MBARI

Monterey Bay Aquarium Research Institute

2016

Annual Report


GROVE

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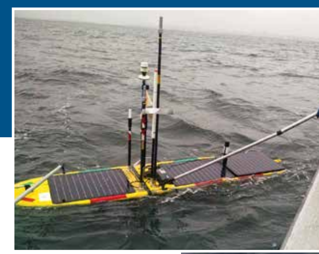
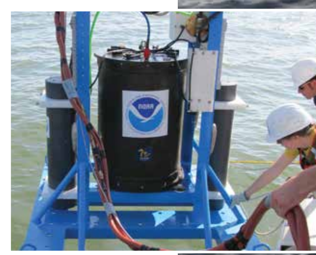
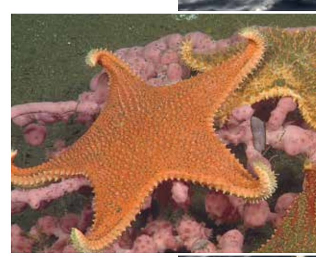
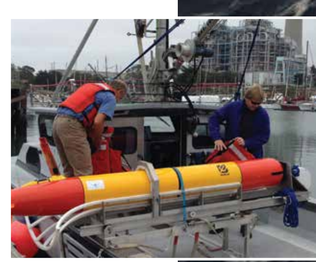








View from the Masthead

It is often said that we know more about the surface of Mars than the interior of Earth's ocean. To many, however, that seems like a gross overstatement. Surely, after eons of human exploration, discovery, and study we must know much more about our own Earth than Mars! But a quick look at this year's annual report shows that despite years of study, mysteries surrounding the ocean remain unsolved and many discoveries are yet to be made.

The vast and dynamic nature of the ocean—from its surface to its seafloor—is truly impressive. Access to the ocean's interior is extremely limited and the interconnectedness of a mindboggling web of life, constantly driven by changing chemical and physical conditions, defies easy comprehension. There is no doubt that there is much to learn. The age of exploration and discovery on Earth is alive and well, particularly as we document the profound changes that are now taking place—changes that herald a future ocean that will likely be significantly different from the one we know today. Now, more than ever, we need to understand what a changing ocean means for the life within it and for human society. With so much to do, where do we start?

Monterey Bay ranks among the world's premier sites for ocean investigations. Its variety of habitats, species diversity, deep-water canyon, and connection to the North Pacific make it an exceptional natural laboratory. It is ideally matched for meeting MBARI's mission of combining science and engineering to yield new tools and techniques for accessing the sea and visualizing its inner workings. Indeed, that is why we often refer to the bay as a "window to the world." The processes occurring locally and regionally reflect what is occurring on a much larger scale. We use this "window" to conceptualize, develop, and perfect new measurement technologies locally, and then export those capabilities and know-how globally to the larger ocean science community. By freely sharing the knowledge gained, often working with our partner institution, the Monterey Bay Aquarium, we endeavor to engage government agencies, non-governmental organizations, and the general public to bring the wonders and

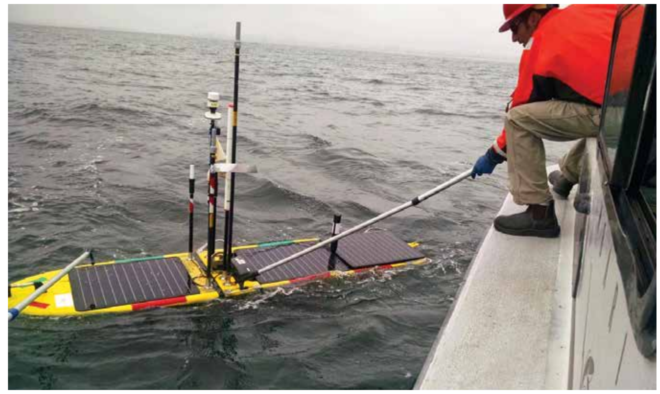
Mechanical Engineer Larry Bird places the electronic "brains" into a benthic event detector. This sphere was then placed in Monterey Canyon, where it will record any landslides or other seafloor events that would otherwise be invisible.

importance of ocean issues to light: what is the state of the ocean today, what does the future hold, and how can we best visualize and communicate this information? All of our work is aimed directly at answering such questions.

"Being there is everything" is another popular quip that perfectly encapsulates the spirit of our research enterprise. As you will see in the pages that follow, our studies of the ocean are largely rooted in observation, documenting the comings and goings of the ocean's inhabitants in concert with the chemical, physical, and geological processes that shape them. This is a huge challenge that we meet by developing and adapting sensors and robotic platforms to complement and expand on what is possible for people to do at sea on ships. Expeditions far from Monterey Bay offer opportunities for comparative studies. The trends and correlations seen locally and afar provide clues about possible cause-and-effect relationships, informing experiments that take place in our laboratories and at sea to answer particular questions or test specific hypotheses. In pursuit of that work, we often encounter bizarre creatures that defy explanation and are sometimes new to science. Impressive rearrangements of the seafloor are also frequently revealed, some of which are the result of geological forces acting over thousands of years, others in a mere blink of an eye. This year's report is meant to give you a sense of that breadth of research and development, and highlight recent findings we think you will find engaging.

MBARI has evolved a great deal since its founding, and 2016 was no exception to that trend. We welcomed four new principal investigators; brief introductions of these individuals are found in the *Behind the Scenes* section of this volume. These talented people are the face of a new MBARI—the next generation of stewards who have the privilege and responsibility of bringing David Packard's vision of MBARI to life in the 21st century.

Looking forward to 2017, MBARI will celebrate its 30th anniversary. That milestone will coincide with expeditions to sites along the US West Coast, as well as the South China Sea, Greenland, and the Arctic Ocean. Other laboratory and field programs will extend our reach further, and together with the expeditionary work we will undoubtedly see another year of unanticipated discoveries and science and engineering breakthroughs. These advancements are sure to remind us of how much more there is to discover about the ocean and how vital the ocean is to sustaining all life on Earth. No single institution can possibly address the totality of these issues. Partnerships and collaborations, both in the US and abroad, are needed—this is another facet of our operation that we will continue to foster in the year ahead.



The hot spot Wave Glider is deployed from the R/V Paragon. *Note multiple antennae for satellite, cellular, and "Wi-Fi" communications.*

Communicating the importance and societal relevance of the scientific and engineering endeavors we undertake is something we constantly aim to improve. With that in mind, the tradition of a printed annual report as it appears here will end. Taking its place in 2017 will be an entirely new format specially designed for online viewing. This new format will allow us to bring you much richer, interactive content than is possible now.

We look forward to 2017, and we hope to hear from you! Follow us by visiting our website, as well as by subscribing to our Facebook, Twitter, YouTube, and Instagram feeds.

Chris Scholin,
President and Chief Executive Officer

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Benthic event detection: www.mbari.org/mbari-engineers-create-smart-boulders-to-understand-how-sand-moves-in-submarine-canyons

Monterey Bay as a Window to the World

Research and development efforts that begin in Monterey Bay, just to the west of MBARI's facilities, often shed light on significant marine processes that are widespread throughout the world's ocean or result in technological developments that have global impact. A new look at the key factors affecting oxygen consumption in a changing ocean, long-term environmental trends, the burgeoning field of "sound in the sea," the export of MBARI's Environmental Sample Processor, and deep-diving studies into the world of bioluminescence are just a few examples of how we leverage work in Monterey Bay to extend our reach far beyond local waters.

The ocean's changing oxygen profile

Global warming is not just a terrestrial issue; it is also impacting the marine environment and perturbing oceanic biogeochemical cycles that are essential to all life. One clear change is in the observed steady decline of oxygen levels in the upper ocean around the world. These trends are real, persistent, and significant, raising the question as to what the cause may be.

Warm water in equilibrium with the atmosphere holds less oxygen than cold water under the same conditions. Yet the differences observed in oxygen concentrations in the upper ocean greatly exceed what can be attributed to solubility and changing rates of upper-ocean mixing alone. Could it be that changing rates of bacterial respiration in the water column—well known as the major sink for both oxygen and organic matter in the ocean—can account for the changes observed in decreasing dissolved oxygen?

Aerobic bacterial respiration is relatively simple to describe. When both oxygen and organic matter are present, bacteria consume organic matter using oxygen to convert it to carbon dioxide, water, and other compounds and, in the process, produce metabolic energy that keeps the bacterial cells alive and reproducing. Like all chemical reactions, the bacteria work faster at higher temperatures. One sees this happen in daily life. Food left on a warm countertop for a time "spoils" while leftovers placed in the refrigerator last longer. And if the refrigerator fails and the food inside becomes warm, it spoils quickly. Clearly bacterial respiration and metabolism respond to, and are controlled by, temperature.

The Ocean Chemistry of Greenhouse Gases Group, led by Scientist Peter Brewer, began looking into this by compiling oxygen consumption rates gathered from the upper one thousand meters of the ocean from multiple sites around the world ocean, and found that the consumption rates were consistent with the rule that chemical reaction rates are controlled by temperature. The fact that data from such disparate sites from around the world ocean yield such a consistent relationship illustrated a basic principle. The consistency of organic matter composition throughout the world ocean was shown by oceanographer Alfred Redfield and colleagues many years ago, and this fact has been a fundamental lesson taught to oceanography students for decades. Consistent organic matter composition yields consistent rates.

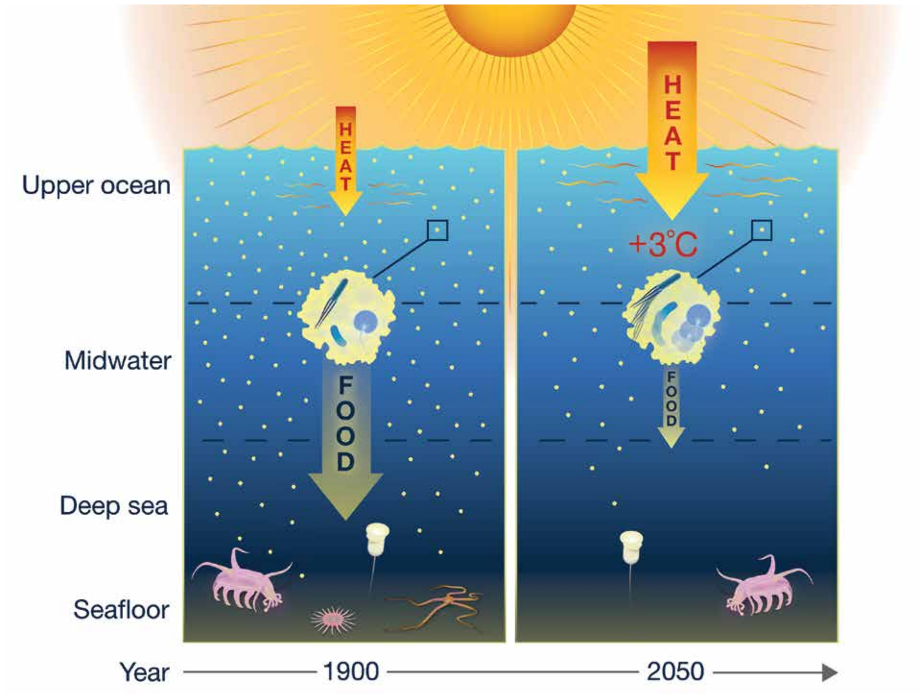

Figure 1. The natural process of bacteria recycling sinking organic matter in the upper ocean is essential to maintaining the fertility of the ocean. Organic detritus (dead microbes, animal waste, etc.) slowly sinks into the upper ocean where the majority of the material is oxidized by bacteria. The oxidized material in turn provides the nutrients for phytoplankton growing in the upper ocean. Whatever organic matter falls through and sinks to the seafloor provides food for midwater organisms and ultimately benthic organisms. Bacterial metabolism is greatly affected by temperature: the warmer the water, the faster bacteria respire and consume the organic matter and draw down the oxygen dissolved in seawater. In a warmer ocean, this would mean that the respiration would happen faster and at a shallower depth resulting in a shallower oxygen minimum and a diminished food supply to both the midwater and benthic organisms.

Having shown that the rate of aerobic oxidation of organic matter in the upper ocean does indeed follow simple chemical kinetics, Brewer and his team can now predict how much faster bacteria will oxidize organic matter in a future warmer ocean. The results of this calculation show that for even small changes in temperature, substantial increases in metabolic rates arise. The end result is that for warming of the ocean by two degrees Celsius, microbial oxygen consumption rates will increase by about 30 percent, and for three degrees Celsius, by about 50 percent. The predicted effect is that marine organic matter will be consumed increasingly faster by bacteria at shallower depths since heat is invading the ocean from above as the Earth's atmosphere warms.

Two immediate consequences of this increase in microbial oxygen consumption rates are that oxygen will be consumed at an increasing rate and that the net flux of organic matter from the sea surface to the deep sea will be reduced. If bacterial metabolism is more rapid, there will be less organic matter left to sink into the deep sea (Figure 1).

The oxygen decline is merely a trend—the real issue is the change in the cascade of food for marine life in the deep sea. Even if there is plenty of oxygen, if bacteria consume more of the food supply there will be less food for the more complex multicellular animals in the midwater and, in particular, for benthic communities on the seafloor. They will either strive to move to shallower depths for food—and face challenges in doing so—or simply decrease in number to match their new food-limited circumstances.

Based upon these interpretations related to fundamental chemical reaction rates in the ocean, it is likely that the deep sea and benthos will experience slightly higher oxygen levels but have a reduced food supply, since oxygen and food—the rain of organic matter—will increasingly be consumed at the warmer shallower depths.

Monterey Bay in the age of uncertainty

As the largest ocean basin on the planet, the Pacific's tremendous thermal imprint drives global climate variation. For example, the equatorial Pacific El Niño drives dramatic changes in precipitation in such far-reaching places as the southeastern US, Argentina, and Africa. The ocean off California, including Monterey Bay, is also intimately linked to El Niño, as well as longer multidecadal cool/warm variations like the Pacific Decadal Oscillation (PDO). Variations observed in Monterey Bay thus provide a window to how prevailing ocean conditions impact a much larger region of the world (Figure 2).

For almost two decades following the 1997-98 El Niño, Monterey Bay had been cooler than average. This regime shift in the late 1990s was associated with a change in phase in the PDO from warm (since 1976) to cool. Then recently, over the last

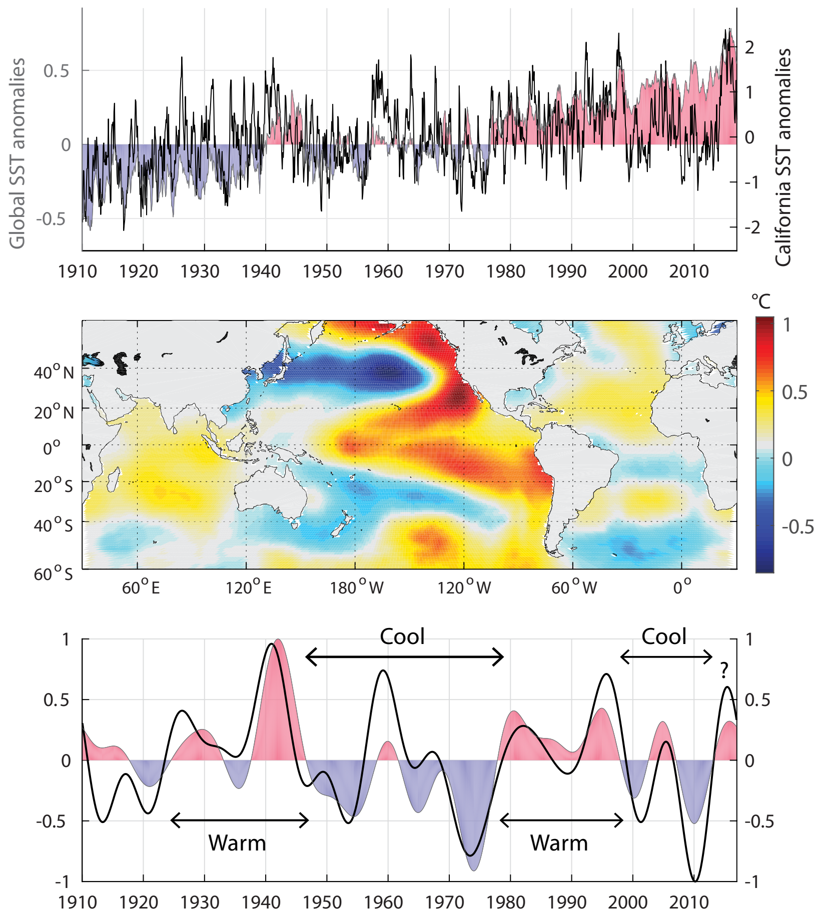

Figure 2. Top panel shows the monthly sea-surface temperature (SST) anomalies for the globe (red indicates warm, blue indicates cool) and for a narrow strip along the coast of California (line) from 1910 to 2016. Note that the California temperatures are more variable (SST axis is twice as large as the global one). The middle panel depicts a sweep of anomalies in sea-surface temperature (in red), with corners in Alaska, at the point where the dateline crosses the equator, and in southern Chile, characteristic of the Pacific Decadal Oscillation (PDO). The time series of this variability is shown in the bottom panel (colors) and is well correlated with the PDO time series. The line is the same analysis carried out on the narrow California strip, almost identical to the global one, but with larger excursions. Well identified PDO regime shifts are indicated (warm periods in pink, cool in purple) in the bottom panel.

several years, the bay warmed dramatically for an extended period, unlike anything seen since the early 1940s. The 1940s warm period was followed by several decades of cooler than average conditions and the collapse of California sardines and associated fisheries. Are the recent events signaling the dawn of a new era?

During the cool period preceding the recent Monterey Bay warming, two new and related climatic phenomena, which were not apparent in the previous century of records, were uncovered. In the first phenomenon, called El Niño Modoki, warming was concentrated in the central equatorial rather than the eastern Pacific. In the second, the North Pacific Gyre Oscillation was characterized by a flip-flopping horseshoe pattern of anomalous sea-surface temperature extending from the central equatorial Pacific to the California coast and Alaska and then back around to Japan. These climatic phenomena have had clear biological consequences. For example, the basin-wide synchrony in alternating populations of anchovies and sardines in California, Japan, and Peru observed over the past 50 years was disrupted; Peru and Japan remained synchronous, but not California.

The beginning of the recent warm event in late 2013 was associated with an extreme case of the North Pacific Gyre Oscillation, where oceanic water within the horseshoe pattern became unusually warm. This feature became known as the "blob." As the blob grew, warm water was pushed into Monterey Bay beginning mid-2014. The warming continued through 2015 and was immediately followed by the 2015–2016 El Niño. This combination of events compressed the cool and productive upwelling habitat very close to shore and produced atypical ecosystem consequences.

Unusual and dense coccolithophore phytoplankton and very toxic *Pseudo-nitzschia* diatom blooms formed offshore and inshore, respectively, during the summer of 2015. The extreme toxicity of the diatom bloom, which caused the closure of the lucrative Dungeness crab fishery, has been linked by a team led by MBARI Research Specialist John Ryan to anomalous concentrations of silicate observed in the Monterey Bay time series. This long record, collected by Scientist Francisco Chavez and his group for more than 25 years, has been crucial in identifying these relationships. While unusually low levels of nutrients (nitrate, phosphate, and silicate) were found during the 2013-2016 warm event, the concentration of chlorophyll, an indicator of phytoplankton productivity, remained surprisingly high (Figure 3).

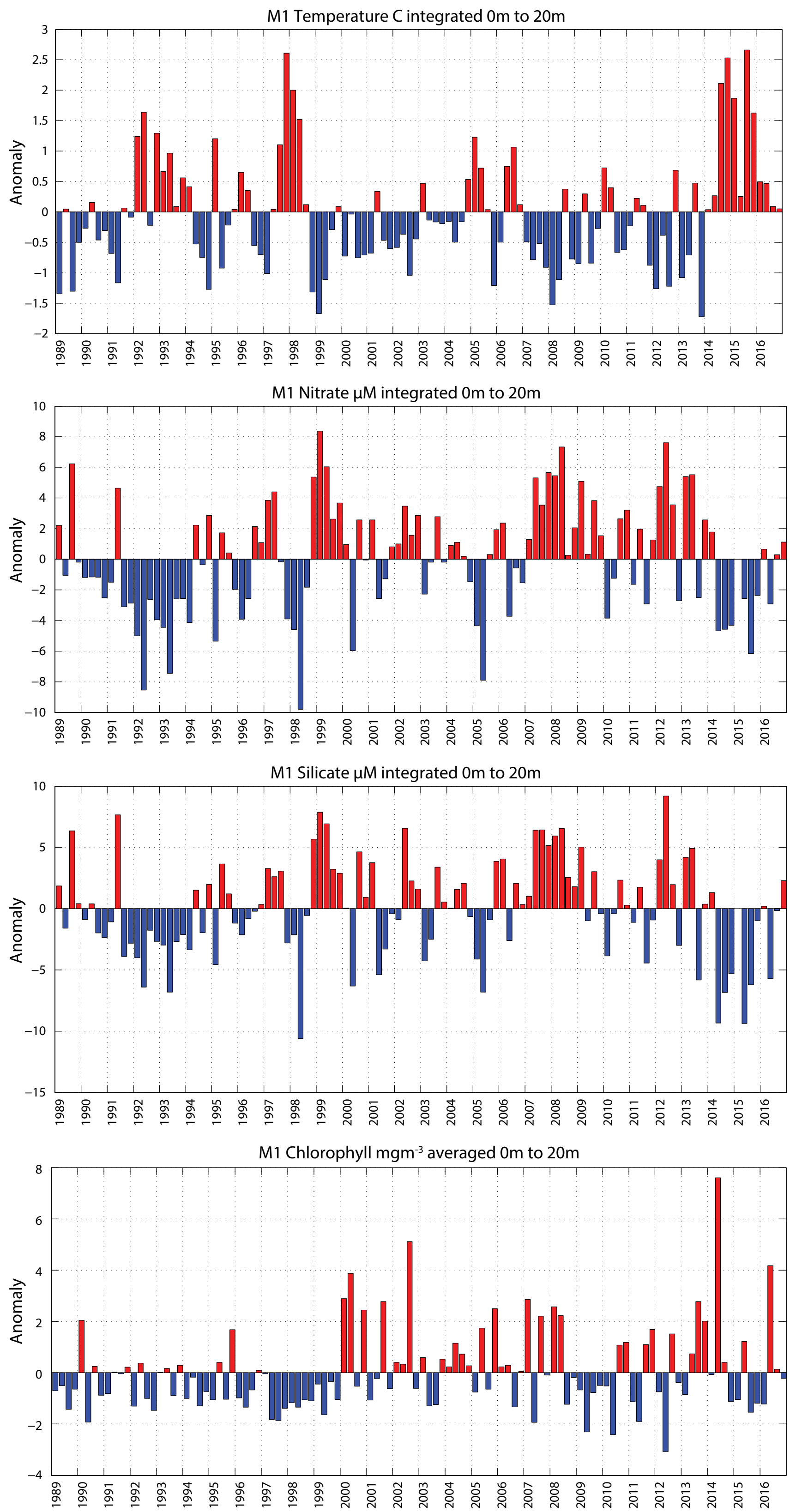

Figure 3. Time series of seasonal anomalies of temperature, nitrate, silicate, and chlorophyll from the top 20 meters at M1 mooring site in Monterey Bay, California. Climate phenomena or shifts are indicated on the various panels.

In fall 2015, pelagic red crabs (*Pleuroncodes*) arrived with El Niño along with salps and a variety of southern zooplankton. This mixture of northern and southern species produced record levels of zooplankton diversity. The ecosystem death and destruction predicted for the so-called Godzilla El Niño never materialized, and the 2015-2016 El Niño never reached levels that were seen in 1982-1983 or 1997-1998. However, the extended three-year warm period may have extended biological consequences yet to be discovered.

Temperatures in Monterey Bay cooled by mid-2016, but odd conditions persisted. Red crabs have remained in Monterey Bay, and large concentrations of sunfish (*Mola*) and leatherback turtles (*Dermochelys*) were observed north of the bay. The heavy rainfall predicted for the 2015-2016 winter never materialized but instead has appeared for the 2016-2017 winter.

So will the unusual and mostly unpredictable conditions felt in Monterey Bay over the past three to four years continue? Does the unprecedented string of warm years indicate another multi-decadal regime shift? What would a new shift look like, and will it produce new climate phenomena? What role is a warmer planet playing in present-day conditions, and what role will it play in the future? While scientists have made tremendous advances in the understanding of links between climate and ocean variability and how the marine ecosystem responds to such variations, there is still much work to be done. Marine ecosystem models are improving but still are not quite able to provide the predictions needed to sustainably manage the world ocean. MBARI is playing an important role in this arena through the development of new systems and methods for autonomous studies of ocean conditions and life in the sea.

A world of sound beneath the ocean surface

Sound travels orders of magnitude farther than light in the ocean, and sound travels more than four times faster in water than in air. The efficacy of sound transmission is evident in the fact that rainfall on the sea surface can be heard in the deep sea. In the largely dark ocean, marine animals use exquisite physiology to produce, receive, and interpret sound—capabilities essential to communication, foraging, and navigation. The effective propagation of sound through the ocean and the necessary use of sound in the oceanic web of life define an emergent dimension of ocean stewardship—protection of acoustic habitat. Human activities introduce noise to the ocean, and this noise can disrupt the web of life through acute and chronic impacts.

In collaboration with the Monterey Bay National Marine Sanctuary and academic institutions along the California coast, MBARI Research Specialist John Ryan and his team embarked on a feasibility study in passive acoustic monitoring—listening to sound in the ocean. Listening across a large frequency range reveals the complex and important world of sound. Ocean sound sources include biophony (sound generated by marine life), anthrophony (sound generated by human activities), and geophony (sound generated by earth processes). Enriching ocean stewardship requires advancing our understanding of how anthrophony affects marine life.

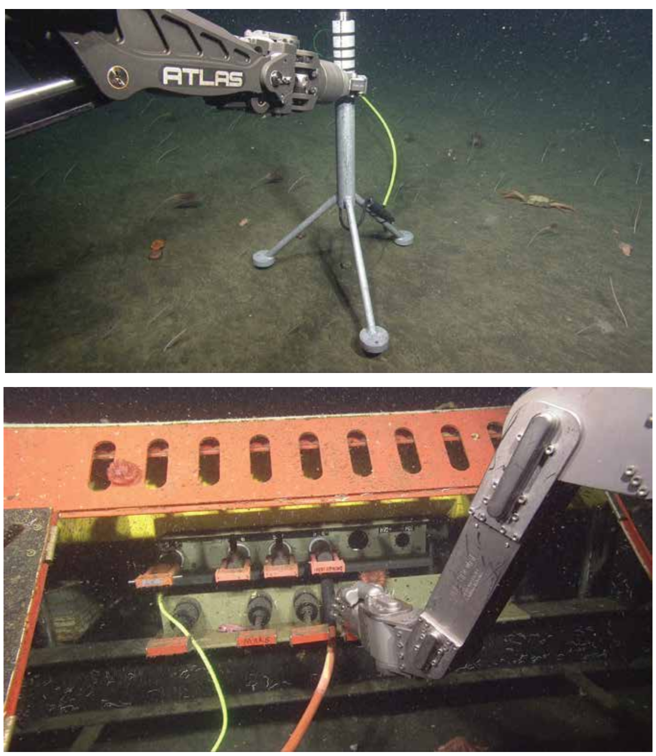

Figure 4. Top, the hydrophone (one meter tall) is placed on the seafloor; bottom, ROV pilots use the robotic arm to plug the hydrophone cord into the main node of the MARS cabled observatory.

As a guiding resource in this stewardship, the National Oceanic and Atmospheric Administration (NOAA) released the *Ocean Noise Strategy Roadmap* in 2016. This document identifies National Marine Sanctuaries as key assets in achieving protection of acoustic habitat. Informing policy makers on how they can move forward to tackle the potential impacts of anthrophony requires careful scientific inquiry and effective listening within our marine sanctuaries, requirements that MBARI's infrastructure uniquely meets. Connected to a deep acoustic habitat in the heart of the sanctuary is a hydrophone on the Monterey Accelerated Research System (MARS) cabled observatory that brings the deep ocean soundscape to shore and to analytical tools in real time, 24 hours a day, seven days a week (Figure 4). MARS enables continuous recording of a broad frequency range, a necessary foundation for effective soundscape research and education. Because acoustic monitoring creates voluminous amounts of information, MBARI's expertise in translating "big data" into insightful research is also a critical asset.

Biophony

Research in biophony spans very low-frequency (less than 20 hertz) to very high-frequency (greater than 50 kilohertz) vocalizations of marine mammals. The lowest frequency vocalizations are from the largest animal species that has ever lived on earth, the blue whale, and its cousin known as the greyhound of the sea, the fin whale. Both of these species use the biologically rich habitat of the marine sanctuary, and their vocalizations are prevalent in MARS hydrophone recordings. The key to acoustically recognizing their presence and activities is to identify the "voiceprints" of their vocalizations (Figure 5).

The most prominent differences in the vocalizations of these two species are their duration and pitch. The blue whale call has a much longer duration and different frequency ranges of peak sound energy than the fin whale pulses (Figure 5). An analysis of the time series from the start of recording in August 2015 through the end of 2016 reveals seasonal and interannual variations in the ocean background noise levels and the vocalizations of these two species (Figure 6).

Focusing only on the low-frequency range in which these giants vocalize, ocean background sound has been quieting since August 2015 (Figure 6a,b). Throughout the time series, the

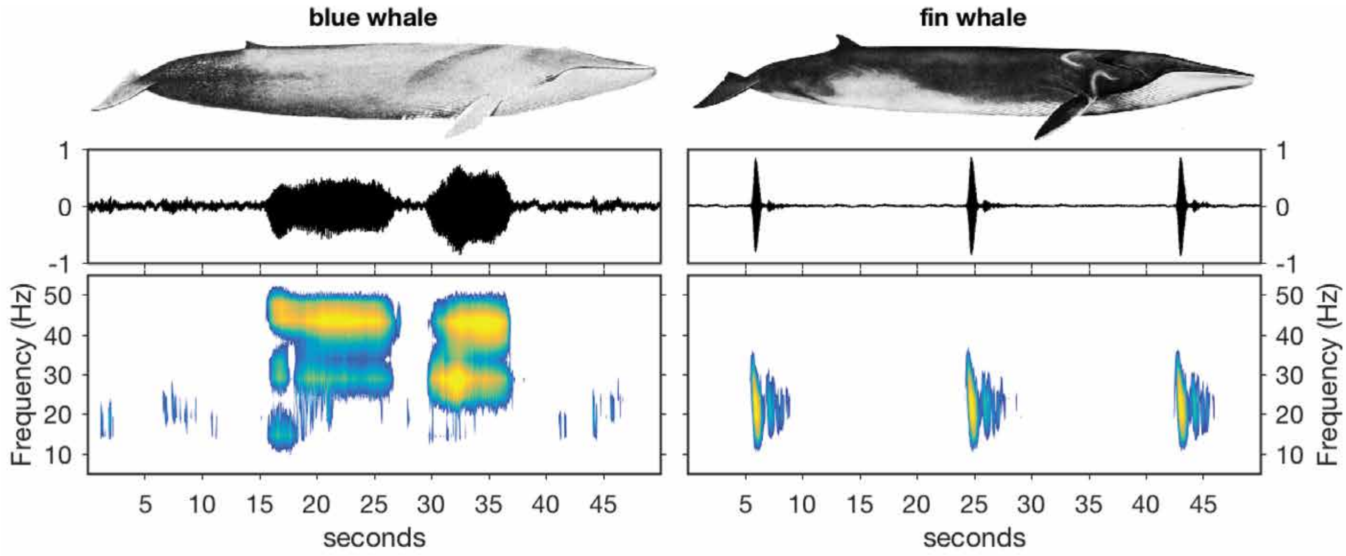

Figure 5. Contrasting vocalizations of blue and fin whales (which can grow up to 30 meters and 22 meters, respectively), represented as waveform (top) and spectrogram (bottom). Both are visual representations of sound intensity as a function of time and frequency, with warmer color indicating greater intensity in the spectrograms.

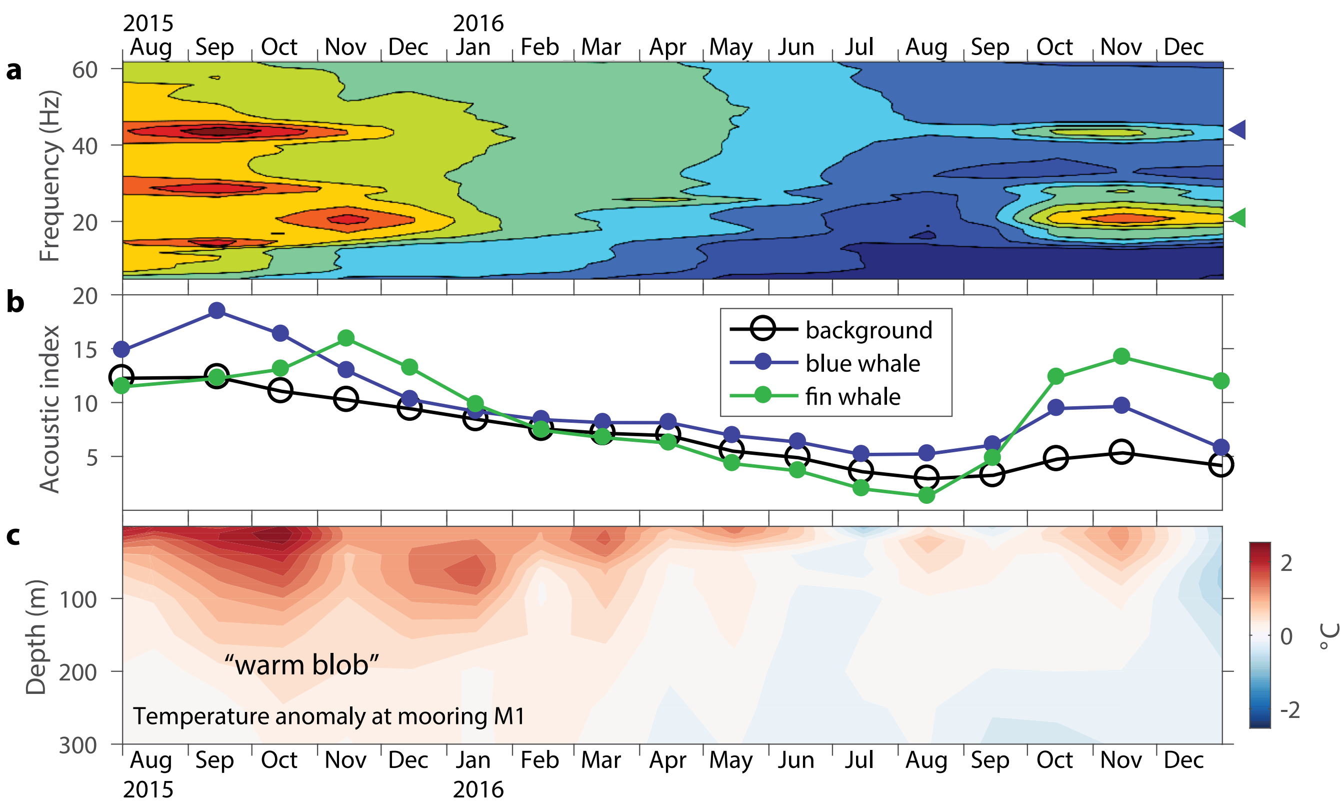

Figure 6. (a) Monthly average sound energy (power spectral density) in the low frequency range. Warmer colors indicate greater sound energy. The blue and green triangles along the right axis identify peak frequencies for blue and fin whales, respectively (Figure 5). The time series at these frequencies are shown relative to the average across the frequency range of five to 60 hertz (background) in (b). (c) Monthly anomalies in water column temperature at the MBARI M1 mooring; anomalies define whether a given month was unusually warm or cool compared to the long-term average for that month.

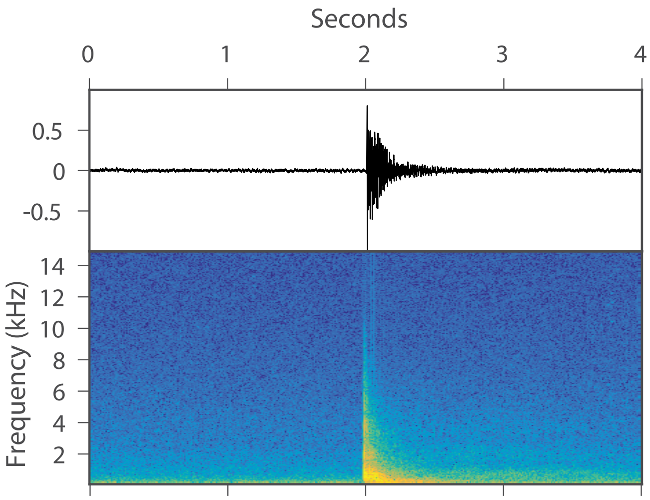

Figure 7. Acoustic detection of a fishery explosion, represented as waveform (top) and spectrogram in kilohertz (bottom; color represents $\log_{10}$ of power spectral density).

greatest average energy occurs at the frequencies at which blue and fin whales vocalize, attesting to the dominance of biophony in this low-frequency range. Both species exhibited peaks in average vocalization signals during the fall periods of 2015 and 2016 (Figure 6b). Vocalization energy for both species rose above the background by a similar level in fall 2015, with blue whales peaking two months before fin whales. In contrast, fin whale signal peaked much higher above background and endured longer than blue whale signal during fall 2016 (Figure 6b).

These patterns suggest interannual variability in use of the sanctuary habitat by these species. Temperature anomalies at the mouth of Monterey Bay show large interannual variation in the environment during this period, with fall 2015 having been strongly influenced by a prolonged period of anomalously warm water conditions in the northeast Pacific (the so-called "warm blob", Figure 6c). Further environmental data analysis and application of other methods to automatically detect, classify, and count individual vocalizations are being applied to better understand the ecology of these prominent migratory giants.

Anthrophony

Research in human-caused sound includes vessel noise coming from near and far, as well as a surprisingly frequent noise linked to fishing-related explosions. The intention of these detonations is to deter curious and hungry pinnipeds, such as seals and sea lions, from interfering with fishing operations. The sudden and intense nature of the sound is pronounced in both the waveform and spectrogram representations (Figure 7). The intensity is accurately represented relative to background in the waveform plot of the unfiltered recording. During the hour from which this example was taken, nine such explosions were detected. According to researchers at Scripps Institution of Oceanography, who are examining explosion noise along the California coast, nearly one thousand explosions have been detected in a single month at MARS.

Geophony

Research in sounds generated by earth processes includes sound sources from the ocean surface (wind, rain), the seafloor (landslides), and Earth's crust (earthquakes). Strong low-frequency rumbles, frequently evident in routinely produced spectrograms,

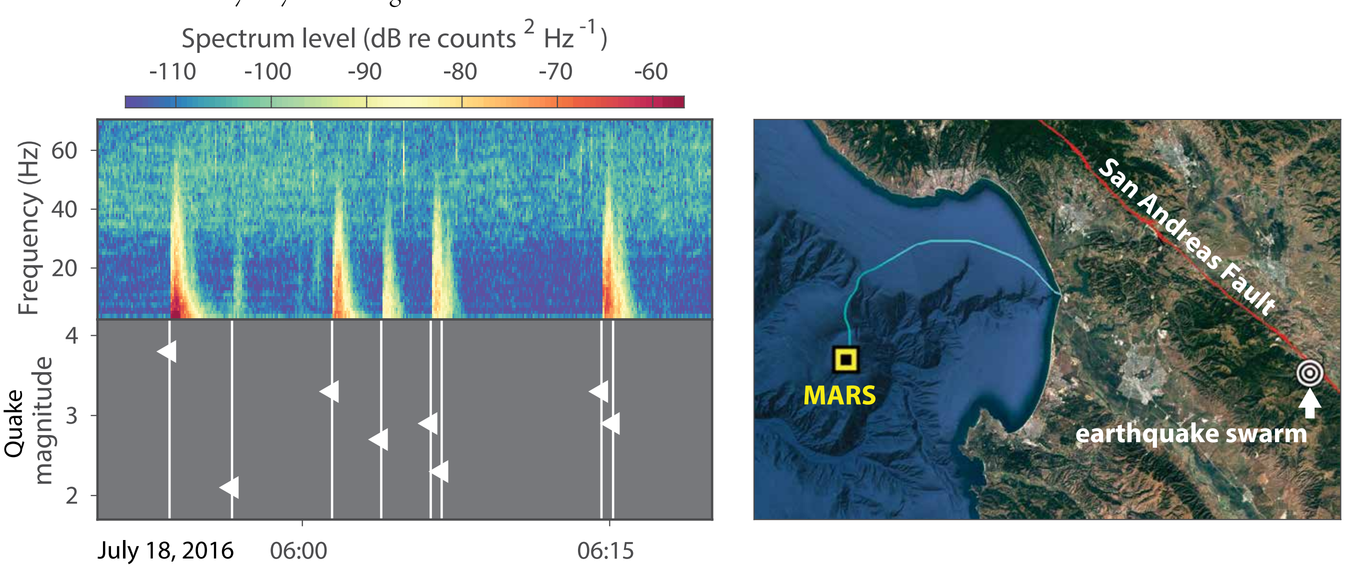

Figure 8. Spectrum showing the sounds of an earthquake swarm (top left) recorded by the MARS hydrophone on July 18, 2016, relative to earthquake magnitudes measured by USGS (bottom left and right).

have been linked to earthquakes (Figure 8). Their distinct signal facilitated development of an automated detection methodology. Analysis of the time series showed as many as 40 earthquakes recorded in a single day.

Education

Recordings from the MARS hydrophone have been used in undergraduate and graduate student projects, including the MBARI summer intern program, Stanford University, the Naval Postgraduate School, and Scripps Institution of Oceanography. Public outreach has been supported by a prototype mobile exhibit developed at MBARI, which was demonstrated at the NOAA Sanctuary Exploration Center in Santa Cruz and in primary school classrooms. Recordings from the MARS hydrophone have been incorporated into a primary school telepresence program of California State Parks that reached over 46,000 students during the 2015–2016 school year.

Looking forward, the team plans to expand its use of sound information from submarine geological structures and processes to biological populations and foraging ecology. Both passive and active acoustic methods are valuable for advancing the understanding and management of marine ecosystems.

A homegrown technology finds use around the world

Life on Earth is dependent on a myriad of marine microorganisms that are largely invisible to the naked eye. In the ocean, this unseen majority forms the very base of the food web, catalyzing countless biochemical reactions that transform matter and energy and maintain ocean ecosystems crucial to the survival of sea creatures and humans alike. Given the importance of the oceanic microbial community, it is no surprise that marine researchers are focusing efforts to reveal the diversity and function of these organisms and how environmental changes may alter the activities of these important microbes in the future.

In that regard, marine microbiology and biomedical research have a great deal in common. Modern analytical techniques allow researchers to discover, quantify, and monitor how organisms adapt and respond to changing environmental conditions. Indeed, even to the trained eye, marine microbiology and medical microbiology laboratories look similar and are filled with common pieces of equipment. What sets them apart? The biggest difference is where sample materials come from—while samples are relatively easy to collect for medical research (depending on the individual patient), marine microbiology requires the ability to collect material from the ocean, at times very far from land and deep below the sea surface. Accessing study sites is often not trivial, sometimes requiring sophisticated ships and specialized equipment. Complicating matters further is the limited amount of time researchers spend at sea; logistical and practical constraints severely limit when, where, and how many samples are collected.

Many years ago MBARI initiated a program to address this fundamental limitation by developing the Environmental Sample Processor (ESP), a type of robotic instrument (Figure 9). The ESP was designed to automate the process of collecting and preserving samples, as well as for processing that material immediately after collection. This enables some routine analyses, usually conducted in a laboratory, to be done on-site, underwater if needed, without requiring a human operator. MBARI has been at the forefront of developing this technology, generically referred to as an ecogenomic sensor, for nearly two decades, proving its viability, commercializing the first working example of this device, and providing support for ESP operations around the world.

The year 2016 marked an important milestone for this program as the ESP was used for studies that spanned sites from the Atlantic to the Pacific. Over the course of six regional studies carried

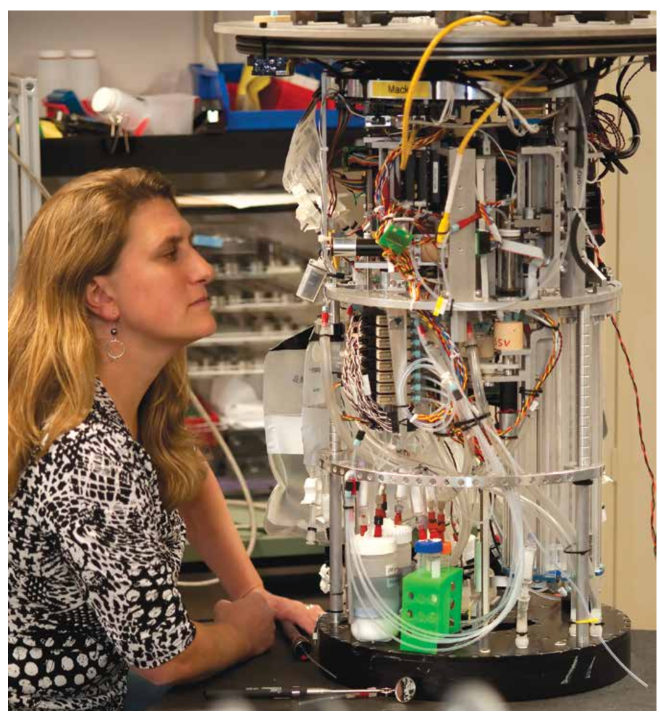

Figure 9. Research Specialist Christina Preston examines the inner workings of the Environmental Sample Processor.

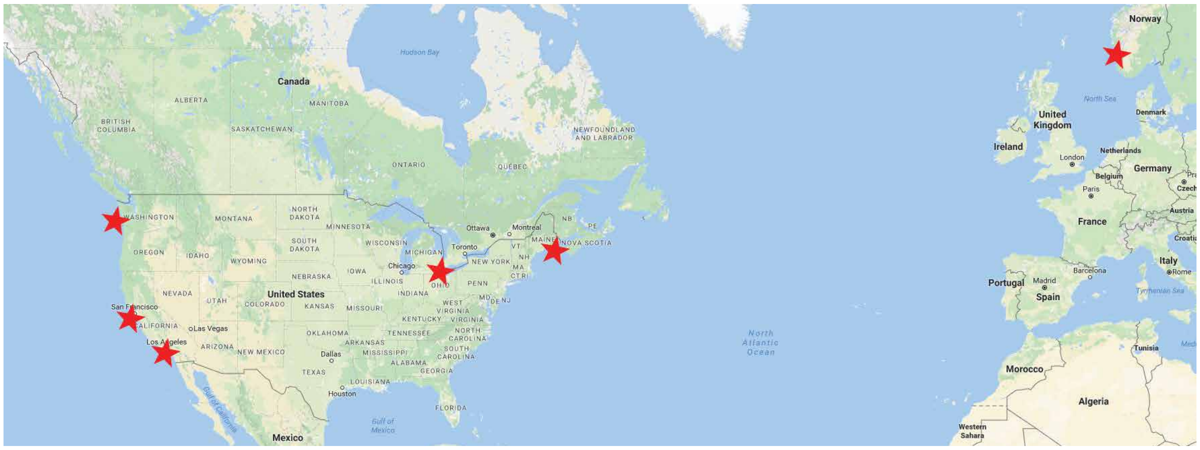

Figure 10. In 2016, the ESP team deployed Environmental Sample Processors in Norway, the Gulf of Maine, Lake Erie, coastal Washington, Monterey Bay, and San Diego.

out in Norway, the Gulf of Maine, Lake Erie, coastal Washington, Monterey Bay, and San Diego (Figure 10), MBARI scientists and engineers worked with collaborators from academic, non-profit, and government institutions to transfer ESP technology and operational know-how.

The work in Norway focused on the detection of microbes that respond to oil spills or natural hydrocarbon seeps. The primary goals of this laboratory effort were to demonstrate that detection of specific groups of "oil-eating" microbes can serve as a proxy for detecting the presence of oil in seawater. The researchers also wanted to validate the performance of the ESP for automating the detection of those oil-degrading microbes in seawater. The vision behind this project is to place Norwegian and other offshore oil and gas operators in a leading position regarding environmental monitoring practices. This work was sponsored by the Norwegian Research Council and was carried out in conjunction with the International Research Institute of Stavanger.

In the Gulf of Maine, a network of sensors were designed to aid state officials in forecasting outbreaks of toxic algae that can accumulate in shellfish and, thereby, pose a human health risk. MBARI scientists and engineers partnered with a group from the Woods Hole Oceanographic Institution and McLane Research Laboratories to set up an ESP network. Shellfish harvest is regulated to prevent paralytic shellfish poisoning, a serious illness for humans who eat shellfish contaminated with the toxins produced by a microscopic alga, *Alexandrium*. Data from the ESP array were used by resource managers in Maine, New Hampshire, and Massachusetts, as well as by the shellfish industry, to forewarn of this possibility. ESP deployments in the Gulf of Maine (Figure 11) were supported in part by a Partnership for Innovation: Building Innovative Capacity grant from the National Science Foundation (NSF) that pairs academic and commercial entities to help fuel innovation.

One instrument was placed in Lake Erie to provide early warning of toxic algae outbreaks, particularly near the water intake for the city of Toledo, Ohio. That ESP was acquired by NOAA for use by researchers at Great Lakes Environmental Research Laboratory, whose team developed a new assay for the ESP to detect microcystin, a toxin produced by the cyanobacteria *Microcystis*.

Figure 11. The ESP is launched in the Gulf of Maine in a collaboration with Woods Hole Oceanographic Institution.

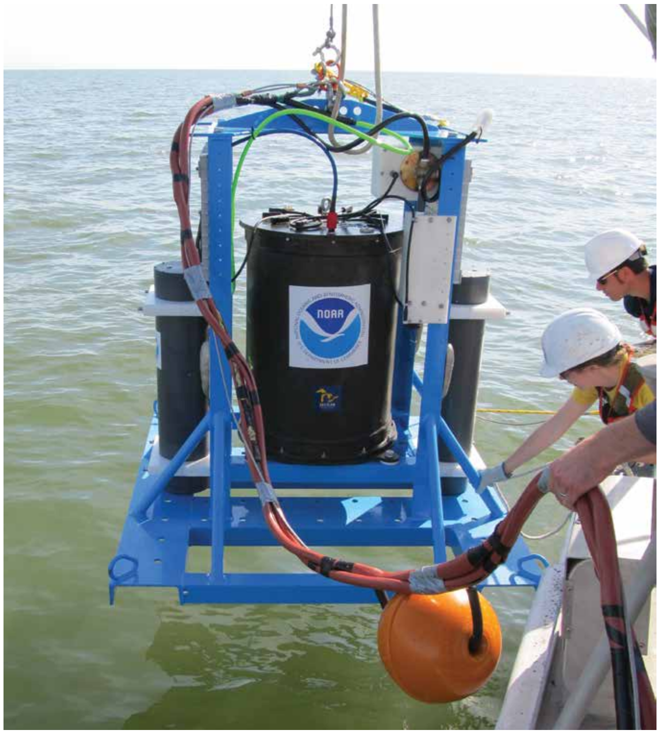

Figure 12. The ESP is deployed in a custom mooring built by the Great Lakes Environmental Research Laboratory to allow the instrument to sit on the lake bottom.

Each year, Lake Erie experiences significant blooms of poisonous *Microcystis* that can contaminate drinking water (Figure 12).

Off the coast of Washington, an ESP was deployed as part of a larger regional ocean observing network. Like its counterparts in the Gulf of Maine and Lake Erie, this ESP was equipped to detect harmful algae. Of primary concern are particular species of diatoms (*Pseudo-nitzschia*) that produce domoic acid, a neurotoxin. Similar to the work in the Gulf of Maine, the Washington ESP was positioned to provide an early warning of toxic algae that can contaminate shellfish and pose a human health hazard. This instrument was placed at the Northwest Enhanced Moored Observatory site with support from NOAA. An excellent public website was developed where deployment information was posted in near real time.

Finally, the instruments deployed in Monterey Bay and off San Diego were used to collect and preserve samples for subsequent laboratory analyses that are presently not feasible to conduct onboard the ESP. Collaborators from the University of Georgia, sponsored by NSF, used the Monterey Bay instrument to study how bacteria facilitate sulfur cycling. Of particular interest is dimethylsulfoniopropionate (DMSP), an important metabolite produced by marine phytoplankton and seaweeds that also contributes to giving the ocean its characteristic odor. When bacteria break down DMSP, they create a volatile compound that acts to seed cloud formation and block solar radiation, potentially influencing the Earth's heat budget. In order to understand the metabolic pathways responsible for this elemental cycling it was necessary to collect samples multiple times per day for an extended period of time to correlate DMSP levels with gene activity of the bacterial community present each day. The ESP was central to making that study possible.

The ESP deployment near San Diego was both an engineering test and a scientific experiment. Scientists at the Scripps Institution of Oceanography needed to collect a large number of samples from shallow water and preserve them for many months without any human intervention. They needed these samples to track changes in the microbial community at a particular site over time. Prior to this work, samples collected and preserved using the ESP on coastal moorings or drifters have been retrieved within one month. However, this project required a six-month deployment—a record for a shallow-water (about 15 meters below the surface) ESP deployment both in terms of the length of time the instrument had to operate on a fixed number of batteries as well as the length of time samples needed to be preserved before retrieval. Those achievements were made possible by new software control and power management developments carried out by MBARI over the past year, and sample preservation experiments carried out at Scripps. The material collected will be subjected to genetic analyses to determine what microbial species were present, how that population changed over time in response to changing environmental conditions, and how those patterns relate to changes in patterns of gene expression. This project was supported by the Gordon and Betty Moore Foundation.

MBARI scientists and engineers continue to advance ESP technology to enable its use on autonomous underwater vehicles (see page 43). The goal is to provide a new means of detecting and following dynamic features in the ocean that are hotspots of biological activity, and then triggering sample acquisitions without necessarily requiring human intervention. These collaborations provide a means for transferring technology developed at MBARI, and the insights gained from those efforts, to the greater oceanographic community.

Unraveling the mysteries of bioluminescent organisms

After centuries of research on bioluminescence—the ability of organisms to make light—many fundamental questions still remain unanswered: How many times has the luminescent capability arisen and in which organisms? What still-unknown chemicals power the ability to make light? What are the genes required to become luminescent? In what ways do luminous animals use the light?

Answering these questions would allow scientists to better understand the factors controlling changes in deep-sea communities, enhance the understanding of the evolutionary history of animal life, and reveal connections that drive oceanic community interactions. The understanding of bioluminescence can also help in the development of instruments for taking a rapid census of ocean life and provide powerful tools for biotechnology and biomedical research.

Recent technological advances, including genome sequencing and low-light color cameras, have allowed Scientist Steven Haddock and his team to make progress in addressing many of these issues. Using deep-diving submersibles, they have been able to collect organisms in pristine condition, leading to the discovery that many species that were thought to be non-luminous can actually make light. These species are found within a wide range of animal groups including sea anemones, pteropods (swimming snails), arrow worms, doliolids (swimming barrels), siphonophores, and several types of swimming polychaete worms (Figure 13). Only by recovering animals that are healthy and relatively undisturbed were the researchers able to observe these natural abilities. These breakthroughs led scientists to determine that more than three quarters of the midwater animals are capable of bioluminescence. The team also found that all the species in a certain group of siphonophores use bioluminescence to lure fish as prey. As part of this work, Haddock and his colleague Philip Pugh gave new names to two of these animals, including *Erenna sirena*, which was the first found to perform such behavior (Figure 14).

With so many undocumented glowing creatures, mysteries abound about the chemicals and proteins they use to make light, many of which are new to science. The team investigated one of the most interesting of these, a swimming worm called *Tomopteris*, which emits golden yellow sparkles of light instead of the more typical blue-green. By extensive purification and precise molecular characterization, collaborator Warren Francis determined that the yellow of *Tomopteris* comes from a unique molecule that was not known to have light-related functions in other animals. Because it is one of the only luminous reactions in the sea known to make yellow light, this molecule could lead to new avenues of chemical research (Figure 15).

In contrast to the unknown chemistries, the most common light emitter is a molecule called coelenterazine. Surprisingly, the team has shown that many unrelated organisms, like jellyfish, single-celled plankton, shrimps, fishes, some worms, even the vampire squid, all use coelenterazine. This is at least partially explained

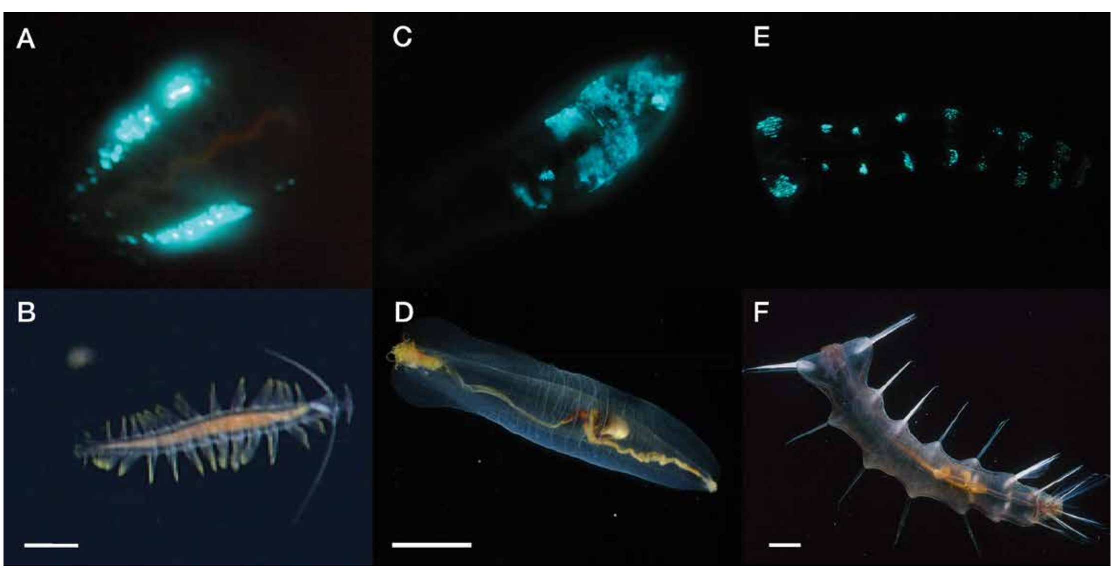

Figure 13. Polychaete worms from as deep as 3,500 meters were found to be able to produce bioluminescent light (top row), but the chemistry of these light emissions is still unknown. A,B are Tomopteris *(blue-emitting form), C,D, are* Poeobius *(one of top two most common annotations in the whole database), and E, F are* Flota*. Scale bars are one centimeter and apply to upper and lower pairs.*

Figure 14. Five species of deep-sea siphonophores in the genus Erenna *(approximately 45 centimeters long), including two new to science, were found to use bioluminescent lures dangling from their tentacles to attract fish. In the deep ocean, where prey can be scarce. Adaptations like this help seemingly simple organisms use sophisticated methods to thrive.*

by dietary links, as organisms gain the necessary chemical from the prey they consume. But this powerful molecule has to be generated somewhere, and the team set out to determine how.

The chemicals that make light ultimately originate from processes encoded in an organism's DNA. By sequencing genomes (organisms' complete sets of genes) and transcriptomes (those genes expressed at a given moment), one can search for the genetic pathways that convey luminescence ability. So far the transcriptomes from jumbo squid, vampire squid, more than 30 comb jellies, and dozens of jellyfish have revealed many of the necessary proteins that these organisms use in their bioluminescent displays. But the most engaging quest is to find the genes that synthesize the ocean's most popular light-emitting substance, coelenterazine. None of the genes encoding for such a substance in a marine animal has yet been found, so success in this regard could lead to major biotechnological breakthroughs including the ability to use a luminous glow to light up processes that are happening inside cells or tumors.

Another technology that has helped MBARI scientists tackle new areas of luminescence research is the application of ultra-sensitive color cameras capable of recording natural behaviors at ultra-high resolution down to depths of 4,000 meters. This ability to document displays at a sensitivity comparable to that of the human eye was impossible even five years ago. Now Haddock and colleagues can document behaviors that scientists have only witnessed in a fleeting moment, while huddled at the tiny port-hole of a submarine. This technology should help researchers test their ideas about how organisms are using their biological light in their own ever-dim environment. Up to this point, much of the knowledge of the behavior of deep-sea animals comes from piecing together a series of speculative stories. With a better understanding of how organisms interact using light, whether in finding food or finding mates, researchers can better predict how changes in organism distributions will affect the fate of the many interconnected species in the sea.

This is an exciting era to be examining bioluminescent creatures; researchers are gradually unveiling a peek at the mysteries of this enigmatic capability that is so common among the majority of organisms living in the deep sea.

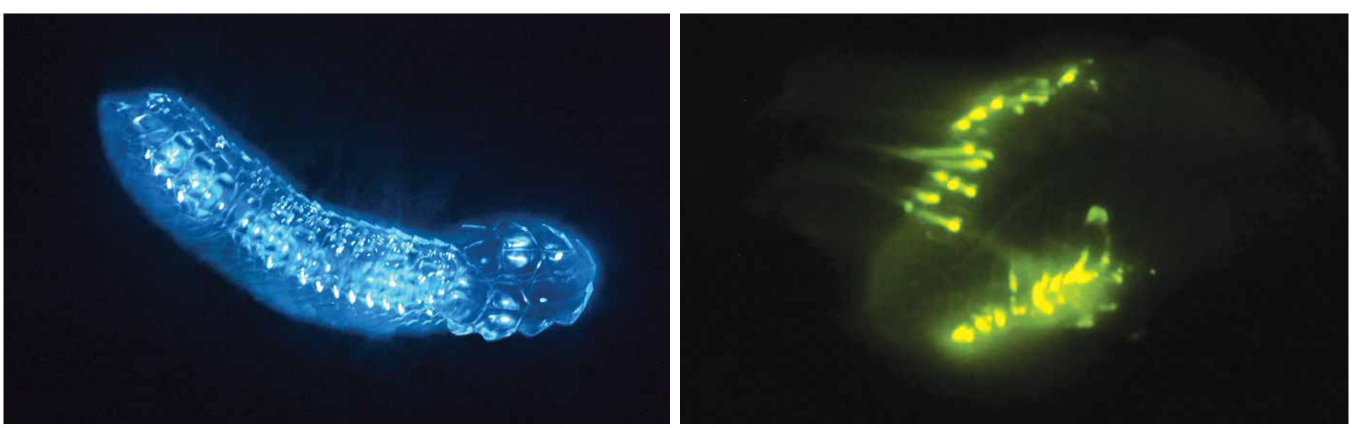

Figure 15. Luminescence from most organisms in the ocean, including the siphonophore Frillagalma *shown at the left, is blue, but the worm* Tomopteris *makes a brilliant golden glow.* Frillagalma *are an average of 12 or 13 centimeters long.* Tomopteris *ranges in size from eight to 50 centimeters long.*

Hosting ocean engineers from around the world

Monterey provided a window to the world of ocean science, engineering, and policy with the local hosting of the international Oceans 2016 conference. Senior Research and Development Engineer Bill Kirkwood co-chaired the event, along with Associate Director Jill Zande of the Marine Advanced Technology Education (MATE) program, based in Monterey. The annual event is sponsored by the Marine Technology Society and the IEEE's Oceanic Engineering Society.

Figure 16. MBARI hosted a booth in the Oceans 2016 exhibit hall.

The four-day event featured 130 exhibitors, 11 tutorials, eight workshops and special sessions, 20 student posters, and a record number of abstract submissions resulting in 510 technical presentations. Total conference registration also set a record at just under 1,400 in total attendance. MBARI staff helped organize the conference and staffed a booth in the exposition hall (Figure 16). A number of MBARI researchers also gave talks or presented tutorials and the chair of MBARI's Board of Directors, Julie Packard, welcomed the attendees to a special evening event at the Monterey Bay Aquarium (Figure 17).

Figure 17. Julie Packard, executive director of the Monterey Bay Aquarium and chair of the MBARI Board of Directors, welcomes conference attendees during a gala held at the aquarium.

Related web content:

Acoustic spectrogram animations: www.mbari.org/at-sea/cabled-observatory/mars-science-experiments/mars-hydrophone-data
NOAA Ocean Noise Strategy Roadmap: cetsound.noaa.gov/road-map
Video of ESP mooring: youtu.be/wW7tNITWV-o
Washington ESP data: www.nanoos.org/products/real-time_habs
Woods Hole ESP data: science.whoi.edu/esp/fieldcelldat
MARS Observatory: www.mbari.org/at-sea/cabled-observatory
Oceans 2016: www.oceans16mtsieeemonterey.org
Bioluminescence: biolum.eemb.ucsb.edu

Project Teams:

Ocean Chemistry of Greenhouse Gases

Project leads: Peter Brewer, William Kirkwood
Project manager: Edward Peltzer
Project team: Denis Klimov, Paul McGill, John Ryan, Farley Shane, Peter Walz, Matthew Wojciechowicz

Monterey Bay Time Series

Project lead: Francisco Chavez
Project manager: Tim Pennington
Project team: Marguerite Blum, Jules Friederich, Brent Jones, Monique Messié, Reiko Michisaki, Kathleen Pitz, Erich Rienecker, Jeff Sevadjian, Chris Wahl

Soundscape Research and Education

Project leads: T. Craig Dawe, John Ryan
Project manager: John Ryan
Project team: Danelle Cline, David French, Kevin Gomes, Ken Heller, Mathieu Kemp, George Matsumoto, Paul McGill, Yanwu Zhang
Collaborators: Andrew DeVogelaere and Lisa Uttal, Monterey Bay National Marine Sanctuary, Monterey, California; John Joseph and Tetyana Margolina, Naval Postgraduate School, Monterey, California; Brandon Southall, University of California, Santa Cruz; Alison Stimpert, Moss Landing Marine Laboratories, California

Sensors: Underwater Research of the Future

Project lead: Chris Scholin
Project manager: James Birch
Project team: Holly Bowers, Kevin Gomes, Scott Jensen, Roman Marin III, Doug Pargett, Christina Preston, Brent Roman, John Ryan, William Ussler III, Kevan Yamahara
Collaborators: Andrew Allen, Scripps Institution of Oceanography, La Jolla, California; Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Thierry Baussant, International Research Institute of Stavanger, Norway; Alexandria Boehm, Center for Ocean Solutions, Stanford, California; Laurie Connell, University of Maine, Orono; Tim Davis, Great Lakes Environmental Research, Ann Arbor, Michigan; Edward DeLong and David Karl, University of Hawaii, Manoa; Gregory Doucette, NOAA, National Ocean Service, Charleston, South Carolina; Clement Furlong, University of Washington, Seattle; Kelly Goodwin, Southwest Fisheries Science Center, La Jolla, California; Dianne Greenfield, University of South Carolina, Columbia; John Griffith and Steve Weisberg, Southern California Coastal Water Research Project, Costa Mesa; Steven Hallam, University of British Columbia, Vancouver, Canada; Ron Kiene, University of South Alabama, Mobile; John Mickett, Applied Physics Laboratory, University of Washington, Seattle; Stephanie Moore, Northwest Fisheries Science Center, Seattle, Washington; Mary Ann Moran, University of Georgia, Athens; Cody Youngbull, Arizona State University, Phoenix

Zooplankton Biodiversity and Biooptics

Project lead: Steven Haddock
Project manager: Lynne Christianson
Project team: Séverine Martini, Darrin Schultz, Jacob Winnikoff
Collaborators: Anela Choy and Bruce Robison, MBARI; Casey Dunn, Brown University, Providence, Rhode Island; Warren Francis, Ludwig Maximilian University, Munich, Germany; Claudia Mills, Friday Harbor Labs, University of Washington; Yuichi Oba, Chubu University, Kasugai, Japan; Phil Pugh, National Oceanography Centre, Southampton, United Kingdom; Joseph Ryan, Whitney Labs, University of Florida; Erik Thuesen, The Evergreen State College, Olympia, Washington; Ilia Yampolsky, Russian Academy of Sciences, Moscow; Paul Yancey, Whitman College, Walla Walla, Washington

Oceans 2016

Conference Co-Chairs: William Kirkwood, MBARI and the Oceanic Engineering Society, Jill Zande, Marine Advanced Technology Education
MBARI Oceans 2016 Monterey Team: Doug Au, Kevin Gomes, Cindy Hanrahan, Rich Henthorn, Brett Hobson, Brian Kieft
Organizing Committee: Brian Bingham and Jeffrey Paduan, Naval Postgraduate School, Monterey, California; Matt Gardner and Deidre Sullivan, Marine Advanced Technology Education, Monterey, California; Liesl Hotaling, Stevens Institute of Technology, Hoboken, New Jersey; Chris Kitts, Santa Clara University, California; Erika Montague, OceanGate, San Francisco, California; Mike Pinto, Retired, Monterey, California; Brock Rosenthal, Ocean Innovations, La Jolla, California; Jake Sobin, Kongsberg Underwater Technology, Washington D.C.

Expeditions

Field expeditions far from Monterey Bay give MBARI staff a chance to explore unfamiliar territory and delve deeper into investigations that are not possible to stage close to home. In 2016, expeditions also strengthened our collaborations with external research organizations locally and as far away as the Great Lakes and the Canadian Arctic. While some of these forays involved sending our own research vessels far afield, others made use of our portable robotic vehicles that were packed up and sent off to work from our collaborators' facilities and ships.

Geological surveys of the changing Arctic edge

MBARI's mission to develop and apply novel marine technologies is substantially enhanced via international research collaborations. In the fall of 2016, the institute's autonomous underwater vehicle (AUV) and small remotely operated vehicle (MiniROV) teams participated in an expedition with Canadian researchers to advance studies of geohazards and geologic processes on the little-studied seafloor of the Arctic Ocean.

The cruise on the Canadian Coast Guard Icebreaker *Sir Wilfrid Laurier* (Figure 18) was a continuation of an ongoing collaboration with colleagues from the Geological Survey of Canada and Fisheries and Oceans

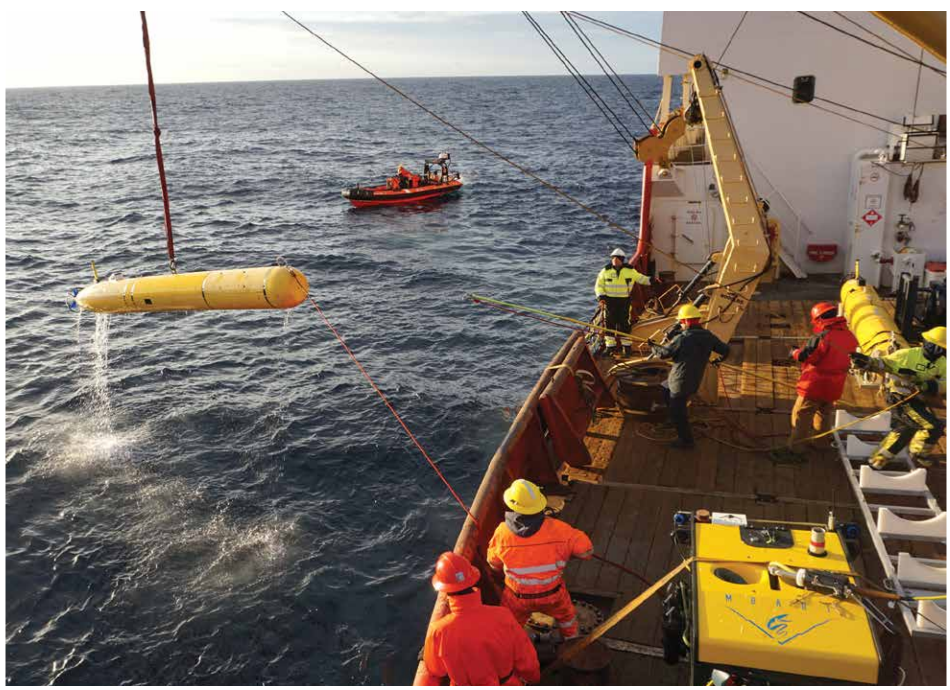

Figure 18. A mapping AUV is recovered after a seafloor survey. The second mapping AUV and the MiniROV are on the deck of the Canadian Coast Guard Ship Sir Wilfrid Laurier.

Canada, to learn more about the Canadian sector of the Beaufort Sea (Figure 19). Scientist Charlie Paull, who has now made five trips to the Arctic, was the MBARI lead investigator for the project.

Historically, most of the Canadian Beaufort Sea was covered in ice year-round and was one of the least accessible and explored regions on Earth. Bathymetric maps of this area, drawn from the widely spaced survey lines, were of very coarse resolution. Less than a decade ago essentially nothing was known about the specific character and potentially unique processes that shape the seafloor on the margin of the Beaufort Sea. However, sea ice extent in the Beaufort Sea has declined dramatically in the past decade and the sea surface above the shelf edge and upper continental slope between water depths of 100 and 2,000 meters are now often ice-free in the early fall. The reduction in ice cover due to global warming is making access to the Arctic easier, which will inevitably increase human activities in this area. Thus, it is increasingly important for scientists to explore the region to document baseline conditions before human interference complicates the picture, and to provide a basic understanding of this environment and current geologic processes for facilitating management decisions.

Starting in 2009, industry, government, and academic groups have conducted systematic detailed bathymetric mapping surveys of the Beaufort Shelf. These new regional bathymetric maps revealed a remarkable collection of unusual seafloor morphologic features (including extensive slide scars; large formations called mud volcanoes where mud or slurries, water, and gases were exuded from the seafloor; and numerous circular push-up features). MBARI became involved in efforts to explore this further in part because of the institutional focus on developing robotic instruments capable of making the type of detailed measurements required. In addition, it provided an excellent opportunity to further our understanding of the processes that shape portions of the Arctic seafloor, and to assess whether those processes are unique to that setting.

MBARI's technological contributions to this collaborative endeavor began with ROV operations (in 2003 and 2010) to observe the seafloor and to sample gas-venting features. That work was expanded in 2012 to include the MiniROV, a relatively small ROV developed in part with support from the Canadian government, that was specifically designed for work in this area. The efforts conducted through 2012 showed that gaseous methane was escaping from the shelf, which is likely sourced from the thermal warming of the decomposing relict submarine permafrost and other gas-bearing materials under the shelf. In 2013 MBARI's participation was augmented with the combined operation of the MiniROV and a mapping AUV. In 2016 MBARI's contribution to this program was expanded further with the simultaneous operation of the MiniROV and two mapping AUVs. Coordinating the operations of three vehicles on a ship of opportunity required skillful work on the part of both the AUV and ROV teams led by Hans Thomas and Dale Graves.

The international research team focused its two most recent expeditions on assessing the origin and mechanics of submarine landslides and the environmental setting and activity of mud volcanoes. The MBARI AUV surveys were the cornerstone of the program collecting one-meter horizontal resolution bathymetry, seafloor reflectivity, and sub-bottom profiles of selected areas. In total, 10 AUV dives were undertaken. Four of these were conducted to repeat surveys of features studied in 2013 to assess changes in seafloor bathymetry or near-surface geology indicative of very recent mud volcano activity. The MiniROV was used as a strategic tool to ground-truth the AUV images and explore intriguing features in detail as well as collect new information on the geology and benthic habitats in these unique settings.

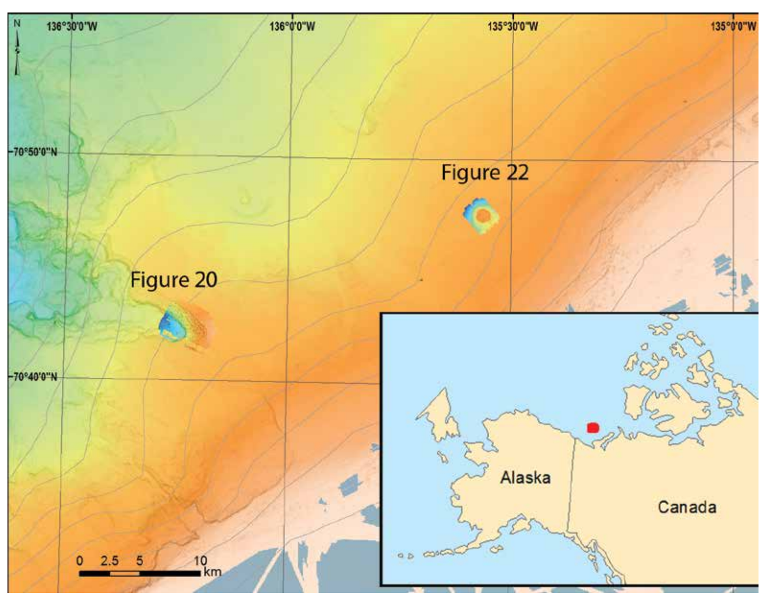

Figure 19. Large map shows location of the detailed surveys in Figures 20 and 22 and the inset map shows the survey area with respect to North America.

While scars associated with submarine landslides occur on many continental margins, the extent of landslide scars on the flanks of the Beaufort Sea is exceptional. New bathymetric maps collected from ships revealed that the entire lower continental slope below 1,200 meters is marked by submarine landslide scars and, in places, the scars of the slope failures extend up to the shelf edge. The question is: what makes this area so vulnerable to landslides?

Detailed bathymetric surveys, collected with AUVs, were conducted in three small areas within a coalesced slide scar complex along the shelf edge to help discern the processes associated with these slope failures (Figure 20). The slide scar structure was more than 50 kilometers long. The headwalls of these scars contain staircases of rotated blocks, which apparently failed along a discrete, presumably weak, subsurface horizon. The "freshness" of the geomorphology, interpreted from the high angularity of the rotated blocks, and the absence of a cover of sediment on the surface of the scars suggests the failures occurred since the last glaciation (approximately 10,000 years ago) and possibly much more recently. In geologic terms, this indicates this section of the Arctic margin is unusually dynamic.

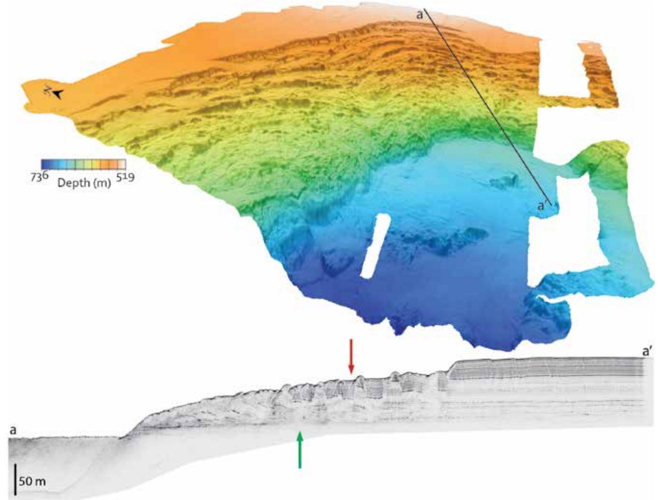

Figure 20. A perspective view of the seafloor bathymetry shows the headwall of a landslide scar. Below a sub-bottom profile of the section a-a' illustrates rotated blocks overlying the slide plane (red arrow) and failure surface (green arrow).

Areas where the collapsed subsurface horizon projects out onto the seafloor were the targets of MiniROV exploration. Multiple mounds were associated with distinctive orange iron-oxide-rich sediment (Figure 21) and venting; shimmering waters were observed above the mounds in water depths of about one kilometer. In shallow waters, such stains are known to characterize submarine brackish-water springs (less salty than the surrounding seawater). The shimmering waters indicate active fluid flow emanating from the seafloor. This is the first documentation of brackish fluid flows seeping from the seafloor in such deep water. Interestingly, the presence of brackish waters in the seafloor sediments has also been detected in sediment cores collected over the course of all cruises conducted along this margin, which suggests that such occurrences are widespread on the Beaufort slope. Evaluating the potential connection between the infusion of brackish waters derived from decomposition of permafrost and extensive occurrence of submarine landslides is a topic of ongoing research.

While submarine mud volcanoes are known to occur along many active continental margins, they are less common on passive margins such as in the Beaufort Sea where tectonic compression between colliding plates is not a driving force. Thus, the processes that occur on and build submarine mud volcanoes are poorly known, and it is usually hard to know whether they are still active. AUV surveys of the two mud volcanoes that were previously mapped in this area in 2013 were repeated, and a third mud volcano was mapped for the first time (Figure 22). Software Engineer David Caress processed the new data, which show the fine-scale shape of the mud volcanoes in exquisite detail. Comparison of the maps from the repeat surveys conducted three years apart show obvious bathymetric changes, indicating multiple eruptions have occurred between 2013 and 2016.

Figure 21. This image of a seafloor mound associated with a distinctive orange stain was taken with the MiniROV at a depth of about one kilometer. Shimmering water was observed rising from the seafloor at this and other similar mounds. (Area in the image is about 75 centimeters wide.)

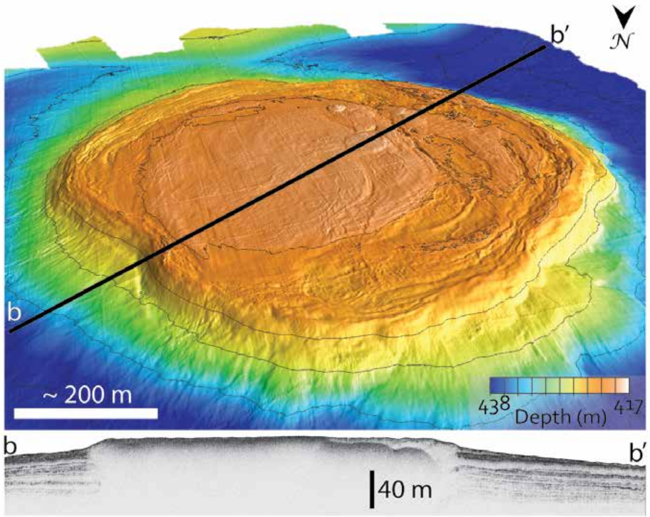

Figure 22. A perspective view showing the seafloor bathymetry of a nearly flat-topped mud volcano mapped with the AUV. Below a sub-bottom profile b-b′ shows the structure across the top of this mud volcano.

Figure 23. The MiniROV took this image of a tongue of a mudflow (rough surface texture extending from upper left to lower right), which was observed flowing downslope on the flank of a mud volcano. At the time this image was collected, the thermal probe mounted on the arm was inserted about two centimeters into the flow, with the MiniROV and its arm held stationary. A wake of smoother sediment developed downstream of the probe as the mud flowed slowly around the probe. (Area in the image is about 27 centimeters wide.)

During a MiniROV dive to investigate the nature of these changes, an active mudflow was encountered—a tongue of mud could clearly be seen moving slowly down the side of one of the mud volcanoes' flanks (Figure 23). Measurements made with the MiniROV showed the flowing mud had a temperature of 23 degrees Celsius (compared to ambient water of about 0.4 below zero Celsius), indicating that the material had recently ascended from considerable subsurface depths. Bubbles (presumably composed of methane) were observed to be emanating from the active mudflow. This is likely the first time an eruption of a submarine mud volcano has been recorded in the Arctic.

The results of MBARI's ROV and mapping AUV operations during five short cruises to the Arctic have provided invaluable insight into the processes occurring on the margin of the Beaufort Sea. This section of the Arctic seafloor has progressed from being almost unknown to having some of the best-surveyed submarine features in the world.

An undersea volcano proves to be an ideal study site

Having a frequently erupting submarine volcano within the reach of MBARI's research vessels allowed several breakthroughs in recent years for Scientist David Clague and his Submarine Volcanism Group. The team focuses on investigating how submarine volcanoes work in order to improve understanding of the hazards they and terrestrial volcanoes might pose. On a broad scale, submarine volcanoes, such as Axial Seamount on the Juan de Fuca Ridge, provide an excellent setting to study volcanoes in general because the magma storage reservoirs and plumbing of the volcano are simpler and much better imaged using seismic techniques than those of even well-studied volcanoes on land, such as Kilauea in Hawaii. Axial Seamount is now perhaps the premier site to study how volcanoes work because it is frequently active, with eruptions in 1998, 2011, 2015, and another eruption expected in 2019 to 2020. It is also well instrumented with cabled real-time seismometers and deformation sensors through the Ocean Observatories Initiative (Figure 24).

Clague's group has been documenting Axial's eruptive history since first collecting shipboard bathymetry soon after a 1998 eruption. Subsequent visits, coupled with AUV bathymetry data and ROV-collected sample analyses, have allowed the team to determine the extent of new lava flows after several eruptions. Repeated mapping of the area—increasingly detailed due to improvements in the technology—helped to accurately define the area and volume of the lava flows. Before and after maps provide detailed information about the 1998 and 2011 eruptions, and showed that new flows reuse many of the same fissures as earlier eruptions and that the lava is distributed downslope using many of the same flow channels.

Just a few years later, in late April 2015, Axial Seamount erupted yet again, this time from fissures extending 17 kilometers to the north from near the same area where the 1998 and 2011 eruptions had begun but progressed south. The 2015 flows are much more

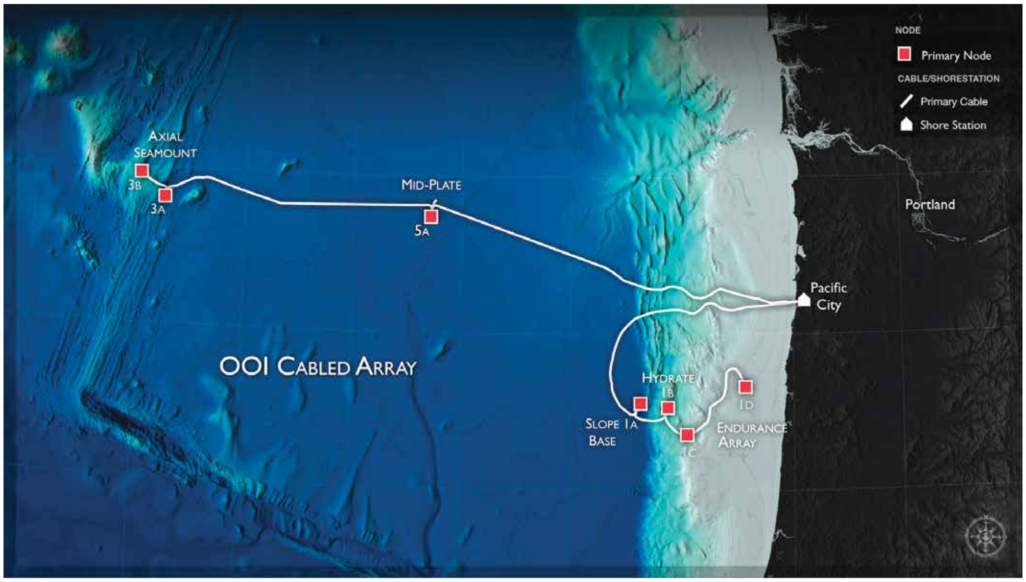

Figure 24. The Regional Science Node of the Ocean Observatories Initiative supports sophisticated observatories at Axial Seamount and Hydrate Ridge, with suites of instruments both on moorings and served by a cable from shore. A diverse array of geophysical, chemical, and biological sensors, as well as cameras, provide real-time information from this site.

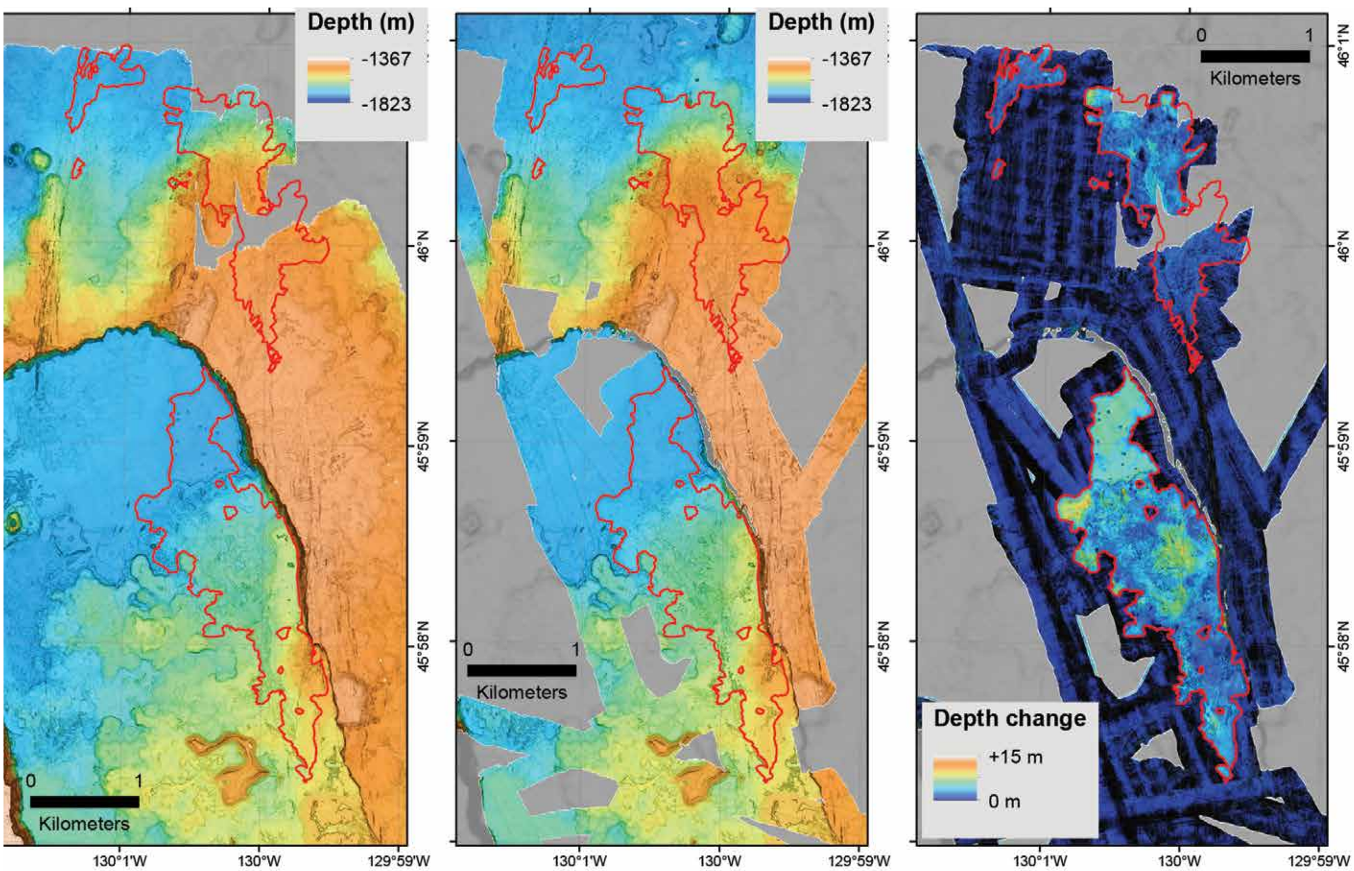

Figure 25. The three panels show the bathymetry prior to the 2015 eruption (left), after the 2015 eruption (middle), and the difference, colorized with a scale of just 15 meters, between the before and after maps. Almost all the flows in and near the summit caldera are less than 10 meters thick and many are just one to two meters thick. Without high-resolution AUV data before and after the eruption, such thin flows would be very difficult to map. The outlines of flows erupted in April and May 2015 are shown in red.

voluminous than either of the prior historical eruptions and the eruption lasted much longer, about a month compared with about a week. The new flows near the summit covered areas MBARI had mapped in prior years, so these flows could be determined in great detail and their volume calculated (Figure 25), once a post-eruptive survey was completed by Woods Hole Oceanographic Institution, and the new data were processed at MBARI.

The largest portion of the lava was erupted along the north rift zone where slow, steady eruption produced flows up to 125 meters thick. Unfortunately, the only maps of this region prior to the eruption have low resolution and many details of the flows are not as well established by comparing with those mapping data. However, remotely operated vehicle observations of flow margins were used to ground-truth the extent of the flows determined from the mapping data (Figure 26).

The 2015 eruption was characterized by several tens of thousands of explosive noises that were apparently caused by steam explosions that fragmented pillow lavas (Figure 27), which then define which parts of the lava field were active at different times. Exploded pillows were rare in flows erupted in 1998 and 2011 and in prehistoric flows.

The 2015 eruption provides the first opportunity to connect what happens at the seafloor, such as where the lava flows erupt and what their compositions are, with the structure of the magma reservoir. The eruption tapped into two discrete parts of the magma system: a southern portion that consists mostly of hotter melt and a northern portion that consists of slightly cooler slurry of crystals and melt.

Figure 26. The 2015 black pillow lava flow is evident on top of older flows sprinkled with thin sediment. Such contacts are easy to map from the ROV when fresh, but the sharp distinctions fade quickly and become difficult to identify after just a few years. (Area in image is about 2.5 meters wide.)

Figure 27. This pillow lava was shattered by a steam explosion during the 2015 eruption. Tens of thousands of explosive sounds were recorded during the eruption that were most likely the sounds of explosions such as this. (Area in image is about one meter wide.)

In 2016, two MBARI mapping AUVs were deployed simultaneously for 13 surveys to map the entire extent of the new flows on the north rift zone and to collect additional high-resolution maps of the middle and deep south rift zone in anticipation of the next eruption. When Axial next erupts, these surveys will provide pre-eruptive high-resolution maps to enable detailed analysis.

In addition to mapping the details of the new lava flows, the high-resolution AUV data can also be used to map relative vertical changes of the volcano over time that accompany accumulation of magma at depth, causing uplift of the summit, and emptying of the magma reservoir during eruptions, causing subsidence. These vertical changes are on the order of a few meters and are usually measured using changes in water pressure at a few pressure sensors deployed on the bottom and wired to the cabled observatory, or using a pressure sensor carried from benchmark to benchmark using an ROV every few years. The in situ instruments, like all sensitive instruments, are prone to drift that makes them good at determining *when* dramatic changes take place (such as those caused by evacuation of the magma reservoir during an eruption), but not as sensitive to the slow inexorable uplift caused by accumulation of magma between eruptions.

The high-resolution bathymetric data from the MBARI mapping AUV provide a regional look at the size and shape of the entire edifice as it uplifts and subsides. With careful processing, so the difference maps exclude any areas with new lava flows and the two data sets are registered precisely, the difference map from 2015 (a few months after the eruption was over) and a year later in 2016 show that the pattern of uplift and subsidence is much more complex than could be determined using a few in situ instruments. The data also show that either the sensor in the central caldera is drifting or the site used as a zero uplift/subsidence point is not actually vertically stationary. When the next series of benchmark measurements are made in summer 2017 and the AUV survey is repeated at the same time, we should be able to determine if any of the benchmarks are vertically stable and what the overall pattern of surface deformation looks like. That in turn will lead to a much-improved understanding of how magma enters and moves between the melt and the crystal slurry parts of the summit reservoir.

In the long run, what is learned at Axial Seamount should lead to improved understanding of the behavior of more hazardous volcanoes on land and a reduction in the risks they pose.

Keeping a close eye on a spectacular deep-sea coral garden

Sur Ridge, an underwater mountain about 37 kilometers (23 miles) west of Point Sur, is one of the few locations within the Monterey Bay National Marine Sanctuary (MBNMS) where deep-sea corals have been discovered (Figure 28). A team of researchers led by MBARI Scientist Jim Barry and MBNMS Research Coordinator Andrew DeVogelaere returned to Sur Ridge twice in 2016 to further understand the life forms in this deep-sea habitat. The researchers first discovered these coral and sponge communities (Figures 29, 30, and 31), including forests of bamboo corals unknown in other areas of the sanctuary, during exploratory ROV dives three years earlier.

Repeated dives in June and August using the ROV *Doc Ricketts*, equipped with high-definition cameras, sensors, and other tools, allowed the team to continue exploration of the ridge to determine where these coral and sponge assemblages occur in relation to physical and biological factors that may play key roles in regulating their distribution, abundance, and productivity. Are geological and oceanographic features the main determinant of the success of coral and sponge assemblages, or do biological factors, such as predation, also play key roles?

Since their earlier explorations at Sur Ridge, the researchers have been trying to understand why this area is such a favorable habitat for corals. In June 2016, they revisited corals they had marked two years prior and took video of them from the same angles as before. By comparing videos from past years and from more recent ROV dives, researchers hoped to determine changes in the coral colonies, including growth, aging, and the effects of predators or other damage. Because many coral species can live for centuries, the team also collected corals at different depths for radiocarbon dating to help determine their ages—are corals of the same size also equal in age, or do growth rates differ along the ridge? This information will help elucidate the potential longevity of individual corals as well as how growth and survival may vary within coral populations in this complex and poorly understood habitat.

Corals are passive feeders and rely on currents to guide food to their polyps—the small, soft-bodied organisms that make up coral colonies. Video surveys were also conducted with the ROV to assess the biological communities within various regions of Sur Ridge. These surveys, consisting of many 50-meter-long transects, were used to determine the community composition and abundance of corals, sponges, and associated species at each local site, and provide an indication of how these biological communities vary among sites at the ridge. The corals' main source of food is particles of organic material, so the researchers collected water samples to determine the amount of particulate

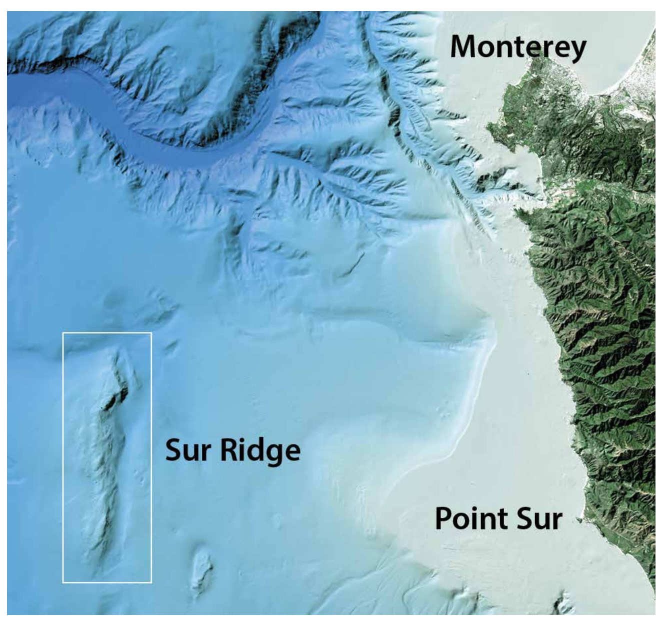

Figure 28. Sur Ridge is a seamount 37 kilometers off the California coast.

Figure 29. Corals like these long-lived pink bubblegum types (up to three meters tall) create important microhabitats for many other animals including crustaceans, basket stars, anemones, and fishes.

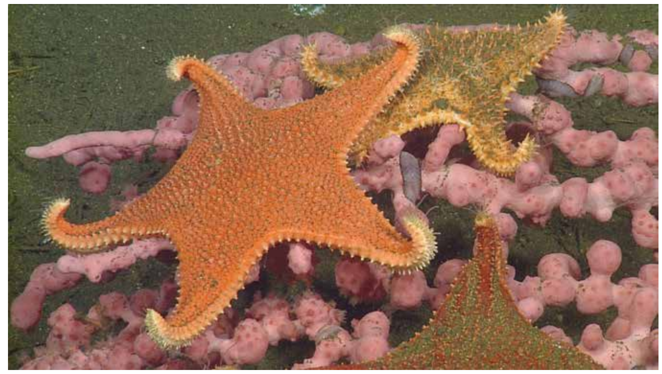

Figure 31. Corals also directly provide nutrition for some animals, like these sea stars (about 20 centimeters across), which eat coral polyps.

Figure 30. Pink snailfish (17 centimeters long) are relatively common at Sur Ridge, hiding amongst the abundant coral and sponge structure.

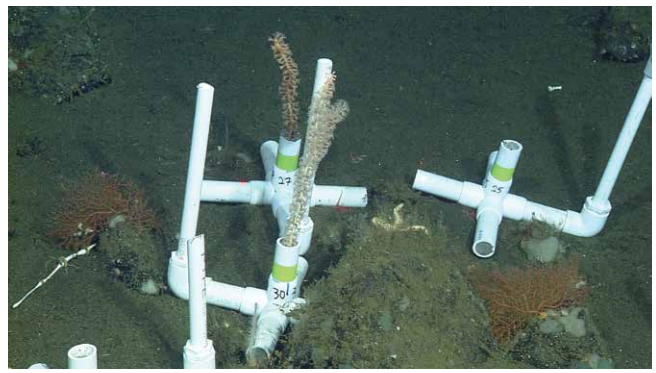

Figure 32. Previously placed bamboo coral transplants (tallest pipe about 30 centimeters) were revisited to evaluate methods for potential coral restoration efforts.

food available in the region and noted other biological factors such as predation. The researchers also measured environmental factors such as temperature, oxygen, current flow, and the topography and slope of the habitats to begin to understand the relative importance of factors allowing coral assemblages to thrive at Sur Ridge.

As a proactive effort to conserve deep-sea corals, Barry and DeVogelaere initiated experimental coral transplant studies at Sur Ridge to develop methods that might be used to restore barren areas impacted by human activities such as trawling or pollution. During the June expedition, they revisited the site of a transplant experiment they had begun about a year earlier. In this experiment bamboo corals were collected using the ROV, brought to the surface, planted into plastic pipes, and then returned to the seafloor. Upon returning one year later, no corals were found alive in the experimental garden (Figure 32). While the results were disappointing, science is a process of iteration and refinement. With that spirit in mind, Barry and his group revised their methods and set up a new experiment in the same area on the seafloor. When the team revisited this site 12 weeks later in August 2016, they were delighted to find that nearly all of the transplanted bamboo corals were alive and appeared to be very healthy.

Many unanswered questions remain concerning the deep-sea communities living at Sur Ridge. While the researchers have observed an abundance of coral and sponge gardens in the region, deep-sea corals are thought to be a fragile community sensitive to environmental change. Research at Sur Ridge is helping to clarify the roles that the region's geology, biology, and oceanography play in the diversity, abundance, and distribution of coral and sponge communities, as well as the potential threats posed by climate change, pollution, fishing practices, and other human activities. Conservation of this unique resource begins with understanding.

Figure 33. The MBARI long-range AUV team worked closely with the USGS staff to launch and recover the vehicle in Lake Michigan.

A long-range AUV provides comprehensive surveys of Lake Michigan plankton

A key MBARI research tool designed to study the ocean has proven to be just as valuable for studying a large shallow freshwater lake. MBARI's *Tethys* long-range autonomous underwater vehicle (LRAUV) travelled to one of the world's largest freshwater ecosystems—the Great Lakes—to help develop a new approach for much-needed ecological surveillance. Faced with questions about the health of the food web in Lake Michigan, the US Geological Survey (USGS) turned to MBARI to demonstrate Tethys's ability to observe and analyze plankton communities at various depths in the lake.

Ever since the introduction of several invasive species of clams, the water in the lake has progressively become as clear as a tropical sea, much to the delight of tourists. However, the foundation of a normal food chain in a water body like Lake Michigan should be based on the primary producers that not only cloud the water, but also provide food for fish, like sculpin, alewife, smelt and other baitfish, as well as Pacific salmon stocks.

The USGS Great Lakes Science Center has been monitoring plankton booms and busts using satellite imagery coupled with vessel-based surveys. *Tethys* was used in conjunction with these tools to expand the USGS data sets by providing an accurate depiction of plankton from the lake surface to 80-meter (260-foot) depths.

Software Engineer Brian Kieft and Mechanical Engineer Brett Hobson prepared for the mission by adjusting ballast and adding extra flotation devices to the LRAUV to work in the less-buoyant environment of the vast freshwater lake. They then shipped the vehicle to Michigan and soon began deployments (Figure 33).

Tethys was designed for extended endurance, enabling both persistent observing presence and long-distance exploration. For these studies of lake ecology, the AUV carried physical, optical, and acoustic sensors that together provided an interdisciplinary view of plankton populations and their environment. Plankton make up the base of marine and freshwater food webs, and phytoplankton play an important role in Earth's biogeochemistry by

Figure 34. LRAUV tracks through Lake Michigan.

absorbing carbon dioxide and producing oxygen. Data gathered by *Tethys* along tracks across the lake offered insight into Lake Michigan's planktonic food webs and provided useful information for both fisheries management and climate change studies (Figure 34).

Data were sent to shore in near real time. After the cruise, the data were uploaded and made available via MBARI's Spatial Temporal Oceanographic Query System (STOQS), an open-source software program that allows scientists to explore large data collections and visualize measurements in both space and time. Scientists could view data collected by *Tethys*, adjust the survey waypoints as desired, and reveal conditions offshore. The full-resolution data uploaded to STOQS proved to be more comprehensive than what traditional vessel-based observations yield (Figure 35).

The project successfully demonstrated how *Tethys*, an emergent technology, can expand the USGS's ability to observe plankton communities in the Great Lakes ecosystem. This project, the first survey of its kind ever conducted in Lake Michigan, is certain to yield new discoveries and valuable insight into this massive, yet still unresolved, freshwater ecosystem.

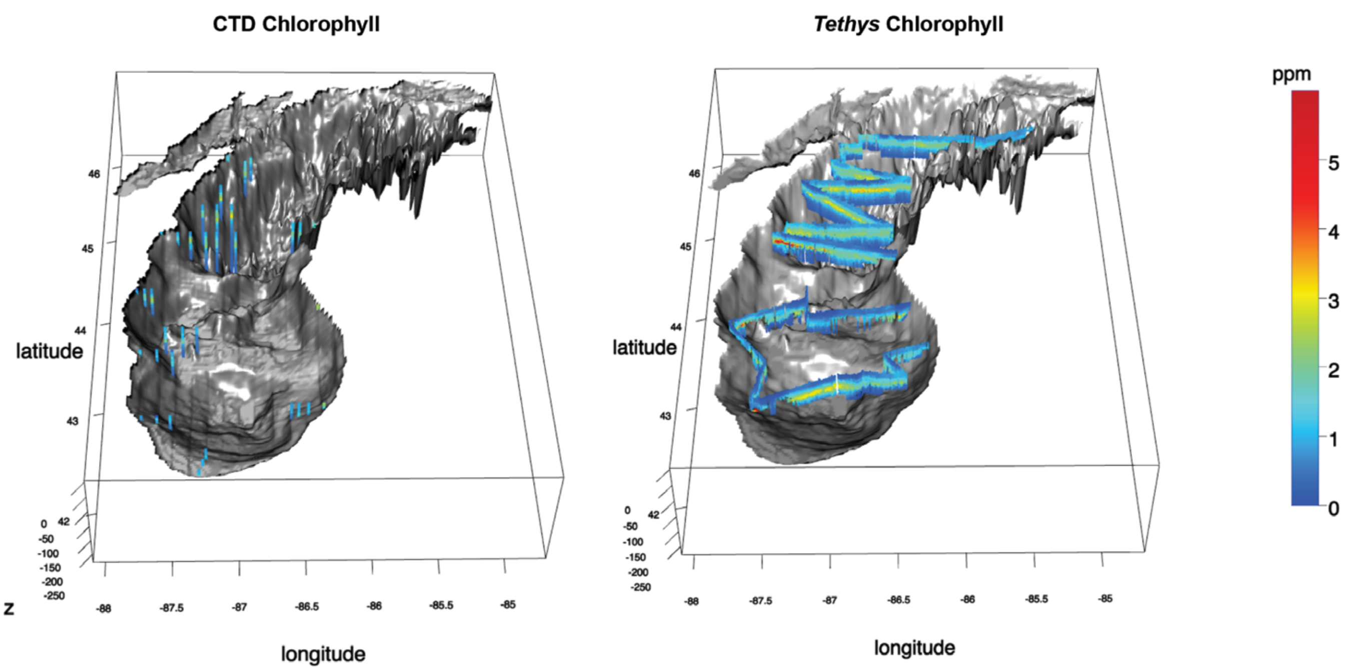

Figure 35. Three thousand data points for chlorophyll were collected from the ship (left), and 140,000 data points were collected from the LRAUV (right). The LRAUV also collected data on water backscatter, conductivity, temperature, density, oxygen, and photosynthetically active radiation.

Related web content:

Arctic expedition logs: www.mbari.org/at-sea/expeditions/canadian-arctic-2016-expedition

Axial Seamount Cruise logs: www.mbari.org/at-sea/expeditions/northern-2016-expedition

Great Lakes news: www.mbari.org/mission-to-the-great-lakes

Video of LRAUV recovery: www.youtube.com/watch?v=bXpyr0Tunjw

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Continental Margins and Submarine Canyon Processes

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Benthic Biology and Ecology

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Great Lakes Project

Project leads: Brett Hobson, Brian Kieft
Project manager: Brian Kieft
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Technology Push/Science Pull

Over the years it has become increasingly evident that technology developed for one purpose often finds application at MBARI in completely unexpected ways, enhancing a range of research projects that were never anticipated when the original engineering development was undertaken. MBARI's Technology Roadmap builds on that legacy by setting forth a path to improve instruments, methods, and systems to enable a new era of discovery. This "push" of new technology paired with the "pull" of cutting-edge scientific inquiry often leads to major, and sometimes unanticipated, breakthroughs. Here we pay tribute to our time-honored tradition of merging engineering development and marine science, and the interdisciplinary partnerships that make such work possible.

An autonomous video system to enhance midwater surveys

A new autonomous system is transforming the way researchers will perform video surveys in the ocean midwater in the future. For over two decades, MBARI researchers have conducted video transects of animals in Monterey Bay's mesopelagic region, the upper kilometer of the water column, using remotely operated vehicles (ROVs). These surveys contribute to one of MBARI's longest running research projects, which is aimed at understanding the species that live in the midwater and how their populations change over time. In addition to identifying and counting species, the researchers have collected corresponding environmental data such as oxygen content, temperature, and salinity of the bay. Results of these studies have revealed surprising changes

Figure 36. The i2MAP Midwater Imaging AUV is launched from the R/V Rachel Carson

Figure 37. Research Specialist Kim Reisenbichler, right, and AUV Group Leader Hans Thomas inspect the i2MAP AUV after a trial run. The camera is protected by a dome at the front of the vehicle.

in the midwater community as oxygen levels have changed and some species have been displaced from their historical niches. This work has provided important insights about how an amazingly complex web of life, far from the public eye, connects to iconic animals and commercially important species that typically garner a great deal of attention. How can we scale these types of observations so that they are not strictly reliant on having access to a dedicated ship and ROV? How can the technology be made more affordable for use by other ocean research and education institutions?

Under the leadership of Electrical Engineer Mark Chaffey and Research Specialist Kim Reisenbichler, the Investigations of Imaging for Midwater Autonomous Platforms (i2MAP) Project team set out to develop such a system by modifying an existing *Dorado*-class AUV to carry a robust, high-resolution, autonomous imaging system—an ambitious and challenging task. Their goal was to develop a platform that requires less human intervention, runs quieter, and takes higher quality footage than the ROV to enhance the collection of video data and to reduce the institutional resources required.

Since ROVs are deployed from a ship and require human operators during their entire mission, an AUV was an appealing platform for the i2MAP system (Figure 36). The AUV can be programmed to independently perform functions such as routine video surveys, freeing up the ship and personnel for other tasks such as experimentation and field tests of new technology.

Many ROVs are noisy and slow and emit more light than needed for midwater surveys. The noise and lights agitate some agile fishes, squids, and crustaceans that swim away when they sense an ROV approaching. However, the AUV is quiet, its light system is designed specifically for midwater surveys, and it travels faster, which helps reduce survey bias. Finally, the AUV is equipped with a state-of-the-art camera with the potential to upgrade to higher quality video formats in the future.

It has taken the project team four years of design work and testing to complete the first i2MAP AUV that meets their standards. Initial field trials of this system in 2015 produced observations that surpassed those from MBARI's ROVs, while moving at twice the speed of the ROV-based surveys. In 2016, the team focused on improving the robustness of the software and interface used to operate the AUV, and proving the durability of the innovative, pressure-tolerant camera dome design used to optimize the optics (Figure 37).

Life in the deep sea is enigmatic and difficult to observe over extended periods of time. MBARI's midwater project proves that videography is an invaluable tool for discovering how animals in that realm relate to environmental conditions and to each other. The trends observed from midwater surveys in Monterey Bay and elsewhere around the globe will help researchers reveal how midwater food webs in the ocean change in response to ongoing and future climatic alterations, and learn how such changes may impact human society. By exporting the i2MAP system, MBARI aims to provide a new asset for the oceanographic community to pursue that goal with lower costs and logistical constraints than present-day technologies afford.

Understanding the impacts of changing environmental conditions

Understanding the consequences of climate-driven alterations in ocean conditions for marine ecosystems and their societal impacts is increasingly important as the speed and magnitude of observed changes throughout the globe continue to rise. The burning of fossil fuels is increasing atmospheric concentrations of carbon dioxide, which in turn drives ocean warming, acidification (lower pH), and deoxygenation of deeper waters. Each of those changes alone or in combination can affect the survival and success of a host of marine organisms (see related story on page 4).

In the California Current Large Marine Ecosystem, coastal upwelling is becoming more frequent and persistent as the climate warms, causing potentially stressful conditions for some marine species. Upwelled waters are increasingly bathing coastal environments with more acidic and oxygen-poor waters as the deep waters are drawn to the surface. While marine ecosystems along the west coast of North America thrive on the nutrients that are injected into surface waters by upwelling, there is also a delicate balance between the potential benefits and liabilities of coastal upwelling for many species. Phytoplankton blooms fueled by nutrients provided by upwelling are a strong stimulus for coastal production throughout the food web, but if low oxygen and pH levels in surface waters are more stressful for key species that sustain important food webs, coastal fisheries may become increasingly vulnerable to future climatic shifts.

Figure 38. Intern Aileen San monitors abalone to see how they fare in different environmental conditions simulated in the laboratory.

Research on the influence of upwelling conditions on nearshore marine species is a focal point for Scientist Jim Barry's Benthic Biology and Ecology Group. While this sounds straightforward, there are a multitude of issues to consider. First, upwelling varies in both frequency and duration. Results from experiments have shown that juvenile abalones are sensitive to changes in the duration of upwelling conditions. For short periods, the animals are tolerant, but under extended upwelling, growth and survival suffer. Second, upwelling events off the California coast typically arrive with drops in sea temperature, oxygen, and pH. If marine animals are sensitive to such conditions, which factor or combination of factors is actually responsible?

Barry's team has developed a laboratory-based upwelling simulator to enable experiments that can disentangle the individual and combined effects of simultaneous changes in temperature, oxygen, and pH levels for various life stages of red abalone and other species (Figure 38). This simulator allows researchers to alter the oxygen, temperature, and pH of aquarium waters over short time scales (about 30-minute periods), comparable to normal upwelling off Monterey. But the simulator can also control the nature of upwelling-like conditions and can mimic a typical event with a drop in temperature, oxygen, and pH, or change conditions so that only one or two of these parameters change. In this way, researchers can test the response of species to a range of conditions, for example, simulating an upwelling event that does not include a drop in temperature or one in which oxygen rises rather than decreases (Figure 39). The simulator can

Figure 39. Scientist Jim Barry, left, and Research Technician Chris Lovera in the MBARI seawater laboratory, where the new simulation system includes the panel at right, the controls on the computer on the table, and the tanks, which are filled with abalone for an experiment.

also control the duration and magnitude of changes in water conditions. To allow experiments to be statistically rigorous, the simulator can control 15 separate tanks simultaneously (presently four are assembled and operational). Ultimately, the upwelling simulator will be a key tool in generating new understanding of the relationship between coastal ocean conditions, climate change, and ocean health.

The upwelling simulator prototypes have already supported studies to understand the influence of changing ocean conditions on the performance of individual species and interactions among coastal species. Red abalone in Monterey Bay were the basis of a thriving commercial fishery for decades before their populations crashed late in the last century. Studies using the upwelling system helped show that successful spawning of red abalone is impacted strongly by ocean acidification, but is unaffected by reduced oxygen levels, and is even improved by warming waters. Understanding such cause-and-effect relationships offers insights into what the future may hold under different environmental regimes.

The impacts of changing ocean conditions such as a shift in temperature or pH can vary greatly among species, and differential responses may then alter important interactions among co-occurring species. For example, shore crabs, juvenile abalone, and whelks (sea snails) are impaired to different degrees by ocean acidification and warming, and all are found together in California's coastal habitats. However, because shore crabs are highly sensitive to acidification and exhibit lower feeding rates and survival under low pH conditions, their predation on juvenile abalone or whelks is greatly reduced, with a net benefit to these molluscs.

A leap in understanding concerning the future health of marine ecosystems depends upon a combination of observations, measurements, and experimental studies that can clarify the influence of ocean change on the success of individual species as well as integrated marine communities. It has been relatively simple to assess the response of individual species to a change in temperature or other environmental factors. It is quite difficult to scale up such studies to generate an understanding of the influence of simultaneous changes in multiple environmental factors across vibrant assemblages of interacting species within diverse marine biological communities. The upwelling simulator and systems like it will allow researchers to address the complex environmental and ecological factors that are shaping the future of coastal marine communities.

Tracing plastics through the ocean food web

Plastic waste can be found in nearly all marine environments from surface waters to the deepest seafloor sediments. Ecosystem impacts from this widespread contamination include physical, biological, and chemical effects. The distribution and fate of plastics in the open ocean are poorly known even though these offshore waters comprise the largest living space on the planet. Communities of deep-sea animals form complex food webs that also yield food for humans, making it important to understand the patterns and processes by which these pollutants are distributed.

Microplastics (defined as smaller than five millimeters in diameter) are the most abundant types of plastic in the ocean, and may exert the largest ecosystem-scale effects due to their small sizes, pervasiveness, and potential for being ingested by pelagic organisms, ranging from zooplankton to large predatory fishes. To better understand what happens when midwater animals ingest and process microplastics, in situ feeding experiments were conducted with larvaceans in Monterey Bay. These studies were enabled by the development of the DeepPIV instrument at MBARI.

Larvaceans were chosen for these experiments because they are highly abundant filter feeders that can be found throughout the ocean. Each builds a complex mucus filter that forms a "house" in which the animal lives, and an inner filter that collects food particles from the water column. "Giant" larvaceans of the genus *Bathochordaeus* (from one to 10 centimeters long) are generally 10 times larger than other larvacean species, constructing mucus houses that can reach one meter in diameter. When the filters clog, giant larvaceans abandon their houses and then construct new mucus structures, usually on a daily cycle. Past work by MBARI scientists has shown that discarded *Bathochordaeus* houses sink rapidly to the seafloor and contribute significantly to the vertical transport of carbon to the deep sea. Recent efforts using DeepPIV at MBARI have measured filtration rates as high as 80 liters of seawater per hour for giant larvaceans, which comprise the highest reported rates of filtering by midwater organisms. Extending the filtration impact to the population level suggests that giant larvaceans have the potential to filter all of the seawater within their nominal depth range in Monterey Bay in as little as two weeks. Due to this extremely high filtering capacity and the similarity in size of microplastics and the larvacean's principal food sources, giant larvaceans may be one of the key marine species significantly concentrating, ingesting, and transporting these pollutants through the water column.

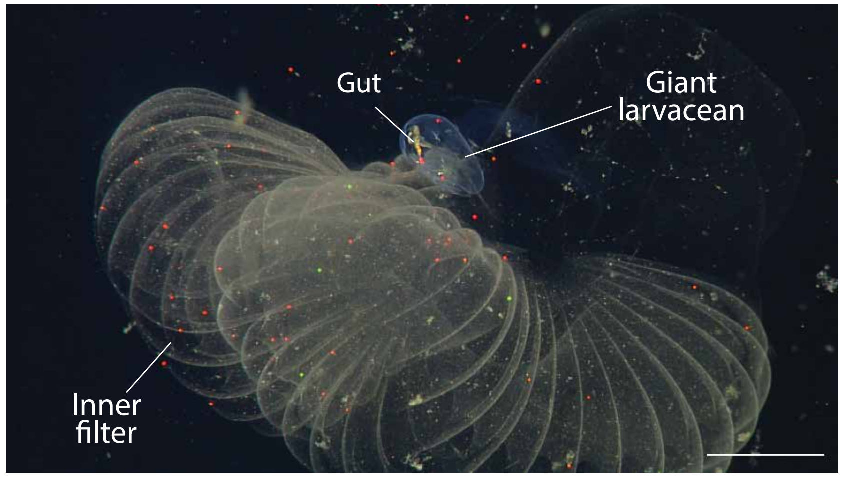


Figure 40. During feeding experiments, the colorful microplastics were observed inside and attached to the inner filter, and inside the gut of tadpole-shaped giant larvacean. Scale bar corresponds to two centimeters.

Since early 2015, a team of engineers and scientists led by Electrical Engineering Lead Alana Sherman and Postdoctoral Fellow Kakani Katija have been developing DeepPIV, an instrument that allows for the visualization and quantification of small-scale fluid motion. In 2015, DeepPIV was built and integrated on MBARI's smallest remotely operated vehicle (MiniROV). By the end of 2016, DeepPIV was integrated on all three of the institute's ROVs. In addition to camera and laser housings, DeepPIV was originally equipped with a dye injector, which was used to release fluorescent dyes to help visualize fluid motion. The dye injector was then modified to allow for the passage of microplastic particles for particle-injection studies. This modification enabled in situ feeding experiments of filter-feeding organisms, such as larvaceans, during subsequent midwater cruises with Scientist Bruce Robison and Postdoctoral Fellow Anela Choy.

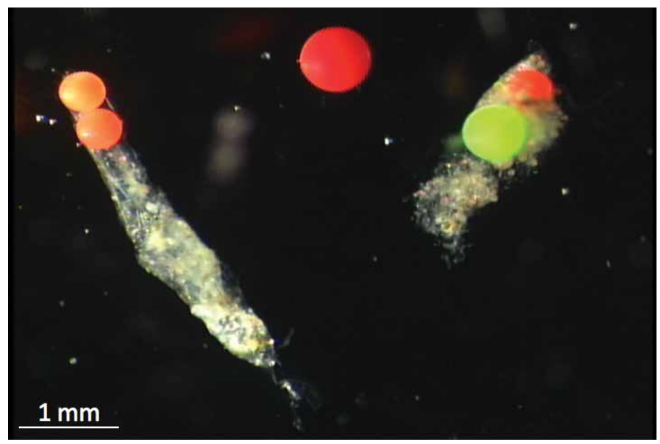


Figure 41. Collected giant larvaceans were maintained in an aquarium in a cold room. Their fecal pellets shown here unequivocally contained microplastics, proving such particles can pass through the animal and be moved to deeper waters.

In 2016 this team injected microplastic particles adjacent to the houses of actively feeding giant larvaceans (specifically *Bathochordaeus stygius*) to evaluate whether larvaceans ingest microplastics and to determine the size range of ingested particles. Microplastics were observed to enter the inner filters; the particles that did not attach to the mucus house were ingested (Figure 40) and later processed into fecal pellets (Figure 41). Unlike microplastics suspended in the water column, microplastic particles trapped within the collapsed filters of discarded *Bathochordaeus* houses and their fecal pellets would travel quickly to the seafloor. These relatively fast sinking rates (approximately 500 meters per day) would reduce the likelihood of interception, consumption, or degradation of the plastic particles during their descent.

Results from this work reveal a previously unknown and novel biological transport mechanism that could move large amounts of microplastics rapidly from shallow waters to the deep sea. Since discarded houses and fecal pellets of giant larvaceans (in addition to the larvaceans themselves) are widely consumed by other pelagic, midwater, and benthic animals, microplastics could be easily transported through marine food webs. A better understanding of the rates at which microplastics are concentrated by pelagic filter-feeders, and their sinking rates into deep water, is still needed to evaluate the overall impact of microplastics on marine food webs and nutrient cycling in the ocean. Fortunately, with technological developments at MBARI, including the DeepPIV, these topics can be addressed directly in ways that were previously impossible.

Persistence pays off

Changes and episodic events in the deep sea can have profound long-term effects on ocean health and global climate, but observing and recording these changes in remote locations are extremely difficult. Indeed, the need to develop new capabilities for establishing a persistent presence in the ocean, with an array of observing and sensing instruments throughout the water column is one of the stated goals of MBARI's Technology Roadmap. MBARI engineers and scientists are engaged in a variety of efforts to create this capability for studying a wide range of ocean phenomena.

In 2016, one MBARI team reached a major milestone in this pursuit of unattended, nonstop ocean monitoring when the Benthic Rover (Figure 42) and associated instruments completed a full year of unattended operations deep on the seafloor. The Rover had crawled across more than one and a half kilometers (about one mile) of seafloor, all the while taking pictures and collecting important environmental and biological data at the Station M research site—a flat, muddy area four kilometers deep and approximately 220 kilometers from the California coast (Figure 43). Operating in tandem with the Rover were a tripod-mounted time-lapse camera and a sensor that recorded sinking particles (Figure 44). MBARI Scientist Ken Smith relies on this information in his research on how life on the seafloor receives its food supply, and how a changing climate is affecting and being affected by life in the abyssal depths of the ocean.

Some of the Station M instruments measure sinking particulate organic carbon in the form of marine snow—bits of phytoplankton and zooplankton detritus, as well as fecal matter—that drifts down to the seafloor. Organisms in this abyssal realm rely upon marine snow as their primary source of food. The Benthic Rover records how much of the marine snow is consumed by the seafloor community. While in transit, the Rover takes overlapping images every meter with a high-resolution camera to document seafloor animals and detritus. It also carries a fluorescence-imaging system that detects the wavelength of light given off by chlorophyll from phytoplankton that sank from the surface waters.

As the Rover transited the seafloor for those 12 months, it collected respiration measurements of organisms in the sediment at 158 sites. The sedimentation event sensor—a particle trap with a camera moored in the water above the seafloor—captured 4,520 images. The time-lapse camera system, despite suffering a glass sphere implosion two weeks into the deployment, still collected useable images for over seven months.

One of the most significant findings from the last few years of the Rover's deployments involved several large pulses of marine snow that rapidly sank to the seafloor. A fluorescence imaging system on the vehicle (Figure 45) captured a record of two major events in April and July. The dramatic July event was characterized by large masses of very fresh (chlorophyll-rich) material blanketing the seafloor. Such pulses may be related to stronger

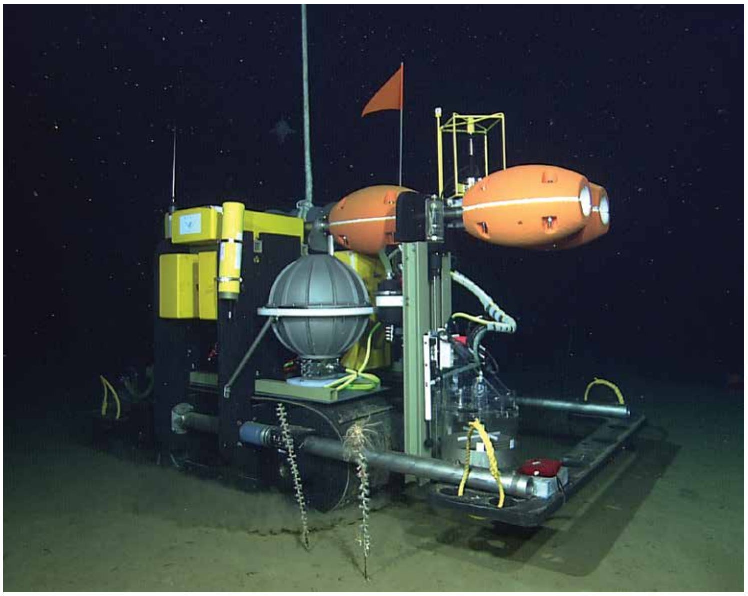


Figure 42. The Benthic Rover reached a new milestone by operating autonomously on the seafloor for more than a year.

Figure 43. Station M is approximately 220 kilometers from the California coastline.

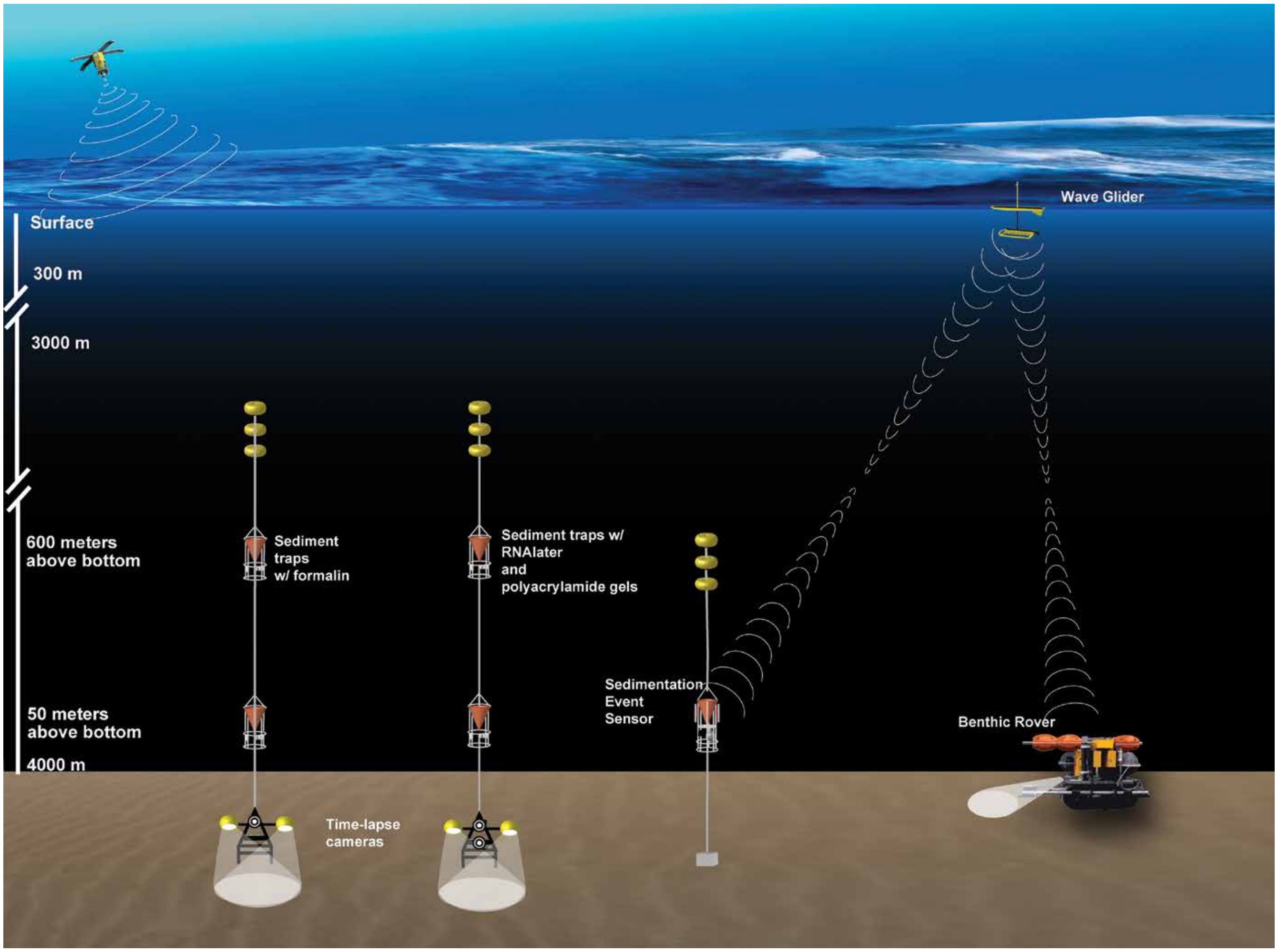


Figure 44. A suite of instruments perform long time-series monitoring of the seafloor at Station M, offshore of the California Coast. Most of the instruments are autonomous, working independently at depth (4,000 meters) without outside control for a year at a time.

along-shore winds that drive the upwelling of nutrients in coastal to offshore waters. The nutrients spur the growth of phytoplankton and zooplankton, which increases the amount of marine snow that rains down to the seafloor.

The two large pulses would have gone undetected without the long-term presence of the Benthic Rover. In documenting such events, the Rover helped solve an important piece of Earth's carbon-cycle puzzle—showing that a much larger percentage of carbon than previously expected can sink rapidly from the surface into deeper water. These periodic events can now be factored into global climate change models.

The real success of this year-long deployment goes beyond the extensive dataset. By relying on these long-term instruments, the use of ships—which incur costs for fuel, personnel, and other expenses—has been greatly reduced. Over the past 10 years, the use of ship time for this project has drastically decreased while the team's persistent measurements at Station M have significantly increased using the Benthic Rover and sedimentation event sensor combined with the time-lapse camera.

The long-running observations collected at this research site have provided a baseline for ongoing and future studies. By instrumenting the site, scientists are less likely to miss the brief yet important episodic events which have proven to play a critical role in the oceanic surface-to-seafloor carbon flux—measurements that would be missed altogether if observations were restricted to only occasional ship expeditions.

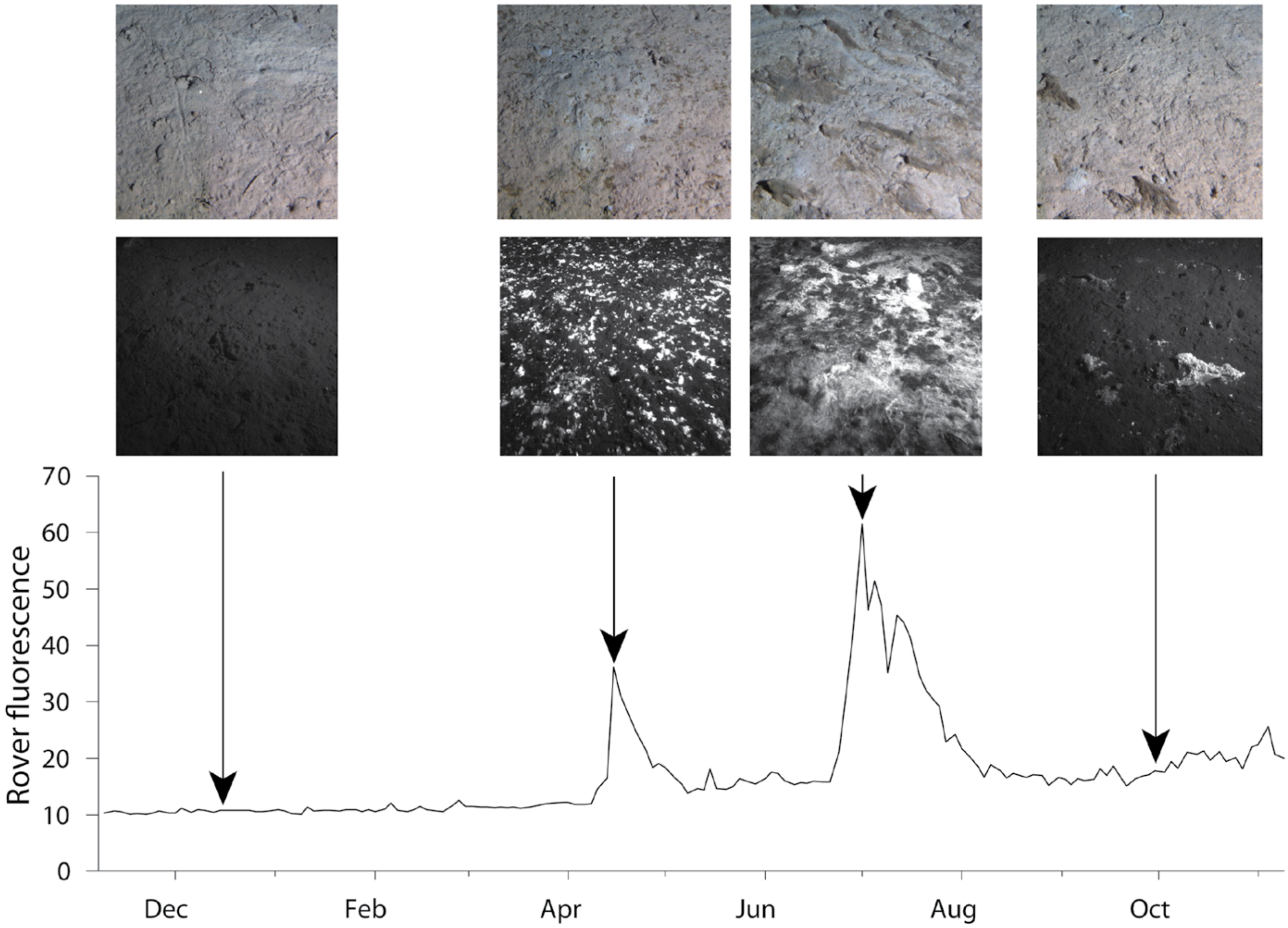


Figure 45. Recent time series of seafloor fluorescence measured by the Benthic Rover at Station M from November 2015-November 2016. Two peaks mark events with rapid deposition and degradation of chlorophyll on the seafloor. Fluorescence images (black and white) and color images (each showing an area about 30-centimeters square) are shown during periods of varying detritus coverage for comparison. Chlorophyll appears white in the fluorescence images.

Revealing the diversity of phytoplankton lineages in the sea

Microscopic marine phytoplankton contribute approximately half of global primary production, creating oxygen and organic compounds through photosynthesis to sustain the aquatic food web. In 2016 Alexandra Worden's Microbial Ecology Group completed a decade-long study of plankton diversity resulting in the unusual discovery of two previously unknown phytoplankton lineages.

Eukaryotic phytoplankton have internal compartments called organelles that serve essential functions. Inside the cell, the nucleus holds genetic material needed for reproduction and controls the activities of the cell. Energy is produced through photosynthesis in a pigmented organelle, the chloroplast. Another organelle, the mitochondrion, is involved in respiration. Early eukaryotic phytoplankton evolved these traits over eons via a process known as endosymbiosis, where organisms combined to yield the modern lineages we see today. For example, a eukaryotic cell engulfed a photosynthetic cyanobacterial cell and then reduced it over time to a chloroplast controlled by the eukaryotic host. In addition to maintaining the photosynthetic capability, the chloroplast still carries a portion of the cyanobacterial DNA, though much of that DNA has been eliminated or moved to the nucleus of the eukaryotic cell. Recent studies have recognized that the known lineages of phytoplankton are more diverse than previously thought, but new, very different lineages are rarely discovered at this point in time. In fact, in the last decade only two other ancient eukaryotic phytoplankton lineages have been discovered.

The new lineages discovered by Worden's team were first observed in 2007 in the eastern North Pacific Ocean about 800 kilometers offshore from MBARI. Worden's team was developing a database to establish a baseline for documenting phytoplankton populations throughout the world ocean. The work involved repeat sampling and analysis of climate-sensitive regions around the globe, including the Bay of Bengal, the Caribbean Sea, the Sargasso Sea in the North Atlantic, Monterey Bay, and the eastern North Pacific. Using a sophisticated analytical method developed with collaborators at Oregon State University, the study resulted in the discovery of two widespread marine lineages that are evolutionarily distant from any known phytoplankton.

One of the new phytoplankton groups is comprised of tiny cells less than three microns in diameter that are genetically very similar. That group of phytoplankton is a distant relative of known algae and appears to be the product of a secondary endosymbiosis, where a eukaryotic organism engulfed another eukaryote that already had a chloroplast. The other new group, comprised of slightly larger cells three microns or larger in diameter, is genetically diverse, and is also different from other known algae; it appears to be the product of a tertiary endosymbiosis. Both of these uncultured organisms appear to be relatively more abundant in warm, low-nutrient waters and can represent up to 10 percent of eukaryotic phytoplankton in samples from the Sargasso Sea based on genetic analyses. These lineages appear to be more abundant during the time of year when nutrients are lowest, in a region that may represent the warmer, nutrient-poor "ocean deserts" of the future. However, the exact roles these new lineages play in food webs are still not known as they have not yet been cultured in a laboratory.

Figure 46. Research Technician Lisa Sudek and Postdoctoral Fellow Kenneth Hoadley with the bioreactors used for culturing microbes while simulating environmental conditions, under controlled levels of carbon dioxide and nutrients.

One method researchers employ to understand how phytoplankton will respond to increasing areas of low productivity in the ocean is to culture and study relevant phytoplankton in the laboratory. Worden's laboratory studies involve high-tech bioreactors—sophisticated systems for culturing microbes wherein a realistic simulation of environmental conditions, carbon dioxide, and nutrients can be controlled (Figure 46). In addition, the cultured species are subjected to genetic analysis to identify specific genes that confer particular metabolic capabilities. Comparing the genetic makeup of different organisms and how they respond to different conditions provides insights into how these algae thrive in the ocean. By combining "technology push" (bioreactor development and genetic analyses) and "science pull" (questions about what controls the growth and distribution of these organisms), Worden's team is developing a context for understanding how climate change may impact marine algae in the future. They are also identifying which genes can be used to sense a particular species' reaction to limited nutrients in the ocean. With this knowledge, MBARI investigators and scientists worldwide could implement this sensing capability on a large scale, particularly by using autonomous platforms to study different types of environmental stressors acting on specific phytoplankton species over swaths of the ocean that would be difficult or practically impossible to do using ships alone.

By pairing laboratory studies with the field surveys that repeat sampling of key marine ecosystems, Worden's team can characterize microbiomes—capturing information on the majority of members of each microbial community in different regions. The first set of baseline data constituting about 10 million unique genetic sequences was released in December 2016. A second release of microbiome data from the deep sea and deep-sea sediments is targeted for late 2017, alongside microbiome data from other surface ocean regions, such as the climate-sensitive Arctic. Using cutting-edge DNA analytical technology developed largely for biomedical research applications, the team was able to discover new genes that are not found in known organisms and demonstrate that previously unknown phytoplankton lineages are widespread in the oceans.

Related web content:

i2MAP: www.mbari.org/automating-a-20-year-survey-of-deep-sea-animals
Benthic Biology and Ecology Group: www.mbari.org/science/seafloor-processes/biology-and-ecology
Deep PIV: www.mbari.org/observing-the-feeding-currents-of-larvaceans
Marine Microbial Ecology Group: www.mbari.org/science/upper-ocean-systems/marine-microbes
Station M: www.mbari.org/station-m-time-series

Project Teams:

Investigations of Imaging for Midwater Autonomous Platforms

Project leads: Mark Chaffey, Kim Reisenbichler, Bruce Robison
Project manager: Kim Reisenbichler
Project team: François Cazenave, Rich Henthorn, Rob McEwen, Brian Schlining, Rob Sherlock, Hans Thomas
Collaborators: Henk-Jan Hoving, GEOMAR Helmholtz Center for Ocean Research, Kiel, Germany

Benthic Biology and Ecology

Project lead/manager: James Barry
Project team: Charles Boch, Kurt Buck, Dale Graves, Chad Kecy, Josh Lord, Chris Lovera, Jim Montgomery, Patrick Whaling
Collaborators: Giulio DeLeo, Steve Litvin, and Fio Micheli, Hopkins Marine Station of Stanford University, Pacific Grove, California; Steve Monismith, Stanford University, California; Brock Woodson, University of Georgia, Athens

DeepPIV: Measuring Fluid Motion in the Deep Sea

Project lead: Alana Sherman
Project manager: Kakani Katija
Project team: Jon Erickson, Dale Graves, Chad Kecy, Denis Klimov
Collaborators: James Barry, Anela Choy, and Bruce Robison, MBARI

Pelagic-Benthic Coupling

Project leads: Alana Sherman, Ken Smith
Project manager: Christine Huffard
Project team: John Ferreira, Rich Henthorn, Brett Hobson, Linda Kuhnz, Paul McGill, Brian Schlining, Susan von Thun
Collaborators: Drew Burrier, Moss Landing Marine Laboratories, California; Jeffrey Drazen, University of Hawaii, Honolulu; Katherine Dunlop, Heriot Watt University, Edinburgh, Scotland; Jennifer Durden and Henry Ruhl, National Oceanography Centre, Southampton, United Kingdom; Danielle Fabian and Larissa Lemon, California State University, Monterey Bay, Seaside; Timothy Shaw, University of South Carolina, Columbia

Ecology and Dynamics of Phytoplankton

Project lead: Alexandra Worden
Project managers: Sebastian Sudek. Alexandra Worden
Project team: Rachel Harbeitner Clark, Kenneth Hoadley, Camille Poirier, Lisa Sudek
Collaborators: Stephen Callister, Pacific Northwest National Laboratory, Richland, Washington; Stephen Giovannoni, Oregon State University, Corvallis; Yun-Chi Lin, National Taiwan Ocean University; Amala Mahadevan, Woods Hole Oceanographic Institution, Massachusetts; Victoria Orphan, California Institute of Technology, Pasadena; V.V.S.S. Sarma, National Institute of Oceanography, Visakhapatnam, India

Weird and Wonderful

Animal behavior and unusual-looking creatures not only pique the curiosity of our experienced researchers, but also the public's interest. Finding that squid engage in cannibalism, or that crabs employ other animals as vehicles for getting around in the deep, are the kinds of things that attract attention from a wide audience. These finds also provide insight into how animals survive in a hostile environment. Sometimes the finds are man-made, but long forgotten, such as a jet engine discovered on the seafloor, which led to a bit of a treasure hunt for information to find out just how it got there. Such surprising revelations and chance encounters are the inspiration for this year's installment of the weird and wonderful.

Hitchhiking deep-sea king crabs

Much of the deep seafloor is flat, muddy, and relatively featureless, providing little shelter for prey that have nowhere to hide. Juvenile king crabs may have evolved a unique solution for evading predators on these muddy plains—they hitch rides on wandering sea cucumbers. MBARI's Jim Barry and Linda Kuhnz and their colleagues observed small crabs clinging to the sea cucumber *Scotoplanes* during an ROV dive in March 2011. After making these observations, the scientists searched for similar interactions between crabs and sea cucumbers in other areas by reviewing video collected from soft-sediment areas near Monterey Bay and in rocky areas near Sur Ridge off the Big Sur coast. They examined about 2,600 *Scotoplanes* and found that almost one quarter of them carried juvenile crabs (a type of king crab called *Neolithodes diomedeae*, Figure 47). While virtually all of the juvenile king crabs they saw in deep, flat, muddy sediment areas were clinging to *Scotoplanes*, the ones observed in rocky portions of Sur Ridge were found hiding among rocks or corals. The researchers speculate that the young crabs use the sea cucumbers as protection from predators when they cannot find protection elsewhere. Life in the deep sea is challenging; the observations of symbioses between crabs and sea cucumbers illustrate how deep-sea animals rely on one another in novel and unexpected ways.

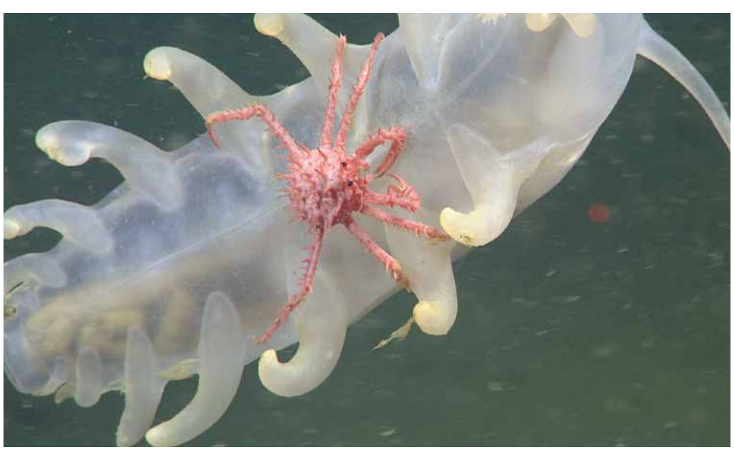


Figure 47. A juvenile king crab clings onto its host sea cucumber. The body of the crab is approximately two centimeters long.

Chimaera observed in nearby waters

The chimaera of Greek mythological fame was a fearsome creature that could breathe fire and had a body made from several different animals (Figure 48). The pointy-nosed blue chimaera, a deep-sea fish, also looks quite unusual but does not share the fire-breathing capability of its namesake. Marine chimaeras are thought to have diverged from sharks around 400 million years ago and, like sharks, they have skeletons of cartilage. A chimaera differs from a shark in having an upper jaw that is fused to its skull and in having non-replaceable tooth plates, much like a bird's beak. Known informally as ghost sharks, chimaeras are relatively common and widespread in the deep sea. However, there are only 38 described species around the world. MBARI Research Technician Lonny Lundsten and his colleagues found evidence that an unidentified chimaera observed by a remotely operated vehicle (ROV) in Monterey Bay (Figure 49) is the same species that had previously been thought to exist only in the Southeastern Pacific off the coast of Australia, New Zealand, and New Caledonia. The researchers believe that the physical characteristics of the fish they saw match the official species description of the pointy-nosed blue chimaera, or *Hydrolagus trolli*. Their alternative hypothesis is that the fish in MBARI's ROV videos is an entirely new species of chimaera. Until one is collected and brought to the surface for analysis, the true identity of the observed chimaera remains a mystery.

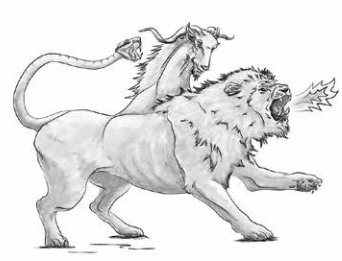


Figure 48. The mythological Greek chimaera was a fierce animal made up of parts of various animals.

*Figure 49. This pointy-nosed blue chimaera (*Hydrolagus cf. trolli*) was videotaped by MBARI's remotely operated vehicle* Tiburon *near the summit of Davidson Seamount, off the coast of Central California at a depth of about 1,640 meters. This fish is just over one meter long.*

Uncovering a personal connection to an unusual find

When a jet engine was discovered on the seafloor of Monterey Bay during a routine ROV dive in 2014 it caught the attention of two MBARI employees—Deputy Director of Marine Operations Chris Grech, who has a strong interest in aviation history, and Information Engineering Group Lead Kevin Gomes, who may have a personal connection to the historic wreckage. Grech turned to aviation experts for help identifying the find (Figure 50), but it wasn't until spring of 2016 that he learned from NOAA marine archaeologists that the engine came from an F8U Crusader jet (Figure 51). This type of jet was used extensively in the 1950s and 1960s, and a number of them were based at Moffett Field, just over the Santa Cruz Mountains from the crash site.

Grech started poring over old newspaper stories from the Moffett Field Historical Society and other historical sources, looking for records of any Crusader jets that might have crashed in Monterey Bay. He found evidence that six different Crusader jets had crashed in the Monterey Bay area between 1957 and 1960. He also learned that Gomes's uncle was a naval aviator who had successfully ejected from a Crusader over Monterey Bay in 1959. Grech also located a fisherman who was an eyewitness to one of these crashes in the early 1960s, when two F8 jets collided in midair. The fisherman has helped establish the probable location of a number of the other missing F8 sites.

Armed with this newfound wealth of information, Grech and Gomes are trying to pin down exactly which Crusader crash yielded the debris that MBARI researchers found on the seafloor.

Figure 50. Part of a jet engine discovered in September 2014 on the Monterey Bay seafloor. The engine, which is about a meter in diameter, has been colonized by rockfish and sea anemones.

Figure 51. F-8 Crusader jet in flight.

Cannibalism in the deep sea

The behavior patterns of deep-sea animals have long been a subject of mystery and speculation, but analysis of two decades' worth of behavior recorded on video has revealed that the diets of *Gonatus* squid include a surprisingly high incidence of predation on members of their own species (Figure 52). MBARI Scientist Bruce Robison and former Postdoctoral Fellow Henk-Jan Hoving suggest several reasons for a high incidence of cannibalism. *Gonatus* squid grow rapidly, are active swimmers, and have among the highest metabolic rates of all cephalopods (octopus, squid, cuttlefish, and nautilus). They only spawn once in their lifetimes, and after the female successfully broods her single batch of eggs, she dies. For these reasons *Gonatus* squid are voracious eaters. Their cannibalistic behavior may also be a strategy to reduce competition for food or mates.

The diet of gonatid squid is important to understand because, in some parts of the North Pacific, they may be more abundant than commercial fish species. *Gonatus onyx* is the most abundant species of this genus off California. This prevalence of *G. onyx* has positioned it and other *Gonatus* species as important prey items for many regional oceanic species, such as fishes, sharks, whales, and seals. Learning about the diet of *Gonatus* squid enables scientists to better understand the structure of oceanic food webs and the flow of nutrients throughout North Pacific ecosystems.

Figure 52. Gonatus berryi *squid (right) in the process of consuming another* Gonatus berryi*. The bodies of these squid are approximately 15 centimeters long.*

On the Horizon

The coming year will bring advances toward realizing several long-term priorities outlined in the institute's Technology Roadmap. For example, work to generate electrical energy from waves, and send genomic sensors out on long unattended missions will enhance our ability to study, observe, and track changes in ocean conditions over long periods of time. A new laser scanning system will enable efficient one-centimeter scale mapping of the distant seafloor. And a special collaborative effort will provide the science needed for the Monterey Bay Aquarium's conservation efforts aimed at reducing plastic pollution in the ocean.

Harnessing energy from wave motion

One obstacle to the implementation of persistent oceanographic instrumentation and vehicles is the availability of energy. Traditionally, oceanographic systems have relied on bringing along energy in batteries for vehicles or capturing solar and, sometimes, wind power for buoy-based instrumentation. Although these approaches are mature, they represent a limitation on what can be accomplished and are not able to support the fleets of autonomous vehicles that are becoming more and more common. Only by developing new sources of energy and techniques to transfer energy to autonomous vehicles will a widespread persistent and capable presence in the ocean be realized. To address this challenge, Mechanical Engineer Andrew Hamilton and his team are developing a system that converts the energy present in ocean surface waves to electrical energy. Capturing wave energy offers the potential to realize an increase of 10 times more energy available onboard a typical oceanographic buoy on the sea surface.

Figure 53. Engineers Andrew Hamilton, left, and François Cazenave during a test of the wave energy buoy's new propulsion system. The design of this device was made possible by collaboration with Liquid Robotics, Inc.

This wave-energy project has already fielded a system that achieves its goal of increasing available energy fivefold. Engineering and testing continue to increase the reliability of the system (through repeated deployments and refinements) and the power-capture capability of the system (through the implementation of advanced control techniques). Two developments are on the horizon for 2017. First, utilizing fundamental technology from Liquid Robotics' Wave Glider, the system will evolve to allow it to stay in one location without being anchored (Figure 53). Second, the team will explore techniques for docking and recharging autonomous vehicles underwater. This project comes with considerable technical risk but, if successful, these capabilities will ultimately create a home base and communications hub for a fleet of autonomous underwater vehicles that can migrate around the ocean with greatly expanded capability and longevity compared to what is currently possible.

A fleet of mobile ecogenomic sensors

Resolving spatial and temporal variability in microbial processes that drive fundamental biogeochemical cycles in the ocean requires sampling at different locations and depths faster than microbial populations and environmental parameters change in time. Gaining a more detailed understanding of how organisms respond to fluctuating environmental conditions is essential for projecting the longer term and larger scale consequences of ocean change for marine systems and people. Accomplishing that task in the open sea using traditional ship-based expeditions poses many challenges. Robotic systems, on the other hand, offer means for accessing and sampling the ocean in ways not possible before, and in ways that uniquely complement the use of research ships.

Scientists and engineers working as part of MBARI's Sensors: Undersea Research of the Future (SURF) Center, in partnership with the Center for Microbial Oceanography Research and Education (C-MORE), are addressing this challenge by developing a new ocean sensing and sampling system known as MiVEGAS (multiple vehicle ecogenomic automated samplers).

MiVEGAS consists of three long-range autonomous underwater vehicles fitted with third-generation Environmental Sample Processors (Figure 54). These vehicles are designed to operate and collect environmental data unattended in the ocean for extended periods. The vehicles then use that information to direct the collection of up to 60 samples from the sea surface to depths of up to 300 meters. The samples are immediately preserved, capturing the native state of organisms' genetic material and proteins. These precious samples will enable researchers to document the diversity of species and better understand the role they play in maintaining ocean ecosystems.

The three vehicles that comprise MiVEGAS are named *Ahi*, *Aku*, and *Opah*, after three pelagic fish found in the open waters around Hawaii. These vehicles are projected to be operational in 2017. Their development was made possible with support from C-MORE, the Gordon and Betty Moore Foundation, and the National Science Foundation's Ocean Technology and Interdisciplinary Coordination Major Research Instrumentation Program.

Figure 54. Makai*, a prototype of the MiVEGAS system, fitted with a third-generation Environmental Sample Processor sampling system, is prepared for a test deployment in Monterey Bay by, from left, engineers Brian Kieft and Brett Hobson and MBARI President/CEO Chris Scholin. The vehicle is designed to collect up to 60 samples from the ocean surface to 300 meters depth over a period of days to weeks.*

Tracking plastic contamination in the ocean food web

The human imprint of plastic pollution is now evident in all marine ecosystems. Scientists have documented plastics everywhere from white sand beaches and colorful coral reefs to the deepest, darkest trenches of the ocean. Plastic in the ocean imposes physical hazards to marine animals that eat or get tangled in it. Ocean plastic pollution presents a chemical hazard to the marine animals that ingest it (Figure 55). This toxic load includes both the synthetic ingredients in the plastic itself, and the contaminants that adhere to the plastic from the surrounding seawater.

MBARI Postdoctoral Fellow Anela Choy and Scientist Bruce Robison will team up with Monterey Bay Aquarium Science Director Kyle Van Houtan to initiate a new research project examining the complex ecosystem impacts of plastic pollution in Monterey Bay. Unlike previous studies focused primarily on shallow coastal systems and beaches, this research will characterize plastic pollution impacts on deep-sea ecosystems.

The team will work closely with MBARI engineers and ROV pilots to develop new tools to sample microplastics from various water depths. Additionally, Choy and Robison will bring their expertise on midwater food web ecology to study the chemical fingerprints of plastic pollution. They will examine how contaminants are transferred through predator-prey feeding interactions and, ultimately, how human seafood consumers might be impacted.

The Monterey Bay Aquarium (MBA) is working to reduce the sources of ocean plastic pollution, both through education and public outreach, as well as through national and international policy engagement. This collaborative project with MBA will thus connect MBARI's empirical ecosystem research and engineering developments to the large-scale societal problem of plastic pollution and the fate of this pervasive man-made material in the ocean. It will also provide a new approach for assessing the scale and impact of the problem, providing much-needed data to the search for solutions.

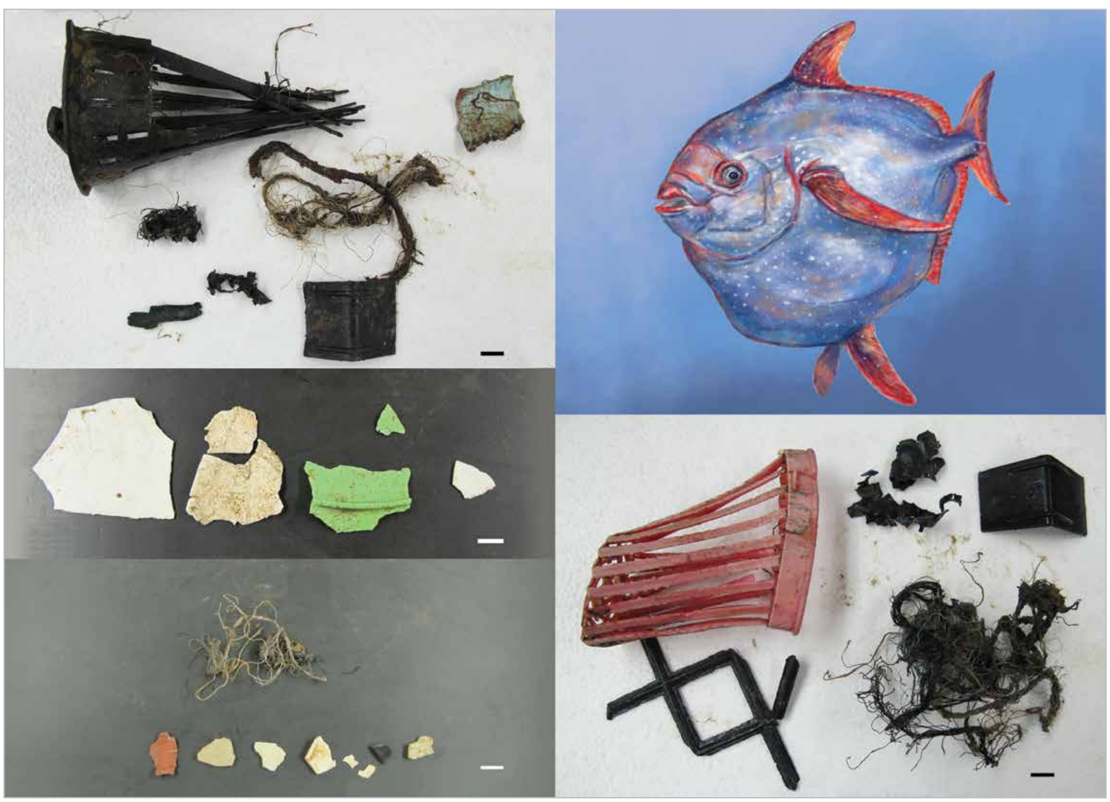


Figure 55. Examples of anthropogenic marine debris found in opah stomachs in earlier studies. Each of the photos represents debris found within one individual stomach. Scale bars are one centimeter (Choy & Drazen 2013, Marine Ecology Progress Series*). Drawing (top right) shows an opah of the genus* Lampris guttatus.

Sharpening our focus on the fine details of the seafloor

Knowledge of seafloor morphology and its character, and an ability to detect change over time, are critical to many deep-sea geological, chemical, and biological research efforts worldwide. MBARI's Ocean Imaging Project team, led by Software Engineer David Caress, is developing a seafloor mapping system that combines one-centimeter-scale topography with two-millimeter-resolution color photography when operated from an altitude of two to three meters off the seafloor. This system is currently fielded from the institute's ROVs, but the ultimate goal is to achieve efficient and very high-resolution surveys in the deep ocean using autonomous vehicles.

In 2017, this project team will greatly improve MBARI's low-altitude survey capability with the delivery of a subsea lidar system optimized for seafloor mapping. Lidars use discrete laser pulses to measure topography that can be combined to yield a three-dimensional image. The topographic resolution achieved with this class of laser scanner depends on the spacing between soundings, which in turn depends on the scan rate and the field of view. The first deep-rated subsea lidar became available from 3D at Depth, a small Colorado company, about four years ago. Starting in 2013, MBARI has leased a prototype unit and incorporated it into a survey system that also includes a 400-kilohertz multibeam sonar, stereo color still cameras, and an inertial navigation system. An example of bathymetry data produced by the prototype lidar (Figure 56) from 2016 surveys in Monterey Canyon documents fine-scale morphological changes associated with sediment transport events.

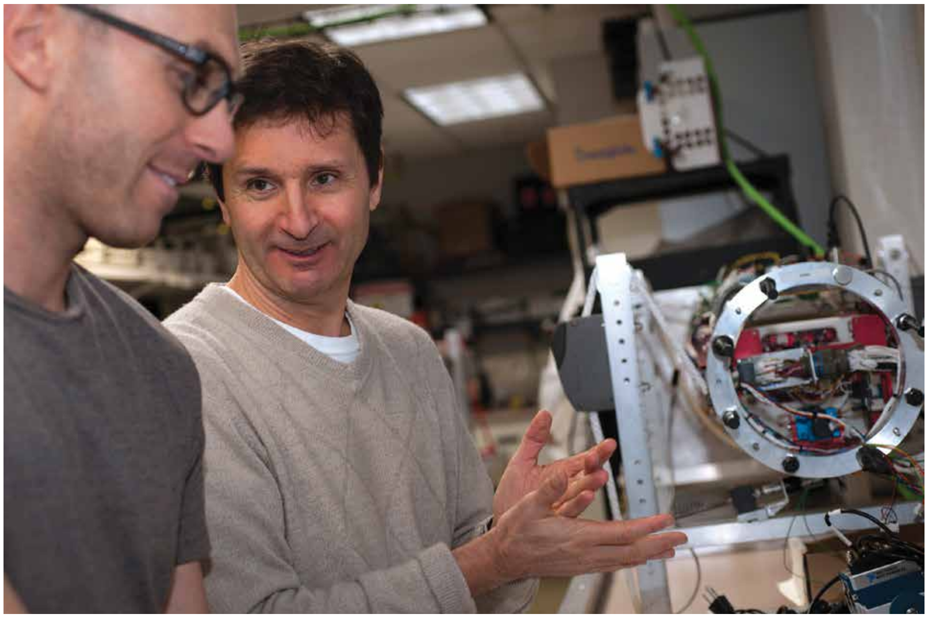
Compared to its commercially available predecessor, the new lidar will have a much wider field of view (90 degrees instead of 30 degrees), a faster survey speed (0.5 meter per second instead of 0.2 meter per second), and a 4,000-meter depth rating (instead of 3,000 meters). At present a full ROV dive allows a one-centimeter-resolution survey of as much as a 100-meter-by-100-meter area. With the new lidar, MBARI will be able to survey areas three times larger with the same resolution. The factory acceptance test of the custom-made unit is expected in spring 2017, and sea trials of that instrument will take place aboard the R/V *Rachel Carson* in the summer.

Figure 56. Map of a single 1.4-meter-wide swath of one-centimeter lateral resolution lidar bathymetry collected in Monterey Canyon from ROV Doc Ricketts *following a large sediment transport event. The ROV flew this survey line 2.5 meters above the seafloor at a speed of 0.2 meters per second. Small scour features left by the turbidity current are clearly visible. Also shown is a rattail fish (about a half-meter long) that obligingly sat still as the ROV and laser scanner passed overhead. A new lidar system scheduled for sea trials in 2017 will achieve the same resolution bathymetry with a swath that is 3.5 times wider (five meters at the altitude shown here) and can be collected more than twice as fast.*

Behind the Scenes:
New Investigators Join MBARI's Team

MBARI welcomed two new principal investigators, Senior Scientist Kelly Benoit-Bird and Principal Engineer Mathieu Kemp, in 2016. Their unique skill sets in bioacoustics and AUV technology, respectively, complement the breadth of expertise at MBARI. Two additional principal investigators, Scientists Andrea Fassbender and Yui Takeshita, joined MBARI early in 2017 and both will focus their research efforts on marine biogeochemical cycling.

Mathieu Kemp has made many contributions in several technical areas throughout his career, but his focus since 2000 has been on autonomous underwater vehicle (AUV) design and applications. Kemp joined MBARI as a principal engineer with a top priority of developing a series of biologically inspired technologies aimed at increasing AUV persistence. By increasing the mean time between failures of these vehicles, science missions can be executed for longer periods, increasing our presence in the ocean and making it easier to observe changes in a highly dynamic environment. One approach Kemp is taking to achieve this goal focuses on improving vehicles' awareness of the state of their own health to better predict and prevent faults and failures. Attaining this goal of increasing vehicle persistence has profound implications—it frees the research vessels and people required for AUV operations to perform other tasks. Prior to joining MBARI, Kemp was the director of concept development at Bluefin Robotics. He received a PhD in physics from the University of North Carolina at Chapel Hill.



Principal Engineer Mathieu Kemp, right, and Research Specialist Ben Raanan integrate their fully functional LRAUV used as a testbed. Combined with advanced signal processing algorithms, a plethora of sensors on this vehicle are expected to provide a holistic snapshot of the vehicle's health.

Kelly Benoit-Bird uses sound to visualize the complex marine ecosystems that exist below the surface of the ocean. Previously a professor at Oregon State University, she uses active sonar as her main research tool and has found many opportunities at MBARI to study predator-prey relationships and biological hot spots (often found where two water masses meet). Benoit-Bird plans to investigate these relationships using MBARI's mapping AUV to study how groups of organisms are structured. She also plans to exploit the capabilities of MBARI's remotely operated vehicles (ROVs) and AUVs to expand her research to study how environmental conditions in the deep ocean affect the grouping and distribution of animals far below the surface. The use of ROVs allows Benoit-Bird to overcome a significant challenge—integrating acoustics with imaging. Her innovative use of sonar is a key component of MBARI's initiative to use new technologies to visualize the hidden world beneath the ocean surface. Benoit-Bird holds a PhD in zoology from the University of Hawaii.

Senior Scientist Kelly Benoit-Bird installs acoustic sensors on the R/V Rachel Carson.

Andrea Fassbender comes to MBARI from the Pacific Northwest where she followed her PhD studies at the University of Washington with postdoctoral research at the Pacific Marine Environmental Laboratory (PMEL). Her doctoral research included the analysis of seven years of data from instruments measuring aspects of the carbon cycle on two surface moorings in the North Pacific Ocean in addition to observations from research vessels, floats, and satellites. One of the study sites, Ocean Station Papa in the subarctic Pacific Ocean about 1,200 kilometers west of Vancouver Island, Canada, showed dramatic seasonal variation in calcium carbonate production and the carbon cycle—complex interdependent processes that transport carbon from the ocean's surface to its depths. At MBARI, Fassbender plans to take advantage of data collected with MBARI moorings, ROVs, and AUVs to examine marine carbon uptake and its subsequent export from the ocean surface and midwater region to depth. She will continue to develop innovative approaches and novel tools to explore regional variability in oceanic biogeochemical cycling and its effects on climate.

Scientist Andrea Fassbender shows figures from an ongoing project evaluating the efficiency of ocean carbon uptake throughout the global ocean.

Yui Takeshita earned his PhD from Scripps Institution of Oceanography, followed by postdoctoral research at Scripps and, more recently, at the Carnegie Institution for Science. At Scripps, he helped develop the Benthic Ecosystem and Acidification Measurement System to measure in situ benthic chemical fluxes in shallow tropical ecosystems and used the system to successfully measure net calcification and production rates on a coral reef at Palmyra Atoll. Takeshita's long-term goals at MBARI are to expand his interests in sensor development and field work toward applying autonomous sensing technology to observe coastal carbon cycles. He intends to study the fluxes of forms of carbon between the atmosphere and the ocean, as well as between the ocean and the seafloor to provide data for researchers to gain a more comprehensive understanding of the dynamics of carbon cycling.

The addition of these four talented principal investigators marks the beginning of a new period of innovation at MBARI. Collectively, their research and engineering development goals align with the objectives set forth in MBARI's Technology Roadmap and Strategic Plan, and complement MBARI's current cadre of scientists, engineers, and marine operations professionals. We welcome Matt, Kelly, Andrea, and Yui!

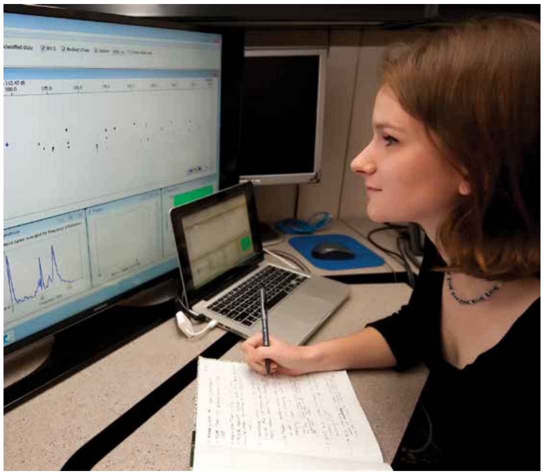
Scientist Yui Takeshita uses autonomous sensing technology to observe coastal carbon cycles.

Celebrating 20 Years of Summer Interns

The summer of 2016 marked the 20th year of the formal MBARI Summer Internship Program for undergraduate students, graduate students, and educators, under the direction of Education and Research Specialist George Matsumoto. In that time, MBARI has hosted 295 interns and 64 staff members have served as mentors guiding the interns in their projects.

The 10-week program places an emphasis on the interns' professional development. Interns work on specific research projects and also interact with other interns and mentors working on different projects. This helps emphasize the peer relationships between scientists and engineers, part of MBARI's mission.

Alumni from the program are scattered around the world, engaged in a variety of endeavors including research, conservation, education, medicine, law, and several other fields. A few alumni have become valued members of the MBARI staff.




2016 summer interns at work, clockwise from top left: Ellen Jacobs uses software specifically designed to analyze acoustic signatures to identify beaked whales from other whale species (See story on page 8). Nicholas Raymond helps young visitors to the MBARI Open House build their own remotely operated vehicles. Maria Corrochano-Luque uses a flow cytometer to determine the abundance of phytoplankton cells in samples of cultures. Bryce Corbett uses environmental DNA to detect the presence of marine organisms such as anchovies and krill in Monterey Bay.

Awards

Kelly Benoit-Bird

Project of The Year Award for Resource Conservation and Resiliency (Presented by Kurt Preston of the US Strategic Environmental Research and Development Program)

Peter Brewer

American Geophysical Union Maurice Ewing Medal

Anela Choy

L'Oreal USA for Women in Science Fellowship

Valeria Jimenez, PhD

PhD awarded, University of California, Santa Cruz (Alexandra Worden, mentor)

Kelly Lance

US Fish and Wildlife Service Ivory Crush Design Challenge Winner

Alexander J. Limardo

University of California, Santa Cruz, Outstanding Teaching Assistant Award

Masters of Science degree awarded, University of California, Santa Cruz (Alexandra Worden, mentor)

Victoria Orphan

MacArthur Fellowship

Alexandra Worden

American Academy of Microbiology Fellowship

MBARI

IEEE Oceanic Engineering Society Institute Award

Project Teams and Summaries

Acoustical Ocean Ecology

Project lead: Kelly Benoit-Bird
Project manager: Chad Waluk
Collaborator: Ken Smith, MBARI

Patchiness, or the spatial variability in biomass at relatively small scales, is a key feature driving animal behavior, biogeochemical cycles, nutrient dynamics, and ecosystem structure. To address the role of heterogeneity in ecosystems, this work focuses on simultaneously addressing three challenges: developing methods for quantifying patterns in the biota, identifying the processes underlying observed patterns, and understanding the consequences of those patterns on ecosystem processes. Since this team arrived at MBARI in mid-2016, it has been building partnerships within the institute, identifying available resources, and building capabilities for future work. To that end, the team collaborated with Ken Smith's group to analyze data from water column tests of the mapping autonomous underwater vehicles (AUV) and prepared results for publication. Together with MBARI engineers, operations staff, and Smith's group, the team developed deployment and data analysis protocols for future efforts. The team worked with MBARI engineering staff to design and begin fabrication of hardware for mounting acoustic systems on research vessels and an ROV.

Aquarium-MBARI Partnerships

Project lead/manager: George Matsumoto
Project team: Stephanie Bush, Anela Choy, Rachel Harbeitner Clark, Judith Connor, Frank Flores, Kim Fulton-Bennett, Kevin Gomes, Dale Graves, Kakani Katija, Linda Kuhnz, Lonny Lundsten, Thom Maughan, Paul McGill, Melinda Nakagawa, Craig Okuda, Mike Parker, Bruce Robison, Jose Rosal, Kyra Schlining, Jim Scholfield, Farley Shane, Jordan Stanway, Nancy Jacobsen Stout, and Susan von Thun
Collaborators: Hank Armstrong, Athena Barrios, Rita Bell, Alicia Bitondo, Christy Chamberlain, Mike Chamberlain, Paul Clarkson, Jim Covel, Jeff Doyle, Andrew Fischer, Randy Hamilton, Sal Jorgensen, Tommy Knowles, Koen Liem, Sue Lisin, Kenneth Maguire, Andrea McCann, Enrique Melgoza, Eric Nardone, Raul Nava, John O'Sullivan, Chris Payne, Ken Peterson, Margaret Spring, Scott Stratton, Kim Swan, Jaci Tomulonis, Kyle Van Houtan, Cynthia Vernon, Patrick Webster, and Mary Whaley, Monterey Bay Aquarium, Monterey, California

The two institutions collaborated on a number of different projects in 2016 including the current temporary *Tentacles* exhibit and a prototype white shark camera tag. The Monterey Bay Aquarium continues to provide an unparalleled education and outreach outlet for MBARI's research activities, and MBARI staff have given a number of presentations to aquarium educators, volunteers, and other staff. The two organizations worked together to help inform the public and policy makers on ocean issues and to increase social media attention on aquarium and MBARI stories.

AUV Infrastructure Support

Project leads: David Caress, John Ryan
Project manager: John Ryan
Project team: Mike McCann, Brian Schlining, and Rob Sherlock

Software efforts included maintenance of the MB-System software used to process and visualize seafloor mapping data, further development of the Spatial Temporal Oceanographic Query System (STOQS) for visualization and analysis of water column and seafloor data, and initiation of software development for processing data from the new midwater visual transect AUV (see page 29). Hardware efforts involved improvements and upgrades to the seafloor mapping AUV. Community engagement occurred through participation in professional meetings and online forums.

AUV Science Operations Using Terrain Relative Navigation

Project leads: Charles Paull, Steve Rock
Project manager: Brett Hobson
Project team: David Caress, Rich Henthorn, Rob McEwen, Hans Thomas

The project team is transitioning the Terrain Relative Navigation (TRN) system, developed jointly with Stanford University, for routine science use on MBARI AUVs. During 2016 the team added to the inventory of high-resolution seafloor maps within one of the Monterey Bay National Marine Sanctuary Ecologically Significant Areas that is a suspected habitat for rare deep rockfish. Follow-on dives with the MiniROV used this new map and TRN during bioacoustics flights above the bottom, followed by ground-truth imaging of selected rockfish in their rocky habitats. The MBARI Iceberg AUV also used TRN to accurately return to sites on the sheer walls of Monterey Canyon, which are an analogue for the sides of free-drifting icebergs that are the focus of a 2017 expedition to Greenland, funded by the National Aeronautics and Space Administration (NASA).

Central and Northern California Ocean Observing System (CeNCOOS)

Project lead: David Anderson
Project manager: Aric Bickel
Project team: Fred Bahr, Jennifer Patterson
Collaborators: Jeff Anderson and Frank Shaughnessy, Humboldt State University, California; Jack Barth, Oregon State University, Corvallis; Rob Bochenek, Axiom Data Science, Anchorage,

Alaska; Yi Chao, University of California, Los Angeles, and Remote Sensing Solutions, Inc., Monrovia, California; Kenneth Coale, Tom Connolly, and Jason Smith, Moss Landing Marine Laboratories, California; Dan Costa, Chris Edwards, Michael Jacox, Raphael Kudela, and Andrew Moore, University of California, Santa Cruz; Ken Davis, Ryan Walter, and Dean Wendt, California Polytechnic State University, San Luis Obispo; Jeff Dorman and William Sydeman, Farallon Institute, Petaluma, California; James Doyle, Naval Research Laboratory, Monterey, California; Meredith Elliott and Jaime Jahncke, Point Blue Conservation Science, Petaluma, California; Ashley Erickson and Steve Monismith, Stanford University, California; John Largier, University of California, Davis; Karina Nielson, Romberg Tiburon Center for Environmental Studies, California; Jeff Paduan, Naval Postgraduate School, Monterey, California; Chad Whelan, CODAR Ocean Sensors, Mountain View, California

In June 2016 CeNCOOS received a five-year renewal award from the National Oceanic and Atmospheric Administration's (NOAA) Integrated Ocean Observing System to continue operation of the regional association. Under this grant, investigators from 10 institutions operate 13 shore stations, two meteorological stations, 27 surface current-sensing high-frequency radars, three regional-scale numerical models, two glider transects, and a data portal that provides access to the real-time continuous monitoring and legacy data. An "imaging flow cytobot" that sucks in seawater and captures videos of the plankton streaming past a miniaturized camera was deployed at the Santa Cruz Wharf in October just in time to capture a red-tide bloom. These "eyes on the ocean" support marine operations and coastal hazards readiness, monitor trends and variability in climate, and contribute to sustaining healthy environments and ecosystems. Additional support came from NASA for studies on harmful algal blooms and from NOAA for ocean acidification and marine biodiversity work. Conditions in the Eastern Pacific were less extreme in 2016 than previous years that included five years of drought, record-high temperatures in the northeast Pacific, and the third-largest El Niño of the century. Rainfall near the end of 2016 lowered the salinity in many of the region's estuaries and eased the drought conditions in northern California.

MBARI Intern Desmond Ho photographs oysters at the Hog Island Oyster Company, where CeNCOOS monitors water quality in partnership with the oyster growers.

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 Aerospace, Phoenix, Arizona; Hervé Claustre, Laboratoire d'Océanographie de Villefranche, France; Todd Martz, Scripps Institution of Oceanography, La Jolla, California; Steve Riser and Dana Swift, University of Washington, Seattle; Jorge Sarmiento, Princeton University, New Jersey

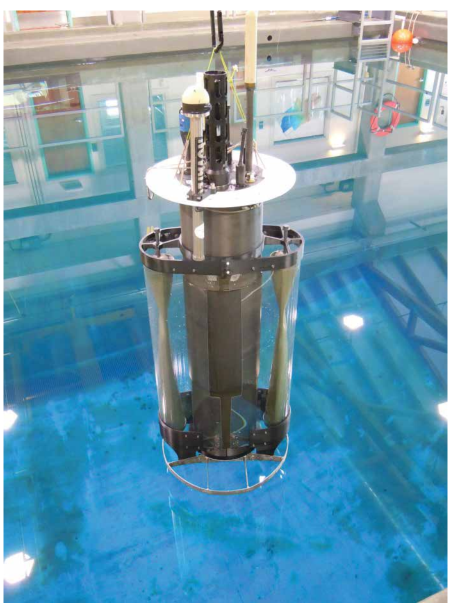
The team continued to develop chemical sensors and deployed 35 floats throughout the world ocean in 2016. The goal is to have a global network of chemical sensors on profiling floats that can document carbon, oxygen, and nitrate cycles at the seasonal and interannual scale worldwide. The cycles of these elements can be used to make quantitative estimates of air-sea carbon transport, net community production (primary production minus respiration), carbon export from surface waters to depth, and the ecosystem dynamics that control the flow of these chemicals. The major focus of this team effort is to contribute to the Southern Ocean Carbon and Climate Observations and Modeling program to instrument the Southern Ocean.

Research Specialists Hans Jannasch and Carole Sakamoto preparing a profiling float with MBARI pH and nitrate sensors for deployment in the California Current.

Coastal Profiling Float

Project leads: Ken Johnson, Gene Massion
Project manager: Gene Massion
Project team: Paul Coenen, Brent Jones, Eric Martin, Paul McGill, Ed Mellinger, Josh Plant, Jose Rosal
Collaborator: Dana Swift, University of Washington, Seattle

The Coastal Profiling Float is designed for research aimed at understanding the health of the ocean. A warming climate, increased use of nitrogen fertilizers, acidification, loss of sea ice, decreasing oxygen concentrations, and a variety of other processes are expected to impact coastal waters in the coming years and decades. Understanding the effects of these processes on fundamental biogeochemical processes will require years to decades of ecosystem-wide measurements in the ocean's coastal zone where the majority of primary production occurs. To provide this scale of observing capability, an observing platform that can be operated for decades with a life cycle cost in line with current and projected funding is critical. The global Argo array has proven the viability of profiling floats for large-scale observing systems. This team is adapting that technology for use in the coastal zone with an overall cost for the Coastal Profiling Float similar to the floats used in the global Argo array. The team reached a milestone in 2016 when the Coastal Profiling Float transitioned from the design-test-redesign phase of development to the test-refine phase with extensive at-sea tests. The team routinely processes the data acquired from the field engineering tests to check the science data quality.



The Coastal Profiling Float is tested in MBARI's test tank.

Continental Margins and Submarine Canyon Processes

Project lead: Charles Paull
Project manager: Roberto Gwiazda
Project team: Krystle Anderson, James Barry, Larry Bird, Kurt Buck, David Caress, Cristian Carvajal, Mark Chaffey, John Ferreira, David French, Dale Graves, Bob Herlien, Brett Hobson, Brian Kieft, Dennis Klimov, Chris Lovera, Eve Lundsten, Mike McCann, Tom O'Reilly, Monica Schwehr, Alana Sherman, Hans Thomas, Patrick Whaling
Collaborators: Daniel Brothers, Katie Coble, Tom Lorenson, Mary McGann, and Kurt Rosenberger, US Geological Survey, Santa Cruz and Menlo Park offices, California; Scott Dallimore, Geological Survey of Canada, Sidney, British Columbia; Andrea Fildani, Statoil, Norway; George Hilley, Stanford University, California; Daniel Parsons, University of Hull, United Kingdom; Esther Sumner, Will Symons, and Peter Talling, University of Southampton, United Kingdom; Jingping Xu, Ocean University of China

The team focused on the successful execution of the Coordinated Canyon Experiment (CCE), a multi-institution program with partial support from the United Kingdom's Natural Environment Research Council, the United States Geological Survey, and Ocean University of China. The goal is to directly document the passage of sediment density flows through the axis of Monterey Canyon and determine the impact these flows have on the seafloor morphology. The experiment includes an array of monitoring equipment at 16 sites along the canyon to depths of 1,850 meters. Most of the instruments in this array were recovered for servicing and redeployed twice in 2016. The floor of the canyon was mapped using the mapping AUV twice in 2015 and four times in 2016 to quantify changes in the seafloor. Seven events have been registered by the CCE array as of the end of 2016, including two sediment-transport events that passed through the canyon for more than 50 kilometers, with average velocities of 5.4 and 4.2 meters per second. These are the highest sediment transport velocities ever measured using monitoring instruments.

Submarine fans are very subdued features associated with subtle changes in seafloor slopes. The Navy Fan was originally surveyed in the early 1970s using state-of-the-art techniques for the time period, which measured meter-scale bathymetry. MBARI's 2015 AUV surveys repeated the old surveys of Navy Fan at higher resolution. Postdoctoral Fellow Cristian Carvajal's analysis of the data illuminates the complexity of sedimentary processes and geomorphology in deepwater fan systems, which will be of great interest for the scientific community.

Controlled, Agile, and Novel Observing Network (CANON)

Project leads: Francisco Chavez, Chris Scholin, Robert Vrijenhoek, Alexandra Worden
Project manager: Francisco Chavez
Project team: Marguerite Blum, Danelle Cline, Duane Edgington, Kevin Gomes, Brett Hobson, Brent Jones, Brian Kieft, Thom Maughan, Mike McCann, Monique Messié, Reiko Michisaki, Tom O'Reilly, Tim Pennington, Carlos Rueda-Velasquez, John Ryan, Jason Smith, Chris Wahl, Yanwu Zhang
Collaborators: Yi Chao, University of California, Los Angeles, and Remote Sensing Solutions, Inc., Monrovia, California; Steve Chien, Jet Propulsion Laboratory, Pasadena, California; Andrew Thompson, California Institute of Technology, Pasadena; and staff from the National Marine Sanctuaries

CANON is a technology development program to improve methods for observing the fluid ocean mechanistically and over time. The ocean contains many ephemeral features that are displaced by currents or mixed vertically by winds. Many of these features (harmful algal blooms, anoxic zones, low pH seawater, fronts, eddies) and the resulting life in the sea are of great scientific and social interest, yet the ability to predict their origin and evolution is limited. Short monthly field experiments in 2016 included deployments of the long-range AUV, the *Dorado* AUV, and the Wave Glider to test developments and understand the evolution, distribution, and response of the marine ecosystem to physical forcing. A coordinated experiment with collaborators in the fall enabled the study of biological hot spots associated with horizontal and vertical fronts. The hot spots are areas that aggregate zooplankton and attract a variety of predators. Predictive models of the response to short- and long-term variations in climate require an improved understanding of these processes.

Core Conductivity, Temperature, Depth (CTD) Data

Project leads: Erich Rienecker, John Ryan
Project manager: Erich Rienecker
Project team: Marguerite Blum, Dale Graves, Reiko Michisaki, Edward Peltzer, Kim Reisenbichler, Bruce Robison, Rich Schramm, Rob Sherlock

Support continued on the maintenance, operation, calibration, and configuration of the core CTD instruments, electronics, and related hardware. Following implementation of dual oxygen sensors on both ROVs, production of near real-time quality-control plots has helped ensure collection of high-quality oxygen data. Wire loads for CTD casts were measured to establish safety factors that are consistent with national research fleet standards. Hardware and software were purchased for both ships so that wire loads can be monitored in real time and recorded for later analysis.

Core Mooring Data

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

This project provides for the institutional support of core data from MBARI moorings. Combined hourly and daily NetCDF files were produced for all quality-controlled data, from August 1989 through August 2016, and made available to the general public.

Core Navigation

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

The project team maintained navigation hardware on the ROVs and ships and maintained and developed software for automated processing and archiving of navigation data. ROV navigation data were edited and monitored for quality. The team kept pace with the flow of incoming data and integration of navigation data into the video annotation database.

Cytometer Technology for Autonomous Platforms

Project lead/manager: Tom O'Reilly
Project team: Francisco Chavez, Denis Klimov, John Ryan, Chris Scholin
Collaborators: James Bellingham and Heidi Sosik, Woods Hole Oceanographic Institution, Massachusetts; Peter Lopez, New York University; Heike Schmitz and Lisa Ziccarelli, Jupiter Research Foundation, Los Altos, California; Jarred Swalwell, University of Washington, Seattle

Marine microbial communities play a critical role in Earth's biosphere, so it is important to improve understanding of these micro-

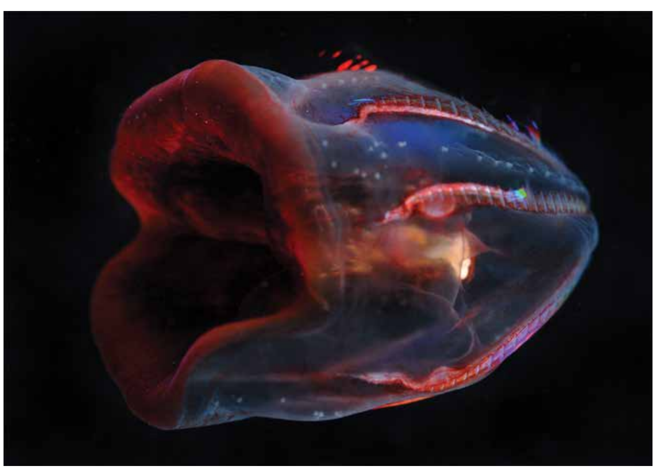
Participants in the mobile cytometer microscope workshop hosted by MBARI, June 1-3, 2016.

bial systems and relationships, and how they may be responding to changing climate and other anthropogenic influences. This project team surveyed and evaluated existing and emerging technologies for small autonomous cytometers and microscopes that could potentially be integrated with autonomous underwater and surface vehicles. The project convened a workshop, attended by instrument developers and manufacturers, to discuss important science-use cases and current technical barriers to development of small mobile autonomous instruments. Workshop participants formed small groups that meet to discuss new developments and next steps. This feasibility study also resulted in collaboration with instrument developers from academia and industry. (See the Jupiter Foundation project page 58.)

DEEPC: Dimensions of Biodiversity

Project lead/manager: Steven Haddock
Project team: Darrin Schultz, Jacob Winnikoff
Collaborators: Joseph Ryan, University of Florida, Saint Augustine; Erik Thuesen, Evergreen State College, Olympia, Washington

The aim of the DEEPC project (Diversity, Evolution, and EcoPhysiology of Ctenophores) is to understand the evolutionary pressures that drive adaptation and diversification in extreme environments. Specifically, the team is gathering genomic, chemical, environmental, and physiological data from comb jellies (ctenophores) to examine the phylogenetic relationships of these species, the evolutionary lineages where depth transitions have occurred, and the evolutionary genetic changes that have allowed species to adapt to shallow- and deep-water habitats. Toward this end, the researchers have generated high-quality transcriptome data (that reflect all the genes that are actively expressed) from 35 ctenophore species collected as deep as 4,000 meters. In 2016, the team gathered respiration data, performed pressure tolerance experiments, developed tools for visualization and analysis of massive data sets, collated metabolic gene sequences from the transcriptomes, and generated diagrams illustrating the relationships between the species. This work will provide a baseline of deep-sea ctenophore biodiversity, which will be important for detecting ecological change in the face of anthropogenic stressors.



Bathyctena chuni *is one of the earliest described deep-sea ctenophore species. They are able to adapt to, not withstand, the great pressure, using proteins that have evolved to function well at those depths.*

DeepPIV: Measuring fluid motion in the deep sea

Project lead: Alana Sherman
Project manager: Kakani Katija
Project team: Jon Erickson, Dale Graves, Chad Kecy, Denis Klimov
Collaborators: James Barry, Anela Choy, and Bruce Robison, MBARI

Marine organisms generate signals that can be observed by predators and prey. In addition to chemical, visual, acoustic, and electromagnetic signals, organisms create and detect hydromechanical cues that elicit a variety of ecologically beneficial behaviors. However, studies of hydromechanical cues in the ocean are lacking due to the difficulty of measuring those processes at appropriate size and time scales in the ocean. To address this need, the team has been developing DeepPIV, an instrument that enables fine temporal and spatial scale measurements of fluid motion in situ. In 2016, DeepPIV was successfully integrated on all of MBARI's ROVs and was used during midwater and benthic cruises. These efforts resulted in expanding the utility of DeepPIV while addressing several science questions related to the ecomechanics of larvaceans and deep-sea corals and sponges. Using DeepPIV, the team was able to measure the filtration rates of two species of giant larvacean (*Bathochordaeus*) in the midwater and flow produced by sponges and corals on Sur Ridge.

Differential Contributions of Archaeal Ammonia Oxidizer Ecotypes in Relation to Their Changing Environment

Project lead: Francisco Chavez
Project managers: Francisco Chavez, Jason Smith
Project team: Marguerite Blum, Tim Pennington
Collaborator: Christopher A. Francis, Stanford University, California

The National Science Foundation funded this collaborative study that involves collecting samples for genetic analysis of the diversity, abundance, and activity of ammonia-oxidizing communities. Samples were collected at stations M1 and M2 during 2016 Monterey Bay time-series cruises. The initial data analyses reveal an increase in nitrogen remineralization, starting after the spring phytoplankton bloom, followed in time with a rise of ammonium and then nitrite in the subsurface waters. Experiments were also conducted during CANON cruises to study the physiology and kinetic traits of wild populations of ammonia-oxidizing microorganisms. An AUV was used to study small-scale variability in nitrification rates and the associated microbial communities.

EarthCube Integrated Activities: Collaborative Proposal: Cross-Domain Observational Metadata Environmental Sensing Network

Project lead/manager: Carlos Rueda-Velasquez
Collaborators: Mike Botts, Botts Innovative Research, Inc., Madison, Alabama; Janet Fredericks, Woods Hole Oceanographic Institution, Massachusetts; Felimon Gayanilo, Texas A&M University, Corpus Christi; Krzysztof Janowicz, University of California, Santa Barbara

The goal of this project, funded by the National Science Foundation, is to promote the capture of metadata about environmental sensors and their deployments such that information on the data source and quality can be determined at every stage of data generation and use. The focus is on making it easier for stakeholders (from sensor manufacturers to data managers and aggregators) to capture and exploit such information. The team implemented a semantic repository and associated tools and enhanced community of users to guide the team's vision and promote the use and assessment of the tools.

Education and Research: Testing Hypotheses (EARTH)

Project lead/manager: George Matsumoto
Collaborators: Corey Garza, California State University, Monterey Bay; Kristin Hunter-Thompson and Janice McDonnell, Rutgers University, Newark, New Jersey

Twenty educators gathered in New Brunswick, New Jersey, for the 2016 EARTH workshop. The workshop was co-hosted by MBARI and Rutgers University with partial funding from the National Science Foundation for Polar Interdisciplinary Coordinated Education. Polar researchers were invited to share information to help teachers bring real data into the school curriculum. Four satellite workshops were hosted by previous EARTH participants, and discussions for further dissemination of EARTH materials and workshop format continued.

Fault Detection, Diagnosis, and Mitigation for Long-Duration AUV Missions with Minimal Human Intervention

Project leads: Brian Kieft, Yanwu Zhang
Project manager: Yanwu Zhang
Project team: Ben Raanan, Jordan Stanway
Collaborators: Mark Abbott and James Bellingham, Woods Hole Oceanographic Institution, Massachusetts

For AUVs to succeed in complex and long-duration missions, they must be reliable in the face of subsystem failures, even when those failures are unanticipated by the programmers or operators. Toward this end, the Office of Naval Research provided funding for developing methods for AUVs to autonomously detect faults and failures, identify the causes, and choose the best response to allow the mission to continue if possible, and at least ensure the vehicle and data are recovered safely. The team designed a diagnostic tool to automatically characterize patterns that relate to vehicle performance, including failures, directly from AUV sensor data gathered on previous operations. The team found that using machine-learning techniques and MBARI's repository of AUV data provided a framework capable of identifying and classifying nominal AUV performance and specific failures with a high probability of detection and few false detections. A key feature of the framework is that it does not rely on expert knowledge, but instead automatically learns the relationship between the executed control policy and the vehicle's performance directly from the data.

Full-Speed *Dorado* Simulator

Project lead/manager: Rob McEwen
Project team: Kent Headley

In the second year of the project, terrain relative navigation (TRN) was added to the AUV simulator and the team increased simulation speed up to 200 times real speed. TRN first records altitude as the vehicle flies, then matches it against an onboard map to provide a position fix. This eliminates the constantly accruing navigation error inherent in dead reckoning, which is especially valuable for the longer deep dives. The team can now simulate various TRN code changes and parameters for a two-hour mission along a canyon wall in about five minutes, and avoid costly sea-trials for every permutation.

Functional and Genomic Diversity in Vitamin B_1 Metabolism and Impacts on Plankton Networks and Productivity

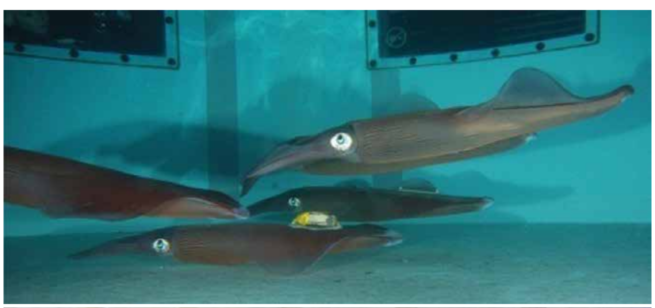
Project leads: Alexandra Worden, Stephen Giovannoni
Project manager: Alexandra Worden
Project team: Magdalena Gutowska, Maria Hamilton, Sebastian Sudek

Many organisms, from humans to some oceanic plankton, need vitamins that are made by other organisms. Thus, in nature there is traffic in vitamins, which move from self-sufficient vitamin producers to consumers that are reliant on the surrounding community. Vitamins are small organic molecules required for metabolism, and therefore they have the potential to alter the health and productivity of entire ecosystems if the supply is insufficient. This research project explores the cycling of vitamin B_1 (thiamin) by planktonic cells at the base of the ocean food chain. This team will study thiamin biochemistry in plankton, using comparative genomics and cell cultures, and it will measure thiamin-related plankton interactions in natural and stimulated phytoplankton blooms. The team focused on planning for cruises in the North Atlantic and North Pacific Oceans and research activities involving graduate students, postdoctoral fellows, and undergraduate students. The project, funded by the National Science Foundation, also includes the creation of a teacher professional development program aimed at preparing low-income, historically underrepresented, and other educationally underserved students from rural areas to pursue science, technology, engineering, and math careers.

A High-Resolution Bio-Sensor to Simultaneously Measure the Behavior, Vital Rates, and Environment of Key Marine Taxa

Project lead/manager: Kakani Katija
Collaborators: Tom Hurst and T. Aran Mooney, Woods Hole Oceanographic Institution, Massachusetts; Kenneth Alex Shorter, University of Michigan, Ann Arbor

To address questions regarding marine animal behavior, physiology, and ecology, the research team developed an innovative biosensor technology—the invertebrate tag, or ITAG—for keystone soft-bodied invertebrates such as squids and jellies. The ITAG simultaneously measures fine-scale animal behaviors and samples high-resolution physical-biogeochemical environmental data. The sensor, affixed to the organism, samples across temporal and spatial scales relevant to the animal, providing vital information about its basic biology and community interactions. The team initially integrated light, temperature, and pressure sensors with accelerometers and magnetometers in a tagging package to study and characterize squid behavior in the laboratory. Project engineers began miniaturizing and testing sensors for dissolved oxygen and salinity, which will be integrated into the new tagging package. The team also tested deployment methods and collected behavioral data of swimming jellyfish at the Monterey Bay Aquarium. The eventual ability to link behavioral and environmental data from free-ranging soft-bodied invertebrates will enable the study of animal activity and climate-related environmental changes—such as ocean acidification and the ocean carbon cycle—that have the potential to significantly affect the health of the ocean. This project is funded by the National Science Foundation.



The invertebrate tagging package (ITAG) affixed to squid (above) and jellyfish (below) maintained in the laboratory.

An Integrated MBARI Time-Series Program

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

MBARI supports three time-series projects that span the water column from the surface ocean through the midwater to the deep seafloor in one of the most productive and economically important areas of the world ocean. The goal of this project is to integrate the information from the three time series, both technically and scientifically. This provides an opportunity to track the flow of energy and organic carbon, including production and utilization, through the water column to the seafloor as well as determining climate-driven ecosystem changes. The team collected data from the major 2015-16 El Niño event and revisited the impact of the 1997-98 El Niño on the local ecosystems. While El Niño's effect on physics is clear, identifying its biological consequences is challenged by biological patchiness and the delayed and non-linear nature of ecosystem response to environmental changes.

Jupiter Foundation/MBARI Collaboration

Project lead: Francisco Chavez
Project manager: Tom O'Reilly
Project team: Brian Kieft, Denis Klimov
Collaborators: Roger Dellor, Kurt Kiesow, Heike Schmitz, and Lisa Ziccarelli, Jupiter Foundation, Los Altos, California

The team of collaborators from the Jupiter Research Foundation and MBARI began work on a Wave Glider-based microscope payload and convened a workshop on mobile cytometers and microscopes (see the cytometer project on page 55). The team also discussed the creation of ducted radio-frequency experiments using an airborne surveillance system.

Life on the Dark Side: Complex Trophic Interactions of Marine Microbial Eukaryotes

Project leads: Alexandra Worden and collaborators Patrick Keeling, Thomas Richards, Alyson Santoro
Project manager: Alexandra Worden
Project team: Susanne Wilken, Chang Jae Choi
Collaborators: Patrick Keeling, University of British Colum-

bia, Vancouver; Thomas Richards, University of Exeter, United Kingdom; Alyson Santoro, University of California, Santa Barbara

Eukaryotic microbes are different from other microbes because they can exhibit significant behavior changes, much like multicellular eukaryotic organisms. This study looks at eukaryotic microbial lifestyles that are often overlooked in marine ecosystems: parasitism, mixotrophy (where organisms can perform photosynthesis and consume other microbes), and saprotrophy (digestion of dead or decayed organic matter). In 2016 the team discovered an important group of predators in the ocean and several new dimensions of mixotrophy as well as new microbial paths of organic matter processing in the ocean. This project was funded by the Gordon and Betty Moore Foundation.

Long-Range AUV: Coordinated Observations of Marine Organisms and Ocean Features

Project leads: Francisco Chavez, Brett Hobson, Chris Scholin, Yanwu Zhang
Project manager: Brett Hobson
Project team: Jon Erickson, Brian Kieft, Denis Klimov, Ed Mellinger, Tom O'Reilly, Ben Raanan, Carlos Rueda-Velasquez

The team focused on transitioning the vehicles from the development phase into routine operations by MBARI science groups. One pilot program is testing whether an LRAUV can replace ship operations for the long-running Monterey Bay Time Series. Good agreement was found between the measurements and samples collected by ship and with a vehicle that ran in parallel with ship operations. The program is also expanding through the Targeted Sampling project (see page 65) and the three new vehicles carrying Environmental Sample Processors for a collaboration with the University of Hawaii (see page 43).

Marine Microbiology Investigator Award

Project lead/manager: Alexandra Worden
Project team: Charles Bachy, Maria Hamilton, Kenneth Hoadley, Valeria Jimenez, Alexander J. Limardo, Yun-Chi Lin, Lisa Sudek

This project involves laboratory and field-based research to further the understanding of phytoplankton genomics, physiology, and population dynamics, interactions with other marine microbes, and how phytoplankton uptake of carbon dioxide will change under natural and human-induced perturbations. Phytoplankton perform half of global primary production yet it is not clear how these communities will respond to global change. This project made major strides in 2016 in understanding responses to high carbon dioxide and nutrient limitations that are predicted under future climate scenarios. Data from cruises between 2007 and 2015 were combined in a synthesis of the Eastern Boundary Current system (currents found on the eastern side of oceanic basins) to identify hot spots of diversity and microbial activity.

Midwater Ecology

Project lead: Bruce Robison
Project manager: Kim Reisenbichler
Project team: Stephanie Bush, Anela Choy, Craig Okuda, Rob Sherlock
Collaborators: Kathrin Bolstad, Auckland University of Technology, New Zealand; Ben Burford, Hopkins Marine Station of Stanford University, Pacific Grove, California; Henk-Jan Hoving, GEOMAR-Helmholtz Centre for Ocean Research, Kiel, Germany; Karen Osborn, Smithsonian Institution, Washington, D.C.; Katie Thomas, Duke University, Durham, North Carolina

The Midwater Ecology Group focused on determining the species composition, ecological structure, and dynamics of the midwater community over Monterey Canyon, as a proxy for the largest animal communities on Earth. In a new thrust of the project Postdoctoral Fellow Anela Choy used bulk stable carbon and nitrogen isotope values to elucidate the trophic structure of the midwater community. Samples of fishes, crustaceans, cephalopods, and jellies were prepared and submitted for analyses. The team continued to use the Midwater Respirometry System to determine the oxygen consumption requirements of key species and conducted behavioral studies, a new sub-discipline of deep-sea research. These studies make it clear that the habitat of midwater communities is changing quickly; gaining the knowledge to predict the consequences is a critical goal of this research program.

Midwater Time Series

Project lead: Bruce Robison
Project manager: Rob Sherlock
Project team: Kim Reisenbichler, Brian Schlining
Collaborators: Steven Haddock, Mike McCann, Monique Messié, Kyra Schlining, and Susan Von Thun, MBARI; Henk-Jan Hoving, GEOMAR-Helmholtz Centre for Ocean Research, Kiel, Germany

This project uses video transect data that provide unique insight into the ecology of mesopelagic animals. Begun in the early 1990s, the time series now exhibits temporal and depth trends for many of the animals annotated. For example, it has become apparent that many species increase in abundance in the late summer/fall. These changes in abundance exhibit a strong seasonal pattern over the depth range of the data, down to 1,000 meters. The seasonal cycle of Monterey Bay has been well-described in regard to the surface waters, and the Midwater Time Series extends that seasonality—and its implications for carbon cycling, nutrient flux, and climate change—into the deeper ocean of Monterey Bay. In 2016 the team continued to make joint transecting dives with the ROV *Ventana* and i2MAP AUV (see page 29) with plans to transition to using the AUV to conduct the time series in 2017.

MiniROV Enhancements

Project leads: Dale Graves, Mike Risi
Project manager: Dale Graves
Project team: Rich Schramm, Brian Schlining

The team successfully implemented a distributed messaging system that allows the MiniROV to connect its control system software code with any platform and any programming language. The system provides opportunities for developing new control algorithms for tracking marine organisms or testing other developments. The team also automated the logging of vehicle data and metadata to the data files, and implemented automatic transfer of the files for storage and retrieval. A third task in 2016 was the development of a scaled-down Video Annotation and Referencing System (VARS) for deployment with the MiniROV. The digital video recorder on the vehicle was linked to VARS to assist with real-time annotation during the dives. The VARS database and video files are transferred to permanent storage on shore at the completion of each expedition.

Molecular Ecology and Evolution of Marine and Aquatic Organisms

Project lead: Robert Vrijenhoek
Project manager: Shannon Johnson
Project team: Corinna Breusing, Julio Harvey, Mike McCann, Kristine Walz
Collaborators: Asta Audzijonyte, Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia; Roxanne Beinart, Woods Hole Oceanographic Institution, Massachusetts; David Caress, Francisco Chavez, David Clague, Steven Haddock, Roman Marin III, Monique Messié, Charles Paull, Tim Pennington, Christina Preston, and Kevan Yamahara, MBARI; Jose Carvajal and Greg Rouse, Scripps Institution of Oceanography, La Jolla, California; Jennifer Fisher and William Peterson, Southwest Fisheries Science Center, Newport, Oregon; Jonathan Geller, Moss Landing Marine Laboratories, California; Magdalena Georgiva and Crispin Little, University of Leeds, United Kingdom; Peter Girguis, Harvard University, Cambridge, Massachusetts; Shana Goffredi, Occidental College, Los Angeles, California; Sook-Jin Jang, Jumin Jun, Won-Kyung Lee, Eunji Park, Yong-Jin Won, and Seon-Jeon Yeon, Ewha Womans University, Seoul, South Korea; Elena Krylova, Shirshov Institute of Oceanology, Moscow, Russia; Steven Morgan and Eric Satterthwaite, University of California, Davis; Karen Osborn, Smithsonian Institution, Washington, D.C.; Thorsten Reusch, HOSST Graduate School, Kiel, Germany; Heiko Sahling, University of Bremen, Germany; Verena Tunnicliffe, University of Victoria, Canada; Anders Warén, Swedish National Museum, Stockholm; Nerida Wilson, Western Australia Museum, Welshpool; Haibin Zhang, University of Science and Technology of China, Hainan

Understanding how populations and species of marine and aquatic organisms are connected in time and space has been the main focus of research by the Molecular Ecology Group. Understanding organismic dispersal and connectivity on evolutionary time scales provides a basis for assessing the uniqueness of individual species and their contributions to global biodiversity. The team transferred samples of animals and associated bacterial symbionts collected during the past 30 years from deep-sea hydrothermal vents and hydrocarbon seeps throughout the world ocean to other research collections. The National Science Foundation funded the curation and transfer of specimens and DNA samples to the Scripps Institution of Oceanography Museum. Other samples will be transferred to the Smithsonian Museum of Natural History.

The project team continued their investigations of biological diversity at the Pescadero Basin and Alarcon Rise hydrothermal vents in the Gulf of California. Studies also focused on tubeworms and their sulfur-oxidizing bacterial symbionts from Mexico to Oregon. High-throughput genetic sequencing methods were coupled with traditional morphological assessments of planktonic diversity in samples from Monterey Bay and along the California margin.

Monterey Accelerated Research System (MARS)

Project lead/manager: T. Craig Dawe
Project team: Ken Heller

The National Science Foundation funds the ongoing operation and maintenance of the MARS cabled observatory deployed on Smooth Ridge in Monterey Bay. The observatory provides access to the deep ocean for engineering testing of instrumentation destined for ocean observatory science worldwide. It was also host to long-term research projects including the Berkeley Seismological Laboratory and MBARI's Monterey Ocean Bottom Broadband Seismometer and a passive acoustic monitoring station (see page 8).

The seismometer experiment terminated in August 2016 due to a loss of connectivity. Funding to recover, repair, and replace the cable is pending. Plans were made for deployment of a geodetic seismic sensor module from the University of Washington Applied Research Laboratory, a bioluminescence detector for an MBARI project, and the redeployment of an MBARI camera and sensor suite. The team began developing a "mininode" that can replace the main electronics and power supply while these units are being refurbished and upgraded. They are also evaluating a spare connector because the current connector could become a potential failure point if the node is recovered for refurbishment.

Mooring Maintenance

Project leads: Francisco Chavez, T. Craig Dawe, Kevin Gomes
Project manager: Jared Figurski
Project team: Paul Coenen, David French, Craig Okuda, Rich Schramm, Chris Wahl

Oceanographic time-series data are fundamental for characterizing baseline conditions of oceans and for monitoring natural and anthropogenic change. MBARI's mooring program has been providing data to internal researchers, the oceanographic community, and the public since 1989. The mooring maintenance project oversees the annual turnaround of the M1 oceanographic buoy and at-sea maintenance during the year. (See photo inside back cover)

National Marine Sanctuaries as Sentinel Sites for a Demonstration Marine Biodiversity Observation Network (MBON)

Project lead/manager: Francisco Chavez
Project team: Shannon Johnson, Mike McCann, Monique Messié, Reiko Michisaki, Kristine Walz, Kevan Yamahara
Collaborators: David Anderson, Aric Bickel, and Jennifer Patterson, Central and Northern California Ocean Observing System, MBARI; Ali Boehme and Collin Closek, Center for Ocean Solutions, Stanford University, California; Steven Bograd, Lynn deWitt, John Field, Elliott Hazen, and Jarrod Santora, National Marine Fisheries Service; Jennifer Brown and Andrew DeVogelaere, Monterey Bay National Marine Sanctuary, Monterey, California; Maria Kavanaugh, Woods Hole Oceanographic Institution, Massachusetts; Frank Muller-Karger, University of South Florida, Tampa

In the second year of this five-year project, water samples for detection of environmental DNA (genetic material collected from the environment rather than isolated from an organism) were collected autonomously on AUVs equipped with sampling canisters. These samples and archived samples from 2008 to 2015 were processed with real-time assays to detect anchovy and diatom genetic sequences. Samples collected with the Environmental Sample Processor and long-range AUV were similarly processed demonstrating that AUVs are a viable method for autonomous collection of environmental DNA samples. The data indicate large numbers of anchovies were present in Monterey Bay from 2013 to 2015 when numerous whale sightings were recorded. At the end of 2016, eDNA samples from the Monterey Bay Time Series were selected for a survey spanning microbes to whales as part of the collaborative, multi-institutional effort to determine how the diversity of organisms at one station changed seasonally over four years.

OASIS5 Applications

Project lead: Craig Okuda
Project manager: Bob Herlien

The OASIS mooring controller is an electronics package that collects data from different instruments and sends these data back to shore in a usable form. The controller has been used in MBARI moorings and respirometers for years, but needs to be periodically updated as components become obsolete. During 2016 the team completed the design and implementation of the various components of the new OASIS5 system. They implemented and tested the hardware and firmware, and ported and tested the overall OASIS software on the resulting system.

The O-Buoy Network of Chemical Sensors in the Arctic Ocean

Project lead/manager: Francisco Chavez
Project team: Jules Friederich, Jeff Sevadjian
Collaborators: Bigelow Laboratory, East Boothbay, Maine; CH_2M Hill, Englewood, Colorado; Cold Regions Research and Engineering Laboratory, Vicksburg, Mississippi; Environment Canada, Toronto; Purdue University, West Lafayette, Indiana; SRI International, Menlo Park, California; University of Alaska, Fairbanks

The National Science Foundation-funded O-Buoy project has designed, built, and deployed 15 buoys in sea ice in the Arctic Ocean as of 2016. These buoys measure three sentinel atmospheric chemicals (carbon dioxide, ozone, and bromine oxide) along with meteorological and other data. This unique network of buoys, coordinated and clustered with other buoys in automated drifting stations, will enable the scientific community to observe and better understand the impact of Arctic sea-surface change on atmospheric chemistry. Independent information on spatial and temporal patterns of carbon dioxide sources and sinks in the Arctic Ocean is of extraordinary value for terrestrial and oceanic carbon cycle flux models as well as atmospheric transport models, and thus improve the ability to predict future regional and global carbon dioxide fluxes. A major accomplishment in 2016 was the generation of final data sets for atmospheric partial-pressure carbon dioxide (pCO_2) with a high degree of accuracy that is unprecedented for an autonomous system in the Arctic Ocean.

Ocean Acidification and Hypoxia Mooring in the Southern California Bight

Project lead/manager: Francisco Chavez
Project team: Jules Friederich, Jeff Sevadjian, Chris Wahl
Collaborators: Orange County Sanitation District, Newport Beach, California

This collaborative project, funded by the Orange County Sanitation District, serves to build and improve instrumentation and moorings to measure ocean acidification and hypoxia (low oxygen) in relation to other environmental variables in the Southern California Bight. From late 2015 through 2016, an instrumented mooring designed and built by MBARI was deployed twice off Newport Beach, collecting five months of continuous measurements. MBARI staff also trained the sanitation district employees and provided expertise in evaluation and synthesis of the collected data. The next mooring to be deployed will use the latest OASIS controller, providing valuable experience in at-sea operations.

Ocean Imaging

Project leads: David Caress, Charles Paull
Project manager: David Caress
Project team: Larry Bird, Doug Conlin, Andrew Hamilton, Rich Henthorn, Brett Hobson, William Kirkwood, Eric Martin, Mike Risi, Monica Wolfson Schwehr, Hans Thomas, Erik Trauschke
Collaborators: Giancarlo Troni, Pontificia Universidad Católica de Chile, Santiago

The existing low-altitude ocean imaging system on the ROV *Doc Ricketts* was deployed from the R/V *Western Flyer* in 2016 for repeat surveys in Monterey Canyon as part of the Coordinated Canyon Experiment. On cruises in May and October the team surveyed a roughly 100-meter-by-100-meter area around the benthic instrument node deployed amongst sediment waves at 1,850 meters depth in Monterey Canyon, repeating a survey initiated in December 2015 (see the Continental Margins project on page 54). The project team designed, fabricated, and tested a new articulating mount for the survey system on ROV *Ventana*. This mount allows the survey system to rotate from down-looking to forward-looking so that the system can be kept at right angles to the seafloor while surveying flat to vertical terrain. Initial tests were successful in automatically articulating the survey frame while running survey lines.

Outline Video Annotation and Video Technical Advisory Group (TAG)

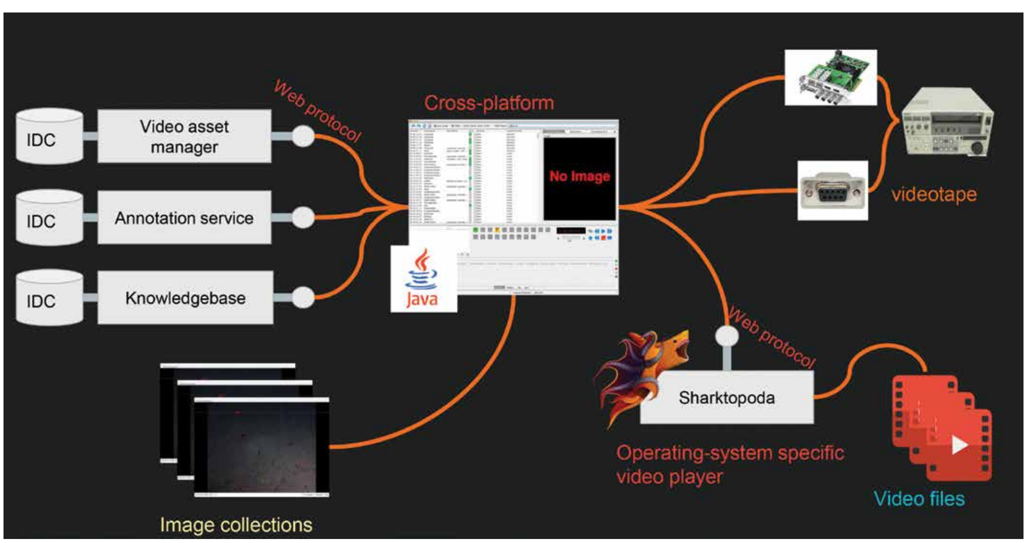
Project leads: John Ryan and Brian Schlining (Annotation); Duane Edgington and Danelle Cline (TAG)
Project manager: Nancy Jacobsen Stout
Project team: Neil Conner, Linda Kuhnz, Lonny Lundsten, Mike McCann, Todd Ruston, Kyra Schlining, Rich Schramm, Susan von Thun

Significant 2016 milestones for the new MBARI Media Management system included the installation and testing of new video-capture equipment aboard the R/V *Rachel Carson*, a major project design review, and significant hardware and software developments for video file storage, management, and playback. Working in collaboration with MBARI's Video TAG, efforts to explore and develop automated detection and classification methods continued, including fostering partnerships with key experts in industry and research. Using the Video Annotation and Reference System (VARS), video laboratory staff annotated over 500 hours of new video in 2016, bringing the current number of individual observations in the database to nearly 5.3 million catalogued over more than 29 years. These data, the VARS software, and the Deep-Sea Guide remain publicly available and are used by researchers around the world. For example, the US Army Corps of Engineers identified VARS as a tool to be used in the Portland District civil engineering program.

Park-n-Fly AUV for Long-Term Surveys in Extreme Environments

Project leads: Charles Paull, Ken Smith
Project manager: Brett Hobson
Project team: Kent Headley, Rich Henthorn, Rob McEwen, Paul McGill, Alan Sherman, Hans Thomas

This project is investigating the concept of a persistent presence in the deep ocean by an AUV that would conduct seasonal seafloor imaging and bioacoustics surveys at the 4,000-meter-deep Station M site and remain at the site (See story on page 34). The initial plan is to conduct a normal 17-hour *Dorado* AUV mission, but spread those operational hours over one year with long hibernation periods during which the AUV would be securely parked near the seafloor. During 2016 the team initiated long-term tests to uncover possible damage to the buoyancy foam by the continuous high pressure or energy loss from the batteries over a yearlong deployment. Field tests of the candidate AUV science payload were also run at Station M, and the design concept for the AUV, its parking station, and the deployment methods were being developed in advance of design reviews in 2017.



Updated software components of MBARI's Video Annotation and Reference System (VARS) will be joined with new video capture and management modules as well as a vast storage infrastructure to form the MBARI Media Management System (M3).

Precision Control Technologies for ROVs and AUVs

Project leads: Brett Hobson, Mike Risi, Steve Rock
Project manager: Steve Rock
Project team: David Caress, Rich Henthorn, Rob McEwen, Charles Paull, Hans Thomas

The team improved the automated pilot aids on the ROVs used by the Ocean Imaging Project to perform large area seafloor surveys with stereo cameras, sonars, and lidar. It also developed and field-tested a first version of a control system for long duration autonomous tracking of midwater targets. A target application for this work is deployment on a National Science Foundation-funded vehicle (the Mesobot) being developed under a joint, multi-year effort with Woods Hole Oceanographic Institution. The team's work with AUVs included continued development of algorithms to make the capability of terrain-relative navigation more robust and reliable. In addition to supporting field deployments of this capability, efforts focused on developing a new technique for mission planning that would identify intermediate waypoints that maximize the probability an AUV will reach its target location when performing return-to-site missions such as monitoring sites for change. Other work focused on enhancing an AUV control system to improve the safety of operation when flying close to the seafloor on imaging missions.

Quantifying Nutrient-Virus-Phytoplankton Interactions and Their Impacts on Marine Biogeochemistry

Project leads: Alexandra Worden and collaborators Maureen Coleman, Seth John, Matthew Sullivan, and Jacob Waldbauer
Project manager: Alexandra Worden
Project team: Charles Bachy, Lisa Sudek, Charmaine Yung, Amy Zimmerman
Collaborators: Maureen Coleman and Jacob Waldbauer, University of Chicago, Illinois; Seth John, University of Southern California, Los Angeles; Matthew Sullivan, Ohio State University, Columbus

Viruses in the ocean infect and rupture marine phytoplankton. This project is focused on developing fundamental insights into viral infection processes and how viral infection is modulated under nutrient-limiting conditions. It addresses both viruses infecting cyanobacteria and viruses infecting eukaryotic phytoplankton. Field experiments were performed in Monterey Bay and the North Atlantic, new viruses were isolated and genome sequenced, and whole genome-level analyses were performed that investigate both host and virus responses to generate a synthesis that crosses multiple domains of life and key marine taxa. The project was funded by the Gordon and Betty Moore Foundation.

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

Project leads: James Birch, John Ryan, Chris Scholin
Project manager: John Ryan
Project team: Holly Bowers, Francisco Chavez, Kevin Gomes, Brett Hobson, 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 Alyssa Gellene, University of Southern California, Los Angeles; Yi Chao, University of California, Los Angeles, and Remote Sensing Solutions, Inc., Monrovia, California; Greg Doucette, National Oceanic and Atmospheric Administration/National Ocean Service, Charleston, South Carolina; Raphael Kudela, University of California, Santa Cruz; G. Jason Smith, Moss Landing Marine Laboratories, California

An economically devastating harmful algal bloom (HAB), involving extensive closure of fisheries, affected much of the northeast Pacific coast in 2015. This algal bloom occurred during the prolonged oceanic temperature anomaly known as a mid-latitude marine heat wave—or more colloquially as the "warm blob." Caused by diatoms of the genus *Pseudo-nitzschia*, this event produced the highest particulate concentrations of the biotoxin domoic acid ever recorded in Monterey Bay. As MBARI worked in collaboration with a multi-institutional team funded by the National Oceanic and Atmospheric Administration, extensive multidisciplinary observations were acquired in Monterey Bay during the event. MBARI's ecosystem time-series data enabled researchers to explain a key cause of this bloom. A quarter century of MBARI nutrient measurements in Monterey Bay revealed that the HAB occurred in a chemically anomalous environment. The nutrient silicate was disproportionately depleted relative to other nutrients during the prolonged warm anomaly. This depletion turned to exhaustion when the bloom of toxigenic diatoms occurred, as diatoms build their cell walls from silicate. Previous laboratory and field studies have shown that silicate limitation can increase toxin production in *Pseudo-nitzschia*. This observational finding not only helps to explain the exceptional nature of this HAB, but also guides development of HAB modeling and prediction.

Responses of Atmospheric Oxidants and CO_2 to Dramatic Changes in Arctic Sea Ice

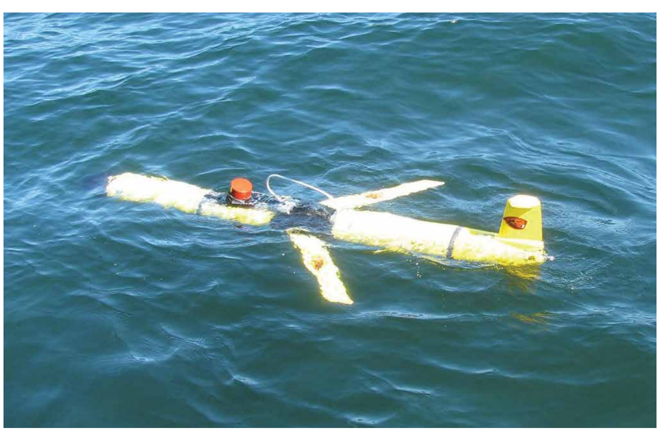
Project lead/manager: Francisco Chavez
Project team: Jeff Sevadjian
Collaborators: Bigelow Laboratory, East Boothbay, Maine; Cold Regions Research and Engineering Laboratory, Vicksburg, Mississippi; Florida State University, Tallahassee; Purdue University, West Lafayette, Indiana; University of Alaska, Fairbanks

This analysis project, funded by the National Science Foundation, enables scientific progress from the novel and highly successful O-Buoy observational efforts (see page 61). Chemical, meteorological, and other data collected by these O-Buoys are being analyzed to determine when, and under what meteorological conditions, partial-pressure of carbon dioxide (pCO_2) in the Arctic Ocean deviated from that on land. An initial focus is to relate chemical observations to changes in sea-ice cover. Atmospheric carbon dioxide absorption into seawater, moderated by the sea-ice cover, causes acidification of the waters and drawdown of climate-warming carbon dioxide. For these reasons, it is expected that the atmosphere and its chemistry will respond in a complex manner to sea-ice change and Arctic warming, but researchers lack the ability to make predictions with confidence, given only basic, or worse, mechanistic understanding of the relevant processes. Modeling of long-range air mass transport will be combined with the O-Buoy measurements to develop a region-wide understanding of the relationship between the atmosphere and sea ice.

Revolutionizing Our Understanding of Ocean Ecosystems

Project lead: Kelly Benoit-Bird
Project manager: Chad Waluk
Collaborators: Jack Barth and Geoffrey Hollinger, Oregon State University

Marine ecosystems are complex, driven by processes that are patchy, dynamic, and ephemeral. A team of engineers and scientists aims to change how to observe and understand complex, undersampled marine ecosystems. The goal is to unify low-power bioacoustic sensors and long-endurance underwater gliders to develop onboard control algorithms that guide the gliders to respond dynamically to complex ocean food webs, and to showcase the strength of this approach in a series of ocean experiments. Creating a persistent smart-sensor platform that allows researchers to detect undersea features will make it possible to find the transient biological hot spots that drive ecosystem processes over scales relevant to fisheries management, endangered species protection, climate change response, and new ocean uses such as renewable energy. In 2016, the team completed the integration of a prototype low-power echosounder into the glider, reduced electrical noise in the system (which increased the range from an initial limit of 50 meters to approximately 150 meters) and calibrated the sensors in the seawater test tank. Integration culminated in a successful 24-hour field test off the Oregon Coast. The data quality from this mission is exceptional, providing spatial resolution and dynamic range significantly exceeding original design specifications. This project is funded by the Keck Foundation.



The newly integrated acoustic glider at the surface on its first at-sea test.

SeeStar Camera

Project lead: Steven Haddock
Project manager: Chad Kecy
Project team: François Cazenave, Danelle Cline, Thom Maughan

The team concentrated on the design of the third-generation SeeStar camera system. A number of portable imagers were evaluated as replacements to the current camera. Work also began on a sensor module; this is an optional housing that allows the user to add oceanographic instruments to complement the captured images. A number of commercial off-the-shelf central processing units were also evaluated as the control boards in the camera and sensor modules.

Shallow-Water Free Ocean Carbon Dioxide Enrichment (FOCE) System Science

Project leads: James Barry, William Kirkwood
Project manager: George Matsumoto
Project team: Peter Brewer, Bob Herlien, Chad Kecy, Chris Lovera, Edward Peltzer, Karen Salamy, Jim Scholfield, Farley Shane, Peter Walz
Collaborators: Paul Leary, Steve Litvin, Nik Myers, Steve Palumbi, and Judy Thompson, Hopkins Marine Station of Stanford University, Pacific Grove, California

The shallow-water FOCE system was removed from Monterey Bay in 2016 in preparation for a thorough system and design review before the system goes back out into the field. The system is designed to enable experiments on the effects of ocean acidification on natural seafloor biological assemblages.

Tactical Undersea Network Architectures

Project leads: Andrew Hamilton and collaborator Andrew Stewart, University of Washington Applied Physics Laboratory, Seattle
Project manager: Andrew Hamilton
Project team: François Cazenave, John Ferreira
Collaborators: Columbia Power Technologies, Corvallis, Oregon

In this project, MBARI provided engineering and testing support to the University of Washington's efforts to apply wave-energy conversion technology to the larger Defense Advanced Research Projects Agency (DARPA) goals of a persistent undersea network. This DARPA project shares some of the goals of the MBARI wave-energy conversion efforts and has thus benefitted from MBARI experience, computational tools specific to the wave-energy conversion problem, and testing infrastructure. Successful test-tank and at-sea testing took place at MBARI in August 2016.

Targeted Sampling by Autonomous Underwater Vehicles

Project leads: Francisco Chavez, John Ryan, Chris Scholin, Robert Vrijenhoek, Yanwu Zhang
Project manager: Yanwu Zhang
Project team: Brett Hobson, Brian Kieft, Denis Klimov, Rob McEwen, Ed Mellinger, Carlos Rueda-Velasquez, Jordan Stanway, Chris Wahl
Collaborators: James Bellingham, Woods Hole Oceanographic Institution, Massachusetts

Traditional ship-based methods for detecting and sampling dynamic ocean features, such as fronts, are often laborious and challenging, and long-term tracking of such features is practically impossible. This project is developing methods to enable AUVs and autonomous surface vehicles to autonomously, yet collaboratively, detect and sample ecologically important oceanographic processes by using onboard sensors and water sample acquisition systems. Scientific insights into a variety of ocean processes are used to derive real-time algorithms for carrying out targeted sampling activities while taking maximum advantage of the vehicles' flexible behaviors and growing endurance. A targeted sampling capability allows researchers to direct a limited number of marine assets to specific regions of interest and collect desired measurements and samples absent a human presence. Progress made to date is exemplified by peak sample capture in chlorophyll patches, detection and tracking of coastal upwelling fronts, and sampling with an Environmental Sample Processor in the AUV at chlorophyll peaks. Targeted sampling has demonstrated its value in enhancing the efficiency and accuracy of ocean studies, leading to new scientific findings.

Three Species of Cephalopods

Project lead: Stephanie Bush
Project manager: George Matsumoto
Project team: Anela Choy, Kim Reisenbichler, Bruce Robison, Rob Sherlock
Collaborators: Paul Clarkson, Bret Grasse, Michelle Kaiser, John O'Sullivan, Taylor Sakmar, and Ellen Umeda, Monterey Bay Aquarium

The team collected deep-sea cephalopods for display in the Monterey Bay Aquarium's *Tentacles* exhibit, exposing the public to the lives of animals that few people have previously had the opportunity to see and learn about. The team has had continued success in encountering the flapjack octopus *Opisthoteuthis* sp. A, and made improvements in keeping this species in captivity, with one individual retained for 52 days. With additional observations, the researchers have learned more about the ecology and behavior of this species. While *Opisthoteuthis* sp. A is not a strong swimmer, the team found that both juveniles and adults spend more time in the water column when current speeds are high, allowing themselves to be carried to different locations, presumably in search of food and potential mates. Additionally, despite efforts to find these octopuses across their known depth range, the majority have been located very close to 400 meters depth.

Juvenile (left) and adult (right) flapjack octopus, Opisthoteuthis *sp. A.*

Torquaratorid Acorn Worm Diversity and Ecology

Project lead/manager: Karen Osborn
Project team: Linda Kuhnz
Collaborators: Nick Holland, Scripps Institution of Oceanography, La Jolla, California

Torquaratorid acorn worms are abundant and diverse members of deep seafloor communities around the world. Their numbers and feeding habits indicate that they are ecologically important members of these communities. The team has accumulated a wide selection of specimens and has already described three new genera and six more species within the family. In 2016 they sequenced a wide variety of specimens from all over the world to create an updated and much expanded molecular phylogeny for the group. This phylogeny is essential to determine the relatedness of all of the new species to those described so far and to define the higher taxonomy so we are able to describe and name examples of the remaining genera. The team also began work on the descriptions of two new species and their unusual symbionts—other animals that live in close association with the acorn worms.

This new acorn worm species being described is from the Gulf of California. Spherical eggs released by the mature female can be seen as well as a teardrop-shaped flatworm symbiont. These symbionts are surprising for two reasons, they live at depths well below any previously described and they are internal symbionts.

Vehicle Persistence

Project lead/manager: Matt Kemp
Project team: Dale Graves, Eric Martin, Mike Parker, Ben Raanan

Improvements in vehicle persistence—the ability to remain operative for a period of time—are not keeping pace with future ocean sensing needs. This new MBARI research group has begun examining ways of mitigating this with the development of a hardware module capable of detecting vehicle faults before they occur.

Wave-Energy Conversion for Oceanographic Applications

Project lead/manager: Andrew Hamilton
Project team: François Cazenave, Jon Erickson, John Ferreira, Rich Henthorn, Scott Jensen, Denis Klimov, Eric Martin

The wave-energy buoy developed under Defense Advanced Research Projects Agency (DARPA) funding is capable of harvesting wave energy for powering oceanographic instrumentation. In 2016, the engineers tackled elements of station-keeping through analysis and at-sea testing. (See story page 42)

Wave Glider Hot Spot

Project leads: Brian Kieft, Tom O'Reilly
Project manager: Tom O'Reilly
Project team: Mark Chaffey, Chris Wahl
Collaborators: Ed Delong, University of Hawaii, Honolulu; Ivan Masmitja and Joaquin del Rio, Polytechnic University of Catalunya, Spain; Christoph Waldmann, Bremen University, Germany; David White, National Oceanography Centre, Southampton, United Kingdom

This project provides a communications relay and acoustic geolocation tracking functions on a Liquid Robotics Wave Glider. This communications hub supports a range of MBARI science projects, retrieving data and monitoring the health of at-sea equipment without requiring a crewed ship to visit the experiment site. The communication links also provide an interactive console, allowing shore-based users to log into the Hot Spot via cellular network or satellite and from there to other vehicles and sensors, so that the user can perform manual data retrieval, system reconfiguration, troubleshooting, and other tasks, without the need for a ship or physical recovery. The project team has developed software that executes on the Hot Spot's main computer, including utilities that automatically transfer data over communication links, and applications that autonomously navigate the Wave Glider to geolocate and follow acoustic targets.

Wave Glider Sensor Payload Box and Tow Body Engineering

Project leads: Francisco Chavez, Thom Maughan
Project manager: Thom Maughan
Project team: Doug Conlin, Bob Herlien, Craig Okuda

MBARI has been designing, engineering, and deploying moorings for over two decades. This project aims to leverage the recently developed OASIS5 mooring controller (see page 61) hardware and software on the Wave Glider autonomous surface platform. Progress to date has been on mechanical integration of the OASIS5 hardware in a Wave Glider Sensor payload box. The tow body attaches to the Wave Glider and provides a vehicle for instrument integration four meters below the surface. In 2016 the team began integrating embedded high-performance computing hardware in a custom housing.

Wireless Power and Data Wet Mateable Instrument Connector

Project leads: James Barry, Thom Maughan, Edward Peltzer
Project manager: Thom Maughan

Instruments on ocean-deployed platforms that require periodic maintenance or calibration require connectors that can be joined in water in order to remove and replace the instrument without pulling the platform. Wet mateable connectors are expensive and have reliability issues such as corrosion, limited mating cycles, and electrical faults. A novel approach to the problem has been invented at MBARI (patent US20120175969) that uses wireless power and data transfer through an impervious plastic housing as a connector. This project team succeeded in building working prototypes of this connector for use with low-power (below five watts) ocean instruments.

Invited Lectures

James Barry
Citizens' Climate Lobby, Monterey, California

Monterey Bay Aquarium, Monterey, California

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

Monterey Bay Regional Climate Summit, Monterey, California

Western Society of Naturalists Meeting, Monterey, California

Kelly Benoit-Bird
San Francisco State University, Tiburon, California

University of Aberdeen, Scotland

Vetlesen Distinguished Lecture, University of Rhode Island, Kingston

Aric Bickel
University of California, Davis

Peter Brewer
Royal Society Discussion Meeting, London, United Kingdom

Francisco Chavez
Argentina-US Ocean Science Meeting, Mar del Plata, Argentina

AtlantOS Biodiversity and Fisheries Workshop, Kiel, Germany

Bluefin Futures Symposium, Monterey, California

Eminent Scholar Lecture Series, University of South Florida, Tampa

The Diane Rehm Show, National Public Radio

University of Bremen, Germany

University of Algarve, Faro, Portugal

Anela Choy
National Academies of Sciences Ocean Studies Board, Washington, D.C.

Smithsonian Institution, Washington, D.C.

Brown University, Providence, Rhode Island

University of Massachusetts, Boston

David Clague
American Geophysical Union Fall Meeting, San Francisco, California

Danelle Cline
Ocean Networks Canada, British Columbia

Judith Connor
Monterey Bay Aquarium, Monterey, California

San Jose State University, California

Duane Edgington
Keynote, IEEE Annual General Meeting, University of Victoria, British Columbia, Canada

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

Magdalena Gutowska
GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

Steven Haddock
California State Summer School for Mathematics and Sciences, Santa Cruz

Ctenopalooza Workshop, St. Augustine, Florida

San Francisco State University, California

Seymour Marine Discovery Center, Santa Cruz, California

University of California, Santa Cruz

Ken Johnson
Bermuda Institute of Ocean Science, St. Georges

Keynote, Global Climate Observing System Conference, Amsterdam, the Netherlands

Laboratoire d'Océanographie de Villefranche, Villefranche-sur-Mer, France

Sustained Observations for Carbon Cycle Science and Decision Support, Boulder, Colorado

US Ocean Carbon and Biogeochemistry Summer Workshop, Woods Hole, Massachusetts

Kakani Katija
American Physical Society, Portland, Oregon

American Society of Limnology and Oceanography Ocean Sciences, New Orleans, Louisiana

Boise State University, Idaho

California State University, Monterey Bay, Seaside

Hopkins Marine Station of Stanford University, Pacific Grove, California

Occidental College, Los Angeles, California

Society of Integrative and Comparative Biology, Portland, Oregon

University of British Columbia, Vancouver, Canada

University of California, Berkeley

University of Hawaii, Manoa

William Kirkwood

Ocean Technology Conference Asia, Kuala Lumpur, Malaysia

Sea Tech Week, Brest, France

Singapore Autonomous Underwater Vehicle Challenge

Séverine Martini

Mediterranean Institute of Oceanography, Bordeaux, France

George Matsumoto

2nd European Conference on Scientific Diving, Kristineberg, Sweden

Center for Excellence in Education, Gilroy, California

Ctenopalooza Workshop, St. Augustine, Florida

Keynote, International Association of Amusement Parks and Attractions, Orlando, Florida

Monterey Bay Aquarium, Monterey, California

Monterey Bay National Marine Sanctuary program, Carmel, California

Oceans 2016 Conference, Monterey, California

Pajaro Valley Unified School District, Watsonville, California

SpectorDance, Monterey Museum of Art, California

Monique Messié

Summer School in Senegal: Ecology of Eastern Boundary Upwelling Systems, Saint-Louis

US Climate Variability and Predictability Program

Tom O'Reilly

Wave Glider User Meeting, Monterey, California

SeaTech Week, Brest, France

Charles Paull

American Geophysical Union Fall Meeting, San Francisco, California

INCISE International Submarine Canyon Symposium, Victoria, Canada

International Geological Congress, Cape Town, South Africa

International Symposium on Seafloor Observations, Qingdao, China

Korean Polar Research Institute, Inchon, Korea

Marine Technology Conference, Busan, Korea

Northern California Geological Society, Orinda, California

Taiwan Ocean Research Institute, Kaohsiung

Bruce Robison

GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

Golden State Waters Action Summit, The Bay Institute, San Francisco, California

Middlebury Institute of International Studies, Monterey, California

National Academies Keck Futures Initiative Conference, Beckman Center, Irvine, California

Steve Rock

Catch the Next Wave Conference, London, United Kingdom

Brian Schlining

Underwater Video Working Group, University of Rhode Island, Kingston

Susan von Thun

Citizen Science Symposium, Aquarium of the Pacific, Long Beach, California

Alexandra Worden

Centre for Microbial Diversity and Evolution, Victoria, Canada

GEOMAR Helmholtz Centre for Ocean Research, Kiel, Germany

International Symposium on Microbial Ecology, Montreal, Canada

Massachusetts Institute of Technology, Cambridge

Moss Landing Marine Laboratories, California

Stanford University, California

University of California, Santa Cruz

Yale University, New Haven, Connecticut

Yanwu Zhang

University of Porto, Portugal

Amy Zimmerman

Moss Landing Marine Laboratories, California

Mentorships

James Barry

Charles Boch, postdoctoral fellow (effects of current and future upwelling variability on abalone life history)

Josh Lord, postdoctoral fellow (ecological community responses to warming and ocean acidification)

Daryll Carlson, undergraduate student, Stanford University (effect of warming and ocean acidification on juvenile abalone growth and calcification)

Crystal Ng, PhD student, Stanford University (effect of acidification and hypoxia on interactions between giant kelp [*Macrocystis pyrifera*] and some of its grazers [amphipods, snails])

James Barry, Charles Boch

Aileen San, undergraduate summer intern, California State University, Monterey Bay (carry-over effects of fertilization in stressful conditions on red abalone, *Haliotis rufescens*, larval development)

Tiffany Thisner, undergraduate summer intern, California State University, Monterey Bay (effects of ocean acidification on sperm motility in the red abalone *Haliotis rufescens*)

Kelly Benoit-Bird

Mei Sato, postdoctoral research associate, Oregon State University (biophysical dynamics in upwelling ecosystems)

Elan Portner, PhD student, Stanford University (El Niño impacts on midwater forage resources and predator-prey dynamics)

Aric Bickel

Desmond Ho, graduate summer intern, University of California, Santa Barbara (connecting science with the public: utilizing different avenues to convey science)

Peter Brewer, Edward Peltzer

Matthew Wojciechowicz, graduate summer intern, Dartmouth College (advanced MATLAB techniques for Raman spectral processing)

David Caress, Charles Paull

Monica Wolfson Schwehr, postdoctoral fellow (high-resolution seafloor mapping)

Francisco Chavez

Bryce Corbett, undergraduate summer intern, Southern Illinois University (exploring eDNA methodologies as a way to detect relationship between anchovies and krill in Monterey Canyon)

Kathleen Pitz, postdoctoral fellow (measurement of biodiversity through environmental DNA analysis)

Alice Ren, MS student, University of Maine, Orono (declining oxygen concentrations in the California Current)

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

Anela Choy

Jesse Suggs, undergraduate student, California State University, Monterey Bay (mercury levels in micronekton species of Monterey Bay)

David Clague

Ruohan Gao, PhD awarded, University of Texas at Austin (storage, fractionation, and melt-crust interaction of basaltic magmas at oceanic and continental settings)

Morgane le Saout, postdoctoral fellow (segmentation and structure of mid-ocean ridges revealed by high-resolution mapping)

Christina Maschmeyer, MS awarded, University of South Carolina (automated lava flow classifier using high-resolution bathymetry and side-scan data)

Danelle Cline, Duane Edgington

Dallas Hollis, California State University, Sacramento (automated detection of deep-sea animals)

Danelle Cline, Chad Kecy

Doug McLeod, undergraduate student, California Polytechnic State University, San Luis Obispo (design and test of an underwater sensor module)

Danelle Cline, John Ryan

Ellen Jacobs, undergraduate summer intern, University of California, San Diego (a comparison of detection and classification techniques of Cuvier's beaked whales in passive acoustic monitoring data)

Kim Fulton-Bennett

Teresa Carey, graduate student, University of California, Santa Cruz

Steven Haddock

Liza Gomez-Daglio, PhD student, University of California, Merced (biodiversity and phylogeography of shallow-water jellyfish)

Cheyenne Payne, undergraduate summer intern, University of California, San Diego (characterizing and defining the optimal conditions for select protist photoprotein activity and testing for photoprotein activity in doliolid tunicates)

Séverine Martini, postdoctoral fellow (bioluminescence: from biological surveys to organism detection)

Alex Damian Serrano, PhD student, Brown University (evolution of predation in siphonophores)

Darrin Schultz, PhD student, University of California, Santa Cruz (genomes of luminous organisms)

Holly Swift, PhD student, University of California, Merced (plankton evolution and genetics)

Jacob Winnikoff, PhD student, University of California, Santa Cruz (biochemical and physiological adaptation to the deep sea)

Cristine Huffard, Linda Kuhnz, Ken Smith

Danielle Fabian, summer intern, California State University (deep-sea epibenthic echinoid [*Echinocrepis rostrate*]: indicators of change on the deep-sea floor)

Kakani Katija

Nadege Aoki, undergraduate student, Cornell University (swimming behavior of the pelagic worm *Tomopteris*)

Natalia Mushegian, undergraduate student, University of California, Berkeley (swimming biomechanics of the pelagic worm *Tomopteris*)

Kakani Katija, Bruce Robison

Diana Li, PhD student, Stanford University (jet propulsion of squid larvae)

Chad Kecy

Sean Carter, undergraduate student, California Polytechnic State University, San Luis Obispo (design and test of a smart NiMH battery charger)

Brian Kieft, Tom O'Reilly

Ivan Masmitja, PhD student, Polytechnic University of Catalunya (onboard algorithms to automatically geolocate underwater acoustic targets from a moving hot spot)

Linda Kuhnz

Christian Luna, Michelle Ramirez, and Oscar Sanchez, high school students, Watsonville High School (how does the amount of dissolved oxygen and levels of turbidity affect the abundance and diversity of crabs in Elkhorn Slough?)

Seventy students in the Watsonville Area Teens Conserving Habitats program, Aptos High School, Pajaro Valley High School, and Watsonville High School (experimental design and random sampling protocols)

Gene Massion

Nicholas Raymond, graduate summer intern, University of California, Davis (evaluation of inertial measurement unit performance for water column velocity estimation of coastal profiling floats)

George Matsumoto

Marcus Chavez, Samantha Reynoso, and Brenna Roby, high school students, Watsonville High School (how do tides affect biodiversity in the mudflats?)

Valeria Chavez-Aguilar, Sergio Hernandez, and Maria Martinez, high school students, Watsonville High School (how does *Ulva* affect species diversity within the pickleweed at Elkhorn Slough?)

Mike McCann

Noemi Cuin, Lesly Garcia, Jose Sanchez, and Samuel Villavicencio, undergraduate students, California State University, Monterey Bay (adding "Contour Plot" radio buttons to STOQS user interface)

Leobardo Lara, Bilal Sattar, and Juan Vargas, undergraduate students, California State University, Monterey Bay ("Cardboard" mode viewing of spatial-3D scenes in STOQS)

Vitou Pen and Devon Rusconi, undergraduate students, California State University, Monterey Bay (building predictive models for classifying measurements in STOQS)

Monique Messié

Alaina Smith, undergraduate summer intern, University of Hawaii at Manoa (factors affecting plankton type dominance in Monterey Bay)

Melinda Nakagawa

Sam Aruiza, Maritza Eguiza, and Isaac Ruiz, high school students, Watsonville High School (how does the speed of water flow affect the diversity of plankton population?)

Charles Paull

Cristian Carvajal, postdoctoral fellow (stratigraphic evolution of deep-sea channels)

Zachary Sickman, PhD student, Stanford University (detrital zircon geochronology of grains found within Monterey Canyon)

William Symons, PhD student, University of Southampton (how well do sediment traps reflect the deposits on the canyon flanks?)

Tim Pennington

Gabriela Chavez, summer intern, New York University (ocean variability in Monterey Bay, California, and connections to global climate, 1989-2016)

Bruce Robison

Alicia Bitondo, MS student, Moss Landing Marine Laboratories (developmental and ecological changes in juvenile and subadult *Chiroteuthis calyx*)

Ben Burford, PhD student, Stanford University (the use of chromatophore displays by the Humboldt squid for intraspecific communication)

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

Anela Choy, postdoctoral fellow (pelagic food web structure using stable isotopes and amino acids; mercury and plastics as pelagic pollutants)

Svenja Christiansen, MS student, University of Kiel (distribution, eddy association, and biogeochemical importance of the pelagic polychaete *Poeobius sp.* in the tropical Atlantic)

Katie Thomas, PhD student, Duke University (eyes and vision of the mesopelagic squid *Histioteuthis heteropsis*)

Steve Rock

Marcus Hammond, PhD student, Stanford University (benthic and iceberg mapping using AUVs)

Sarah Houts, PhD student, Stanford University (safe low-altitude operation of AUVs in uncertain terrain)

Stephen Krukowski, PhD student, Stanford University (optimized trajectories for terrain-relative navigation)

Aditya Mahajan, PhD student, Stanford University (feature-based navigation)

Jose Padial, PhD student, Stanford University (terrain relative navigation using imaging sonars)

David Stonestrom, PhD student, Stanford University (benthic and iceberg mapping using AUVs)

Adam Wiktor, PhD student, Stanford University (automated tracking of midwater animals)

Carlos Rueda-Velasquez

Elijah Meckler, undergraduate summer intern, Williams College (implementation of a domain-specific language for long-range AUV *Tethys* mission scripts)

Ken Smith

Larissa Lemon, MS student, California State University, Monterey Bay (growth and reproduction of abyssal holothurians in the Northeast Pacific)

Drew Burrier, graduate summer intern, Moss Landing Marine Laboratories (an examination of the physical setting at Station M via the Benthic Rover)

Susan von Thun

Jennifer Valenzuela, undergraduate summer intern, San Jose State University (communicating science to public audiences)

Robert Vrijenhoek

Corinna Breusing, PhD awarded, GEOMAR, University of Kiel (symbiont diversity and host-symbiont specificity in Pacific deep-sea tubeworms)

Alexandra 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)

Rachel Harbeitner Clark, PhD student, University of California, Santa Cruz (deep-sea eukaryotic life)

María Corrochano-Luque, undergraduate summer intern, University of Seville (examining the possibility of phagotrophy in the polar alga *Micromonas* sp.)

Charlotte Eckmann, PhD student, University of California, Santa Cruz (ecology of phytoplankton)

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

Maria Hamilton, PhD student, University of California, Santa Cruz (ecology and physiology of polar eukaryotes)

Kenneth Hoadley, postdoctoral fellow (photobiology of picoeukaryotes)

Valeria Jimenez, PhD awarded, University of California, Santa Cruz (ecology of photosynthetic eukaryotes)

Alexander J. Limardo, MS awarded, University of California, Santa Cruz (speciation among green algae and environmental factors influencing growth)

Yun-Chi Lin, postdoctoral fellow (distribution and community structure of photosynthetic eukaryotes)

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

Charmaine Yung, postdoctoral fellow (genomic analysis of marine microbial eukaryotes and their associated bacteria)

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

Publications

Anderson, C.R., R.M. Kudela, M. Kahru, Y. Chao, L.K. Rosenfeld, **F.L. Bahr, D.M. Anderson**, and T.A. Norris (2016). Initial skill assessment of the California Harmful Algae Risk Mapping (C-HARM) system. *Harmful Algae*, **59**: 1-18, doi: 10.1016/j.hal.2016.08.006.

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Breusing, C., A. Biastoch, A. Drews, A. Metaxas, D. Jollivet, **R.C. Vrijenhoek**, T. Bayer, F. Melzner, L. Sayavedra, J.M. Petersen, N. Dubilier, M.B. Schilhabel, P. Rosenstiel, and T.B. Reusch (2016). Biophysical and population genetic models predict the presence of "phantom" stepping stones connecting Mid-Atlantic Ridge vent ecosystems. *Current Biology*, **26**: 2257-2267, doi: 10.1016/j.cub.2016.06.062.

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Durden, J.M., T. Schoening, F. Althaus, A. Friedman, R. Garcia, A.G. Glover, J. Greinert, **N. Jacobsen Stout**, D.O.B. Jones, A. Jordt, J.W. Kaeli, K. Köser, **L.A. Kuhnz**, D. Lindsay, K.J. Morris, T.W. Nattkemper, J. Osterloff, H.A. Ruhl, H. Singh, M. Tran, and B.J. Bett (2016). Perspectives in visual imaging for marine biology and ecology: From acquisition to understanding. In: *Oceanography and Marine Biology: An Annual Review*, **54**: 1-72, edited by R. N. Hughes, D. J. Hughes, I. P. Smith, and A. C. Dale. CRC Press.

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Fischer, A.M., **J.P. Ryan**, and **E.V. Rienecker** (2016). Fine scale mapping of the structure and composition of the Elkhorn Slough (California, USA) tidal plume. *Estuarine, Coastal and Shelf Science*, **184**: 10-20, doi: 10.1016/j.ecss.2016.10.035.

Fossette, S., **K. Katija**, J.A. Goldbogen, S. Bograd, W. Patry, M.J. Howard, T. Knowles, **S.H.D. Haddock**, L. Bedell, E.L. Hazen, **B.H. Robison**, T.A. Mooney, K.A. Shorter, T. Bastian, and A.C. Gleiss (2016). How to tag a jellyfish? A methodological review and guidelines to successful jellyfish tagging. *Journal of Plankton Research*, **38**: 1347-1363, doi: 10.1093/plankt/fbw073.

Francis, W.R., **L.M. Christianson**, M.L. Powers, C.E. Schnitzler, and **S.H.D. Haddock** (2016). Non-excitable fluorescent protein orthologs found in ctenophores. *BMC Evolutionary Biology*, **16**: 167, doi: 10.1186/s12862-016-0738-5.

Francis, W.R., M.L. Powers, and **S.H.D. Haddock** (2016). Bioluminescence spectra from three deep-sea polychaete worms. *Marine Biology*, **163**: 255, doi: 10.1007/s00227-016-3028-2.

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Cover: An MBARI mapping AUV is recovered after a survey of the seafloor in the Beaufort Sea in the Canadian Arctic. A second mapping AUV and the MiniROV are on the deck of the Canadian Coast Guard Ship *Sir Wilfrid Laurier*. Photo by Charles Paull. See page 18.

Back cover: Clockwise from top left, a seafloor mound with a distinctive orange stain, both mapping AUVs on deck of the *Sir Wilfrid Laurier* ready for the next mission, the MiniROV is recovered from the Beaufort Sea, a sediment core sample. All photos by Charles Paull except the seafloor image, which was taken with the camera on the MiniROV. See page 18.

Inside front cover: Deckhand Josh Thompson prepares the crane for loading the R/V *Rachel Carson* for a research cruise on Monterey Bay. Photo by Rob Sherlock.

Above: Operations Engineer Chris Wahl, left, and Observatory Engineer Jared Figurski, ready to launch the recently serviced M1 mooring back into Monterey Bay. See page 58. Photo by Lee Morrow.

Image credits, by page: 2: Todd Walsh; 3 (top): Tom O'Reilly, (bottom): Todd Walsh; 5: Illustration by Kelly Lance; 9: Whale images, NOAA; 11: Todd Walsh; 12 (bottom): Bruce Keafer, Woods Hole Oceanographic Institution; 13: Tim Davis, Great Lakes Environmental Research Laboratory; 14 (all): Steven Haddock; 15 (bottom both): Steven Haddock; 16 (both): Doug Au; 18: Charles Paull; 22 (top): National Science Foundation's Ocean Observatories Initiative; 26 (top): Marisa Lubeck, US Geological Survey; 29: Rob Sherlock; 30: Kim Fulton-Bennett; 31 (both): Todd Walsh; 33 (bottom): Kakani Katija; 35: Illustration by Annette Gough; 37: Todd Walsh; 40 (drawing): Illustration by Kelly Lance; 41 (top left): US Navy; 42: Todd Walsh; 43: Jim Birch; 44: Photos by Anela Choy, Illustration by Kelly Lance; 46, 47, 48, and 49 (all): Todd Walsh; 50 (top to bottom): Todd Walsh, Peter Walz, Courtesy of L'Oreal, Todd Walsh; 51 (top to bottom): Kayt Jonsson/US Fish and Wildlife Service, Todd Walsh, Courtesy of the John D. and Catherine T. MacArthur Foundation, Todd Walsh; 53 (left): David Anderson, (right) Ginger Elrod; 54: Todd Walsh; 55: Todd Walsh; 56: Steven Haddock; 58 (top): Jorge Fontes, (bottom): Kakani Katija; 64: Chad Waluk; 65 (bottom): Karen Osborn. Deep-sea photos are frame grabs from MBARI ROV video.

The online version of this report is available at: www.mbari.org/about/annual-reports. The 2016 Independent Auditors' Report is available online: www.mbari.org/about/financial-reports.

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