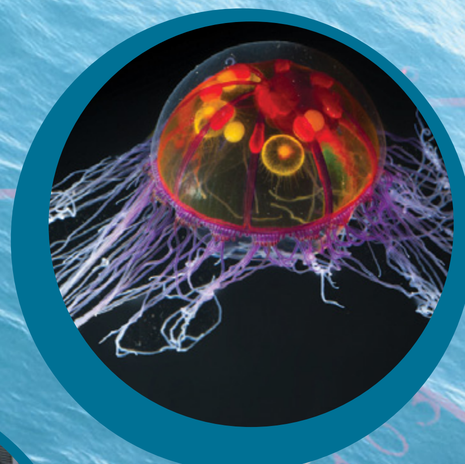
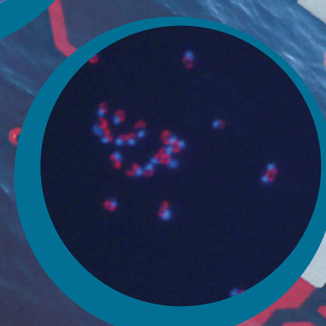
MBARI

Monterey Bay Aquarium Research Institute

TECHNOLOGY ROADMAP

2014





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Executive Summary

David Packard founded MBARI in 1987 with the goal of combining the talents of scientists and engineers to develop new instruments and methods for studying the ocean. From the beginning, a systems approach guided our efforts; access to the sea using the day's cutting-edge platforms and sensors was matched with shore-side support for data storage, retrieval, analysis, and dissemination. Over time, MBARI's marine operations capabilities were enhanced, making it possible to conduct sophisticated field programs both locally and far afield. Our ships became hubs that were used to support a small fleet of autonomous and tethered systems, and researchers on shore routinely began operating robotic sensors remotely. Increasingly those tools were directed at understanding how the ocean responds to both natural processes and human perturbations, and how such changes may in turn impact society. Our 2011 Strategic Plan is guiding this advancement. The philosophy that shaped our formative years has merged with new ideas for characterizing a rapidly changing ocean. However, the Strategic Plan does not identify in detail the key technical capabilities needed to attain that vision. This Technology Roadmap addresses that gap by outlining a path for continuing MBARI's evolution over the coming decade.

Our roadmap outlines a set of engineering priorities that will be coordinated under three overlapping initiatives: *Taking the laboratory into the ocean, Enabling targeted sampling*, and *Advancing a persistent presence*. These initiatives are derived from a series of interconnected scientific challenges that exemplify the research themes articulated in the Strategic Plan, and that motivate specific technological advances that MBARI is poised to attempt. Here the challenges build from a functional perspective beginning with the basic transformations of matter and energy, then transitioning to higher order system concepts, and ending with an integration of activities that cross disciplinary divides. The concept of ocean change serves as an overarching organizational principle for each step of this progression:

Biogeochemical cycles

- Detect and quantify key elements and chemical compounds that actively influence the growth and distribution of marine organisms.
- Develop the means to relate genetic potential and expression at the organismal level to biogeochemical transformations and fluxes at the ecosystem level.

Ecosystem processes

- Advance a detailed, quantitative view of the biological pump—the transport of biologically derived material from surface waters to the deep seafloor.
- Enhance understanding of the fluctuations and fate of forage species, animals that are a primary source of food for populations of larger marine animals.

Ocean visualization

- Map the seafloor in support of geological, chemical, and biological investigations.
- Relate water-column conditions and variability to the abundance, distribution, and activity of biota.

Exploration and discovery

- Devise informatics tools for understanding the ocean and its inhabitants.
- Conduct expeditions and experiments that provide insights into the ocean of the future.

Collectively, these challenges point to a suite of needed technical capabilities and opportunities for MBARI to advance our science/engineering partnerships. The development of chemical and biological sensors will be aimed at revealing the interplay between inorganic and organic matter, and an understanding of how organisms respond to and drive fundamental biogeochemical cycles. We will create cooperative robotic systems for visualizing the multiple trophic levels of marine ecosystems, and for documenting the physical and chemical regimes in which they exist. New sampling systems will be developed for capturing, preserving, and returning material to the laboratory, where sophisticated analytical techniques can measure what cannot yet be determined in situ. The capacity to conduct in situ experiments and to map the seafloor will be enhanced in order to test hypotheses and interpret empirical observations. We will develop new analytical and visualization tools to explore the resulting data, to find patterns and causal connections, and to resolve the interplay between natural and anthropogenic influences. We will pioneer power and communication technologies that let us sustain these systems for long periods at sea in remote locations. To maximize the impact of MBARI's technological advances and innovation, we will export technology to the community at large.

Our prospects for revolutionizing ocean experimentation, observation, and access are excellent due to our ability to invest in high-risk, high-return technologies. Technical progress by industry will enable us to focus our innovation. For example, the cost and power requirements for computation are declining dramatically while the sophistication and reliability of robotic systems are rising rapidly. Communication and navigation capabilities have enabled efficient coupling of widely distributed sensing arrays to large data repositories. The art of amassing and mining diverse and massive data sets is leading to new methods for discovering complex relationships, and for improving predictive skill. These advances have enormous implications for furthering MBARI's mission and for extending David Packard's original vision forward into a modern and rapidly changing world.

Point of Departure

The overarching question advanced in the 2011 Strategic Plan is, "How are the ocean and its inhabitants changing in response to natural processes and human perturbations?" From that perspective a suite of interrelated research themes were advanced to frame specific lines of inquiry: *Exploration and Discovery, Ocean Visualization, Ecosystem Processes*, and *Ocean Biogeochemistry*. These themes are grounded in the recognition that the ocean is undergoing profound changes that could lead to large ecosystem shifts unlike anything humans have previously experienced; however, the extent and magnitude of such shifts are not yet clear.

Our ability to address questions concerning ocean change is fundamentally limited by the lack of key technologies for enabling in situ experimentation, conducting targeted sampling, and providing a persistent sensor presence in the ocean. Work to develop and utilize such capabilities requires a sustained effort where both science and engineering expertise are brought to bear on well-defined problems. This Technology Roadmap establishes that tactical course.

MBARI is uniquely positioned to apply resources and innovative capacity to further our understanding of the structure and function of marine systems. By connecting our science and engineering capabilities to longer-term, socially relevant objectives associated with ocean stewardship, we stand to meet the goals articulated in the Strategic Plan. Our progress will also provide synergistic support for the larger missions of our primary sponsor, the David and Lucile Packard Foundation, our sister institution, the Monterey Bay Aquarium, and our partners, such as those comprising the Center for Ocean Solutions.

MBARI's Operational Domain

Unfettered access to the ocean is an essential cornerstone of the Technology Roadmap. MBARI is located at the head of Monterey Canyon, one of the largest and deepest submarine canyons on Earth. Immediately offshore is a tremendously productive coastal upwelling system with long-term trends that reflect ocean-scale fluctuations. Environments from the Gulf of California and the open waters of the Pacific, to Canada's western shores provide important contrasts to our local setting. When combined, these waters offer fertile ground for developing, refining, deploying, and utilizing new methods, instruments, and systems.


Research vessels Rachel Carson*, left, and* Western Flyer *are the institute's primary platforms for accessing our operational domain. Partnerships with external organizations allow MBARI scientists and engineers to apply tools and techniques developed locally to other regions of the world.*

Problem Statements

This Technology Roadmap builds upon themes articulated in our Strategic Plan. It begins with basic transformations of matter and energy, moves to higher-order system concepts, and culminates with an integration of activities that cross disciplinary boundaries. This progression provides a broad perspective on what will drive research and technology development activities at MBARI for the coming decade. To identify long-term engineering foci, a pair of problem statements has been derived for each research theme. The eight statements highlight specific topics and challenges that demand a suite of capabilities. These needs are then used to identify institutional priorities for coordinating our engineering activities in the future as detailed in the sections that follow.

Biogeochemical cycles

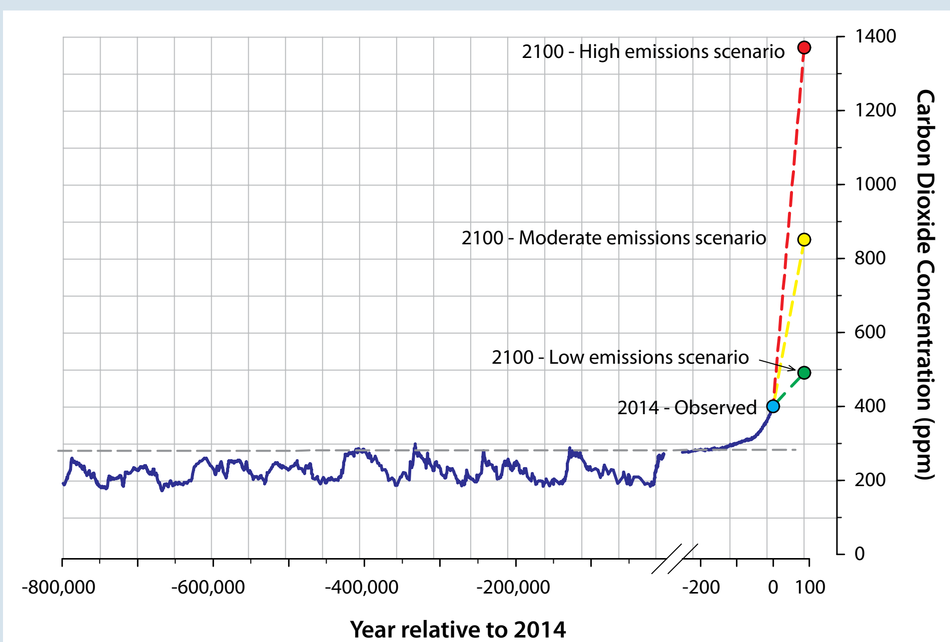
Life in the ocean is governed by interactions between the physical and chemical environment, and the genetic capacities of organisms for survival and reproduction. This fundamental interaction is modulated by natural processes that drive the cycling of elements on which all life depends. That pattern is being increasingly perturbed by human activities, and the consequences of these changes for marine systems and society are not yet known. Needed technologies for investigating these cycles include new chemical and biological sensors and the means to conduct experiments in situ.

Problem Statement #1. *Detect and quantify key elements and chemical compounds that actively influence the growth and distribution of marine organisms*

The world ocean is changing in response to increasing atmospheric carbon dioxide and temperature in ways that will have significant impacts on the cycling of essential elements such as carbon, nitrogen, and oxygen. While there are sensors for measuring select properties relevant to tracking these cycles in the ocean, economic and logistical constraints severely limit the number of discrete observations that can be made at both local and global scales. Robust, cost-effective biogeochemical sensor systems are needed to allow the scientific community to visualize the dynamic fluxes over multi-year time frames on an ocean-basin scale without frequent instru-

An 800,000-year record of atmospheric gas samples reveals a relatively stable concentration of carbon dioxide until a recent and dramatic shift due in large part to the burning of fossil fuel. The ocean has absorbed roughly 30 percent of all carbon dioxide released into the atmosphere since the industrial revolution, resulting in a 26 percent increase in its acidity. Never before has human civilization experienced such conditions. Despite the introduction of various climate change mitigation policies, greenhouse gas emissions increased during the decade from 2000 to 2010. Three scenarios project continued emissions of greenhouse gases that will cause further warming and will affect all components of the climate system.

Sources: 2009 Report on Climate Change Impacts in the United States (http://nca2009.globalchange.gov/800000-year-record-co2-concentration); 2012 Third Symposium on the Ocean in a High-CO2 World, Summary for Policymakers; Climate Change 2013: The Physical Science Basis. International Panel on Climate Change; Climate Change 2014: Mitigation of Climate Change. International Panel on Climate Change.

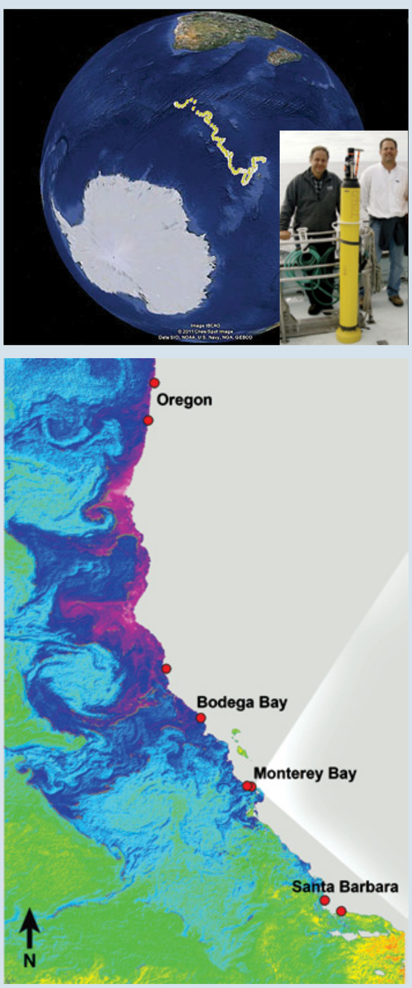


ment recovery and servicing. Similar challenges apply to making more intensive, higher-resolution measurements at particular locations.

Beyond documenting physical, chemical, and aggregate biological changes, there is a pressing need to understand and predict the cumulative, multi-scale impacts of these processes on the ocean system and society. Progress to date has been largely dependent on hindsight reporting of observed change at select sites, not on large-scale, quantitative projections. The capacity for conducting laboratory and field experiments must be enhanced to assess how key species within various ocean environments will respond to future conditions and to enable development of predictive ecosystem models. Such investigations will complement the empirical observations and help to refine and validate the predictive models.

***Problem Statement #2.** Develop the means to relate genetic potential and expression at the organismal level, to biogeochemical transformations and fluxes at the ecosystem level*

The application of advanced techniques to analyze an organism's entire complement of DNA (genome), or collection of expressed genes (transcriptome) and proteins (proteome), has revolutionized our view of how marine life interacts with the physical and chemical environment. However, many challenges limit our ability to apply these

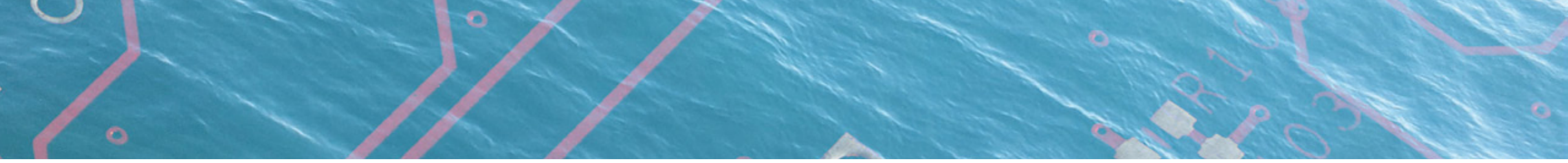


New sensors for assessing ocean acidification

Gathering a steady stream of data about the ocean from around the globe is not practical using only ship-based observations and traditional oceanographic instruments. But by placing sensors on a worldwide Argo array of profiling floats (http://www.argo.ucsd.edu/), researchers are able to learn about changes in ocean chemistry and productivity without necessarily going to sea. By equipping the floats with nitrate sensors developed by MBARI, along with oxygen sensors, phytoplankton blooms can be tracked. Data from the floats are transmitted via satellite to MBARI computers, which run a web-based program allowing the public to view the data in real time. Working with Honeywell, MBARI is helping to modify an industrial pH sensor so that it can be added to the floats to directly measure changes in ocean acidity. The transfer of this technology to other institutions, in concert with industry partners, will allow researchers from around the world to realize a global picture of ocean conditions.

Closer to shore, similar pH sensors have been deployed up and down the West Coast of the U.S. as part of a study as to how nearshore organisms respond to changes in ocean acidity. This intertidal research is a collaborative project involving several West Coast institutions. The team is using genetic and physiological studies to reveal the ways that intertidal animals respond to natural variations in pH, thereby enhancing our ability to predict the fitness of various intertidal species under future ocean conditions. The technology and know-how gained locally will be exported to other organizations to enhance our understanding of changes taking place in the coastal ocean on a much larger scale than would be possible by the West Coast institutions alone.

Top, track through the Southern Ocean of a profiling float like the one pictured in inset; bottom, West Coast sites of an ongoing, multi-institutional intertidal ocean acidification study known as OMEGAS (Ocean Margin Ecosystems Group for Acidification Studies).



advanced analytical techniques in the ocean. First and foremost, there is a need for new ways to collect and preserve material for basic laboratory analyses that are presently not suited for application in situ. Furthermore, since biological communities are not distributed uniformly, a real-time environmental data analysis and classification capability is needed to direct sampling strategies relative to particular combinations of physical, chemical, and optical properties of the water column.

Collecting organisms under a range of naturally occurring environmental conditions is one means of assessing their response and resiliency to environmental variations. However, the multiplicity of forcing functions acting in nature can also obscure some cause-and-effect relationships. For this reason, novel controlled experiments are needed to determine how organisms react to particular perturbations. The outcomes of such studies provide an essential framework for guiding laboratory and field investigations. Ultimately, the application of targeted molecular approaches in situ should allow us to use naturally occurring communities of marine organisms as sensor systems unto themselves.

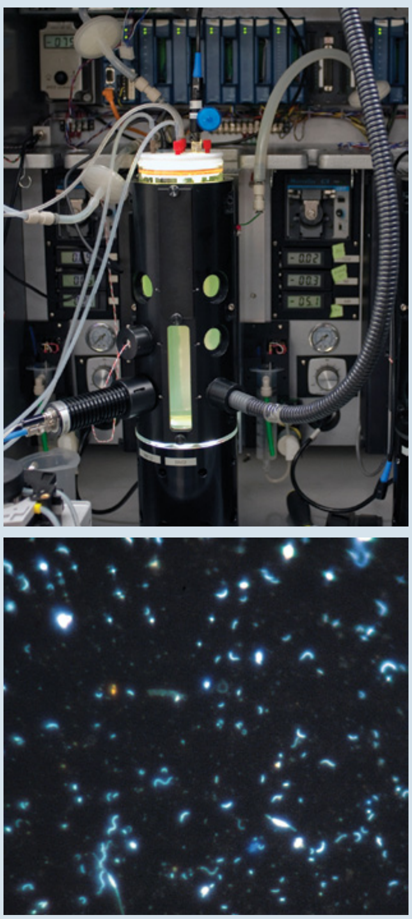
Studying gene expression under controlled conditions

Marine microbes mediate essential biogeochemical processes in the ocean and play a key role in transmitting climate variations throughout the larger ecosystem. However, the population dynamics of the organisms that carry out these fundamental transformations and the mechanisms underlying their response to environmental change are still not well understood.

Genomic techniques provide powerful tools for addressing this problem. Determining the presence and expression of genetic material gives a unique perspective on "who is there" and "what they are doing". Yet, developing a detailed understanding of what triggers the expression of particular traits is extremely challenging in the natural environment due to the diversity of organisms present and ever-changing chemical and physical properties of the water column. Revealing the functionality of this genetic material is a challenge. One approach is to use specially designed chambers to cultivate particular microorganisms in the laboratory under controlled culture conditions. In this way researchers can carefully gauge an organism's response to different environmental conditions and tease apart its genetic and physiological underpinnings.

For larger specimens, MBARI's remotely operated vehicles (ROVs) are used to collect animals such as deep-sea urchins, crabs, clams, snails, and fishes for laboratory studies. Researchers use experimental aquaria to examine the animals' physiological responses to higher carbon dioxide levels, and/or lower oxygen levels, etc. In parallel, novel, controlled experiments are conducted in situ using MBARI's respirometers and Free Ocean Carbon Dioxide Enrichment (FOCE) systems.

Information gleaned from these experimental lines of research can be used to devise new strategies and models that facilitate and inform subsequent work in the natural, "uncontrolled" environment. MBARI's unique suite of platforms, sensors, and samplers provides an unparalleled capability for making such observations to reveal cause-and-effect relationships that otherwise might remain obscure.

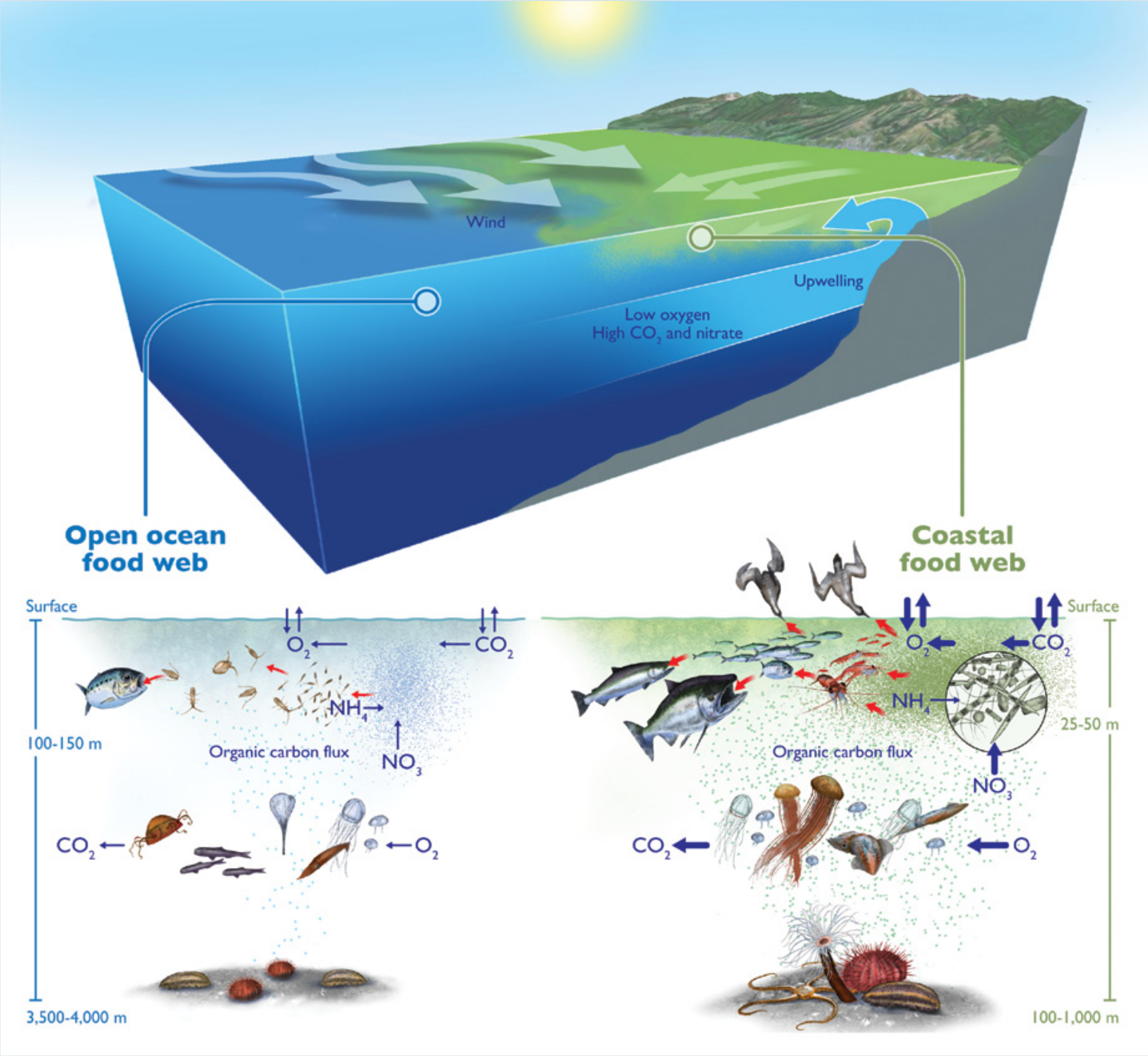


Top, environmental conditions in the culture chamber can be controlled to grow and experiment on microbes such as those pictured in the image below.

The biological pump

The biological pump plays a critical role in the global carbon cycle, with processes involving phytoplankton, several levels of animal consumers, and the bacteria that assimilate and recycle their wastes. Off Central California, coastal upwelling brings cold, nutrient-rich waters from 50–100 meter depths up to the sea surface through the combined effects of wind, Earth's rotation, and the coastline (top panel). Sunlight and natural fertilizers stimulate phytoplankton blooms dominated by large diatoms that feed forage species such as krill and small fishes (lower right panel). The forage species nourish top predators such as birds and larger fishes, producing a complex food web. A large fraction of the organic material produced at the sea surface sinks into the deep sea, providing food for midwater and benthic organisms. In contrast, far offshore, primary production in the nutrient-poor, subtropical open ocean (lower left panel) is dominated by tiny organisms whose grazers are similarly small or slightly larger. Recycled nutrients such as ammonium drive this tighter food web with fewer top predators and less export of material to the deep ocean.

Future oceanographic studies will require technologies that provide a holistic understanding of how marine food webs, nutrient cycles, and the biological pump respond to changes in the ocean environment. Achieving such a detailed mechanistic perspective demands novel means for integrating disparate types of measurements that must be made throughout the water column over extended periods of time and on a large scale. Visualizing that information in a way that provides an intuitive view of ocean ecosystem structure, function and trajectory—something akin to a modern-day animated weather map—would be a powerful vehicle for educating policy makers and the general public about the role that the ocean plays in sustaining Earth's habitability.



Ecosystem processes

Ocean ecosystems arise from a myriad of complex interactions that occur on multiple temporal and spatial scales, resulting in patchy distributions of biological communities and complicated population dynamics. Fluctuations in the coupled biotic/abiotic system can alter food webs in ways that propagate from the surface to the deep seafloor. In turn, these fluctuations impact ecosystem structure and function in ways that are currently difficult to quantify and predict. Technological progress toward these goals requires new ocean-going platforms and the automation of data collection, processing, and visualization.

Problem Statement #3. *Advance a detailed quantitative view of the biological pump*

The flux of the material generated by primary production at the sea surface and its transit through the water column to the seafloor is often referred to as the biological pump. This cascade is central to structuring and integrating marine ecosystems, and carbon serves as a key currency for tracking these processes. New tools and techniques are needed for predicting how ecological changes taking place now at the sea surface and in the midwater will ultimately manifest themselves on the seafloor.

Microbes and phytoplankton are responsible for initiating the flux at the sea surface. While these processes can be measured precisely and routinely, automated methods that do not require intensive human intervention are needed. The next steps of carbon transfer in the water column involve zooplankton and midwater animals, but the complexity and magnitude of their influence on structuring the food web is still poorly understood. Tools for quantifying the role zooplankton and midwater animals play in elemental cycling are required.

In the midwater, most of what is known about carbon cycling is based on cumulative measures like net tows or sediment traps. Intensive ROV-based observations have made it possible to focus on individual components of the community, and to delineate processes at a much finer scale, but they are limited in scope and are essentially just snapshots of individual links within a dynamic network of connections. Automated, long-term measurements of such interactions are necessary.

The amount of particulate organic matter that reaches the ocean floor can be estimated by measuring oxygen consumption at the sediment/water interface, and by quantifying abundance and distribution of conspicuous animals that inhabit the deep benthic domain. Long-term assessments of these fundamental measures in the vast abyssal ecosystem are lacking.

Problem Statement #4. *Enhance understanding of the fluctuations and fate of forage species*

In upwelling systems, forage species—small animals that include krill, squid, and small pelagic fishes—are critical links that transmit primary production at the microorganism level to larger predators, such as marine mammals, birds, and commercially important fishes. Their position in the food web makes them ideal targets for revealing impacts of ecosystem changes.

Methods for observing and modeling the plants and animals at the base of the food web are relatively well developed. Extending that understanding to include forage species, and then to more traditional models for assessing stocks of larger animals, remains a significant challenge. One restriction is that we are not yet able to reliably measure and predict how forage community composition, and fisheries stocks, will respond to changing environmental conditions.

To improve our predictive capability, refinement and expansion of reliable four-dimensional, coupled physical-biological models that include primary producers and forage species are needed.

Ocean visualization

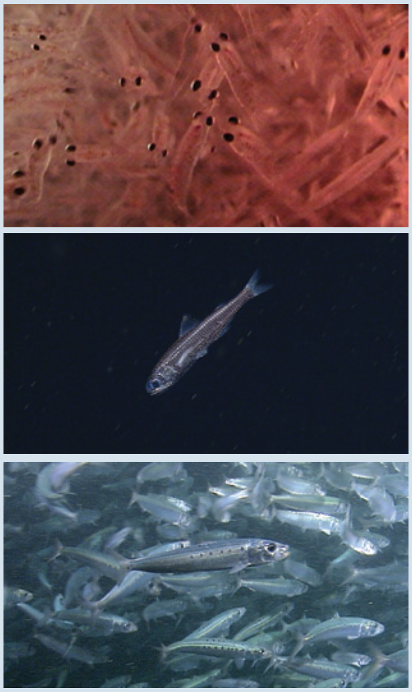
The ocean lies largely beyond human experience due to its vastness and dynamic nature. Documenting ocean change and illuminating its outcomes require quantitative assessments of numerous properties over many scales of space and time. Compared to observations of Earth's atmosphere and terrestrial systems, revealing the ocean's interior, its inhabitants, and the seafloor is extremely challenging. Improved technologies for visualizing the ocean in time and space are needed to advance ocean science, and to enhance our ability to communicate important findings to the public and policy makers.

Problem Statement #5. *Map the seafloor in support of biological and geological investigations*

Human understanding of benthic processes is dependent on the accuracy and resolution of the available seafloor topography. Every technological advance that has increased the resolution of bathymetric data has produced startling new perceptions about the nature of the seafloor and the processes that shape it.

MBARI is on the forefront of advancing seafloor-mapping technology. Our goals are to obtain quantitatively correct bathymetric data at the centimeter-scale, and to directly mesh that information with optical imagery. This new level of resolution is necessary to elucidate geological processes as well as to provide a clear physical framework to observe and understand the distribution, movement, and relationships of benthic fauna. Ultimately, further advances in this technology promise to be among the most powerful ways to document current conditions, and also to confidently assess significant changes in the future.

Achieving centimeter-scale resolution—the scale of many biological processes—requires the development of new technologies and modes of operation. This includes ways of repeatedly navigating over the seafloor with centimeter precision, fielding high-resolution acoustic, chemical, and optical sensors, developing vehicles to carry these new sensors, and generating software and protocols to reliably operate robotic systems for extended periods of time in the deep sea.

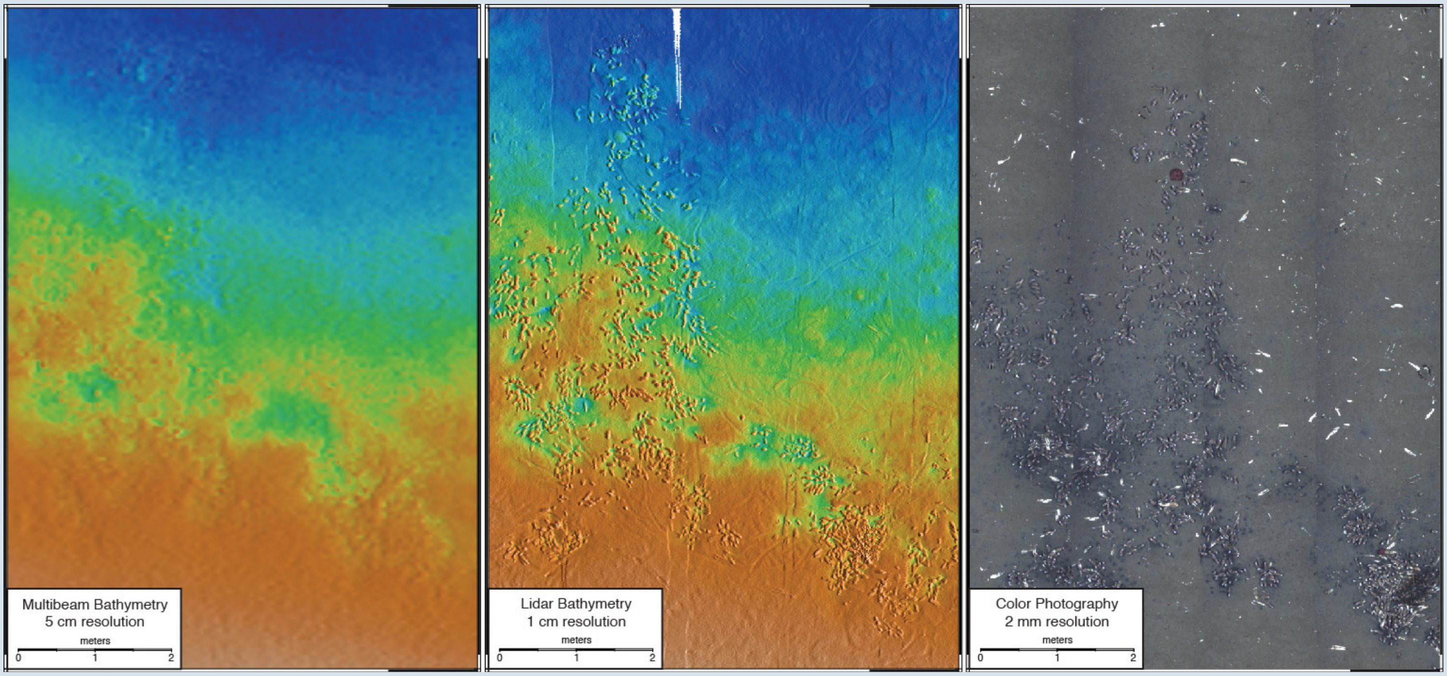


Forage species

In the California Current coastal upwelling regions, nutrients, ocean circulation, and meteorological conditions determine overall ecosystem productivity. However, the structure of the food web determines the spatial distribution, rates, and pathways by which this productivity is cycled through the ecosystem to the deep sea. Central to that cycling pathway in coastal regions are forage species. In upwelling systems these animals include krill and small pelagic fishes near the base of the food web that funnel the organic matter created by photosynthesis to higher trophic levels. This linkage is key to transferring climate-driven variability to larger marine animals including commercially important fishes.

To improve our ability to predict how variations at the base of the food web influence populations of large animals and top predators, refinement and expansion of models that include the forage species are needed. In parallel, researchers need to develop the means for empirically measuring key components of the ecosystem—the diatoms, zooplankton, small pelagic fishes, etc.—to validate and improve the utility of the predictive models.

Forage species include, from top, krill (1–2 centimeters), myctophids (2–10 centimeters), and sardines (10–20 centimeters).



The above maps show a six-meter-by-nine-meter piece of an 80-meter-by-80-meter survey conducted in a single ROV dive; left, five-centimeter resolution bathymetry derived from the multibeam sonar; middle, one-centimeter resolution lidar bathymetry; right, two-millimeter-resolution photomosaic. Both bathymetric maps are illuminated from the right. Note that the lidar bathymetry shows animal tracks not seen in the photomosaic.

Imaging the seafloor

MBARI has been operating an autonomous underwater vehicle (AUV) optimized for seafloor mapping since 2006. This internally developed *Dorado*-class AUV, named the *D. Allan B.*, has conducted over 170 successful surveys yielding one-meter-resolution bathymetry and backscatter data, and five-centimeter-resolution images of subsurface sediment structure. These maps have enabled scientists to identify and characterize recent volcanic flows, earthquake faults, gas seeps, and hydrothermal vents on the deep ocean floor—areas of great interest to geologists, chemists, and biologists. MBARI researchers have become adept at using the mapping AUV to explore areas of interest and then using the maps to target specific sites for ROV-based inspection and sampling. Repeated surveys have been used to detect seafloor change in both volcanic and submarine canyon contexts—the former due to the eruption of lava flows and the latter due to sediment transport via turbidity currents.

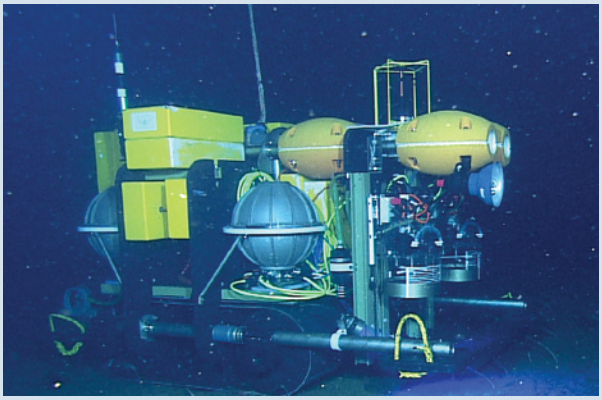
MBARI's current seafloor mapping technology development effort is focused on low-altitude surveys that will enable monitoring of benthic habitats at the scale of the animals that live there. Rather than operating sonars from an altitude of 50 meters, as with the *D. Allan B.*, these surveys are conducted from altitudes of two to three meters, and are intended to yield bathymetry with a resolution of less than five centimeters and photographic imagery with resolution of a few millimeters. The most recent tests done from ROV *Doc Ricketts* at 2,850-meters depth in Monterey Canyon combine a 400 kHz multibeam sonar, stereo cameras illuminated using dual xenon strobes, and a newly available lidar (laser scanner system). As figures here demonstrate, the lidar produces one-centimeter-resolution bathymetry sufficient to image individual animals within a chemosynthetic community. Data processing and navigation are among the most difficult remaining technical challenges to overcome. Ultimately, the goal is to operate the low-altitude survey system from an AUV, but that requires that MBARI obtain or develop a new, low-speed, hover-capable autonomous platform.

Problem Statement #6. *Relate water-column conditions and variability to the abundance, distribution, and activity of organisms*

From the sea surface to the seafloor, the ocean water column can give the appearance of being almost featureless. Despite this seeming homogeneity it is filled with chemical, physical, and biological structural features. In addition to its spatial complexity, the water column has a high degree of temporal variability that is seldom measured. The lack of long-term measurements makes interpretation of these patterns, distributions, and abundance of organisms unpredictable.

Time-series studies yield comprehensive baseline measurements of ocean structure and function. Such assessments are essential for determining and predicting the biological repercussions of changes in temperature, oxygen concentration, acidity, and other perturbations. Sustaining and integrating such measurements from MBARI's unique time-series research is a significant challenge because of the intensive effort required. Furthermore, transferring these methods and technologies to other potential users is severely limited by economic and logistical constraints. The cost, labor, and infrastructure associated with making these primary observations from the top to the bottom of the water column, along with storing, integrating, and querying the data, must be reduced. Progress made toward these objectives will enhance our ability to continue this vital research locally, and catalyze the transfer of MBARI's tools and techniques to many others around the world.





From left, mooring in Monterey Bay, launch of the remotely operated vehicle Ventana*, the Benthic Rover on the seafloor.*

Towards integrated and sustainable time-series measurements

The ocean is in transition and as its stewards we must be able to recognize, measure, and evaluate the consequences of this unprecedented change. Critical to this challenge is establishing baselines that make the effects of change apparent. Time-series studies are dynamic baselines that reveal natural patterns of variability, and how these patterns are altered by human-induced changes.

MBARI's three ongoing time-series studies focus on different habitats: the upper water column, the ocean's vast midwaters, and the deep seafloor. Each effort employs different technologies yet together they cover the entire ocean habitat from surface to benthos. Each has proved invaluable in providing new ways to understand ocean processes. Nowhere else in the world is such coverage available.

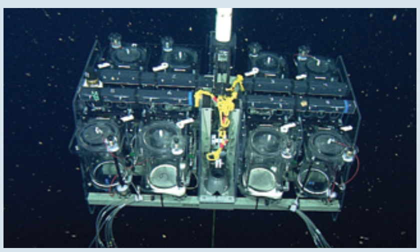
The drawback of time series is that they require a long-term commitment of resources to sustain the measurements. MBARI has embarked upon a unique project to integrate and automate time-series research. The goal is to link the three studies to measure material and energy flux through the whole ecosystem and to do so with advanced technologies that make it far less costly. Ultimately, this approach will be exportable to researchers around the world to support studies on a global scale.

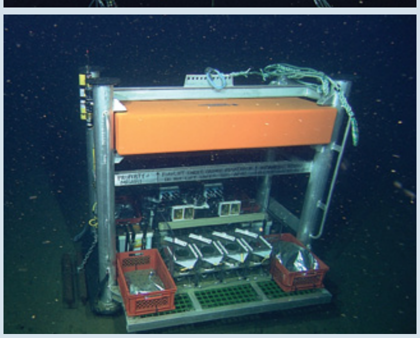
Exploration and discovery

Access to the sea and the varied environments found within our operational domain fuels MBARI's engineering innovation and methods development and leads to scientific discovery. Technological and scientific progress that we achieve regionally creates opportunities for applying our operational know-how and expertise elsewhere throughout the world ocean. Technologies needed to address this broad theme range from improving data analytics to enhancing the means for conducting field research.

***Problem Statement #7.** Devise informatics tools for understanding the ocean and its inhabitants*

The quantity of ocean data has increased exponentially over the past three decades. Satellites, in situ sensor arrays, ROVs, autonomous platforms, molecular biological studies, and numerical models have all contributed to this ever-growing influx of information. The emerging challenge for handling marine data comes at a time when commercial entities are spurring a technological revolution in interpreting large and diverse data sets. Advances in computer science, mathematics, and domain-specific knowledge are creating a technical foundation





The Midwater, top, and Benthic Respirometer Systems, below, each have eight chambers for controlled experiments on the impacts of decreasing oxygen on the metabolism of deep-sea animals. The Free Ocean Carbon Dioxide Enrichment system, above right, can be deployed on the seafloor for months at a time to test animal responses to increased concentrations of carbon dioxide or other chemical perturbations.

Understanding the limits of life

MBARI has been uniquely successful in dealing with a problem that has plagued deep-sea biologists for more than a century. How can you trust the results of physiological measurements made on specimens captured at depth, hauled to the surface, and studied in a shipboard laboratory or ashore? The drastic changes in pressure and temperature inherent to this approach have always made the data from such experiments questionable. MBARI has developed three new instruments that make it possible to carry out the needed measurements in situ, eliminating the complications of pressure and thermal stress.

The Benthic and Midwater Respirometer Systems (BRS and MRS) measure the oxygen consumption rates of animals under a variety of controlled experimental conditions, in their natural habitat. Deployed by an ROV, each system is self-contained and preprogrammed. The Free Ocean Carbon Dioxide Enrichment (FOCE) system provides a chamber in which different concentrations of carbon dioxide can be injected while the apparatus rests on the seafloor. By placing specimens in a chamber, researchers can compare the reactions of those receiving the dose of carbon dioxide with those living just outside the chamber. The BRS, MRS, and FOCE all provide the means to assess how deep-living species will fare under conditions that realistically represent the future ocean.

that MBARI can draw upon as the flow of information from ocean sensor systems continues to expand.

There are several pressing needs in the realm of marine data analytics: information management and analysis systems for data already in hand as well as for data that will be acquired in the future; new analytical tools that more fully utilize the information being collected; and integration of data collection and computer models to distill information quickly for more effective study and management of the ocean and its resources.

Problem Statement #8. *Conduct expeditions and experiments that provide insights into the future ocean: expansion of oxygen minimum zones as a case study*

The oxygen minimum zone (OMZ) is a persistent midwater layer of reduced oxygen content. OMZs occur in about 15–20 percent of the global ocean, and a pronounced OMZ is found beneath the surface waters of Monterey Bay and its contiguous waters. Ongoing research at MBARI has clearly demonstrated that the regional OMZ is expanding and that this change is having a measurable impact on certain species; this pattern is also reflected elsewhere in the world. Beyond being a focal point of scientific inquiry, the expansion of OMZs is also of great concern to resource managers and conservationists.

There are a number of significant challenges to be faced when investigating this changing ocean landscape, including measuring oxygen and related parameters over time and space, determining causes of declining oxygen levels, and characterizing the impacts of these changes on keystone species and communities. Current research at MBARI is contributing extensively to such assessments. Moreover, whereas most oceanographers are limited to inferring consequences of changing oxygen conditions, MBARI is uniquely tackling this problem by conducting controlled experiments in situ to directly evaluate cause-and-effect relationships.

Advancing OMZ research further will require quantifying the distribution patterns of many more species than is possible at present, and those measurements are labor intensive even with the specialized capabilities MBARI possesses at present. Consequently, new tools and techniques are needed to assess community composition and biomass within the context of well-characterized chemical/physical horizons. This information is also needed for formulating and executing new targeted experiments to investigate the mechanisms underlying changes gleaned from time-series studies. The same considerations apply equally to synergistic investigations focused on ocean warming and acidification.

Engineering Challenges and Opportunities

The scientific challenges and technology needs identified in the preceding section are complex and of interest to ocean researchers and resource managers around the globe. Embedded within these large issues are unique opportunities for MBARI to contribute fundamental technological advances that will enable innovative research efforts locally and elsewhere. From that perspective, we will advance three overarching institutional priorities for coordinating a broad suite of engineering activities:

- ***Taking the laboratory into the ocean***
- ***Enabling targeted sampling***
- ***Advancing a persistent presence***

Each of these concepts is briefly summarized below along with a set of opportunities to which MBARI is poised to respond.

Taking the laboratory into the ocean

One of MBARI's hallmarks is developing technologies for carrying out experiments in situ. This has proven to be extremely valuable for addressing questions related to ocean acidification, expansion of oxygen minimum zones, and the emergence of dead zones. These studies were based on realistic climate scenarios, fundamental chemical principles, and historical observations. How will the projected changes impact marine life and humans? What sampling and sensor systems are needed to test these projections, and where should they be located? How can various sources of information be combined to gain insights into trends and to establish testable hypotheses?

MBARI's operational assets and ready access to the sea ideally position the institute to address such questions. For example, in situ experiments on methane hydrates and carbon dioxide in the deep sea demonstrate the necessity of making measurements under ambient conditions. Similarly, the development of tools for observing midwater animals in their natural state has led to numerous discoveries that would have been impossible to achieve using traditional methods like trawling. The FOCE system and in situ respirometers are presently providing the means to assess the responses of organisms to experimental manipulations that mimic conditions of the future ocean. Profiling floats equipped with biogeochemical sensors provide a way to autonomously detect fluxes of material through broad swaths of the ocean over multi-year time scales, without recovery and service. The Environmental Sample Processor (ESP) can be used to quantify nucleic acids

An intersection of goals: the Packard Foundation, the Monterey Bay Aquarium, the Center for Ocean Solutions, and MBARI

- One of the David and Lucile Packard Foundation's long-term goals is to restore the health and productivity of the world ocean, on which all life depends.
- The mission of the Monterey Bay Aquarium is to inspire conservation of the ocean.
- The Center for Ocean Solutions works to solve the major problems facing the ocean and prepares leaders to take on these challenges.
- MBARI's overarching goals are to:
    - Develop or adapt innovative technologies that allow researchers to identify and resolve important questions and advance our understanding of the ocean.
    - Utilize those developments to explore and understand how natural ocean systems operate and how they respond to natural and anthropogenic change.
    - Transfer the knowledge gained, solutions devised, and the technology developed to communities outside of MBARI—researchers, educators, policy makers, resource managers, industry, and the general public.

and other biochemical signatures in near real-time, where they naturally occur. In all cases, the objective has been to retrieve information from the field directly, under natural conditions, and eliminate the traditional requirement for shore-side analyses of retrieved samples. MBARI is uniquely suited to continue this line of work.

The volumes and types of information collected in the future will present many opportunities as well as significant technical challenges. Some new sensors—especially those based on imaging and genomics techniques—will generate enormous amounts of information. Their use and integration with traditional measurements must be supported by equally sophisticated tools for data analysis. New analytical techniques will be needed for detecting relationships between disparate data types, and for revealing signals indicative of ocean change. Coupled physical-biological models will continue to be refined to help reveal the organizational and dynamic principles of marine ecosystems. However, to fully exploit the potential of this approach, methods for linking empirical observations to the models must be improved and the means to experimentally validate projections must be enhanced.

With these ideas in mind, MBARI can maintain its leadership in conducting in situ experiments by:

- Continuing development of novel chemical and biological sensors for use in the ocean, especially for investigating biogeochemical processes and the determinants of organism survival.
- Developing new ways for capturing organisms in situ and for conducting experimental manipulations under ambient conditions.
- Developing new tools and techniques for identifying, quantifying, and characterizing species ranging in size from picoplankton to zooplankton and larger animals.
- Developing methods for seamlessly merging molecular biological data with other environmental observations.

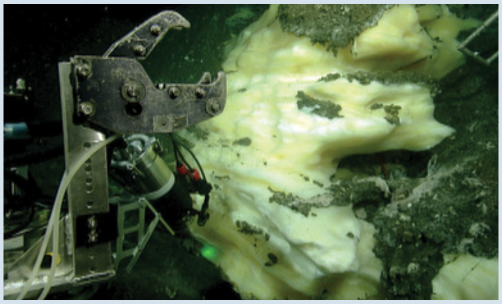
Enabling targeted sampling

High-resolution maps of the seafloor and detailed renderings of the water column are essential for directing future ocean observation and sampling activities. Where are the features of interest? How do they change over time? How can a limited number of collections or the placement of high-value instru-

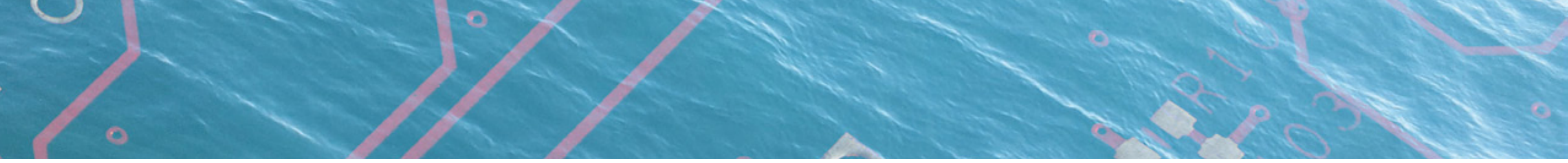
Leveraging new technology

In an age of rapid technological progress, advances in the ocean sciences can emanate from domains far removed from the sea. For example, Raman spectrometers are optical systems which provide information about the chemical composition and molecular structure of material. Although such devices have been in use on land for years, advances in the 1990s made the systems sufficiently small and capable such that in 2000 MBARI scientists and engineers adapted one of these delicate instruments for use in the ocean. The first in situ experiment using the instrument resulted in Raman spectra of liquid CO_2 and CO_2 hydrates at the high pressures and near-freezing temperatures of the deep sea. Subsequent studies have used the spectrometer to examine rock samples, shells, bacterial mats, ice-like methane hydrates, and pore waters in the seafloor sediments, opening a path to new insights in deep-sea chemistry and biology.

Other new technologies that MBARI is adapting for use in the ocean include genomic instrumentation such as digital PCR, advanced rechargeable battery systems, advanced mapping sonars, lidar imaging sensors, and next-generation navigation systems.



The green laser of the Raman spectrometer points at a wall of gas hydrate in Barkley Canyon. By focusing the beam and examining shifts in frequency of the light scattered back, scientists can ascertain the structure of the water cages that bind the gas into the massive ice-like structure seen here.



ments be optimized to test a specific hypothesis or to meet an observational need?

MBARI has historically met the challenges associated with targeted sampling by specifically directing ROVs to collect material or make particular measurements. More recently, the tandem use of AUV mapping and directed ROV operations has significantly improved on that model for a host of seafloor studies. The Controlled, Agile, and Novel Observing Network (CANON) initiative takes targeted sampling a step further. In CANON, a heterogeneous mix of mobile and drifting platforms is applied to observe changes in upper-water-column communities over time and space. The information obtained in real-time is used to direct sampling activities and to address questions concerning organismal responses to natural perturbations.

Precision navigation is one of the key challenges related to achieving targeted sampling capability. Developing time-series observations of the seafloor requires precise geo-registration of discrete observations so that data sets obtained at different times, even if separated by decades, are directly comparable. Within the water column, the navigation problem is different. Distinct water masses and the organisms within them are in constant motion. Consequently, a fundamental challenge for studying pelagic communities is to identify their trajectories in space and time, and to follow them. This kind of biologically focused observing can provide a new avenue for studying how marine organisms respond to their environment and to each other, as well as allowing direct observation of their life cycles.

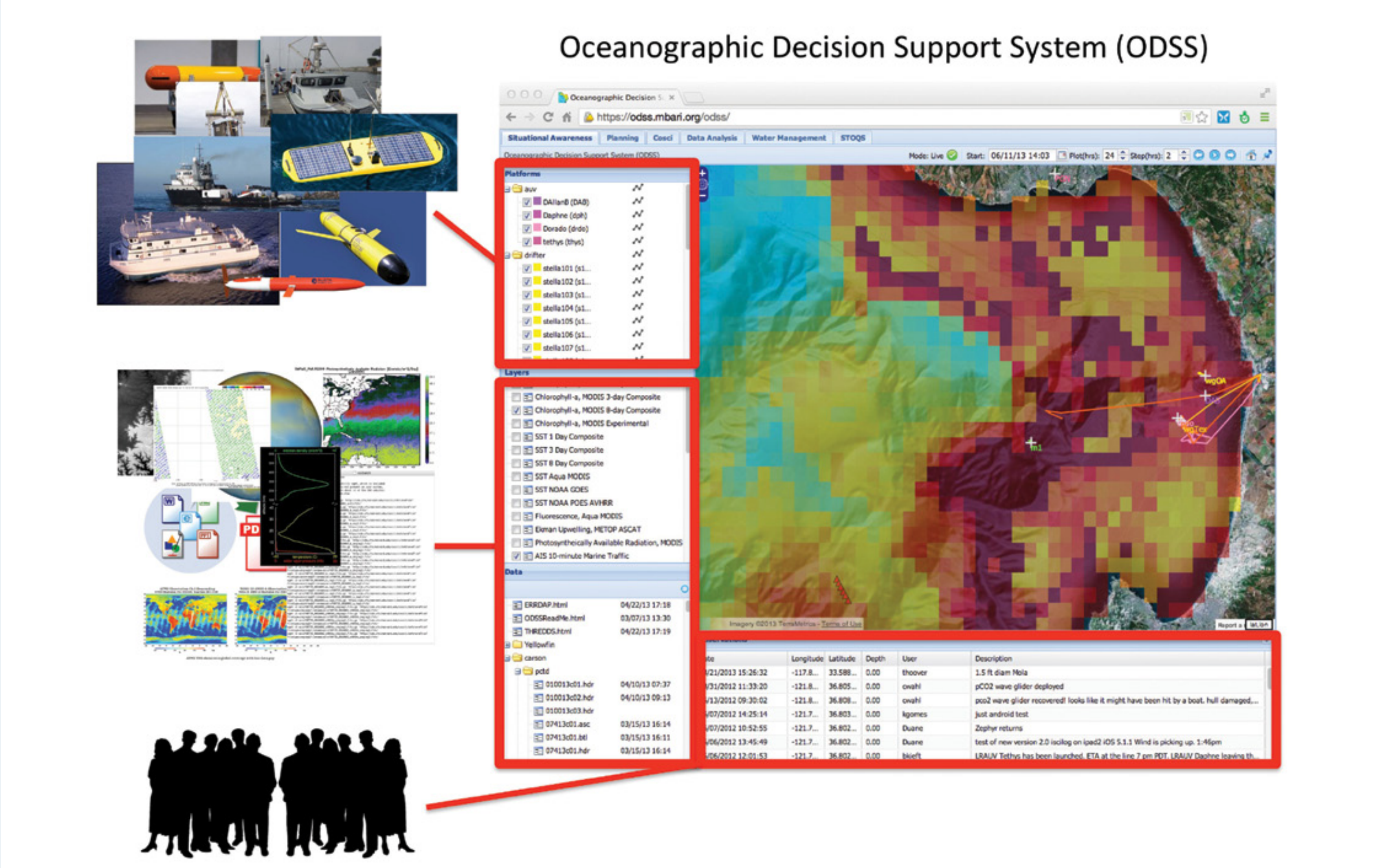
Autonomy and system reliability are important to realizing a robust targeted-sampling capability that can function without constant human supervision and in remote locations. Enabling non-expert users to operate a robotic platform, or a group of robotic platforms, under real-world constraints is a formidable challenge, yet one that is key to transferring this new technology to the scientific community at-large. System reliability also becomes critically important as deployments extend in duration, and missions requiring coordinated measurements become increasingly complex. Subsystem failures and unanticipated environmental challenges must be tolerated without always necessitating human intervention. These engineering challenges are in many ways analogous to creating driverless cars and managing drone networks, but underwater operation in the far reaches of the ocean complicate the problem space significantly.

Specific technological pursuits related to targeted sampling include:

- Automating classification schemes for real-time characterization of marine features, organisms, and communities to identify targets for selective sampling.
- Developing capabilities to coordinate both human-controlled and fully autonomous systems that acquire, preserve, and return samples of seawater, plants, animals, and other material.
- Developing seafloor and water-column navigation, mapping, and sensing capabilities with an accuracy that allows us to quantify change at the scale of individual organisms.
- Developing methods for assimilating empirical observations into four-dimensional, coupled physical and biological models.

Advancing a persistent presence

MBARI's goal of establishing an extended ocean presence dates to its founding with the investment in ships, ROVs, and the OASIS moorings. Over the years, the number and diversity of robotic systems developed at MBARI have increased, and now includes AUVs, the Benthic Rover, the mini ROV, the FOCE systems, in situ respirometers, benthic camera systems, the deep-ocean Raman in situ spectrometer, the ESP, and the Monterey Accelerated Research System cabled observatory. We also employ a broad range of commercially built robotic systems including buoyancy-driven gliders and floats, Wave Gliders, and other systems. Every science thrust



The Oceanographic Decision Support System is used to coordinate interdisciplinary field programs by providing a situational awareness of multiple platforms and sensors, top, and their associated data streams, middle, and a forum for investigators to exchange ideas and chart future activities.

Innovation through integration

A modern interdisciplinary oceanographic field program may involve multiple ships, moorings, drifters, and various types of robotic platforms, all of which must operate in concert with one another. Success depends on being able to integrate the diverse capabilities and varied data streams from such assets into a focused and effective "super system". MBARI is in a unique position to bring a critical mass of engineering talent to realize such capabilities, and to evaluate their scientific application over a period of years. The ability to sustain engineering development and application efforts reaps powerful dividends: underlying technical challenges are identified and can be solved iteratively based on firsthand field experience, new scientific methods are devised and tested, and the interdisciplinary nature of the work catalyzes collaboration with others from organizations outside MBARI. The collaborative element brings new talent to bear on problems, and provides a mechanism for transferring MBARI innovations beyond the walls of our institution.

A number of high-impact technologies have come out of MBARI's work to develop integrated ocean observing systems, including the Programmable Underwater Connector with Knowledge (PUCK), the Shore Side Data System, and the Software Infrastructure and Application for MOOS. PUCK is now an Open Geospatial Consortium standard, implemented by several manufacturers. Current work includes developing the Oceanographic Decision Support System—a web-based portal that allows scientists and engineers to interact with large-scale ocean observing systems.

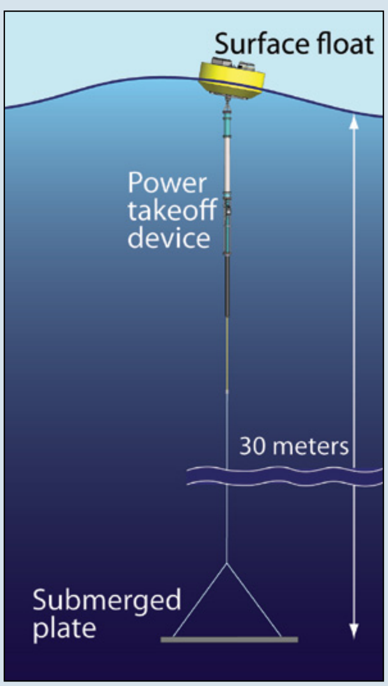
at MBARI uses robotic systems in one way or another, and all of them have benefited directly from having a dedicated fleet of MBARI-owned and operated ships that facilitated their development and application. How do we further capitalize on such investments and advances?

A focus on sustaining robotic systems in the ocean is one way to significantly expand MBARI's regional presence without necessarily increasing ship usage beyond current levels. In that context, energy use and storage remain fundamental design drivers and performance limiters for virtually every type of in situ ocean instrument or robotic platform; power management must be improved. Looking forward, cooperative, multi-platform observing systems are becoming practical, allowing for greater geographic coverage and for specialization to accomplish particular tasks. To fully exploit this opportunity, the means for communicating with an array of next-generation robotic systems must be enhanced.

In addition to developing a vision for the future, it is essential to preserve the recorded data of the past. The information MBARI has amassed thus far is a legacy of our enhanced ocean presence. A long-term, sustainable system must be in place to ensure archival digitization of the historic database, so that data mining can continue into the future. Work to develop that capacity must anticipate the advent of new sensors and platform systems so that the accruing information builds on that legacy.

MBARI is ideally positioned to combine ship operations, robotic platforms, and data systems to extend our ocean presence. A suite of platforms and sensor systems can be readily assembled and deployed to serve a wide range of investigations. The data we have collected to date can be mined to enhance hypothesis generation, and to develop schemes for testing ecosystem models and projections. Future activities in this area include:

- Improving the energy efficiency of sensors and platforms, and the means for safely fielding energy-dense power sources.
- Developing more capable, next-generation robotic and communication systems.



Invention

The demanding science problems central to MBARI's strategic plan pose unique technical challenges. Powering ocean instruments is one such challenge—our ability to make many measurements in remote regions is often limited due to lack of electrical energy. Adapting solar and wind power for moorings was an early and significant advance, but on mooring sizes used by MBARI these approaches only generate about 50W year-round in Monterey Bay. Consequently, MBARI pioneered the Power Buoy concept to translate wave energy into electricity. A theoretical understanding of object dynamics near the ocean surface and the ability to accurately model mooring systems allowed MBARI engineers to achieve a sixfold increase in power generated, creating new opportunities for further advances like recharging AUVs and powering more demanding instruments in areas that may not be readily accessible.

MBARI has a history of technical innovation. Unique ocean research tools devised at MBARI include the Video Annotation and Reference System, ROV tool sleds, ROV *Tiburon*, ESP, the gulper water-sampling system for the *Dorado* AUV, in situ respirometers and FOCE systems, and the *Tethys* long-range AUV.

Schematic illustration of MBARI's wave-power buoy.

- Developing sensors that provide well-calibrated measures of specific ocean properties over multi-year timeframes, without requiring routine and frequent instrument recovery and service.
- Developing tools for preserving, exploring, and mining multi-disciplinary data sets.

Path Forward

The challenges highlighted above offer many opportunities for focusing engineering activities at MBARI, and for improving the coordination of our current and future research and development programs. Areas where scientific opportunity and technological need clearly intersect include: sensors and sampling, data analytics and visualization, energy for in situ systems, navigation and localization, autonomy, and robotics. These focal areas are common to many of the scientific problems outlined above, are highly relevant to meeting the larger goals articulated in our Strategic Plan, and are consistent with themes MBARI has concentrated on in the past. They also shine a light on socially relevant objectives, and illustrate ways that MBARI can provide synergistic support for the larger missions of the Packard Foundation, the Monterey Bay Aquarium, and our partners such as those comprising the Center for Ocean Solutions.

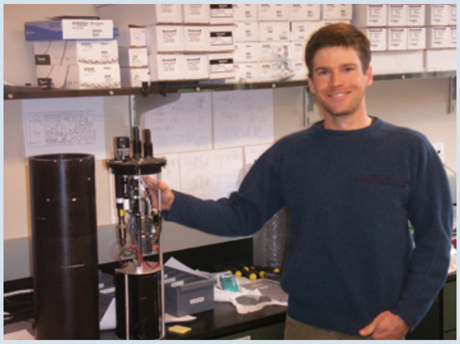
Implementation of the Technology Roadmap

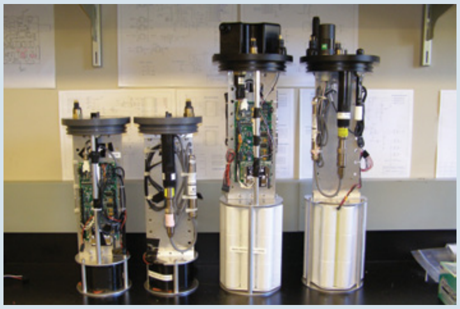
Implementation of the Technology Roadmap will be achieved chiefly through a continuation of our competitive, internal proposal process. We will also continue to selectively leverage funds from external sources. For the annual internal call for proposals we will seek projects that aim for significant science and technology advancements over a five- to 10-year

Technology transfer

The impact of MBARI's technology is amplified by transitioning innovations to the larger community. The most effective method of transfer depends on a variety of factors including complexity, cost, fit with existing methodologies, and the technical sophistication of adopters. Software capabilities can sometimes be transitioned effectively via open-source methods. For example, MB-System is widely adopted open-source software for processing sonar data to make underwater maps. Other more complex systems, such as the In Situ Ultraviolet Spectrophotometer (ISUS) nitrate sensor and the ESP, are best licensed to external manufacturers that can build and support a large user base. Yet other technologies like the ROV vibracore and drilling systems, while scientifically important, do not have a large enough user community to warrant commercialization. In such cases MBARI has built dedicated systems for a few external adopters.

People are often the key to effective technology transfer. MBARI postdoctoral fellows have participated in the development and/or use of technologies like the deep-sea laser Raman spectrometer, ISUS, and ESP. As these individuals move on to establish their own laboratories, MBARI technologies and know-how often follow and become part of their new research programs. The planned expansion of MBARI's postdoctoral fellowship program will create new opportunities for disseminating innovation. Through inter-institutional exchanges and by hosting researchers from other organizations, MBARI's operational techniques and knowledge have been exported to France, Canada, Germany, Italy, Spain, Portugal, Taiwan, China, Mexico, Japan, and a variety of regions in the U.S.





Todd Martz of Scripps Institution of Oceanography with Durafet pH sensors modified during his postdoctoral appointment at MBARI for use in the ocean.

period, punctuated by well-defined milestones that demonstrate unequivocal progress toward meeting our long-term goals. Ideas for internal projects that have a high payoff and are highly innovative, and that are not likely to be supported by traditional, low-risk granting agencies, will be given priority. Extramural projects that address Technology Roadmap priorities should complement internally funded programs. Externally supported programs should allow us to augment our project teams with partners from other organizations, increase our education and outreach capacity, and/or carry out work beyond our traditional operational domain. For both internally and externally funded projects, proposal solicitation and review will ensure that the state-of-art is known, that new opportunities are brought to the fore, and that revelations pointing to needed directional changes are identified. The commitment to disseminate MBARI technology and know-how will create additional opportunities for enhancing partnerships with academicians, resource managers, policy makers, and industry representatives throughout the world.

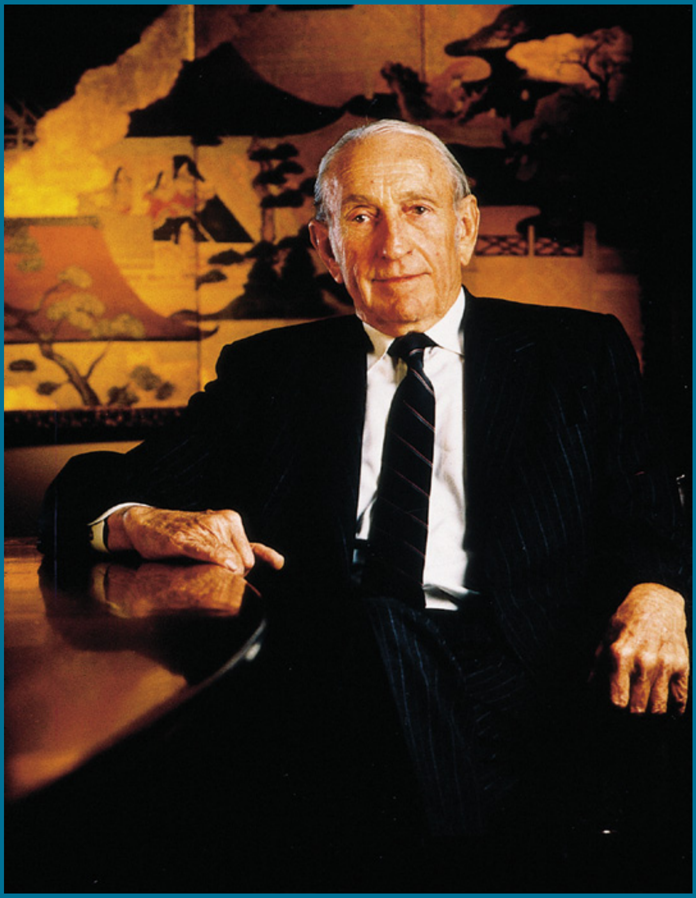
Development oversight

MBARI's institutional objectives incorporate a range of rapidly evolving capabilities and concepts. Coordinating these efforts will require that we be aware of progress in several cross-cutting disciplines, and that we use that knowledge to chart our own course. What technological developments are we uniquely poised to tackle alone? What capabilities are best obtained by working in partnership with other institutions? What elements are already being met by commercial entities and research institutions, or are outside our development scope? In addition to the vetting that occurs via a competitive, annual proposal process, advisory groups of scientists and engineers will be tasked to keep abreast of relevant advances as they relate to MBARI's Technology Roadmap. These groups will assist the MBARI management and staff in setting programmatic priorities. Those priorities, in turn, will contribute to preparing new project proposals as well as guiding long-range planning associated with maintaining and enhancing our facilities. In parallel, the Marine Advisory Committee will recommend upgrades or additions to marine operations assets, in order to implement new technologies or accommodate forthcoming activities. MBARI's Board of Directors will periodically review priorities set forth in the Technology Roadmap and the success of its implementation, and will make appropriate recommendations as required.

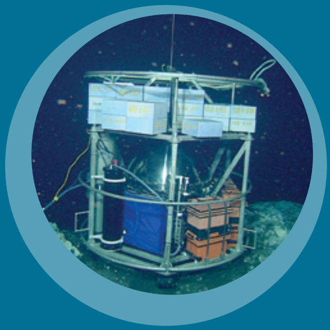
Final considerations

We seek to create, exploit, and disseminate disruptive capabilities that will transform ocean exploration and discovery. MBARI's Strategic Plan and Technology Roadmap provide a framework for such advancement. The science/engineering problems we have chosen to focus on are an ideal complement to MBARI's physical location, facilities, and ethos, and are well matched to the goals of our primary sponsor and partners. These plans will be updated periodically to reflect progress made, changing priorities, and technological innovations that lead to new science and engineering partnerships aligned with our unique mission and capabilities. Toward that end:

- Division directors will adjust MBARI's staffing and organization based on institutional need and trajectory.
- To help bring in new talent for stimulating research and development programs, the postdoctoral fellowship program will be doubled.
- Succession planning to fill vacated science and engineering positions will be based on recruiting individuals with appropriate skills, who demonstrate a commitment to the ideals and directions set forth in the Strategic Plan and Technology Roadmap.
- Refinement and implementation of MBARI's facilities master plan will be carried out in concert with our Board of Directors and the Packard Foundation.



David Packard, founder of the
Monterey Bay Aquarium Research Institute



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Please cite this report as:
Monterey Bay Aquarium Research Institute (2014). Technology Roadmap 2014 .
Retrieved from: http://www.mbari.org/about/TechnologyRoadmap.pdf.

This Technology Roadmap was developed with input from the MBARI Board of Directors and staff, led by a steering committee comprised of Chris Scholin, Doug Au, Jim Bellingham, Joel Birnbaum, Curt Collins, Steve Etchemendy, Bruce Gilman, Ross Heath, Charlie Paull, and Bob Spindel. Kai Lee served as observer representing the David and Lucile Packard Foundation.

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