

Blue Exploration

BETH BAKER

New technologies and networks are expanding knowledge of life in the deep

Exploring life under the sea has never been more urgent. The oceans are a critical source of food for billions of people around the globe, especially in developing countries. According to a 2018 report by the UN Food and Agriculture Organization (FAO), global fish production peaked in 2016 at 171 million tons, with nearly half of that coming from aquaculture. Fish capture and aquaculture provide a livelihood to nearly 60 million people. To meet the growing demand, global fish stocks are caught at increasingly unsustainable levels—from 10 percent caught unsustainably in 1974 to 33 percent in 2015.

At the same time, climate change is exacerbating problems in the oceans, from acidification and toxic algal blooms to shifting ranges for fish and other organisms. The oceans, which constitute 71 percent of the Earth's surface, play a critical role in trapping greenhouse gases such as carbon dioxide. Yet despite their significance, much is unknown about the world's oceans. "The ocean is a cryptic universe," says Steven Murawski, professor at the University of South Florida College of Marine Science and former director of scientific programs at the National Oceanic and Atmospheric Administration (NOAA). "We know a heck of a lot about the skin of the world from satellites, but we know so little once you pull back the skin."

Scientists and engineers are intensifying their efforts to develop new technologies and to adapt existing ones for marine exploration. Artificial intelligence (AI) is being used to more



High-definition cameras are among the many tools giving researchers a new look underwater. Shown here is a school of black jack. Photograph: Anna Varona.

accurately count fish. Deep-diving animals with sensors are gathering data in areas never before explored by human researchers. New instruments can observe microorganisms with increasing precision.

"We're seeing an explosion of ways that we can have a look at biology in the oceans," says Ru Morrison, executive director of the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS). "We used to have to do everything by boat. New technologies are giving us unprecedented looks at how ecosystems function."

To help manage the flood of data, digital networks around the globe are working to integrate massive electronic libraries to aid researchers, policymakers, industry, and fisheries managers.

Ocean observatories expand

In the United States, this effort is embraced at the federal, state, and regional levels, often with the support of private stakeholders. Leading the initiative is the US Integrated Ocean Observing System (IOOS), based at NOAA and made up of 17 federal agencies and 11 regional networks, such as NERACOOS. The challenge given

to IOOS is immense, says executive director Carl Gouldman. A 2009 law established the IOOS to integrate a broad range of data from the Great Lakes and the oceans, from the coasts to the Exclusive Economic Zone some 200 nautical miles offshore. “We have 34 core variables that we’re trying to include in our work and meet societal benefit areas,” says Gouldman, “everything from ecosystem science to human health to safety at sea, storm surge and flooding, to charting and mapping.”

More is known about the physics and the chemistry of the oceans than of the biology. “That’s where the neat stuff is happening,” says Gouldman. “We’re getting the smartest folks in the nation to integrate biology into the system.”

Hassan Moustahfid, currently at FAO in Rome, is the biology/ecosystem project manager. His first IOOS pilot project, launched in 2009 on 50 Hawaiian islands, aimed at supporting sustainable reef fisheries. The challenge was to bring together data from a range of government agencies and other stakeholders. “We created a biological observation system to integrate the data to make sure the scientists and managers use them in a meaningful way,” says Moustahfid. IOOS now hosts maps and data portals for all 11 regions, opening up a wealth of biological information.

The CeNCOOS portal, for example, for central and northern California, includes video and real-time observations of biological cover on the seafloor, recorded from a towed camera sled; trends in the spread of canopy-forming kelp; and the health of marine mammals, among many other data sets. By deploying multipurpose buoys with sensors to measure nitrate and phosphate concentrations, NERACOOS has created an integrated nutrient observatory to help predict harmful algal blooms, a major concern for the New England fishery and for human health.

Other tools are also helping researchers understand harmful



Researchers improve efforts to predict harmful algal blooms. Shown here are *Gloeotrichia echinulata* under an epifluorescent microscope. Photograph: US Geological Survey, Reston, VA.



A deep profiling mooring deployed by the NSF-funded Oceans Observatories Initiative in 2014, from the research vessel Thomas G. Thompson. Photograph: Kendra Daly.

algal blooms. Scientists are using the Environmental Sample Processor (“lab in a can”) to collect and analyze water samples on site. The tool, developed at the Monterey Bay Aquarium Research

Institute, uses molecular detection technology to identify specific microorganisms and algae on a near real-time basis, rather than shipping samples to a lab and waiting for results.

New explorer of the deep volcanoes?

The Axial Seamount lies some 300 miles off the coast of Oregon along the Juan de Fuca Ridge. Its volcano has erupted three times in the last 15 years and is expected to erupt again in the next few years. Geologist John Delaney, of University of Washington and a leader of NSF's Ocean Observatories Initiative, hopes to be ready with a new remote autonomous underwater vehicle (RAUV), a driverless car with amazing capabilities. "[The volcano] is a huge planetary feature that has always been interacting with the ocean, but humans have almost never witnessed the power and impacts of the eruptions which release very exotic microbes that live on the ocean floor," says Delaney.

An RAUV could be parked in its "garage" on the seafloor, connected to a source of power and communication. The vehicle "goes off and does whatever it's been told to do with some precision," he says. "It's the underwater equivalent of robots on Mars except the turnaround time is milliseconds, and it's able to do a great deal in terms of high definition cameras and high resolution sonar. It can actually do real-time genomic analyses. It can do chemical studies. It can look at organisms that are nearly invisible in the water column by using laser scanning or high-resolution photography and video."

Delaney has been looking into a model called the Sabertooth, made by Swedish auto manufacturer Saab and already in use by other countries. With OOI's underwater cable already in place, the Axial Seamount would be an ideal site to test this new technology at an active volcano, he says. Delaney hopes that with interested parties that include industry and the US Navy, the \$3 million to \$5 million investment will come through in time for the next eruption.



Saab's Sabertooth Double Hull. Photograph: Courtesy Saab Seaeye Sabertooth.

The Imaging FlowCytobot has been designed by Heidi Sosik and Rob Olson of Woods Hole Oceanographic Institute to look at phytoplankton. A 2016 study by Sosik and colleagues published in *Science* tracked the tiny bacterium *Synechococcus* for 13 years at Martha's Vineyard Coastal Observatory. The team found that the bacteria bloomed up to 4 weeks earlier over that time due to warming conditions that caused the cells to divide faster. This could significantly affect other animals in the food web, from fish to whales and birds.

The NSF's role

As one of IOOS's partner federal agencies, the National Science Foundation (NSF) launched the Oceans Observatories Initiative (OOI) in 2014. The OOI has invested \$386 million in major construction of platforms and instruments intended to operate for at least 25 years. "The long-term commitment to this is very unusual," says Kendra Daly, professor at University of South Florida College of Marine Science and a former director of OOI.

The OOI has deployed a sophisticated networked system of sensors,

located in five sites: two in the North Pacific, one off of Chile, one in the Irminger Sea in the North Atlantic, and one south of Cape Cod. The latter, called the "pioneer array" will operate there for 5 years. OOI will then consider proposals to move the array to a new site, such as the Gulf of Mexico.

One of OOI's remarkable feats was the installation of a fiber-optic cable array that crosses the Juan de Fuca tectonic plate. "This fiber-optic cable is stretched from Oregon across the Pacific and is attached to the

Machine-learning on a commercial vessel

The Nature Conservancy is partnering with commercial fishers to use video cameras and artificial intelligence (AI) to better manage the fishery and track the size and species of bycatch. Rather than pay humans to either be on board observing or sitting at home staring at video footage, AI systems are doing the work at much lower cost.

“One of the things we’re trying to have the machine help us with is activity recognition,” says Chris McGuire, marine program director of the Nature Conservancy in Massachusetts. “On a typical day trip there may be only 3 hours of fish handling in 16 hours. We’re trying to get to the place where we don’t have to collect video when nothing’s happening.” By reducing the amount of video, the data could be transmitted wirelessly rather than physically.

“The harder part, once you get the video, is how to enable the machine to do the rote tasks—hundreds of fish will be discarded and we want to identify the species, measure the length, and do that in an automated way,” he says.

To take on this challenge, the Nature Conservancy sponsored a machine-learning competition. Some 450 teams competed for a \$50,000 prize. Participants were given 2000 30-minute video segments and asked to develop AI to determine the length and species of fish shown. One of the difficulties is finding enough labeled images of say, winter flounder, for the computer to learn on. “Our problem is actually pretty complicated because there are a lot of variables,” says McGuire. The winning teams were “highly accurate” with length and number of fish, but less so with identifying species.

The Nature Conservancy is using this electronic monitoring technology with the New England groundfish fishery. So far, 25 commercial fishing vessels—10 percent of the fleet—in New England have volunteered to test the new technology. Similar efforts are underway in the West Coast groundfish and Alaska longline fisheries, the Pacific tuna longline fishery, as well as operational programs in the United States, Australia, and Canada.



This shows a screen capture of the machine-learning algorithm at work, by a top finisher in the competition hosted by DrivenData (<http://drivendata.co>) with The Nature Conservancy. Red text are the algorithm outputs, and blue text are the true values. Image: @drivendata.org

Juan de Fuca Ridge, delivering electric power,” says John Delaney, with the University of Washington and an OOI leader. “It has a 10-gigabit-per-second bandwidth so you can run experiments using live video streaming, with information from the water column and from all the different parameters.”

The new observatories are yielding fresh insights. “We’re able to observe

episodic events that we can’t observe from ships,” Daly explains, such as the annual spring bloom of phytoplankton. “Many animals in the ocean try to plan their reproductive effort to that spring bloom. Then their larvae have enough food to survive and recruit to other stages. The timing of the spring bloom is important to the biology of the whole system, and that’s been very difficult to measure before.”

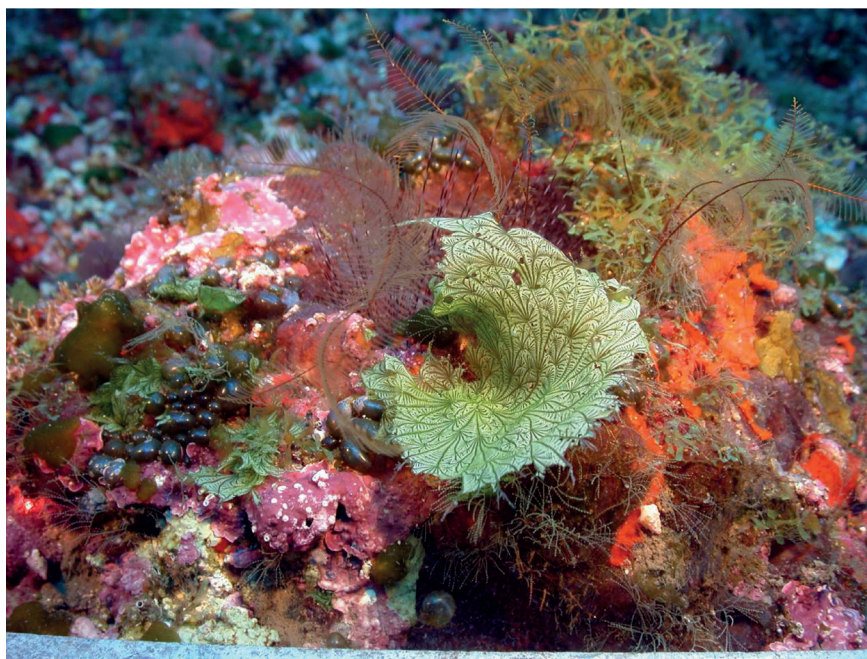
Other technology allows new views into the water column. “For decades moorings have used railroad wheels as an anchor and wires that go up to a surface or near-surface float that holds it tight,” says Daly. Researchers would hang instruments at various depths, but “we might not choose the right depth where dynamic processes are occurring.” At planning meetings, scientists expressed the need for a way

to take measurements throughout the water column. The result was profiling moorings which have small vehicles that can move up and down through the water column. A profiling mooring deployed in 2014 moves from 200 meters in depth to the surface. “They have to be very well engineered and large enough to withstand ocean waves and bad weather,” says Daly.

Such tools give researchers the chance to better monitor the vertical migration of zooplankton, for example. Zooplankton move closer to the surface in the night to feed, then deeper in the day to avoid predators. Another research focus is the relationship of oxygen, carbon dioxide, and phytoplankton. “Phytoplankton are drawing down 26 percent of the anthropogenic carbon dioxide from the atmosphere,” says Daly. “Those pathways are very important to understand.”

Monitoring marine biodiversity

The US Marine Biodiversity Observation Network (MBON), an activity funded primarily by NOAA, NASA, and the Bureau of Ocean Energy Management, grew out of a 2010 interagency workshop (see May 2013 *BioScience*; <https://doi.org/10.1525/bio.2013.63.5.8>), preceded by years of consultation. “Many groups are monitoring biodiversity and how changing ecosystems are impacting species,” says Gabrielle Canonico of NOAA who heads MBON. “But there wasn’t a lot of sharing of that information or integration of the observations.” By 2014, MBON had launched three 5-year demonstration projects aimed at finding the best ways to collect and integrate marine biodiversity observations. The three projects—Arctic MBON in Alaska’s Chukchi Sea, Santa Barbara Channel MBON in California, and the Sanctuaries MBON in the Florida Keys; Monterey Bay, California; and Flower Garden Banks in the Gulf of Mexico—are looking at the effectiveness of a variety of tools, such as e-DNA methods, automated image analysis, remote sensing of ocean habitats, ship surveys



As part of its Marine Biodiversity Observation Network research, the Flower Garden Banks National Marine Sanctuary is testing the use of Environmental DNA as a tool for monitoring biodiversity at different depths.
Photograph: NURC/UNCW and NOAA/FGBNMS.

and other traditional observing methods, and data management.

“We’re trying to work out how to better integrate biology into our routine [marine] observing, both in the US and globally,” says Canonico. “There’s been a lot of monitoring for many decades. It’s about liberating and sharing those data.”

On a global scale, as part of the Group on Earth Observations Biodiversity Observation Network, MBON connects with other networks interested in supporting marine biodiversity such as the Ocean Biogeographic Information System, the Global Ocean Observing System, and *Ocean+ Data*, an initiative by the UN Environment World Conservation Monitoring Centre.

“Marine biodiversity knowledge is still quite limited globally,” said Juliette Martin, *Ocean+ Data* project co-leader in Cambridge, England. “We have a good understanding in shallow and coastal waters, but as you move offshore, that knowledge becomes more scattered. There are also gaps

in knowledge—spatial gaps, but also seasonal, taxonomic, and so on.”

Ocean+ Data, launched in January, directs users to 183 global marine and coastal datasets and tools focused on biodiversity, such as AquaMaps, which generates predicted maps of the distributions of 25,000 species of fish, marine mammals, and invertebrates globally. In its first 6 months, *Ocean+ Data* had 2000 visits to the site, primarily from the United States, followed by users in the United Kingdom and Brazil. In November, the group plans to launch *Ocean+ Habitats*, focused on seagrasses, mangroves, cold- and warm-water corals, saltmarshes, and other important marine habitats.

“We’re keen on people getting in touch and saying whether they want their data listed or if they notice a gap. We want it to be collaborative and consultative, and we’re looking for feedback,” says Martin.

Key to making this and other sites accessible has been implementing international data standards. In February the regional association of

IOOS in the Pacific Northwest hosted the first US IOOS biological training workshop, to teach researchers how to integrate their data with these global networks.

One fish, two fish

Of the 600 managed fish species in federal zones, “a large fraction are data-poor,” says Murawski. Species such as haddock and red snapper have relatively large amounts of resources directed to them, while less popular ones, such as amberjack and Atlantic tripletail in the Gulf of Mexico, have fewer.

Acoustics, a Cold War technology, has been adapted and used for decades to track schools of fish and marine mammals. Although the traditional technology was useful for finding a large mass of fish, it could not identify the species or size of individual fish. Researchers are now combining sound with video cameras being towed through the oceans. “It’s like traditional fish finders on steroids,” says Murawski. Data can now be gathered continuously, at relatively high speeds, covering huge distances. In the Northeast, for example, the Habitat Mapping Camera System (HabCam) is being used to assess the health of Atlantic sea scallops, the most valuable fishery in the United States. “What’s happened in the last 5 years has been a big push to operationalize these systems, rather than running small experiments, to actually have them work on spatial scales that are relevant to the management of resources,” says Murawski.

The challenge becomes how to read all the data being collected. “I’ve been wearing out grad students, training them—which takes a while—to distinguish one species of snapper from another,” says Murawski. One promising solution is to employ AI, adapting facial recognition technology into “fish-al” recognition. “We’re working hard to perfect the system to give reliable products,” he says. “How many red snapper, how large, what are their habitats? If we can do this, we can revolutionize the whole process [of



Billfish, sea turtles, and elephant seals are among the species used by researchers to explore the depths. Here, a large billfish is tagged with a tracking device.

Photograph: Derke Snodgrass, NOAA/NMFS/SEFSC/SFD

counting fish].” Similar technology could be used to count bats or many other organisms.

A collaborative funded by the US Fish and Wildlife Service, NOAA, and Florida Fish and Wildlife Service is working on its second prototype combining acoustics, video, and AI recognition to count fish. A parallel effort is ongoing at Woods Hole Oceanographic Institute. “If we put pedal to the metal we’re a year out from using this system,” says Murawski.

Animal telemetry and genetic barcoding

Animal telemetry has advanced significantly over the last 30 years, with tagged animals ranging from 6-gram salmon smolts (intermediate stage of maturity) to 150-ton whales.

IOOS’s Animal Telemetry Network is bringing together representatives of 13 (and counting) regional self-organized collaborative animal telemetry groups. “We’re the catcher’s mitt for the data, so that every researcher

doesn't have to build that network for themselves but can benefit from a national network," says Gouldman.

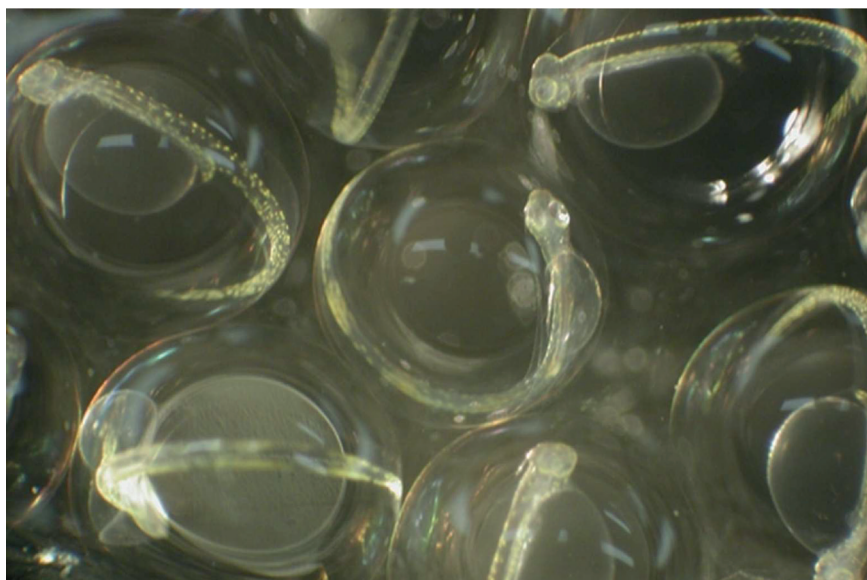
In addition to tracking and learning the lifecycle of tagged animals, "We're putting sensors on animals, and they're becoming oceanographers for us," says Gouldman. "The most amazing example is the elephant seals who dive hundreds of meters and bring us data. Seals are routinely going out on feeding forays, and it may be to places where we don't have instruments on an ongoing basis."

Researchers are also gaining new insights through DNA sequencing of fish eggs. Most of the bony fishes reproduce by broadcasting eggs and sperm into the water. The eggs float for only one or two days before hatching into larvae. Scientists are now gathering fish eggs and extracting the DNA. Using robotics, each egg is identified through the Barcode of Life. A study published in 2015 by researchers at Scripps Oceanography Institute at the University of California, San Diego collected 260 egg samples over a 2-year period and accurately identified 13,000 fish eggs from 39 species. These data increased knowledge of spawning areas in a marine protected area. The method has been used on a limited scale, but "we're one step away from massive barcoding of fish eggs in the ocean," says Murawski.

Moving forward

The new technologies also present new challenges. "We're drowning in data," says Murawski. "If we're going to invest a lot of money in sophisticated sensors, we need to do the synthesis of this big data to make them into products that humans can understand."

Additionally, the same technology that yields research insights can be used by commercial fleets to catch fish that once were more difficult to find. Balancing the ever-increasing efficiency of fishing with sustainable fisheries management is a constant struggle.



Scientists are using DNA sequencing of fish eggs to identify the spawning areas that need to be protected. Photograph: Matt Wilson/Jay Clark, NOAA NMFS AFSC.

Further reading

- Food and Agriculture Organization of the United Nations. 2018. The State of the World Fisheries and Aquaculture—Meeting the Sustainable Development Goals. United Nations.
- Harada A, et al. 2015. Monitoring spawning activity in a southern California marine protected area using molecular identification of fish eggs. PLOS ONE. doi:10.1371/journal.pone.0134647.
- Hunter-Cevera K, et al. 2016. Physiological and ecological drivers of early spring blooms of a coastal phytoplankter. Science. doi:10.1126/science.aaf8536.
- US Marine Biodiversity Observation Network. <http://marinebon.org>. (Website includes related data and resources.)

And funding is always in question. "There's technology and there's the capacity to put things out," says Morrison of NERACOOS. "[OOI] was envisioned at \$100 million a year, but is really funded at about a third of that. As with everything else, our ability to do things is limited by the amount of funding we get."

Gouldman is optimistic, though, about IOOS and its partners applying new technologies on a global scale. Developing nations are trying

to identify best practices in fisheries sustainability and healthy oceans, and IOOS is committed to sharing what they have learned. "One of the big tenets is making the data openly available for maximum use," he says. "A lot of our work is on open-source software and making the techniques interoperable. We're pushing that philosophy on a global scale."

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