Aqua Incognita

THE QUEST TO ESTABLISH OUTPOSTS IN THE FAR REACHES OF THE OCEAN

by Ken Kostel

There is a jar of money in the conference room of the Mooring Operations & Engineering (MOE) team at Woods Hole Oceanographic Institution. It is a United Nations kaleidoscope of bills and coins that MOE team members didn't have time to convert back to U.S. currency before returning from one of their many assignments around the world.

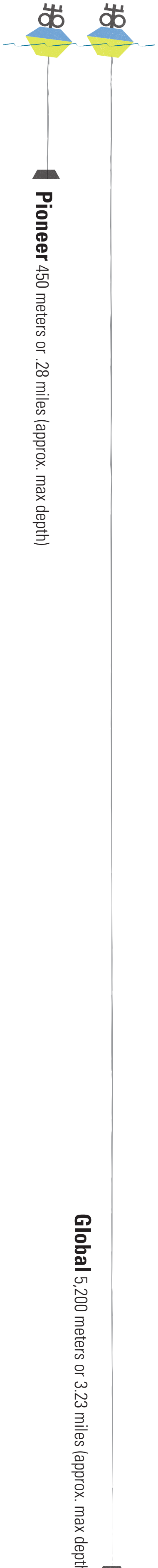
Members of the team are often called upon, sometimes at the last minute, to fly to an exotic port of call, hop on a research ship, and help deploy miles of mooring lines in remote corners of the ocean. Before they head to the airport, team members can make withdrawals from the jar so they will have enough local currency for a meal during a layover or a taxi to town when they reach their destination. On a recent afternoon, someone had riffled the contents for a few Norwegian kroner—maybe enough for a beer before turning in after a long day of travel.

Until about two years ago, the jar contained no money from the countries bordering the Southern Ocean at the bottom of the Earth.

That changed when the ocean science community began to achieve its long-sought goal of

The research icebreaker *Nathaniel B. Palmer* operated by the National Science Foundation takes a wave during mooring recovery in the Argentine Basin in November 2015. (Photo courtesy of Mitch Elend, University of Washington)


NSF



establishing long-term outposts in the ocean to collect sustained, round-the-clock data. The National Science Foundation's (NSF) Ocean Observatories Initiative (OOI) included four nearly identical sets of instrumented moorings with autonomous underwater gliders in critical, high-latitude locations: the Irminger Sea off Greenland; the North Pacific off Canada; the Argentine Basin off the southeast coast of Argentina; and the Southern Ocean southwest of the tip of South America.

In recent years, MOE members and their mountains of gear have become a regular sight in places as far-flung as Reykjavik, Iceland, and Punta Arenas, Chile, as they get ready to recover and replace the moorings and service these so-called Global Arrays. But nothing can change the remote and hostile parts of the equation for these locations. "They've had very little human presence for a reason," said John Kemp, who heads the MOE team at WHOI. "When we went to the Southern Ocean Array in 2015, that was some of the nastiest weather I've ever seen."

Lisa Clough, head of the Ocean Section in the Division of Ocean Sciences at the NSF, has a term for the parts of the globe selected to host the Global Arrays: "These places really are aqua incognita."

Tom Kleindinst, WHOI

The dream of ocean observatories

In their quest to establish a sustained monitoring presence in the ocean, the ocean science community in 1988 created two observatories to gather data around the clock and over extended periods of time: the Bermuda Atlantic Time Series (BATS) and the Hawaii Ocean Time-series (HOT). But these were in the generally placid subtropics.

The following year, scientists went a step further and put a long-term mooring off the coast of Iceland, but it was lost within a few months when the rough sea generated forces on the mooring line beyond anything the engineers had anticipated.

In 1994, researchers from WHOI, Lamont-Doherty Earth Observatory, and the University of California Santa Barbara tried again, this time deploying an array of five moorings in the Arabian Sea. It was part of a yearlong project to study the relationship between the upper ocean and the Asian monsoon, whose rains help feed nearly one billion people.

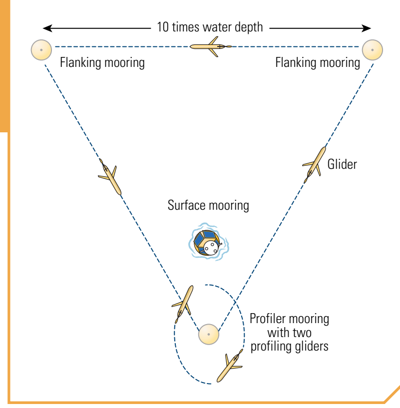
One mooring at the center of the array carried 32 instruments to measure temperature, salinity, currents, dissolved oxygen, chlorophyll, and light transmission and intensity in the ocean—an unprecedented amount and diversity of data at the time. The mooring also included

Above: A surface buoy and other equipment are loaded on the research vessel *Neil Armstrong* in Woods Hole before a voyage. Below: The ship glides up to a Global Surface Mooring in the Irminger Sea in July 2017.


James Kuo, WHOI

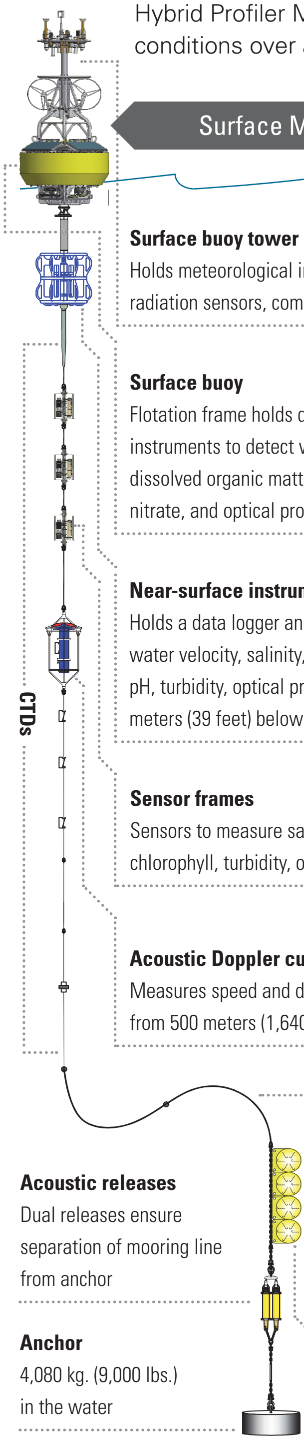
MEET THE MOORINGS:

Global Arrays



Each Global Array is slightly different, but the arrays generally consist of a Hybrid Profiler Mooring and two Flanking Moorings laid out in a triangle with sides ten times as long as the water is deep, and one Surface Mooring stationed inside. The Hybrid Profiler Mooring supports motorized platforms that continuously record measurements through nearly the entire water depth. The two Flanking Moorings hold instruments at fixed depths. Two gliders circle the Hybrid Profiler Mooring, and three more orbit the array to measure conditions over a wider scale.

Surface Mooring



Surface buoy tower
Holds meteorological instruments, solar panels, wind turbines, solar radiation sensors, communications, GPS, and recovery beacons

Surface buoy
Flotation frame holds data logger, solar panels, batteries, and instruments to detect wave height, salinity, temperature, turbidity, dissolved organic matter, carbon dioxide, oxygen, chlorophyll, nitrate, and optical properties of the water

Near-surface instrument frame
Holds a data logger and instruments that detect carbon dioxide, water velocity, salinity, temperature, depth, nitrate, solar radiation, pH, turbidity, optical properties, chlorophyll, and oxygen at 12 meters (39 feet) below the surface

Sensor frames
Sensors to measure salinity, temperature, depth, chlorophyll, turbidity, oxygen, and carbon dioxide

CTDs
Measure salinity, temperature, and depth between 30 and 1,500 meters (100 to 4,920 feet) depth

Acoustic Doppler current profiler
Measures speed and direction of water currents from 500 meters (1,640 feet) to the surface

Inverted catenary
The mooring line is 1.3 times longer than the water depth so that it forms an inverted catenary that eliminates tugging on the line caused by waves at the surface.

Acoustic releases
Dual releases ensure separation of mooring line from anchor

Glass flotation spheres
Flotation to allow recovery of the mooring

Anchor
4,080 kg. (9,000 lbs.) in the water

Flanking Mooring

Subsurface flotation sphere
Foam flotation sphere 30 meters (98 feet) below the surface with instruments to detect dissolved oxygen, pH, chlorophyll, salinity, temperature, and depth

Subsurface flotation sphere
Foam flotation sphere 150 meters (490 feet) below the surface with a bio-acoustic sonar to detect zooplankton and fish

Midline acoustic release
Separates the mooring line into two sections for recovery

Subsurface flotation sphere
Foam flotation sphere 500 meters (1,640 feet) below the surface with instruments to detect salinity, temperature, and depth and an acoustic Doppler current profiler to measure speed and direction of currents from the sphere to the surface

Controller cage
Acoustic modem to communicate with gliders, computer, and data logger

Glass flotation spheres
Flotation to allow recovery of the mooring

Acoustic releases
Dual releases ensure separation of mooring line from anchor

Anchor
2,720 kg. (6,000 lbs.) in the water

Hybrid Profiler Mooring

CTD
Measures salinity, temperature, and depth

Bumper stop
Limits the travel of the profiler

Motorized profiler
One or more profilers move up and down the line, making one round trip every 20 hours to measure salinity, temperature, depth, oxygen, chlorophyll, turbidity, and water velocity

Bumper stop

a surface buoy with meteorological instruments to study the interplay between air and sea and communications equipment that sent data to shore via satellite. The data were also made freely available to the public on a website—another first.

In a nod to the lessons of Iceland, the designers had reinforced the central mooring and saw it survive a beating from waves kicked up by monsoon winds that exceeded 40 miles per hour. The community was ready to make long-term ocean observing a reality.

In the late 1990s and early 2000s, ocean scientists and engineers laid the groundwork, first to bolster arguments in favor of a sustained observing presence in the ocean, and later, as support grew, for what a robust series of ocean observatories should do, how they should be designed, and where they should be located. The scientists saw the need for the instruments to provide the widest possible range of different measurements to look at ocean processes from the atmosphere to the seafloor over wide areas and long time periods—decades, if possible.

The goal was to capture the full complexity of the ocean and its interaction with other, often distant, parts of the Earth system. "To get a good picture of what's going on, we need an understanding of what's going on globally," said Rick Murray, director of the NSF Division of Ocean Sciences. "The world is connected to itself."

The dream comes true

In 2006, the NSF gave the go-ahead to launch the Ocean Observatories Initiative, a $386-million project to build and deploy three types of ocean observatory systems and maintain them for 25 years: Two Coastal Arrays off the U.S. East and West Coasts would focus on coastal ocean dynamics and ecosystems, a Cabled Array off the Pacific Northwest would focus on geophysical and biogeochemical phenomena, and a set of Global Arrays would create a sustained presence in the aqua incognita.

"From a global perspective, we knew the high latitudes are important," said WHOI physical oceanographer Bob Weller, chair of the OOI Science Oversight Committee. "But we had no sustained observations from the surface to the bottom there."

In the undersampled high-latitude regions, crucial processes play out that have impacts on air-sea exchanges of heat and carbon dioxide, Earth's climate, the global circulation of the ocean, and ocean ecosystems—all of which, in turn, may be disturbed by the impacts of a warming planet.

In addition, the location of each Global Array is designed to fit into other international efforts to monitor ocean processes far from shore. The array at Station Papa in the Northeast Pacific, for example, takes advantage of a site that has been monitored and sampled for decades by both the United States and Canada and includes pre-existing instruments and infrastructure into its design. The Irminger Sea site selected by OOI is near another long-term monitoring effort operated by a U.S.-United Kingdom-European consortium known as OSNAP (Overturning in the Subpolar North Atlantic Program) and was designed to fit into the OSNAP mooring network.

"We sorted it out to give us the best bang for the buck," said Weller, who also helped lead the 1994 Asian monsoon study.

As much as the arrays look over the horizon, however, they also rely very heavily on the lessons learned from past long-term moorings like the ones Weller and others put to sea. "We owe a huge debt to the foresight of the people setting things up twenty, fifty years ago," said Clough. "Looking back even ten years, I'm amazed at the foresight and investment they made."

Sophisticated and tough

Each Global Array is laid out in a triangle roughly 12 to 30 miles (20 to 50 kilometers) on each side in water ranging from 8,900 to 16,400 feet (2,700 to 5,000 meters) deep. At two corners of each array are flanking moorings that hold instruments down to 4,900 feet (1,500 meters). At the third corner of the triangle is a mooring with one or more autonomous profilers, which move up and down the mooring line once or twice a day from depths of 560 feet (170 meters) to near the seafloor.

Three moorings simultaneously measuring conditions over a broad area offer a bigger picture than a single ship visiting once or twice a year could provide. The configuration and spacing allow scientists to monitor and record the development of relatively localized phenomena in the ocean such as phytoplankton blooms and eddies—swirling water masses that sometimes break off from large currents—that can have a measurable impact well beyond their relatively limited footprint. Eddies can affect the physics, chemistry, and biology of the ocean across hundreds of miles and influence the weather even farther afield.

And while the profiler mooring provides a detailed view through the water column of a single location, a pair of autonomous profiling gliders orbits nearby to provide a

Photo courtesy of Mitch Eland, University of Washington

Moored profilers like this travel up and down Global Array mooring lines, making a round trip every 20 hours, to collect high-resolution data from remote parts of the ocean, which scientists can see online within hours of collection.

Sheri White, WHOI

The technical complexity of deploying Global Array moorings in the challenging places where they are located means that much of their success rests in the design, preparation, and staging done by engineers and mooring technicians.

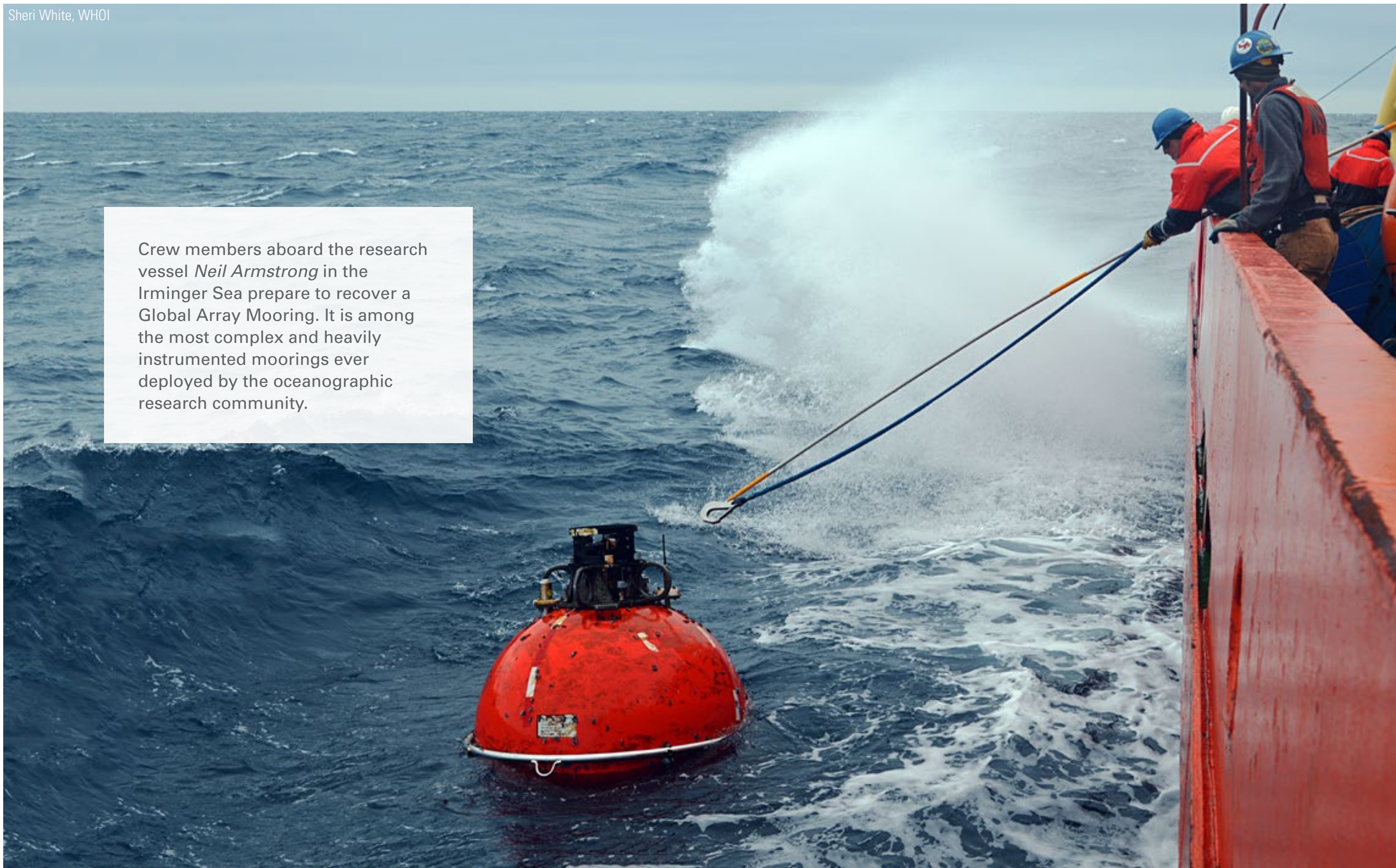
to a satellite. The data are then made available to scientists and the general public on the OOI website.

The sole component of a Global Array on the surface is a buoy near the profiling mooring. It is one of the most instrument-heavy platforms ever put in the ocean. In addition to sensors fastened along the mooring line itself, the surface buoy holds sensors that monitor conditions immediately below the surface, including water temperature and salinity; nitrate concentrations, dissolved oxygen, and carbon dioxide; and biological activity. It also supports a meteorological station that records a range of atmospheric conditions so that scientists can better understand how the ocean and atmosphere interact over time. Added to that is communications equipment that relays data back to shore in near-real time, and wind turbines, solar panels, and rechargeable batteries to power the instruments day and night. In addition, it has reinforced construction to enable everything to stand up to whatever the high-latitude oceans can throw at it over the course of a year. All of this adds up to a platform that weighs four tons and is unprecedented in its size, complexity, and durability.

"These places are hostile and remote and these moorings are out there for a year," said Paul Matthias, the OOI program manager at WHOI. "There's no opportunity to repair them if something goes wrong. It's almost as if you're on another planet."

similarly high-resolution look at the top 656 feet (200 meters) of the ocean. At the same time, another pair orbits the entire array to provide a wider ocean view. These gliders and other parts of the Global Array can be reprogrammed from shore to gather measurements of an unexpected event or change in conditions.

The gliders also solve a dilemma for the Global Arrays of relaying data back to shore from beneath the surface. Unlike Coastal Array moorings, almost all of the elements of Global Arrays are submerged and so incapable of communicating with shore. But when underwater gliders circling the array get close to a mooring, they download data from the mooring through the water via an acoustic modem, surface, and transmit the data



Sheri White, WHOI

Crew members aboard the research vessel *Neil Armstrong* in the Irminger Sea prepare to recover a Global Array Mooring. It is among the most complex and heavily instrumented moorings ever deployed by the oceanographic research community.

WHOI mooring technician Meghan Donohue splices a line on the research vessel *Neil Armstrong* during a long trip from Woods Hole to the Global Array in the Irminger Sea.

Into the high latitudes

In the summer of 2013, the first Global Array was deployed, at Station Papa. It was followed in the fall of the following year by the Irminger Sea Array and, in the spring of 2015, by the arrays in the Southern Ocean and Argentine Basin.

Maintaining a year-round presence in the ocean is anything but simple—or inexpensive. Originally conceived in an era of brighter budget outlooks, all four were envisioned to operate for decades. But each trip to one of the Global Arrays requires nearly 20 shipping containers full of equipment to be staged from a distant port.

The reality of new federal budget constraints demanded that the NSF consider all cost-cutting options available. In 2017, NSF made the difficult decision to adopt a recommendation laid out in a study by a National Research Council committee of its ocean sciences program and announced that the Southern Ocean and Argentine Basin arrays would be suspended later in the year. At the same time, said Division of Ocean Sciences Director Rick Murray, the NSF is looking for other ways to advance scientific discovery in the far southern latitudes and continue to make the more than two years of already-collected data freely available online. "The region is difficult to study, but it remains important to address science questions that can only be answered by being there."

Even when an expedition is compromised by bad weather, just making the effort to travel to remote and seldom-visited parts of the ocean has paid dividends. In 2015, WHOI physical oceanographer Sebastien Bigorre was the chief scientist on the first cruise to recover and replace the moorings in the Southern Ocean—to "turn" the moorings, as it is called. Faced with 33-foot (10-meter) waves, Bigorre decided not to have the ship wait out the storm near the moorings, but instead chose to travel even farther south to gather whatever data that conditions would allow from the edge of the vast Circumpolar Current that sweeps unobstructed around Antarctica. Occasionally, the current sheds mammoth eddies that travel hundreds of miles and affect everything from the deep ocean to the atmosphere.

Last year, Bigorre returned to turn the Argentine Basin Array and encountered two storms that halted work, plus a third that the ship was able to dodge while returning to port, but not without sailing through 70-knot winds. That set his mind to work—the strong currents he sees sweeping through the array and the fierce winds on the ocean above must be linked.

"What fascinates me is I learn more every time I go there," said Bigorre. "Even if you don't see anything at the surface, the instruments tell you there is so much going on. Everything is linked. I can't wait to go back." ▲

Ship crew members and mooring technicians aboard *Neil Armstrong* deploy a mooring during a rare calm day in the Irminger Sea. The yellow "hard hats" protect glass flotation spheres that hold mooring lines upright in the water.

Thinking Global

Photo by Sheri White, WHOI

Irminger Sea (60°N, 39°W)

WHOI physical oceanographer Bob Pickart has called the Irminger Sea "the windiest spot on the global ocean." That makes it not only a difficult place to observe for any length of time, but also an important place to study how the air and ocean interact. The Irminger is where warm surface waters flowing north lose their heat to the atmosphere, become colder and denser, and sink to the seafloor to form the so-called North Atlantic deep water that helps drive Earth's "global ocean conveyor" circulation system. The region is also where the Atlantic and Arctic Oceans connect. As the Arctic warms and more sea ice and glaciers thaw, the influx of more buoyant fresh water threatens to reduce deep-water formation. The Irminger Array was specifically designed to integrate with another large monitoring effort recently undertaken by institutions in the U.S., U.K., and Europe: the Overturning in the Subpolar North Atlantic Program (OSNAP).

Argentine Basin (42°S, 42°W)

The Argentine Basin is home to a strong, deep current that was discovered by chance only in the 1990s, but that is far from any coastline to help steer the flow. "That tells you how little we know about this part of the ocean and how much is actually going on," said WHOI physical oceanographer Sebastien Bigorre. It is also a place where water masses meet—cold, deep water flowing south from the North Atlantic; warm, fresh water from the Southern Ocean; and extremely cold, extremely deep water from Antarctica. It is unlike almost any other ocean, but very few observations from the region exist, other than from a ship- and mooring-based program by the National Oceanic and Atmospheric Administration known as the Southern Ocean Meridional Overturning Circulation (SAMOC) Initiative and occasional releases of free-floating Argo floats. Data from the OOI Global Array augment these efforts and bolster the Southern Ocean Observing System (SOOS) made up of nearly 50 universities and institutions worldwide. (Deployments were suspended in 2017.)

Southern Ocean (55°S, 125°W)

Sailors don't like to frequent the Southern Ocean, a place where they can encounter 60-knot winds and 33-foot (10-meter) waves—even in the summer. But the region is experiencing unprecedented changes with far-reaching consequences. The site for this Global Array at the edge of the Southern Ocean, chosen based partly on findings by the Diapycnal and Isopycnal Mixing Experiment in the Southern Ocean (DIMES), is another key part of the Earth's "global ocean conveyor" circulation. The region is also critical to understanding how the ocean can take up and sequester large amounts of the greenhouse gas carbon dioxide from the atmosphere. The first OOI mooring deployments in 2015 provided the first time-series data of heat and water mass movement from the region ever recorded—something of particular interest to the people of Chile as the country struggles with a persistent drought caused by changing wind and atmospheric pressure patterns over the ocean. (Deployments were suspended in 2017.)

Station Papa (50°N, 145°W)

Station P or Papa in the Northeast Pacific is a Global Array with a history. The site has been occupied continuously since 1949, first by a meteorological ship keeping station at the site and, beginning in the early 1980s, by a surface mooring operated by the NOAA Pacific Marine Environmental Lab. In addition, the Canadian government has sponsored cruises to collect data and samples three times per year along Line P, which stretches from Station Papa to Victoria, British Columbia, since 1981. The long history and thorough understanding of Station Papa make it a popular location for process studies, where multiple platforms are engaged in intensive multidisciplinary studies for a period of weeks to months to improve understanding of critical phenomena such as ocean acidification. "It's a widely studied area with a long data set," said OOI Program Manager Greg Ulses. "It was an easy one to pick."