A Sea Change for U.S. Oceanography

Marine scientists are confronting declining budgets and a shrinking research fleet as torrents of data from new technologies remake their field

SINCE 1996, OCEANOGRAPHER KIPP Shearman has relied on a duo known around the lab as Bob and Jane to measure chlorophyll and other environmental parameters in the ocean off the Oregon coast. Roaming the sea for 3 to 5 weeks at a time, the pair never complains and comes up for air just every 6 hours. They're 2-meter-long automated submersibles called gliders, and the reams of data they've collected have allowed Shearman's team at Oregon State University, Corvallis, to make novel insights into changing marine ecosystems.

The gliders are cheaper than sending scientists out in ships to make measurements, Shearman says, and they can remain at sea nearly indefinitely. He named the machines after some senior colleagues, and, "We kid them that we're replacing them with robots."

There's a glimmer of truth to that notion. Two cultural shifts are simultaneously shaking the foundations of oceanography in the United States—and fueling a debate about the future direction of a fast-changing field. Fewer scientists are going to sea as a result of a shrinking science fleet, flat budgets, and skyrocketing costs. At the same time, oceanographers are using a growing array of high-tech devices—such as satellites, gliders, and vast networks of sensors tethered to the sea floor—to remotely collect more data than ever before without getting wet.

The trends are helping to transform oceanography "from small science to big science," says technologist James Bellingham of Monterey Bay Aquarium Research Institute (MBARI) in Moss Landing, California. That shift, in turn, is affecting how researchers study an increasingly urgent set of problems, including overfishing, ocean warming, and acidifying seas. It is also altering the culture of oceanography, including how scientists share data and how young oceanographers are trained.

Online
sciencemag.org
Podcast interview with author Eli Kintisch (http://scim.ag/pod_6124).

The churning is prompting contradictory emotions, however. The decline of the U.S. science fleet is "a catastrophe that's happening in slow motion," warns Bruce Appelgate, who heads ship and marine operations at the Scripps Institution of Oceanography in San Diego, California. But "we've entered a new era in oceanography, and it's for the best," declares oceanographer Sydney Levitus of the U.S. National Oceanic and Atmospheric Administration (NOAA) in Silver Spring, Maryland.

A waning fleet

A symbol of the changes remaking marine science floats alongside the dock at the Woods Hole Oceanographic Institution (WHOI) in Massachusetts. In its glory days, the research vessel *Atlantis* boasted adventures that kept it at sea for 10 months a year. Last year, it was out of port for only 8 months. Idle, the 84-meter-long vessel has the vacant feel of an abandoned steel office building, albeit a floating one. Labs and workshops sit empty; just a few crew members and students were busy during a recent visit. "We've had our thumb out looking for work," says Captain A. D. Colburn. He was "grateful" that Canadian scientists hired the ship for a monthlong mapping mission this past summer. But fewer U.S. researchers are using *Atlantis* as a result of funding issues and because its equipment is undergoing recertification tests to deploy its celebrated partner craft, the piloted submersible *Alvin*. So Colburn is confronting "a lot of face time with my computer," he says glumly, echoing a common refrain these days among oceanographers.

The dormancy is a product of decades-long policy shifts. During the Cold War, the U.S. Navy was the main benefactor of the nation's marine scientists, whose studies on ocean mixing and sound scattering served

CREDIT: TRISTAN PEERY, OREGON STATE UNIVERSITY

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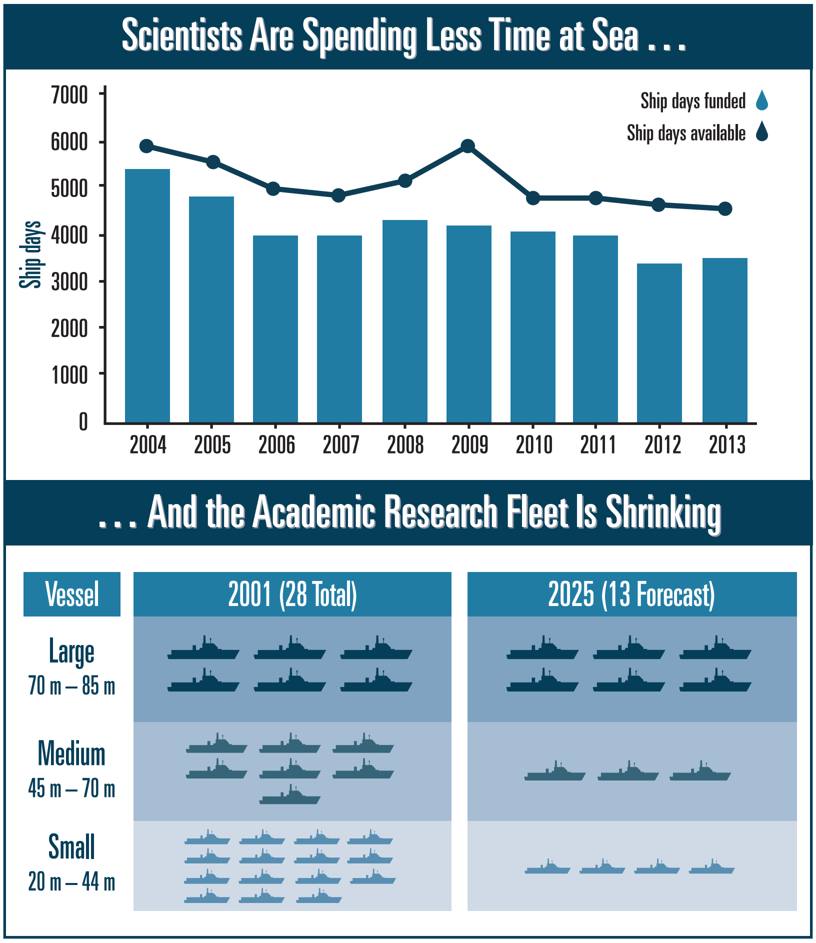
Robot overboard. Gliders offer scientists like Kipp Shearman a nearly permanent presence at sea.

military needs such as for undersea warfare. As the Navy has steadily reduced its support for academic oceanography, researchers have pieced together support from up to nine federal agencies; NOAA, the National Science Foundation (NSF), and the Navy are now the main funders. The fraction of federal research funding devoted to ocean sciences plummeted as the Cold War wound down, from roughly 7% in the 1970s to 3.5% in the 2000s, analysts estimate.



Landlocked? Fewer ships and less money mean getting to sea is increasingly challenging for university researchers.

While budgets have stagnated, the U.S. science fleet has shrunk and the price tag for expeditions has skyrocketed. Academic oceanographers rely largely on government-built vessels operated by the University-National Oceanographic Laboratory System (UNOLS), a consortium of 62 universities and government laboratories. In 2001, UNOLs boasted 28 ships; now there are 19, and fleet officials project that there will be 13 in 2025, barring new federal commitments. Meanwhile, operating costs for the five largest UNOLS ships, which can support dozens of scientists for months at a time, have doubled in the last decade to roughly \$36,000 per day. Daily costs for smaller ships have increased by 50%, to about \$8000 per day. Such increases—along with hefty investments in new technologies—are reshuffling marine science budgets: This year, for the first time, NSF's Division of Ocean Sciences, a major UNOLS funder, expects to spend more of its \$352 million budget on ships and infrastructure than on support for research grants.

One result is that, in a bid to pinch pennies, funding agencies have been urging scientists to use smaller, less expensive ships for their work when possible. That can create problems, researchers say. As part of a 2005 geological study of Hawaiian volcanoes, for instance, geologists deployed 35 seafloor seismometers using one of the larger UNOLS vessels, the 85-meter-long *Melville* operated by Scripps. When they returned the following year to retrieve them, NSF stipulated that the researchers use the smaller and less-costly *Ka'imikai-o-Kanaloa*, operated by the University of Hawaii, which lacks the *Melville*'s heft and ability to maneuver laterally. The downsizing contributed to two mishaps in rough seas, says Scripps geophysicist Gabi Laske, the cruise leader. In one, a 200-kg seismometer smashed against the side of the vessel as the crew tried to haul it on deck, causing minor damage to a sensor. "It's extremely unlikely this would have happened with a larger ship," Laske says. "It's these little things that make science in the ocean more dangerous and more difficult."

The combination of fewer ships, increasing costs, and stagnating budgets is also creating a worrying feedback loop. Researchers interested in going to sea say they are having a harder time getting their proposals funded—and NSF has in the past suggested that requests that don't include costly ship time might have a better chance of winning approval. Discouraged, some researchers have simply stopped trying to do science aboard ships. "The last thing we want to do is spend a lot of time working on a proposal that is not going to be successful," says biological oceanographer Dennis McGillicuddy of WHOI.

In 2011, a UNOLS survey of 355 oceanographers found that 62% had at some point been "reluctant" to ask for at-sea funding, citing a "perception of low award rate for proposals with ship time." Ironically, that reluctance could further hasten the decline of the fleet, because it reduces demand and funding for the vessels. Indeed, officials say the demand for ship time is declining.

Many UNOLS vessels, some of which are 40 years old, are also showing their age or suffering from underfunded maintenance programs. Last year, three of the fleet's four large vessels operating from Pacific ports had serious technical problems. The 84-meter-long *Thomas G. Thompson*, for instance, was sidelined for half a year with a busted main thruster, a calamity that was "very disruptive" for several major cruises, says official Douglas Russell of the University of Washington (UW), Seattle, which manages the ship. (Some blame availability of parts, not the maintenance schedule, for the problem.) And in early 2012, the U.S. Coast Guard had to rescue the *Kilo Moana*, a 57-meter-long vessel operated by the University of Hawaii, after corrosion punched a 6-centimeter hole in its hull. "Not only are we losing ships, but the condition of the ships is such that they're breaking down," says Peter Wiebe, an oceanographer at WHOI and former UNOLS chair.

The prospects for major improvements are relatively bleak. A 2001 UNOLS plan called for building 10 new ships by 2020 for a fleet size of 16. The proposed additions included seven large ones, to "maintain fleet capacity" (*Science*, 21 January 2005, p. 338). So far, however, replacements have come more slowly than envisioned and just three new

CREDITS: UNOLS

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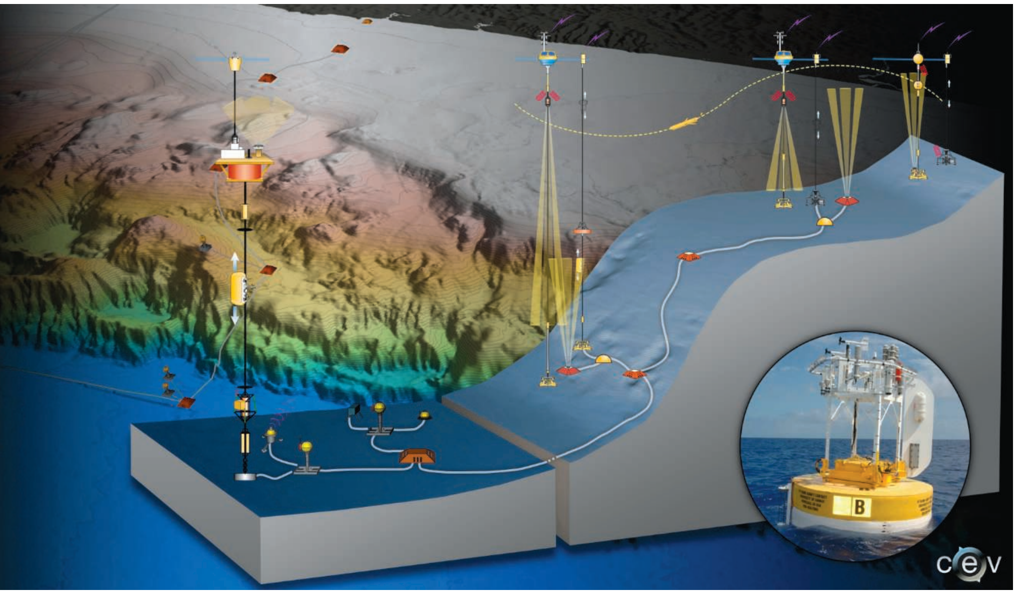
ones have appeared, including two large ships with less range than the vessels they replaced. Three are getting tested or are under construction, and three others are on the drawing board but unfunded. If those three fail to materialize, vessel retirements would shrink the fleet to 13 vessels in 2025. A smaller fleet will be "increasingly unable to meet science user demands," concluded a 2009 UNOLS report. "[M]ulti-ship operations" would be more difficult to schedule, it warns, as would "expeditions in remote areas."

Even stabilizing the fleet at 13 vessels could become a stretch given current U.S. budget problems. This past June, NSF and Navy officials recommended that UNOLS retire some smaller ships sooner than planned in order to create savings that "would be used to bolster the schedules of the remaining vessels." That framework troubles researchers who primarily work in coastal and nearshore waters, where the smaller ships are an advantage. The plan will create "a big gap" in the fleet, McGillicuddy says.

The downsizing doesn't necessarily mean disaster, says Rodey Batiza, an official with NSF's ocean research branch. Modern ships feature more capable laboratory spaces than their predecessors and can deploy robotic payloads that can roam widely, enabling vessels to collect "1000 times more data in a day than they did a decade ago," Batiza says. But many oceanographers are not persuaded. "The ocean is undersampled now, and it was undersampled when we had 28 ships," McGillicuddy says. "The new tools don't obviate the need for research vessels."

The bottom line, believes former UNOLS Chair Bruce Corliss, dean of the Graduate School of Oceanography at the University of Rhode Island (URI), Narragansett Bay, is that "we have a significant crisis for the UNOLS fleet."



Wired sea floor. A panoply of sensors and robots will provide fully powered, real-time data through the Ocean Observatories Initiative.

The marine tech revolution

The fleet's woes are all the more striking in contrast to the dazzling new data-gathering tools that oceanographers now deploy. Walk the deck of a research vessel built in the 1970s, and you'll find shiny new submersibles, buoys, and other devices sporting the latest in batteries, communications, and cameras, often built by graduate students half as old as the ships. These are the tools of a technological revolution in oceanography that began some 3 decades ago, with the 1978 launch of SEASAT, the first civilian oceanographic satellite. During just 3 months in orbit, NASA estimates SEASAT collected as much data—including sea surface temperatures, wind speeds, and ice conditions—as had been acquired by all ships during the previous century.

Now, automated devices are gathering even more data from more places, including far below the top centimeter of seawater that satellites can probe. Since 2004, for example, the global Argo program, comprised of 3500 drifting devices packed with electronics, has extensively profiled the oceans to a depth of 2000 meters (*Science*, 27 April 2012, p. 405). Costing roughly $10,000 each, the floats measure temperature, pressure, and salinity as they rise and sink over a 10-day cycle, reporting data continually by satellite. The floats collect some 120,000 profiles each year, dwarfing the 15,000 or so that ships collected just a few decades ago. Researchers slicing and dicing Argo data have already produced more than 1100 scientific publications, including papers with new insights into the ocean's heat content and major currents.

Physical and chemical oceanographers have benefited most, but biologists are eager to catch up. "We have physics envy," says biological oceanographer David Karl of the University of Hawaii, Manoa. He is just one researcher hoping to benefit from the next generation of Argo floats, which will include sensors able to monitor biological activity, such as the rate of marine photosynthesis.

Other cutting-edge automated instruments are essentially floating laboratories. The Lexus of these devices is called the Environmental Sample Processor (ESP), developed by MBARI. About the size of a large trash can, the ESP usually hangs roughly 20 meters below the ocean surface off a moored buoy. Inside, a robot draws in water samples, extracts RNA from them, and uses a microarray to detect certain microorganisms' genes. MBARI recently commercialized the machine and researchers hope to use it to monitor fisheries, sewage pollution, and harmful algal blooms. The ESP is "really the only show in town" when it comes to high-tech remote biological oceanography, Karl says.

The ESP costs roughly $175,000, but its more affordable robotic brethren "democratize" the ability to do studies once within the reach of only larger laboratories, says MBARI's Bellingham. For example, submersible gliders like Oregon State's Bob and Jane can cost $125,000 to $150,000 each, making them "something that under a normal research grant you can buy," he says.

Falling technology prices are also spurring innovation. One barrier to developing new marine science gear has been the cost of the cruises needed to test it at sea. But many gliders, robotic submersibles, and floats now can be tested off small vessels near shore. At URI, marine engineer Chris Roman and colleagues are using that approach to develop a new device on a relatively small budget of $1 million. The tubular float snaps one high-resolution photo of the ocean floor every second as it drifts in shallow waters, where floats like Argo can't operate. "We approached it as: 'What could we do with a very simple instrument?' " Roman says. If it works, the floating photographer could make the weekly chore of catching and counting fish in nearby Narragansett Bay far less arduous for graduate students.

The marine technology renaissance isn't just about tinkerers building single instru-

CREDIT: OOI REGIONAL SCALE NODES PROGRAM AND THE CENTER FOR ENVIRONMENTAL VISUALIZATION, UNIVERSITY OF WASHINGTON

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ments; it is also enabling researchers to envision and install vast instrument networks that are linked to land by kilometers of fiber optic cable. The wired ocean includes a new Japanese 20-site seismology network, a 12-site network that will ultimately dot European seas, and a U.S. network that connects several coastal sensor arrays. The most ambitious project is the Ocean Observatories Initiative (OOI), an international, Internet-connected network featuring 804 physical, chemical, and biological sensors in six separate arrays from Greenland to southern Chile (*Science*, 16 November 2007, p. 1056). Whereas battery-powered seafloor sensors can conk out, sensors on the OOI network, now under construction, will get a steady supply of power from land. With an estimated cost of $770 million, scientists predict that OOI, which is scheduled to go live in the deep ocean next year, will give them immediate access to data, a rare treat. In the process they'll get a front-row seat to ephemeral or fast-moving seafloor phenomena, such as undersea methane burps, that can be hard to capture during relatively brief research cruises.

These new systems will produce unprecedented torrents of data. And like space and genome scientists before them, oceanographers now face the challenge of efficiently storing, using, and sharing their largess. One difficult task will be learning how best to combine and properly label incompatible data sets, says URI oceanographer Peter Cornillon. Another will be making sure all the data get used; it's becoming increasingly common that some data go unanalyzed after a cruise or project—a notion that would have been unthinkable just a few years ago.

New day. Three-thousand-five-hundred Argo floats provide unprecedented daily ocean data.

The arrival of big oceanography is engendering a new commitment to sharing data. Traditionally, scientists jealously guarded their data for 2 years after collection, giving them time to publish, says John Gould of the National Oceanography Centre in Southampton, U.K. Some geochemical data collected on cruises during the 1990s "didn't see the light of day for 10 years," he notes. Now, raw satellite, Argo, and glider data are available nearly instantly online, and sharing is becoming the norm.

A new process

Such changes are helping reshape and enhance a variety of oceanographic projects, which generally fall into two broad categories. One is "process" studies, which examine specific phenomena through experiments that can last days, weeks, or perhaps a month. The other includes monitoring or survey efforts that gather data over a long period in different places, or annually at the same spot, in order to track changing conditions.

Process experiments highlight the growing capabilities of modern ships, which can host big, multidisciplinary teams working in clean, roomy labs equipped with devices, such as DNA sequencers or mass spectrometers, that were previously available only on land.

The New Generation of Sea Scientist

Veteran oceanographer Margaret Leinen fondly remembers the regular stream of lengthy ocean cruises that she and her fellow students enjoyed during their training in the 1970s—and the outsized demand for their labor. Senior scientists asked: "How many times can we get students to go to sea before they rebel?" recalls Leinen, director of Harbor Branch Oceanographic Institute in Fort Pierce, Florida.

Now, however, "seafaring adventures are a much smaller part of the way we perceive our careers than those who are 15 or 20 years older," says Rebecca Walsh Dell, who recently received a doctorate from the Woods Hole Oceanographic Institution (WHOI) in Massachusetts. Of the five students who joined her Ph.D. program the same year, only one, who focuses on biology, has relied on data collected on ocean cruises for their graduate research, she says. The others have used remote sensing data, modeling studies, or data from the Argo network. "The traditional model—design an experiment, deploy equipment, collect the data, spend 2 years writing the paper—none of us did that." The students eventually made it on a cruise, she says, "but only to see how the sausage gets made."

Core curriculum. Time at sea is no longer a mandatory part of oceanographic education.

That doesn't mean young scientists don't still dream of exploring the high seas. A summer fellowship that trains graduate students to lead research cruises has "more students signing up than we can accommodate," says Bruce Appelgate, who runs the program at the Scripps Institution of Oceanography in San Diego, California. "We've got a tremendous interest among students in getting out to sea."

Overall, about 45% of the approximately 2500 graduate students in U.S. oceanography programs saw time at sea the year before, according to a 2011 survey conducted by the University-National Oceanographic Laboratory System. It also found that 75% of U.S. ocean scientists within 4 years of completing their postgraduate training planned to request future ship time. Still, that is less than the 85% of scientists with more than 20 years of experience who said the same. And WHOI oceanographer Peter Wiebe is dismayed that the institute's graduate students routinely turn down invitations to take a berth on an upcoming cruise. "We end up bringing European or Asian students," he says.

That's a danger sign for some oceanographers. Kipp Shearman of Oregon State University, Corvallis, says that the master's degree students he supervises "get real skilled real fast" at programming gliders and interpreting the data they provide. But that can't replace "the experience of doing ship-based research." John Gould of the National Oceanography Centre in Southampton, U.K., worries that data are being "handed on a plate to young scientists on the Web sites, and there might be this tendency [not to question] the numbers." But "turn the clock back 20 years," he says, and "you went out and collected your own data, you applied your own expertise to it, and you had to question whether things [were] what they seemed."

–E. K.

CREDITS (TOP TO BOTTOM): ADAM Ü/PICASA/NOAA; 2012 SCRIPPS INSTITUTION OF OCEANOGRAPHY/UNIVERSITY OF CALIFORNIA, SAN DIEGO

They also emphasize the evolving role of the research vessel as a mother ship for an array of mobile technologies. In 2011, for example, a 50-scientist team used a pair of big ships to help launch a study called LatMix that used a phalanx of tools to study surface stirring—a fundamental ocean process poorly described by computer models. Working in the Gulf Stream off the coast of Cape Hatteras, North Carolina, the researchers released tracking dyes, robotic submersibles, and floats, and even called in an airplane to help keep a close eye on moving water masses. The "impressive" project set a recent scientific meeting abuzz, says Rebecca Walsh Dell, a postdoctoral researcher at Scripps.

Similarly, MBARI researchers have deployed ships, robot submersibles, and ESP, their floating gene analyzer, in multifaceted efforts to study California's Monterey Bay. In one 2009 campaign, the scientists used real-time data from an ESP to guide the submersibles to interesting sampling locations. Combining the data revealed in new and startling spatial detail how zooplankton flock to otherwise invisible boundaries between warm and cold water masses.

Autonomous or remotely controlled assets are also allowing researchers to collect data in rough seas or remote areas that can be too dangerous for ships. When Superstorm Sandy hit the New Jersey coast last year, for example, Rutgers University researchers were able to deploy a glider that offered a unique look at how the storm scrambled near-shore sediments and water layers (*Science*, 9 November 2012, p. 728).

Biological oceanographers are also hoping to chart new territory, for example by building devices that can track individual organisms. Measuring biological activity has often meant sampling creatures as they waft by one particular spot in the ocean. Advanced sensors and software, however, could enable a submersible to follow visual, chemical, or biological cues. "Smarts on board—that's the nirvana we'd like to move towards," says Oregon State's Mark Abbott.

The closest thing so far is a torpedo-shaped robot called *Tethys* which combines aspects of a propeller-driven submersible and a buoyancy-driven glider. It can wait for weeks in areas of interest before racing to a specific site—and it travels four times faster than previous gliders. One of its designers, MBARI's Bellingham, hopes that similar tools will one day travel alone to an algae bloom during its initial stages of development and then monitor its growth and decline, which generally takes a month.

A watchful eye

The growing mix of technologies is also reenergizing the once relatively obscure world of long-term monitoring studies, enabling what Hawaii's Karl calls a shift from the "snapshot view of the ocean to the full-length movie perspective."

As recently as the 1990s, "environmental monitoring" was seen as anathema to funders interested in big experiments focused on specific questions, Karl says, and "something you would never put in a proposal, especially to NSF." But now, analyzing how ocean ecosystems influence and react to climate change, pollution, and overfishing have become important to researchers and policymakers alike. And that means developing baseline information on the ocean's "normal" conditions—such as water chemistry and seasonal fluxes in plankton—and then keeping an eye on how things change.

Human-crewed ships will continue to be essential for some survey projects, such as a global effort to understand climate variability called CLIVAR, because only they can perform complex measurements at sea, such as genetic and chemical isotope analyses. But automated devices, such as the Argo float network, are also demonstrating the value of monitoring for monitoring's sake. In part, that's because the floats go places that ships often don't, with the network covering every ice-free region of the open ocean. "The Southern Hemisphere has been so poorly observed almost anything we find will be new," says NOAA oceanographer Levitus, a member of the Argo science team.

And Argo is extending into new frontiers,

Ahoy, Telepresence

One way oceanographers are coping with dwindling ship time is by using "telepresence" video technology to connect landlocked scientists with colleagues at sea. Last summer, one such virtual cruise marked the first time the technique was used to help direct an autonomous submersible mission.

The 3-week expedition explored seafloor seeps near the Blake Ridge, roughly 500 km off the South Carolina shore. The research team was split between a small group of scientists and engineers aboard the National Oceanic and Atmospheric Administration vessel *Okeanos Explorer*, which features a suite of cutting-edge video and data communication tools, and about a dozen scientists and students on shore at the University of Rhode Island, Narragansett Bay. To find seeps, the shipboard team deployed an autonomous robotic submersible called *Sentry* each evening and retrieved it the following morning.

Screen time. Scientists on shore wave to colleagues at sea during a telepresence cruise.

CREDIT: ALEX DECICCIO/INNER SPACE CENTER, URI

Sentry's sonar, image, and sensor data were sent daily via satellite to the scientists in Rhode Island for analysis. The shipboard team, meanwhile, analyzed ship sonar data for clues to possible seep areas. Together, the two groups used the information to identify promising areas for *Sentry*'s daily dive and plan the spacing of its zigzag search pattern. Scientists call the virtual cruise a modest scientific success, noting that it discovered five new seeps in an area previously known to contain only one.

Equally important, perhaps, was that the effort demonstrated how virtual cruises can enhance training for students, even undergraduates. It's tough for a college student to get a spot on a research cruise, notes one of the students on the shore team, junior Meghan Rose Jones of the University of Miami in Florida. So it "was an opportunity which would have not been otherwise possible," she says. Even if she had gotten a berth, Jones thinks she might have spent many more hours standing watch than analyzing data. Instead, she learned to use two mapping software programs and participate in research decision-making.

By the end of the cruise, Jones and several graduate students "were the ones discovering what the seafloor was like" and making dive plan suggestions, says lead scientist Cindy Van Dover, director of the Duke University Marine Laboratory in Beaufort, North Carolina. The team expects to get even more out of a 5-day return expedition next year to Blake Ridge. It will feature the *Jason* tethered submersible, which can collect samples of water, rocks, and sea life. **–E. K.**

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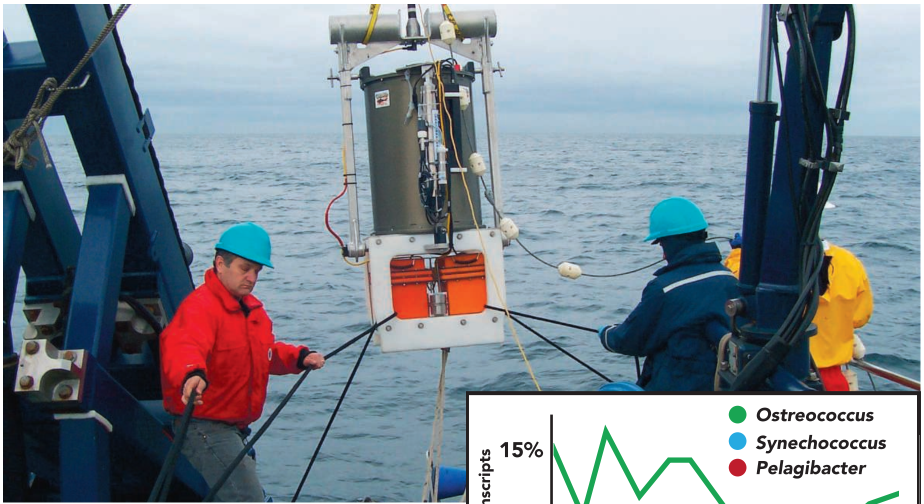
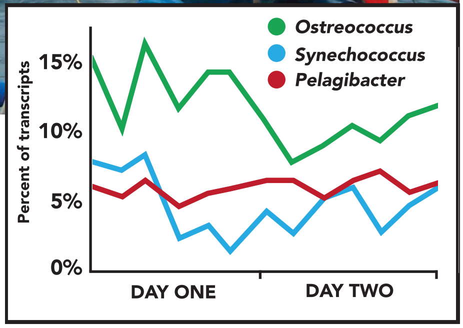
as polar scientists begin to deploy new rugged floats below sea ice. Argo is also helping eliminate a seasonal bias in oceanographic data, created by the tendency of researchers to avoid cold weather cruises. "A main finding has been that the ocean is more variable than we thought," Levitus says. Charting those changes and fluctuations is helping researchers do weather, climate, and fisheries "forecasting much better than we have ever done in the past," he adds.

Evolving technology is underscoring the power of sustained monitoring in other ways. In the late 1980s, researchers established sites near Bermuda and Hawaii, dubbed BATS and HOT, where ships and moored instruments take monthly readings. The sites have played a key role in helping scientists determine the fluctuating physical, chemical, and biological patterns that make up the ocean's baseline. But even monthly readings may not be enough to detect certain phenomena, researchers say. In 2011, for example, UW's Matthew Alford published new findings that suggest the breaking of seafloor waves happen more rarely than expected. Key to that finding were readings from a moored profiler he deployed on a cable at the HOT site that sampled the whole water column each hour for more than 2 years. "Most of the time, monthly readings taken from ships will completely miss the phenomenon" he says. Other researchers say the success of BATS and HOT suggest that it would be worth setting up new monitoring sites in areas important to global climate, such as the Arctic or northern mid-Atlantic.

Seafloor scientists are hoping to literally see fireworks with some of their new monitoring tools. Researchers have never witnessed an undersea volcanic eruption from beginning to end, notes oceanographer John Delaney of UW Seattle, one of OOI's leaders. But the payoff could be so great that researchers have built one section of the groundbreaking sensor network on the Axial Seamount, an active underwater volcano about 500 kilometers west of the Washington state coast that erupts every 10 to 15 years. "Next time it erupts we can be there," Delaney says. He's got his fingers crossed that the sensor array, which includes video, chemical, and seismic equipment, can survive the harsh environment.

Biologists are also eager to examine the exotic bacteria that the volcano spews with an underwater mass spectrometer and DNA sequencer. "By the time we [usually] get there, they've diluted or wafted away," Delaney says. Now, researchers can relax on shore in comfort, knowing OOI is always watching.





Extrasensory. The Environmental Sample Processor (*above*), a floating genetics laboratory, can track the occurrence of marine microbes (*right*).

CREDITS: MBARI; (INSET) ADAPTED FROM OTTESEN *ET AL., PNAS* 110 (5 FEBRUARY)

A sea of tradeoffs

These high-tech tools are also bringing some contentious issues to the surface: The relatively high cost of systems like OOI is forcing U.S. oceanographers to confront difficult choices over how to spend limited funds. The unfolding debate sometimes pits building bigger ships against smaller ones, or ships against unmanned robotic craft—or mobile robots against static sensor networks. Deciding which tradeoffs to make will be "very, very important," UW's Delaney says. Researchers might "go to sea less," for instance, "but the data flow from these new systems is around the clock, 365 24/7, for decades."

Others are challenging the ship-centric mindset that dominates planning in marine science. At URI, for instance, Cornillon has weighed in on a campus debate about what sort of vehicle should eventually replace the university's 38-year-old research ship, *Endeavor*, which it operates for NSF. He's not against obtaining a new vessel, but says his colleagues should focus on "very quickly" evolving oceanography technologies. "The development of these will be as or more important to an institution such as URI than having its own ship," Cornillon says. He and his colleagues have envisioned a scenario for 2030 in which phalanxes of airborne drones and submersibles conduct a tightly choreographed analysis of sea-air interactions, with a ship's role undefined. Colleagues applaud such creativity, but questioning the need for a big vessel has made Cornillon "not terribly popular with many," he admits.

There's also disagreement about the value of large seafloor observatories like OOI. Floats, gliders, and robotic submersibles are well-suited for tough economic times, advocates say, because of their relatively low prices and flexibility. In contrast, OOI will require expensive ship time for maintaining the network, which could command as much as 16% of the NSF Division of Ocean Science's budget beginning in 2015. The project "really is a huge tax on everything," Alford says. "Are there other places that we haven't seen that we could be studying instead?" asks WHOI engineer Dana Yoerger. "There's a whole world to explore."

To help set priorities, the U.S. government's main ocean research advisory panel is working on a report, due next year, that will review fleet needs. At NSF, ocean science chief David Conover wants scientists to go even further. He'd like the field's diverse constituencies to write a consensus "decadal survey" with numbered priorities for projects, as scientists in astronomy and other facilities-intensive fields have done. "It's not just about how you slice the pie, it's about making the case to grow the pie," he says.

That's certainly a case researchers feel has been poorly made in Washington. "Studying the oceans should be funded comparable to research in outer space," says UW's Delaney. But with a depressing budget outlook and the oceanographic community at odds over its future path, that's "a dialogue nobody has the guts to be having."

–ELI KINTISCH