maine's coastal zone have a diversity and abundance of intertidal and subtidal life greater than many other regions of the East Coast north of the tropics. Primary production of marine phytoplankton in the Gulf had distinct and pronounced seasonal

9 Kohl, J.G. 1869. History of the Discovery of Maine. Vol. I in W. Willis, ed., Documentary History of the State of Maine. Portland: Maine Historical Society.

pulses or periodicities that lend themselves well to one of the research priorities of Bigelow Laboratory—the ecology and physiology of phytoplankton.

Bigelow Laboratory, therefore, was not founded in a remote, rural, isolated, unlikely, and unpromising site, but rather in close proximity to an easily accessible and exciting body of water, as Henry Bigelow had recognized 60 years before, with an abundance of opportunities and favorable circumstances for research. And, the Laboratory is centrally located for access to all parts of the Gulf of Maine.

On those bright, clear days that occur summer and winter on the coast of Maine, the sun at noon casts a magical and inviting path from McKown Point out to the Gulf of Maine. Could any place be more favorable for marine research than this? As Charlie Yentsch wrote, “no place could be more suitable than the coast of Maine.” Indeed, within a very few years, the Laboratory was attracting scientists from around the world to share in its work.

The Founders: Charlie And Clarice Yentsch

Charlie and Clarice Yentsch founded Bigelow Laboratory in 1974. Their complementary, yet distinct, scientific perspectives and interests shaped the Laboratory’s research philosophy.

Regarding their respective roles, Clarice wrote:

> The good part is that we were complementary partners, each seeking input from the other. We were both committed to excellence. We were both leaders. Charlie indeed was the inspiration and mentor to all—including myself. His early research provided the scientific basis for the Laboratory. The contribution I claim was more the development of the organization, connection with the community of scientists and locals, and hospitality.

Early in his career at WHOI, Charlie revealed his independent and innovative perspective. First, with his colleague John Ryther, he developed a novel and inexpensive method of estimating ocean productivity. It depended on no more than knowledge of sunlight on the sea surface; chlorophyll in the water; instrumentation of the utmost simplicity—the Secchi disc; and their previously derived relation between chlorophyll and photosynthesis. This was later accepted as a reliable method. Second, Yentsch and Ryther broke with tradition that governed the submission of research proposals to funding agencies by institutional administrations. After advising the Woods Hole administration, they prepared and submitted their own successful research proposals and received the requested grants.

This independent spirit led Charlie to leave Woods Hole in 1967 and join the faculty at the newly formed Nova (now Nova Southeastern) University in Fort Lauderdale, Florida. There he met Clarice, who was one of the first graduate students at Nova University. Clarice completed her PhD in Biological Oceanography in 1970. In the same year, she and Charlie married and moved to Massachusetts to form the University of Massachusetts Marine Station (UMMS).

Clarice wrote:

> Charlie's passion for salt water was first inspired by the limestone marine fossils in the roadside outcrops of his native Kentucky. As a young child, he moved to California and lived near the shores of the Pacific. He was awed by his first looks through a glass face plate while snorkeling and later as an adult described it "like observing living microorganisms under a microscope." As a teen, he was a surfer and lifeguard on Hermosa Beach. He then joined the U.S. Navy and served during World War II.
>
> My passion for water started in fresh water. Our family cottage was on Sylvan Lake in northern Wisconsin. This lake became a daily refuge and sanctuary for me during the summers. After college, I received a scholarship from the University of Wisconsin Botany Department permitting me to participate in a summer course at the Marine Biological Laboratory in Woods Hole, Massachusetts. Two of the instructors inspired me—Luigi Provasoli, then of the Haskins Laboratory of Yale University, and Robert R. L. Guillard, then of WHOI. These two men later became the honored namesakes of the Provasoli-Guillard Culture Collection of Marine Phytoplankton at Bigelow Laboratory. With that introduction, I focused my imagination on microorganisms in salt water.
>
> Charlie had worked in several research environments starting with Florida State University in Tallahassee and the associated Coastal and Marine Laboratory in Sopchoppy, Florida. He

went on to graduate school at the University of Washington, Seattle, and the associated Friday Harbor Marine Laboratory in the San Juan Islands. From there, he was recruited to join the small staff at WHOI. In addition to his own research, Charlie worked with visiting students and colleagues to transfer recent technology and expand the base of competent ocean science observation and data collection.

Charlie's enthusiasm for WHOI waned after he was there a decade when the unified system of colleagues was reorganized *for efficiency* into separate departments: biology, chemistry, physics, and geology. For Charlie and others, this demarcation violated the philosophy of Henry Bigelow. Granted, the different sciences bring their own tools and specialties, yet all colleagues must think and imagine together in order to focus creative human intellect and energy. Charlie, a biological oceanographer, along with Bill Richardson, a physical oceanographer, and others objected to this departmentalization and helped to lead a palace revolution that failed. It was clear to the failed-coup members that they would need a strategy to exit the institution and for each to find a new laboratory home.

Bill Richardson was the first to leave. He moved to the University of Miami Marine Laboratory and then to Nova University. Charlie followed Bill to Nova in 1967 to join the faculty as Biological Oceanographer.

The shared foundation beliefs of Bill and Charlie were informal, yet clearly defined:

- The sea must be studied as a unit (from Henry Bigelow).
- Every ocean scientist must be proficient in both the laboratory and the field or at sea.
- Administration must be minimal, leaving the scientist to concentrate on research.
- The staff organization must be non-hierarchical and non-departmentalized.
- The work must be fun. Good times should include families and pets.

These tenets were the glue between Bill and Charlie. They became motivated to create an environment conducive to creativity, and the opportunity presented itself at Nova.

> Much of the research of the new oceanographic laboratory resulted in significant breakthroughs. Many good and joyful things happened over those first few years. However, financial woes became the dominant point of discussion, and the administrative burden started to cripple the faculty in their attempts to do stellar research.
>
> By 1970, Charlie became convinced that he and his team should move elsewhere. He longed to be back in the vicinity of the Gulf of Maine. In early spring, Charlie accepted an offer from the University of Massachusetts to open a new marine laboratory in Gloucester on Cape Ann. This laboratory was to arise from the refurbishment of an old seaside quarry building and be called the University of Massachusetts Marine Station. The site seemed to be ideal. Charlie signed the contract after reviewing and approving the architectural drawings for the Laboratory refurbishment. He then co-created and signed a five-year strategic plan with the university. Yet, he soon encountered major problems.

Events That Led To The Move To Maine

The arrangements with the University of Massachusetts were deficient in three ways: the laboratory space promised was wholly inadequate and not renovated, archaic university personnel policies forbad married couples from working together in the same department, and university policy prevented the acquisition of a boat for sampling at sea.

Clarice wrote:

> Local residents who were interested in science and our contribution to the community collaborated with us to form the Cape Ann Society for Marine Science, a not-for-profit foundation that could accept donations and purchase, run, and maintain a small research vessel. A 40-foot party boat was purchased, retrofitted with ocean science gear, and renamed R/V *Bigelow*.
>
> Our time in the communities of Gloucester and Rockport was cherished, but the relationship with the university was oppressive. We became more intent than ever to form a laboratory that would have an empowering environment for creativity. We added one tenet to the

original list: the Laboratory must welcome professional couples and qualified family members. This proved to be not only prudent but a highly effective recruiting strategy.

When Charlie learned that the National Marine Fisheries Laboratory in West Boothbay Harbor was destined to be closed, his interest was piqued, and he placed a call to Spencer Apollonio, the Commissioner of Marine Resources in Maine.

The *Gulf Stream* Tragedy

Less than a year after its founding, Bigelow Laboratory was staggered by a tragedy and mystery that struck close to a number of its staff. On Saturday, January 4, 1975, the research vessel *Gulf Stream* left the Laboratory dock at McKown Point for a short cruise in the Gulf of Maine and never returned. There were no clues for its disappearance. Forty years later the cause of its loss is still unknown.

Gulf Stream was a 48-foot, steel-hulled, former oil-drilling support vessel with two 460-horsepower diesel engines. She was operated by Nova University with an experienced crew of five. The scientist in charge was Bill Richardson, the close colleague of Charlie Yentsch at WHOI from 1952 through 1963, and later at Nova University. Richardson was a capable scientist, designer, and engineer who made numerous and significant contributions in the field of marine technology.

The purpose of his visit to the Gulf of Maine in the winter of 1975 was to perfect a heavy-weather buoy program. Richardson designed the buoys that would drift with ocean currents and be tracked by satellites. The results of the buoy development would contribute to a number of national and international programs in oceanography and meteorology. The buoys were intended for deployment in the stormy North Pacific Ocean. Richardson had said, "We need a place to test those buoys where the seas and weather are nasty. Maine is it. You have quite deep water, fairly close to land, and excellent facilities at Boothbay."

Gulf Stream had already gone out from Boothbay Harbor to tend its buoys many times. The weather forecast for January 4–6 was good and the seas moderate. The vessel left Boothbay

Harbor on January 4 to recover eight buoys 30 to 40 miles south. It would then go on to Gloucester, Massachusetts, to spend the night and was scheduled to return to Boothbay Harbor on January 5, but no contact had been made by that date. On January 6, Charlie Yentsch contacted the Coast Guard and asked them to contact *Gulf Stream.* The Coast Guard was not successful, and an alert was issued.

Two local fishermen later testified that the vessel had been seen leaving Boothbay Harbor on the morning of January 6, although there was no record of it having been in the harbor on January 5. On January 7, it was reported that two radio transmissions had been heard from *Gulf Stream.* Nothing more was heard from the vessel. The weather deteriorated badly on January 7, and the Coast Guard had to call off its air and sea searches. Later, one body, that of James Riddle, and one life ring were recovered.

A possible explanation is that the vessel was struck by a tanker en route from Portland to Halifax, Nova Scotia. A foreign-flag tanker was held in Halifax while Canadian authorities examined it for any signs of collision, without result. The vessel was released.

The Coast Guard inquiry concluded:

> There is no evidence that any act of misconduct, inattention to duty, negligence, incompetence, or willful violation of any law or regulation on the part of licensed or certified personnel contributed to the casualty.
>
> There is no evidence of any mayday or distress being sent from the R/V *Gulf Stream* at any time.

The Coast Guard recommended that no further action be taken, and the case was closed.

The loss of *Gulf Stream* and her crew is memorialized at the harborside Fishermen's Memorial in Boothbay Harbor.

In Memoriam

William Springer Richardson

William Ben Campbell

Jack L. Spornraft

James David Riddle

John Wayne Hill

THE FIRST TWENTY-FIVE YEARS OF BIGELOW LABORATORY

The Science Underpinnings Of Bigelow Laboratory In Its First Years (By Clarice Yentsch)

It may seem simplistic, yet the research that was the underpinnings of Bigelow Laboratory in its early years had to do with the molecule of chlorophyll ($C_{55}H_{72}Mg_{405}$). Chlorophyll is ubiquitous on land and sea. It is a photoreceptor, meaning that it absorbs radiant energy from sunlight and acts as a catalyst in the light reaction of photosynthesis that results in ocean productivity. The molecule is conserved, meaning that it is not used up in the reaction. The word equation is

$$\text{carbon dioxide} + \text{water} \xrightarrow[\text{chlorophyll}]{\text{light energy}} \text{carbohydrates} + \text{oxygen}$$

The life-giving process of primary productivity was often measured by radioactive carbon-14 incorporation or by oxygen production. Both methods require sampling and incubation times that are major challenges aboard constantly moving research vessels. One attempt to meet this challenge was made by trying to get an instantaneous snapshot of something that might be a surrogate or proxy for primary productivity. The ubiquitous plant pigment chlorophyll was the obvious candidate.

In the plants of the sea, there are many accessory pigments, in addition to chlorophyll, that are important to both the photosynthetic process and the detection and discrimination of various microalgal groups. These pigments work together to transfer energy and increase the efficiency of photosynthesis. The sum of these processes is ocean productivity. Consumption of these plants results in the various steps of the marine food web. Microscopic plants, the microalgae, were a focus of research at Bigelow Laboratory.

Although Charlie and I were both focused on chlorophyll, our perspectives were different. Charlie's primary goal was to extend the limits of human observation by *zooming out*. Charlie took the *ascending* approach—increasing data collection, information, and understanding as one jumped ever-increasing spatial scales.

In his early career, Charlie had developed a fascination and understanding of optical lenses and filters. He appreciated how the absorption spectra of various natural compounds affected the reflection and transmission of light in water. He made spectral radiometric measurements of pure water, seawater with phytoplankton, seawater with dissolved matter, and seawater with suspended sediments. These suites of measurements formed the basis for his synthesis and mental models probing and understanding the fate of light in seawater. This field of investigation is now referred to as Ocean Optics.

While some scientists may have been content to report their research findings in the peer-reviewed scientific literature, Charlie took it one step further. He asked how this capability might be used to advance the human capability to *see* the ocean? Charlie was fascinated by how one's visual acuity was empowered as one would stand back.

Charlie and his colleagues at WHOI focused their interest in remote sensing on the Gulf of Maine. They asked, "Could certain ocean color features be mapped onto physical forcing functions? Might ocean color help in the interpretation of the physics? Could ocean color trace currents like a dye?"

Charlie, along with several like-minded colleagues, advanced these questions and understandings. They approached the National Aeronautics and Space Administration (NASA) with the idea that a multispectral sensor onboard a satellite could measure the blue and green colors of the ocean, and by forming a ratio of the two colors one could quantify the amount of chlorophyll in the water. Charlie and his colleagues became the first to advocate this approach, which became the basis of ocean color remote sensing in the years to follow.

> In contrast, with the primary goal to push the limits of detection, data collection, and understanding, I took the *descending* approach—increasing accuracy and precision by *zooming in* as one jumped ever-decreasing spatial scales. My curiosity was centered on the living microscopic organisms themselves: their shape, volume, form, function, abundance, "names and addresses," toxic versus beneficial. Their contribution to ocean productivity, growth and cell division processes, and the depletion of those organisms via sinking and grazing were of major interest to me.
>
> We recognized that not only did the chlorophyll and accessory pigments absorb light, they also fluoresce; that is, some of the light energy that is not used for photosynthesis is emitted as fluorescence. Under natural sunlight, a solution of pure chlorophyll has a blue-green appearance; in the dark, if one shines ultraviolet light on the solution, it fluoresces a brilliant red.
>
> An early publication by Charlie and Dave Menzel had resulted in a major shift from using absorption to using fluorescence to measure chlorophyll. Small sample size and increased sensitivity were features of the method. The increase in sensitivity meant that flow-through fluorometry systems became possible on shipboard. Continuous data streams from the sea were realized in both the horizontal and vertical dimensions.
>
> Fluorescence spectral signatures were key to discriminating phytoplankton and useful as a taxonomic tool; one could differentiate the algal groups based on fluorescence signals characteristic of different pigments without having to identify the species microscopically (i.e., the taxonomic approach).

The research interests of Charlie and Clarice were extending the levels of chlorophyll detection. Both were chasing the molecule of chlorophyll over spatial scales of 12 orders of magnitude by zooming in or out.

Adapting the flow cytometer, an instrument used for medical research and diagnostics, to the study of individual phytoplankton cells was among the pioneering achievements of Bigelow scientists involving zooming. They also developed remote sensing techniques for charting the abundance of phytoplankton pigments on global scales. While focusing on vastly different scales, each of these approaches sought to measure chlorophyll as a means of understanding ocean productivity.

Interdisciplinary Oceanography, 1974–1989 And Beyond (By John J. Cullen)

By the time Bigelow Laboratory was founded in 1974, the field of oceanography had blossomed in response to accelerating investments in research and education that began after World War II and extended into the 1960s. The interdisciplinary synthetic vision of consummate oceanographers like Henry Bigelow and Charlie Yentsch still existed, but increasingly, researchers were making their marks with specialized advances in the subdisciplines of biological, chemical, geological, and physical oceanography—that by then were firmly established in the academic departments of major universities. The most influential *phytoplankton people* of the time, however, recognized the importance of interdisciplinary work. Many participated in the multidisciplinary US Coastal Upwelling Ecosystem Analysis program that began in 1974. Biological oceanographer Patrick Holligan of the Marine Biological Association of the United Kingdom worked with colleagues across disciplines to show how phytoplankton blooms were related to physical processes at tidal boundaries near the English Channel, and Charlie Yentsch (who transcended disciplinary tags) had recently described the strong relationship between phytoplankton abundance and the tilting density structure of the ocean associated with large-scale circulation, such as the Gulf Stream. Nevertheless, during this period of expansion in ocean science, funding for research and opportunities for training were focused on specialization more than synthesis, and interdisciplinary ocean research lagged.

The trend to disciplinary specialization in late twentieth-century oceanography was rooted in opportunity; during the period of plenty when investments in university departments and research groups were growing, individual researchers had the time and resources to explore the mechanistic foundations of oceanographic processes. For phytoplankton ecologists, a central challenge was to describe the relationships between environmental factors—light, temperature, nutrients—and the photosynthesis, cell division, and chemical composition of microalgae. Theory was based on results from the laboratory, with the new understanding tested by comparing measurements in nature to hypothetical predictions.

By the 1970s, fundamental theories of phytoplankton ecophysiology had been developed, as had new methods for measuring key processes in the field. But major questions remained unanswered. For example, the two principal frameworks for describing the relationships between nutrient supply, biochemical composition, and growth rates of phytoplankton—Monod and Droop kinetics—were firmly established but not yet integrated in coherent theory. Many thousands of measurements of marine photosynthesis, light, and chlorophyll had been made worldwide, providing a good start for descriptions of how the photosynthetic capabilities of phytoplankton responded to environmental forcing. Yet, controversies were raging about measurements of the biomass, photosynthesis, nutrient uptake, and growth of phytoplankton. Exchanges were restrained in print, sometimes harsh in correspondence, and even more so over beer when the passion for scientific understanding need not be tempered by the existence of a permanent record. No one could state with authority whether phytoplankton in the so-called ocean deserts of the central gyres were growing quickly, supplied by rapidly recycled nutrients, or slowly because nutrient concentrations were too low. More broadly, beyond important foundational principles and models established by the likes of H.W. Harvey, Gordon Riley, John Steele, Dick Dugdale, and Richard Eppley, there was no comprehensive, quantitative, and validated theory to describe the environmental control of the distributions and physiological activities of phytoplankton in the ocean. Phytoplankton research needed a more comprehensive theoretical foundation and better diagnostics; in response, a major research emphasis on the physiological ecology of phytoplankton emerged. By the early 1980s, Bigelow Laboratory was well established as a world-class center of expertise.

Bigelow Laboratory's contributions to phytoplankton research were extraordinary because of its guiding principles: institutional structure (or lack thereof) and a concentration of expertise that could not be justified in a typical university department. For example, shortly after the Laboratory was established about eight researchers worked on the physiology or ecology of phytoplankton, and many more visited for collaborations. Because there was so much going on at McKown Point, Bigelow Laboratory quickly established itself among the cognoscenti as a hotbed of phytoplankton research. Even though Bigelow Laboratory had developed this specialty, interdisciplinary oceanography also thrived; phytoplankton research was always aimed at improving understanding of how the ocean works and phytoplankton were by no means the exclusive focus. In comparison, big institutions, such as Scripps Institution of Oceanography (SIO), had tremendous expertise in phytoplankton, but the investigators were spread among departments and research groups in different buildings, restricting day-to-day interactions. Significant and long-lasting contributions to plankton research were being made by the Food Chain Research Group and the Marine Life Research Group at SIO, and others at Scripps were making important discoveries about the biology of microalgae.

As explained by Clarice, researchers at Bigelow Laboratory applied newly developed tools to explore the distributions and activities of phytoplankton over scales from the smallest cell—detected and characterized with flow cytometry—to ocean basins observed from space. A central theme, described by Charlie Yentsch and Dave Phinney in a benchmark 1989 publication[10], was the bridge between ocean optics and microbial ecology—the intimate links between light and life in the ocean.

Measurements of light in the sea, including the fluorescence of phytoplankton readily available from ocean observation systems, reveal the links between sunlight and life in the ocean. This is how it works: the availability of light has a dominant influence on the growth of phytoplankton, leading to physiological adjustments (pigmentation) and shifts in species composition (dominant cell size) that tend to optimize the utilization of light energy and nutrients. These ecologically favorable changes in the phytoplankton affect their optical properties—light absorption and scattering—thereby strongly influencing the light regime in the ocean, including its color as detected from space and light penetration as measured with in-water optical sensors. Measurements of ocean color and light penetration at different wavelengths can therefore provide estimates not only of phytoplankton abundance, but also of community structure and thus ecological adaptation. These reveal key ecological

10 Yentsch, C.S., D. A. Phinney 1989. A bridge between ocean optics and microbial ecology. Limnol. Oceanog. 34(8):1694-1705.

feedbacks that underlie the relationships between physical processes, primary productivity, and food web structure in the sea. Simply, the light–nutrient regime structures the phytoplankton community and phytoplankton strongly influence the light regime, and these interactions form the bridge between ocean optics and microbial ecology.

The comparison between water and algal pigment absorption spectra hints at many relationships between light and phytoplankton in the ocean that are fundamental to phytoplankton ecology and bio-optical oceanography. The principal photosynthetic pigment, chlorophyll *a*, absorbs blue and red light. Accessory pigments, associated with specific taxonomic groups of phytoplankton, absorb light at other wavelengths that are efficiently transmitted through the water column.

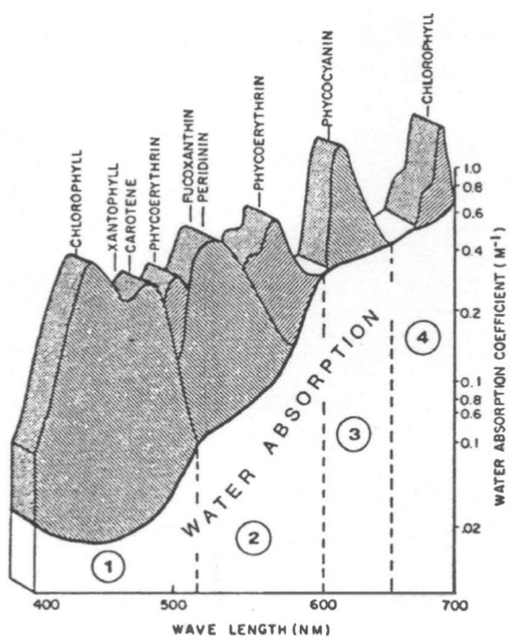

Figure 1. The absorption of light by different algal pigments is related to the *windows of clarity* in water absorption (figure from Charlie Yentsch, 1983[11]).

Community composition and dominant cell size of phytoplankton can be inferred from measurements of the absorption properties of phytoplankton and from the detection of fluorescence emitted when various photosynthetic pigments are exposed to light of different

11 Yentsch, C.S. 1983. Remote sensing of biological substances, in: Cracknell, A.P. (ed.), Remote Sensing Applications for Marine Science and Technology. NATO ASI Series C: Mathematical and Physical Sciences), vol 106. Springer, Dordrecht, pp. 263-297.

colors. The synthesis of relationships between physical forcing, light, nutrients, and the abundance, pigmentation, and cell size of phytoplankton provides the foundation for relating optical measurements of the ocean (from satellites, ships, and autonomous sensor systems) to primary productivity and food web structure.

This field of research could be called bio-optical ecology, a designation that is not yet established. Arguably, its roots were developed by Charlie Yentsch along with other prominent ocean scientists, including Raymond Smith, André Morel, and colleagues. Research on phytoplankton at Bigelow Laboratory during the 1970s and 1980s strengthened these roots, establishing an interdisciplinary approach that stood the test of time. Henry Bigelow's commitment to studying the ocean as a whole is no longer unusual, as it was in the Laboratory's early years. Interactions among experimenters, observationalists, and modelers are commonplace now.

As ocean science progresses in the 21st century, subject to much uncertainty about the future of our planet, interdisciplinary research is increasingly common, as it needs to be. Bigelow Laboratory, a bastion for studying the ocean as a unit, played a role—perhaps small, but undeniably valiant—in returning interdisciplinary research to mainstream ocean science. Henry Bigelow and Charlie Yentsch were critically important: their aim was true.

Early Growth Of The Laboratory

The staff of Bigelow Laboratory in 1974 consisted of 12 scientists and support staff. Within two years, there were 17 scientists, 20 research associates and assistants, and 9 administrative and technical staff. The expansion of the staff in the first years offered critical mass and the benefits and synergy of interdisciplinary research. The Laboratory hosted 97 guest scientists in its first two years. The oceanography community recognized the Laboratory for its excellent work.
In 1975–1976, Laboratory scientists participated in 10 extended research cruises in areas ranging from the Gulf of Maine, to the coast of Peru, and to the Gulf of Naples. Thirty-one published papers and 12 technical reports recorded the results of the work. The work that had begun during the first year continued and was reinforced with the support of additional scientists with differing perspectives and contributions. By its second year, with a nearly fourfold increase in funding

from additional researchers, the McKown Point facilities had become fully utilized. This rapid growth presented challenges for its administration, including space limitations and the need for coordination among a variety of projects in a small but rapidly growing institution.

Bigelow Laboratory focused on physical, chemical, and biological processes controlling basic organic production in coastal and oceanic waters. As Ian Morris, Assistant Director of Research, stated in the Annual Report for 1976–1977, "Much of the understanding of ocean processes was based rather superficially on correlations; our work is based on the concept that such correlations should be translated into more precise causal statements where the underlying biochemical mechanisms can be identified."

In the third year, 1976–1977, funding exceeded $1 million, a fivefold increase from the first year, and Laboratory staff participated in 10 cruises, spending over 900 days at sea. The Laboratory hosted almost 100 guest scientists. The small laboratory, seemingly isolated and hidden away on a remote peninsula on the Maine coast, was attracting scientists from across the nation and the world. As Ian Morris had reported in the Annual Report for the previous year, "Bigelow Laboratory is being watched closely by our colleagues throughout the oceanographic community. Many hope to see it become an example of the future direction which research establishments might take."

In spite of the initial strong support of Maine's congressional delegation, the governor, and the legislature, Charlie Yentsch felt it necessary in his introduction to the 1976–1977 Annual Report to address "our problems with the State of Maine government" following a change of administration. He noted "disagreements, personality differences, and a baffling amount of misinformation." He expressed the hope that an informed understanding of the mission of the Laboratory would lead to recognition and understanding that the Laboratory work is germane to the interest of the state. He noted specifically that a sound concept of the whole marine ecosystem is fundamental to efficacious fisheries management. Yentsch's view of the relation between fundamental oceanography and fisheries research was entirely consistent with that of Henry Bigelow, who never made a distinction between the two and pioneered studies and published in both areas. Nearly 30 years after Yentsch felt compelled to make the connection between the two studies, the US Congress made *ecosystems* management of fisheries a requirement of law. Ironically, at the time of the apparent difficulties with some of the State of Maine government, the Laboratory had initiated a long-term study in close cooperation with Maine's Department of Marine Resources (DMR); the study examined the cause and prediction of toxic algae and paralytic shellfish poisoning (red tide), with its consequences for public health and the shellfish industry.

"It was a very good year," began Charlie Yentsch in the Annual Report for 1977–1978. Intensive field activity, including 13 research cruises and laboratory analyses, and 23 publications of accumulated data and results supported that conclusion. The report noted, "much of the creativity in oceanographic research arises from the meeting of different disciplines and the crossing of artificial barriers frequently erected between individual fields of study . . . and is resulting in the emergence of Bigelow Laboratory as a prominent member of the oceanographic community."

In 1980–1981, Bigelow Laboratory researchers took part in 22 research cruises, in locations including the northeast Atlantic Ocean, off Baja California, and the Arctic Ocean. The following year, staff were at sea on 15 different vessels for more than 475 days. The annual budget of the Laboratory reached $2 million. In 1981, after another change in Maine and DMR administrations, Bigelow Laboratory signed a 20-year lease with the State of Maine for space in certain physical facilities on McKown Point, helping in part to stabilize its prospects for the future.

Over the years, many scientists visited the Laboratory, staying from days to months. They were all a stimulus to the staff—giving scientific advice and perspective, speaking at seminars, participating as research collaborators, or conducting their own research. For example, David Brooks of Texas A&M University visited many summers to continue his studies of the hydrography of the Gulf of Maine. Ramon Margalef of the University of Barcelona, an internationally known and foremost marine phytoplankton researcher, was a visiting scientist at Bigelow Laboratory in 1976. Margalef's contributions to theoretical ecology have made him one of the most frequently quoted ecologists and the recipient of numerous national and international honors and awards. Gunnar Kullenberg of the University of Copenhagen visited Bigelow

Laboratory as a Fulbright Scholar for six months in 1981. He wrote, “the main reasons . . . were to go to a not-too-large place with an individualistic view . . . where one scientific aim is interaction among the basic disciplines with an emphasis on basic, process-oriented research. This I found at Bigelow Laboratory.”

Financial Challenges And Opportunities In Early Years (By Robert Kidd)

Bigelow was founded in 1974 as an independent nonprofit research institution. The independent organizational structure provided an environment attractive to research scientists and conducive to high-quality research. This setting enabled Charlie and Clarice Yentsch to recruit internationally competitive scientists to join the Laboratory. These researchers were experienced and successful in writing grant and contract proposals to federal agencies.

The research positions at Bigelow Laboratory were soft-money positions, meaning that each senior research scientist was responsible for writing grants to cover the cost of their individual salaries, staff, and research projects. In contrast, hard-money positions were typically tenure-track, university-funded positions for nine months per year, paid through tuition and philanthropy with the balance paid through research grants. Writing ongoing successful grant proposals, preparing research results and technical reports, and publishing in scientific journals are all major components of a soft-money research position.

Each year, Bigelow would negotiate an indirect cost rate with its primary granting agencies. The indirect cost rate was then applied to each grant proposal; when a grant was awarded, it included the direct costs of research and a budget line for indirect costs. The indirect cost rate, when charged to all grants, created a pool of funds to pay for Bigelow Laboratory’s facilities and administration.

The Laboratory’s success in research was dependent on institutional financial viability. Charlie Yentsch was a full-time scientist and served as the Laboratory director. His scientific leadership within the Laboratory and at the national level was in large part responsible for the Laboratory’s financial viability. Charlie and his work were well-known throughout the marine research community, and his colleagues at Bigelow Laboratory benefited from the knowledge he gained through his participation at the national level. In 1985, Charlie was appointed to chair the Office of Naval Research (ONR) committee that advised not only the US Navy but also NASA on the use of the space program in ocean science.

In addition to Charlie's accomplishments, the senior research scientists contributed hugely to the success of the Laboratory in the early years. They continually wrote successful research proposals at a sufficient rate to fund their salaries and research programs. Writing successful proposals is very demanding and challenging work. During the 1980s, the average grant covered only about 3–4 months of a senior scientist's salary; a senior scientist would need 3–4 active grants to cover salary in a given year. Additionally, to remain relevant in their field, senior scientists must publish their research results and present them at national meetings. Publishing results advances human understanding and informs future research proposals. Bigelow Laboratory has also always had an extremely skilled and talented cadre of associate and assistant scientists and technicians.

Other important players and programs helped the Laboratory navigate the financial challenges of the early years. The State of Maine played a pivotal role in Bigelow Laboratory's founding by providing laboratory research facilities and an annual $200,000 state appropriation, which further helped support research and build a solid establishment. This appropriation enabled Charlie and Clarice Yentsch to recruit well-known researchers in ocean sciences. This early funding was critical.

When Governor Kenneth Curtis' term ended in January 1975, he was succeeded by Governor James B. Longley who appointed a new Commissioner of Marine Resources. Soon there was pressure on Bigelow Laboratory to find a home of its own. This pressure led trustees Patrick and Helen Jackson to donate 27 acres of waterfront land on Southport Island, Maine to build a new laboratory. In 1979, Governor Joseph E. Brennan succeeded Governor Longley, resulting in the re-appointment of Spencer Apollonio as Commissioner of Marine Resources. His return took the pressure off the need for Bigelow Laboratory to move. The Laboratory had gone as far as selecting an architect to design laboratory facilities for the land on Southport. Building was tempting, particularly to the board of trustees. However, Charlie's focus was on the quality of research, and he fully realized how crucial it was to concentrate his and the Laboratory's efforts on quality science and research to ensure that its scientific reputation continued to evolve. Bigelow Laboratory continued to operate in the McKown Point facilities for 38 years (1974-2012).

Throughout those years they made improvements to the leased laboratories. Both the facilities and lease expenses were modest. The modest costs allowed a lower indirect cost rate, and a larger fraction of each grant could be allocated to the direct costs of research. Given the soft-money structure of the Laboratory's revenue, low-cost facilities were a benefit.

The amount of state money diminished and eventually ended after 18 years, while the size of the research staff was increasing. It was clear that the Laboratory needed to cultivate other sources of revenue to ease the challenges inherent in the soft-money funding structure.

Apart from the appropriation from the State of Maine, there was very little money outside of grants and contracts available to fund gaps in senior research scientists' salaries. When Charlie was able to allocate some of this money to an individual scientist, he did it based upon a plan of preliminary research, which an individual investigator would prepare for Charlie and others at the Laboratory to review. If approved, the preliminary research would be undertaken, and the findings could then be incorporated into a new research proposal to a federal agency. The limited institutional money available for discretionary spending was thus utilized to advance science by positioning a researcher to be successful. The concept of tenure, common in a university, simply was not in the vocabulary at Bigelow Laboratory.

Bigelow Laboratory established two shared-use science facilities—a major step that helped stabilize funding. These were the Center for the Culture of Marine Phytoplankton (CCMP) directed by Robert R.L. Guillard and the J. J. MacIsaac Flow Cytometry/Cell Sorting Facility directed by Clarice Yentsch. Funding for such facilities, unlike individual investigator grants, tended to be more stable due to longer funding periods and higher probability for ongoing renewal.

The CCMP was a positive development for Bigelow Laboratory. It brought multiyear funding from NSF and created a national advisory committee that set forth recommendations to NSF regarding the collection. The committee recommendations included performance guidelines as well as facilities requirements for the collection, which were supported by NSF as well as Bigelow Laboratory. Facility needs offered tangible philanthropic fundraising goals, which energized Bigelow Laboratory's trustees and administration. The Laboratory undertook renovations to the Dock House—an abandoned coal-storage shed— where the culture collections were established, and a standby generator was purchased to sustain the proper culture temperatures during power interruptions. These important facility requirements accelerated Bigelow Laboratory's efforts to integrate private philanthropy into the annual revenue of the Laboratory. From the beginning, it was realized that the CCMP contained organisms that could be mass cultured and potentially be used for commercial purposes. The vision that Bigelow Laboratory might someday derive revenue from products or spin-off companies to help support its research mission was part of the Laboratory's long-range thinking.

In the fall of 1978, NSF convened committees of scientific and business leaders in seven states to introduce a program that became known as the Experimental Program to Stimulate Competitive Research (EPSCoR). The seven states were chosen because they had the smallest amount of federally funded research per capita. EPSCoR was intended to help these states expand their amount of competitive research. Charlie Yentsch was invited by NSF to serve on this program. The Maine EPSCoR Committee, chaired by Harris J. "Pete" Bixler, then president of Marine Colloids Inc. and later a Bigelow Laboratory trustee, responded to the opportunity and wrote an EPSCoR planning grant that was funded by NSF. I was drafted by Charlie and Pete to become a member of the Maine EPSCoR Committee. At the conclusion of the planning grant, the State of Maine submitted a successful EPSCoR proposal to NSF. The Maine proposal contained work at the University of Maine and Bigelow Laboratory.

The EPSCoR funding at Bigelow Laboratory provided funds for marine research and, again, the opportunity for the Laboratory to recruit internationally competitive research scientists. It could offer them competitive salaries for a few years to establish their own research programs at Bigelow Laboratory. The goal of the EPSCoR program, stimulating competitive research, was in synchrony with the Laboratory's goal to recruit bright new investigators.

Charlie and Clarice created a laboratory experience and culture that brought out the best in people. The financial and administrative challenges of operating as a soft-money laboratory were constantly on the agenda during the Laboratory's formative years. Solving challenging problems with colleagues who conducted themselves from positions of deep mutual respect, certainly made the work of advancing the Laboratory's mission through the developmental years both rewarding and pleasant.

Peter Larsen wrote:

Over the past 40 years, I have been lucky to have been involved in many collaborative research efforts. These collaborations were made easy and seamless because of the flat, non-hierarchical organization of Bigelow Laboratory. We were able to work with one another without the intercessions of department heads or group leaders. We worked as one big egalitarian group. This is attributable to the vision of Charlie Yentsch and his founding philosophy.

The Annual Report for 1981 supplements Robert Kidd's review of the financial realities of the early years 1981–1982, which contains a revealing statement by Earl L. Green, Chairman of the Board of Trustees, concerning the financial position of the Laboratory:

The Laboratory needs funds for all manner of objectives that cannot be paid for out of research grants and contracts, including the costs of manpower for raising funds. The Laboratory was started eight years ago with no stable financial resources of its own. It has now managed to lay aside an unexpended current fund reserve of $95,197. That, right now, represents the only measure of financial stability and thus of financial flexibility the Laboratory has. By itself, it cannot generate the income needed for non-grant purposes, such as a Public Information Coordinator or a Fundraising Coordinator.

> During the last year, the trustees took four significant steps toward trying to solve the fund-shortage problem. One was to launch a general public appeal, which we hope will be the first of a sequence of Annual Appeals. Our target was to raise $50,000. We raised $41,032. Of that, $19,810 was contributed by 25 of 28 Trustees specifically for the expenses of quarters for the Marine Phytoplankton Collection. For the next year, our target is $60,000. The second step was to broaden our approaches to large private foundations. The third step was to create a Building Fund with a target of $10,000 for the next year. This is not the fund by which we expect to build a $10,000,000 research facility. This is the fund by which we hope to be able to meet the needs for small remodeling jobs before the people concerned die of old age.

In subsequent years, trustees and members of the public contributed generously to a capital construction fund and a growing endowment for non-research-supported operating expenses.

Establishing Innovative And Unique Facilities

In the early 1980s, Bigelow Laboratory assumed the responsibility for technology transfer to the ocean science community with the establishment of two shared-use facilities: the Center for the Culture of Marine Phytoplankton, now the National Center for Marine Algae and Microbiota, and the J. J. MacIsaac Flow Cytometry/Cell Sorting Facility, now the Facility for Aquatic Cytometry. A third center, the Remote Sensing and Image Analysis Facility, was established with funding from NASA, NSF, and ONR to provide the computer resources needed to display and analyze satellite images and house an extensive archive of Coastal Zone Color Scanning (CZCS) imagery entrusted to Charlie Yentsch by NASA and NOAA.

The Culture Collection

In November 1981, a grant from NSF made the establishment of the Culture Collection of Marine Phytoplankton (CCMP) at Bigelow Laboratory possible. The scientist in charge was Robert R. L. “Bob” Guillard, who had managed the collection previously at WHOI.

Facilities at Bigelow Laboratory were adequate to handle this collection, but a major fund-raising effort was soon initiated to create more space as the collection began to expand. Major holdings from the University of Washington, Scripps Institution of Oceanography, Texas A&M University, Yale University, and other sources soon became part of CCMP.

Rhonda Selvin was the assistant curator and later curator of the collection; she helped transfer the collection to Bigelow Laboratory. The WHOI cultures required careful handling as they were transferred to Bigelow Laboratory.

Rhonda Selvin wrote:

> I worked with Bob Guillard as his Research Associate and Assistant Curator, setting up the collection in Maine while he orchestrated from Woods Hole—[This was] from 1980 until he made the move in 1982. In 1984, I became Curator, with strong support from Bob, Charlie, and the unanimous vote of the Advisory Committee that I helped Bob put in place. I served in this role until early 1992. I assisted Bob in the initiation, planning, and execution of the courses that have become a world standard, and I also trucked with delight between Yale and Bigelow Laboratory to incorporate the culture gifts of Luigi (Provasoli) and Irma (Pintner). We cataloged and trialed many of the seawater media still in use today.

The NSF set a condition for the transfer of the collection to Bigelow Laboratory: it must be intimately connected to an active research program by the curator and the staff. A major focus of the Bigelow Laboratory research was the comparative trace-metal physiology of phytoplankton. Bob Guillard studied trace-metal requirements of plankton algae as part of his continuing studies of culture techniques for maintaining phytoplankton collections. Bob considered this one of his lifelong interests. He said this about his interest, "the one extremely important difference between the open oceanic environment and the coastal environment is the trace-metal availabilities. In the oceanic domain, [trace metals] occur at such low concentrations that even a few years ago people could not measure them. If attempted, polluted samples were collected."[12]

The collection would also be a source of marine microbiota for research at other institutions and in a variety of scientific disciplines. In its first six months, CCMP shipped 350 cultures for food

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12 From the Lab Log, Newsletter of Bigelow Laboratory for Ocean Sciences, Summer 1989.

for larval shellfish to aquaculture shellfish hatcheries as far away as Tasmania. Within two years, 103 genera were maintained, and 850 shipments were made nationally and internationally to university researchers, for example, in Chile, Australia, and Norway.

The culture collection was renamed the Provasoli–Guillard Center for the Culture of Marine Phytoplankton in 1986, and Luigi Provasoli and Bob Guillard were honored by Bigelow Laboratory for their pioneering work in the culture of marine microplankton.

Luigi Provasoli, born in Italy, began his career studying insects important in agriculture but soon found his lifelong interest in the nutrition of algae and protozoa and their growth in culture. After World War II, he moved to New York where for the next twenty-five years—with collaborators Seymour Hutner, Irma Pintner, and Caryl Haskins—he made many important discoveries on the nutrition, physiology, and cultivation of algae, protozoa, and invertebrates. Bob Guillard had met and worked with Provasoli at the Marine Biological Laboratory at Woods Hole, Massachusetts. The development of seawater culture media and completely artificial growth media were an important part of that work. Luigi Provasoli died in 1992.

In 1987, 836 cultures were shipped from the CCMP. Short courses in phytoplankton culture were introduced, attracting students from all over the world. In 1987 and 1988, students from the United States, Canada, Mexico, Spain, and Morocco attended these courses.

Renovation of the Dock House, began in 1988 and completed in 1989, tripled the size of the CCMP facilities and ensured that the culture strains were housed in the utmost reliable conditions.

Bob Guillard became emeritus director of the culture collection in 1989 with unlimited access to the facility for pursuing his own research. When Bob Guillard resigned as director of the CCMP, his colleagues and students organized what they called "BobFest." Scientific papers associated with that event, and dedicated to Bob, were published in two issues of *Biological Oceanography.* Bob received two major awards in the field of aquaculture. He was made an Honorary Life Member of the National Shellfisheries Association in 1995 and an Honorary Life Member in the

World Aquaculture Society in 1998. In 2001, he received the Award of Excellence presented by the Phycological Society of America. Bob Guillard isolated numerous algal strains, one of which (*Thalassiosira pseudonana*) was the first eukaryotic alga to have its genome sequenced. In recognition of his many contributions, Bob was honored by colleagues who have named a genus and three species in his honor.

In July 1989, Bob Andersen joined Bigelow Laboratory as the new director of the CCMP. One of Andersen's first challenges was to computerize information about the strains in the collection. Once the information was computerized, the CCMP began publishing a catalog of strains to inform the scientific community about what strains were available. The first catalog was published in 1991, but after the 1997 catalog, everyone had a computer and could view the strains online. The website was continually updated, whereas the catalogs were only updated with each new edition.

Bob Andersen also helped increase the collection size by actively seeking new strains from the scientific community and by isolating strains himself. He wrote:

> When I arrived, the staff were discarding or culling strains. It was argued that the staff was too small to maintain that number of strains. I obtained additional funding to increase the staff, and by various efficiency steps, made better use of the staff time.

Although the oceanographic community knew about the culture collection, Andersen's arrival brought access to different scientific communities (phycology, cell/molecular biology, biotechnology). These communities were increasingly using cultures whereas oceanography was becoming more process- and modeling-oriented.

In the early 1990s, the center began extracting and storing DNA (deoxyribonucleic acid) from the phytoplankton that researchers who do not have capabilities to culture organisms for their own studies could order. (Genetic materials are more stable than phytoplankton cells and therefore are easier to ship.) The center also began using cryopreservation to maintain the algal strains.

Bob Andersen wrote:

> The most sensible means for maintaining microorganisms is by cryopreservation. We received funds to implement this program, and by the time I left in 2009, over half of the strains were cryopreserved. Not all strains cryopreserve reliably, but for those that do, this removes all the work of culture media preparation, perpetual culture transfers, and so forth—a huge saving of time and staff work.

Andersen examined oceanic ultraplankton collected from the Atlantic and Pacific Oceans and examined many structural species-diagnostic features of the plankton. He found and described for the first time new species of open-ocean phytoplankton. The techniques he used enabled the investigators at the Laboratory to examine and reconstruct the *internal* ultrastructure of cells. The new species are equivalent to mammals or flowering plants in taxonomic ranking; that is, they represent a high taxonomic ranking. Examinations by independent technologies confirm that these species are new and different from all other groups of life.

In 1991, with an NSF grant, the Laboratory acquired a transmission electron microscope (TEM) with capabilities far beyond standard electron microscopes. For example, TEM can give exact locations of elements such as phosphorus and iron *within* cells.

In 1992, by Act of Congress, the center was designated the nation's official repository for phytoplankton. The CCMP benefited from extensive modernization in 1994 and served thousands of researchers annually. By the new century, the center had an international advisory panel, providing research materials for bioenergy, pharmaceuticals, aquaculture, toxic blooms, and food sources.

The Flow Cytometry Cell Sorting Facility

Medical sciences had developed flow cytometry for studying individual cells and particles based upon fluorescence—the light emitted by cells upon certain stimulations— and light scattered by the cells. In 1981, Clarice Yentsch adapted the technique of flow cytometry and introduced it to oceanography for the study of individual plankton organisms.

A flow cytometer is used to force cells into a narrow stream of drops, each drop containing one cell. The stream passes through a laser beam where the light from the laser is either scattered or absorbed by the cell. Scattered light reveals information about the size of each cell, while the fluorescence stimulated by the absorbed light reveals information about cell contents. The cytometer measures and simultaneously records the light scattered or fluoresced by each cell at the rate of 2,000 cells per second. This information is analyzed for cell physiology, enzyme activity, DNA, and viability. The stimulated fluorescence is characteristic of different pigments and thus for different algal groups. Further, the fluorescence varies characteristically depending on the physiological state of cells.

A grant from NSF in 1982 provided the funding needed to purchase a flow cytometer and create the flow cytometry facility. The facility was subsequently named in honor of Jane J. MacIsaac, a senior research scientist at Bigelow Laboratory who succumbed to cancer in 1982. It had several purposes: 1) to develop protocols for the application of flow and imaging cytometry to aquatic sciences; 2) to enhance information transfer through workshops and research papers; and 3) to provide access to state-of-the-art instrumentation to all members of the oceanographic research community.

The advent of flow cytometry and cell sorting opened up vistas to previously intractable questions regarding light partitioning, carbon partitioning, cell size, species-specific interaction, detritus, selective grazing, interspecies interaction in natural populations, and much more. A prediction that this would be the only instrument in the ocean sciences for the next decade was not accurate. Rob Olson at WHOI made a cytometry instrument to take to sea which enabled MIT's Penny Chisholm to discover the small ancient *little greens Prochlorococcus* responsible for oxygenation of Earth's atmosphere, judged one of the most important discoveries of the century. By cell sorting she was able to discern that what had been interpreted as noise at the small-size end of the histogram was, in fact, exceedingly numerous (billions upon billions) *Prochlorococcus*.

Many who were guest researchers at the J. J. MacIsaac Flow Cytometry/Sorting Facility at Bigelow Laboratory went back to their home institutions enthusiastic about their results and wrote proposals to acquire this technology. Today, it is standard instrumentation in marine laboratories and on shipboard. Lessons learned in the early years with Bigelow Laboratory's flow cytometer were presented at ocean science conferences and at an international conference in the specialized field of cytometry. Clarice Yentsch and Paul K. Horan, who had developed the technology for medical sciences, edited a special issue of *Cytometry*, which contained 22 papers devoted entirely to "Cytometry in Aquatic Sciences."

Rick Spinrad came to Bigelow Laboratory in the fall of 1982. His research focused on optical characteristics of phytoplankton to account for variations of color reflection and attenuation depending upon species, size, shape, physiological state, and other characteristics. The Laboratory used flow cytometry to investigate the optical properties of *individual* phytoplankton cells— their absorption, reflectance, and fluorescence at specific wavelengths. Such information would advance the uses of flow cytometry and satellite imagery in estimating marine production.

Rick Spinrad wrote:

> The study of underwater optics has direct relevance to a wide range of applications. Understanding the behavior of light in the surface ocean contributes to a better understanding of photosynthesis in marine phytoplankton. Similarly, anything that changes the light field in the marine environment could impact capabilities for photographing or detecting objects in the ocean, so the navy had interest in optics for its applications to non-acoustic anti-submarine warfare.
>
> As one of just a small number of American scientists working in the field of ocean optics in the late 1970s and early 1980s, I was quite familiar with Charlie Yentsch's legacy work in ocean color remote sensing. I was also becoming familiar with Clarice Yentsch's truly revolutionary thinking about the use of flow cytometry in ocean sciences.
>
> The potential for the application of flow cytometry was intriguing. In the study of optics, one knows that three factors contribute to the way in which a particle (i.e., a phytoplankton cell) either scatters or absorbs light: particle size, particle shape, and particle's index of refraction. Now imagine that you are trying to study how a specific phytoplankter, at various growth

stages, might absorb or scatter light. Traditionally, the only way to do this was with bulk optics; one studied the properties of a volume of water containing lots of cells, then divided the net impact by the concentration of cells to determine the individual cell's properties. This technique was inelegant at best, and not particularly insightful. We could count and size individual particles, but there was no way that we could observe the optical properties of each particle. That is basically where we were with ocean optics in the early 1980s until flow cytometry came along. Clarice had solved that problem by bringing the Coulter EPICS flow cytometer to McKown Point. Now we could measure at least the size and refractive index of individual phytoplankton cells.

The experience of working with Charlie and Clarice was unparalleled anywhere in the ocean sciences. Bigelow Laboratory went on to grow as a bastion of ocean optics research, and today is still considered ground zero in the development of critical knowledge about the behavior of light in the sea.

Remote Sensing And Image Analysis Facility

The possibility of synoptic broad-scale measurements of potential ocean productivity became a reality with the launch of the Coastal Zone Color Scanner (CZCS) in October 1978.

Clarice Yentsch wrote:

Charlie convinced NASA that the space program could have an *eye in the sky* for ocean productivity. Eventually, NASA agreed to place an instrument on the NIMBUS G (later NIMBUS 7) satellite as a proof-of-concept mission. Charlie was a member of the NIMBUS Experiment Team (NET), an advisory group whose purpose was to advise NASA on the interpretation of the ocean color measurements made from space.

The CZCS was multispectral with five bands in the visible and near infrared range (443, 520, 560, 670, and 750 nm) and one thermal infrared channel. The sensor had a design lifetime of one year, and all budgeting and funding were based on the one-year time frame. However, although designed as a proof-of-concept experiment with a life expectancy of one year, the CZCS data continued to stream for eight years, or until 1986.

As a member of the Nimbus Experiment Team, Charlie received a subscription of digital CZCS data that arrived on large-diameter computer-compatible tapes. By 1982, Bigelow Laboratory had several hundred tapes containing the raw satellite data. Over the next several years, grants from NSF, NASA, ONR, and the National Oceanic and Atmospheric Administration (NOAA) enabled Bigelow Laboratory to acquire the computer resources needed to read data off the tapes and perform analyses to calculate pigment concentrations and sea surface temperature. With these resources in place, the Remote Sensing and Image Analysis Facility was officially established in 1986.

Janet Campbell came to Bigelow Laboratory in the fall of 1982 with the goal of establishing the remote sensing facility and pursuing its research objectives. Janet described the process by which the Laboratory acquired the hardware and the capability to analyze a myriad of images.

Janet Campbell wrote:

> When I arrived, Bigelow Laboratory did not have a computer system capable of reading the data on the tapes at the Data Center. Notwithstanding this limitation, the data tapes were shared with colleagues in New England. Notably, the United States used these data in its dispute with Canada over the offshore boundary between the two countries. CZCS data showing Georges Bank as a distinctive habitat **[image from JC]** was used to argue that it should be managed by one jurisdiction, namely the United States. Canada argued for an equidistant boundary that crossed Georges Bank. Ultimately, Canada's argument prevailed in a decision by the world court (International Court of Justice) in The Hague, Netherlands.
> The technology associated with producing satellite images preceded the computer technology needed to display and analyze the images. At the time the CZCS was launched in 1978, this task could only be done arduously with large mainframe computers. A group of oceanographers at the University of Miami's Rosenstiel School of Marine and Atmospheric Science, with support from NASA, developed a special set of software, called Digital Signal Processor (DSP), that was designed to ingest and display CZCS data and allowed the user to analyze the data quantitatively. With this system, we were finally able to utilize data stored in the digital tapes at the Laboratory's Data Center.

Bigelow Laboratory's Tenth Anniversary

After ten years of operation, Clarice Yentsch wrote:

> Bigelow Laboratory is a small laboratory on a human scale. The first ten years represents a cherished combination of freedom and order in both time and environment. The sense of commitment to excellence is driven by a collective and cooperative intelligence . . . Imagination, speculation, documentation, and synthesis of interpretation are all important aspects of this adventure that has been shared by employees and volunteers.

In the first ten years, the Laboratory received funds from more than 33 sources, some of which supported Laboratory investigations on several occasions. They included state, regional, and federal agencies; private corporations; universities; nonprofit institutions; research institutions; and private philanthropic donations.

The Laboratory enjoyed continued growth and financial stability in the early years, with each year having a margin of revenue in excess of its expenses.

The primary sources of funds over the years—soft-money research grants—were subject to unpredictable federal budgetary decisions made far removed from consideration of the sustainability of long-term basic research. The work of Bigelow Laboratory was among the most difficult to understand or explain as a fundamental need while modern society remained focused on short-term budget priorities. Charlie wrote, "The case for basic research is difficult to articulate, primarily because it involves conceptual thought about problems and ideas not familiar to the general public."

Bigelow Laboratory research focuses on organisms that are microscopic and sub-microscopic, far beyond the experience or imagination of most people and far from land in the middle of the ocean and in the abyssal depths of the sea. Unlike many sciences such as archaeology, astrophysics, geology, or nuclear energy, it is much more complex in time with ever-changing interactions. It is neither Newtonian with relatively simple basic principles nor of unchanging dynamics. The rate of change deep within the systems of study may be a breathtaking multiple times per *hour.* The identification and understanding of those characteristics, fundamental to the operation of global systems, has occurred only from the *free play of free intellects* and development of more sophisticated and expensive technologies. Justification for the funds that make possible their study is a never-ending necessity.

Figure 2. Bigelow Laboratory's financial status by the end of its 1986 fiscal year. (from Bigelow Laboratory's 1984–1986 Biennial Report "Focus").

Bigelow Laboratory Associates Program

In 1986, Bigelow Laboratory launched a membership program called Bigelow Laboratory Associates. As Administrative Director, Robert Kidd took on the task of creating the first appeal for membership. Robert worked with Charlie Parker, a scientist who had joined Bigelow Laboratory from WHOI, to write the first three-panel fundraising brochure.

Robert Kidd wrote:

> We struggled with the copy and creating a mailing list. It was a humbling experience. Proceeds raised during the early years of the annual fund were modest. When I see Chris Flower as a regular participant at the summer lectures, I appreciate the foresight and the work of the Bigelow Laboratory Trustees and staff that helped to advocate and sustain this program.

In 1988, Christopher Flower, trustee, led the expansion of the Bigelow Laboratory Associates program. By 1989, there were more than 300 active members. The Associates Program sought to promote public understanding of the Laboratory's work while providing a means of building a private endowment for the Laboratory over the long term. Scientific lectures during the summer became the hallmark of this effort, introducing the work of the Laboratory to residents and summer visitors in the Boothbay region. The lectures have been ongoing through all the years since 1989.

Chris Flower wrote:

> Initial trustee leadership was provided by William S. Danforth. Communications Director Jennifer Logan provided initial staff support with assistance from a small group of volunteers.
>
> The purpose of the program was threefold:
>
> - to promote the understanding among the public of oceanography in general, and more specifically, of the Laboratory's work in the Gulf of Maine and the global ocean
> - to provide an opportunity for people who share an interest in the ocean to socialize in the coastal and marine settings available at the Laboratory

- to provide a means of building private support for the Laboratory over the long term

During the first year of the program, emphasis was given to building a core group of supporters and developing a schedule of casual educational events. The summer lecture series became the cornerstone of the Associates Program, with presentations by Bigelow Laboratory scientists and other speakers of interest. Boat trips, open houses, and science days rounded out the annual events. Over 100 enthusiasts joined the first year. Membership grew in the 1990s under the guidance of Fran Scannell, Bigelow Laboratory's Development Director.

The Bigelow Laboratory Associates served as a vital tool for attracting supporters to the Laboratory as well as informing the community of Bigelow Laboratory's global contribution to ocean science.

Education Programs

In 1990, the Laboratory began to increase its role in education for primary and secondary students and teachers. Two programs were created that year, the Gaia Crossroads Program and the Bigelow Laboratory Orders of Magnitude (BLOOM) program.

Gaia Crossroads (1990–1996)

Gaia Crossroads was a K–12 education project that explored the use of satellite imagery as a resource for teaching. The project was initiated in 1990 with advice and assistance of Dr. Richard Podolsky of the Island Institute of Rockland, Maine and an education grant for computers from Apple Inc. Satellite images and software donated by the Island Institute were loaded into the computers, and participating Maine teachers were trained to use these resources in their classrooms for teaching a wide range of subjects.

Janet Campbell created the Gaia project in collaboration with teachers in Boothbay Harbor and Wiscasset, Maine.

Janet Campbell wrote:

Apple had just announced a new education grants program called Crossroads and was calling for concept papers to be submitted in early January 1990.

Arden (Georgi) Thompson, a teacher of K–8 gifted and talented students in Wiscasset, believed that the project should not be limited to high school students. Thus, I invited K–12 teachers and administrators from Boothbay and Wiscasset to a meeting where Richard Podolsky demonstrated the software. A small group of teachers worked with me to submit the concept paper to Apple. Ours was one of more than 1,300 concept papers submitted, and eventually, we received 1 of the 20 Crossroads grants awarded that year.

Bigelow Laboratory's Crossroads grant involved the donation of 20 computer workstations, which at the time were far beyond what schools could afford. The project was named "Gaia Crossroads." It was informed by the Gaia hypothesis, a view of Earth as a single living organism, symbolized by Gaia, the Greek goddess of Earth. [13] According to this hypothesis, the atmosphere, ocean, soils, rocks, and all living organisms work together as a balanced system. This concept had given rise to a new science known as Earth Systems Science that integrates the traditional scientific disciplines into a meaningful, holistic worldview.

The Maine Aspirations Foundation and Maine Space Grant Consortium provided some support for me, as project director, and allowed me to hire Cyndy Erickson as project coordinator.

The goal of the program was to stimulate the interest of elementary school students and sustain their interest through high school. Weeklong workshops were conducted each summer beginning in 1990 to introduce the teachers to the topic of remote sensing and train them to create thematic maps of their town and the surrounding area using the computer systems. Thematic maps created by the students were later published in an environmental atlas of the Gulf of Maine[14].

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13 Lovelock, J.E. Gaia, A New Look at Life on Earth. Oxford University Press, 1979.

14 Conkling, P.W., ed., 1995. From Cape Cod to the Bay of Fundy: an Environmental Atlas of the Gulf of Maine. Cambridge: The MIT Press.

A second grant from Apple in 1993 enabled us to expand the program to 24 additional schools (8 districts) in Maine. The grant provided two workstations for each district while the district provided one, so the project continued to span grade levels from elementary to high school. In 1994, new school districts agreed to provide all the computers for their teachers while we continued to furnish the software, satellite images, summer workshops, training, and technical support for teachers.

By the time the program ended in the fall of 1996, there were 134 participating teachers representing 87 schools in Maine and New Hampshire. Cyndy Erickson and a team of teachers produced a guidebook containing lesson plans and activities that had proven successful. The *Guidebook to Using Satellite Imagery in the Classroom and Community* was published by Bigelow Laboratory in 1997.

The Keller BLOOM Program

The Bigelow Laboratory Orders of Magnitude (BLOOM) program was conceived by Maureen Keller, Clarice Yentsch, and trustee Jim McLoughlin in the spring of 1990. The program provided a weeklong, hands-on residency program at the Laboratory for 16 Maine high school students, one from each county, with demonstrated aptitudes in science. Each student worked with a Bigelow scientist. All costs, including accommodation and food, were covered by individuals and businesses in Maine that sponsor the program. The program included a sampling cruise on the Sheepscot or Damariscotta River estuary, followed by the compilation and analyses of collected data, discussion of results, and report preparations and presentations. The week also included discussion of science and public policy, scientific ethics, and career directions. The program hoped to stimulate careers in science among talented students.

Tom Keller wrote:

> Maureen and Clarice were insistent on at least equal distribution of females to males. This also meant that both male and female chaperones were needed for the lodging of 16 seventeen- to eighteen-year-olds.

Apart from the obvious connotation of a bloom of phytoplankton, orders of magnitude is derived from the fact that Bigelow Laboratory scientists study phytoplankton at scales ranging from the smallest cells, with diameters of one-billionth of a meter (10^{-9} meters), to the scale of the vast blooms seen in satellite images (10^{9} meters). Bigelow Laboratory's biennial report for 1985-86 "Focus" was structured around this theme with each page corresponding to a different scale.

The program was named the Keller BLOOM program upon the premature death of scientist Maureen Keller in 1999.

Leadership Transitions And The Lean Years

Charlie Yentsch remained Executive Director until 1988 when he decided to retire from that position to devote full-time to his research. After a six-month sabbatical spent in La Jolla, California, he and Clarice returned to Bigelow Laboratory and remained as active research scientists.

In 1985, Long Island University awarded Charlie an honorary PhD degree, recognizing his achievements as one of the pioneers of modern oceanography. The Association for the Sciences of Limnology and Oceanography (ASLO) presented him with a Lifetime Achievement Award in 1999.

Clarice wrote:

> As Charlie and I gained experience working in various laboratory environments, it became clear that some were empowering while others were not. Together, we were intent on doing everything that we could to promote a positive work environment to foster scientific exploration and creativity.
>
> Charlie was honored as a leader and innovator, yet he will be remembered as a *beloved maverick* by those who knew him best. Charlie's lifelong passion was learning about the seasons, cycles, and ever-changing dynamics of the ocean. He created a positive and equitable learning environment on shipboard, in the Laboratory, and at home. He held a reverence for all life and found the simplest forms most compelling. Always non-hierarchical

> in his belief of human potential, he put every person and every idea on a par to be tested. He cherished skeptically-minded colleagues."

After their sabbatical in California, Clarice continued as a senior research scientist at Bigelow Laboratory, but she began to turn her attention toward education. Clarice worked to establish the not-for-profit Maine Mathematics and Science Alliance in 1992, and to co-create and administer Maine's NSF Statewide Systemic Initiative. Clarice is the recipient of the Mary Ann Hartmann Award (1997) and the Deborah Morton Award (1998)—both for original scholarship, leadership and mentoring in Maine.

Patrick Holligan, a regular visiting scientist at the Laboratory, agreed to serve as Acting Director at Charlie's retirement as director. During this time, a search committee was formed and reviewed applicants for a permanent Executive Director. The position was offered to Holligan, an indication of the strong support and admiration for him held by members of the Bigelow Laboratory community. After considerable thought and soul searching, Patrick declined the offer and returned to Plymouth Marine Laboratory in the UK. Subsequently, the Board appointed Lewis S. (Lew) Incze, one of the senior scientists, to serve as Executive Director. Lew was Executive Director until the end of the 1994 Fiscal Year. Turbulent times were just beginning when Lew assumed the responsibility.

In 1990, the board of trustees adopted a plan of strategic goals, objectives, and course of action for the next ten years. It outlined scientific programs, educational initiatives, facilities plan, and financial plan. Over the next two years, the Laboratory experienced a major upheaval when Maine's Department of Marine Resources undertook the construction of a new facility for itself on McKown Point. This plan required the destruction of several buildings, including laboratories and offices that had been occupied by Bigelow Laboratory since its founding. The relocation caused considerable interruption of scientific work—a very stressful situation for an institution that was running full speed all the time. Through careful planning and negotiations, some parts of the facility were improved, but for many, it was a lot of work with little or no gain. This was followed by an unexpected withdrawal of the modest state subsidy that had assisted the Laboratory for the previous 18 years. That subsidy was crucial to pay for some of the operational costs that grants do not cover, and it immediately created an ongoing budget deficit that the Laboratory's modest private fundraising could not cover.

One way to save the Laboratory from financial collapse was to affiliate with the University of Maine. Properly structured, an affiliation could bring the expertise and research focus of Bigelow Laboratory to the university while expanding opportunities for Bigelow scientists to become involved in formal college degree programs. This had the potential for a positive situation at a time when public institutions and small nonprofit research institutions were facing many challenges nationally. The proposal to affiliate with the university was developed over a 12-month period of intense discussions and negotiations. The final package was presented to the Laboratory staff in the spring of 1993.

Lew Incze (Director 1991–1994) wrote**:**

> The final negotiated plan with the University of Maine was not as favorable to us as we had hoped, particularly in a few key areas, and the staff were deeply divided on whether or not to accept it—about 50:50. Charlie's emotional appeal to maintain the independence of the Laboratory tipped the scales. He didn't disagree with my analysis a few days before despite great sadness at the idea (he and I had met privately about it), but ultimately, he could not go along with it. He was correct that the university simply would not welcome Bigelow Laboratory in the way we needed to make the merger acceptable.

In July 1994, Lew Incze resigned his position as director to return to science, and the board of trustees appointed Chris Garside, Mike Sieracki, and Maureen Keller, three senior scientists, to lead the Laboratory.

Lew Incze wrote:

> I had been director from 1991 until the end of the fiscal year, June 30, 1994. In my last year, I had a balanced budget, just barely, but it was in the black—an important and satisfying victory for everyone. The Troika—what the scientists called the three leading scientists—came after me. Each had a defined area of primary responsibility, and they reported as a group to Chairman of the Board Len Cronkhite. That is, there was no director during this time (1995–1996). They worked until the time Sandy Sage took over.

The Troika—Chris Garside, Maureen Keller, and Michael Sieracki—helped sustain the recovery of the Laboratory as it emerged from the difficult years when expenses exceeded revenue. It is a testament to Lew Incze's and the Troika's leadership abilities, as well as the collegial, self-governing ability of the senior scientists as a whole, that the Laboratory was able to navigate this turbulent period of instability and uncertainty.

The Annual Report for 1994 noted that the Laboratory, now celebrating its 20th anniversary, had made considerable progress in its first 20 years.

The report stated:

> Bigelow Laboratory will continue to be an independent, creative scientific community where oceanographers and marine scientists pursue excellence in research on critical global and regional issues concerning natural resources and the environment. Bigelow will integrate into this high-quality research an innovative scientific education program to benefit its own scientists, students, and the public and industry.

In 1998, total revenues of the Laboratory were over $3 million, of which 80 percent was from NSF, NASA, ONR, and NOAA.

Regional Engagements 1994–1999

The Association for Research on the Gulf of Maine (ARGO-Maine) was established in 1985 between Bigelow Laboratory, University of Maine, Maine Department of Marine Resources, Maine Geological Survey, and Maine Maritime Academy. Its purpose was to facilitate and coordinate research in the Gulf of Maine. Associate members later were Bowdoin College, Gulf of Maine Aquarium, Maine State Planning Office, and Mount Desert Island Biological Laboratory. An 80-foot research vessel, renamed the R/V *ARGO Maine*, was transferred from NSF to the Maine association and operated by Maine Maritime Academy. It supported a number of research cruises in the Gulf of Maine and on Georges Bank over the years.

Alliance With The University Of New England

As part of its vision for education outreach, in 1994 Bigelow Laboratory formed an alliance with the University of New England (UNE) in Biddeford, Maine. The alliance blossomed into a partnership that strengthened both institutions. It broadened the UNE marine science curriculum and led to several collaborative research efforts funded in national competition. UNE professors and Bigelow researchers submitted successful research proposals to NASA and EPSCoR that provided opportunities for UNE students to accompany Bigelow Laboratory scientists on research cruises in the Arabian Sea and the Gulf of Maine. The staffs of the two institutions developed a Master of Science program in marine sciences, and the number of students enrolled in UNE's marine science program tripled over the time of the alliance.

Phytopia

Annette de Charon and Michael Lizotte developed the award-winning *Phytopia* CD-ROM program in cooperation with UNE and NASA's Jet Propulsion Laboratory. This program allowed students to interactively study phytoplankton from the Bigelow culture collection. Students were able to run virtual experiments on phytoplankton photosynthesis and respiration; they could vary environmental conditions to discover how these factors affect phytoplankton assemblages. The program offered realistic, simulated laboratory experience to students who do not have oceanographic research facilities of their own.

Gulf Of Maine Ocean Observing System

In the late 1990s, Bigelow Laboratory partnered with the University of Maine and other organizations in the region to establish the Gulf of Maine Ocean Observing System (GoMOOS)**.** The purpose of GoMOOS was to collect and make available real-time physical, biological, and chemical data from the Gulf of Maine. GoMOOS operated an array of 10 buoys that recorded and transmitted data hourly on 20 parameters, including weather and sea state, sea surface temperature, and chlorophyll. Collin Roesler was the principal investigator responsible for the chlorophyll data (measured from fluorometers). In addition, to complement the buoy data, satellite data from SeaWiFS and NOAA's weather satellites were acquired on a daily basis. Both buoy and satellite data was made readily accessible via a website operated by GoMOOS. Thirty-three organizations from Nova Scotia to Rhode Island were supporting members of the network.

GoMOOS became the pilot project for other regional coastal ocean observing systems operating across the US and in other countries.

CHRONOLOGY OF RESEARCH

From its beginning, Bigelow Laboratory's primary focus had been on those organisms that are the foundation of all life in the sea and upon those fundamental forces and processes that support or control those organisms. Over the years, the Laboratory has studied other issues in the sea, the technologies of investigation have evolved, and new and innovative capabilities have been pioneered and developed to a level of sophistication unimagined in 1974. However, the primary focus endures because it is concerned with fundamental life processes in the sea and with global biogeochemical processes.

This summary of research at Bigelow Laboratory will show the revelation and an evolving story of increasingly intricate and interwoven patterns of interactions among phytoplankton and much smaller microorganisms—ultraplankton—not understood or even recognized at the beginning of this story. It will show the emerging understanding of the relations among phytoplankton, bacteria, viruses, dissolved organic matter, and zooplankton, and how the physiology and metabolism and productivity of each group are consequences of and bear upon the dynamics of all the other components. We see here the emerging understanding of the intricacies and interactions of close couplings of a highly evolved, robust and resilient, and adaptable *system*. It is an astonishingly dynamic system. It is upon the proper functioning of these previously unknown or little understood or even mysterious processes that all the other living components of the sea—shellfish, finfish, marine mammals, seabirds—rest and depend. We see an increasing understanding and concern of how this system of microorganisms within the sea influences processes within the atmosphere and their effects upon the climate of the whole planet.

Some explanation of the organization or order of presentation of this research may be helpful. The chronology of Laboratory progress had to be reconciled with a coherent presentation of the themes, that is, the research topics such as ultraviolet radiation or toxic algae or technological developments. A theme is introduced into the narrative in the year in which it began in the Laboratory, and its story is continued as an entity without interruption until its progress is completed or brought up to date. In some cases, of course, the progress of themes is ongoing. When its story is complete, the narrative, as identified by dates in the text, reverts to the year in which the theme began and continues from that point, treating each new theme whenever it is introduced in the same fashion.

Research Themes In The First Ten Years (1974–1984)

Two general categories of themes encompassed Bigelow Laboratory research in the early years. The first category was basic process-oriented research aimed at understanding the composition, ecology, physiology, and dynamics of phytoplankton and primary production. The Gulf of Maine served as a model for studying processes in temperate seas characterized by seasonal phytoplankton blooms, while processes in other biogeographic provinces (upwelling zones, polar seas) were studied on expeditions (cruises) to those regions.

The second category included marine biology and oceanography close to shore. The focus was on toxic algal blooms and the responses of intertidal shellfish, oil spills, and nutrient limitations of intertidal seaweeds. It also included estuarine processes—hydrographic, chemical, and biological—and inventories and characterizations of intertidal and benthic communities along the coast of Maine. The aim was to understand the physical and biochemical processes operating in the estuaries and nearshore environment of the Gulf of Maine and the communities of living organisms inhabiting those places. While this research was basic, it had practical aspects that complemented monitoring programs of Maine's DMR.

Years 1974–1977

In the first year, 1974–1975, the work of the Laboratory included the dynamics of chlorophyll and phytoplankton concentrations, species composition of phytoplankton, photosynthetic rates, pattern of carbon dioxide assimilation by photosynthesis in the Gulf of Maine, and physical control of those dynamics by the *critical mixing-depth* of the Gulf. Work had begun on the comparative biochemistry of differently sized algae. This work was a natural connection to studies, including laboratory cultures, of toxic algae in cooperation with the red tide—toxic algae— monitoring of the Department of Marine Resources.

Toxic Algae

The locations and sizes of toxic algae blooms in Maine coastal waters were mapped by images from aircraft. Patches were 5–10 miles long and 1–2 miles wide. In the laboratory, tests of water from the patches of toxic algae suggested it is inhibitory to other algal species. It had previously been thought that shellfish were not affected by ingested toxic algae. However, it was found that toxins and pollutants derange metabolic rates; that is, respiratory needs or energy requirements of shellfish that had ingested toxic algae are not met by feeding rates, leading to potential starvation.

Sandra Shumway studied the physiological symptoms of toxic algae on various species of shellfish in the Gulf of Maine, finding that they may show a variety of sublethal manifestations, including increased or decreased rates of feeding or respiration, altered cardiac activity, shell valve closure and thus isolation from the environment, and mucus production. All the responses are species-specific and dependent upon the shellfish species and algal-specific interaction.

The rates at which bivalves (clams, mussels) become toxic and detoxify from ingested toxic algae were established by Ed Gilfillan and Ray Gerber; this activity was found to be species-specific and temperature dependent. It was found that stressed bivalves may detoxify rapidly. The problem with monitoring for toxic algae blooms suspended in the water column, which do not always coincide with infected shellfish bivalves, was complicated by the discovery of large concentrations of resting cysts of toxic algae in bottom sediments along the Maine coast. The toxicity of the cysts was found to be at least 10 times and perhaps as much as 100 times that of the motile forms of the algae. This discovery would affect the monitoring program for public safety.

Toxic algae outbreaks cause the loss of millions of dollars in Maine's shellfish industry. A rigorous monitoring program is necessary to reduce the risks of human sickness or death. A comprehensive monitoring program for toxic algae was expanded by the Department of Resources in cooperation with Bigelow Laboratory and several US Coast Guard stations. Alternatives were sought to the mouse bioassay monitoring method (invariably fatal to the mouse) used for years by Maine, but cooperative work with the Department of Resources found that simple chemical tests for monitoring shellfish toxins used in other areas are not useful in Maine.

Betty Twarog's research focused on the question of what conditions trigger a toxic algae bloom. Is it genetically derived, or environmentally induced, perhaps by iron deficiency? Iron deprivation was found to be a signal for toxin production by many toxic bacteria that may then be ingested by dinoflagellates, the red-tide organisms.

The effects of trace metals on toxin production were studied in several species of dinoflagellates, including the leading cause of red tide, *Alexandrium tamarense.* Three novel neuroactive compounds were isolated from those strains which may enable insights into the action of the toxin.

What is the role of water mass movements in containing or dispersing the toxic organisms? At the instigation of Patrick Holligan, the Laboratory developed a vertical pumping system, capable of sampling at 500 liters per minute, which greatly increased the accumulation of essential data of every relevant parameter needed for monitoring toxic algae. Ongoing research into the ecology of toxic algae indicated a need for modification of the traditional monitoring program focused on sampling plankton to include the hydrographic dynamics that concentrate toxic cells.

Studies of red tide were expanded from Cape Cod to the Bay of Fundy, and a cooperative arrangement between NASA and the Laboratory provided satellite imagery for detecting red-tide blooms off New England. Studies of the newly recognized *brown tide* were initiated. Brown tides are not toxic but can cause significant problems by reducing light penetration, clogging shellfish gills, and destroying habitats.

In later years, a layer of suspended particles near the bottom of the Gulf of Maine was found to contain dormant cysts of toxic algae. It was studied to determine the cause—whether natural or human-induced (as from fishing activities?)—of re-suspensions of cysts from bottom sediments.

Years 1974–1977 Continued

Oil Spills

While the Laboratory pursued the study of toxic algae in the intertidal and subtidal zones of the Maine coast, the impact of oil spills on commercial shellfish was also studied. In Searsport Harbor five years after an oil spill, clam populations in affected areas were reduced to eight percent of their initial numbers with an almost complete failure of recruitment.

Techniques were developed for identification for sublethal effects of oil contamination. Ed Gilfillan looked at the effects of the oil spill on the rate of carbon uptake by soft shell clams. He found that the clams exposed to oil assimilated less carbon than clams not exposed to oil. This meant that it was possible to document sublethal oil spill effects—a new concept and ability at that time.

Ed Gilfillan wrote:

> I began to think about ecological processes in terms of integrating plant and animal dynamics. If one could look at the rate of carbon dioxide fixation by phytoplankton using radioactive carbon-14 labeling, why not continue to trace the flow of energy from phytoplankton to filter-feeding animals?
>
> It was pretty straightforward to look at how much of the carbon-14 taken up by the animals was actually assimilated into animal tissue. It was possible to determine the total amount of carbon-14 consumed by the animal and the amount of carbon-14 excreted in feces. Comparing the two determinations yields the efficiency of the filter feeders in terms of the ratio of carbon-14 taken in to the amount excreted.

Benthic and intertidal seaweeds, important primary producers, are extremely vulnerable to oil pollution. Laboratory researchers studied the loss of upper intertidal plants and the protracted periods of oil contamination in Maine's Piscataqua River and on the coast of France. Transplant experiments related to an oil pollution site in France showed that oil did not reduce growth rates, and transplanted plants assumed the growth characteristics of the endemic populations, indicating the rates were under environmental rather than genetic control.

The Bay Study

In 1976, the Laboratory established a sampling station in Boothbay about three miles from the Laboratory, which made possible both weekly sampling—twice weekly during plankton blooms—throughout the year regardless of the weather and the participation of most of the researchers on a collaborative, multi-disciplinary basis. Water could be returned to the Laboratory for analysis rather than relying on shipboard analyses. In addition to standard measurements, such as temperature, salinity, and chlorophyll, the Bay Study allowed retesting and refinement of new methods before using them at sea. New methods developed to measure electron transport activity, nitrate reductase activity, particulate protein, carbon and nitrogen determinations, and organic excretion—all related to microbiota physiology—were included in the periodic samplings. Nitrate uptake ratios, particulate RNA–DNA ratios, and phytoplankton nutritional status were included. RNA (ribonucleic acid) is involved in protein synthesis and varies with growth rate; DNA (deoxyribonucleic acid) is fundamental to gene structure and is quite constant. Thus, the RNA–DNA ratio is variable with time. It was found that the RNA–DNA ratio increased twenty to thirtyfold following the increase of nutrients in the fall, just prior to and during the fall phytoplankton bloom in September and October. The ratio correlates with and is indicative of the growth rate of phytoplankton.

The Bay Study was the embodiment of the philosophy and primary focus of the Laboratory: the cooperative, interdisciplinary investigations of the physical and chemical environment and the production and physiology of phytoplankton, enabling documentation of the *what* of the microbial world and of the *how* and the *why* of the observations.

Physiological Processes

Ian Morris explored the particular metabolic pathways of cellular carbon fixation in phytoplankton photosynthesis and found it to be different from previous assumptions about phytoplankton and from that of land plants. The investigation showed that certain algae have alternative and adaptive physiologies for differing environmental conditions, enabling them to photosynthesize with greater efficiencies at extremes of light, oxygen tension, and carbon dioxide. The interaction of two major enzymes appears to be the mechanism for these adaptations. Various types of algae have relatively different proportions of these two enzymes that are manifested as species' responses to specific environmental conditions. These research explorations showed that cells pursue alternate processes or pathways which play a contributory role in nutrient production. The research required the development of new tools and techniques and adaptations of existing ones. New techniques were developed or adapted for this work: Electron Transfer Systems (ETS), gas chromatography, and a continuous chemostat versus a batch culture.

Coastal Dynamics

Coastal and estuarine oceanographic observations on the influence of freshwater runoff on physical, chemical, and biological characteristics of Maine's estuaries began on a continuing basis. Chris Garside and Charles Parker found that estuaries in Maine are highly productive, but unlike other East Coast estuaries, they derive their means of production from offshore — the sea—rather than from the rivers. The factors leading to formation of cold bottom water in the Gulf of Maine were determined by Tom Hopkins, and it was found that the bottom water has warmed about 4˚C, a significant increase since Henry Bigelow made the original measurements.

The timing of the spring and fall phytoplankton blooms was documented. The spring bloom, predictable from surface warming, is probably the single most important event for the larvae of many fishes. The fall bloom, stimulated by the renewal of nutrients from bottom waters by the breakdown of warm, stratified surface waters of summer, is frequently associated with the appearance of toxic algae, and its extent and duration are larger and longer than in the spring or summer.

Dissolved Organic Matter

Phytoplankton production of dissolved organic matter (DOM) in the normal course of photosynthesis was widely recognized in seawater. At Bigelow Laboratory, Tim Mague and Bill Skea investigated the chemical composition, subsequent fate, and significance of the extracellular DOM. This required sensitive analytical techniques in microchemistry to be developed. Measurements of glycolic acid in seawater as an excretion product from phytoplankton and assessments of its significance for phytoplankton and as a substrate for bacterial growth were initiated. It was found that the natural release of amino acids by phytoplankton is the source of a major component of extracellular DOM in marine waters.

Organic materials released into the environment by phytoplankton, either by excretion or cell decomposition, are the carbon source for a variety of metabolic activities in the sea. The study of DOM and the kinetics of its synthesis and decomposition required the separation of large numbers of organic materials in extremely low concentrations. It would lead to a better understanding of the ecological–physiological role of the large pool of dissolved organic carbon in the sea. It was found that high light intensity causes an increase of incorporation (i.e., photosynthesis) of carbon into particulate organic matter but stimulates an increase in the excretion of dissolved organic materials as well. Thus, the total production remains the same but is shunted into different pathways; the particulate matter retained in cells adds to phytoplankton biomass, while the dissolved organic fraction supports greater bacterial biomass.

Laboratory studies of the rates and nature of organic matter excretions continued. Only 10 percent of particulate organic matter is transferred from one trophic level to the next. The remaining 90 percent of the excreted or degraded organic materials is a foundation of bacterial activity which provides a food source for filter feeders. Verification of naturally excreted DOM thus demonstrates the reality of a soluble as well as a particulate (phytoplankton) link in the food web.

The total biomass of DOM is about two orders of magnitude greater than all living and nonliving particulate organic matter in the sea. But most DOM is very old, unreactive, and of high molecular weight. Why this DOM becomes unreactive was explored. This DOM results primarily from terrestrial sources (humic and fulvic acids) that leach into rivers and find their way to the sea. Any low molecular DOM is readily taken up by microbes, leaving the more unrefractive DOM that radiocarbon dating shows to be thousands of years old.

Years 1974–1976 Continued

Electron Transfer System

Subsurface and deepwater spatial and temporal distributions of nitrogen, carbon, and oxygen are controlled primarily by intracellular enzyme activities of microorganisms that regulate respiration, denitrification, sulfate reduction, ammonium excretion, and nitrate regeneration.

Only secondarily do temperature, pressure, and the chemical environment affect those distributions. Ted Packard pioneered the use of the Electron Transfer System (ETS), a very sensitive technique for estimating potential respiration (and thus potential energy requirements), much more sensitive than other standard methods. The technique is based on rates of enzymatic activity which can be used to calculate rates of oxygen, nitrate, or nitrite consumption. It was found that a deepwater oxygen-minimum zone had high ETS activity, meaning that the oxygen depletion was not solely due to hydrographic dynamics, as previously thought, but must in part result from biological activity of considerable amounts of microorganisms living in those deep waters. This investigation was later expanded into the eastern tropical Pacific Ocean, the Peru Current, deep waters off the northwest coast of Africa, and the North Atlantic.

The ETS system, measuring potential rates of oxygen consumption or of depletion, was used to measure the flow rate of ocean currents in the very deep waters of the southeast Pacific Ocean. Thus, it was calculated that it took 225 years for water to flow from the Southeast Pacific Basin to the Peru Basin, a distance of 4,225 kilometers.

From the new ETS method of estimating oxygen consumption, largely by respiration of plankton, it is possible to compare that consumption with oxygen production from photosynthesis and the production of new organic materials. To sustain shellfish and finfish populations, oxygen production must exceed oxygen consumption; that is, there must be a surplus of food production over food consumption in the water column. The two in the water column of the Gulf of Maine were found to be approximately equal, an unsustainable situation. Future work would investigate this difficulty.

Nitrogen Cycling

Nitrogen in the form of ammonia or nitrate is required by plants as a component of proteins, nucleic acids, and other important organic molecules. The critical role of nitrogen as a potential limiting factor in phytoplankton production was a major concern of the Laboratory in the early years. Its role, previously assumed but not proven and still uncertain, was confirmed by Dick Dugdale and Jane MacIsaac comparing nutrient-rich upwelling areas off Peru and with nutrient-poor water of the Sargasso Sea. The work succeeded in standardizing the kinetic relation between growth and nitrogen as a limiting substrate for natural populations of plankton algae for much of the world's oceans.

Nitrogen essential for phytoplankton growth is available in two forms—ammonia (NH_3 a chemically reduced form) and nitrate-nitrogen (NO_3 an oxidized form). The source of nitrate in the sunlit, surface zone is usually by overturning and mixing of surface waters or by upwelling from deeper nutrient-rich waters. The source of ammonia, in contrast, may be from the metabolism (excretion) of zooplankton or bacterial remineralization. Phytoplankton cells in the euphotic zone may use either nitrate or ammonia. Bigelow Laboratory developed a model describing the source of nitrates and an enzymatic method for measuring the excretion rates of ammonia by vertically migrating zooplankton.

Frederick King investigated excretion by zooplankton of nitrogen in the form of ammonia, a source for recycled nitrate-nitrogen. The rate of ammonia excretion may limit the rate of phytoplankton production dependent upon continuing supplies of nitrate. Measuring that rate of excretion may be possible by measures of enzymatic activity. The relative contributions of micro- and macrozooplankton to excretion of ammonia for phytoplankton nutrient supplies was studied in the Laboratory as part of the effort to better understand the factors governing the sources of nitrogen supporting primary productivity.

Phytoplankton will preferentially use ammonia if available because it is easier biochemically to use but may store nitrate in times of nitrate sufficiency, which may enable them to metabolize for two or three cell divisions during periods of depletion of external nitrogen sources.

Quay Dortch studied the environmental circumstances and adaptability of phytoplankton cells to shift from nitrate to ammonia assimilation as the form of nitrogen varies with the seasons, and she developed methods of identifying and measuring various forms of nitrogen *within* individual cells.

Quay Dortch wrote:

> I arrived in the fall of 1982 as one of six new scientists that came within about a year—four of them were funded by the NSF EPSCoR program. Looking back on my years at Bigelow Laboratory (1982–1986), I am astonished at what scientifically productive years they were. My memory is of a constant struggle to obtain funding but in a wonderfully collegial environment.
>
> My first funding at Bigelow Laboratory was to study nitrate and ammonium uptake and assimilation in marine phytoplankton. The original proposal requested such a small amount of money that when the program manager called me to tell me I was funded, he also told me they had decided to give me more money than I had asked for.
>
> Funding from NOAA National Undersea Research Program and NSF permitted a study of biological activity in bottom layers in the Gulf of Maine. All of us had the opportunity to go down to the bottom of the Gulf of Maine in the *Johnson Sea Link* submersible to collect samples, which was one of the highlights of my scientific career

Laboratory work by Mike Mickelson and Claudia Mickelson investigated the competitive abilities of species of phytoplankton in culture to assimilate nitrate under varying nutrient conditions–those of a steady state of nutrient availability and those of cyclical availability. They were the first direct measurements of nitrate uptake by phytoplankton from nitrate concentrations typical of those in open oceans. Results show distinct species differences in nitrate uptake that are reflected in the overall distribution of species with respect to oceanic nitrate supply.

A new method for measuring very low concentrations of nitrogen in the sea was developed by Chris Garside and tested in the Sargasso Sea and other waters of low nutrient content. The method makes possible estimates of productivity previously impossible with colorimetric methods. This work was one of several projects made possible by the EPSCoR program.

Bacteria that convert nitrogen into forms (nitrates) useable by phytoplankton use the energy derived from that process to synthesize organic matter consumed by other organisms. Thus, bacteria contribute to the total productivity of the sea. But, estimating the rate of that productivity is difficult. The Laboratory developed a method of measuring enzymatic activity that is a measure of the productivity of the nitrifying bacteria. New methods were developed to measure chemoautotrophy, a non-photosynthetic source of energy for bacteria, on total production. One group of bacteria (chemoautotrophic bacteria) oxidizes ammonia to nitrite and a second group oxidizes nitrite to nitrate. Each step results in new bacterial production and increases of bacterial biomass and regenerates nitrate for phytoplankton production. But, some bacteria (heterotrophic bacteria) use preexisting sources of organic material as energy sources and do not add to *new* production. Enzymatic techniques were developed to distinguish between these two types of bacterial production and improve estimates of total new production.

Laboratory work continued to focus on new technique development to identify and measure a suite of processes in surface waters and deep-sea waters that govern nitrogen cycling and its various forms on enzymatic activities and oxygen consumption, all for refined calculations of marine production.

Comparative studies of nutrient-rich upwelling areas and the perennially nutrient-poor Aegean Sea show that algae in the Aegen have lost the ability to utilize nitrate-nitrogen, a singular evolutionary adaptation to an extreme environment. Presumably, protein synthesis by phytoplankton would depend upon assimilation of ammonia derived from the metabolism of zooplankton, as suggested by later research of the Laboratory.

Continuing work in later years off the coast of Peru related a maximum zone of nitrite-nitrogen to an elevated rate of ETS activity, to particulate nitrate, and to phaeophytin, a breakdown derivative of chlorophyll. The observations suggest an explanation for the elevated nitrite concentrations found in the deep waters off Peru.

Years 1974–1976 Continued

Intertidal And Benthic Surveys

Patterns of ecological assemblages in the intertidal zone for much of the Maine coast were inventoried by a team under the direction of Peter Larsen. All existing data on the coastal zone were compiled to be analyzed by appropriate scientists and related to the associated components of the ecosystem. The work showed pockets of different assemblages reflecting the microclimates of the regions, but the work was complicated by the differing ranges of tide and by variations of temperature and salinity. Particular attention was given to the Sheepscot River estuarine benthos with detailed inventories in which a rich diversity of species was found and previously unknown species were identified. Field sampling of the intertidal flora and fauna of the coast undertaken for the US Office of Coastal Zone Management and the Maine State Planning Office was completed in 1978.

Peter Larsen wrote:

> This was extremely manpower intensive and meticulous work that could not have been accomplished without the contributions from 10–12 interns from Bates and Colby Colleges who did so much of the work. The result was a very large database, the most comprehensive accounting of the Maine coast ecosystem to date. It served as a springboard for several related activities over the next four decades.
>
> Along with the intertidal survey, we had other field- and laboratory-intensive projects. One was a baseline survey of the benthos of Georges Bank being done in preparation for possible oil exploration on this world-famous fishing ground. Several cruises were taken, and a team was organized to process the many samples, as with the coastal work.
>
> We accrued a major interdisciplinary program, at least in part, because of our large invertebrate database. In the late 1970s, US Fish and Wildlife Service (USFWS) began an effort to document the workings of major ecosystems in the US. One area selected was the rocky coast of New England. The task was to document, explain, map, and model the functional ecosystem components, from microbes to moose, of the coastal zone. Bigelow Laboratory's previous experience and diverse, enthusiastic staff made us an attractive partner for the major consulting companies that were competing for this large, long-term contract. In fact, we were partners on four of the seven proposals submitted. We were on the winning proposal with the job of preparing the estuarine and marine sections as well as contributing to other sections such as human impacts on the ecosystem.

> During the 1970s, driven in part by the OPEC oil embargo of 1973–1974, there was interest in locating a site to build an oil refinery in Cobscook Bay in eastern Maine that was known for its deepwater entrance, very large tidal range, ice-free winters, and high biodiversity. Because of the biodiversity and the proximity of so many habitat types, we had done considerable sampling in the bay. We were invited to join a team to do further ecological assessments funded by the company proposing the oil refinery. The Carter administration, however, deemed Cobscook Bay an unsuitable location for an oil refinery and its attendant shipping, pipelines, and other attributes. Through NOAA and USFWS, it sued in federal court under several environmental laws. Bigelow Laboratory was contracted to support the suit and prepare expert testimony. My task was to prove that the Cobscook Bay environment was unique: no equivalent environment occurred elsewhere, and therefore, the loss of Cobscook Bay habitats due to a spill would remove a singular, irreproducible ecological resource. Using our extensive database, we were able to show that Cobscook Bay is indeed unique in many aspects, including the number of species, presence of Arctic and sub-Arctic species, subtidal species occurring in the intertidal zone, and the phenomenon of *giantism* in several species, among others. We were able to conclude that Cobscook Bay had the highest biodiversity in the Western Atlantic north of the tropics. For these and other reasons, the refinery was never built. This brought up the question—why did these ecological anomalies coexist in Cobscook Bay?

An inventory and habitat monitoring program of a rocky shore and a mudflat intertidal zone in Acadia National Park in 1990 was in its fourth year for establishing baseline data to assess future changes and to assess the environmental health of the region. The focus was on the upper and lower extremes of the intertidal zones, the most sensitive to such changes as rising sea level, sublethal increases of pollutants, or catastrophic impacts such as oil spills.

Cobscook Bay

Cobscook Bay is home to more marine species than any coastal embayment north of the tropics. Nine hundred species of marine invertebrates have been found, and a total of more than 1500 species is estimated. One hundred species are found in the intertidal zone that are found only subtidally in other regions**.** The very narrow entrance and the tides in the bay that run up to 24 feet make it unique. With the support of the largest private marine research grant that had ever been awarded in Maine, Bigelow Laboratory in collaboration with other researchers began a two-year study of the bay in 1994. They found that light sufficient to support production reaches all depths of the bay. Nutrients are never depleted to the point of limiting plant growth. The growth of intertidal and subtidal algae is extremely rapid, and their growing season is longer than had been expected. Two large counter-rotating eddies within the bay were discovered that help explain the high levels of nutrients and the retention of such particles as eggs and larvae.

Cobscook Bay was the focus of a number of industrial proposals and is a complex of energy inputs. Because of its convergence of natural features, it is an extremely valuable "proving ground" for modeling natural energy flows. In cooperation with staff from five other state and federal agencies, and using satellite images, aerial photography, computer models, and field date, water movements within and to and from the bay and definitions of specific habitats could be identified for the first time.

Casco Bay

Intertidal plant communities in Casco Bay are a rich source of food and habitat for marine and estuarine animals and are very vulnerable to oil pollution. The Laboratory inventoried the productivity and distribution of saltmarsh plants and dominant seaweeds. Remote sensing made possible estimates of saltmarsh and intertidal and subtidal macroalgae areas and abundance in the area around the bay. Total macroalgal production may exceed phytoplankton production in Casco Bay.

An intensive study of the hydrography of Casco Bay and the incorporation of previously collected data made it possible to understand the impacts of oil spills and pollutants on the productivity of the bay. A semi-enclosed circulatory system, discovered in this work, would trap and retain any material introduced into the bay. There are a number of complications in this gyre, but the net effect is a movement of spilled material into intertidal areas and marshes.

Peter Larsen wrote:

Whereas I had experience in pollution biology in graduate school, there was limited opportunity to continue this interest in the Gulf of Maine. That is, until a program called Ocean Pulse, later named the Northeast Monitoring Program, came along in the late 1970s. This National Marine Fisheries Service (NMFS) initiative attempted to predict future changes in fishery resources by looking lower down the food chain, through surveys and monitoring, for indicators that could be precursors to future higher-level impacts. The researchers had worked in several embayments along the East Coast and felt they understood environmental conditions in waters regarded as polluted. Now they wanted to find out what a non-impacted bay would look like.

I was fortunate to be chosen to characterize and monitor the bottom conditions in Casco Bay. We did a thorough benchmark benthic survey and then monitored select stations for a few years. Among the parameters measured were benthic community structure, trace metals, polycyclic aromatic hydrocarbons (PAHs), and polychlorinated biphenyls (PCBs). The results were quite unexpected. Contrary to being emblematic of a pristine ecosystem, Casco Bay turned out to be as impacted as any other East Coast bay. In fact, some of the lead levels in both sediments and biota were among the highest seen in the coastal environment. Some sites had PAH concentrations comparable to some of the most polluted harbors in the world. The very dangerous PCBs had been banned back in the 1970s, but they appeared in Portland Harbor in the 1980s.

Coastal Pollutants

A survey of the Penobscot estuary documented the vast extent and persistence of sawdust depositions of the late nineteenth and early twentieth centuries. The modified communities of benthic invertebrates that colonized the sawdust beds were described, and the distribution of toxic contaminants and their impacts on benthic organisms were surveyed in the estuaries and harbors of Midcoast Maine. Sediment cores throughout Casco Bay and along the coast to Boothbay Harbor were collected for analyses of trace metals and contaminants. Some levels were found to be higher than those from other severely stressed areas. The work included the compilation of an accessible database for contaminated sediments for the entire Gulf of Maine.

A method for detecting nitrosamines, an extremely dangerous carcinogen, at low concentrations was developed for use on pollutants in the sea. Nitrosamines are formed by a combination of nitrite and amines, both found in a variety of environments. Some preliminary results indicate that certain materials that reach the oceans may contain large quantities of nitrosamines.

Seaweeds

A study of control of macroalgae, or seaweeds, by nutrient limitations and the excretion of organic materials by seaweeds under various conditions was undertaken. Knowledge of macroalgae dynamics was much less than that of phytoplankton. Jerry Topinka determined rates of growth for a number of species; as a result, it was estimated that the production of seaweeds may be much greater than previously believed.

Effects of nitrogen concentrations on intertidal seaweed growth and production were investigated in the laboratory. It was found that seaweeds may become nitrogen-deficient and nitrogen-limited, but production of macroalgae was shown to be relatively immune to nitrogen depletion because of the ability of these larger macroalgae to store and release nitrogen when needed for their own use. Thus, the productivity of macroalgae, unlike phytoplankton, may be prolonged during periods of low nitrate concentrations in the water and thereby complement the periods of plankton production; that is, seaweed production may continue in summer when phytoplankton production is normally low because of nutrient limitation.

The use of a multiband laser from low-flying aircraft to induce chlorophyll fluorescence in seaweeds by exciting major groups of accessory pigments (other than chlorophyll) was explored as a promising method to estimate the distributions and abundance of subtidal seaweeds. Laboratory work showed that fluorescence signatures are quite uniform within a particular group of macroalgae but differ substantially between groups, thus enhancing the potential uses of the technology for species identification.

Maine’s seaweeds shift their photosynthetic production from carbohydrates and proteins in summer to lipids in cold-weather months, an anti-freeze physiological adaptation. This physiological shift was later found within Antarctic phytoplankton.

New calculations of the total length of Maine's shoreline were based upon salinity records to provide appropriate designations of estuarine boundaries. The shoreline was determined to be 4,166 miles (6,705 kilometers). Based upon this estimate, the Maine shoreline may support 520,000 tons of brown algae.

Year 1976–1977

Coastal Oceanography

In 1976–1977, the ongoing research programs inshore and offshore were expanded to include deepwater investigations of chemical and biological metabolism. The continuing programs began to yield important and unexpected results; for example, it was confirmed that the Sheepscot River estuary adjacent to Boothbay Harbor, as previously suspected, is an unusually productive area in the coastal zone sustained not by freshwater nutrient enrichment as are other estuaries along the east coast, but by nutrients carried by inflows from deeper offshore waters. The detection of homogenous, high-salinity bottom water in the estuary, later identified by Tom Hopkins and Toby Garfield as Gulf of Maine Intermediate Water, was indicative of this offshore source of nutrients. Because of this continuing inflow of the offshore source of nutrients, tidally mixed into the euphotic zone, the Sheepscot estuary maintains high production during the summer when other areas suffer low production. This was a significant addition to understanding how the Gulf of Maine coastal system works.

Ongoing studies of the Sheepscot estuary and the Hudson River estuary made it possible to compare productivity processes in unpolluted and polluted systems, as well as nutrient loading and regeneration. The Laboratory was also involved in a study of the ecological impacts of a deepwater dump site in the New York Bight.

The Laboratory occupied 213 oceanographic stations in the Gulf of Maine focused on a 30-mile-wide corridor from Cape Ann, Massachusetts to the Penobscot River, the most complete data record to date at the time. The data showed a number of cyclonic and anticyclonic circulatory gyres maintained by three upwelling areas off New Hampshire, southwest of Cape Elizabeth, and near Monhegan Island, ME. The gyres act as concentrating mechanisms for upwelled nutrients which support dense phytoplankton populations. The gyres may also be the locations for fish larvae for whom abundant food may be concentrated within the gyres A surprising result was the discovery of a previously unknown non-tidal current along the edge of the shelf flowing northeastward, contrary in direction to the previously recognized southwesterly current. Its dynamics drive nearshore horizontal and upwelling circulation.

In cooperation with NMFS, Bigelow scientists collected data on primary production and water chemistry on Georges Bank forming the southern boundary of the Gulf of Maine. More data on Georges Bank were gathered than in the previous 100 years. Analyses show that the bank creates a water mass different from that of the Gulf. This water mass is retained in the sunlit surface waters on the bank because of the shoal water and clockwise eddy-like circulation around the bank. Whereas the Gulf of Maine shows seasonal periodicity in primary production, Georges Bank is consistently productive throughout the year. Tidal action on the bank sustains the levels of nitrate nutrients necessary for the high year-round production.

Year 1977–1978

Phytoplankton Dynamics

The Laboratory continued research to explain how various environmental factors control the growth, abundance, distribution, and species composition of phytoplankton populations. Can variations in the chemical path of carbon assimilation within cells during photosynthesis identify the physiological state of phytoplankton and so identify the controlling environmental factors? Can the ability of a species to switch its mechanism for photosynthesis under certain environmental conditions offer it selective advantage that might cause changes in the species composition in the phytoplankton population? Fieldwork showed that indeed there is a shift in the production of carbohydrate versus, for example, protein depending upon nutrient deficiency following the spring bloom.

Studies in wide-ranging oligotrophic oceanic regions showed similar patterns of physiological activity among those regions. Laboratory work showed that some species may in fact shift their physiological functions in response to changing environmental conditions, and laboratory work on phytoplankton cultures showed that there are species-specific differences in responses to differing photoperiod (light–dark patterns) shifts.

This work relates to the observations from the world ocean by Dolors Blasco and Burton Jones that patterns of species distributions are repeated from one area to another. There appears to be a physiological basis for these patterns, and they can be explored in the laboratory. In the early 1980s, characterization of phytoplankton species assemblages in various ocean regions continued, with analyses of environmental parameters associated with those patterns and the biological and biochemical interactions within those assemblages.

Upwelling Zones

Deepsea biochemical processes and regulatory mechanisms that control the temporal and spatial distributions of nitrogen, carbon, and oxygen were investigated in upwelling zones. The biochemical processes involved are primarily the intracellular enzyme activities of marine organisms. The regulatory mechanisms are the temperature, pressure, and the chemical environments surrounding the organisms. The investigation proceeded by identifying the locations in the sea of those enzymatic activities by means of the Laboratory's ETS technology. The use of specific respiratory enzymes permitted examination of growth kinetics of microorganisms in deepwater oceanic areas. Those kinetics affect the vertical profiles of biologically important nutrients such as nitrate- and nitrite-nitrogen.

Upwelling areas in deep waters off Baja California, Peru, and Northwest Africa share three assemblages of phytoplankton populations in common, their locations being a function of advective processes. An intriguing discovery was the daily vertical migration of dinoflagellates in upwelled areas. Their ability for migration defies their conventional classification as *plankton*, generally defined as passive drifters.

Studies continued in 1979 and 1980 on upwelling systems that are essential for making the nutrients that would otherwise be locked into deep waters available for primary production in sunlit surface waters, thus limiting marine production. The role of winds upon the differing rates of production off Peru and off the northwest coast of Africa was found to be decisive. Both are productive regions, but the high winds off Africa appear to mix phytoplankton into deep waters below light sufficient for photosynthesis. The Peru upwelling system supports primary production that feeds the most productive fisheries—anchovies—in all the world. At times, these blooms had taken the form of red tides visible from the air for a thousand miles along the Peruvian coast. When anchovies are in smaller numbers (because of overfishing?) the unconsumed red tide organisms sink into the depths and die and are decomposed by bacteria, whereby the depths become stagnant. The Laboratory worked to discover the relations between the red tide blooms, the deep-sea stagnation, and the status of the anchovy populations.

Analysis of previously gathered data over several years in the Peru upwelling region was undertaken to identify the physical changes associated with the presence, absence, or abundances of particular species.

Year 1979–1980

Remote Sensing

One of Bigelow Laboratory's first programs was a continuation of the pioneering work by Charlie Yentsch. His work had developed techniques of high-altitude observation and photography that could reveal large-scale distribution patterns of marine organisms —particularly phytoplankton—and thus overcome the limitations of spot-sampling from ships. One of the earliest efforts (maybe the first) to conduct "sea-truth" surface measurements of phytoplankton pigments for comparison with observations from space took place in July 1975. An agreement with NASA provided that observations from the manned US–Soviet orbiter APOLLO-SOYUZ would be calibrated by measurements taken by the Laboratory from surface vessels.

The Coastal Zone Color Scanner (CZCS), launched by NASA in October 1978, brought opportunities for the first time for observing large-scale patterns of ocean productivity. Ocean color images began to appear in 1979.

A major focus of the Laboratory's remote sensing research was to understand and differentiate the effects of phytoplankton pigments on the color of surface waters and to distinguish their effects from that of other substances such as dissolved and particulate organic materials—detritus. This capability made it possible to estimate the amount of chlorophyll using remotely sensed radiance measurements, a field that became known as *ocean color remote sensing*.

A major goal of ocean color remote sensing was to estimate primary productivity with the aim of understanding the role of phytoplankton in the absorption of carbon dioxide by means of photosynthesis. The rates of photosynthesis can be estimated from temperature, light, and chlorophyll, all detectable by satellites, and a focus of the Laboratory has been measurements of the interrelationships of those parameters.

Steve Ackelson continued research to characterize species by their pigment composition and fluorescence. Satellite images of ocean color in surface water were augmented by laser stimulation of chlorophyll fluorescence to provide wide-scale maps of phytoplankton distributions and characterizations of the populations. Some kinds of phytoplankton may be distinguished by chlorophyll fluorescence for larger cell sizes like diatoms and dinoflagellates and by phycoerythrin fluorescence for small cell sizes, both detectable by satellites.

In August 1997, a new ocean color sensor, the Sea-viewing Wide Field-of-View Sensor (SeaWiFS), was launched as a joint venture between NASA and Orbital Sciences Corporation. This ushered in a new era of ocean color observations from. NASA formed an Ocean Color Science Team in 1997 that included Charlie Yentsch and William (Barney) Balch.

Warm-Core Rings

Satellite imagery was combined with observations from vessels on *warm-core rings* derived from the northern edge of the Gulf Stream and with clockwise circulation, to analyze the rings' impacts on basic production, inshore–offshore exchanges of water masses, and regional climate. The imagery showed that the rings are not small features; they are about 100 kilometers in diameter and last six months or longer. There are similarities between the rings and the North Atlantic Ocean itself. Both have a core of warm water in which productivity was presumed low and a rim of high-velocity water comparatively rich in plankton. In both cases, the productivity is related to the extent of vertical movements of water, little vertical movements in the cores and extensive vertical movements in the high-velocity rims. Each ring in effect is a cylinder that extends to the bottom and carries with it a large heat content. As they move onshore they affect local coastal climates.

The entry of warm-core rings from the inshore edge of the Gulf Stream into the Gulf of Maine is responsible for a major inflow of deep offshore slope water that settles into the deep basins of the Gulf. There, it enhances the counterclockwise eddies throughout the Gulf. The annual variations of productivity in the Gulf of Maine may thus be dependent upon the timing and number of rings. The dynamics and variations of the eastern Maine coastal current were studied, in part, by satellite images with respect to its delivery of nutrients from deep basin waters and their impact on productivity of the eastern and western Maine coasts.

The development, evolution, and decay of a warm-core ring were studied in the winter of 1981–1982 by a satellite, four vessels, an aircraft, and 5000 man-days. Compared to the spring phytoplankton bloom in surrounding stable water, the bloom within the ring was delayed because of its vertical mixing regime. The study was able to follow the development and decline of the bloom, but conventional and intermittent observations were less than optimal in this highly dynamic system; at-sea observations could be made on only 65 days of its more than 210-day life cycle. Long-term remote sensing is essential for understanding such an event.

In collaboration with researchers at Princeton University and MIT, Joseph Wroblewski developed an ocean basin scale model of productivity of the North Atlantic Ocean using ecological, physiological, and physical parameters, with further modeling for refinements based upon warm-core ring influences. Previous studies of rings from the Gulf Stream showed they are large enough and important enough to be included in a model of the North Atlantic as a whole. The surface water within the rings is radically different from surrounding water and affects the availability of light and nutrients to the phytoplankton.

Productivity In The Gulf Of Maine

Stratified and vertically mixed waters in the Gulf of Maine are clearly recognizable in satellite images. The mixed areas are at least five times more productive than stratified areas and make up about 30 percent of the area of the Gulf. They contribute approximately two-thirds of total production. The images show that distribution of productivity is much more complex than suggested by shipboard observations; thus, traditional estimates of global productivity may be quite misleading.

A new investigation began in 1982 on the relations between phytoplankton, zooplankton, and oceanographic *fronts*—the interfaces between distinct water masses. Because of their particular hydrodynamics, fronts sustain production in some areas beyond the traditional spring and fall production periods dependent upon stable, nutrient-rich waters.

The vertical distributions of phytoplankton and zooplankton in the Gulf of Maine in June are similar—the zooplankton feeding on the phytoplankton—but in September, their vertical distributions are quite different. Post-naupliar zooplankton are concentrated near the surface in September rather than with the subsurface chlorophyll maximum, whereas naupliar zooplankton are found within the chlorophyll maximum layer. The differences in depth distributions would seem to suggest evolutionary adaptations to avoid feeding competitions among different ages within a species.

A maximum particle layer 10–20 meters thick and 30 meters above the bottom of the Gulf of Maine was found to include high numbers of calanoid copepods, another example of *structuring*. The world's ocean is by no means a uniform homogenous body of water. The significance of such structuring is a continuing object of investigation.

Trace Metals

Through the 1970s, laboratory and field work verified the critical role of nitrate-nitrogen and ammonia in the physiology of phytoplankton. By then, there was increasing awareness of the importance of trace metals—iron, zinc, manganese, copper—in the sea. Some phytoplankton species conform to recognized oceanographic regions; others are wide-spread across boundaries. These differences seem to result from the trace metal requirements of the various species. The

Laboratory developed a system capable of bio-assaying many phytoplankton species under controlled conditions and trace metal availability and initiated a study—much of it at sea—of trace metal metabolism in many species.

It was increasingly apparent that trace metals have important roles in phytoplankton physiology. The Laboratory expanded its studies of those roles and the roles of deep-ocean industrial waste disposal on phytoplankton. The culture collection made it possible to determine that oceanic species can obtain trace metals essential for growth from extremely low concentrations in strong contrast to coastal species that are unable to do so.

Extremely small *ultraplankton* (less than 10 μm in size) were studied by Lynda Murphy in the Laboratory, particularly regarding their trace metal requirements. Iron seems to be the most important trace metal for phytoplankton. It is found in greatest amounts in coastal waters. Its deficiency results in reductions of chlorophyll and carotenoid pigments which can be measured by changes in spectral characteristics of cells. Manganese is also important. It is required as a catalyst for many enzymes and to activate the photosynthetic energy transfer system. Oceanic plankters need less iron than coastal forms, and their iron requirement is related to available manganese. The Laboratory studied the toxicity of copper on microalgae. It was found that oceanic plankters may use iron and manganese to detoxify copper.

As carbon dioxide levels and acidity in the oceans increase, changes in the cycling of trace metals may have impacts on phytoplankton physiology and community structures with impacts throughout the ocean systems. Bigelow Laboratory scientists studied distributions of specific elements *within* individual cells to understand how the cells use and accumulate very low concentrations of essential metals in seawater, how the metals modify the availability of micronutrients and their impact on global biogeochemical cycling. The studies examined three-dimensional distributions *within* cells of silicon, phosphorus, sulfur, chlorine, potassium, calcium, manganese, iron, copper, and zinc at previously unattainable levels of resolution. This analytical capability makes it possible to understand the environmental influences on the trace-metal content of diatoms, improve the ability to reconstruct past climate and ocean conditions, and predict future environmental changes.

Bigelow Laboratory researchers made the first direct measures of trace-metal nutrients in natural phytoplankton groups in major oceanic regions, from the Sargasso Sea to the tropical Pacific Ocean near New Zealand. Laboratory researchers also participated in a cruise in the South Pacific as part of a thirty-nation, ten-year exploration of the large-scale distributions of trace metals throughout the world's ocean.

Iron in coastal waters was found to vary markedly with the seasons and to be similar to nitrogen in its influence on phytoplankton growth—a very important trace constituent. In some coastal areas, iron may be a limiting growth factor. Hilary Glover observed physiological signs of iron deficiency in cultures of phytoplankton.

Seasonal variations in soluble iron in surface coastal waters may be the result of land runoff rather than inflows from deep water. Iron may be a cause of toxic dinoflagellate blooms predominating over diatom blooms off Monhegan Island, east of Boothbay Harbor. The hydrography of that area was investigated for a possible source of trace metals (e.g., copper, lead, zinc, cadmium) that would favor dinoflagellates over diatoms.

It was found that coastal clones of a phytoplankton species initiate reproductive processes in response to iron limitation. Oceanic clones of the same species do the same in response to silicate limitations. Copper was found to be toxic at very low levels to oceanic clones; coastal clones were not so affected. Studies were made on the effects of industrial wastes on phytoplankton physiology, finding differences among the kinds of phytoplankton.

The effects of widespread lead and cadmium from industrial sources, characterized by the Environmental Protection Agency as priority pollutants, were examined on several phytoplankton species in culture.

Year 1980–1981

During this period, Bigelow Laboratory researchers took part in 22 cruises to regions that included the northeast Atlantic Ocean, off Baja California, and the Arctic Ocean.

Sediments In The Gulf Of Maine

Bottom sediments are eventually the depository of much of the organic matter produced in the overlying water column. John Christensen began a new study of the metabolism and major chemical pathways of organic matter in the sediments of the Gulf of Maine in cooperation with other institutions in Maine. The researchers wanted to understand the source of the organic matter that sustains deepwater benthic fauna in the Gulf. Their study included the release of nutrients from the sediments of deep basins, as well as the metabolism of the fauna within the sediments and whether those organisms facilitate the release of nutrients from sediments back into the water column. The study indicated that the sediments are a complex and important part of the coastal marine ecosystem.

As much as 20 to 30 percent of the phytoplankton of the Gulf of Maine is oxidized in the sediments. The estimate is based upon 1) rates of bacterial sulfate reduction under anaerobic conditions, 2) organic matter oxidation by the more common oxygen-respiring organisms, and 3) organic matter burial. However, fish and shellfish that are harvested are equivalent to less than one percent of the annual plant production. The deposition of unconsumed plant material in sediments has implications for nitrogen cycling within the Gulf. Much of the organic matter that settles to and is incorporated within bottom sediments is metabolized to nitrogen gas that is inert for most organisms. Over half of the nitrogen that enters the Gulf of Maine may be lost as inactive nitrogen gas. Thus, this process removes usable nitrogen from coastal sediments and the ocean as a whole.

Because of the need to balance estimates of production and consumption within the marine food web of coastal waters, Leon Cammen initiated research into the energy sources for benthic invertebrate deposit feeders. In addition to bacteria as a food source, it was found that those animals may derive most of their energy from microalgae carried to the bottom in fecal pellets of zooplankton. The research included evaluation of the usefulness for food of nonliving material such as mucus and cellular debris produced by microbes.

Year 1981–1982

Laboratory staff members were involved in surveys to recommend a Marine Sanctuary along the Maine coast established by NOAA. Additionally in 1981–1982, the staff were at sea on 15 different vessels for more than 475 days.

The Dock Study, The Mediterranean, And A Norwegian Contract

Soon after the establishment of the flow cytometry facility at Bigelow Laboratory on McKown Point, weekly sampling of the water at high tide off the end of the Laboratory dock began. The Dock Study was supported by staff members, community volunteers, and summer students. With the growing accumulation of data, patterns of strong seasonal cycles of microscopic populations and natural variations from year to year became apparent.

In collaboration with French oceanographers, Bigelow Laboratory scientists worked to clarify the hydrodynamics in the western Mediterranean Sea, the Straits of Gibraltar, and off northwest Africa. The work explained the causes of the most intense oxygen-minimum zone of the Mediterranean.

The Laboratory was contracted by a Norwegian firm to evaluate the suitability of sites along the Maine coast for salmon aquaculture farms. The criteria include temperature and salinity ranges for optimum growth of juvenile salmon; adequate tidal exchanges with the open sea; protection from excessive wind and waves; and access to the pens from shoreside facilities, roads, and electric power. The extent of winter ice cover that could damage pens also needed to be determined. In the course of the work, small upwelling areas were found that in the winter brought warmer bottom waters to the surface, beneficial for juvenile salmon.

Herring

Research was initiated by David Townsend into the production, dispersal, and survival of herring larvae in eastern Maine coastal waters, an important production area for a major fishery in the Gulf of Maine. The focus of the work became the dispersal of larvae by coastal currents. It was found that larvae survived poorly in the estuaries in winter, but those that were moved offshore by coastal eddies enjoyed good winter survival. A January cruise found herring larvae in deep waters over much of the Gulf of Maine. The spring abundance of larvae in the near-coastal waters was attributed to an inshore transport of larvae from offshore waters. An analysis was developed of the chemical composition of otoliths (inner ear bones) of herring, in cooperation with a researcher at the University of Hawaii, that reflected environmental temperatures and provides clues for the wintering sites of the larvae and environmental influences on recruitment abundances.

Year 1982–1983

Continuous sampling and technique verification

Louis Codispoti developed an inexpensive moored water sampler that can continuously monitor chemical parameters. It was tested on several occasions for many days at a time off Monhegan Island with satisfactory results. The data were used to examine the effects of tides, winds, and storms on the supply of chemical nutrients to the algae, including toxic algae, growing off Monhegan.

Since its introduction in the 1950s, the accuracy of the widely used carbon-14 method of estimating marine photosynthesis was the subject of uncertainty and of what exactly it was measuring. Uncertainties in estimates of ocean productivity were results of these questions. Peter J. leB. Williams compared the technique with other methods in oligotrophic waters which could provide critical test conditions. The results vindicated the reliability of the method for measuring net primary production.

Years 1984–1988

Ocean Optics

As part of the continuing study of colors at the ocean surface associated with marine productivity, Bigelow staff were invited to participate in a cruise in the North Sea in 1987 sponsored by Plymouth (UK) Marine Laboratory. On this cruise, it was demonstrated for the first time that flow cytometry instrumentation could be taken to sea to obtain optical data of high quality. The development of fluorescent techniques with flow cytometry for shipboard uses made it possible to study microorganisms in real time while at sea. Fluorescence-specific light scatter was found to vary significantly and characteristically among species.

Coccolithophores

While many of the research projects at Bigelow Laboratory reached far beyond the Gulf of Maine, a phenomenon was beginning to occur in the Gulf in the 1980s that attracted the attention of phytoplankton ecologists and geochemists worldwide. Massive blooms of a coccolithophore species, *Emiliania huxleyi*, began to occur during summer months. The timing was fortuitous because it coincided with Bigelow Laboratory's new remote sensing computer system capable of detecting the blooms from space.

Coccolithophores, unlike other phytoplankton, have distinct optical properties due to their external plates, called coccoliths, composed almost entirely of calcium carbonate that greatly increase light scatter and reflectance. This, in turn, increases the rate of light absorption and enhances the rate of heating within surface waters. Like other phytoplankton species, coccolithophores flourish in stratified surface waters; they further stratify the surface waters as the water absorbs more heat due to the added light-scattering. Patrick Holligan published the first paper on mesoscale coccolithophore blooms in 1983, which documented blooms of coccolithophores on the western European continental shelf that is 100,000 km^2 in area. Up to this point, no one had documented them elsewhere.

Janet Campbell wrote:

> In 1987, I was invited to a meeting in Copenhagen to advise ICES[15] on applications of remote sensing. At that meeting, a participant mentioned that he saw mysterious white patterns in satellite images of the North Sea. The features were obviously in the water for they showed characteristic eddy patterns typical of ocean currents, similar to the swirls you see after adding cream to coffee.

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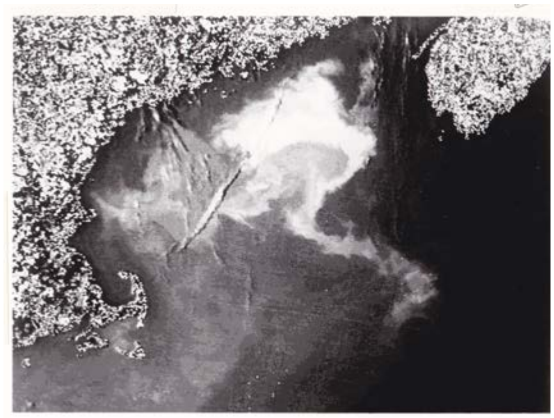
15 International Council for Exploration of the Sea (ICES) is a global organization that develops science and advice to support the sustainable use of the oceans.

I decided to look for similar patterns in satellite images of the Gulf of Maine. When I enhanced an image from the summer of 1983, the result was astonishing! There, in the middle of the Gulf of Maine, was an enormous white feature that we later determined to be a coccolithophore bloom. We then began analyzing images from the remaining summers (1984–1987) but found no evidence of a coccolithophore bloom during those years.



A coccolithophore bloom in the Gulf of Maine in summer 1983 revealed by enhancing an AVHRR image. The linear streaks are vapor trails from aircraft flying over the Gulf.

Meanwhile, assuming it was an annual occurrence, Steve Ackleson sent a proposal to ONR to study the bloom the next summer, and he received funding that included ship time to sample the bloom. Imagine how nervous we were in June 1988 when we began to look for a coccolithophore bloom. Imagine our excitement when one morning there it was! A megabloom! The bloom had either occurred overnight or it was the first clear day we could see the surface from space. At any rate, the bloom occurred that year for the first time in five years.

The water samples collected during the cruise were filled with coccoliths, tiny intricate calcium carbonate plates that had been shed from the *Emiliania huxleyi* bloom. Bigelow Laboratory scientists followed its progress during that summer and the following two summers when less intense blooms occurred.

Steve Ackleson wrote:

My first encounter with a coccolithophore bloom was during a research cruise to Wilkinson Basin in 1988. We left on the evening of July 6, 1988, and steamed through the night to the location of the feature seen in the satellite images. When the sun came up, Charlie Yentsch came running down to the staterooms to wake us up, so we could see the amazing water color.

> We were struck by the brilliant turquoise color of the water—as if we had run aground in Bimini!

During the early 1990s, even bigger blooms of coccolithophores, covering half a million square kilometers, began to occur in the North Atlantic just south of Iceland. The principles of bloom formation appeared to be the same as for the Gulf of Maine, yet the scale was vastly larger.

Coccolithophores are one of the largest sources of calcium carbonate on the planet. They scavenge bicarbonate in seawater and convert about half of it to calcium carbonate. Coccolithophores fix the other half into organic matter. Periodically, the coccolith plates are shed from the plants and drop to the ocean floor creating massive sinks for carbon, as well as associated organic carbon, and reducing the amount of carbon dioxide in the ocean and atmosphere—a major factor in stabilizing global climate—and help to maintain the natural pH, or alkalinity, of the seas.

Years 1986–1988 Continued

A Diversity Of Results

An archive of 120,000 Secchi disc measurements, collected in the northern hemisphere since the early 1900s, were compared with recent remotely sensed ocean-color images. Secchi discs are simple white discs of standard size lowered into the water, the depth where they disappear being noted. While at WHOI, Charlie Yentsch and John Ryther had shown that Secchi disc measures of light penetration into the sea combined with chlorophyll measures and sea-surface light intensity could reliably estimate primary production rates. Comparison of the two methods, the Secchi disc data and the ocean image data, showed similar distributions of chlorophyll-containing organisms correlated with vertical mixing of the water column.

Flow cytometry can measure genetic variability in marine phytoplankton. Research has shown that much of the variation of optical properties of dinoflagellates is due to environmental influences. However, a small but highly significant component could only be accounted for by genetic differences. Such genetic differences may be essential for the persistence of the species in a changing environment.

John Cullen studied the sea surface microlayer, a habitat created at the atmosphere–ocean interface that is physically and ecologically distinct from the rest of the ocean. It is less than one millimeter thick and may be recognized at times as a *slick*. Small-scale circulation patterns within slicks may cause the aggregation of particles including potentially unique phytoplankton populations.

Ultraplankton

Blue-green algae (*cyanobacteria*) until recently had not been recognized as contributing significantly to marine production; because of technical problems of collecting such minute organisms, their contributions went uncounted. Determining their contribution to primary production became essential to correctly re-evaluate all previous estimates of primary production, particularly in central oceanic waters where they are predominant. Therefore, it was important to establish their ecological and environmental positions in the sea and their photosynthetic characteristics.

By 1981, these small cyanobacteria, *Synechococcus*, had been recognized by researchers at MIT as ubiquitous members of phytoplankton communities. These extremely small organisms (≤3 μm), called ultraplankton, are now estimated to provide three-quarters of total primary production for central gyres of the Atlantic and Pacific Oceans.

Phycoerythrin is the major photosynthetic pigment in those organisms, sufficiently different from other pigments to permit identification of cyanobacteria by fluorescent methods. Research into characteristics of cyanobacteria indicates that they function best at low light intensities deep in the euphotic zone. The Bigelow Laboratory culture collection developed methods of holding ultraplankton in culture—an extremely difficult challenge because so little was known of their physiology - and it was found that many have unusual nutritional requirements such as growth enhancement by nickel and selenium.

In terms of productivity and biomass, cyanobacteria are one of the most important components of the photosynthetic community, accounting for 60–70 percent of its biomass. Because of their very small size and extreme fragility, routine observations and isolation in culture are difficult, but the Laboratory was able to study them from many perspectives. New carotenoid (yellow-orange) pigments have been discovered in ultraplankton that provide diagnostic characteristics for field studies. Two general classes were recognized: red-pigmented cyanobacteria and golden-brown algae. Some pigments may be critical to survival at very low light intensities whereas others may act as sun screens at high light intensities. The two classes show different depth distributions and size variations. Their abundance is believed to be due to their increased light absorption efficiencies and nutrient uptake capabilities that are a result of their extremely small size; that is, because of their high surface-area-to-volume ratio they absorb light efficiently, and because of their small size, they have negligible sinking rates and high response to water viscosity.

Using its newly developed technique for detecting nitrate, the Laboratory found that ultraplankton can use nitrates at concentrations *twentyfold* lower than coastal plankton. The Laboratory has found that ultraplankton grow efficiently in very dim blue light typical of that found in the bottom of the illuminated layer of deep oceans. Their ability to use that light and assimilate nitrate at concentrations twentyfold less than found in coastal waters enables ultraplankton to grow below oligotrophic oceanic surface waters at depths where nitrate is in greater but still small supply. The Laboratory culture center worked to characterize the ultraplankton using the flow cytometry technique, and molecular biology provides methods of identifying kinds of microalgae below the level of identification by electron microscopy.

Hilary Glover wrote:

> The vastness of the open seas makes ultraplankton the major contributor to world ocean productivity even though photosynthesis per square meter is much greater in coastal waters. Bigelow Laboratory scientists were at the forefront of research that demonstrated that *picoplankton* (very tiny cells <2 μm in diameter) are the dominant primary producers in the open seas. I always remember Charlie bursting into the laboratory in 1979 exclaiming, "We're throwing it away!" We had been filtering sea water to extract the phytoplankton

using traditional filters, but the red color of the filtered sea water was evidence that tiny cyanobacteria were passing through the filter and being overlooked. Bob Guillard had a few of these red cyanobacteria known as *Synechococcus* in culture, and I immediately started photosynthesis experiments. Applying new methods of single cell identification by epifluorescence microscopy and flow cytometry, we were able to identify, sort, and enumerate three phytoplankton groups based on their distinctive pigment signatures. Cellular rates of photosynthesis could then be assessed at sea in those fractions that were solely *Synechococcus*. My laboratory and field studies demonstrated that the distribution of phytoplankton at depth was related to their pigmentation. Red *Synechococcus* cells were most efficient photosynthesizing at low-intensity blue-green wavelengths near the nitracline, while green picoplankton outcompeted them at the base of the photic layer in the blue-violet light. Oceanographers at other institutions were also investigating these organisms, and I was thrilled to be invited to give a presentation at the 1984 American Association for the Advancement of Science symposium in New York on this topic. Subsequently, a number of us represented Bigelow Laboratory at the 1985 NATO Photosynthetic Picoplankton meeting in San Miniato, Italy.

Open ocean systems were traditionally thought to be static aqueous deserts of low productivity with a slow, steady-state diffusional supply of nitrate across the thermocline. By adopting new methodologies, increased sampling frequency, and discoveries of a diverse picophytoplankton, the old view was challenged. Part of the success of these very small organisms is their high surface area to volume, which enhances light absorption and nutrient uptake. Chris Garside's super-sensitive nitrate method allowed us to determine its uptake in nutrient-poor waters.

Our 1980s data demonstrated that there is considerable spatial and temporal variability in the pasturage of the open sea caused by episodic wind-induced transport of nutrients into the upper layers. These events increase nitrate supply to surface *Synechococcus* which rapidly enhances photosynthesis to produce transient blooms that are quickly grazed down by small zooplankton. My chemostat studies demonstrated that oceanic *Synechococcus* clones grew at comparable rates to algae but at lower nitrate concentrations. Furthermore, *Synechococcus* populations growing in nutrient-depleted surface waters of the Sargasso Sea rapidly responded to very small (20 nM) nitrate pulses. The observed increase in cellular photosynthetic rates was in direct proportion to their ambient nitrate environment. While prochlorophytes were present, they cannot use nitrate and thus depend on ammonium. By 1990, our data added to the general consensus that there is rapid cycling of carbon and nitrogen in the open sea driven by synergistic interactions between photosynthetic picoplankton and their grazers in the water column.

Ultraviolet Radiation

Tenfold increases in ultraviolet (UV) radiation because of ozone depletion in the atmosphere over the Antarctic stimulated Bigelow Laboratory researchers to look for an accurate and reliable method of predicting the consequences on basic productivity and the health of marine food webs and biogeochemical cycles. Michael Lesser investigated the effects of increased UV radiation reaching the ocean surface. Trial calculations suggested a 10–15 percent reduction of near-surface photosynthesis from chlorophyll destruction by UV radiation.

Laboratory cultures of Antarctic microalgal populations were studied for changes in their productivity and biochemical composition, and whether differential sensitivity to UV radiation leads to changes of species composition. It was thought that the research could also reveal how organisms protect themselves from radiation, possibly leading to applications for human protection.

Later work showed that oceanic surface communities have accumulated UV-absorbing compounds that protect cells from UV radiation. Donna Lee Cheney, chair of the Bigelow Laboratory trustees in 2004, reported, "The results of our research are benefiting people directly through discovery of natural antioxidant and ultraviolet radiation-blocking compounds now in medical and pharmaceutical applications."

An increase of UV radiation can change the trophic interactions among planktonic species, directly affecting the amount of organic material that passes through this major segment of the marine ecosystem. Studies of different levels of UV radiation on the food of copepods and on the copepods themselves show that the growth rates and sizes of the food may change, affecting the feeding rates of copepods. Elevated ultraviolet radiation was found to decrease growth rates and increase sizes of a common phytoplankton organism. When these were fed to a copepod common in the North Atlantic, the copepod fed at a rate 66 percent faster than when fed on phytoplankton grown under normal UV radiation. But, codfish larvae exposed to sublethal UV radiation eat less and remain smaller, increasing their risk of predation and mortality.

Year 1989–1990

Feeding Baskets And Antiseral Labelling

It was found in 1990 that golden algae (ultraplankton) use microtubules associated with their flagella to form feeding baskets that engulf bacteria. Bacteria in recent years have been found to be a major pathway for energy and carbon transfer in the ocean. Golden algae are common and widespread in the oceans and important in the *bacterial loop* by their capture of bacteria.

Lynda Murphy developed a method to identify important species components of a community of microalgae. It depends upon adding polyclonal antisera combined with fluorescent labels. The antisera are species-specific and bind to *their* cells; with fluorescence, they may be identified by flow cytometry. Such identification of community composition is important for understanding why communities with different compositions respond differently to changing environmental circumstances.

Productivity In The North Atlantic

The spring bloom of phytoplankton in the North Atlantic is first dominated by diatoms. These sink upon depletion in the sea of silica which forms their shells, taking much of their produced organic carbon into deep waters. Diatoms are succeeded by smaller phytoplankton cells which do not sink and are grazed by zooplankton.

On a cruise to the North Atlantic, a large ammonium-nitrogen maximum was detected just below the euphotic zone, the result of zooplankton metabolism. This was the first observation of such a large feature and is indicative of high levels of near-surface regeneration of nutrients and re-utilization and retention in plankton production and therefore low levels of export of that particular production to the deep ocean.

Spring phytoplankton blooms arise primarily from favorable light and nutrient supplies. Temperature is a minor influence on the bloom, but the timing of the bloom in relation to temperature may have a major influence on the zooplankton response—slower zooplankton development in colder years—and thus whether the productivity of the bloom is channeled into the pelagic or the benthic realm. Slower zooplankton development means less zooplankton consumption of phytoplankton production that then, unconsumed, sinks to the benthos. This variability of food quality transferred to the bottom caused up to an eightfold difference in macrobenthos production between warmer and cooler years.

Years 1990-1992

Dimethyl Sulfide

About 40 million tons of dimethyl sulfide (DMS) is transferred from the ocean to the atmosphere annually. That is about one half the amount added to the atmosphere from human activities. The amount from the ocean is the result of the breakdown of phytoplankton. In 1990, Maureen Keller learned that of more than 100 clones of phytoplankton maintained in the culture collection, significant DMS production comes from just a few classes of microalgae: the dinoflagellates that include red-tide organisms and a class of phytoplankton called *prymnesiophytes* that include coccolithophores.

Coccolithophores were found to produce ten times as much DMS as other species in surrounding waters even though their chlorophyll concentrations were similar. Many of the seasonally dominant phytoplankton in the Gulf of Maine, except for diatoms, are among the largest producers of DMS. Nitrogen-limited algae produce more DMS, and healthy cells retain DMS—they do not release it. The role of zooplankton and bacteria in breaking algal cells and thereby releasing DMS and other volatile compounds that impact atmospheric chemistry and climatology was investigated.

Above the sea surface, DMS is oxidized to sulfur dioxide—a major component of acid rain—and converted to sulfate aerosols that form nuclei for cloud formations that reflect sunlight from Earth's surface, both with implications for climate change.

***Flow Cam* And Vertical Mixing**

Sub-micrometer-size particles (less than 2 micrometers in diameter), including living microorganisms, viruses, and nonliving detrital particles, play important roles in the basic chemistry and biology of marine systems, population and food web dynamics, and biogeochemical cyclings. Michael Sieracki developed an automated image analysis system, called *Flow Cam*, to support studies of the nature and distributions of these particles, their abundance, size spectra, and fluorescence measured using image-analyzed epifluorescence microscopy. This work was carried on off Bermuda and in the Gulf of Maine.

Research into two aspects of the coupling of physical forces and the production of phytoplankton communities focused on 1) unstratified waters where nitrate-nitrogen is transported to the euphotic zone to support continuing production and 2) stratified waters where ammonia is the major source of locally recycled nitrogen. Large differences in cell abundance, cell sizes, and bio-optical properties were found to be associated with the two systems.

Years 1992–1994

Nutrient Algorithms

As a result of a field study of nutrient distributions in the Pacific Ocean, it was found that algorithms could be developed using readily available temperature and salinity data to predict nutrient concentrations. Similar algorithms were developed for the Gulf of Maine using a database of 9,000 observations.

Photosynthetic dinoflagellates were found to have ingested whole cells for food in addition to manufacturing their own, thus combining characteristic of both animals and plants.

Years 1994–1996

Coral Reefs

The Laboratory's growing understanding of ocean optics was applied to coral reefs, which are home to one-fourth of all marine species, to interpret their dynamics and monitor their health as revealed by their color signatures in satellite images. With such a large proportion of all marine species and distribution through so much of the world's ocean, the health of coral reefs is indicative of the health and viability of ocean life as a whole—of the integrity of the seas.

Arabian Sea

Physical forces are major drivers of marine productivity all over the world. The Arabian Sea experiences southwest monsoons that force upwellings of cold, nutrient-rich waters, producing high rates of primary production and rich fisheries. The southwest monsoons are followed by northeast monsoons. The Arabian Sea is the only ocean system that fully reverses its circulation on a semi-annual basis. It is one of the most energetic ocean current systems in the world, causing the greatest seasonal variability of phytoplankton observed in the ocean.

Record changes in Arabian Sea phytoplankton blooms as a result of climate change were studied at sea and from remote-sensing data. In unprecedented efforts to address the challenge of climate change and the global environmental crisis, Bigelow Laboratory scientists collaborated with those from WHOI and SIO in studying the Arabian Sea from satellites and ships. Intensive planning for this work began in 1990–1992. The focus was on the high productivity of the sea and its chemical cycles as they influence carbon dioxide absorption from the atmosphere and circulation between the sea and bottom sediments—all in the context of climate change. The studies indicate that the Arabian Sea, disproportionately of all the world's ocean, is one of the most important oceanic carbon sinks in the world.

Lobsters

A program to predict lobster landings by field sampling newly settled larvae was started by Lew Incze. Special sampling techniques were developed by Rick Wahle and proven to be reliable for estimating abundances in the preferred inshore cobble beds. It was found that densities of newly settled juveniles could differ significantly, substantially, and consistently between two areas in proximity, perhaps because of the patterns of coastal currents or prevailing winds. A sampling instrument for lobster juveniles was adapted for use on manned submersibles to extend the studies farther offshore and into deeper waters. In 1989, in collaboration with other states and Canada, a program was established to monitor *in situ* sampling of the success of larval settling in lobsters, sea urchins, and red crabs.

Years 1996–1998

Gulf Of Maine North Atlantic Times Series

The Gulf of Maine North Atlantic Time Series (GNATS) is a program, under the leadership of Barney Balch, that records marine environmental conditions on a transect across the Gulf of Maine from Portland, ME to Yarmouth, Nova Scotia. Its data were collected frequently from commercial ferries and other vessels over the years. The GNATS data include optical, physical, chemical, biological, and bio-optical properties along the transect that are continuously measured from the vessels while underway.

GNATS has monitored environmental changes resulting from multiple years of extreme freshwater runoff. It has provided critical ocean color calibration and validation data for NASA satellites and the first comprehensive regional assessment of carbon fixation in this large marine ecosystem. GNATS was part of the Laboratory's continuing investigation of the general health of the Gulf of Maine ecosystem and the role of phytoplankton growth for sequestering carbon dioxide and providing the foundation of the Gulf's food web.

Barney Balch wrote:

> The idea came from Charlie Yentsch who along with Dave Phinney had been sailing aboard the ferry between Maine and Nova Scotia beginning in the 1970s. They would drop a sampling bucket over the side every half hour to measure temperature, salinity, chlorophyll, and nutrients during the 11-hour voyage. Oceanographic instrumentation was becoming ever more sophisticated, so I approached the ferry company that ran the M/S *Scotia Prince* to see if they would agree to have Bigelow Laboratory scientists riding the ship. They agreed. I then proposed to NASA to enhance the flexibility of my observational capabilities by building a mobile laboratory in a half-size shipping container and putting it on the back of a 38-foot

truck. The truck would be fitted-out with an array of pumps and scientific instruments. The trailer-laboratory makes possible rapid response to significant oceanographic developments and the opportunity of periods of good weather necessary for good satellite images. When the weather forecast was for clear skies over the next couple of days (a relatively rare occurrence in the foggy Gulf of Maine!), the truck would be driven aboard the ferry. Instruments collected data continuously along the ferry track to provide concurrent sea-truth data for comparison with the satellite images on those clear days and for intercalibration among the variety of instruments. The program, which began in 1998, is now one of the longest-running coastal ocean data transects in the world, spanning more than 20 years and 200 crossings of the Gulf of Maine.

Arctic Ocean

Bigelow scientists led efforts in the Arctic Ocean to establish baseline conditions to assess the impact of climate change. The Arctic regions are warming faster than other parts of the planet with a dramatic reduction of the extent of sea-ice coverage over the ocean. The Arctic Ocean is three percent of Earth's ocean but has 25 percent of the continental shelves, and 10 percent of Earth's rivers flow into the Arctic Ocean. From these sources comes a substantial part of the nutrients that enrich the North Atlantic and its fisheries. The Bigelow Laboratory group, sampling bottom sediments and their nutrient loads, was part of the 60 scientists on US and Canadian icebreakers that crossed the Arctic Ocean, passing over the North Pole in 1998. Atmospheric chemistry and marine systems dynamics of the Arctic Ocean continue to be studied by Laboratory researchers as part of ongoing, multi-institutional programs. Within the collaborative project, Laboratory scientists study the interactions of micro-aggregates produced by phytoplankton upon cloud formations that influence the extent and rate of sea-ice formation and melting. The work includes the collection of data from the atmosphere, sea ice, ocean waters, and ocean sediments. The data provide a strong baseline for assessment of climate change.

REFLECTIONS ON THE HISTORY OF BIGELOW LABORATORY

To look 25 years into the future at the time of the founding of Bigelow Laboratory would have seemed a foolish exercise o futile speculation into remote depths of the unknowable. To understand how much has been accomplished in that time, how the inspiration for the founding has been realized, one may be forgiven for being amazed and delighted and perhaps bemused by the achievements and successes of the Laboratory.

Charlie and Clarice Yentsch had a very clear vision of what they wanted to accomplish—not a *laboratory* or an *institution* as such but a collaboration of like-minded researchers. They had a remarkable, indeed rare, depth of commitment to that goal. It was a revolutionary path they took—the one less traveled—with a daunting prospect of known and unknown and unforeseeable obstacles and difficulties to be overcome with a high risk of disappointment. There was no model for them to follow. There was no other independent, unendowed marine research facility to emulate. They came as strangers to a seemingly improbable location on the coast of Maine and committed their future with only the hope of highly uncertain and worrisomely variable sources of support to sustain their work from highly competitive and short-term research grants from a limited number of granting agencies. There were indeed some years of serious financial stress without a clear path to stability and security, and Charlie had to record some hostility for a time from parts of Maine's government. Charlie wrote, ". . . at times, my hope seems an impossible objective. A day with unemployment or immigration officers, liability insurance agents, the IRS—and the hurdles seem so enormous as to make me nearly admit defeat. And then someone will pass my office door to recount with glee their day's findings."

Charlie and Clarice attributed the survival and flourishing of their vision and their Laboratory to the skilled and committed scientific and technical and support people that had gathered together, sharing their vision and dedication; Charlie called it "a vital enthusiasm for the health and wellbeing of the Laboratory and a determination to work together in the pursuit of better understanding of the world's ocean." Recognition goes to the trustees of the Laboratory and people of the public who sensed, without fully understanding, the value and indeed excitement of basic research into the strange and remote world that is the focus of the Laboratory. Lastly, success is also credited to the encouragement of the numerous visiting scientists from institutions here and abroad who shared their vision and came to support and complement their research. The scientific, technical, and educational record of Bigelow Laboratory has more than justified their hopes and efforts. Charlie and Clarice knew, of course, there were knowledge frontiers of the world's ocean to be crossed—that was their purpose—but could they have guessed that the work of their collaborations would lead to basic revisions of the established *truths* of marine science of the early 1970s? Could they have known that the chemical composition of microalgae is not uniform as had been thought but varies systematically, and the vast open ocean areas are not depauperate but support levels of production by organisms and processes not imagined at the founding of the Laboratory? Could they have imagined the astounding technologies adapted or developed in the Laboratory: the ability to find and *see* within the most minute cells, count and characterize those cells, analyze their genetic structure at rates of thousands of cells per second, multiply that structure a *billion* times, detect nutrients at levels that are orders of magnitude lower than were previously thought possible, and estimate intracellular enzymatic activities of sparse populations of microscopic organisms at great depths in the sea?

Even more profound and enthralling than technological advances is the continuing revelation—it has only just begun—of the evolutionary and biological intricacies and interactions among the microbiota of the sea. As they become apparent and understood, we begin to perceive the fundamental importance of their well-being to the well-being of the global systems upon which all life depends. The work of the Laboratory has contributed to knowledge of extraordinary evolutionary and adaptive characteristics of microorganisms in the sea, characteristics that on reflection are profoundly revolutionary to our understanding of biological processes and their impacts on all life on Earth. The work shows intimate and ever-adapting interactions among all kinds of microbiota that contribute to stable and sustained ocean productivity. It shows genetic evolution and adaptability that enables life to colonize every corner of the sea—even those that are impossibly inhospitable to life of any form.

The research of the Laboratory revealed that much of the dynamics of the sea and atmosphere are under evolutionary and biological control rather than control by purely physical hydrodynamics, and the physiology of microscopic organisms in the sea are determinants of global atmospheric conditions. The species composition and diversity—the presence or absence of species—is controlled by the organisms themselves. Much of the diverse investigations of the billions of those cells and organisms that are found in the sea converge on the cells' reactions to and impacts upon climate change and warming seas and the cells' reactions to ultraviolet radiation—concerns that were common to much of the work of the Laboratory.

The researchers of Bigelow Laboratory have revealed and studied extraordinary evolutionary developments and adaptations that enable viruses and microbiota to exist and thrive in hostile and impossible habitats in polar and tropical oceans and in the greatest depths of the seas — adaptations that, remarkably, make life possible in every dimension of the ocean. The evolution and variations of photosynthetic pigments use every intensity and the full spectrum of light. The evolution of pigments and the sizes of the smallest microbiota permit them to exploit nutrients in the deeper ocean depths and thereby maintain ocean productivity otherwise impossible. Biochemical evolution—the *eating* of iron—makes primary biological production possible where light does not exist. Morphological-physiological adaptations protect microalgae from viral infections, and specialized genes enable viruses with high nutrient requirements to infect microbiota that prefer low-nutrient environments. Viral infections limit excessive production of microbiota with possible adverse consequences to the intricate balance of biological systems. Microalgae have evolved vertical migrations of hundreds of meters that import essential nutrients from dark depths into the euphotic surface zone where photosynthetic production is possible. Consumption of phytoplankton by *sextillions* of zooplankton restrain excessive plant growth and at the same time recycle preferred forms of nitrogen to sustain phytoplankton production.

It is increasingly apparent that the climate that has been so benign and favorable to life on Earth has evolved and been stabilized—to a degree only quite recently in geological time and is now only partially understood—by the interconnections and interactions of immense numbers of microscopic particles in the sea that were the objects of research at Bigelow Laboratory. But, that benign environment, it is now clear, may be destabilized if the intricate balance among all components is jeopardized.

In 1984, at the end of a summary of its first ten years, Charlie and Clarice asked, “Can we predict what the future will be for Bigelow? . . . No, but in a rational world, things should go well.”

APPENDICES

Executive Directors

Charles S. Yentsch 1974–1988

Patrick M. Holligan Acting Director 1988–1989

Dennis L. Taylor 1989–1990

Lewis S. Incze 1991–1994

Chris Garside, Maureen Keller, and Michael Sieracki 1995

Louis E. Sage 1996–2007

Chairpersons – Board of Trustees

William G. Lawrence 1974–1977

Jospeh T. McColgan 1977–1980

Earl L. Green 1980–1982

Arthur M. Johnson 1982–1990

David H. Donan 1990–1991

Leonard W. Cronkhite 1991–1994

John B. Hayes 1994–1996

Neil Rolde 1996–2004

Senior Research Scientists

Charles S. Yentsch

Clarice M. Yentsch

Ian A. Morris

Edward S. Gilfillan

Thomas S. Hopkins

William Skea

Jerry A. Topinka

Dolors Blasco

Jane MacIsaac Dugdale

Richard C. Dugdale

Christopher Garside
Ray Gerber
Hilary E. Glover
Peter F. Larsen
Timothy H. Mague
Claudia A. Mickelson
Michael J. Mickelson
Theodore T. Packard
Burton H. Jones
Charles E. Parker
Frederick D. King
Louis A. Codispoti
John P. Christensen
Maureen D. Keller
Leon M. Cammen
Frances Quay Dortch
Robert R.L. Guillard
David W. Townsend
Peter LeB. Williams
Richard W. Spinrad
Janet W. Campbell
Steven G. Ackelson
John J. Cullen
Patrick M. Holligan
Lewis S. Incze
Lynda P. Murphy
Joseph S. Wroblewski
Robert A. Andersen
Michael P. Lesser
Michael E. Sieracki
Betty M. Twarog

Sandra E. Shumway

David A. Phinney

William M. Balch

Patricia A. Matrai

Richard A. Wahle

Joaquim A. Goés

Helga do R. Gomes

Michael P. Lizotte

Charles J. O’Kelly

Cynthia H. Pilskaln

Collin S. Roesler

David M. Fields

Susan D. Wharam

Glossary

aerosol – a system of colloidal particles dispersed in a gas

algorithm – any mechanical or recursive computational procedure

anaerobic – absence of oxygen

archaea – a primitive form of bacteria

bacterioplankton – the bacterial portion of the plankton and the smallest organisms in the ocean (0.2–0.6 micrometers in diameter). Photosynthetic bacteria are major contributors to ocean's biological productivity.

benthic – living on or in the bottom of bodies of water

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

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

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

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

chemoautotrophy – a process that needs only carbon dioxide as a carbon source but that obtains energy by oxidizing inorganic substances clones – a lineage of genetically identical individuals

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

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

critical mixing depth – that depth of vertical mixing in the sea that is sufficient to restore nutrients to the euphotic zone but is not so great as to sweep phytoplankton below the euphotic zone

cryopreservation – a process in which cells or whole tissues are preserved by cooling to sub-zero temperatures

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

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

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

endemic – native or restricted to a certain region.

enzymes – a class of proteins serving as catalysts, chemical agents that change the rate of a reaction without being consumed by the reaction

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

eukaryote – a type of cell with a membrane-enclosed nucleus and membrane-enclosed organelles

euphotic zone – the surface layer of sea waters where light is sufficient for photosynthesis

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

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

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.

heterotrophy – a mode of gaining nutrition by eating other organisms or their by-products

invertebrate – an animal without an internal skeleton made of bone
kinetics – the study of phenomena related to motion, as kinetic energy

microbiota – archaea, bacteria, and viruses

oligotrophic – ocean regions of low productivity

pelagic – part of the upper layers of the open ocean

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

phycoerythrin – a pigment associated with the photosynthetic process

phytoplankton – the plant component of the suspended or floating microscopic animals, plants, and bacteria in the ocean, collectively known as plankton. Composed mostly of single-celled algae and bacteria, phytoplankton carry out photosynthesis and are at the base of the marine food web. 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

picoplankton – the fraction of plankton composed by cells between 0.2 and 2 micrometers in diameter (see also ultraplankton)

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

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

ultraplankton – plankton less than 2 micrometers in size. This term often refers to the smallest known microorganisms, including bacteria, and viruses.

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.

virus – a submicroscopic particle consisting of a single nucleic acid surrounded by a protein coat, having the ability to reproduce only within a living cell