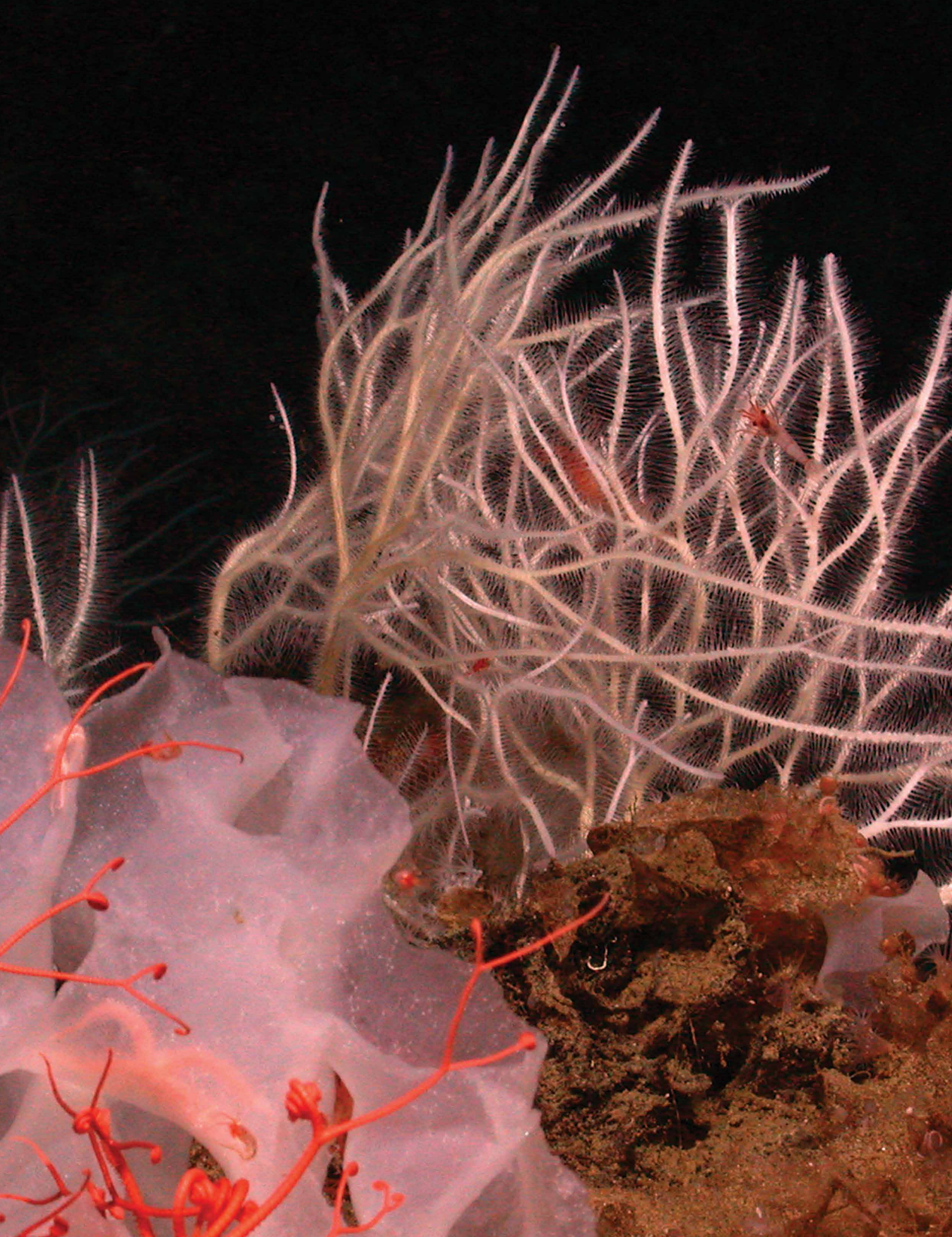
MBARI

Monterey Bay Aquarium Research Institute

2014

Annual Report



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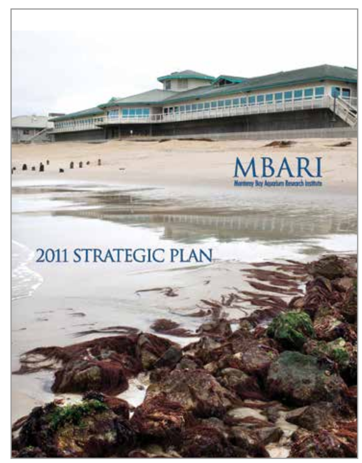
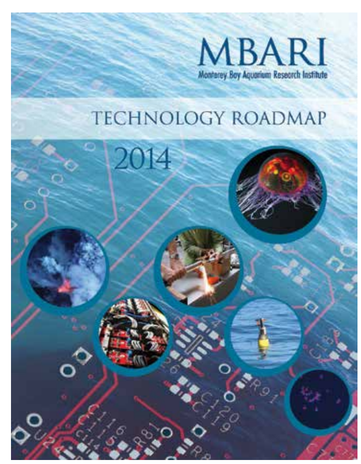
From the Masthead

When David Packard founded MBARI in 1987, he challenged us to develop new methods, instruments, and analytical systems to address fundamental problems in ocean science and to identify new directions where innovative technologies would accelerate progress. This directive fundamentally rests on fostering peer relationships among scientists and engineers, ready access to the sea, and effective communication with the broader oceanographic community as well as the public.

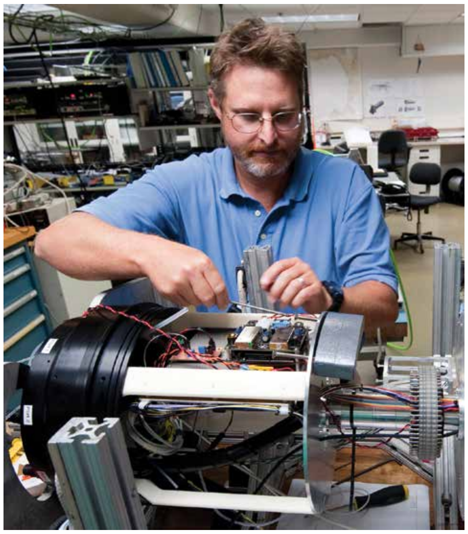
Since our founding, the tools and techniques developed at MBARI have increasingly been organized around the concept of detecting ocean change—understanding how the ocean is responding to both natural processes and human activities, and how such changes may impact society. This focus is critically important now as we see unprecedented alterations taking place in marine systems on a global scale: warming, acidification, declining oxygen, rapid reductions in sea ice cover, retreating glaciers, and sea level rise. There is no doubt that ocean ecosystems are on the move, and it is very likely that the ocean of the not-so-distant future will in many ways be different from the one we know today. Given the interconnections between the ocean, the atmosphere, and land, people are also likely to experience profound environmental changes unlike anything before, regardless of how close they live to the seashore.



In 2011 we published a Strategic Plan that captured MBARI's plans to document a rapidly changing ocean under the guise of four major research themes: *Exploration and discovery, Ocean visualization, Ecosystem processes, and Biogeochemical cycles.* However, the Strategic Plan did not identify technical capabilities needed to attain that vision, so in 2012 we set out to develop a Technology Roadmap to addresses that gap.



The Technology Roadmap took root with input from staff from all divisions and it carries key contributions from MBARI's Board of Directors and representatives of the David and Lucile Packard Foundation. Collectively, we laid out a set of socially relevant science challenges based on the themes articulated in the Strategic Plan. Those questions were used to derive a set of engineering priorities which in turn will be coordinated under three overlapping initiatives: *Taking the laboratory into the ocean,*



Mechanical Engineer Doug Pargett builds the third-generation Environmental Sample Processor.

Enabling targeted sampling, and Advancing a persistent presence. We also outlined a strategy for implementing the roadmap, including forming technical advisory groups to improve project review and prioritization, and guidelines for soliciting extramural grants in addition to the funds made available through the Packard Foundation. Publication of the 2014 Technology Roadmap two years after initiating the writing effort is a notable accomplishment for all of us at MBARI.

Reflecting back on our efforts to craft and implement this vision served as the inspiration for organizing the 2014 Annual Report. Like the Technology Roadmap, the projects highlighted here build from a functional perspective beginning with the basic transformations of matter and energy, then transition to higher order system concepts, and end with an integration of activities that cross disciplinary divides. Throughout this volume the opportunities and challenges of merging science and engineering are apparent. And it is also clear that none of that work would be possible without unfettered and expert access to ocean.

For that reason, this year's *Behind the Scenes* section is dedicated to those who work in the Division of Marine Operations (DMO)—the ship crews, remotely operated and autonomous underwater vehicle teams, and all who make day-to-day seagoing activities possible. DMO's contributions to scientific discoveries and engineering advancements are innumerable and, to the uninitiated, can be easy to overlook. Yet, at MBARI, project leads and their support staff are quick to point out how essential our marine operations personnel are in carrying out MBARI's unique mission.

Looking back on 2014 further, I am proud that we succeeded in casting long-term plans that will serve society as well as remain true to David Packard's original charge to focus on fundamental research and development. We've learned a great deal about how to stimulate innovation, and gained a sense of the unique role that MBARI can play in advancing the ocean sciences. As a result, we also see new opportunities for furthering the larger goals of the Packard Foundation, the Monterey Bay Aquarium, our partners comprising the Center for Ocean Solutions, and the Monterey Bay National Marine Sanctuary, as well as many other oceanographic research institutes locally and around the world.

There is no doubt that the year ahead will bring its own set of challenges and opportunities, some that were anticipated and others that were not! A major undertaking of 2015 is an expedition to the Gulf of California. The trip to Mexico rests on a series of scientific investigations that span all four research themes highlighted in the Strategic Plan. Those studies, and the many others that will take place in local waters, are made possible by the Packard Foundation's investments in MBARI's science programs, engineering developments, and infrastructure improvements. The roadmap for the foreseeable future is set—we are off to the races!

All of us at MBARI look forward to the unanticipated discoveries that the coming year will undoubtedly bring. We hope you do, too, and we invite you to follow our progress on the web, YouTube, Facebook, or Twitter.

Chris Scholin
President and Chief Executive Officer

Related web content:

2011 Strategic Plan: www.mbari.org/about/sp/MBARI_Strategic_Plan_2011.pdf

2014 Technology Roadmap: www.mbari.org/about/TechnologyRoadmap.pdf

MBARI website: www.mbari.org

MBARI on Facebook: www.facebook.com/MBARInews

MBARI on Twitter: twitter.com/MBARI_news

MBARI on YouTube: www.youtube.com/MBARIvideo

Biogeochemical Cycles

Life in the ocean depends on the surrounding physical and chemical environment and the capacities of organisms to grow, survive, and reproduce. These fundamental interactions change continually as a result of natural processes that modulate the cycling of elements on which all life depends. Those interactions are being increasingly perturbed by human activities, and the consequences of these changes for marine systems and society are not yet known. For these reasons, MBARI is developing improved ocean sensors and other technologies to help understand the processes that underlie natural and anthropogenic change in Monterey Bay and beyond.

A very warm Pacific Ocean

The eastern Pacific was unusually warm in 2014 and numerous temperature records were broken in western North America, from Alaska to Arizona. For the second summer and fall in a row, Monterey Bay attracted enormous schools of anchovies and their predators—birds, sea lions, dolphins, and throngs of humpback whales very close to shore (Figure 1). What was going on?

During a typical year, trade winds push water across the Pacific from the Americas to Indonesia. However, when the trade winds reverse in the western Pacific as they did in spring of 2014, the shift

Figure 1. Humpback whales were a common sight in Monterey Bay in 2014, sometimes coming in close to shore, such as this day in July when the whales were right offshore of the MBARI building.

prompts predictions of a condition known as "El Niño", an ocean and atmosphere phenomenon that has significant effects on global weather patterns. A strong El Niño results in warm sea-surface temperatures and increased rainfall and floods in California and northern Peru, and drought in the West Pacific.

The large El Niño was not to be. What did materialize were unusually warm sea-surface temperatures in the North Pacific during the second half of 2014 (Figure 2). The North Pacific patterns were similar to those observed during El Niño, but without the large area of anomalously warm water in the eastern tropical Pacific. These unusual North Pacific conditions helped make 2014 the warmest year ever observed globally and over the 120-year instrumental record for California.

The timing and duration of the warm condition in 2014 was captured beautifully by sensors on MBARI's M1 mooring in Monterey Bay (Figure 2). A sea-surface temperature of 18 degrees Celsius was observed in late August, the warmest ever measured during the 25-year record at that site, warmer than the 1997-98 "El Niño of the century." The warmer-than-average North Pacific temperatures were enhanced in Monterey Bay and the California Current during summer, as the cold-ocean/hot-land gradient lessened, weakening winds that normally drive the upwelling of cold, nutrient-rich water to the surface. Less wind after July resulted in unusually warm, clear, and relatively unproductive coastal waters. Measurements of nitrate, a key nutrient that fuels growth of phytoplankton, were surprisingly low (Figure 3).

MBARI-developed sensors have allowed measurement of nitrate near the surface at the M1 mooring since 2002. The nitrate values measured during the second half of 2014 are the lowest on record. During upwelling events in normal years, nitrate concentrations at the mooring increase to values from five to 30 micromolar. Yet, from August through November of 2014, the average daily nitrate did not exceed one micromolar. This was unprecedented.

Such low nitrate concentrations were accompanied by lower than average levels of chlorophyll, indicating a decrease in phytoplankton abundance, although not as dramatic as what one would surmise from just sea-surface temperature and nitrate values alone.

One significant difference between the warm 2014 conditions in Monterey Bay and El Niño conditions was that, during El Niño, a relatively thick layer of warm, nutrient-poor waters on the surface caps the nutrient-rich waters below, limiting plant growth. During 2014 the warm water layer was thinner, and some deep-water nitrate that was supplied to the surface waters was consumed immediately and therefore never measured at M1.

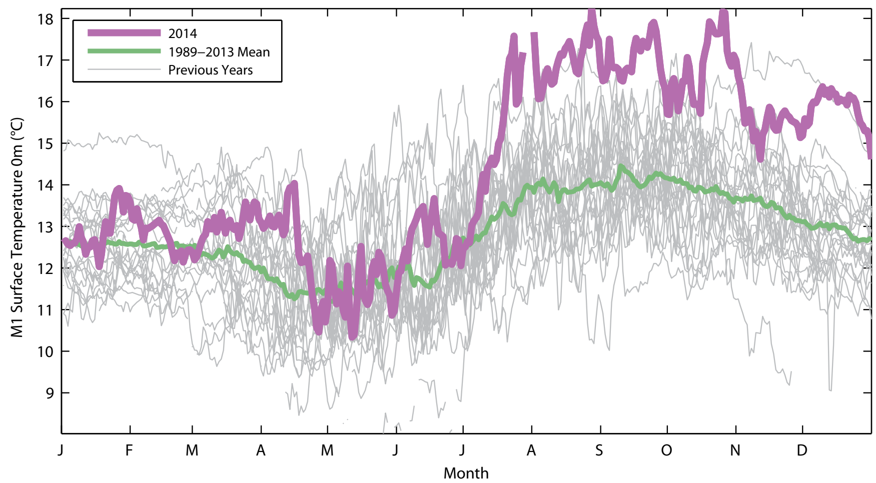


Figure 2. Daily sea-surface temperature measured at the M1 mooring in Monterey Bay during the second half of 2014 was well above average with the highest temperature since 1989.

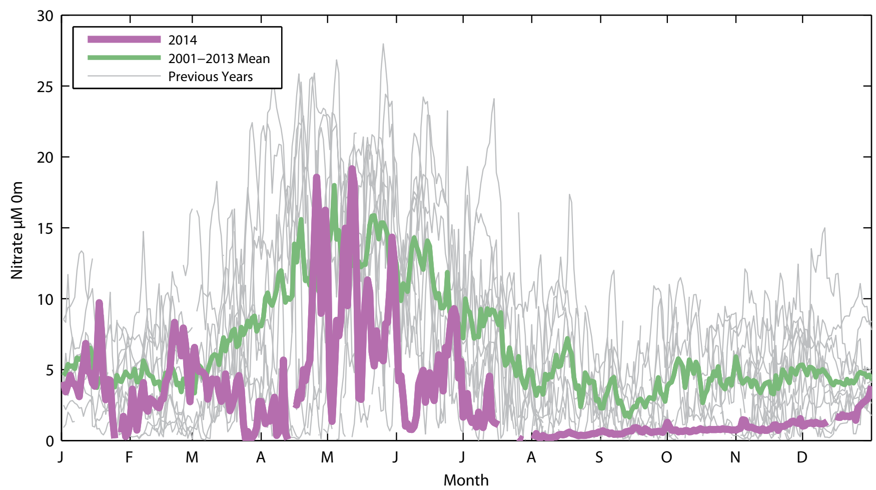


Figure 3. Daily surface nitrate measurements at the M1 mooring during the second half of 2014 showed that these were the lowest since the record began in 2002.

The bonanza of marine wildlife seen in Monterey Bay, and the whales in particular, resulted from the lower but significant levels of primary productivity and a contraction of the upwelling ecosystem that is normally about a hundred kilometers broad along the coast to a system that is one-tenth that wide and present within Monterey Bay. An abundance of whales was observed feeding on anchovies in the bay, but not many in other places where they normally forage such as near the Farallon Islands off San Francisco. The unusual distribution of wildlife may be a consequence of predators chasing concentrated prey that would normally be spread out over a much larger area.

The unusually warm and anomalous 2014 leads us to a more speculative topic: What is in store for Monterey Bay and the North Pacific in coming years? Observations of ocean biology may provide some answers. Plants and animals are immersed in their surrounding environment, and depend on it for growth and survival, so they are more sensitive to detecting change than our present-day instruments. For example, a few years ago the populations of sardines in the California Current began dwindling. This decrease affected the bluefin tuna that spend time foraging here before returning to the western Pacific to spawn. These changes were eventually detected by fisheries researchers, but many months or even years later. The recent bonanza of whales in Monterey Bay over the past few years has been attributed to increases in the populations of anchovies, which may have replaced the sardines. Were these cascading ripples preludes to a record warm 2014 and a change of regime?

One of MBARI's future challenges will be to develop technology to track marine life as oceanographic properties such as temperature and nitrate are currently tracked today. Ultimately researchers hope to use naturally occurring communities of marine organisms as sensors unto themselves to predict what lies ahead for life in the sea.

A sensor array for the coastal ocean

A warming climate, ocean acidification, loss of sea ice, decreasing oxygen concentrations, increased runoff from the use of nitrogen fertilizers on land, and a variety of other processes, are expected to impact coastal waters around the globe in future years. Further, the coastal zone is naturally an area of extreme variability. Tracking and understanding the consequences of these natural and human-caused perturbations thus requires networks of sensor systems capable of sustained operations over decades. Ken Johnson's Chemical Sensors Group is developing a coastal profiling float (CPF) to meet those needs (Figure 4). Building on the success of the global Argo array of free-drifting profiling floats, the coastal system is designed to anchor on the seafloor at depths down to 500 meters, then travel up through the water column to the surface while measuring an array of chemical and biological properties. At the surface, the float sends the measurements collected back to shore via satellite and descends to depth again.

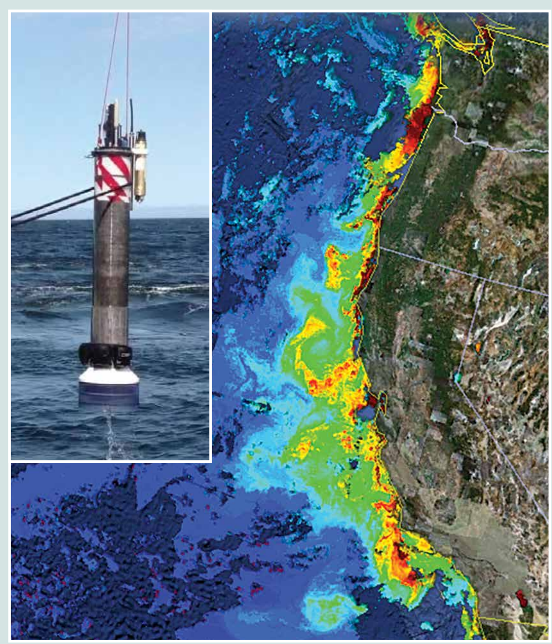


Figure 4. This graphic of sea surface temperature shows a variety and scale of some oceanographic features along the West Coast of North America. Inset: A prototype of the coastal profiling float, which is about 1.5 meters tall.

The coastal float is designed for a persistent presence at sea. The instrument can be recovered as needed, but generally will require no operator intervention other than onshore processing of near-real-time data. Minimizing at-sea operational costs for a large array of CPFs (hundreds of platforms deployed over thousands of kilometers of coastline) and over several decades is essential if researchers are to understand the consequences of ocean change in the coastal zone and its societal implications.

Robots chasing robots: A new paradigm for studying biogeochemistry

How can researchers understand the processes governing ocean biogeochemistry and marine ecology when the subject of study is constantly varying over time and space? Using traditional sampling methods and ships seems like a logical solution to the problem, but sending people to sea to maintain an extended presence over large areas and long stretches of time is not practical; a new paradigm is needed for studying ocean biogeochemistry and for improving predictions of future ocean conditions.

MBARI's Controlled, Agile, and Novel Observing Network (CANON) Initiative, led by Francisco Chavez and Jim Bellingham, is working to accomplish that goal by utilizing an assemblage of smart, autonomous devices that are designed to cooperate with each other to make desired measurements even without a human operator. To elucidate complex ocean processes, a well-resolved spatial perspective integrated over time greatly simplifies interpretation and allows the removal of spatial distortions and measurement artifacts. For example, the M1 mooring in Monterey Bay can swing in or out of the periodic upwelling plume that originates north of the bay, giving radically different views of ocean conditions. Having the time-varying spatial information relative to upwelling plumes, associated fronts, and the chemical features that result would be more useful and extensible, and thus greatly improve our understanding of the California Current Ecosystem.

As a test case the CANON team has focused on an ammonium feature that is important for understanding nitrogen cycling and the flux of carbon from surface waters to depth. Measurements made over the past decades, together with more targeted ones in recent years, have shown that ammonium accumulates in the waters near the base of the euphotic zone, the area where there is barely enough light to support phytoplankton photosynthesis. The source of this ammonium is degradation of organic matter generated by photosynthesis, either in the guts of animals or by microbial decomposition. Recent studies have revealed that this subsurface ammonium pool is also a zone of active nitrification, the process by which ammonium is oxidized to nitrate by microorganisms. Nitrification completes a key part of the nitrogen cycle, which begins when deeper water with high-nitrate concentrations is upwelled or mixed into surface waters and converted into organic matter by photosynthesis. The organic matter produced by phytoplankton is food for zooplankton and small fishes that, in turn, sustain predators such as birds and larger fishes in a complex food web. Some of the organic matter returns to depth as sinking particles or migrating zooplankton to be converted back to nitrate by microbes as described above. Understanding where and how fast this process occurs is critical for generating models that simulate biogeochemical cycles and predict how these might change in the future. It has only recently been discovered that this nitrogen cycle is mostly completed very close to the sea surface, however much remains to be resolved about how these processes vary over different scales of space (from a meter to kilometers) and time (hours to days).

To track subsurface ammonium, the CANON team employed a suite of autonomous vehicles during the fall field campaign. It is necessary to have the ability to track and sample repeatedly over time in order to understand how this feature influences net primary production and flux of carbon to depth. Capturing its time/space evolution using autonomous devices requires determining the positions of sensor systems—a challenge while working under water. A global positioning system (GPS) can receive signals from space and determine position very accurately on land or above water. Because GPS signals do not penetrate the sea surface, acoustic communications are used for undersea communication.

During the September and October field experiments in Monterey Bay, this challenge became clear when robots were used to follow a subsurface patch rich in ammonium (Figure 5). The patch and overlying waters were sampled from a ship, by MBARI staff and their collaborators, several times per day, over many days, for biogeochemistry and microbiology. Sediment traps measured the vertical flux of organic material that fuels nitrification at the base of the euphotic zone. The team also measured turbulence to estimate the mixing of nitrate into surface waters and used sophisticated isotopic and gas measurements to estimate net community production, and the air-sea exchange of carbon dioxide.

During the experiment, autonomous vehicles and ships were equipped with acoustic communication devices. One long-range autonomous underwater vehicle (LRAUV) sent a signal that was used to determine its position underwater. That particular LRAUV was programmed to locate the water temperature that matched the depth of the maximum ammonium, then drift and adjust its buoyancy to actively remain at that temperature. Two other autonomous robots were programmed to follow the first LRAUV. One, a Wave Glider surface vehicle, used GPS to con-

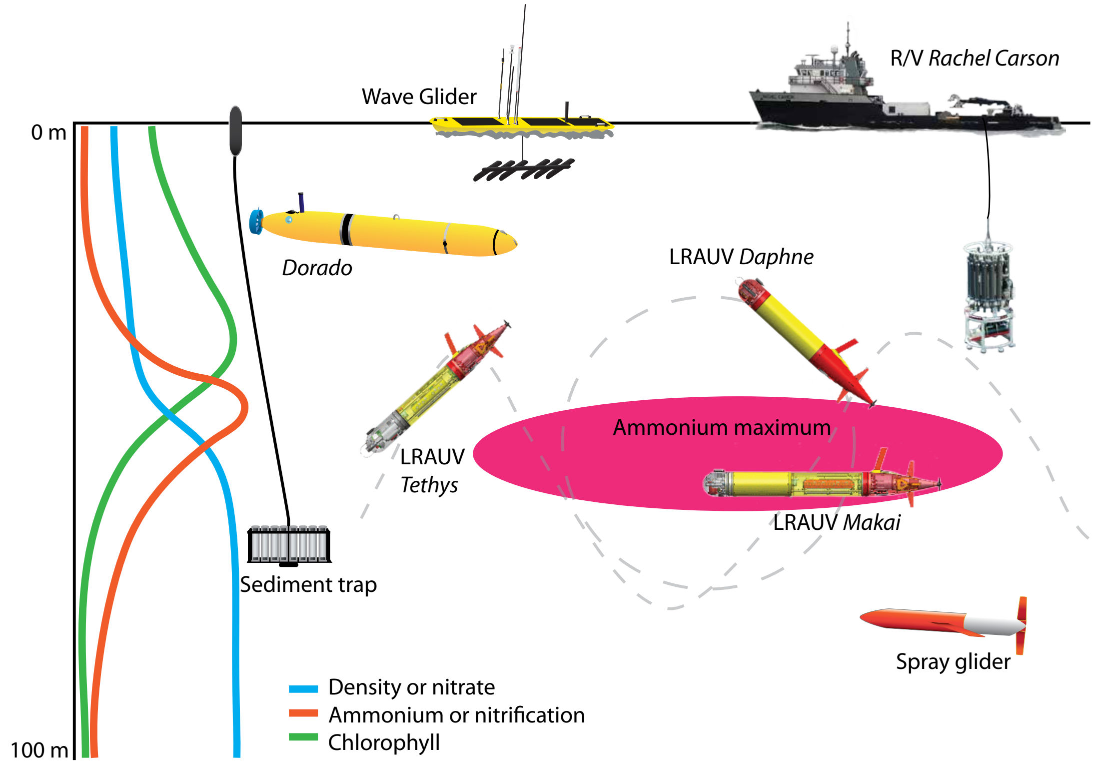


Figure 5. During the CANON fall 2014 field campaign a suite of autonomous vehicles was deployed and coordinated to track chlorophyll, nitrate, and subsurface ammonium or nitrification.

tinuously relay its changing position and that of the first LRAUV back to shore. The other robot, a second LRAUV made vertical profiles along the drifting LRAUV's path, providing a continuous record of conditions above and below the ammonium maximum. A third LRAUV used data relayed to shore from the Wave Glider to gather information on larger scale distributions of ocean conditions around the Wave Glider (Figure 5).

The ships R/V *Rachel Carson* and R/V *Western Flyer* could also communicate with the underwater robots and navigate close to them to collect water samples for biogeochemical analyses (Figure 6). Researchers aboard the research vessels and those on shore could track the minute-to-minute activities using collaborative tools incorporated into MBARI's web-based data portal called the Oceanographic Decision Support System (ODSS) to determine the changing positions of all the assets relative to remote-sensing images of temperature, chlorophyll, etc. The integration of all the information captured revealed a surprisingly complex view of nature at work (Figure 7).

The ability for teams of autonomous sensor systems to operate in the ocean in a coordinated manner has many applications. Traditional single-ship operations cannot measure the ocean simultaneously over a broad area or for long periods of time. Fleets of vehicles could therefore be used either in support of

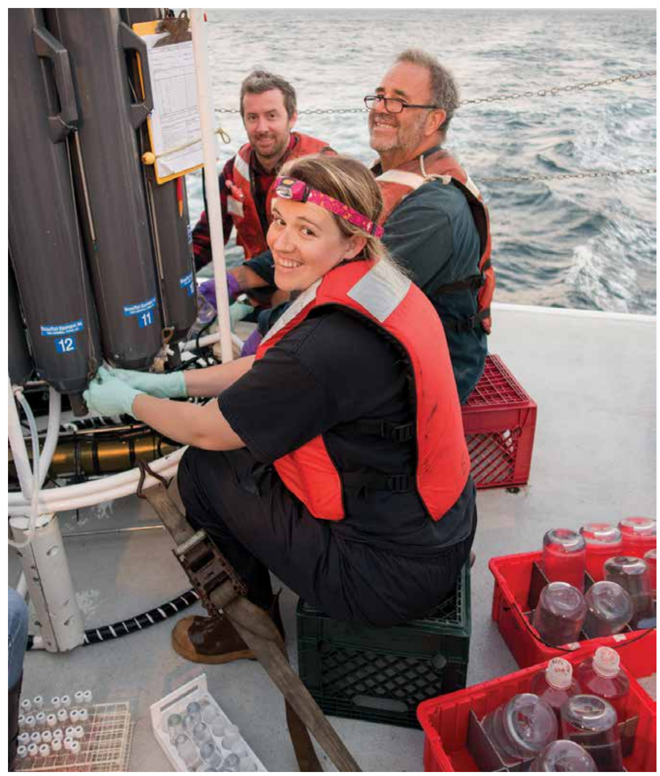


Figure 6. As soon as the CTD rosette was hoisted onto the back deck of the R/V Western Flyer, *the onboard science team (from foreground to back) Research Technician Marguerite Blum, Research Specialist Tim Pennington, and Postdoctoral Fellow Jason Smith carefully collected water samples from the Niskin bottles.*

Figure 7. Wave Glider (red) used acoustic communications to automatically follow Makai*, a submerged long-range autonomous underwater vehicle (LRAUV; green) that adjusted its buoyancy to drift at a fixed temperature for three days. A second LRAUV,* Daphne *(orange), also used acoustic communications to follow* Makai *and map the physical environment around it in three dimensions. Periodically researchers aboard the R/V* Rachel Carson *collected water samples next to* Makai *to measure biochemical processes. Inset shows location of experiment in Monterey Bay. Inset shows location of experiment in Monterey Bay.*

focused process experiments or for longer-term ocean observation. In either case, the robots' ability to transmit information to each other and human observers, and to autonomously use data collected by their sensors to locate features of interest and adaptively sample them absent human intervention is paramount. Using robots to find the feature or process of interest rapidly is also key to directing the activities of devices so they can sample effectively.

Autonomous vehicles that can collect samples for laboratory analyses and provide information about zooplankton, fish, and marine mammals will help scientists to develop a realistic picture of the relationships between oceanographic processes and life in the sea. Our hope is that with these new tools, researchers will be able to better predict what lies in the future for ocean ecosystems.

Decoding DNA to understand marine microbes

The ocean holds a bewildering array of microscopic life. Many of the marine microbes are so tiny that they are difficult to study or even to identify under a microscope. For this reason, scientists often look at the genes—DNA—of microbes to figure out how they are related to one another. Methods for decoding DNA have revolutionized the medical field as well as ocean sciences, and have been foundational to developing hypotheses about how organisms function in their natural habitats. Such genomic analyses often involve searching large databases to compare the genetic material of one microbe to that of others. Unfortunately, existing databases are woefully incomplete when it comes to organisms in the ocean, including some of the key photosynthetic eukaryotic groups.

Eukaryotes are a tremendously diverse group of organisms that include everything from humans and plants on land to tiny marine algae less than one thousandth of a millimeter in diameter. These organisms are grouped together because they all contain cells with well-defined internal structures such as nucleii. Bacteria, in contrast, lack these internal structures. Perhaps because they are so small and diverse, the tiniest eukaryotes in the ocean are still not well understood. Minuscule eukaryotes have large, complex genomes compared to bacteria or even to

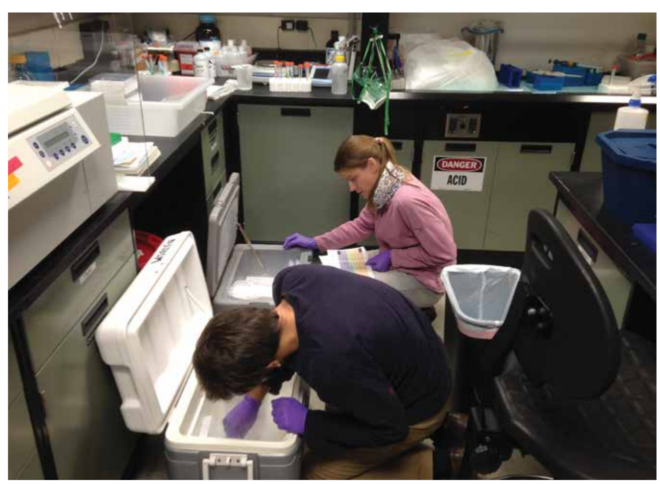


Figure 8. Postdoctoral Fellow Charles Bachy and Research Technician Lisa Sudek sort through the samples for genomic testing.

humans. Because it takes so much time and effort to sequence their genomes, most eukaryotes that have been sequenced are those considered valuable from a biomedical, industrial, or agricultural perspective. Those genomes are not very useful for marine microbiologists because they are so different from most eukaryotic marine microbes. Although large databases exist for genetic information on marine bacteria, until recently there was no database covering even a fraction of the microscopic marine eukaryotes.

To help address this problem, MBARI microbiologist Alexandra Z. Worden and her team helped compile a groundbreaking database that provides a wealth of data on this vast group of single-celled organisms. Researchers from around the world cultured over 650 microbial eukaryotes whose genomes were then sequenced (Figure 8). The resulting database includes some of the most abundant and ecologically important microbial eukaryotes in the ocean—organisms that support global fisheries, supply oxygen, and absorb carbon dioxide from Earth's atmosphere. The resulting Marine Microbial Eukaryotic Transcriptome Sequencing Project database was made public in 2014.

Worden's group has continued working with genomes in the database to gain insights into how algae synthesize vitamins and photosensory proteins. The team discovered widespread sensory proteins—phytochromes—that convert light into biological signals to influence the organism's overall growth and development. Phytochrome proteins were thought to be absent from most green algae but using the genomic data, the Worden team showed that most marine green algae in the prasinophyte group actually have phytochromes. The team also showed that the phytochrome signaling system is akin to that in land plants where these proteins control 10 percent of the organism's complement of genes. Not surprisingly, some of these newly detected phytochromes have

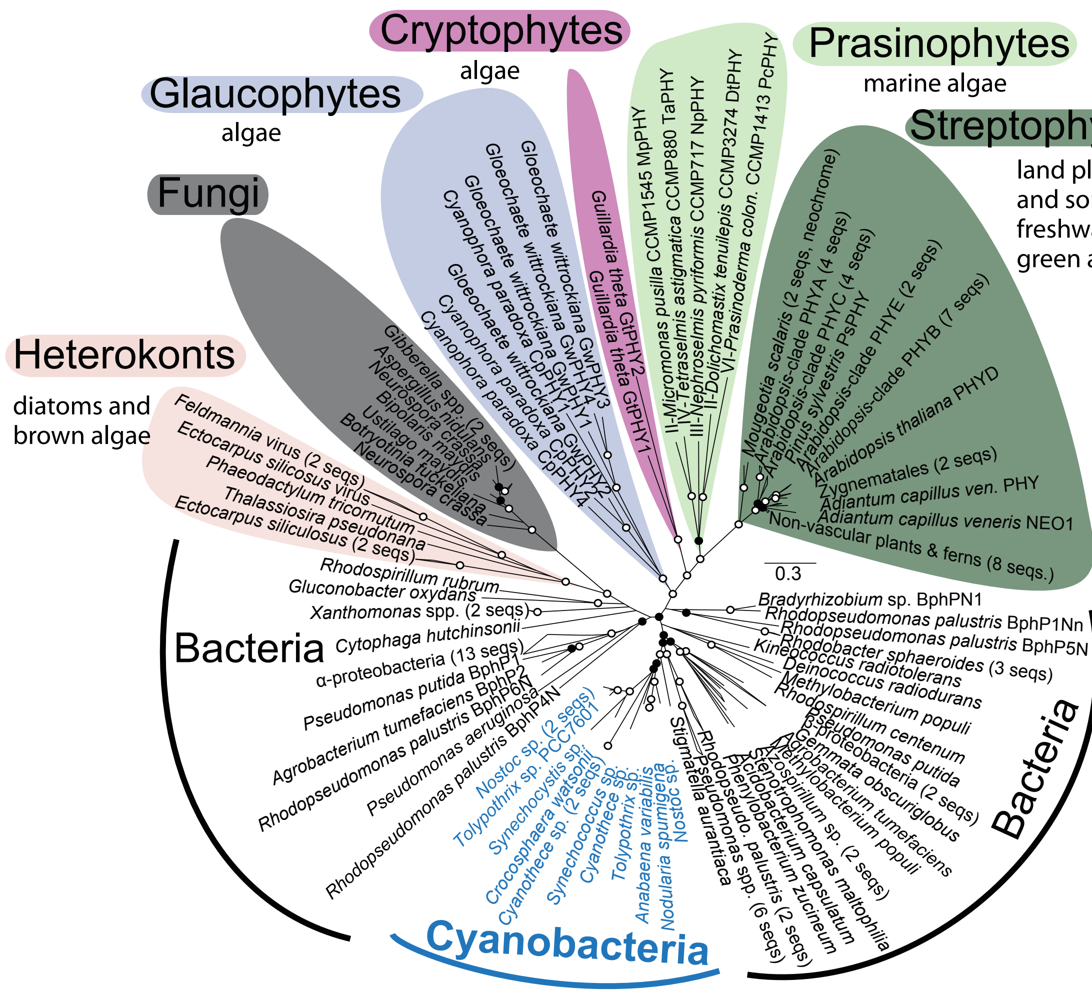


Figure 9. Evolutionary tree of the phytochrome protein, a photosensor known in a wide variety of organisms, but previously unknown in marine green algae. The phytochrome was discovered in marine green prasinophyte algae. Figure adapted from Duanmu, Bachy et al. PNAS 2014.

spectral properties very different from land plants, detecting light wavelengths that are more typical in aquatic environments than the red/far-red light perceived by terrestrial plant phytochromes (Figure 9). This regulator presumably plays an important role in shaping the responses of algae and even non-photosynthetic organisms to changes in environmental conditions.

In follow-up work Worden and her group discovered phytochrome proteins in other eukaryotic groups as well, thanks to the new database. Over time, scientists around the world may also use this trove of information to better understand the ecology and roles of marine microbes and their evolutionary relationships.

Ocean acidity-sensor contest comes to MBARI

Human activities such as burning coal, oil, and gas have released hundreds of billions of tons of carbon dioxide into Earth's atmosphere. About one third of this carbon dioxide has dissolved in the ocean. This has caused the ocean to become more acidic, with possibly devastating effects on corals and many other marine organisms.

Unfortunately, most oceanographers do not have access to instruments that can measure the acidity (pH) of the ocean precisely and continuously for long periods of time. Existing methods for measuring the pH of seawater either require hand processing of individual water samples or expensive instruments for making the measurements in situ. Even the more expensive instruments require frequent, expert servicing and do not work well in the extreme pressure of the deep sea.

In a search for potential solutions, Wendy Schmidt, president of the Schmidt Family Foundation, partnered with the XPRIZE Foundation to create the Wendy Schmidt Ocean Health XPRIZE, a global competition to design robust pH sensors that can accurately and affordably measure ocean pH.

Eighteen teams, including one from MBARI, qualified to compete for two prizes: a $1 million accuracy prize, based on instrument performance, and a $1 million affordability prize, based on instrument cost and usability. All systems will be evaluated for accuracy, precision, stability, affordability, and ease of use. They must also function down to 3,000 meters (almost 10,000 feet) below the ocean surface.

MBARI hosted the first two testing phases of the competition from September to December of 2014. The first phase involved testing the basic accuracy of each competing instrument in MBARI's seawater laboratory (Figure 10). During the second phase, the competing instruments were tested in MBARI's 142,000-liter test tank for about two and a half months to determine the accuracy and consistency of each instrument (Figure 11).

Those instruments that survive the lab and tank trials will be further tested in a real-life coastal setting—a dynamic environment, with natural variation in pH due to winds, tides, currents, and runoff. The final test will take place in the open ocean and

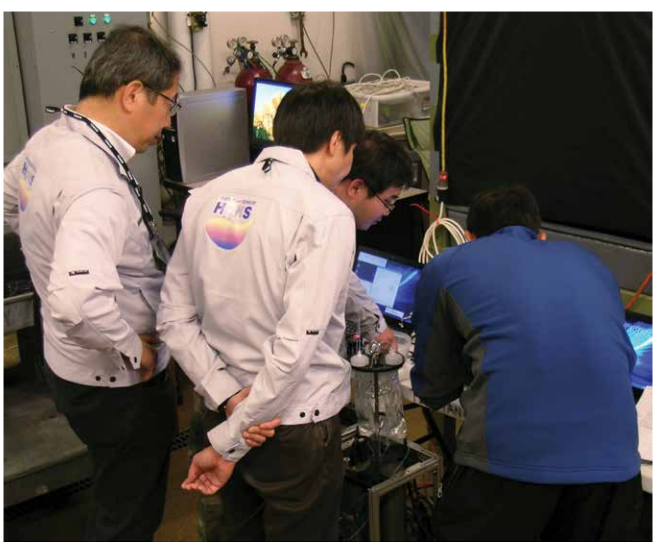


Figure 10. Members of a team from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) prepare their pH sensor for testing in MBARI's seawater lab.

Figure 11. Entries in the XPRIZE pH sensor competition were suspended in the MBARI test tank for more than two months to test their effectiveness.

require each instrument to take a series of pH measurements from the sea surface down to a depth of 3,000 meters. Measurements will be compared against reference samples analyzed onboard a research vessel using the best available laboratory techniques.

One long-term goal of the competition is not simply to identify new sensors, but also to inspire investment in research. The XPRIZE Foundation has found that for all of its previous competitions, the amount of money invested in winning the prize has been five to ten times the prize itself. Another goal is to spur business development.

Ocean chemists are not the only ones who will benefit from the development of reliable and affordable ocean-pH measuring systems. Such instruments could also be useful for fishing and aquaculture industries, as well as for governmental agencies. Eventually, ocean researchers and resource managers may be able to tap into a worldwide network of pH sensors, just as meteorologists currently use a worldwide network of weather stations to monitor global temperatures.

MBARI's participation in this effort aligns precisely with Founder David Packard's original charge for the institute—to develop new instruments, systems, and methods for studying the ocean, and to do so for the public good.

Related web content:

Argo array: www.argo.ucsd.edu/

Oceanographic Decision Support System: odss.mbari.org/odss/

Marine Microbial Eukaryote Transcriptome Sequencing Project: marinemicroeukaryotes.org/

Wendy Schmidt Ocean Health XPRIZE: oceanhealth.xprize.org/

Project teams:

Monterey Bay Time Series

Project lead: Francisco Chavez
Project manager: Tim Pennington
Project team: Marguerite Blum, Gernot Friederich, Jules Friederich, Brent Jones, Monique Messié, Reiko Michisaki, Jeff Sevadjian, Jason Smith, Chris Wahl

Coastal Profiling Float

Project leads: Ken Johnson, Gene Massion
Project manager: Gene Massion
Project team: Paul Coenen, Brent Jones, Mike Parker, Wayne Radochonski, Chris Wahl

Controlled, Agile and Novel Observing Network (CANON) Initiative

Project leads: James Bellingham, Francisco Chavez, Chris Scholin, Ken Smith, Alexandra Z. Worden
Project manager: Francisco Chavez
Project team: Larry Bird, Danelle Cline, Duane Edgington, Kevin Gomes, Thom Maughan, Mike McCann, Monique Messié, Reiko Michisaki, Chris Wahl

Ecology and Diversity of Picophytoplankton

Project lead: Alexandra Z. Worden
Project managers: Sebastian Sudek, Alexandra Z. Worden
Project team: Charles Bachy, Chang Jae Choi, Magdalena Gutowska, Valeria Jimenez, Alexander Limardo, Camille Poirier, Melinda Simmons, Lisa Sudek, Jeltje van Baren, Susanne Wilken, Amy Zimmerman
Collaborators: Patrick Keeling, University of British Columbia, Vancouver, Canada; J. Clark Lagarias, University of California, Davis; Adam Monier and Thomas Richards, University of Exeter, United Kingdom; Betsy Read, California State University, San Marcos; Alyson Santoro, University of Maryland, College Park

Ecosystem Processes

Life in the ocean depends on a myriad of interactions among a diversity of organisms. Complex processes transmit fluctuations of matter and energy throughout the entire food web, from the ocean's surface to the deep seafloor, affecting Earth's climate as well as human health and prosperity. Gaining a more detailed understanding of how organisms respond to highly ephemeral, spatially varying processes is therefore central to attaining a predictive understanding of the longer term and larger scale consequences of environmental change.

Assessing ecological impacts in a marine sanctuary

Researchers at MBARI and the Monterey Bay National Marine Sanctuary (MBNMS) frequently work together on a host of initiatives including sharing data concerning natural resources in the sanctuary and experimental research projects. MBARI's portfolio of work within the sanctuary is wide-ranging, from long-term data series obtained from moorings and repeated oceanographic sampling, to a growing seafloor mapping program. Collaborative biological studies have provided a wealth of information concerning the biodiversity and changes in marine ecosystems in the sanctuary from surface waters to the abyssal plain.

If a shipping container sinks and nobody sees it, does it matter?

Although an estimated 10,000 shipping containers are lost at sea and sink each year, it is exceedingly rare to find them. So a shipping container that landed on the seafloor in Monterey Bay has presented a special opportunity for scientists to carefully analyze the impact of such deep-sea waste. How is sea life affected when a large metal box falls into its midst? Does the paint or material of the container itself pose a hazard?

MBARI researchers discovered the shipping container during an otherwise routine remotely operated vehicle (ROV) dive in 2004 at a depth of 1,281 meters. The MBNMS staff learned that the container was one of many that were lost from the deck of a Chinese vessel during a winter storm (Figure 12).

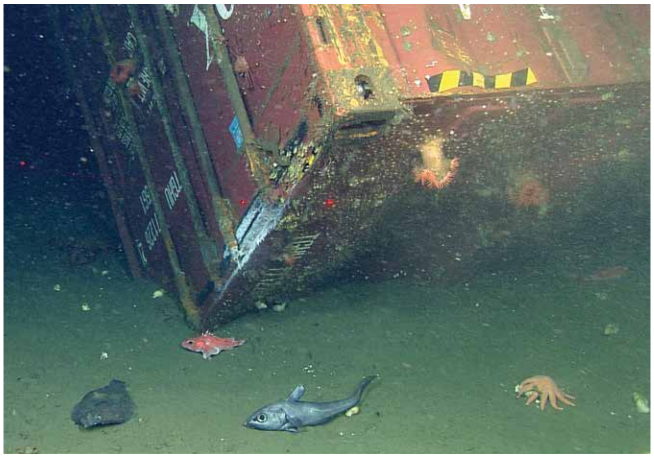


Figure 12. This shipping container, full of tires, was found at a depth of 1,281 meters.

Figure 13. Close-up view of tunicates, hydroids, and other invertebrates on a 28-centimeter-wide section of the shipping container.

Figure 14. An array of four types of experimental containers is assembled on the ROV for transport to the seafloor for studies on which animals colonize each kind of material.

MBARI Scientist Jim Barry and MBNMS Research Coordinator Andrew DeVogelaere have been leading a team to assess the ecological effects of the container on the seafloor community. ROV video transects of the container and sediment-core samples revealed that the characteristics of the seafloor sediments and the abundance of deep-sea animals differed near to (within 10 meters) and distant from (up to 500 meters) the container.

The average grain size of muddy sediments was greater near the container, suggesting that the acceleration of near-bottom ocean currents around the container resuspended and swept away some of the finer sediment, leaving heavier, coarser material behind. Some deep-sea species, such as large snails (*Neptunea* sp.) and thornyhead rockfish (*Sebastolobus* sp.), were more abundant very near the container, while others, especially sea pens and sea cucumbers, decreased in abundance near the container (Figure 12). In addition, a large number of sessile invertebrates that are typically more common in rocky deep-sea habitats have colonized the metal structure of the container (Figure 13). Overall, these effects of the container are very mild, perhaps in part due to the low toxicity of the container's cargo of car tires.

MBARI and MBNMS have now expanded this study to assess the effects of different antifouling paints used on containers, and recently initiated a colonization experiment in the deep sea using four different surface types (two rock, two steel; Figure 14). Five of these arrays of small simulated containers have been placed on the seafloor at a depth of 250 meters, and are expected to accumulate colonists over the next year or two—the monuments were placed at a somewhat shallower depth to increase the rate of colonization. When the monuments are recovered, the team will compare the species composition and densities of settlers on the different surfaces. Hopefully, the study will reveal the influence of different materials and anti-fouling paints on various species of deep-sea invertebrates that typically colonize rocky surfaces, as well as lost shipping containers.

Combining forces pays off for conservation and research

Collaborations between MBARI and MBNMS scientists have also focused on several of the Sanctuary Ecologically Significant Areas (SESAs), defined, in part, from MBARI explorations and studies (Figure 15). For instance, the joint shipping-container study highlighted the potential unseen impacts of the global problem of containers lost at sea each year. Similar discoveries within the sanctuary, such as a scuttled barge and a jet engine found in 2014, contribute to the sanctuary's mandate to protect and manage its cultural and historical resources.

Collaborative studies in other SESA sites include Davidson Seamount, where the sanctuary's goal of conserving deep-sea corals benefits from MBARI ROV dives to document the distribution of biological resources. ROV exploration of Sur Ridge, led by Barry and DeVogelaere, revealed an unexpected abundance of deep-sea coral and sponge communities, including forests of bamboo corals unknown in other areas of the sanctuary. Experimental studies on the capacity to translocate corals between sites will help the sanctuary evaluate the potential for repopulating sites that may be damaged by trawling or other activities (Figure 16).

MBARI activities also contribute to sanctuary conservation policy. Scientists Steve Haddock, Francisco Chavez, Charlie

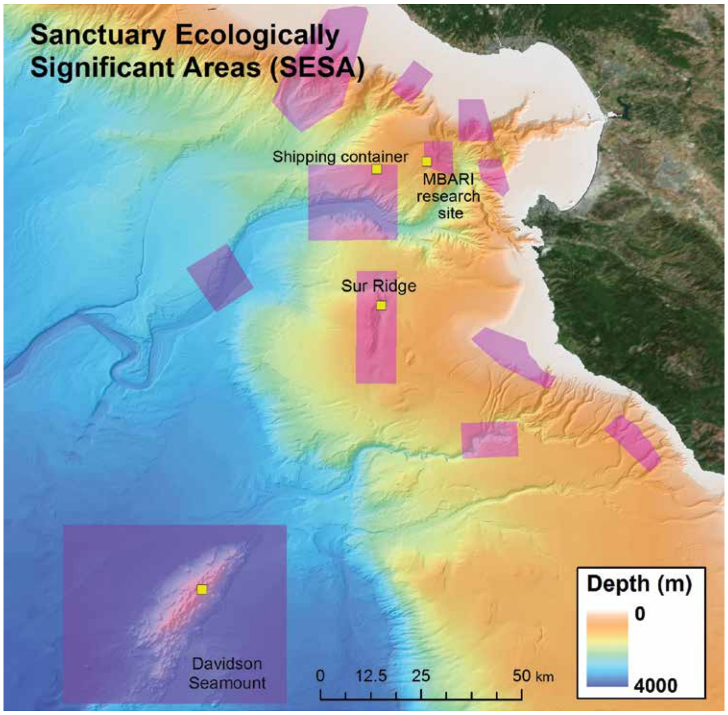


Figure 15. MBARI researchers work with the research staff of the Monterey Bay National Marine Sanctuary in several of the Sanctuary Ecologically Significant Areas. Yellow squares mark coral studies under way at Sur Ridge and Davidson Seamount, and the shipping container and MBARI research sites.

Paull, and Jim Barry serve as formal advisors to the Sanctuary Research Activity Panel or Sanctuary Integrated Monitoring Network (SIMoN) Science Committee. These groups provide insight at regular meetings and review applied research documents. Of special interest in 2014 was the collection of data from MBARI's video archives, geological maps, and coral research that informed a collaborative effort of fishermen, regulators, and conservationists to modify boundaries that define essential fish habitat. These habitat areas, managed by NOAA Fisheries, designate areas off-limits to fishing practices that disturb the seafloor.

MBARI's ongoing observations and monitoring of ocean acidification, harmful algal blooms, and midwater jellies also help inform National Marine Sanctuary Condition Reports. These reports are used by resource managers and congressional staff to assess the health of our nation's coastal regions. On a local level, nitrate observations from MBARI's Land Ocean Biogeochemical Observatory greatly influenced the selection of wetland projects designed to decrease erosion in Elkhorn Slough (the main channel of the slough is part of the sanctuary). All resource managers also have access to summaries of MBARI monitoring efforts in an easy-to-use summary format through the SIMoN website.

Sur Ridge—an oasis in the deep sea

On regional seafloor maps, Sur Ridge appears as a feature of the continental slope 32 kilometers west of Monterey. Early maps indicated that this was a long, bump-like rise about 1,000 meters below the ocean surface which, until recently, garnered little interest from scientists. In comparison, Davidson Seamount, a far more prominent extinct subsea volcano farther south, has received much more attention. Collaboration between MBARI's Jim Barry and the sanctuary's Andrew DeVogelaere led to a few exploratory ROV dives on Sur Ridge in 2013, initially targeting the steepest locations, in hopes of finding exposed rock surfaces inhabited by deep-sea corals. Expectations were low, and the group anticipated mostly sediment-covered outcrops and few corals. They couldn't have been more wrong.

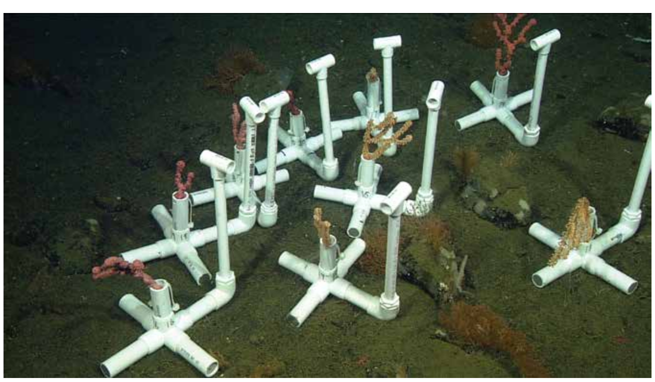


Figure 16. Left, at Sur Ridge, researchers are testing the efficacy of transplanting two species of corals to learn whether damaged areas of the seafloor could be recolonized through human mitigation efforts. The handle of each apparatus is about 30 centimeters high. Right, markers have been placed next to various corals on Sur Ridge to identify sites for long-term observations. These corals are about 60 centimeters tall.

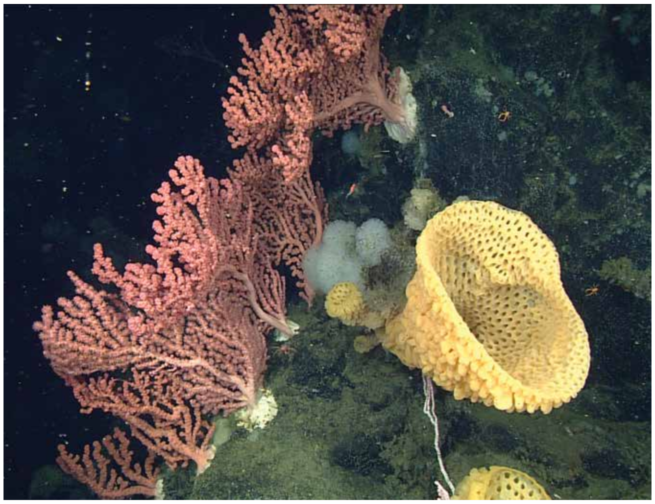


Figure 17. Sur Ridge is home to a wide range of corals, sponges, and other invertebrates, such as this assemblage found at a depth of 940 meters. These pink corals are about 120 centimeters tall.

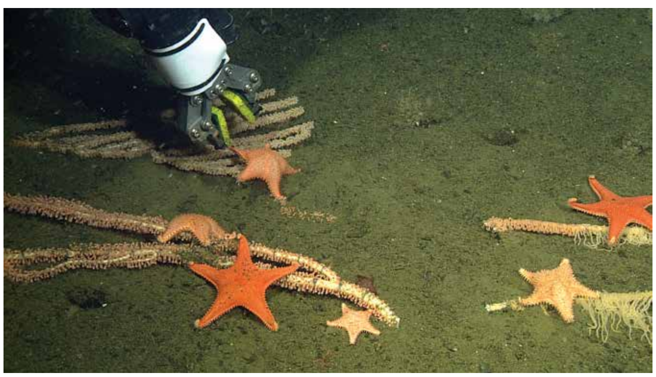


Figure 18. Fallen corals, such as this Isidella tentaculum*, attract high numbers of predators, as evidenced by the sea stars feeding on these corals. The sea star in the foreground is about 23 centimeters across.*

The first ROV dive landed on the mud-covered seafloor at 1,200-meters depth, about 100 meters away from the base of the steep slope at the northeastern end of the ridge. As expected, sea stars, sea cucumbers, and sea pens were common on the sediment-covered plain. As the ROV flew to the west toward the first expected outcrop, corals were seen on much of the rubble at the ridge base. A few tens of meters farther, steep rocky cliffs emerged from the dark, barely within the range of ROV lights. The cliffs were black from the slow accumulation of manganese crust and were covered with a wide range of large bubblegum and bamboo corals, huge glass sponges, and other invertebrates. From a depth of 1,200 meters at the base, the ROV roamed up to near 800 meters depth—very close to the top of the seamount. Rather than the expected sediment-dominated rubble, corals were abundant on the steepest part of the ridge (Figure 17).

A second dive on a less-steep section at the south end offered another surprise. The faunal assemblage on the seafloor included quite a few corals, and was dominated by large deep-sea sponges. The difference in the observed communities was striking, and appeared to be related to the steepness and the nature of the seafloor.

In 2014, Barry and DeVogelaere teamed up again to broaden the ROV exploration to additional sites. They found that the ridge had another undiscovered secret—although there was more sediment along the central ridge area, boulders and other smaller outcrops accommodated what appeared to be a pristine assemblage of corals, especially bamboo corals. These corals were more abundant and larger than those found on Davidson Seamount, and their distribution was widespread along a wide swath observed during a few ROV dives. These spectacular coral forests are likely akin to the old-growth terrestrial forests found in some of our national parks. Moreover, the high abundance of bamboo corals (and other species) is important to the sanctuary, because of concerns that the relatively small populations found on Davidson Seamount are highly vulnerable to disturbance.

The research team placed a series of markers near corals on the ridge as a baseline population study for future comparisons. They also sampled corals to determine age and maturity, and investigated predators of various corals. The predation studies focused on the number and diversity of sea stars and other animals that attack corals. Although the pace of sea star movement may seem too slow to be harmful to its prey, they are likely a very real threat to coral survival. Initial results indicated that a number of corals are attacked by predators; when a coral falls over, the number of predators increase, apparently leading to its death (Figure 18). One bamboo coral, *Isidella*, has specialized tentacles along its base, which appear to inhibit predators from crawling up the basal stalk. The long tentacles are covered with stinging nematocysts. A short experiment in the deep sea, repeated in the laboratory aboard the *Western Flyer*, confirmed the defensive function of the tentacles. Sea stars placed on the basal tentacles quickly crawled away, while those placed on the coral's feeding tentacles turned their stomachs inside out and began feeding immediately.

Future high-resolution mapping of the entire ridge using the mapping AUV will provide better comparison of the distribution of corals and sponges relative to seabed bathymetry, and a more thorough understanding of the geologic complexity of Sur Ridge. With these maps in hand, the science team will return to the site, eager to investigate more of this rare, lush oasis in the deep sea.

Testing new methods to identify tiny organisms

Understanding and tracking the health of ocean ecosystems is a daunting task given their enormity, diversity, and variability in time. Zooplankton surveys provide a key insight in that regard. These tiny organisms (Figure 19) constitute critical links in the marine food web, consuming primary producers (phytoplankton), and providing sustenance for commercially important fishes and other animals. Some zooplankton such as copepods and krill spend their entire lives drifting in the pelagic open ocean, while other animals spend only part of their lives in the plankton as eggs and larvae. The seasonal abundance and spatial distribution of eggs and larvae provide essential data for the management of commercial fisheries and marine reserves. But measuring the distribution and abundance of planktonic organisms is notoriously difficult because of their small sizes, complex behaviors, and patchy distributions.

Marine biologists have historically employed a variety of sampling devices to assess zooplankton abundance, ranging from relatively simple devices like nets to more complex devices like acoustic imagers (see page 18). Each device has specific uses and strong proponents, but for the most part zooplankton diversity remains grossly undersampled at local, regional, and global scales.

Regardless of the sampling methods used, plankton must still be identified and enumerated in a manner that allows comparisons across time and space. Some planktonic organisms, like jellyfish, are visible to the naked eye, but the majority of zooplankton species are microscopic. Traditional methods for identifying zooplankton are time-consuming and require examining them under a microscope. The results are more or less accurate depending on the expertise of the researchers. The problem is compounded in some species such as flatfish or crabs in which the eggs and larvae within a family may be indistinguishable in morphological analyses. Furthermore, taxonomic experts for various groups of plankton have become scarce as universities and museums face economic pressures to support more lucrative pursuits. Finally, the interval between sample acquisition and data generation can be significant, creating problems for fisheries managers tasked with making decisions about the status of a fishery or the health of a marine protected area.

The Molecular Ecology Group led by Bob Vrijenhoek launched the Sampling and Identification of Marine Zooplankton (SIMZ) project to develop efficient molecular tools for better assessing the diversity and abundance of zooplankton. During the past two years, the SIMZ team has focused on adaptation of MBARI's *Dorado* AUV and its gulper system to autonomously obtain water samples, and on the application of high-throughput DNA tests to identify and enumerate zooplankton. Testing the new sampling and identification technologies requires verification with conventional methods that are accepted as standards. To that end, the SIMZ team collaborated with specialists at the University of California Bodega Marine Laboratory and the NOAA Northwest Fisheries Science Center. Net tows collected from Monterey Bay were analyzed using both morphological and molecular techniques and the results were compared.

The new molecular methods proved to be faster than the labor-intensive microscopic studies. For example, the collaborating experts processed 10 net-tow samples in five days. In contrast, the SIMZ team provided taxonomic information for 20 samples in half the time using next-generation DNA sequencing (NGS) technology. There was overlap in identifications by the two methods, but differences in taxonomic resolution were apparent. For example, NOAA experts were able to morphologically

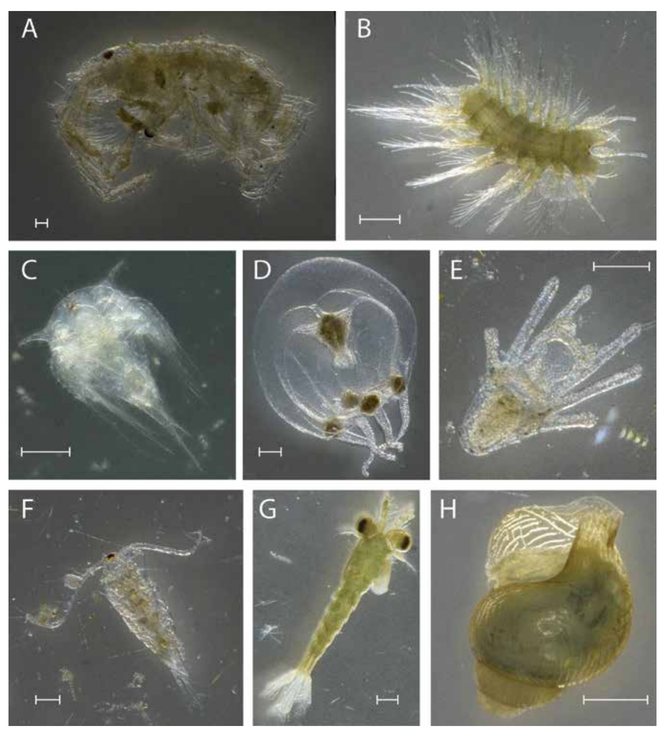


Figure 19. Zooplankton collected in Monterey Bay: (A) amphipod, (B) polychaete, (C) barnacle larva, (D) medusa, (E) echinoderm larva, (F) copepod, (G) krill larva, (H) gastropod. All white scale bars are 100 μm in length.

Engineering a more precise water sampler for an elusive quarry

Plankton nets have been used for decades and are unparalleled in their ability to concentrate zooplankton from very large volumes of water (Figure 20A). Despite their relatively low cost and high efficiency, they yield imprecise measurements because they mix plankton from different water layers or horizontal patches into a single volume. In contrast, Niskin bottles (Figure 20B) capture relatively small volumes of water from discrete depths and provide contextual environmental data such as conductivity, temperature, depth, and chlorophyll concentration. The SIMZ team has used these well-established methods to "ground-truth" the samples obtained with newer technologies pioneered at MBARI. The team's first efforts were conducted during deployments of MBARI's Environmental Sample Processor (ESP). The ESP effectively sampled small, passively dispersed zooplankton, but larger, more motile organisms appeared capable of escaping its intake stream. Subsequently, the SIMZ team shifted its efforts to the *Dorado* AUV equipped with 10 gulper samplers, each of which could rapidly intake 1.8 liters of water.

Gulper samples obtained in 2011 from a geographical grid in Monterey Bay revealed tantalizing patterns, but the sample volumes were small and replication was limited. Correlations between zooplankton abundance and chlorophyll concentrations were documented, but unsurprisingly, the results only demonstrated that these primary consumers were most abundant where their phytoplankton food was concentrated. To address more specific ecological hypotheses, the SIMZ team needed a targeted approach to replicate samples from specific physical features and biological processes that might be responsible for the observed correlations. Consequently, they collaborated with Research Specialists Yanwu Zhang and John Ryan to refine sampling designs and develop adaptive sampling algorithms for directing the AUV. During the next several expeditions, the team acquired water samples from pre-defined targets such as chlorophyll thin layers and upwelling fronts.

It soon became apparent that 10 gulper samples per AUV deployment were insufficient because the bottle-to-bottle variance for samples collected from a particular environmental feature might exceed the strength of zooplankton signals collected from that feature. Thus, the team encouraged development of a new 20-gulper midsection for the *Dorado* AUV (Figure 21), engineered by AUV Group Leader Hans Thomas and coworkers from the marine operations team. The new 20-gulper system, with modified adaptive sampling algorithms developed by Yanwu Zhang, was tested and successfully deployed for research studies in Bodega Bay, California, in 2014.

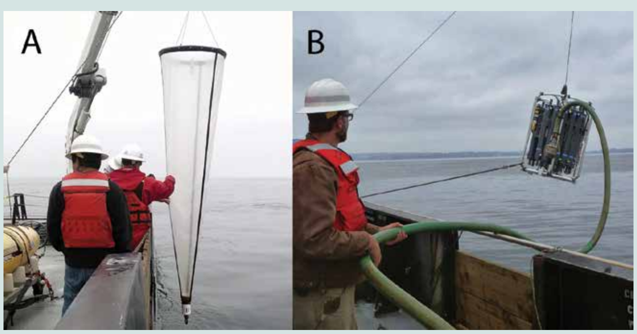


Figure 20. Water sampling methods: (A) vertical plankton net; (B) CTD/Niskin bottle rosette deployed from the R/V Rachel Carson.

Figure 21. The redesigned AUV midsection now holds 20 gulper water samplers.

identify different species and life-history stages of species such as krill, whereas the molecular methods could only indicate their presence or absence in samples. The NGS assays did not correlate with counts of individual krill in their various life stages. However, this was not unexpected since a previous study by the SIMZ team found that the amount of DNA in the various life-stages of a copepod species (eggs, larvae, males, and gravid females) differ greatly, so DNA tests cannot necessarily determine how many individuals of a particular species are present in a sample. Nonetheless, NGS assays often exceeded taxonomic experts' abilities by identifying cryptic zooplankton like fish eggs and polychaete larvae (Figure 22). The methods used for NGS

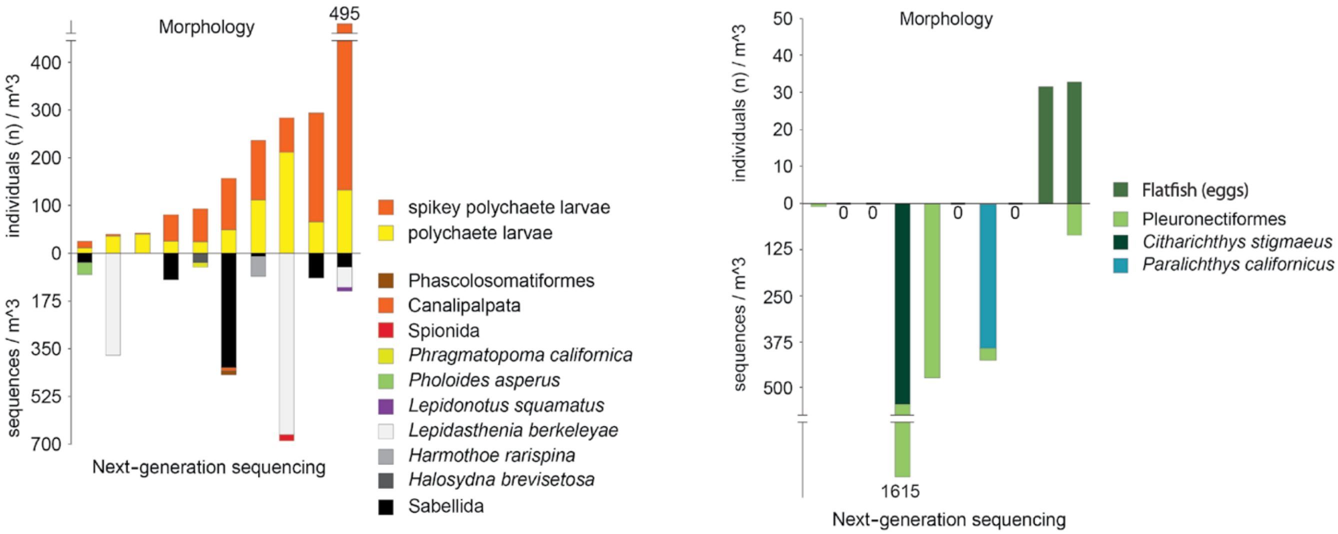


Figure 22. Assessment of polychaete worms (left) and flatfish eggs (right) from net-tow samples. Samples are rank ordered by abundance from microscopic morphology studies with number of individuals per cubic meter from individual counts (upper plot) and next-generation sequencing (NGS) (lower) appear on the y-axis. The NGS data provided useful taxonomic information for the worms but were not quantitative. For the fish eggs, NGS detected two common flatfish species not discernable by morphology.

are biased for or against certain species depending on the target gene so the SIMZ team uses a two-gene assay that more comprehensively samples across disparate species. These improved assays are far more accurate, especially when combined with recently improved search algorithms. The coverage of marine taxa in molecular repositories like GenBank and the Barcode-of-Life-Database is growing rapidly, and a significant part of SIMZ teams efforts during the next year will be to augment and quality control databases held in the public domain. With current molecular and statistical methods, the SIMZ team is now able to closely replicate and often exceed the qualitative taxonomic coverage obtained by their collaborating experts.

Alternate molecular methods have the potential to be more quantitative. For example, the sandwich hybridization assay developed by MBARI's Chris Scholin for surveys of harmful algal blooms was adapted for studies of zooplankton. This technique directly counts molecules indicative of a particular species or taxonomic group, and was most recently used to estimate the abundance of polychaete worms with reasonable accuracy (Figure 23).

The SIMZ team used these methods to assess zooplankton diversity in samples obtained with vertical net tows taken between Monterey, California, and Cabo San Lucas, Baja California, Mexico. Time of sampling (day versus night) influenced the abundance of certain genetic sequences. For example, copepods and larval crustacean sequences were more abundant in daytime samples, which is consistent with their vertical migra-

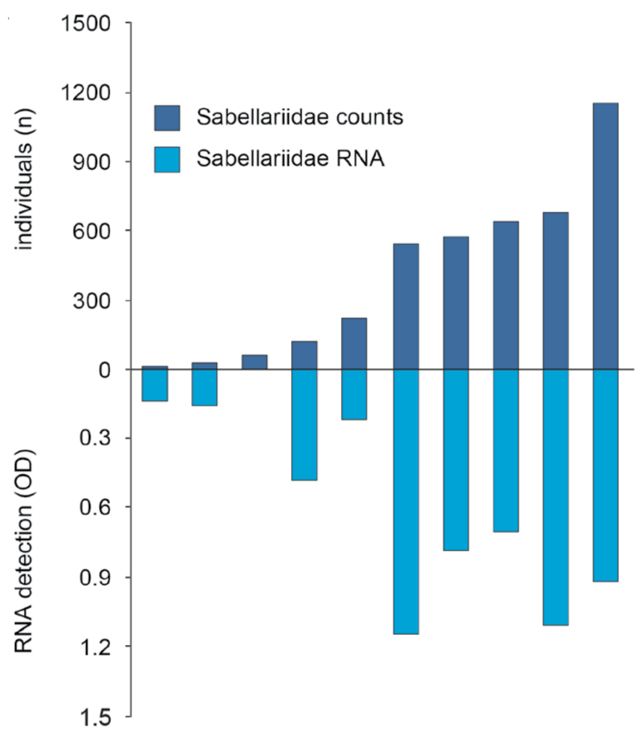


Figure 23. Detection of sabellariid polychaete worms from net-tow samples: the rank-ordered counts of "spikey worms" based on microscopy (upper plot) versus optical density (OD) of detected sequences from sandwich hybridization assays (lower plot) were more closely aligned than the microscopy-NGS comparisons.

tion patterns. More significantly, zooplankton diversity shifted notably north and south of Punta Eugenia, Baja California Sur, Mexico. These rapidly obtained molecular results are consistent with previous descriptions of zooplankton from this region.

High-resolution environmental sensors and molecular analyses generate voluminous data sets that must be integrated across space and time. This creates a need for better tools to visualize the information so researchers can access and analyze it more efficiently. Because the data are obtained at different sampling rates generated by sensors and molecular technologies, their integration creates a significant challenge. To meet that need MBARI's software engineers worked with Vrijenhoek's group to create the Spatial, Temporal, Oceanographic Query System (STOQS), a tool for visualizing and manipulating disparate data during exploratory analyses. STOQS simplifies the management of sample data by providing an easy web interface for data exploration and discovery (See page 27). Future plans include integration of next-generation sequencing data into the STOQS database and continued development of software tools for data analyses. Advances in information management and new analytical tools will contribute to more effective study of available and future data for better management of the ocean and its resources.

Related web content:

Sanctuary Integrated Monitoring Network: http://sanctuarysimon.org/

Shipping container video: www.youtube.com/watch?v=vFxtNsUPRKE

Project teams

Benthic Biology and Ecology

Project lead/manager: James Barry

Project team: Kurt Buck, Chris Lovera, Craig Okuda, Josi Taylor, Patrick Whaling

Collaborators: Erica Burton, Andrew DeVogelaere, and Chad King, Monterey Bay National Marine Sanctuary, Monterey, California

Molecular Ecology and Evolution of Marine and Aquatic Organisms

Project lead: Robert C. Vrijenhoek

Project manager: Shannon Johnson

Project team: David Clague, Danelle Cline, Julio Harvey, Mike McCann, Charles Paull, John Ryan, Yanwu Zhang

Collaborators: Shawn Arellano, Anna Van Gaest, and Craig Young, Oregon Institute of Marine Biology, Charleston; Asta Audzijonyte, Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia; James Barry, James G. Bellingham, Francisco Chavez, Roman Marin III, Monique Messié, Tim Pennington, Kristine Walz, Lisa Ziccarelli, MBARI; Gregory Doucette and Christina Mikulski, Center for Coastal Environmental Health and Biomolecular Research, Charleston, South Carolina; Jennifer Fisher and William Peterson, Southwest Fisheries Science Center, Newport, Oregon; David Foley, Southwest Fisheries Science Center, Pacific Grove, California; Jonathan Geller, Moss Landing Marine Laboratories, California; Shana Goffredi, Occidental College, Los Angeles, California; Nicholas Higgs and Crispin Little, University of Leeds, United Kingdom; Jumin Jun and Yong-Jin Won, Ewha Womans University, Seoul, South Korea; Elena Krylova, Shirshov Institute of Oceanology, Moscow, Russia; Raphael Kudela, University of California Santa Cruz; Margaret McManus, University of Hawaii at Manoa; Steven Morgan and Eric Satterthwaite, University of California, Davis; Karen Osborn, Smithsonian Institution, Washington, D.C.; Greg Rouse, Scripps Institution of Oceanography, La Jolla, California; Heiko Sahling, University of Bremen, Germany; Igor Schulman, University of Southern Mississippi, Stennis Space Center; Tom Schultz and Cindy Van Dover, Duke Marine Laboratory, Beaufort, North Carolina; Verena Tunnicliffe, University of Victoria, Canada; Zhihong Wang, University of North Carolina, Chapel Hill; Anders Warén, Swedish National Museum, Stockholm; Geoffrey Wheat, University of Alaska, Fairbanks; Nerida Wilson, Western Australia Museum, Welshpool; Brock Woodson, University of Georgia, Athens; Katrina Worsaae, University of Copenhagen, Denmark; Haibin Zhang, University of Science and Technology of China, Hainan

Sampling and Identification of Marine Zooplankton

Project leads: Julio Harvey, Robert C. Vrijenhoek

Project manager: Shannon Johnson

Project team: Francisco Chavez, Danelle Cline, Mike McCann, John Ryan, Hans Thomas, Yanwu Zhang

Collaborators: Jennifer Fisher and William Peterson, Southwest Fisheries Science Center, Newport, Oregon; Jonathan Geller, Moss Landing Marine Laboratories, California; Steven Morgan and Eric Satterthwaite, University of California, Davis

Ocean Visualization

Understanding the consequences of oceanic change requires repeated quantitative assessments of the ocean's interior, its inhabitants, and its bottom topography. The integration of MBARI technologies—remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), sensors, and data-management tools—has had an enormous impact on studies of the seafloor, such as enabling researchers to gain new insights into submarine volcanoes and changes in deep-sea canyons.

The expanding submarine volcano

The life cycle and impacts of deep-sea volcanoes have long been research themes of MBARI's Submarine Volcanism Group led by David Clague. Recent advances in ocean bottom imaging, coupled with persistent, repeated visits to important research sites, have shed new light on submarine volcanic activity. Work done in 2014 proved groundbreaking when the *D. Allan B.* mapping AUV was used to detect the expansion of Axial Seamount's caldera—a result of a build-up of magma below.

Axial Seamount lies on the Juan de Fuca Ridge off the coast of Washington, and it is the most active volcano in the northeast Pacific; substantial eruptions occurred there in 1998 and 2011. Discrete measurements of seafloor changes have been made by several research organizations almost every year since the 1998 eruption. An array of instruments have been placed in the caldera to enable continuous monitoring of earthquakes, gas emissions, and vertical deformation as part of the Regional Scale Nodes (RSN) cabled observatory of the federal Ocean Observatories Initiative (OOI).

MBARI began mapping the summit of Axial Seamount in 2006 and by 2009 had completed mapping the floor of the summit caldera, the upper flanks of the volcano around the caldera, and down the upper south rift zone where the 1998 eruption occurred. A few months after the 2011 eruption, MBARI returned and re-mapped the region covered by the new lava flows, taking advantage of the 10-centimeter vertical resolution provided by the AUV system to map the new flows. As noted in the 2011 MBARI Annual Report, the pre- and post-eruption surveys were co-registered to make a difference map that Clague's team used to determine the extent of the flows and their thickness with remarkable accuracy. The detailed map allowed the team to calculate the volume of the submarine eruption for the first time rather than simply estimating the volume.

While MBARI was mapping the new lava flows, MBARI Adjunct Bill Chadwick from the National Oceanic and Atmospheric Administration and his colleague Scott Nooner from the University of North Carolina used recently placed pressure sensors to establish a new post-2011-eruption vertical-deformation baseline. These measurements were made in and near the caldera where MBARI had previously mapped. When they returned in 2013, they determined the caldera floor had risen since 2011 as magma refilled the underground magma chamber.

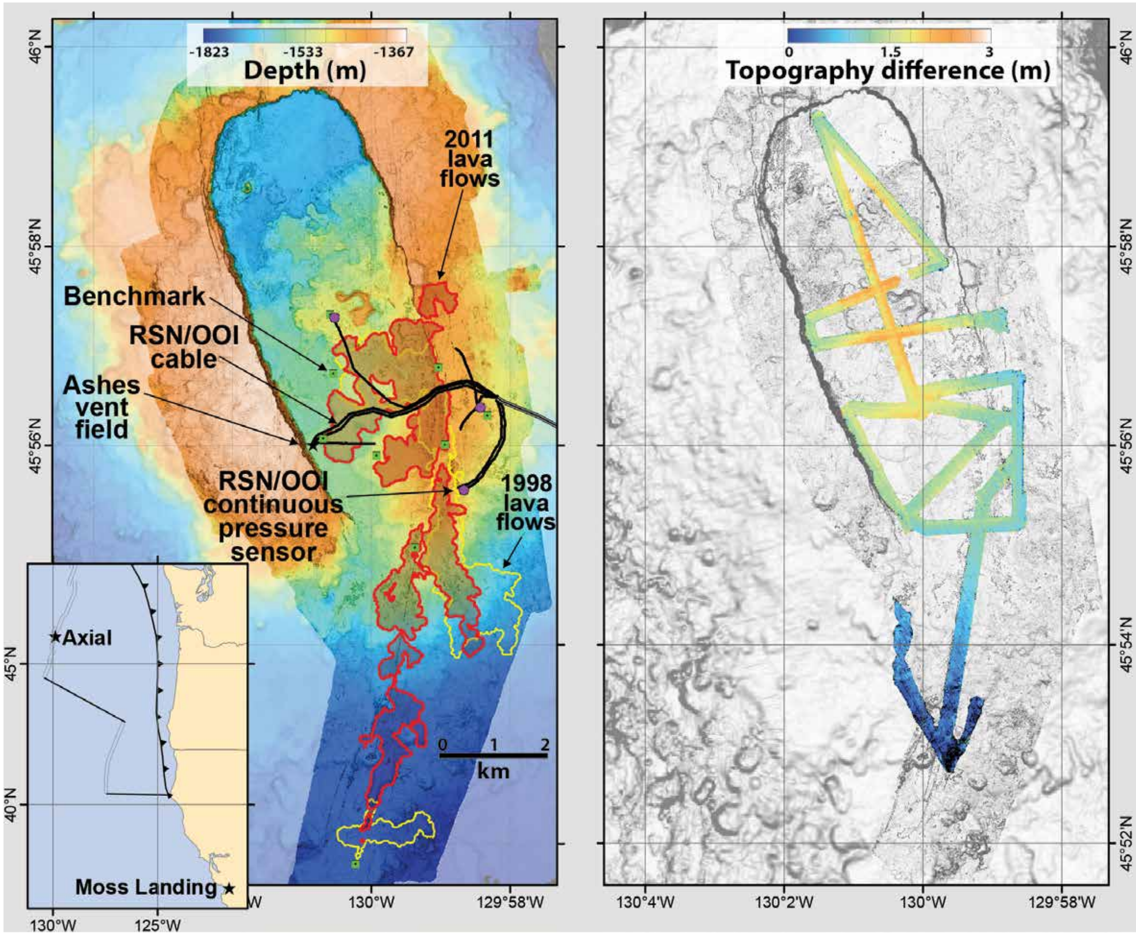


Figure 24. Left: Maps of the location in the NE Pacific (inset) and summit caldera and upper south rift zone of Axial Seamount. Bathymetry collected by the MBARI mapping AUV D. Allan B. *at one-meter resolution at the summit and upper south rift zone of Axial Seamount is superimposed on a map of lower resolution data that was collected with a ship. Locations of the Regional Scale Node of the Ocean Observatories Initiative (RSN/OOI) cables and continuous pressure gauges, pressure measurement benchmarks, and outlines of the 1998 and 2011 lava flows are shown. Right: Deformation map of the topography difference detected by the AUV on a survey in August 2014 at Axial Seamount, shown over bathymetry in gray at the same scale as the map at left.*

Measurements at their benchmarks determined an uplift rate of 60 centimeters per year from 2011 to 2013, a change comparable to what the team was able to detect when mapping the thickness of the 2011 lava flows. With some confidence that additional difference maps would help detect and quantify the magnitude and extent of summit uplift, plans were made to collect another AUV bathymetric survey. When the MBARI team returned to Axial Seamount with the *D. Allan B.* mapping AUV in 2014, a repeat survey was conducted to map, not a thick new lava flow, but the much more subtle and widespread inflation and uplift of the summit of the volcano. This had never been attempted before.

Resolving topographic changes of less than two meters requires that the navigation of the previous and new surveys be precisely co-registered. Co-registration is accomplished by feature-matching using a software tool developed by MBARI Software Engineer Dave Caress and Dale Chayes of Columbia University. The difference map generated (Figure 24) shows that the maximum uplift of 1.8 meters during the three-year period from 2011 to 2014 is located near the center of the caldera, not far from the location of the Chadwick and Nooner benchmark that experienced the greatest uplift between 2011 and 2013. The benchmark instrument provides the ground truth that shows the AUV can indeed be used to map deformation on submarine volcanoes, and may have other applications such as measuring deformation that precedes or accompanies submarine earthquakes and landslides. The AUV method has some advantages over the point pressure measurements in that it can measure the deformation field in a spatially continuous fashion and measure a larger area in a shorter amount of time. However, errors in the AUV method are not yet fully documented because the data have not yet been directly compared with the more precise pressure measurements.

The first-ever success of this innovative AUV method for measuring change on the seafloor inspired the National Science Foundation to support sending a different AUV on the next Chadwick and Nooner cruise set for August 2015 to collect pressure measurements at Axial Seamount. That AUV will repeat some of the MBARI AUV survey areas to tie the AUV mapping results to those of the pressure measurements (Figure 25).

Surface deformation data are key to estimating the size, shape, and depth of a magma reservoir beneath the volcano, and the rate of refilling of the magma reservoir. This, in turn, is used to predict upcoming eruptions. Doing these calculations well requires a three-dimensional map of the deformation field, which is now possible by repeat mapping AUV surveys. The information obtained thus far shows that the deformation is not restricted to the caldera floor and that the rate of refilling is such that the next eruption at Axial Seamount could happen well before the 13-year recurrence interval suggested by the past two eruptions, or even the 11- to 19-year recurrence interval determined from mapping

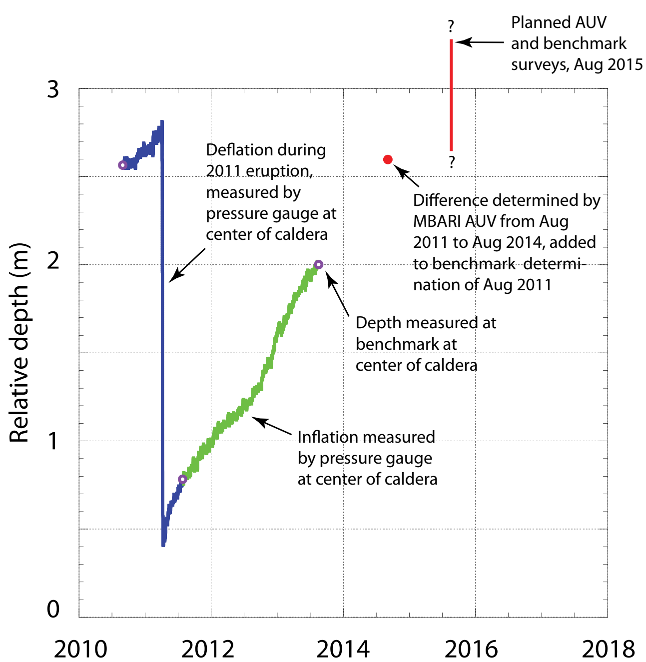


Figure 25. Deformation measured at the center of the caldera at Axial Seamount over the past few years (data provided by Bill Chadwick). The AUV depth difference is consistent with bottom pressure gauge and benchmark determinations, and suggests that the volcano may be priming to erupt again soon.

and dating of prehistoric flows at the summit. [Note: Just as this book was going to press, the predicted eruption occurred on April 23, 2015.] This insight into the likely next eruptions of Axial Seamount could prove invaluable to managers of the extensive cabled observatory infrastructure situated within this active volcano.

Gaining insight into the dynamic nature of deep-sea canyons

Sediment-laden flows (including the wide range of gravity flows from slumps to turbidity currents) are the major processes responsible for moving material from the continents into the deep sea. Over time, the volume of material carried in these flows is nearly equivalent to the total amount of material elevated above sea level by tectonic forces, making them processes of global significance on a par only with rivers in the magnitude of sediment transported. For this reason, geologist Charlie Paull and his team are exploring the physical processes that occur within the axis of Monterey Canyon with an emphasis on the associated submarine sediment flows as a model for what occurs on a global scale.

"Flying an ROV in a tornado" helps set the stage for a multinational experiment

As long as MBARI geologists have been studying sediment flows in deep-sea canyons, the last thing they expected was to be caught right in the middle of one. But that is just what happened in August 2013 when MBARI's ROV *Doc Ricketts* was swept down Mendocino Canyon by an underwater avalanche. This fortuitous encounter yielded exceptional insights into the dynamics of these enigmatic flows.

Sediments suspended in the waters near the seafloor create a dense mass that gets pulled downslope by gravity. These flows can accelerate as they pick up more sediment in their way. Such flows commonly become funneled within submarine canyons. These flows, called turbidity currents, are an important process in submarine canyons. Turbidity currents are the equivalent of rivers in the ocean: they transport sediment, nutrients and pollutants from land to the deep sea (Figure 26). However, unlike most rivers, turbidity currents do not flow continuously but are intermittent, occasionally triggered by earthquakes, large storms, or influxes of sediment-laden floodwater. Some individual flows can be exceptionally large, transporting 10 times the combined annual sediment load from all of Earth's rivers.

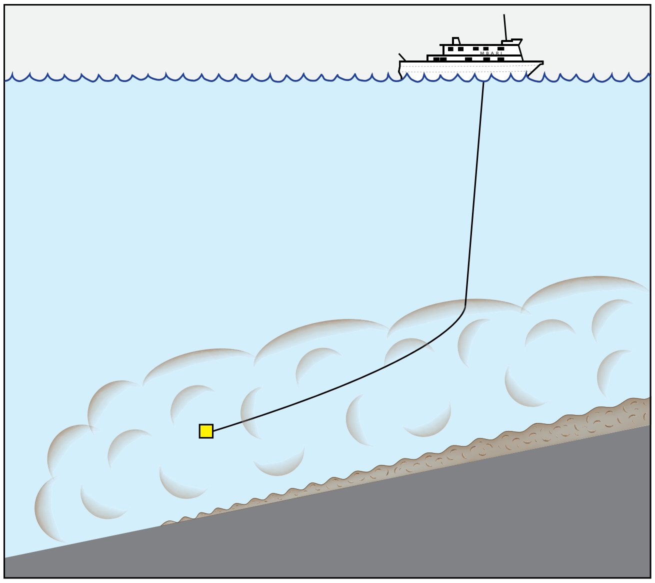


Figure 26. Illustration of a turbidity current sweeping downslope, pulling the remotely operated vehicle along with it.

Understanding turbidity currents remains a major challenge for science: their occurrence is unpredictable and in difficult-to-access locations. Scientific equipment used to document and understand this enigmatic phenomenon must be deployed for long periods to record a potentially hazardous flow. The time spent waiting for these episodic events translates into a major drain on batteries for instruments set to document them, in turn limiting the resolution of the measurements. The only measurements that exist for very large turbidity currents are estimates of their speed based on the time that they snapped seafloor communications cables. These flows likely travel at tens of meters per second—an amazing rate! Only a limited number of studies have succeeded in measuring smaller scale flows in submarine canyons that travel at meters per second. As a result, knowledge of the dynamics of turbidity currents is primarily based on small-scale laboratory experiments involving flows that travel relatively slowly (at centimeters per second), as well as inferences made about flow dynamics from deposits left behind in the geologic record.

It was a lucky break for researchers when the ROV *Doc Ricketts* was diving in Mendocino Canyon off Northern California and the previously clear water became increasingly turbid as the down-canyon current became stronger and stronger. The water soon became so muddy that the pilots could no longer see the seafloor, less than a meter away from the ROV's video camera. A strong current fluctuating in direction was coming down the canyon, yet the pilots managed to maintain position for 18 minutes as pulses of more- and less-turbid water flowed past. At times the top of this turbid layer was seen billowing in front of the vehicle.

Finally, the ROV was spun around by the flow and the pilots were forced to lift off the bottom to prevent damage to the vehicle or its tether. Over the following two minutes the ROV was swept down canyon despite the pilots' best efforts to fly at full speed in the opposite direction. As the ROV ascended so the pilot could regain control, a billowing interface was experienced between turbid and clear water three meters above the seafloor. Despite ascending through a further 80 meters of apparently clear water, the ROV was still being buffeted around and struggling to fly up canyon. "It was like flying an ROV in a tornado," said ROV Pilot Mark Talkovic, who was at the controls that day.

Up on the surface in the ROV control room onboard the *Western Flyer*, the geologists knew they were getting a unique view of the inside of a turbidity current and that it didn't look much like the textbook models. The next hour and a half was spent maneuvering the ROV to investigate the inside of a turbidity current, arguably providing the best insights into these flows to date.

In addition to the video observations, the ROV was continuously measuring salinity, temperature, and the turbidity of the water column enabling the structure of the flow to be further understood. The turbidity data revealed that the apparently clear water in the upper part of the turbidity current contained more suspended sediment than ambient seawater. In fact, the data indicated that the front of the turbidity current had passed by the vehicle 14 minutes before the turbid layer that ultimately swept the ROV down the canyon. Present-day conceptual models suggest turbidity currents have an abrupt flow front; however, in contrast, these observations suggest that the flow front can be more gradual. This calls into question all previous estimates of the velocity of turbidity currents based on submarine cable breaks. The data also showed that the current was highly stratified, but eluded the question of how the layers are coupled.

The information collected reveals our misunderstanding of the dynamics of turbidity currents but also points to the challenge of how to measure them in the future. These observations highlight the need to develop suitable technologies to purposefully and systematically measure similar flows. The incident provided an important basis for the design of an upcoming large-scale, multi-national experiment to be led by MBARI in Monterey Bay.

Experts to embark on major experiment in Monterey Canyon

Researchers from institutions around the world will converge on Monterey Bay in 2015 to undertake a large-scale experiment to study canyon sediment flows. Over the last decade Charlie Paull's group at MBARI and researchers at neighboring institutions have demonstrated that sediment-laden flows occur more than once a year in Monterey Canyon. The proximity of the canyon to MBARI, its known level of activity, and Paull's expertise have made Monterey Canyon an ideal site for a large-scale program to study these flows in their natural setting.

The multi-institution program will include partners and partial support from the United Kingdom's Natural Environment Research Council, the U.S. Geological Survey, and Ocean University of China. This program—called the Coordinated Canyon Experiment (CCE)—will deploy an array of instruments in Monterey Canyon to document and directly sample the passage of sediment-laden flows through the axis of Monterey Canyon. The field experiment will extend over two winter seasons from the fall of 2015 to the spring of 2017. This will be the most comprehensive source-to-sink monitoring of submarine sediment-laden flows ever attempted.

The geologic record shows that kilometer-thick accumulations of sediment occur more than 400 kilometers from shore within the Monterey Fan at the outflow of Monterey Canyon at depths greater than 3,600 meters. The sediment was primarily deposited by flows routed through the meandering Monterey Canyon system. The magnitude of these accumulations attests to the scale and importance of these transport processes. An event can be energetic enough to destroy most monitoring equipment in its path. Indeed, early MBARI explorations of the turbidity currents were foiled by the loss of equipment that turned out to be placed in the perfect spot but were not massive enough to withstand the force of the flows.

The CCE will aim to address basic questions such as how sediment is transported through the canyons, how thick the flows are, how fast the flows move, what triggers them, how the sea-

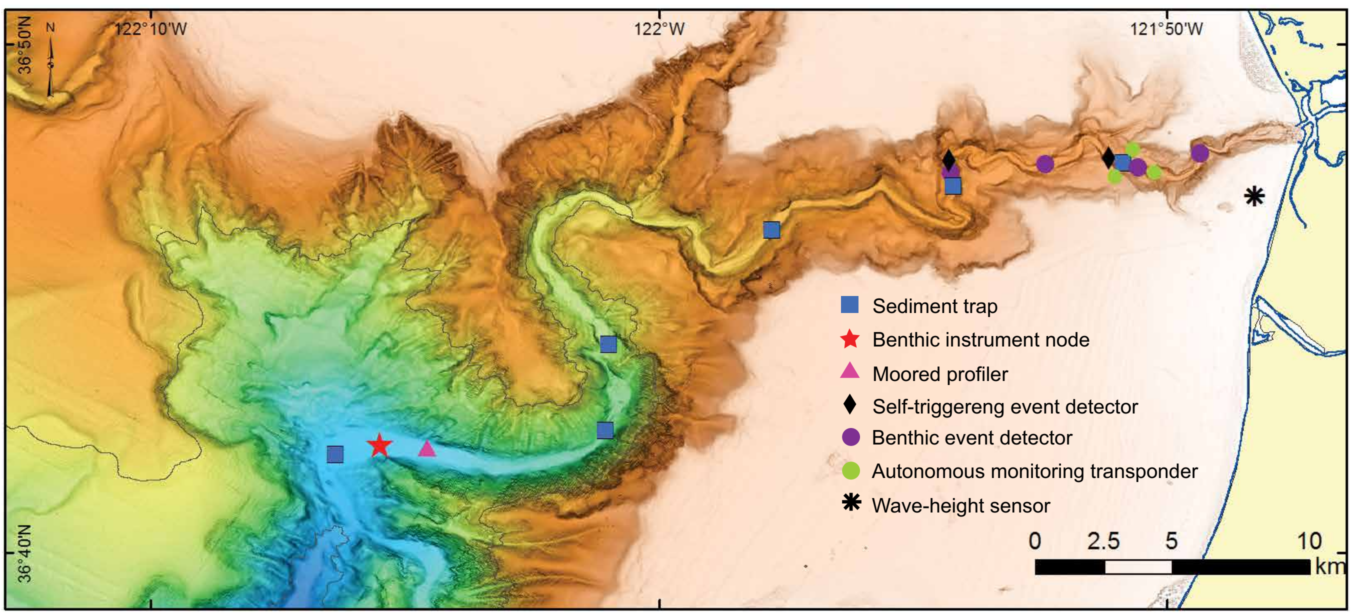


Figure 27. The equipment provided by MBARI and collaborators to be deployed in Monterey Canyon during the Coordinated Canyon Experiment will be anchored by a benthic instrument node (BIN) at a depth of approximately 1,850 meters, where the canyon broadens and flows dissipate. The BIN includes novel software and hardware developed by MBARI to coordinate multiple instruments. A current meter will continuously measure the water velocity above the seafloor for a year and a half. A moored profiler will record turbidity and physical properties profiles of the water overlying the canyon floor directly upstream of the BIN. Six more traditional moorings will be spaced out from above the canyon head out to a water depth of 1,900 meters. Four of MBARI's benthic event detectors—custom-made motion sensors that autonomously record their displacement—will be buried within the floor of the upper canyon. In addition, self-triggering event detectors to be tripped by a bottom current when reaching a threshold velocity, will rise to the surface and communicate the time and their position. A wave-height sensor will be used to ascertain the role of wave-loading on the initiation of sediment transport events. Autonomous monitoring transponders will track the slow motion or "creep" of the seafloor. Repeated high-resolution mapping of the canyon floor with an autonomous underwater vehicle will provide information about the effect of sediment-laden flows on the morphology of the seafloor.

floor evolves in response to flows, and whether these events start at the top of the canyon and flow right out the bottom or only involve a small part of the canyon during an individual event.

The vision for the CCE is to collect as much information on sediment transport events as possible by expanding the scope of instrumentation deployed in the canyon (Figure 27). In preparation for the CCE, marine geological fieldwork within Monterey Canyon in 2014 was aimed at evaluating how well geological deposits found in the canyon represent the sediment particle composition of flows that created them. The sediment coring system mounted on ROV *Doc Ricketts* was used to collect cores along transects at precisely located depths with respect to the canyon floor. Cores were collected at water depths of 300, 500, 800, 1000, 1200, and 1500 meters, including three sites where major instrumentation will be placed in 2015. The sediments sampled in these transects from the floor and lowermost walls of Monterey Canyon (Figure 28) will be compared with sediments collected in traps during flow events. Paull's team will also use a laser particle-size analyzer to measure the grain sizes present in the cores.

Preliminary results show that the sediment found draping the canyon walls is distinctly finer than those collected in sediment traps at the same heights and locations. Apparently sandy sediments are carried in flows to altitudes that are significantly higher than sandy layers found on the canyon flanks. This is precisely why researchers are optimistic that the experiment using a wide range of instruments on the canyon for an extended period will shed new light on the processes that cause major changes on the seafloor globally.

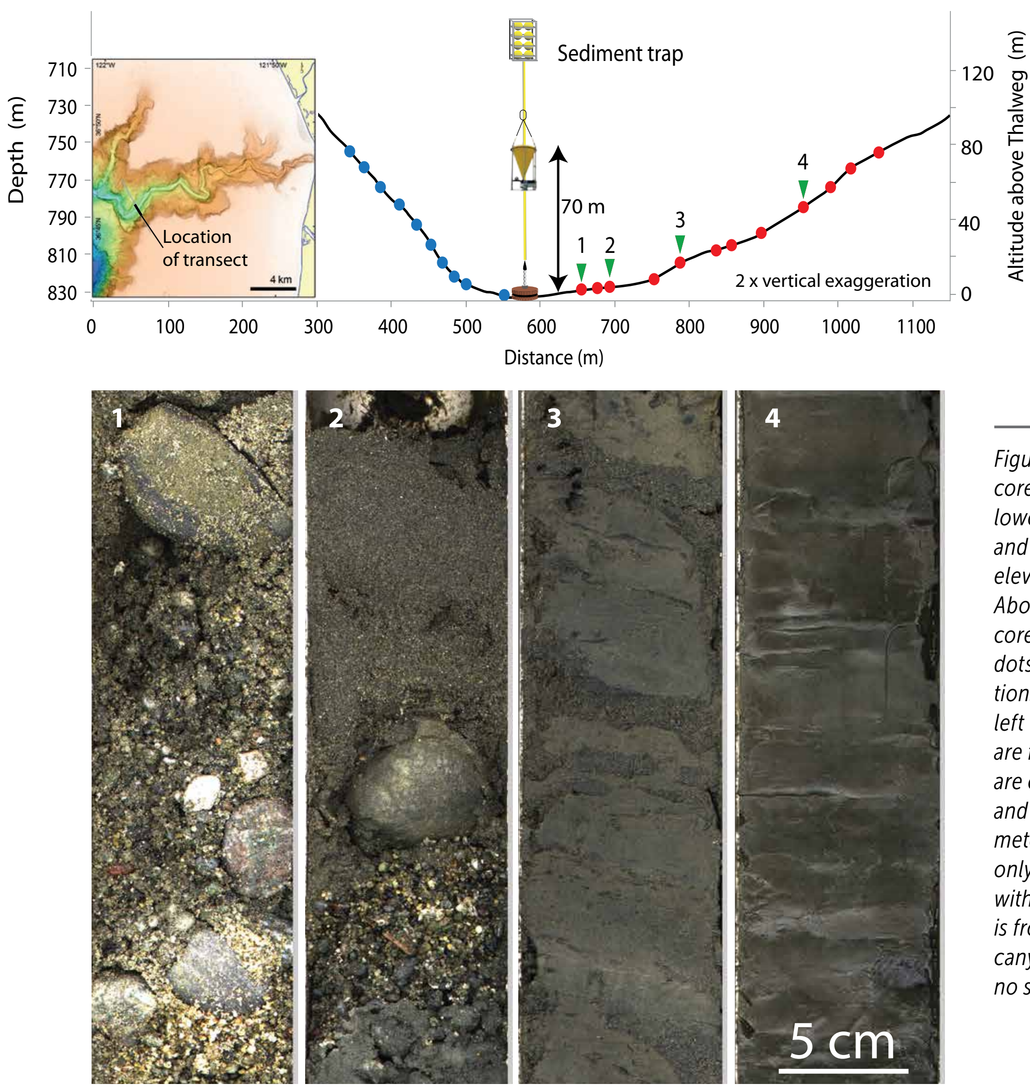


Figure 28. Below, vertically sectioned cores collected by the ROV from the lower flanks of Monterey Canyon and arranged in order of increasing elevation above the canyon floor. Above, the locations of collected cores are indicated with blue and red dots; green arrows indicate the locations of sediment cores below, from left to right. The two cores on the left are from within the axial channel and are composed of poorly sorted sand and gravel. The third core is from 18 meters above the canyon floor and only thin sand layers are observed within a mud matrix. The fourth core is from about 42 meters above the canyon floor and contains essentially no sand layers.

Translating a mass of data into useful visualizations

Advances in sensor and platform technology enable the collection of massive amounts of diverse types of data, making subsequent analyses increasingly difficult. To address this issue, MBARI Software Engineers Mike McCann and Rich Schramm built the Spatial Temporal Oceanographic Query System (STOQS). This open-source software program provides new capabilities for scientists to gain insight from oceanographic data. STOQS uses a geospatial database and a web-based user interface to allow scientists to explore large data collections. The user can see a quick overview of measurements in both space and time, as well focus on a specific parameter or instrument. A user may zoom into a feature of interest, then filter which data to include in the analyses. Different types of visualizations include graphs as well as two- and three-dimensional images and animations. Among the projects STOQS has been used for are the multi-instrument CANON Initiative (page 7) and a project to identify marine zooplankton (see page 17).

Though not originally designed for data produced by inertial sensors, the general design of STOQS allowed it to handle the rotation measurements captured by MBARI's benthic event detectors (BEDs), which tumble along the seafloor as sediment flows through a canyon. Three-dimensional rendering of the record proved particularly appropriate for visualizing motions of a BED. The STOQS web-based user interface allows anyone to select a portion of data to be visualized in three dimensions. In this particular instance it allows users to gain insight into geologic processes operating in Monterey Canyon (Figure 29). When several BEDs instruments are used in the upcoming Coordinated Canyon Experiment to record sediment transport events, STOQS will bring all the data together to help scientists better understand these difficult-to-observe processes.

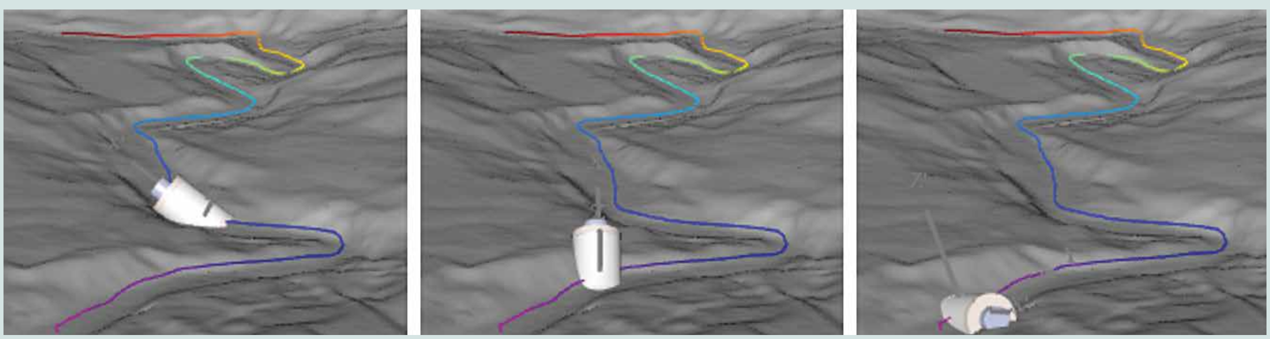


Figure 29. Three frames from a STOQS visualization shows the path and orientation of an instrument that was swept down-canyon in Monterey Bay during a sediment-flow event. The instrument traveled from a depth of 290 meters to 538 meters. Color indicates the number of times the instrument rotated; this instrument made almost 1,200 complete rotations.

Related web content:

Axial Seamount (PDF–page 15): www.mbari.org/news/publications/ar/2011ann_rpt.pdf

MB-System software: www.mbari.org/data/mbsystem/

STOQS video: youtube.com/watch?v=E8wO3qMevV8

Project Teams

Coordinated Canyon Experiment

Project lead: Charles Paull
Project manager: Roberto Gwiazda
Project team: Krystle Anderson, David Caress, Eve Lundsten, Esther Sumner
Collaborators: Phil Barnes, National Institute of Water and Atmospheric Research, New Zealand; Danny Brothers, Katie Coble, and Mary McGann, U.S. Geological Survey, Menlo Park, California; Scott Dallimore, Geological Survey of Canada, Victoria; Dan Parsons, University of Hull, United Kingdom; William Symons and Peter Talling, National Oceanography Centre, Southampton, United Kingdom; Jingping Xu, Ocean University of China

Benthic Event Detectors

Project lead: Charles Paull
Project manager: Brian Kieft
Project team: Larry Bird, Dale Graves, Roberto Gwiazda, Bob Herlien, Denis Klimov, Mike McCann, Alana Sherman, Esther Sumner

Submarine Volcanism

Project lead: David Clague
Project manager: Jennifer Paduan
Project team: David Caress, Bill Chadwick, Brian Dreyer
Collaborators: Julie Bowles, University of Wisconsin, Milwaukee; Paterno Castillo, Scripps Institution of Oceanography, La Jolla, California; Liz Cottrell, Smithsonian Institution, Washington, D.C.; Brian Cousens, Carleton University, Ottawa, Canada; James Gill, University of California, Santa Cruz; Tom Guilderson, Lawrence Livermore National Laboratory, California; James Hein, Jake Lowenstern, and Mary McGann, U.S. Geological Survey, Menlo Park, California; Christoph Helo, University of Mainz, Germany; Rosalind Helz, U.S. Geological Survey, Reston, Virginia; Shichun Huang, Harvard University, Cambridge, Massachusetts; John Jamieson and Tom Kwasnitschka, GEOMAR, Kiel, Germany; Chris Kelley, Ken Rubin, and John Smith, University of Hawaii, Honolulu; Deb Kelley, University of Washington, Seattle; Anthony Koppers, Oregon State University, Corvallis; Jim McClain, Sarah Roeske, and Rob Zierenberg, University of California, Davis; Scott Nooner, University of North Carolina, Wilmington; Michael Perfit, University of Florida, Gainesville; Ryan Portner, Brown University, Providence, Rhode Island; David Sherrod, U.S. Geological Survey, Vancouver, Washington; Adam Soule, Woods Hole Oceanographic Institution, Massachusetts; Ronald Spelz-Madero, Universidad Autónoma de Baja California, Ensenada, Mexico; John Stix, McGill University, Montreal, Canada; Dorsey Wanless, Boise State University, Idaho; Jody Webster, University of Sydney, Australia; Guangping Xu, Colorado State University, Fort Collins

Ocean Imaging

Project leads: David Caress, Charles Paull
Project manager: David Caress
Project team: Larry Bird, David Clague, Katherine Dunlop, Rich Henthorn, Brett Hobson, Eric Martin, Jennifer Paduan, Hans Thomas, Giancarlo Troni

Seafloor Mapping and MB-System

Project lead/manager: David Caress
Project team: Krystle Anderson, David Clague, Doug Conlin, Eve Lundsten, Eric Martin, Jennifer Paduan, Charles Paull, Hans Thomas, Duane Thompson
Collaborators: Dale Chayes, Lamont-Doherty Earth Observatory of Columbia University, New York; Christian Ferreira, University of Bremen, Germany

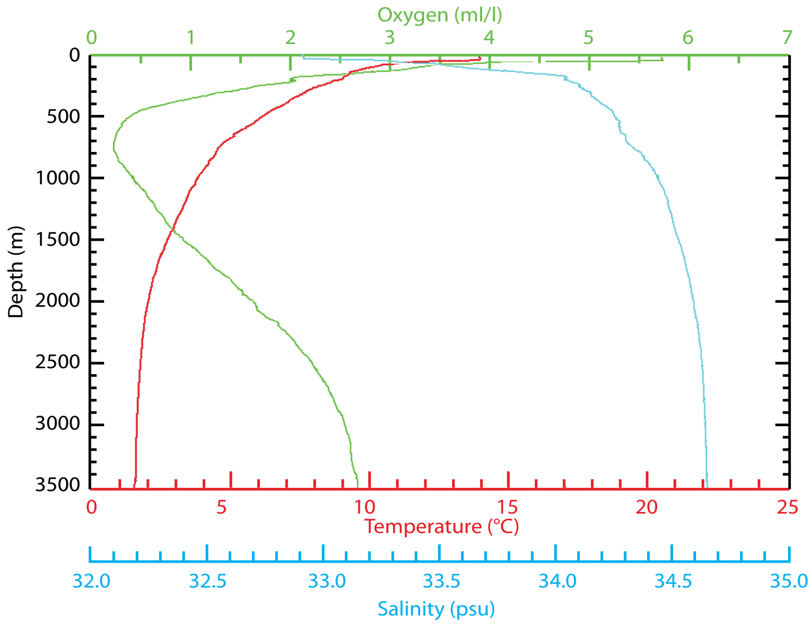
Exploration and Discovery

Exploration inevitably leads to discovery. Many of MBARI's important scientific breakthroughs are the result of going where we had not gone before, looking at new habitats and the organisms that inhabit them, and taking time to document animal behaviors. And sometimes it requires returning to familiar places again and again, just to see what has changed. For these reasons, continued development of new tools and techniques for enhancing access to the ocean, and for exploring its realms from the sea surface to bottom, remains one of MBARI's most enduring research and development themes.

Exploring the oxygen minimum zone

The oxygen content of the entire world ocean is falling. To investigate the consequences of this large-scale change, MBARI scientists are exploring a characteristic attribute of the oceanic water column in Monterey Bay called the oxygen minimum zone (OMZ). In the upper layer of the ocean, oxygen is absorbed to near equilibrium with oxygen in the atmosphere. Oxygen is also produced by photosynthesis in the sunlit surface layer. As the organic matter produced by the phytoplankton in surface waters sinks to intermediate depths of 200 to 1,000 meters, it is decomposed by microbes. That decomposition process consumes oxygen, resulting in the OMZ. Below the OMZ there is less organic matter descending and microbial decomposition is reduced. The depths are influenced by cold, dense, oxygen-rich waters that originate in polar regions. The overall result is a layer with significantly less dissolved oxygen than the waters above or below (Figure 30).

Figure 30. A profile of conductivity (salinity), temperature, and oxygen at depth from instruments on an ROV diving off the California Coast. It shows salinity (blue) increases below the sea surface then levels off; temperature (red) declines with depth, then levels off. Oxygen (green) is high near the sea surface, lowest at mid-depth (500 to 1,000 meters), then increases below 1,000 meters. The precise depths of the oxygen minimum zone varies with location and over time.



When the surface of the ocean warms, the warmer water above does not mix readily with cooler water below, resulting in stratification of the upper layers and less mixing of oxygen-rich surface waters into deeper layers. And as the intermediate depths warm, oxygen levels decrease further because warm water holds less dissolved oxygen than cold water. Global warming is therefore expected to have profound impact on the ocean's oxygen concentration, resulting in a significant expansion of the OMZs.

Measuring these changes and predicting the ecological consequences of the expanding OMZ have been long-term objectives of MBARI's Midwater Ecology Group, led by Bruce Robison. Beginning in 1996, the team has used remotely operated vehicles (ROVs) to make quantitative measurements of the abundance and vertical distribution patterns of the animals that occupy the upper kilometer of the water column over Monterey Canyon. Simultaneous measurements of environmental parameters, including oxygen, are an integral part of these ecological surveys. A significant result of these studies has been the documentation of a 60-to-80-meter vertical expansion of the OMZ and a fragmentation of the resident midwater community as each species responds in its own way to the reduction of oxygen at their preferred depths.

Historically most researchers have measured the OMZ as a two-dimensional profile of oxygen concentration as a function of depth, because the traditional means to measure oxygen is to lower sensors and samplers from the surface, thus sketching a simple, vertical profile (Figure 30). At MBARI the approach is very different because the institute's ROVs can fly into the OMZ to explore it from within. The ROVs have provided a transformative means to observe and sample the animals in and around the OMZ. They enable a truly three-dimensional understanding of OMZ ecology and physiology; and they make it possible to conduct experimental research in situ.

In addition to charting OMZ expansion, Robison's team has discovered that in concert with an upward shift in the top of the OMZ, several key midwater species have also shifted upward in the water column. Among these is the shrimp *Eusergestes similis*, an agile, fast-swimming species that preys on krill and copepods (Figure 31). *Eusergestes* is an important food source for salmon, tuna, squid, and many other commercially valuable species. Is *Eusergestes* being pushed closer to the surface by the enlargement of the OMZ? If so, what are the likely consequences of a continuing decline of dissolved oxygen in the midwater?

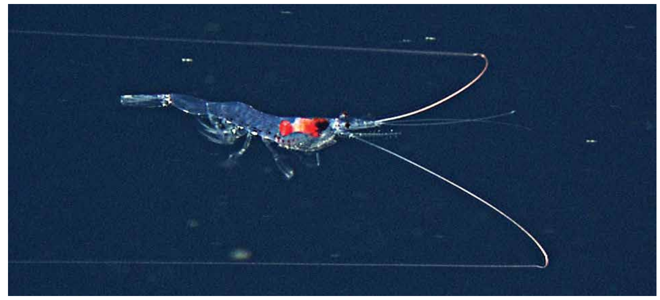


Figure 31. The four-centimeter-long midwater shrimp Eusergestes similis.

The upward movement of the *Eusergestes* population parallels the rise of the top of the OMZ over the last 18 years (Figure 32). While these observations are compelling, at this stage they only represent a correlation and not a demonstration of cause and effect. To carry the investigation further, the midwater team uses an instrument developed at MBARI that measures the oxygen consumption characteristics of a species in its natural habitat. This Midwater Respirometry System (MRS) allows scientists to measure oxygen consumption without subjecting the animal to the physiological trauma of decompression caused by hauling it

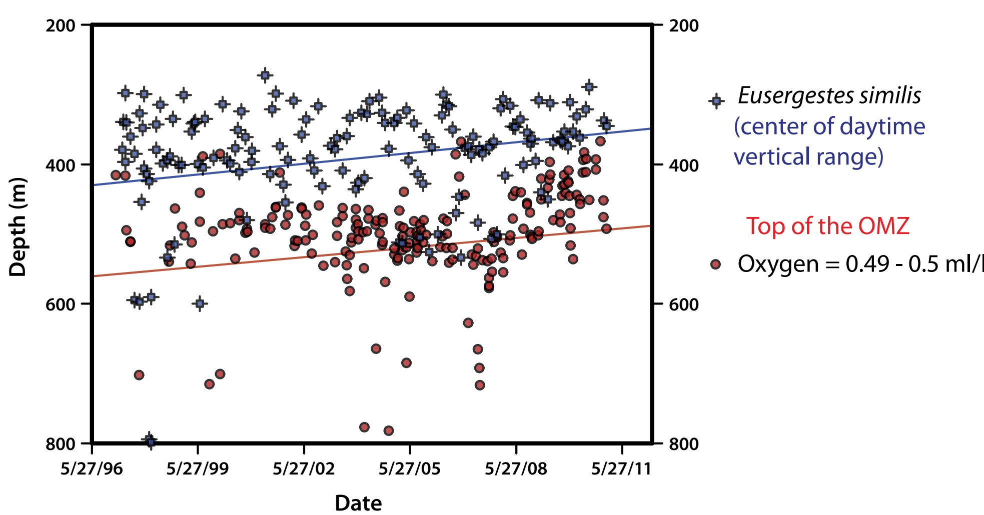


Figure 32. The upward shift of Eusergestes *parallels that of the top of the OMZ.*

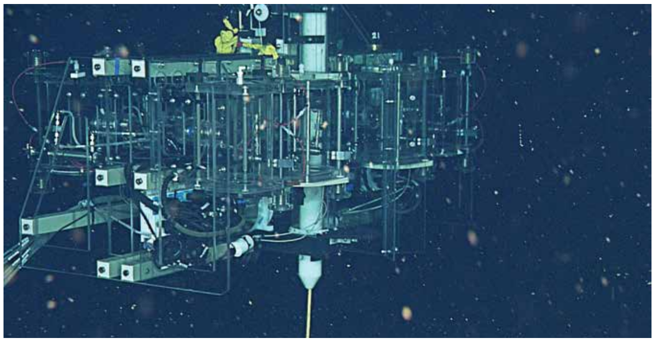


Figure 33. MBARI's Midwater Respirometry System (which is about 1.5 meters long) is attached to an anchored line so that it can remain suspended in the midwater.

to the surface for laboratory measurements—the technique used by virtually all other scientists. MBARI's MRS (Figure 33) is the only instrument of its kind in the world and it gives the midwater team a uniquely valuable insight into the physiology of midwater species like *Eusergestes*.

Any species that consumes oxygen has its own characteristic pattern of oxygen uptake. A mountain climber's body adjusts to the decrease in oxygen that goes with increasing altitude by regulating its oxygen consumption. A climber may breathe deeper and faster, and may slow down the climbing effort. Ultimately, however, the climber's body reaches a point where it can no longer regulate its oxygen consumption and the climber must compensate, either by breathing oxygen from a tank or by moving back down the mountain. The oxygen concentration below which a species can no longer regulate its oxygen consumption is called its "compensation point".

The compensation point for *Eusergestes* has been identified using the MRS. As the OMZ has expanded, the change in depth of *Eusergestes* almost exactly matches the change in the depth where the oxygen concentration equals this species' compensation point. This is strong evidence confirming that decreasing oxygen in the water column is driving a deep-sea species closer to the surface.

Like a great many other midwater species, *Eusergestes* is a vertical migrator. It spends the dark, nighttime hours feeding near the surface where its krill and copepod prey concentrate to feed on phytoplankton. With the rising of the sun most midwater species swim down to spend the day in deep, dark waters where they are protected from visually cued predators. Being forced out of its preferred daytime depth range and up into more brightly illuminated levels, *Eusergestes* becomes much more vulnerable to predators. Many other midwater species are showing similar changes in their distributions, but not all. The MRS is being used to investigate these other species as well.

At the community level, one consequence of OMZ expansion is a phenomenon referred to as ecological fragmentation. Species that formerly co-existed within the same depth range are now being separated because of differing tolerances for diminished oxygen. At the same time, new ecological combinations are being created as upward shifting species are pushed into the depth ranges occupied by species from which they were previously separated. On the other hand, species, like the vampire squid *Vampyroteuthis infernalis* and many gelatinous animals, that adapted long ago to conditions in the OMZ will find that their preferred habitat has grown larger.

Additional ongoing research on the OMZ includes behavioral studies of several species to determine activity levels and energy utilization relative to changing the oxygen concentration. The new version of the MRS allows researchers to change the pH levels in its respiration chambers during an experiment. This makes it possible to investigate how oxygen consumption rates are affected by the ocean's increasing acidity. Comparative studies of the OMZs in the Gulf of California and off the coast of Oregon, each with different oxygen profiles, are also providing insight into the effects of an expanding OMZ and into the ocean of the future.

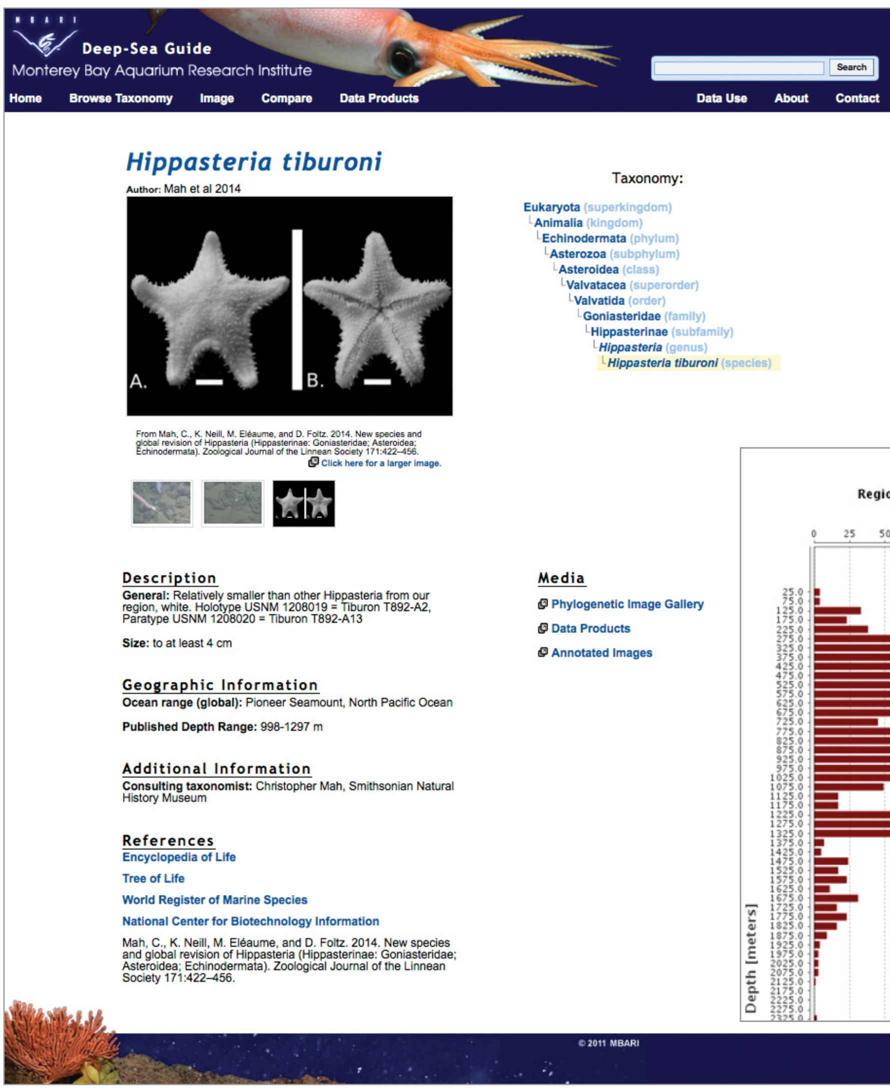
New guide provides a glimpse into years of deep-sea observations

Since MBARI's inception, founder David Packard recognized that an investment in technology and methods necessary for accelerating systematic observation of the deep ocean was lacking. To that end, he laid the foundation for the establishment of a groundbreaking ROV program that aimed to record all observations as high-quality video and to carefully curate them as a centrally managed, widely available resource. The idea was that by developing a system with accurate and easily retrievable records, researchers could efficiently review observations, create baseline biodiversity assessments, and ultimately tackle research problems that were not initially anticipated. In the ensuing years, this revolutionary documentation effort led to what is now known as the Video Annotation and Reference System (VARS). This unique capability has helped distinguish MBARI among its peers; it has been instrumental in revealing innumerable discoveries new to science and inspiring analogous observation programs around the globe.

After over 27 years, MBARI has amassed an unparalleled collection of observations of deep-sea habitats, fauna, and environmental conditions recorded by MBARI's ROVs and other camera platforms. This effort has proven fundamental to understanding how ocean processes, such as the OMZ, have changed over time, and how they may further evolve in the future. Given this treasure trove of information, the VARS team, led by Nancy Jacobsen Stout, recently completed development of a new tool called the Deep-Sea Guide (DSG), which aids in quality control, in-depth exploration, and interpretation of these invaluable records. This interactive, web-based system allows for the correlation and visualization of vast amounts of information.

The exploratory features of the DSG include searching and browsing by name, image, or related organisms; customizable comparison tables; and links to references. Delving deeper into this rich catalog, standardized data products are created to provide a variety of "snapshots" about the distribution of species or geologic features, etc., thus providing more efficient means of review and analysis. These tools also deliver quantitative and qualitative information required for biodiversity assessment studies within MBARI's regions of study, and provide context for hypothesis generation and modeling of future studies to be conducted locally as well as farther afield. In these ways, the DSG is helping to refine sampling and analysis methods, improve the effective exchange of information, and engage the research and education communities at large.

For example, in a recent project with Chris Mah, a research collaborator at the Smithsonian's National Museum of Natural History, researchers from MBARI's Video Laboratory Group reviewed taxonomic classifications, along with the video observations and other information as described in the VARS database concerning certain specimens of sea stars (Figure 34). The



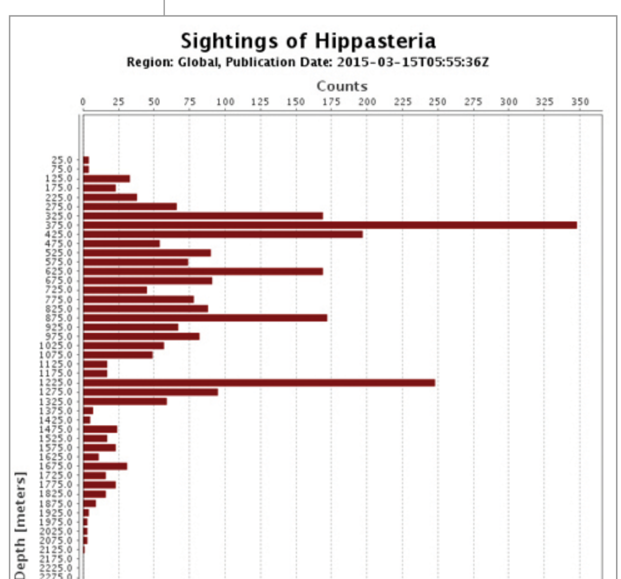


Figure 34. Deep-Sea Guide web page for Hippasteria tiburoni*, a new species of* Hippasteria *collected by MBARI at Pioneer Seamount and described by collaborator Chris Mah in 2014. It was named in honor of the ROV* Tiburon*, the vehicle used for collecting the type specimen. Below, a sample of the graphs available in the Deep-Sea Guide, providing information about the depth, location, time, and frequency of encounters for the selected animal, geological structure, or other feature.*

Deep-Sea Guide was then used as the data hub for correlating and visualizing the information gleaned from different sources, and for documenting and developing further identification strategies. In this example, numerous species that were previously unknown to MBARI scientists were identified, with several of the specimens being entirely new to science. These types of collective data reviews also enable staff to document previously unknown geographic and depth distributions, in situ interactions and behaviors, and habitat preferences of many deep-sea animals. The DSG streamlines the collaborative process of identifying animals and vetting the critical characteristics of species and their close relatives. This will accelerate deep-sea biological studies as more researchers contribute information and disseminate their knowledge to a wider audience.

A more accessible deep-sea camera

One new technology designed to enhance ocean exploration and discovery is a camera system that makes it easier to acquire underwater images on a limited budget. MBARI engineers, under the leadership of Chad Kecy, created the new SeeStar underwater system and, in keeping with MBARI's mission to share new technology, have made the plans and related software available for anyone else who might like to build one.

The SeeStar began as a project to devise a cheap and easily deployable camera that Marine Biologist Steve Haddock and colleagues around the world could use to document jellyfish blooms. Haddock also wanted a system that was versatile enough to be attached to a pier, mounted on a tripod on the seafloor, or carried by a robotic submersible.

Kecy and his team created a system that costs just under $3,000 in parts, and can operate as deep as 300 meters (almost 1,000 feet) for months at a time. The SeeStar has three parts—a camera, a battery pack, and LED lights—each contained in its own pressure housing (Figure 35). The pressure housings are made of relatively inexpensive PVC pipe with plastic end caps. The three pressure housings are connected using commercially available flexible electrical cables. This modular construction makes the SeeStar easy to attach to a variety of platforms. The team selected a relatively inexpensive and easy-to-use camera, then designed a custom circuit board to control both the camera and the LED lights.

It quickly became apparent that the SeeStar system could be used for all kinds of underwater research. In 2014, two SeeStar systems were deployed in Antarctica by a team from Moss Landing Marine Laboratories, providing a unique view of the seafloor under the ice. The Nature Conservancy tested SeeStar as part of a study to count and size rockfishes in marine protected areas (Figure 36). Another group, the California Wetfish Producers Association, used the SeeStar to photograph the eggs and larvae of market squid, to learn more about the animals' life cycles.

Several MBARI researchers have also used SeeStar in their research. One group attached the SeeStar to an autonomous underwater vehicle (AUV) to observe large animals in the open ocean. Another group used a SeeStar-equipped AUV to follow a second robotic vehicle as it traveled across the ocean surface. Video from the SeeStar confirmed that the AUV was able to track the surface vehicle closely, like a white shark stalking a sea

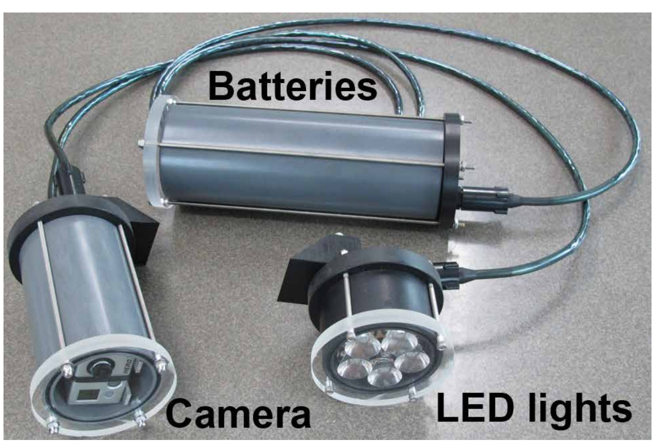


Figure 35. The three modules of the SeeStar camera system allow it to be mounted on many different platforms. The battery housing is about 18 centimeters long.

Figure 36. Photograph taken by SeeStar of rockfish and anemones on a 1.5-meter-wide section of the seafloor of Monterey Bay. By taking many such images over time, researchers hope to be able to monitor changes in fish populations.

lion. A third MBARI group is using SeeStar to document wear and tear on a buoy that generates electrical power from the ocean waves.

Even though the current version of SeeStar is relatively inexpensive, the team will investigate alternative cameras that could provide high-resolution still images and more exposure control, as well as commercially available underwater lighting systems. With MBARI's commitment to sharing developments, the SeeStar system is sure to help marine researchers see things underwater that they've never been able to see before.

Finding a boulder on the seafloor repeatedly is harder than you think

Observing and documenting changes that occur on the seafloor over time is one of the cornerstones of MBARI's activities in Monterey Bay and beyond. Performing these studies requires that an underwater vehicle carrying cameras and perhaps other imaging or sampling devices return precisely to selected sites repeatedly over extended periods. Since MBARI's founding, ROVs have been used for this type of task, and their success is unmatched in the ocean research community. Use of ROVs will continue for the foreseeable future when a human presence is required, to direct collection of sediment core samples or retrieve particular objects or animals, for example. However, missions that require only imaging, measuring properties of the water column, or collecting water samples, can now be performed routinely and autonomously using an AUV. In these cases, AUVs offer considerable cost savings because they can cover a much greater area than an ROV and the requirements for ship and personnel resources are greatly reduced.

Navigation is one of the biggest challenges when performing any underwater return-to-site mission. That is, the ROV or AUV needs to find a particular spot on the seafloor with bull's-eye accuracy. If an area has been visited previously, and a navigation beacon was left there, then the task of finding that exact site is greatly simplified. However, deploying such navigation aids can be expensive, and therefore is only practical for a few very special sites. If a particular region of interest has not been previously visited, then no such aid is available.

The typical method used to locate a site on the seafloor using an ROV and a support ship relies on a combination of the ship's GPS system and an acoustic positioning device, such as an ultra-short-baseline (USBL) system, that provides a range and bearing measurement of the ROV's position with respect to the ship. Given the latitude and longitude of the ship plus the location of the ROV relative to the ship, the latitude and longitude of the ROV can be computed. This method is effective, but because USBL can be off by tens of meters, it is typically left to the ROV pilot to visually locate the actual target site.

When using an AUV, there is no GPS, no USBL, and no pilot. The AUV must provide all of its own navigation without any human intervention. An inertial navigation systems (INS) uses dead reckoning to fill this need for some missions. Dead reckoning calculates the current position based on a known location or position and advances from there using measured or estimated speed, direction, and distance. Dead reckoning by INS relies on a computer and motion and rotation sensors to continuously calculate its position, orientation, and velocity. For example, MBARI's mapping AUV incorporates a high-grade INS that can achieve positioning knowledge approaching 0.01 percent of distance travelled. However, while this is excellent performance, such accuracy is only available when the AUV is within about 150 meters of the seafloor and only if it never loses its "bottom lock" reading of the seafloor, which sometimes does occur. Consequently, even with such a high-grade INS, an AUV may need to surface occasionally for a GPS update to correct for the accumulated navigation error. Even this doesn't solve the problem

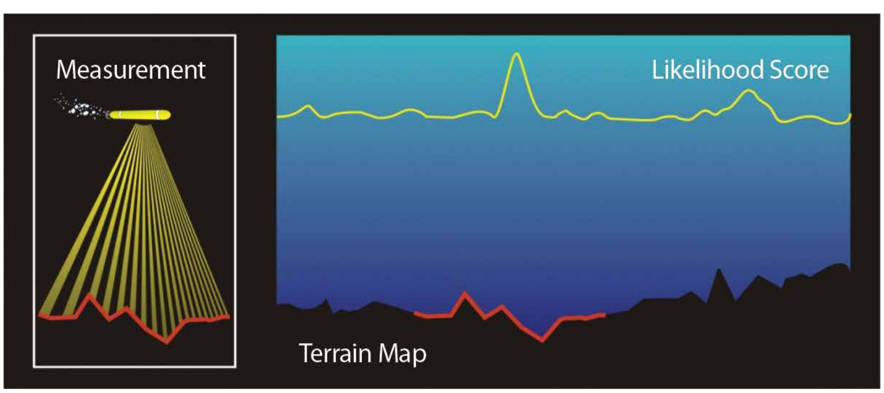


Figure 37. A schematic of TRN operation. Left: The terrain profile (red) is measured by the vehicle. Right: The measured profile is correlated against a map of the terrain to produce a likelihood score. That is, the maximum score is located at the most likely location of the AUV with respect to the map.

for a deep-dive mission since the AUV will be out of bottom lock during its long return to the seafloor. Further, many other AUVs that could be used for these surveys may not be equipped with such high-grade INS systems. Consequently, a new means of navigation is required to enable AUVs to reliably perform return-to-site missions.

Two teams of MBARI engineers, led by Mechanical Engineer Brett Hobson and Adjunct Steve Rock, are working to overcome this challenge by developing a navigation system that references the physical features of the seafloor. This terrain-relative navigation (TRN) approach enables a vehicle to navigate using a bathymetric map as the primary source of information. In essence, it is a sophisticated method of "orienteering" in which the AUV determines its location by comparing measurements of local terrain profiles against a map of the area. Specifically, the AUV uses its altimeter, sonar, or a logger that tracks velocity and altitude to measure the AUV's height above the seafloor. That information, coupled with knowledge of the AUV's depth allows profiles of the terrain to be measured as the AUV flies above the bottom. These measured profiles are then correlated with a stored map to determine its location (Figure 37). The concept of TRN for vehicle control dates to the 1960s when early versions of it were applied to cruise missile control (for occasional updates of position). Recent advances in filtering theory, however, have now made it possible to apply the technique as a real-time measurement capable of operating over any area of the seafloor that has been mapped.

A significant feature of TRN is that it determines an AUV's position with respect to the map rather than an estimate of latitude and longitude. If the map were perfectly matched to actual earth

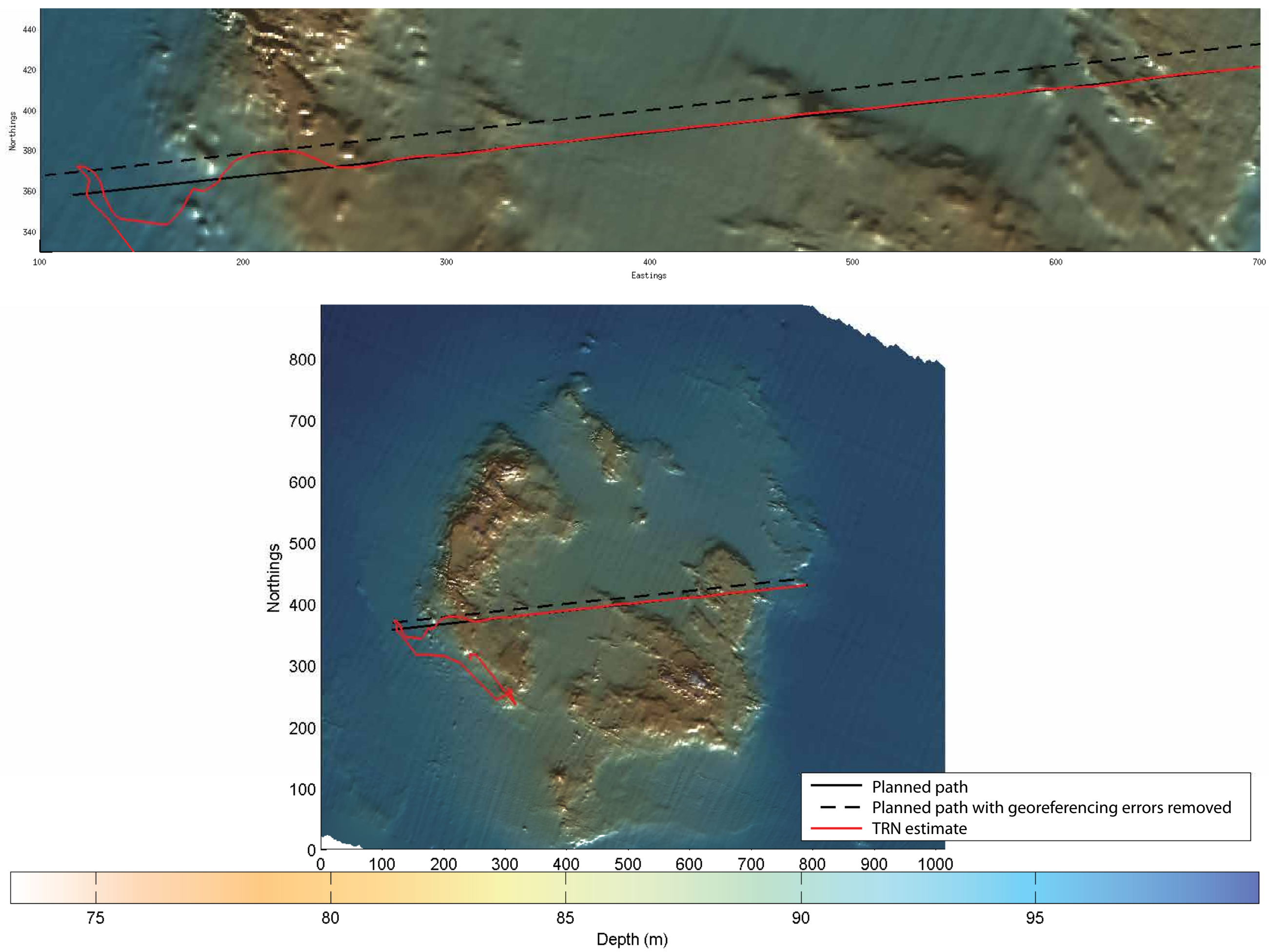


Figure 38. The dashed line is the path the AUV would have flown without TRN, showing an offset of about 20 meters from the AUV's commanded path (black line). Note that the AUV (red line) tracks the desired black line path successfully. At the beginning of the west-to-east crossing, the AUV begins tracking the dashed line. Then, after the TRN filter converges, the AUV drops immediately to track the solid black line. The best estimate of accuracy is that the AUV flew over the true target site within about two meters when using TRN.

coordinates, then a map-relative and an inertial position would be identical. However, maps often have errors that can range from tens of meters to hundreds of meters. Consequently, if a site is selected as a location on a bathymetric map, TRN will guide the vehicle precisely to that spot whereas conventional INS will guide the vehicle to the (possibly incorrect) latitude and longitude.

The capability for an AUV to complete an autonomous return-to-site mission using TRN was successfully demonstrated in 2014. To perform these tests in Monterey Bay, an identifiable feature (a boulder) was selected as a target over which the AUV should fly. Significantly, the bathymetric map used had a known georeferencing error of approximately 20 meters. Hence, if the AUV flew to the latitude and longitude that defined the boulder's actual location on the seafloor based on the map-defined coordinates, it would be missed. The success of the TRN algorithm in identifying the 20-meter offset in the map and automatically correcting the trajectories to fly over the boulder is demonstrated in Figure 38.

A long-term goal for the team is to launch an AUV near the shore, have it transit to a remote site, perhaps tens of kilometers from shore and thousands of meters deep, perform a precise photographic survey of a section of the seafloor, and return home safely. This capability, once perfected, has innumerable applications for efficiently exploring new areas of the ocean bottom. Improving navigational capabilities holds the promise of a powerful way to document current seafloor conditions and thereby assess significant changes that may occur in the future.

Related web content:
Video Annotation and Reference System: www.mbari.org/vars/
Deep-Sea Guide: dsg.mbari.org
SeeStar Camera: www.mbari.org/seestar

Project Teams

Midwater Ecology and Midwater Time Series
Project lead: Bruce Robison
Project managers: Kim Reisenbichler, Rob Sherlock
Project team: Stephanie Bush, Kris Walz
Collaborators: Kat Bolstad, Auckland University of Technology, New Zealand; Danelle Cline, Steve Haddock, Mike McCann, Brian Schlining, Kyra Schlining, Rich Schramm, Susan von Thun, MBARI; Jeffrey Drazen and Richard Young, University of Hawaii, Manoa; William Gilly, Hopkins Marine Station of Stanford University, Pacific Grove, California; Henk-Jan Hoving, GEOMAR-Helmholtz Centre for Ocean Research, Kiel, Germany; Karen Osborn and Michael Vecchione, Smithsonian Institution, Washington, D.C.; Brad Seibel, University of Rhode Island, Kingston

Deep-Sea Guide
Project leads: Brian Schlining, Nancy Jacobsen Stout
Project manager: Nancy Jacobsen Stout
Project team: Linda Kuhnz, Lonny Lundsten, Kyra Schlining, Susan von Thun

SeeStar Camera
Project lead: Steve Haddock
Project manager: Chad Kecy
Project team: François Cazenave, Michael Risi

Precision Control Technologies for ROVs and AUVs
Project leads: Brett Hobson, Michael Risi, Steve Rock
Project manager: Steve Rock
Project team: David Caress, Rich Henthorn, Rob McEwen, Charles Paull, Brian Schlining, Hans Thomas
Collaborators: Shandor Dektor, Marcus Hammond, Sarah Houts, Steven Krukowski, Jose Padial, and David Stonestrom, Stanford University, California

Iceberg AUV
Project leads: Brett Hobson, Steve Rock
Project manager: Brett Hobson
Project team: David Caress, Rich Henthorn, Eric Martin, Rob McEwen, Paul McGill, Hans Thomas,
Collaborators: Shandor Dektor, Marcus Hammond, Sarah Houts, Steven Krukowski, Jose Padial, and David Stonestrom, Stanford University, California

Weird and Wonderful

Frequent exploration in the deep sea often results in glimpses of rare animals, like the elusive anglerfish. Equally important is the chance to try something new to see what happens, such as shining different-colored lights on deep-sea animals. Just as intriguing is the advancement of technology that makes new projects possible, for example, the advent of three-dimensional printing.

Sometimes you just get lucky

Working throughout the water column means dealing with a fluid, three-dimensional environment that is always changing. In midwater research, even though the ship may return back to the same spot on the sea surface, the parcel of deep water under the ship is always different. As a consequence, you never know for sure what you will find when you dive below the surface. That was the case last November when ROV *Doc Ricketts* dove into Monterey Canyon. At a depth of 580 meters the ROV came upon a species that had never been seen alive in its natural habitat—a particular deep-sea anglerfish.

Deep-sea anglerfish are strange and elusive creatures. Fewer than half a dozen have ever been captured on film or video by deep-diving research vehicles. The little angler that MBARI's ROV found is named *Melanocetus johnsonii* (Figure 39). It is also known as the black seadevil and *Doc Ricketts* shot the first video footage ever made of this species alive and at depth.

As anyone who watched the movie *Finding Nemo* can tell you, anglerfish are unusual predators. An angler has a remarkable apparatus on its head—a fishing pole with a luminous lure at the tip that it uses to attract prey. In the darkness of deep water the anglerfish flashes its light to attract prey and draw it near. When a fish or squid swims up, it is quickly inhaled into the angler's huge mouth and trapped by its long, sharp teeth. Given the shape of this angler's body, it is clearly not designed for speed. Instead, these are ambush predators, lurking in the darkness to grab an unwary meal.

Figure 39. The anglerfish Melanocetus johnsonii *(about nine centimeters long) as seen from the ROV* Doc Ricketts.

The shape of this unusual animal observed in Monterey Bay also reveals that it is a female. In this species the males are much smaller and lack the fishing pole and lure. Males are ill-equipped for feeding and their sole purpose appears to be to find a female and mate with her as soon as possible. The eyes of most anglerfish are relatively small. In their dark habitat these fish rely more on sensing the movements of other animals in the water around them than on vision. Organs in the skin along the sides and head of the fish are very sensitive to the slightest movements and they function effectively in the dark.

The deep sea is filled with surprises and wonderful creatures. Humans have only just begun to explore this vast realm and one can only imagine what discoveries are yet to be made.

Here's looking at you, prey

Although the deep sea gets only dim light from the sun, many animals still have large, well-developed eyes. The cockeyed squid *Histioteuthis heterops* is interesting because its two eyes are different sizes: one is about the size one would normally expect on a squid, but the other eye is enlarged and bulges from the squid's head. This big eye may be used to search above for dim silhouettes of its potential prey. MBARI Scientist Steve Haddock has been using short-wavelength blue lights on the ROVs to visualize the natural fluorescence of a host of enigmatic animals. When the blue light shone on *Histioteuthis*, the lens of the enlarged eye was brightly fluorescent (Figure 40). Fluorescent pigments in the lens absorb particular colors of light, and so are thought to help the squid discriminate between dim light from the sun and the bioluminescent light produced by its prey as camouflage.

This is a great example of exploration and discovery—in this case, taking a blue light into the deep sea—opening up a whole new way of seeing things we never knew existed.

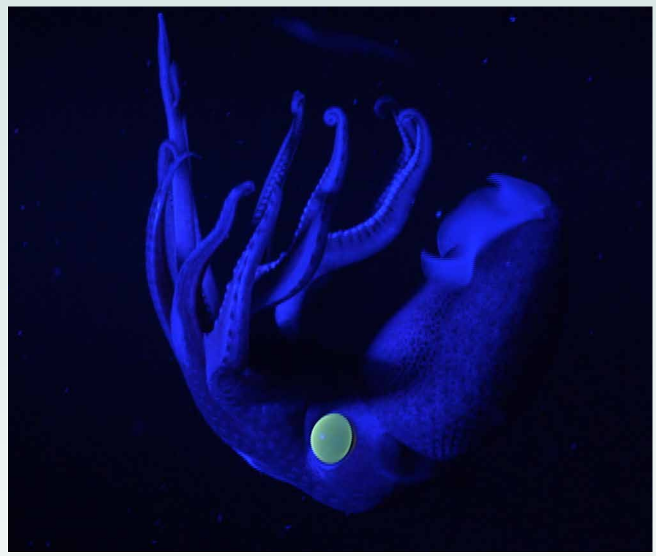


Figure 40. The larger of this squid's two eyes fluoresces a bright yellow-green when seen under blue light. This squid is approximately 100 centimeters long.

A design game-changer

Manufacturing Group Leader Dale Graves puzzled over a problem of size and shape. How could he create a suction sampler for the mini ROV for collecting delicate midwater animals? For years MBARI has used a design based on an original device from Harbor Branch Oceanographic Institute for ROV *Ventana*. That costly, full-sized sampler had a carousel head with internal pockets and blind corners that were impossible to make using conventional machining methods. So the suction head on *Ventana's* sampler was cast in resin by an outside vendor to produce a mold for the final product. For the mini ROV, Graves drafted a digital design for a much smaller suction head sized to fit a vehicle less than a fourth of *Ventana's* size (Figure 41). The new design looked good on the computer screen, but would it be functional?

MBARI's new rapid prototyping system provided the answer. The digital design file was sent to MBARI's machine shop to produce a prototype using a high-definition 3D printer. Looking something like a large, boxy refrigerator, the printer lays down layer after layer of extruded plastic or other material under computer control to produce a prototype or functional product (Figure 42). The rapid prototyping enables a designer to quickly iterate and explore different aspects of a product to select an optimal design. Testing of the new suction sampler prototype showed that a second version wasn't necessary; it worked! Instead of hiring a company to build a customized part and waiting a week for its delivery, MBARI staff can now design innovative solutions, quickly produce parts, and evaluate them in-house. Here's to innovation!

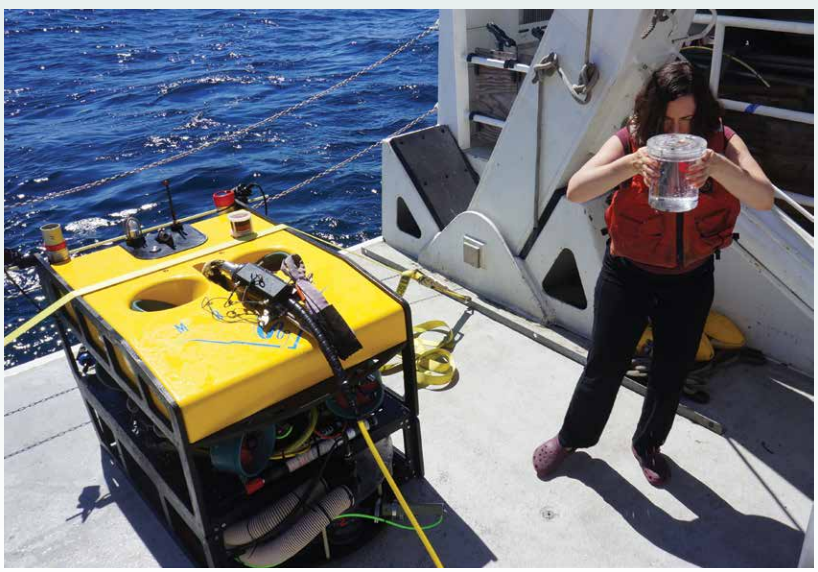


Figure 41. MBARI Adjunct Karen Osborn checks a 1.9-liter sample chamber taken off the mini ROV.

Figure 42. Above, the computer-aided design of the head of a 10-centimeter-tall suction sampler for the mini ROV. Below, a peek inside the design shows the internal pockets and blind corners that would be impossible to machine by traditional methods.

Related web content:
Anglerfish video: youtu.be/VqPMP9X-89o

On the Horizon

The coming year will prove to be both challenging and exciting as we continue to advance a suite of research and engineering initiatives, and work to bring these developments to the public at large. Of the planned activities, MBARI's expedition to the Gulf of California will be a major undertaking. It will encompass a variety of research goals and Mexican collaborators, and will draw on most all of our sea-going capabilities, equipment, and research groups. Another notable effort is the construction of a fleet of MBARI's proven, long-range autonomous underwater vehicles for use by other researchers. At the same time, teams of biological oceanographers will tackle challenges of creating a new paradigm for assessing ocean biodiversity, and a new exhibit at the Monterey Bay Aquarium will highlight ideas and insights stemming from MBARI.

The Gulf of California Expedition

In February 2015 MBARI's research vessels *Western Flyer* and *Rachel Carson* are scheduled to depart for the Gulf of California, Mexico. Surveys using the mapping autonomous underwater vehicle the *D. Allan B.* operated from the *Rachel Carson* will provide high-resolution bathymetric maps to help direct subsequent ROV operations. The first stop for the *Western Flyer* is Ensenada, where Marine Operations Director Steve Etchemendy will host a visit for local collaborators and university students to see the ship and learn about the expedition. A second event for collaborators and students will take place in La Paz, Mexico, where most of the research activities will originate. Geological studies will focus on continental margin tectonics and volcanism. Biological oceanographic studies will examine variability in upper-ocean productivity, chemosynthetic organisms on the deep seafloor, and the influence of low oxygen and other climate-related changes on biology. MBARI will also support the David and Lucile Packard Foundation's Gulf of California program with seafloor mapping operations and mini ROV surveys within the Cabo Pulmo National Park.

Ahi, *Aku*, and *Opah*—the AUVs, not the fishes!

MBARI's SURF (Sensors: Underwater Research of the Future) Center has a long-standing collaboration with the Center for Microbial Oceanography: Research and Education (C-MORE) in using the Environmental Sample Processor (ESP) to support various studies. As part of this continuing collaboration, MBARI is undertaking the building of three new long-range autonomous underwater vehicles (LRAUVs) containing the newest version of the ESP instrument with support from the National Science Foundation. These vehicles have been named *Ahi, Aku,* and *Opah*, after three pelagic fishes

Figure 43. The new Makai *vehicle with an early version of the third-generation Environmental Sample Processor makes its maiden voyage.*

that are found in the open waters around Hawaii. The C-MORE center will begin operating these vehicles in Hawaii in late 2016.

This development presented an opportunity for the LRAUV team to integrate all the design improvements and ideas gathered during more than 8,000 hours of operations in recent years into a new cohort of vehicles. One of the biggest challenges for the LRAUV team will be to figure out how to export this complex robotic system that to date has only been operated by the original design engineers, to an outside group of scientists and their support staff. Over the course of 2015 the team from Hawaii will begin working with their MBARI counterparts during various field experiments in Monterey Bay to learn about the operations of this new system as a step towards ensuring a smooth transition.

Also during 2015, MBARI's own third LRAUV, called *Makai* (Figure 43), a prototype for *Ahi, Aku,* and *Opah*, will be transitioned from the engineering development team to the scientists who can start using it for field work and provide feedback on any aspect of the system that needs refinement.

A new approach to observing marine biodiversity

The extent and depth of the world ocean includes untold billions of individual organisms and an unknown number of species moving through the vast, ever-changing environment. One of oceanography's big challenges is to find ways to autonomously track life in the sea in a way similar to how oceanographic properties such as temperature, nitrate, and chlorophyll fluorescence are currently measured. This challenge of estimating and understanding biodiversity is not unique to MBARI. There are no affordable means by which to routinely make comprehensive biodiversity assessments in the sea and understand how and why they change. Seeking possible solutions, the National Ocean Partnership Program selected three proposals for demonstrating Marine Biodiversity Observations Networks (MBONs): one in the Channel Islands, a second in the Alaskan Arctic, and a third in the Florida Keys and Monterey Bay National Marine Sanctuaries.

With funding from NASA, NOAA, and the Department of the Interior, MBARI joined with partners from the Monterey Bay National Marine Sanctuary, Stanford University, the Center for Ocean Solutions, the Southwest Fisheries Science Center, and the Central and Northern California Ocean Observing System to tackle the Monterey Bay component of the MBON program. MBARI Scientist Francisco Chavez is serving as the lead investigator of the effort. A similar set of partners will work in the Florida Keys in close consultation with the Monterey Bay team. The primary goals are to demonstrate a system for assessing marine biodiversity (Figure 44), and to integrate the findings from such a network with information from a range of other

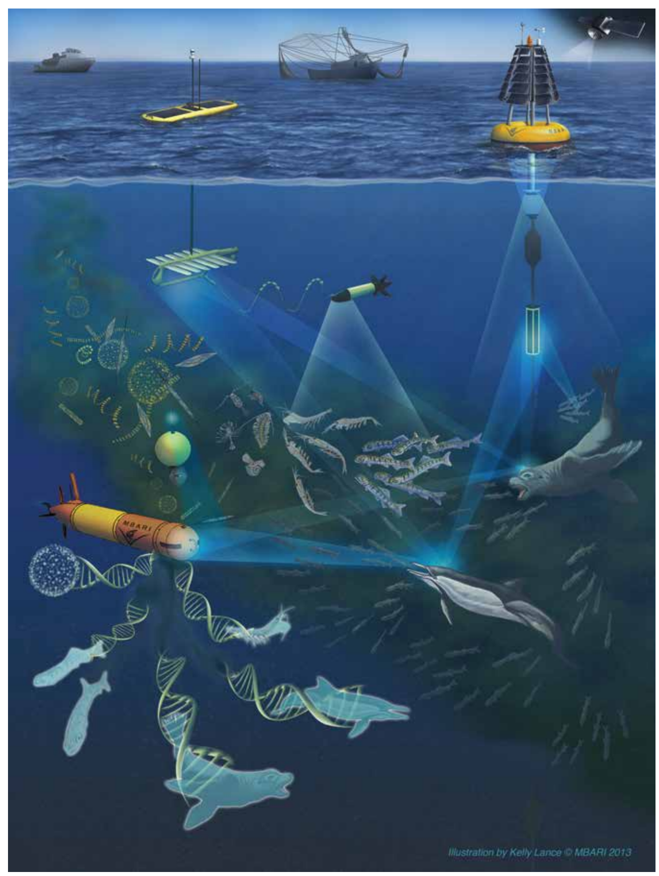


Figure 44. Schematic representation of a pelagic food web and technologies that will support biodiversity assessments in a continental shelf Marine Biodiversity Observation Network.

ongoing research and resource management programs. The teams will provide observational data within a socio-economic context and make the information rapidly accessible to a variety of stakeholders. The ultimate goal will be to develop a plan to transition the demonstration MBON into an operational system.

MBARI staff will lead the team from Monterey Bay and focus on two tasks: to develop new means for tracking biodiversity using genomic techniques and to integrate historical measurements amassed from previous work into the MBON demonstration effort. The first task will capitalize on existing MBARI efforts of several research groups (led by Steve Haddock, Chris Scholin, Bob Vrijenhoek, and Alexandra Worden) using historical samples on which traditional morphological and taxonomic analyses have been completed. These techniques will also be tested on future samples collected by autonomous underwater vehicles equipped with sample-collection devices. The second task is grounded in combining information gathered from partners to determine the key biological elements structuring particular ecosystems, and to understand the forces that drive changes in their abundance and distribution.

Monterey Bay Aquarium to offer a virtual dive to the deep

Starting in spring 2015, the public can embark on a virtual deep-sea expedition when the Monterey Bay Aquarium opens its re-imagined "Mission to the Deep" exhibit, highlighting MBARI's valuable work. Inside the exhibit, a 360-degree video projection of Monterey Canyon immerses visitors in a simulated underwater world (Figure 45). In this otherworldly setting, visitors will discover how MBARI's scientists and engineers use revolutionary new technologies to study the ocean.

Overhead, a half-scale model of MBARI's remotely operated vehicle *Doc Ricketts* (Figure 46) will shine a spotlight around a virtual underwater landscape, revealing videos of mesmerizing deep-sea animals such as vampire squids, sea toads, and jellies that grow more than three feet across. The program also highlights the latest technological tools developed by MBARI engineers, including an autonomous underwater vehicle that MBARI researchers use to explore deep-sea environments.

Interactive displays in the center of the exhibit will let visitors take a simulated dive deep into Monterey Canyon. Visitors will control the dive and will be able to stop at different depths to learn more about the animals or research equipment they see along the way.

The Monterey Bay Aquarium provides an unparalleled outlet for education and outreach about MBARI's research and engineering efforts. MBARI staff were integral to the creation of the new exhibit, as they designed and constructed the accurate model of ROV *Doc Ricketts*. The remodeled "Mission to the Deep" exhibit will be an opportunity to share with visitors what MBARI researchers experience on a regular basis—the fantastic animals and mysterious environments of the deep sea.

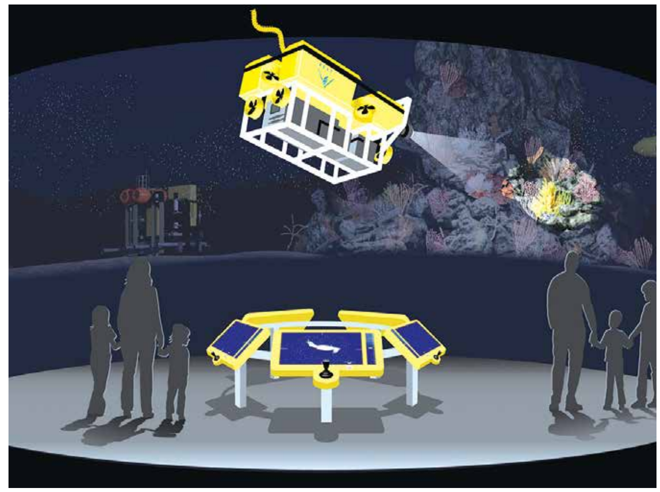


Figure 45. Artist's rendition of the new MBARI exhibit at the Monterey Bay Aquarium. A model of a remotely operated vehicle explores the simulated walls of Monterey Canyon walls to give visitors a feel for an MBARI mission to the deep sea.

Figure 46. Mechanical Engineer Farley Shane was part of an MBARI team that helped construct a model of a remotely operated vehicle for the new "Mission to the Deep" exhibit at the Monterey Bay Aquarium.

Related web content:

Gulf of California Expedition: www.mbari.org/expeditions/GOC15/

Monterey Bay Aquarium Exhibit: http://www.montereybayaquarium.org/animals-and-experiences/exhibits/mission-to-the-deep

Behind the Scenes:

Seafaring crews make MBARI's research and development possible

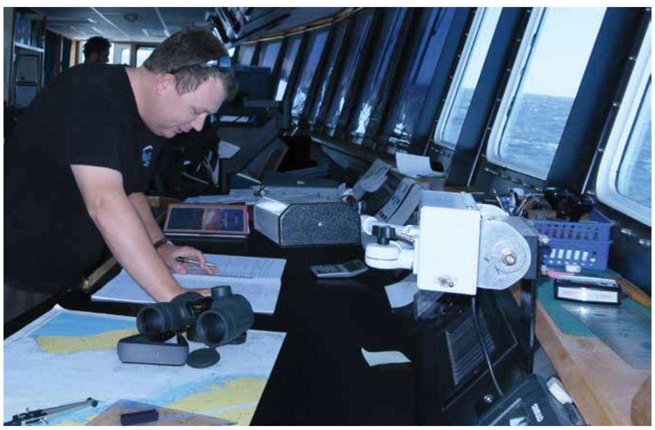
One advantage of MBARI's organization is that scientists and engineers routinely work closely with the same ships, operations crew, and submersible pilots year in and year out. In the broader oceanographic community, researchers go to sea on whichever ship and dates they can secure, often working with a different crew and vessel for each expedition. In contrast, MBARI researchers regularly go to sea on the institute's own two ships, which builds a collegial working relationship between the crews and the scientists and engineers. Working in such close proximity year after year, the crews become an integral part of the research team and often contribute immeasurably to the planning and execution of at-sea efforts in ways that would generally not happen at a traditional oceanographic institution.

The crews who operate the MBARI vessels and vehicles are behind many of the institute's greatest accomplishments. The science and engineering teams can spend months or even years preparing for a particular cruise. They know that when they board the ship a full complement of staff will have made everything ready, the autonomous or remotely operated vehicles will be equipped with the necessary tools, and the everyday details for having an entire team at sea will have been addressed. But that doesn't mean the scientists and engineers take it for granted.

The institute's two research vessels serve complementary purposes. The *Rachel Carson*, a coastal class vessel, usually supports day trips, enabling scientists to make repeated visits to their research sites in

The crews of the two MBARI vessels, the R/V Rachel Carson *(left) and the R/V* Western Flyer*, and of the vehicles aboard those ships, are essential to the success of many of the institute's research programs.*

Paul Ban, first mate and relief master of the R/V Rachel Carson*, charts navigation for an expedition.*



Captain Andrew McKee on the bridge of the R/V Western Flyer*.*

and near Monterey Bay. MBARI engineering staff often rely on the ship for local at-sea tests of new technology under development. The ship is also used for autonomous underwater vehicle (AUV) missions, both locally and as far afield as Canada and Mexico. The *Rachel Carson* has 12 berths, but the living quarters are tight on extended expeditions.

The *Western Flyer*, a larger regional class vessel with overnight accommodations for 14 crew and 11 scientists, typically conducts science cruises of a week or longer, allowing scientists to travel a bit farther and conduct extended experiments at their study sites. On some of the larger expeditions, the *Rachel Carson* fields an advance operation, as the AUV team maps the seafloor so the scientists aboard the *Western Flyer* can then follow and do targeted ROV dives at the sites identified on the maps.

While the research teams are focused on experiments and explorations, the captains and their crews are always looking out for the big picture—sometimes fighting winds and currents just

For more than 25 years, Chief Engineer Mark Aiello has kept MBARI ships in excellent working condition, first working on the R/V Point Lobos*, and now on the R/V* Rachel Carson*.*

to keep the ship on station where the ROV is diving thousands of meters below them. They must remain ever-conscious of the ROV tether's position, to be sure it does not get caught up in the ship's propeller.

Ship engineers are tasked with keeping every ship system in operation as well as making regular improvements to the vessels. On the *Rachel Carson*, the engineers helped turn a former oil-field supply vessel into a solid research vessel. On the *Western Flyer*, the engineers must maintain a wide range of systems typically found on much larger ships.

"The ship engineers rarely get the credit they deserve for keeping the ships running," said *Western Flyer* Master Andrew McKee. "This is a floating micro city with a power plant, sewage disposal, galley, stores."

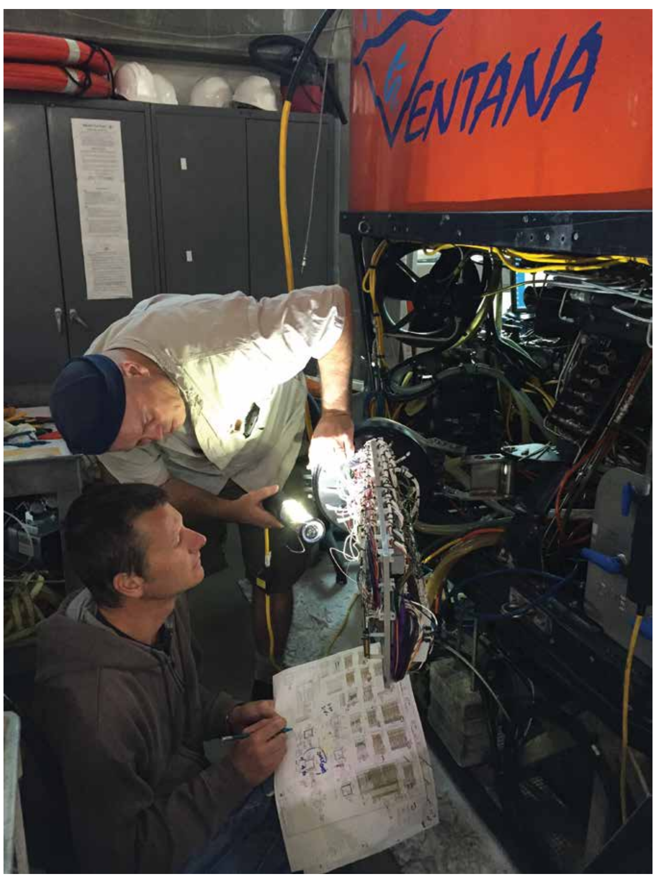
The ships' captains must balance priorities that can be mutually exclusive—safety, science, and schedule. Yet both captains are very clear that the mission of every cruise is to get science done. *Rachel Carson* Master Aaron Gregg said about the many AUV missions they have run, "Our motto is 'Get the data!'"

MBARI ROV pilots are skilled at collecting samples and facilitating the experiments necessary for advancing scientific understanding. Their missions can include taking deep-sea video, collecting animals or sediment samples, testing new instruments, or conducting engineering tasks in the deep sea. Over the years the pilots have become experts at conducting these operations remotely.

The ROV *Ventana*, which operates from the *Carson*, can be employed on very different missions from one day to the next,

Western Flyer *Chief Engineer Matt Noyes and his crew work round-the-clock to assure the smooth operation of the vessel.*

Electronics Officer Dan Chamberlain has been keeping all electronic gear and communications equipment on the Western Flyer *in good working order since the ship first set sail in 1996.*



Ventana *Pilots Mike Burzcynski, kneeling, and D.J. Osborne work on an upgrade of the remotely operated vehicle's control system.*

requiring the pilots to do quick tool reconfigurations. They might also add on an instrument when staff engineers want to test a prototype of the latest technology to quickly evaluate how the instrument will fare in the deep sea.

"Catching translucent jellies that are smaller than a dime is the hardest challenge," *Ventana* Pilot Mike Burzcynski said. "Also, the shrimp that Bruce Robison is trying to catch—they have these long antennae and as soon as they sense something, they dart away."

Robison appreciates the effort that goes into collecting these animals for his research. "You make it look easy, even though we know it is not," he told the crew following a recent *Ventana* dive.

The AUV team's unique challenge is that they cannot make mid-course corrections once the vehicle is in the water, sometimes for dives of as long as 18 hours. "The success or failure of our cruises begins weeks in advance," said AUV Group Leader Hans Thomas. "We've got to have everything ready because once the vehicle is in the water our ability to get in there and tweak it is not there." While the vehicle is running its pre-programmed mission, Thomas and his team spend much of their time designing and developing new vehicles and instruments.

The ROV *Doc Ricketts* is operated from the *Western Flyer*. The pilots stock up on extra parts to get them through any eventual-

AUV Specialist Doug Conlin and AUV Group Leader Hans Thomas inspect the AUV after it returned from a mission.

ity, but they have become masters at making do with the parts they have if a repair is needed when they are far offshore. The pilots of both ROVs take pride in their ability to keep the ROVs running day after day. If the ROV doesn't go in the water, the science day is lost, but thanks to the care and forethought of the crews, those days are rare.

The longer expeditions are hard on all the crew members because it means being away from family, sometimes missing the most important family events. Neither ship has a lot of room to spare, so there isn't much personal space and that can take its toll after weeks at sea.

The captains and pilots say they feel fortunate to work with crews with whom they have a close working relationship, not only with each other, but also with the support staff onshore. Aboard ship, there is frequent crossover between the crews, where each tries to help the other with whatever challenge they may be facing. Despite the challenges that go into operating the ROVs and ships, there are many benefits as well.

Chief ROV Pilot Knute Brekke, right, and Pilot Bryan Touryan-Schaefer make repairs to one of the thrusters from the ROV Doc Ricketts *in the tool shop aboard the R/V* Western Flyer.

"What I find really rewarding is having the opportunity to operate a vehicle of this magnitude for the Packard Foundation and to be able to do science and go places most people will never go," said ROV *Doc Ricketts* Chief Pilot Knute Brekke said. "And to see things nobody else sees. We are privileged."

Project Summaries

Below are brief summaries and listings of team members for MBARI projects supported by the David and Lucile Packard Foundation, but not otherwise highlighted in this report. The full MBARI project portfolio also includes many projects funded by the National Science Foundation, the National Oceanic and Atmospheric Administration, the Gordon and Betty Moore Foundation, the National Aeronautics and Space Administration, Stanford University, the U.S. Department of Energy, and a number of other organizations.

Aerostat Hotspot

Project lead/manager: Brent Roman
Project team: Larry Bird, Denis Klimov
Collaborators: Jared Figurski and John Ryan, MBARI

This balloon-borne radio relay has the potential to provide "over-the-horizon" communications much more inexpensively than satellites. An aerostat "aircraft" is a commercial product called a helikite, a cross between a kite and a balloon that can carry a payload of 1.5 kilograms. Initial estimates indicated that aerostats flown at an altitude of less than 150 meters (500 feet) could maintain real-time, high-bandwidth communications between ships and other low-lying assets up to 15 kilometers (10 miles) away. Ships maneuver freely while flying the helikite as long as the wind velocity remains less than 40 knots. The helikite can be retrieved in minutes when necessary. This year, using inexpensive long-range WiFi transceivers and simple, omnidirectional antennas, radio links were repeatedly demonstrated between a helikite flown over MBARI and the *Paragon* vessel more than 11 kilometers offshore.

Software Engineer Brent Roman conducts the first helikite test flight on the beach.

Aquarium-MBARI Project

Project lead/manager: George Matsumoto
Project team: Jerry Allen, Nancy Barr, Stephanie Bush, Judith Connor, Craig Dawe, Eric Fitzgerald, Kim Fulton-Bennett, Dale Graves, Kevin Gomes, Crissy Huffard, Bill Kirkwood, Linda Kuhnz, Lonny Lundsten, Thom Maughan, Paul McGill, Craig Okuda, Bruce Robison, Kyra Schlining, Farley Shane, Nancy Jacobsen Stout, Ray Thompson, Susan von Thun, Mark Tynes
Monterey Bay Aquarium team members: Hank Armstrong, Athena Barrios, Rita Bell, Alicia Bitondo, Lisa Borok, Christy Chamberlain, Mike Chamberlain, Paul Clarkson, Jim Covel, Jeff Doyle, Andrew Fischer, Randy Hamilton, Sal Jorgensen, Humberto Kam, Tommy Knowles, Koen Liem, Sue Lisin, Kenneth Maguire, Andrea McCann, Enrique Melgoza, Tracy Murray, John O'Sullivan, Eric Nardone, Raul Nava, Chris Payne, Ken Peterson, Katy Scott, Margaret Spring, Scott Stratton, Kim Swan, Jaci Tomulonis, Cynthia Vernon, Patrick Webster, Mary Whaley

Collaborations between the Monterey Bay Aquarium and MBARI reached almost every department and division. The *Tentacles* special exhibit continued to benefit from deep-sea cephalopod collections, including the first-ever display of two species—*Vampyroteuthis* and *Histioteuthis*. The aquarium started revising an exhibit and a program about MBARI. The exhibit involved building a scale model of a remotely operated vehicle (see page 42) and revising the MBARI auditorium program which will have a greater focus on technology.

Automated Detection of Species

Project lead/manager: Danelle Cline
Project team: Duane Edgington
Collaborators: Philip F. Culverhouse, University of Plymouth, United Kingdom; Euan S. Harvey and Mark R. Shortis, RMIT University, Melbourne, Australia; Ajmal Mian, University of Western Australia, Crawley; James W. Seager, SeaGIS, Bacchus Marsh, Australia; Faisal Shafait, NUST School of Electrical Engineering and Computer Science, Islamabad, Pakistan

This international group of collaborators provides a good balance of research and development teams using computer vision systems for aquaculture study. This project uses stereo imagery and state-of-the-art three-dimensional deformable models for improved tracking and identification of animals based on shape and texture. The MBARI team shared current knowledge of tracking, detection, and recognition based on shape and texture used in MBARI's Automated Visual Event Detection system as an opportunity to transfer knowledge and technology to improve aquaculture practices.

Autonomous Underwater Vehicle (AUV) Infrastructure Support

Project leads: David Caress, John Ryan
Project manager: John Ryan
Project team: Mike McCann
Collaborators: Danelle Cline and Thom Maughan, MBARI

Improvements and upgrades were made to the mapping vehicle data systems. Continuing maintenance and development of MB-System, the primary software used for processing and visualization of seafloor mapping data, supported research at MBARI as well as training and research in the greater marine geological community. Development of the Spatial Temporal Oceanographic Query System (STOQS) enabled effective integration of AUV data with a variety of data from other platforms. STOQS three-dimensional visualization was enhanced.

Benthic Event Detectors (BEDs)

Project lead: Charles Paull
Project manager: Brian Kieft
Project team: Larry Bird, Dale Graves, Roberto Gwiazda, Bob Herlien, Denis Klimov, Mike McCann, Alana Sherman, Esther Sumner

Development efforts focused on refining the instrument in preparation for the Coordinated Canyon Experiment (see page 25). Two different package densities and two different package shapes were tested side by side. Over the course of the initial prototype deployment, three canyon events were recorded. Lighter instruments went further down the canyon (as much as 10 kilometers in 48 minutes) while heavier packages travelled only about two kilometers in 10 minutes. Shape did not seem to matter as much as anticipated. A graphical display of all the events to date was created. Several improvements were made to the instruments as a result of lessons learned from the prototypes. Data from the experiments have been useful in steering the requirements for the upcoming experiment. The team also improved shore-side data visualization and access (See page 27).

Spherical BEDs and cubical monuments of varying densities were deployed side by side for a 2014 experiment.

Central and Northern California Ocean Observing System (CeNCOOS)

Project leads: Francisco Chavez, Leslie Rosenfeld
Project manager: David Anderson
Project team: Fred Bahr, Aric Bickel, Jennifer Patterson
Collaborators: Jack Barth, Oregon State University, Corvallis; Barbara Block, Hopkins Marine Station of Stanford University, Pacific Grove, California; Rob Bochenek, Axiom Data Science; Yi Chao, University of California, Los Angeles; Kenneth Coale, Jim Harvey, and Jason Smith, Moss Landing Marine Laboratories, California; James Doyle, Naval Research Laboratory, Monterey, California; Chris Edwards, Raphael Kudela, and Andrew Moore, University of California, Santa Cruz; Rikk Kvitek, California State University Monterey Bay; John Largier, University of California, Davis, Bodega Marine Laboratory; Karina Neilson, Romberg Tiburon Center for Environmental Science, Tiburon, California; Jeff Paduan, Naval Postgraduate School, Monterey, California; Frank Shaughnessy, Humboldt State University, California; Chad Whelan, CODAR Ocean Sensors, Mountain View, California

CeNCOOS coordinates a collaborative effort to monitor, observe, and forecast the coastal ocean. In 2014 new sensors and data streams were initiated, including a seawater chemistry system at the Hog Island Oyster Company on Tomales Bay to monitor ocean acidification, and a second glider line off Trinidad in Northern California, complementing the existing glider transect that runs from Monterey westward into the Pacific. Ocean now-casts and forecasts remain core elements of the CeNCOOS collaborative, and this year investigators developed new computer models, refined forecasts using regional ocean circulation models, and explored new ways to assimilate observations to improve the model forecasts. Funding from NASA enabled the team to work with collaborators to distribute harmful algal bloom (HAB) forecasts, participate in California HAB mapping, and collect observations from citizens on HAB-related mammal strandings. A high-frequency radar array produced continuous observations of ocean currents in Central and Northern California. Accomplishments included the writing and publishing of the CeNCOOS Strategic Plan, the launch of an updated CeNCOOS website, the release of a new data portal, and the hiring of David Anderson as the new director following the retirement of Leslie Rosenfeld.

An autonomous glider launched by Research Technician Chris Wahl departs on a bearing southwest from Monterey across the California Current. Real-time observations by CeNCOOS contribute to the national Integrated Ocean Observing System (IOOS). Gliders, with their autonomous ability to dive 500 to 1,000 meters below the surface, provide data not otherwise attainable.

Chemical Sensors

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Ginger Elrod, Hans Jannasch, Gene Massion, Josh Plant, Carole Sakamoto
Collaborators: Robert Carlson, Honeywell; Todd Martz, Scripps Institution of Oceanography, La Jolla, California; Steve Riser and Dana Swift, University of Washington, Seattle

Efforts focused on the development of sensors for ocean carbon chemistry, primarily pressure-tolerant pH sensors and dissolved inorganic carbon analyzers. With additional support from the National Science Foundation, two arrays of profiling floats with sensors for pH, nitrate, and oxygen were deployed in the Pacific and Atlantic sectors of the Southern Ocean. These instruments are capable of autonomous operation for multi-year periods. In a joint effort with the Honeywell Microsensor Lab, Scripps Institution of Oceanography, and Sea-Bird Scientific, a suite of pH sensors were built and entered in the ongoing Wendy Schmidt Ocean Health XPRIZE competition to evaluate pH sensors. The MBARI team also continued its analysis of the 12-year-long record of nitrate measurements on a mooring in Monterey Bay and another mooring in nearby Elkhorn Slough.

Coelenterazine Biosynthesis

Project lead: Steven Haddock
Project team: Warren Francis

The National Institutes of Health funded this research on the application of transcriptomic data to the study of bioluminescence. The structure of the yellow-fluorescent compound involved in the light emission of the polychaete *Tomopteris* was determined. Photoproteins and luciferases were revealed from a diverse set of deep-sea animals.

Core Conductivity-Temperature-Depth (CTD) Data

Project lead: John Ryan
Project manager: Erich Rienecker
Project team: Gernot Friederich, Mike McCann, Reiko Michisaki, Kim Reisenbichler, Bruce Robison, Rich Schramm

Support continued on the maintenance, operation, calibration, and configuration of the core CTD instruments, electronics, and related hardware. The user interface for real-time ROV data display was upgraded with several improvements. ROV oxygen data are now collected with dual oxygen sensors and are routinely validated with Winkler titrations. CTD rosettes were used more extensively in 2014 than in previous years, with more casts in 2014 alone than the combined casts from the previous three years.

Core Mooring Data

Project leads: John Ryan
Project manager: Mike McCann
Project team: Fred Bahr, Francisco Chavez, Rich Schramm

Support for the collection, processing and archiving of mooring data is provided on an institutional basis rather than through individual projects or divisional budgets. In 2014 the team began modification of the existing archive of NetCDF files to update them with modern metadata standards.

Core Navigation

Project leads: David Caress, John Ryan
Project manager: David Caress
Project team: Knute Brekke, Mike Burczynski, Ben Erwin, Linda Kuhnz, Eric Martin, D.J. Osborne, Randy Prickett, Bryan Touryan-Schaefer, Rich Schramm, Mark Talkovic

Navigation data from the MBARI research vessels and remotely operated vehicles are "core" data streams, which means that these data are considered important to the MBARI community as a whole. The collection, processing, and archiving of core data are provided on an institutional basis with support from all MBARI divisions.

Core Outline Video Annotation

Project leads: John Ryan, Brian Schlining
Project manager: Nancy Jacobsen Stout
Project team: Mark Chaffey, Kevin Gomes, Linda Kuhnz, Lonny Lundsten, Mike McCann, Todd Ruston, Kyra Schlining, Susan von Thun

Significant progress was made in the video team's efforts to upgrade to a file-based video recording system. Investigations on video codecs, recording devices, and system integration options have led to many informative meetings with oceanographic and industry professionals. Collaborations on a larger pilot study continue; field testing of a commercial system and additional individual components are expected in 2015. The Video Annotation and Reference System (VARS) was updated to be compatible with recent operating system releases and the media-capture and playback components were modified to be more modular and flexible in support of the upcoming file-based video recordings. The MBARI Deep-Sea Guide (DSG), a companion web portal for VARS that allows easy, web-based access to species information and MBARI observational data, was also prepared for external debut (See page 31).

Cytometer Technology for Autonomous Platforms

Project leads: Denis Klimov, Tom O'Reilly
Project manager: Tom O'Reilly
Project team: Francisco Chavez, Andrew Hamilton
Collaborators: Rob Johnson and Heidi Sosik, Woods Hole Oceanographic Institution, Massachusetts; Peter Lopez, New York University; Jarred Swalwell, University of Washington, Seattle

Shipboard cytometers provide critical information about marine microbial communities and how they respond to environmental change. This project is investigating cytometer integration into autonomous vehicles such as the LRAUV and Wave Glider,

Engineers Andy Hamilton, left, and Denis Klimov prepare cytometers for at-sea testing, in which water was pumped from a CTD rosette for real-time sampling by multiple instruments.

using existing and emerging technologies. A mobile autonomous cytometer could enable long-duration microbial surveys without the need for an expensive research vessel, and the AUV could potentially investigate under-ice ecosystems in climate-sensitive polar regions. The team evaluated and compared several commercial cytometers on pumped seawater samples at sea onboard the R/V *Rachel Carson*, as well as in the laboratory on cells from known cultures. The team is also exploring new instrument designs—fluorescent imaging cytometers, in particular—and is keeping a close watch on emerging cytometer technologies.

Education And Research: Testing Hypotheses (EARTH)

Project lead/manager: George Matsumoto
Project team: Kevin Gomes, Steve Haddock, Chris Preston
Collaborators: Andy Fisher and Adina Payton, University of California, Santa Cruz; Katy Scott, Monterey Bay Aquarium, California

The 2014 EARTH teacher workshop returned to Moss Landing with support from the Center for Dark Energy Biosphere Investigations. Teachers learned about mass water flow, bioluminescence, the Environmental Sample Processor, science communication, and ocean acidification, and created curriculum to bring these lessons to their students. Educator participants from previous EARTH workshops ran satellite EARTH workshops in Missouri and Florida.

Integrated MBARI Time-Series Program

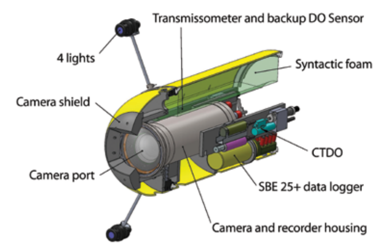
Project leads: Francisco Chavez, Brett Hobson, Bruce Robison, Alana Sherman, Ken Smith
Project manager: Ken Smith
Project team: Kevin Gomes, Christine Huffard, Monique Messié, Reiko Michisaki, Tim Pennington, Mariah Salisbury, Rob Sherlock

MBARI supports three time-series projects that span the water column from the surface ocean and midwater to the seafloor in one of the most productive and economically important areas of the world ocean. The common thread connecting these projects is the cycling of food, organic carbon, from its production by phytoplankton in surface waters to its ultimate sequestration on the seafloor. The three MBARI studies, when combined, will provide an unprecedented time-series data set—including a historical context—to track organic carbon production and utilization through the ocean, allowing us to interpret the impact of changing climate on the oceanic carbon cycle. The team developed a plan to integrate the data from the three time series, both technically and scientifically, and began discussions on how to reduce the cost of conducting these time-series studies while increasing the temporal resolution of the data.

Investigations of Imaging for Midwater Autonomous Platforms (i2MAP)

Project leads: Mark Chaffey, Kim Reisenbichler
Project manager: Kim Reisenbichler
Project team: François Cazenave, Dave French, Richard Henthorn, Eric Martin, Rob McEwen, Bruce Robison, Rob Sherlock, Hans Thomas, Todd Walsh
Collaborator: Henk-Jan Hoving, GEOMAR-Helmholtz Center for Ocean Research, Kiel, Germany

The team determined an appropriate video camera for midwater transects that has good light sensitivity, high frame rates, and excellent high-definition image quality. It also incorporates a built-in video upgrade path. A CTD package was purchased, control electronics were developed, and the pressure housing design was completed. Low-speed stability testing on the *Dorado* AUV at speeds of approximately two knots showed that the midwater transects will be possible without the need for additional stabilizing aids such as wings or duct fins. An interesting aside to the main focus of the stability testing dives was that while recording video to visualize particle flow past the vehicle, the team inadvertently found it was also recording humpback whale vocalizations coming from a nearby pod. As a result, the team is adding the circuitry to record two hydrophone inputs onto the electronics board.



Cut-away view of the i2MAP video imaging module.

Legacy Data Systems Transitions

Project leads/managers: Kevin Gomes, Todd Ruston
Project team: Pat Allen, Peter Braccio, Neil Conner, Joe Gomez, Mike McCann, Rich Schramm

The team was tasked with migrating computing systems from older server technology to newer, more supportable technology. While some early scoping work was done for this project, it turned out to be more complex than originally thought and other priorities took precedence over this work. The team will be looking for opportunities in 2015 to perform the transitions.

LRAUV: Coordinated Observations of Marine Organisms and Ocean Features

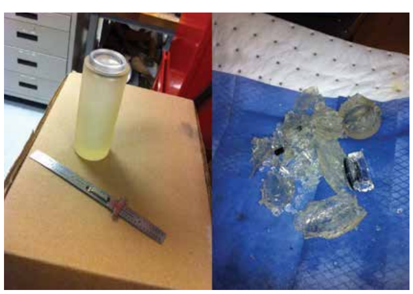
Project leads: James G. Bellingham, Brett Hobson
Project manager: Brett Hobson
Project team: Mark Chaffey, Paul Coenen, Jon Erickson, Brian Kieft, Denis Klimov, Tom Marion, Ed Mellinger, Jim Montgomery, Craig Okuda, Jose Rosal, Carlos Rueda, James Scholfield, Jordan Stanway
Collaborators: Francisco Chavez, John Ryan, Chris Scholin, and Yanwu Zhang, MBARI

The long-range AUV (LRAUV) team focused on supporting science operations, refining the user interface, performing minor upgrades, and building new vehicles. MBARI has logged over 8,000 operating hours on the institute's LRAUVs and in late 2014 finished a third vehicle to support operations with the new third-generation Environmental Sample Processor. The operational highlight of the year was a multi-vehicle collaborative mission with all three LRAUVs, a Wave Glider autonomous surface vehicle, a *Dorado* AUV, and the R/V *Rachel Carson* working together to follow and sample within a small patch of water at depth as it drifted through the bay for over 48 hours (See story page 7).

Long-Term Deployment of Composite Pressure Cases

Project lead/manager: Jon Erickson
Project team: Farley Shane

Two separate material choices for the fabrication of underwater pressure cases were investigated—a polycarbonate-like material and a filament-wound carbon-fiber composite material. Using MBARI's in-house additive manufacturing capability the team produced and tested a series of plastic pressure cases of the polycarbonate-like material to determine the safe working stresses that can be applied to it. The advertised material properties cannot be assumed for design purposes and require test specifications that match the expected use conditions. The major advantage of this type of manufactured material is a reduced need for additional machining operations. Destructive pressure testing of the carbon-fiber material has yet to be done.



The polycarbonate-like material pressure case: before and after testing.

MBARI External Website Upgrade

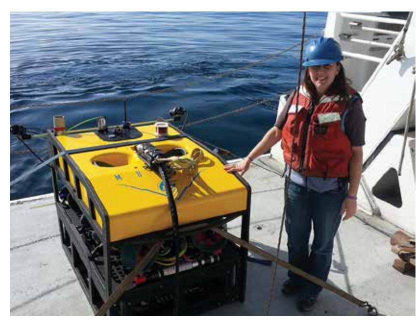
Project leads: Nancy Barr, Kevin Gomes
Project manager: Nancy Barr
Project team: Judith Connor, Kim Fulton-Bennett, Joe Gomez, Annette Gough, George Matsumoto, Reiko Michisaki, Jennifer Patterson, Todd Ruston, Nancy Jacobsen Stout

A sitemap was created to outline navigation for the new MBARI website, the visual design of the site was completed, and WordPress was implemented on a third-party hosting service. A plan was begun to improve access to data and software applications in a coherent manner through the new website. The site infrastructure was built and the top-level pages and templates were produced. A content-strategy document was adopted to guide the ongoing development of web content. Staff members began reviewing and updating content to be migrated to the new site, which is to be launched in 2015.

Mini ROV Upgrades

Project leads: Dale Graves, Charles Paull, Alana Sherman
Project manager: Alana Sherman
Project team: Larry Bird, Frank Flores, Tom Marion, Mike Parker
Collaborator: Scott Dallimore, Geological Survey of Canada, Sidney, British Columbia

The team continued to add functionality and flexibility to the mini ROV, which is a compact remotely operated vehicle capable of being operated on ships of opportunity. A longer umbilical, allowing the vehicle to dive to 1,500 meters, was integrated and tested. A generator was selected and purchased, so that the vehicle system could be operated without having to interface to the ship's power. A midwater sampler was added to the vehicle tool sled, enabling scientists to collect discrete midwater animals using a suction sampler (See page 39). Finally, the main vehicle camera was upgraded. One of the successes for this project was the successful deployment of the mini ROV from the R/V *Western Flyer* in November of 2014, which allowed scientists to do ROV studies in the upper 200 meters of the water column, a region of great interest that was previously inaccessible.



Research Assistant Kristine Walz with the mini ROV on the well deck of the R/V Western Flyer *prior to deployment.*

Monterey Accelerated Research System (MARS)

Project lead/manager: Steve Etchemendy
Project team: Larry Bird, Craig Dawe, Ken Heller, Linda Kuhnz, Thom Maughan

The National Science Foundation (NSF) provides support to maintain and operate the MARS cabled observatory in Monterey Bay. MARS is an observatory facility available to internal and external scientists and developers as both a test bed and a research site. Since November 2008, MARS has been used to test and gather data from a variety of ocean instruments, including a seafloor seismometer, the Environmental Sample Processor, the Free Ocean Carbon Dioxide Enrichment system, the Sediment Event Sensor, and a camera that sends back video images of the seafloor in real time.

Mooring Maintenance

Project leads: Francisco Chavez, Craig Dawe, Kevin Gomes
Project manager: Mike Kelley
Project team: Paul Coenen, Jared Figurski, Dave French, Craig Okuda, Rich Schramm

MBARI's mooring program has been providing data to internal researchers, the oceanographic community, and the public at large since 1989. This is due in part to the maintenance program conducted on the mooring systems. 2014 saw the redeployment of the M1 mooring. Collaboration between MBARI and the National Data Buoy Center continued on a second mooring.

O-Buoy Network of Chemical Sensors in the Arctic Ocean

Project lead: Francisco Chavez
Project manager: Gernot Friederich
Project team: Jules Friederich, Chris Wahl
Collaborators: Jan Bottenheim and Stoyka Netcheva, Environment Canada, Toronto; Patricia Matrai, Bigelow Laboratories for Ocean Sciences, East Boothbay, Maine; Donald Perovich, U.S. Army Corps of Engineers, Hanover, New Hampshire; Paul Shepson, Purdue University, West Lafayette, Indiana; William Simpson, University of Alaska, Fairbanks

In support of monitoring the impact of climate change in the Arctic Ocean, MBARI developed a low-cost, high-precision system that measures the partial pressure of carbon dioxide in the atmosphere. This system has been deployed on buoys moored in sea ice. MBARI has also developed the capability to add sensors (CO_2, pH, oxygen, fluorescence, temperature, and salinity) to measure conditions in seawater under the ice; with the first field deployment in the winter of 2014. Researchers have learned a great deal about deploying sensors in this harsh environment and will deploy devices on an additional buoy in 2015. A total of 10 O-buoys have been moored in the Arctic Ocean to measure a wide variety of atmospheric gases and conditions. The information is provided in near real-time to a variety of users.

Ocean Chemistry of the Greenhouse Gases

Project leads: Peter G. Brewer, William J. Kirkwood
Project manager: Edward T. Peltzer
Project team: Peter Walz
Collaborators: Nikolaus Bigalke and Christian Deuser, GEOMAR-Helmholtz Centre for Ocean Research, Kiel, Germany; Pei-Chuan Chuang, University of California, Santa Cruz; Brendan Kelly and Margaret Spring, Monterey Bay Aquarium; John Kessler, University of Rochester, New York; Chad King, NOAA/Monterey Bay National Marine Sanctuary, Monterey, California

The team revisited the Santa Cruz Basin off the coast of Southern California to continue investigations of disused, but still charted, disposal sites. The mapping AUV was deployed to expand coverage of the seafloor maps. Then in a series of ROV *Doc Ricketts* dives, researchers visually identified objects found with the AUV. The sheer density of objects on the seafloor off Southern California, both within and outside the boundaries of the dump-site areas, compared to what is found inside the protected areas of Monterey Bay, is striking and demonstrates the advantage of designating areas of the ocean as off-limits to dumping and other activities. In other work, the team used ROV *Ventana* in Monterey Bay to conduct experiments simulating a hydrocarbon seep. These successful dives are useful for the development of computational models of oil droplet behavior. They were followed up with an expedition to the coastal region of Northern California on the R/V *Western Flyer* where several natural oil and gas seeps and gas hydrate outcrops were observed and the rising streams of gas saturated oil were sampled and collected. In both cases, the slow exchange of dissolved gas from within the oil droplet and into the surrounding seawater was observed, leading to the suggestion that a significant fraction of gas dissolved in oil in the deep sea can ride within rising oil droplets to the upper ocean. This in situ work and subsequent modeling will help predict the fate of oil and gas leaks from seeps in the deep sea and also from inadvertent hydrocarbon releases from drilling operations.

ROV manipulator arm brings the laser Raman spectrometer probe-head into close contact with a gassy hydrate outcrop in the Eel Canyon basin allowing precise measurement of the gas hydrate composition in real time.

Ocean Observatories Initiative Cyberinfrastructure (OOI-CI)

Project lead: Carlos Rueda
Project manager: Duane Edgington

MBARI is participating in the design and construction of the data-management and infrastructure subsystems of the Ocean Observatory Initiative, a National Science Foundation-funded environmental observatory effort that covers a diversity of oceanic environments, ranging from coastal to deep ocean. In 2014, the team coordinated with other OOI-CI developers to develop and integrate a mission executive module into the OOI framework. The MBARI team enabled several tests on the OOI-CI continuous integration system, and improved robustness and testing. MBARI also provided expertise to the Education and Public Engagement Implementing Organization on semantic technologies and the use of the Marine Metadata Interoperability Project for vocabularies and term mappings.

Pelagic-Benthic Coupling and the Carbon Cycle

Project leads: Alana Sherman, Ken Smith
Project managers: Christine Huffard, Alana Sherman
Project team: Larry Bird, Katherine Dunlop, John Ferreira, Rich Henthorn, Brett Hobson, Linda Kuhnz, Paul McGill, Susan von Thun
Collaborators: Jeffrey Drazen, University of Hawaii, Manoa; Henry Ruhl, National Oceanography Centre, Southampton, United Kingdom; Timothy Shaw, University of South Carolina, Columbia

The team's long-term studies at Station M in the abyssal northeastern Pacific investigate the role of benthic ecosystems in the global carbon cycle, in particular as pertaining to climate change. Autonomous instruments have been developed to make high-temporal resolution measurements over the span of many months in this remote environment. For the past several years three instruments, the Benthic Rover, the Sedimentation Event Sensor (SES), and a time-lapse camera, have been deployed almost continuously at that site. In 2014, the Benthic Rover and SES underwent their first servicing in three years, and the team performed upgrades that will allow for year-long deployments. In 2014 the time-lapse camera documented the largest visible seasonal flux of particulate organic matter sinking to the seafloor in the past 25 years, topping last year's record.

Power Buoy

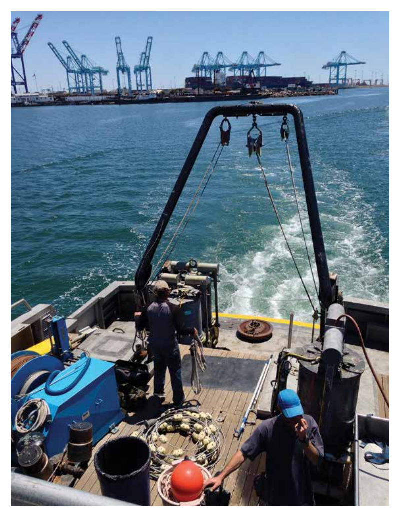
Project lead/manager: Andrew Hamilton
Project team: François Cazenave, Jon Erickson, John Ferreira, Scott Jensen, Paul McGill, Wayne Radochonski, Jose Rosal

The power buoy prototype was deployed for four months and survived the winter storm season. This deployment successfully tested several changes to the system designed to increase longevity. All of these new systems performed as designed and resulted in a deployment that was four times longer than previous efforts. The deployment ended due to hydraulic-oil seal leakage, a new failure mode that is being addressed in preparation for further testing. The team also improved the buoy power electronics and energy storage systems. These developments will make more of the captured energy available to instrumentation both on board the buoy and at the submerged anti-heave plate.

A Regional Comparison of Upwelling and Coastal Land Use Patterns on the Development of Harmful Algal Bloom Hotspots Along the California Coast

Project leads: James Birch, John Ryan, Chris Scholin
Project manager: John Ryan
Project team: Nilo Alvarado, James Bellingham, Holly Bowers, Francisco Chavez, Elif Demir-Hilton, Kevin Gomes, Brett Hobson, Thomas Hoover, Scott Jensen, Brian Kieft, Denis Klimov, Roman Marin III, Mike McCann, Doug Pargett, Christina Preston, Brent Roman, Jordan Stanway, Yanwu Zhang
Collaborators: David Caron and Burt Jones, University of Southern California, Los Angeles; Raphael Kudela, University of California, Santa Cruz; G. Jason Smith, Moss Landing Marine Laboratories, California; Gregory Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Yi Chao, University of California, Los Angeles

The aim of this NOAA-funded project is to advance understanding of the nature and causes of harmful algal blooms (HABs) along the California coast, as a foundational step toward predicting and mitigating their outbreaks. In collaboration with the MBARI CANON Initiative, a field program was conducted in San Pedro Bay during spring 2014. Two moored Environmental Sample Processors (ESPs) were deployed into a bloom of toxin-producing diatoms of the genus *Pseudo-nitzschia*, the first bloom of this HAB genus detected since the beginning of the year. The bloom resulted from upwelling that injected nutrient-rich water into the bay. Bloom activity and toxicity were monitored by the ESPs during the first two weeks of the deployment, after which the bloom waned. The R/V *Rachel Carson* and MBARI's autonomous underwater vehicles provided ecosystem observations and targeted sampling of phytoplankton populations during the transition from blooming to quiescence. MBARI's Oceanographic Deci-



Single-day recovery of three ESP instruments from Catalina Island, Newport Beach, and Huntington Beach. Instruments studied HAB and bacterial dynamics off the San Pedro shelf.

sion Support System and Spatial Temporal Oceanographic Query System provided a robust software infrastructure for managing and understanding data from many observing assets and methods. The team's synthesis efforts included extension of the methods used to describe the diversity of HAB species.

Respirometer Upgrade Project

Project leads: James Barry, Craig Okuda
Project manager: Bob Herlien
Project team: Kurt Buck, Kim Reisenbichler

During 2014, the team developed a pressure-tolerant pH sensor that can be used at depths of up to 4,000 meters for the respirometers that measure animal metabolism in situ. The respirometer team explored other available pH sensors designed for laboratory use and discovered one that tolerates hydrostatic pressure equal to the 4,000-meter depth. The team adapted this sensor for deep-sea studies and produced approximately 25 sensors in late December. These sensors will be deployed in the deep sea and in the MBARI test tank to measure their stability and accuracy. A suite of these sensors were installed on the benthic respiration system for the 2015 Gulf of California Expedition. Ultimately, the team expects that these sensors may be suitable for a number of deep-sea applications.

Deep-sea sensor (20 centimeters long) adapted for the MBARI respirometers.

Salmon Ecosystem Simulation and Management Evaluation (SESAME)

Project lead/manager: Francisco Chavez
Project team: Monique Messié, Reiko Michisaki
Collaborators: Steven Bograd and David Foley, Southwest Fisheries Science Center, Pacific Grove, California; Fei Chai, University of Maine, Orono; Yi Chao, University of California, Los Angeles; Eric Danner, Steve Lindley, and Brian Wells, Southwest Fisheries Science Center, Santa Cruz, California; Roger Nisbet, University of California, Santa Barbara

This project is developing an integrated river-to-ocean model aimed at improving predictions of the growth and survival of Chinook salmon in Central California. These fish depend on rivers, estuaries, and the ocean for their growth, survival, and reproduction requiring a fully integrated approach. A physical-biological oceanic model developed with previous NASA support has been coupled to models of the San Francisco estuary and the upper Sacramento River. The validation of the coupled models is ongoing. The corresponding temperature and food supply solutions will drive a dynamic energy budget for Chinook salmon from the river to the ocean. The resulting coupled models are being used to explore the drivers of variation in salmon growth and maturation, and the impacts of current and future water management, climate variability, and global change.

Sensors: Underwater Research of the Future (SURF) Center/Enhancing Detection Chemistries for Investigating Microbial Ecology

Project lead: Chris Scholin
Project manager: James Birch
Project team: Holly Bowers, Elif Demir-Hilton, Kevin Gomes, Scott Jensen, Roman Marin III, Doug Pargett, Christina Preston, Brent Roman, Carlos Rueda, Bill Ussler III, Kevan Yamahara
Collaborators: Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Thierry Baussant, International Research Institute of Stavanger, Norway; Alexandria Boehm, Center for Ocean Solutions, Stanford University, California; Laurie Connell, University of Maine, Orono; Edward DeLong, Massachusetts Institute of Technology, Cambridge, Massachusetts; Gregory Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Clement Furlong, University of Washington, Seattle; Peter Girguis, Harvard University, Cambridge, Massachusetts; Dianne Greenfield, University of South Carolina, Columbia; Steven Hallam, University of British Columbia, Vancouver, Canada; Julio Harvey and Robert Vrijenhoek, MBARI; David Karl, University of Hawaii, Manoa; Blythe Layton and Steve Weisberg, Southern California Coastal Water Research Project, Costa Mesa, California; Stephanie Moore and Vera Trainer, Northwest Fisheries Science Center, Seattle, Washington; Mary Ann Moran and Vanessa Varaljay, University of Georgia, Athens; Victoria Orphan, California Institute of Technology, Pasadena; George Robertson, Orange County Sanitation District, Fountain Valley, California; Julie Robidart and Jonathan Zehr, University of California, Santa Cruz; Cody Youngbull, Arizona State University, Tempe

DNA and antibody tests are commonly used to assess the presence, abundance, and activity of a wide variety of marine microorganisms. The goal of these two projects is to enable greater use of such methods by developing the means to autonomously collect, preserve, and process discrete samples. Achieving this goal rests on two different types of activities: methods development and instrumentation engineering. This project concerns the former: devising ways to collect a range of microbes, phytoplankton, small invertebrates, and environmental DNA, and interrogate that material using a variety of bioanalytical procedures in both laboratory and field settings. Work associated with the instrumentation development effort is captured separately under the SURF Center proposal. When combined, the methodological and instrumentation advances contribute to creating a class of device known as "ecogenomic sensors"; the Environmental Sample Processor (ESP) exemplifies this concept.

The ESP is a robotic device that automates the collection of discrete water samples, and applies DNA and antibody analytical technologies to detect organisms and substances of interest. In 2014, funding from the David and Lucile Packard Foundation was utilized synergistically with grants from the Gordon and Betty Moore Foundation, the National Science Foundation, the National Oceanic and Atmospheric Administration, and various state agencies to continue to deploy, enhance, and transfer second-generation (2G) ESP technology and operational know-how, and to develop a third generation (3G) system for use on MBARI's long-range autonomous underwater vehicle (LRAUV). The SURF Center oversaw deployments of 2G ESPs in Southern California and in Monterey Bay in 2014 in support of harmful algal bloom and marine microbial research programs. In parallel, a suite of commercially-produced versions of the 2G ESP were deployed in Oregon and in the Gulf of Maine. A prototype of the 3G ESP was integrated with the LRAUV and tested in Monterey Bay.

Shallow-Water Free Ocean Carbon Dioxide Enrichment Experiment

Project leads: James Barry, Peter G. Brewer
Project manager: William Kirkwood
Project team: Kent Headley, Bob Herlien, Chad Kecy, George Matsumoto, Thom Maughan, Edward T. Peltzer, Karen Salamy, James Scholfield, Farley Shane, Peter Walz
Collaborators: Glenn Johnston, Donna Roberts, and Jonny Stark, University of Tasmania, Australia; Steven Litvin, Hopkins Marine Station of Stanford University, Pacific Grove, California; Brock Woodson, University of Georgia, Athens

This year saw the physical realization of the long-planned partnership between scientists and engineers at MBARI, Hopkins Marine Station, and the Center for Ocean Solutions as the shallow-water FOCE project put hardware into the water and began the engineering tests that demonstrated both the feasibility of the study and the precision of control necessary for successful experimentation. Early in the year, divers placed dummy experimental units (frames and plastic enclosures without sensors or powered equipment) at the site near the kelp forest array at Hopkins Marine Station to test whether the experimental chambers could survive the high energy surges of the winter storms. Following this success, the 400-meter-long hoses for delivering CO_2-enriched seawater to the experiments were laid in place by divers, boat handlers, and on-shore technicians. The system was activated, and pressurized with CO_2, and the supply pump was turned on to test for consistent control of the pH. By adjusting the CO_2 pressure in the equilibrator and dialing in different pump rates and thruster speeds, the CO_2 content inside the chamber could be adjusted to conditions predicted to occur 50 to 100 years in the future.

Concurrent with these efforts to establish a shallow water FOCE experiment in Monterey Bay, colleagues from the University of Tasmania in Australia were building a similar FOCE system to be deployed in the shallow waters off Antarctica. MBARI scientists and engineers have advised and supported the design, construction, and deployment work as part of an effort to transfer MBARI technology.

Streaming Data Middleware

Project leads: Duane Edgington, Kent Headley, Bob Herlien, Tom O'Reilly
Project manager: Duane Edgington
Project team: Edward T. Peltzer
Collaborators: Tony Fountain and Sameer Tilak, University of California, San Diego (UCSD)

In 2014 the team continued engagement in this three-year project, primarily staffed at UCSD, to extend the publicly available Open Source Data Turbine (OSDT) framework, and to apply it to a number of research data infrastructures at several research institutions, including MBARI. MBARI's application is the FOCE. Critical feedback was provided to OSDT developers. A local server was set up to provide data streams from MBARI's FOCE experiment to an OSDT Cloudturbine server site (http://cloudturbine.net). The WebScan browser-based interface to Cloudturbine was evaluated and feedback was provided to the development team on its features.

Technology Transfer: Observatory Software

Project leads: Duane Edgington, Kent Headley, Bob Herlien, Tom O'Reilly
Project manager: Duane Edgington
Project team: Paul Coenen, Kevin Gomes, Thom Maughan, Craig Okuda, Carlos Rueda, Rich Schramm
Collaborators: Paul Barter, Chris Cornelisen, Andrew Mahon, and Rowan Strickland, Cawthron Institute, Nelson, New Zealand; Luis Bermudez, Open Geospatial Consortium (OGC), Herndon, Virginia; Arne Bröring, 52°North Initiative for Geospatial Open Source Software GmbH, Muenster, Germany; Joaquin del Rio, Antoni Manuel, and Daniel Toma, Universitat Politècnica de Catalunya, Barcelona, Spain; Tony Fountain, Peter Shin, and Sameer Tilak, University of California, San Diego (UCSD); Janet Fredericks, Woods Hole Oceanographic Institution (WHOI), Massachusetts; Martyn Griffiths, Bruce Howe, Roger Lukas, Ethan Ross, and Fernando Santiago-Mandujano, University of Hawaii, Honolulu; Mohammad Ali Jazayeri and Steve Liang, University of Calgary, Canada; John Liu, Tsinghua University, Beijing, China

The team continued support of the ALOHA cabled observatory at the University of Hawaii, in the use of MBARI's infrastructure, applications, and shore-side data systems for data collection and archiving. Cawthron Institute continued mooring deployment and development based on MBARI's OASIS mooring controller. The MBARI team will support Cawthron if they adopt the OASIS5 mooring controller. The team maintained its collaboration with UCSD to refine UCSD's Open Source DataTurbine, using MBARI data to evaluate Cloudturbine and a WebScan-browser-based interface.

Led by WHOI, the team will collaborate with various institutions to demonstrate mechanisms to enable the creation of standards-based documents that are discoverable and accessible online or directly from enabled instruments, thereby accelerating use and interoperability. MBARI's main role is the use, evaluation, and potential recommendations to enhance the OGC PUCK standard, as well as to further develop a metadata repository system and transition it to the greater community.

Ventana Control System Upgrade

Project leads: Doug Au, Craig Dawe
Project manager: Craig Dawe
Project team: Mike Burzcynski, David French, D.J. Osborne, Michael Risi, Rich Schramm

The ROV *Ventana* has been a workhorse in the arsenal of tools available to MBARI researchers and engineers for over 25 years. In 2013 it became apparent that the hardware and software used to operate *Ventana* were becoming obsolete and impossible to support long term. A commercial vendor and hardware platform were identified that align closely with the needs of not only *Ventana* but several other MBARI projects and a requirements document was developed by the team. The vendor developed a preliminary design and presented a critical design review. The team moved forward on building, integration, and testing the system.

Wave Glider-Based Communications Hotspot

Project lead: Mark Chaffey
Project manager: Brian Kieft
Project team: Paul Coenen, Tom O'Reilly, Chris Wahl

A new Wave Glider SV3 was purchased and assembled by Paul Coenen and tested with onsite support and training from Liquid Robotics. The team integrated a radio, cell modem, and acoustic payload and CTD, oxygen, pH, pCO_2, and chlorophyll sensors for participation in field experiments coordinated with a sub-surface long-range AUV. The team developed the shore-based vehicle control software for Wave Glider navigation commands used for multi-vehicle operations. The Wave Glider successfully located Benthic Event Detectors on the floor of Monterey.

Wave Glider Feasibility

Project lead/manager: Thom Maughan
Project team: Paul Coenen
Collaborators: Jared Figurski, Brian Kieft, Tom O'Reilly, and Chris Wahl, MBARI

An internal advisory group was appointed to ensure optimal use of the Wave Glider for MBARI science. The team also provided support for a number of MBARI projects using the Wave Glider, including an almost-two-month deployment in coordinated multi-vehicle operations as part of the CANON Initiative (See page 7).

Zooplankton Biodiversity and Biooptics

Project lead: Steven Haddock
Project team: Lynne Christianson

The team has progressed in analyzing transcriptomes, the set of all RNA molecules in a population, from many deep-sea invertebrates, demonstrating the utility of these data sets for poorly studied organisms. Detailed information on several major groups of marine animals was generated for the first time. Tools for exploring, plotting, and analyzing the Video Annotation and Reference System data set, and for processing transcriptome data in a phylogenetic context were also written, and shared on MBARI's public software repository.

Awards

Peter G. Brewer

Direct observation of the oceanic CO_2 increase, *Geophysical Research Letters*, 5, 997–1000, 1978 selected for the GRL 40th Anniversary Special Collection of the top 40 papers in 40 years

Francisco Chavez

Ed Ricketts Memorial Award, Monterey Bay National Marine Sanctuary

Elected Fellow, American Geophysical Union

Ken Johnson

Excellence in Partnering Award, National Ocean Partnership Program

Esther Sumner

British Sedimentological Research Group Roland Goldring Award

Alexandra Z. Worden

Marine Microbiology Investigator, Gordon & Betty Moore Foundation

Senior Fellow, Canadian Institute for Advanced Research, Integrated Microbial Biodiversity Program

Degrees Awarded

Melinda Simmons, Ph.D., University of California, Santa Cruz

Warren Francis, Ph.D., Carnegie Mellon University

David Packard Distinguished Lecturer Antje Boetius

Antje Boetius, Ph.D., from Alfred Wegener Institute for Polar and Marine Research, accepts the 2014 David Packard Distinguished Lecturer medal from MBARI President and Chief Executive Officer Chris Scholin (right) for her September lecture titled "The future of the Arctic Ocean: Scientific and technological challenges in the 4-D exploration of ice-covered deep seas."

Invited Lectures

David Anderson
Webinar on Ecological Forecasting, National Oceanic and Atmospheric Administration

Douglas Au
Chabot College, Hayward, California

James Barry
Monterey Bay Aquarium, Monterey, California

Panetta Institute, Seaside, California

National Caucus of Environmental Legislators, Minneapolis, Minnesota

NOAA Ocean Acidification Teacher Workshop, San Francisco, California

Ocean Global Change Biology Gordon Research Conference, Waterville Valley, New Hampshire

NOAA Gulf of the Farallones National Marine Sanctuary, San Francisco, California

Association for the Sciences of Limnology and Oceanography, Honolulu, Hawaii

James G. Bellingham
GEOMAR, Kiel, Germany

Marine Technology Society TechSurge: Ocean Sensors Meeting, Weehawken, New Jersey

Monterey Bay International Trade Association, California State University, Monterey Bay, Seaside, California

Tsinghua University Graduate School at Shenzhen, China

City University of Hong Kong, Kowloon Tong

James Birch
Association for the Sciences of Limnology and Oceanography, Honolulu, Hawaii

Stephanie Bush
Sea and Learn on Saba, Dutch Caribbean

Hopkins Marine Station of Stanford University, Pacific Grove, California

Monterey Bay Aquarium, Monterey, California

David Caress
International Mine Warfare Technology Symposium, Naval Postgraduate School, Monterey, California

Francisco Chavez
Tropical Pacific Observation System 2020 workshop, La Jolla, California

Second Korea-U.S. Ocean Scientists Workshop, Honolulu, Hawaii

Association for the Sciences of Limnology and Oceanography, Honolulu, Hawaii

Ocean Modeling Forum, Seattle, Washington

Third Climate College for the California Department of Fish and Wildlife, Moss Landing, California

Liege Colloquium on Low Oxygen Environments in Marine, Estuarine, and Fresh Waters, Belgium

IV Congreso de Ciencias del Mar del Peru, Lima

Integrated Ocean Observing System Biological Integration and Observation Task Team Workshop, Washington, D.C.

Workshop on Oxygen Minimum Zone in the Mexican Pacific, Ensenada

20th Conference of the Parties for the United Nations Framework Convention on Climate Change, Lima, Peru

David Clague
University of California, Santa Barbara

Geological Society of America, Vancouver, Canada

Judith Connor
Fulbright Scholars, Monterey, California

Monterey Bay Aquarium, Monterey, California

Brian Dreyer
U.S. Geological Survey, Santa Cruz, California

Kim Fulton-Bennett
Monterey Bay National Marine Sanctuary Exploration Center, Santa Cruz, California

Steven Haddock
Yale School of Medicine, New Haven, Connecticut

Aquarium of the Pacific, Long Beach, California

Whitney Laboratory for Marine Bioscience, University of Florida, St. Augustine

University of San Francisco, California

California State Summer School for Mathematics and Science, University of California, Santa Cruz

Harvey Mudd College, Claremont, California

University of Hawaii, Honolulu

Pacific Islands Fisheries Science Center, Honolulu, Hawaii

University of Helsinki, Finland

Lockheed-Martin, Palo Alto, California

San Jose State University, California

Fitzpatrick Institute of Photonics, Duke University, Durham, North Carolina

Julio Harvey

Association for the Sciences of Limnology and Oceanography, Honolulu, Hawaii

NOAA Southwest Fisheries Science Center, Santa Cruz, California

Moss Landing Marine Laboratories, Moss Landing, California

Ken Johnson

University of California, Santa Barbara

Monterey Bay International Trade Association, California State University, Monterey Bay, Seaside

University of Gothenburg, Kristineberg Marine Station, Sweden

Interdisciplinary Coordinated Experiment of the Southern Ocean Carbon Cycle, La Jolla, California

Dissertations Symposium in Chemical Oceanography XXIV, Kauai, Hawaii

U.S. Climate Variability and Predictability and Ocean Carbon and Biogeochemistry Workshop, San Francisco, California

William Kirkwood

Ocean Global Change Biology Gordon Research Conference, Waterville Valley, New Hampshire

Ocean University of China, Qingdao

Linda Kuhnz

Monterey Bay National Marine Sanctuary Exploration Center, Santa Cruz, California

George I. Matsumoto

Monterey Bay Aquarium, Monterey, California

Monterey Area Research Institutions' Network for Education, California

Mike McCann

NOAA Environmental Disasters Data Management Workshop, Shepherdstown, West Virginia

Python Brasil Conference, Porto de Galinhas, Brazil

Charles Paull

International Commission on the History of Geological Sciences, Pacific Grove, California

Geological Society of America, Vancouver, British Columbia

Cordell Bank National Marine Sanctuary Advisory Council, Petaluma, California

Innovation Center for Earth Sciences Workshop, Menlo Park, California

American Geophysical Union, San Francisco, California

Edward T. Peltzer

Bucknell University, Lewisburg, Pennsylvania

Christina Preston

Environmental Sample Processor User Applications and Logistics Workshop, Oregon Health and Science University, Portland

Bruce Robison

Association for the Sciences of Limnology and Oceanography, Honolulu, Hawaii

John Ryan

Ocean Optics, Portland, Oregon

University of California, Santa Cruz

Chris Scholin

Association for the Sciences of Limnology and Oceanography, Honolulu, Hawaii

Gordon and Betty Moore Foundation, Palo Alto, California

Nanjing University, Nanjing, China

Tsinghua University Graduate School at Shenzhen, China

City University of Hong Kong, Kowloon Tong

National Ocean Studies Board, Irvine, California

Esther Sumner

American Geophysical Union, San Francisco, California

Susan von Thun

Monterey Bay National Marine Sanctuary Currents Symposium, Seaside, California

Robert Vrijenhoek

Monterey Bay Aquarium, Monterey, California

California State University, Monterey Bay, Seaside

University of California, Santa Cruz

Alexandra Worden

American Geophysical Union, San Francisco, California

SciLifeLab, University of Stockholm, Sweden

University of Copenhagen, Denmark

15th International Symposium on Microbial Ecology, Seoul, Korea

Keynote, Congress of the International Union of Microbiological Societies, Montreal, Canada

Joint Aquatic Sciences Meeting, Portland, Oregon

University of California, Santa Barbara

University of Southern California, Los Angeles

Yanwu Zhang

Second Chinese Conference on Ocean Observation, Xiamen

Nanjing University, China

State Key Laboratory in Marine Pollution of City University of Hong Kong, China

Mentorships

James G. Bellingham

Ben Yair Raanan, graduate summer intern, Moss Landing Marine Laboratories (fault detection for long-duration AUV missions with minimal human intervention)

Jon Steck, graduate summer intern, Claremont McKenna College (the jelly counter)

James Birch, John Ryan, Chris Scholin

Holly Bowers, postdoctoral fellow (using molecular methods to uncover cryptic species of *Pseudo-nitzschia* in Monterey Bay)

David Caress

Giancarlo Troni, postdoctoral fellow (low-cost underwater vehicle navigation and low altitude, high-resolution seafloor mapping)

Francisco Chavez

Vanessa Izquierdo Peña, graduate summer intern, Instituto Politécnico Nacional Centro Interdisciplinario de Ciencias Marinas (fish and their larvae in the California current in relation to climate variability)

Jesse Lafian, undergraduate summer intern, Tompkins Cortland Community College (varying diel trends in nearshore ocean acidification)

Jason Smith, postdoctoral fellow (nitrogen remineralization in the ocean's twilight zone)

David Clague

Jason Coumans, Ph.D. student, McGill University (the magmatic architecture of the Taney Seamounts)

Katherine Willis, graduate summer intern, Cardiff University (the significance of faults and fissures at Alarçon Rise)

Danelle Cline, John Ryan

Lisa Ziccarelli, graduate summer intern, University of California, Santa Cruz (application of a holographic sensor for plankton ecology)

Steven Haddock

Liza Gomez Daglio, Ph.D. student, University of California, Merced (jellyfish diversity and biogeography)

Warren Francis, Ph.D. student, Carnegie Mellon University (coelenterazine and luminescence chemistry)

Taylor Hersh, undergraduate summer intern, Carnegie Mellon University (transcriptomics-based approach to novel photoprotein analysis in pelagic molluscs)

Holly Swift, Ph.D. student, University of California, Merced (plankton evolution and genetics)

Julio Harvey

Elizabeth Lam, M.S. student, Moss Landing Marine Laboratories (zooplankton detection from ship ballast water)

Rich Henthorn

Cordelia Sanborn-Marsh, undergraduate summer intern, Stanford University (image analysis software for the Sedimentation Event Sensor)

Ken Johnson

Yuichiro Takeshita, Ph.D. student, Scripps Institution of Oceanography (advancing autonomous chemical sensor technology for ocean monitoring applications)

William Kirkwood

Nathan Reed, undergraduate summer intern, San Diego State University (engineering mechanics and design for the Monterey Bay Aquarium's MBARI exhibit)

Linda Kuhnz

Tenaya Edwards, high school student, Aptos High School (macrofaunal distribution and diversity along a sediment grainsize gradient, Younger Lagoon, Santa Cruz)

Nancy Fernandez, high school student, Pajaro Valley High School (the effects of water quality on macroinvertebrate density, biodiversity, and pollution tolerance)

Adriana Gomez, high school student, Pajaro Valley High School (the effects of water quality on macroinvertebrate density, biodiversity, and pollution tolerance)

Josephine Palmer, high school student, Aptos High School (macrofaunal distribution and diversity along a sediment grainsize gradient, Younger Lagoon, Santa Cruz)

Silvano Paniagua, high school student, Pajaro Valley High School (the effects of water quality on macroinvertebrate density, biodiversity, and pollution tolerance)

Isabella Rose, high school student, Aptos High School (macrofaunal distribution and diversity along a sediment grainsize gradient, Younger Lagoon, Santa Cruz)

Maya Yokoyama, high school student, Aptos High School (macrofaunal distribution and diversity along a sediment grainsize gradient, Younger Lagoon, Santa Cruz)

Gene Massion

Laughlin Barker, graduate summer intern, Santa Clara University (buoyancy control for an autonomous coastal profiling float)

Mike McCann, Kyra Schlining

Brent Gibbs, high school student, Monterey Academy of Oceanographic Science (production of Spatial Temporal Oceanographic Query System software informational video)

George Matsumoto

Rigo Collazo, high school student, Pajaro Valley High School, (how does shrimp abundance and diversity differ in regions with different water flow?)

Chantal Fry, high school student, Pajaro Valley High School (*Microcystin* levels in Pinto Lake and neighboring bodies of water)

Antonio Hernandez, high school student, Pajaro Valley High School, (how does shrimp abundance and diversity differ in regions with different water flow?)

Sofia Renteria, high school student, Pajaro Valley High School, (how does shrimp abundance and diversity differ in regions with different water flow?)

Margarita Rincon, high school student, Pajaro Valley High School (*Microcystin* levels in Pinto Lake and neighboring bodies of water)

Adrian Rocha, high school student, Pajaro Valley High School (*Microcystin* levels in Pinto Lake and neighboring bodies of water)

Lillian Uribe, high school student, Pajaro Valley High School, (how does shrimp abundance and diversity differ in regions with different water flow?)

Alvaro Zamora, high school student, Pajaro Valley High School (*Microcystin* levels in Pinto Lake and neighboring bodies of water)

Thom Maughan

Gavin Baker, B.S. student, California State Polytechnic University, San Luis Obispo (embedded high-performance computing for laser holographic image processing on low-power platform)

Cecilia Cadenas, B.S. student, California State Polytechnic University, San Luis Obispo (embedded high-performance computing for laser holographic image processing)

Philip Cooksey, B.S. student, California State University, Monterey Bay (software for Wave Glider control, status request and navigation)

Peter Heatwole B.S. student, California State Polytechnic University, San Luis Obispo (embedded high-performance computing for laser holographic image processing)

Andrew Lam, B.S. student, California State Polytechnic University, San Luis Obispo (electronics and software for microprocessor based system for driving UV LED array for biofouling mitigation experiment and embedded high-performance computing for laser holographic image processing)

Antonio Leija B.S. student, California State Polytechnic University, San Luis Obispo (embedded high-performance computing for laser holographic image processing)

Tim O'Sullivan, B.S. student, California State Polytechnic University, San Luis Obispo (embedded system programming of peripherals on an energy-harvesting boost converter)

Ryan Wardle, B.S. student, California State Polytechnic University, San Luis Obispo (biological experiment design for determining the efficacy of UV-B in inhibiting bacterial growth as a means to biofouling prevention)

Charles Paull

Esther Sumner, postdoctoral fellow (sedimentary processes in submarine canyons)

William Symons, graduate summer intern, University of Southampton (how well do seafloor deposits represent the flows that created them?)

Bruce Robison

Alicia Bitondo, M.S. student, Moss Landing Marine Laboratories (development and behavior of juvenile and subadult *Chiroteuthis calyx*)

Ben Burford, graduate summer intern, California Polytechnic State University, San Luis Obispo (intraspecific communication by the Humboldt squid)

Stephanie Bush, postdoctoral fellow (cephalopod biology, ecology and behavior related to Monterey Bay Aquarium's *Tentacles* exhibit)

Katie Thomas, graduate summer intern, Duke University (ocular anatomy and behavior of the cock-eyed squid)

William Truong, undergraduate summer intern, University of Hawaii at Manoa (statistical analyses of rare species in time-series data)

Steve Rock

Shandor Dektor, Ph.D. student, Stanford University (terrain-based navigation for AUVs)

Marcus Hammond, Ph.D. student, Stanford University (benthic and iceberg mapping using AUVs)

Sarah Houts, Ph.D. student, Stanford University (terrain-based navigation for AUVs)

Stephen Krukowski, Ph.D. student, Stanford University (optimized trajectories for terrain-relative navigation)

Aditya Mahajan, Ph.D. student, Stanford University (feature-based navigation)

Jose Padial, Ph.D. student, Stanford University (feature-based navigation)

David Stonestrom, Ph.D. student, Stanford University (benthic and iceberg mapping using AUVs)

Leslie Rosenfeld

Laura Lilly, California Sea Grant Fellow (new data and information products on marine debris and ocean acidification)

John Ryan

Jennifer Broughton, Ph.D. student, University of California, Santa Cruz (particle size distribution measurements in plankton ecology research)

Ken Smith

Katherine Dunlop, postdoctoral fellow (benthic boundary layer community structure)

Jennifer Durden, graduate summer intern, University of Southampton (benthic megafauna population dynamics)

Robert Vrijenhoek

Corinna Breusing, graduate summer intern, Kiel University (identifying species of *Bathymodiolus brevior* complex)

Jenna Judge, Ph.D. student, University of California, Berkeley (molecular and morphological systematics of marine snails)

Gillian Rhett, M.S. student, Moss Landing Marine Laboratories (community composition of meiobenthos at whale falls in Monterey Bay)

Norah Saarman, Ph.D. candidate, University of California, Berkeley (molecular systematics of California *Mytilus* mussels)

Alexandra Z. Worden

Charles Bachy, postdoctoral fellow (genomic analysis of marine microbial eukaryotes and their viruses)

Chang Jae Choi, postdoctoral fellow (comparative genome/transcriptome analysis of predatory nanoflagellates)

Jian Guo, postdoctoral fellow (influence of nutrients and carbon dioxide levels on algal growth)

Magdelena Gutowska, postdoctoral fellow (vitamin synthesis and utilization networks in marine microbial communities)

Rachel Harbeitner, Ph.D. student, University of California, Santa Cruz (deep-sea eukaryotic life)

Zena Jensvold, undergraduate summer intern, University of Oregon (physiological response of *Ostreococcus* to nutrient depletion)

Valeria Jimenez, Ph.D. student, University of California, Santa Cruz (ecology of photosynthetic eukaryotes)

Alexander Limardo, Ph.D. student, University of California, Santa Cruz (speciation among green algae and environmental factors influencing growth)

Ashley Maitland, undergraduate summer intern, University of Arizona (nutrient stoichiometry and cellular allocation of *Micromonas* strain RCC299)

Melinda Simmons, Ph.D. student, University of California, Santa Cruz (microbial biological oceanography)

Susanne Wilken, postdoctoral fellow (ecology and physiology of marine mixotrophs)

Amy Zimmerman, postdoctoral fellow (nutrient-virus interactions in picoeukaryotes)

Publications

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Cover: Sur Ridge, a 16-kilometer-long submarine ridge west of Point Sur, California, was discovered to harbor a lush community of fishes, corals, sponges, and other invertebrates. See page 15.

Back cover: The deep-sea coral *Isidella* was found growing on Sur Ridge. See page 15.

Inside front cover: *Asbestopluma monticola*, a carnivorous sponge first discovered on Davidson Seamount in the Monterey Bay National Marine Sanctuary, was described by MBARI marine biologist Lonny Lundsten and two colleagues. The fine hairs on the sponge consist of tightly packed bundles of microscopic hooks that trap small animals such as shrimp-like amphipods. Once an animal becomes trapped, it takes only a few hours for sponge cells to begin engulfing and digesting it. After several days, all that is left is an empty shell.

Above: Photographer Alan Gonzales took this stunning photo of the MBARI building from within the surf line. He also captured images of humpback whales feeding just offshore, as can be seen on page 4.

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