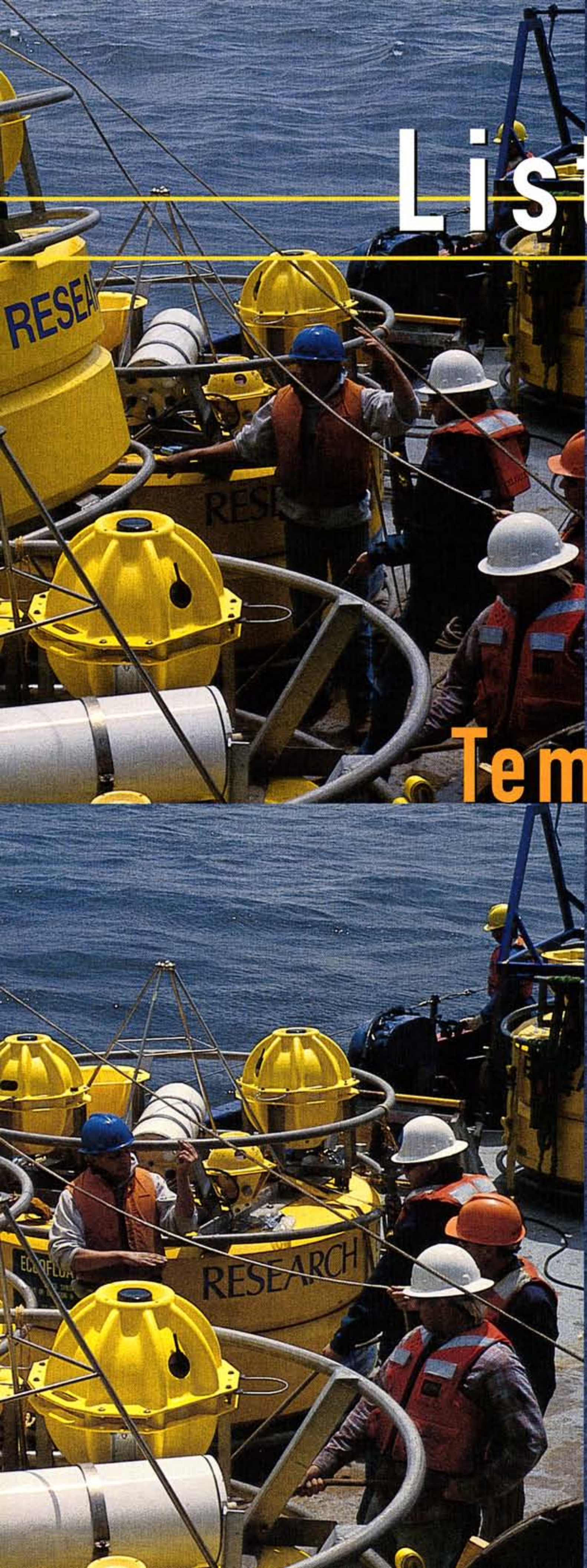
Listening to the Ocean's Temperature



The 1998 North Pacific Acoustic Laboratory cruise (NPAL '98) aboard Scripps's R/V *Melville* involved deployment of instrument arrays essential to the ATOC experiment.

BY JANET HOWARD

If one wishes to have a maximum impact on the rate of learning, then one needs to stick one's neck out at an early time.

Walter Munk

It is a motto that Walter Munk strives to live by, and few could argue that Munk did not "stick his neck out" when he and colleagues set out to take the temperature of the entire Pacific Ocean using sound waves.

The goal of the ambitious venture, called the Acoustic Thermometry of Ocean Climate (ATOC) project, was to devise a new method for tracking long-term changes in climate associated with global warming. Yet, putting the theory into practice presented several scientific hurdles, and there were those who questioned whether it would work. Even Munk admits to having his own secret doubts.

Luckily, the initial results from ATOC, which brought together scientists from more than a dozen institutions, are in agreement with another of Munk's core beliefs: "Things usually work better than people tell you they will."

Originally conceived by Munk and Carl Wunsch of the Massachusetts Institute of Technology, the basic idea behind ATOC is to send sound signals from underwater speakers and track how long it takes them to reach receivers moored to the floor of the Pacific thousands of miles away. Sound travels faster in warmer water; slower in cooler water. Thus, a long-term series of tests that recorded increasingly faster travel times would indicate the ocean is warming.

Scientists will need to track ocean temperatures for a decade to determine if they are increasing because of global warming, said Peter Worcester, principal investigator for the ATOC project. But analysis of the initial 15 months of data from the experiment proves the technique works as a method for measuring the average temperature of vast expanses of ocean.

"The beauty of acoustics is that if you transmit from here to Hawaii, you will naturally get a measure of the average temperature between those two points, because the travel time depends on the temperature of the ocean between the two end points," Worcester said.

The scientists were able to detect variations as small as 20 milliseconds in the hour-long time it took pulses to travel some 3,000 miles (4,800 km) between the underwater speakers and receivers. Those subtle shifts

Marked "research buoy," the subsurface float can carry up to four pop-up buoys mounted on top for mid-experiment data retrieval, as well as emergency position-reference beacons.

allowed the scientists to estimate average ocean temperatures along the signals' pathways to within .006°C.

"It was generally thought that it would be impossible to get measurements this precise at such long ranges," said Munk. "So we are very pleased with the results."

The scientists also were able to detect an expected seasonal swing in upper ocean temperatures of about 2°C.

To date, scientists typically have turned to the atmosphere to monitor changes in global temperature. Because atmospheric conditions are continually shifting, however, it is difficult to discern whether fluctuations in temperature represent a trend caused by human influences or are simply the result of natural variation. The ocean, however, has an enormous heat capacity, allowing it to easily absorb large amounts of heat with only a small rise in temperature. Once it absorbs this solar energy, it also is not quick to give it up. Thus, the ability of the ocean—particularly the deep ocean—to maintain a relatively constant temperature makes it an ideal place to spot long-term changes in climate.

For decades, scientists have relied on dropping instruments from ships to take ocean temperature readings. In addition to being expensive and time consuming, this technique provides incomplete coverage of the vast oceans.

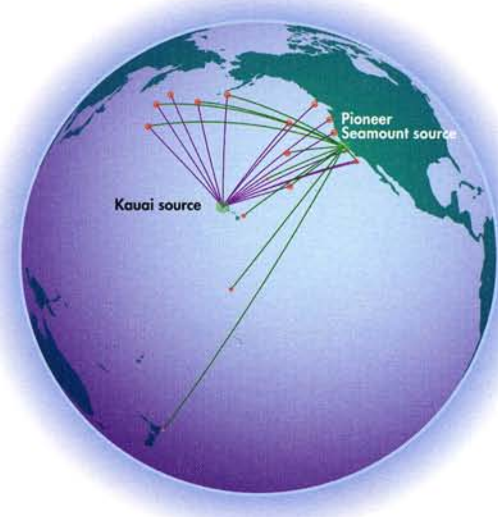
"The problem with just making local measurements is that there is so much variability from month to month and from year to year that it would take hundreds of years to detect any slow, long-term warming," Munk said. "With the measurements we are taking of whole ocean basins, we have a chance to detect any warming in as little as a decade."

Acoustic thermometry capitalizes on the presence of sound channels in the deep sea capable of trapping and transmitting sound over very long distances. The channels are created by the variation of pressure and temperature with depth. Located at a depth of about 3,000 feet (900 m), these deep-sea superhighways act almost like lenses in focusing the sound and guiding it over thousands of miles.

Not all the acoustic energy travels straight down the axis of the sound channel, where sound travels at the so-called sound minimum. Instead, some of the sound waves cycle up close to the ocean surface, where they are bent back down, cross the axis of the channel, and reach close to the ocean floor before being bent back once again toward the surface. By measuring the difference in travel time between sound that traveled a straight course down the axis of the sound channel and that which cycled in waves through various depths of the ocean, scientists can measure how ocean temperatures vary with depth.

The acoustic signals are sent intermittently through the sound channel from underwater speakers also located at a depth of about 3,000 feet

Right, Map of a feasibility study of acoustic thermometry in the North Pacific Ocean. Lines represent acoustic paths from sound sources on the U.S. West Coast and in Hawaii to U.S. Navy and other receivers. Paths cover distances of up to 3,100 miles (5,000 km) in the North Pacific, with a 6,200 mile (10,000 km) path to New Zealand. ATOC represents the first attempt to directly provide average measures of temperature throughout much of the Pacific Ocean basin.



(900 m). The sound sources are deployed off the coast of Kauai and on the Pioneer Seamount, located about 55 miles (90 km) off the coast of San Francisco. The low-frequency signals are then picked up thousands of miles away by sophisticated underwater hydrophones scattered around the Pacific, where the transmissions are so faint that scientists must rely on elaborate computer programs to distinguish them from the ambient ocean noise. While the ocean is frequently referred to as the "silent deep," it is, in fact, a raucous environment. Sounds created by breaking waves, shipping, offshore drilling for oil and gas, military sonars, marine earthquakes, and marine life itself fill its depths.

In addition to vertical strings of hydrophones located at remote sites such as Christmas Island, the ATOC system also uses once top-secret arrays of hydrophones originally deployed along the seafloor by the U.S. Navy to detect enemy submarines during the cold war.

One of the goals of the ATOC scientists is to compare ocean temperatures measured using acoustics with those derived from satellite data. Because satellites cannot measure ocean temperatures directly, scientists have had to rely on satellite recordings of sea level to calculate estimated ocean temperatures.

Peter Worcester stands by as the acoustic receiver is readied for deployment. Moored near the center of the array, the receiver contains data-recording electronics and batteries. Twenty hydrophones strung along the cable are wired to the data-recording device for storage and retrieval of acoustic data.

Below, Daniel Doherty (left) of Scripps and John Kemp of Woods Hole Oceanographic Institution during deployment. A subsurface float bobs in the sea just aft of R/V *Melville* while cable—with hydrophones attached—is trailed off the stern. In the foreground, a line of chain-bound anchors await deployment. Each of these will hold a complete array in place over a precisely determined location on the seafloor.

The estimates were based on the belief that changes in sea level were primarily caused by changes in the heat content of the ocean. A warmer ocean, for example, would cause sea levels to rise because of thermal expansion. But the ATOC scientists discovered that about half of the season-to-season changes in sea level are actually caused by such things as large fluctuations in water mass and changes in salinity—things not included in the earlier satellite calculations.

"People had been using sea-level measurements from the TOPEX/POSEIDON satellite as a proxy for temperature change in the top 100

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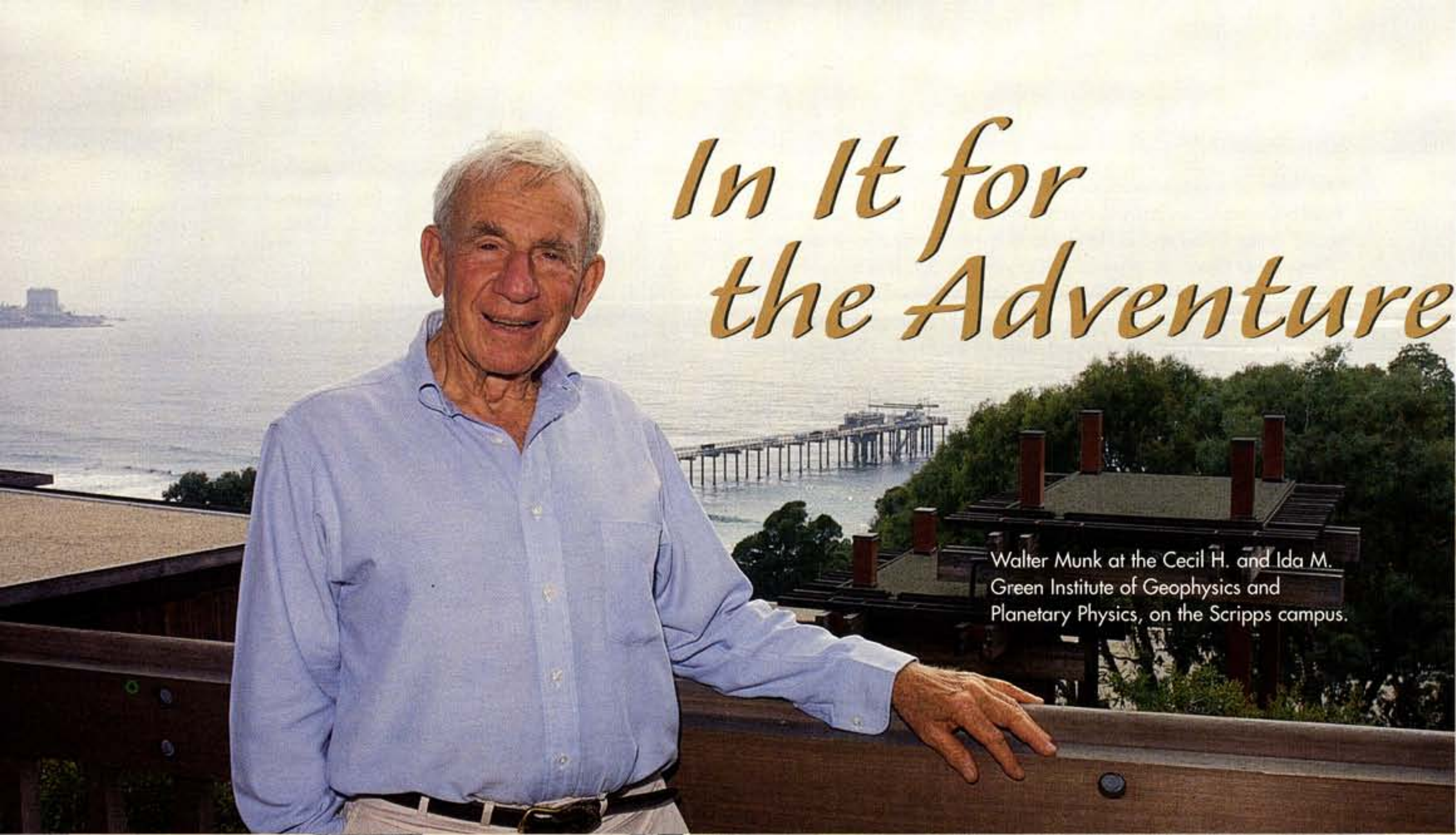
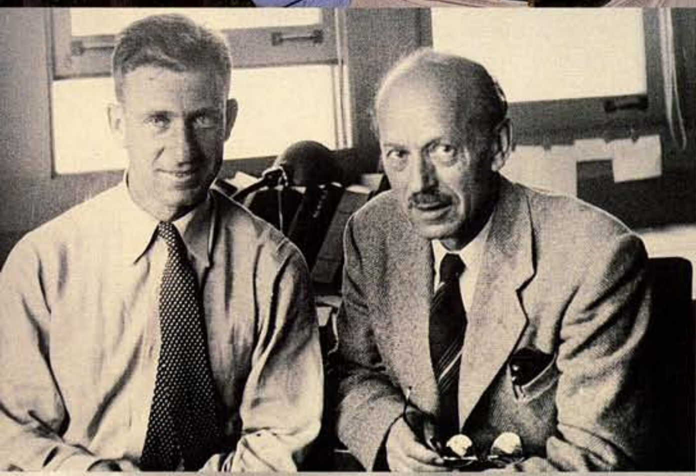
In It for the Adventure



Walter Munk at the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics, on the Scripps campus.



Munk (at left) as a Scripps graduate student in 1940, with then director Harald Sverdrup.

Munk was among the first Scripps scientists to use scuba equipment as a research tool. He is pictured here during the Capricorn expedition of 1952-1953.

If one needs proof that the path to success is simply to follow one's heart, then one need look no further than Walter Munk.

At age 80, he is one of the foremost oceanographers in the world. Yet, it doesn't take long to realize that Munk has spent his life studying the ocean for the sheer fun of it.

"Walter was leaving recently for a trip to Japan, and I asked him whether it was for work or pleasure," recounts Breck Betts, a member of Munk's staff. "He just looked at me and said, 'What is the difference?'"

In addition to admiring Munk's ability to blend work, family, and fun, colleagues also respect his knack for zeroing in on a topic and working doggedly until it is solved.

"When he works on a problem, he lives and breathes it," said Peter Worcester, who has worked with Munk at Scripps since 1972.

Munk has been widely recognized for his fundamental contributions to oceanography. He was awarded the National Medal of Science from then president Ronald Reagan and the Vetlesen Prize, often considered the Nobel Prize of earth science. He is credited with expanding understanding of ocean currents and circulation, deep-sea tides, and wave propagation in both solid and fluid bodies.

Munk also is known for explaining what causes a wobble in the earth's axis during rotation, co-authoring a classic book called, *The Rotation of the Earth*. While Munk drifted into the topic by accident, as in many cases, he left a new field of research in his wake.

"He has a real talent for knowing what the interesting problems are and which ones are attackable based on the knowledge at that time. It is almost like an intuition," said Worcester.

Despite Munk's epic contributions to oceanography, he is quick to admit it was the romance and adventure of oceanography that attracted him to the field.

"I am really not a scholar," he said matter-of-factly. "I am really a scientific adventurer."

Asked about the most exciting thing that has happened in his 50-plus-year career, Munk remembers spending nine months with former Scripps director Roger Revelle on the Capricorn expedition during which the scientific crew tracked the oceanographic effect of a thermonuclear explosion.

"The height of the expedition was landing in Tonga on Christmas Day. We hired a taxi and told the driver to take us to the furthest village we could find on the map and leave us there just to see what would happen. It was a marvelous three days," said Munk.

Munk found his way into oceanography by accident. While completing his undergraduate training at California Institute of Technology, he took a summer job at Scripps so that he could date a young woman vacationing in La Jolla. The summer romance soon faded, but Munk found a new love that was to remain with him for a lifetime: oceanography. After receiving his degree from Caltech in 1940, Munk returned to Scripps to study toward a Ph.D. degree in oceanography.

During World War II, Munk spent six years working on problems associated with amphibious warfare. He and colleagues developed a method to predict sea swell and surf based on weather maps. This method was used to successfully predict high but manageable waves for the Normandy invasion. More than 50 years later, it is an accomplishment that gives Munk a sense of pride.

"We helped save lives and that has been a source of great satisfaction," he said.

Munk also is proud of the Cecil H. and Ida M. Green Institute of Geophysics and Planetary Physics (IGPP), which he helped found at Scripps in 1960 and directed for 22 years.

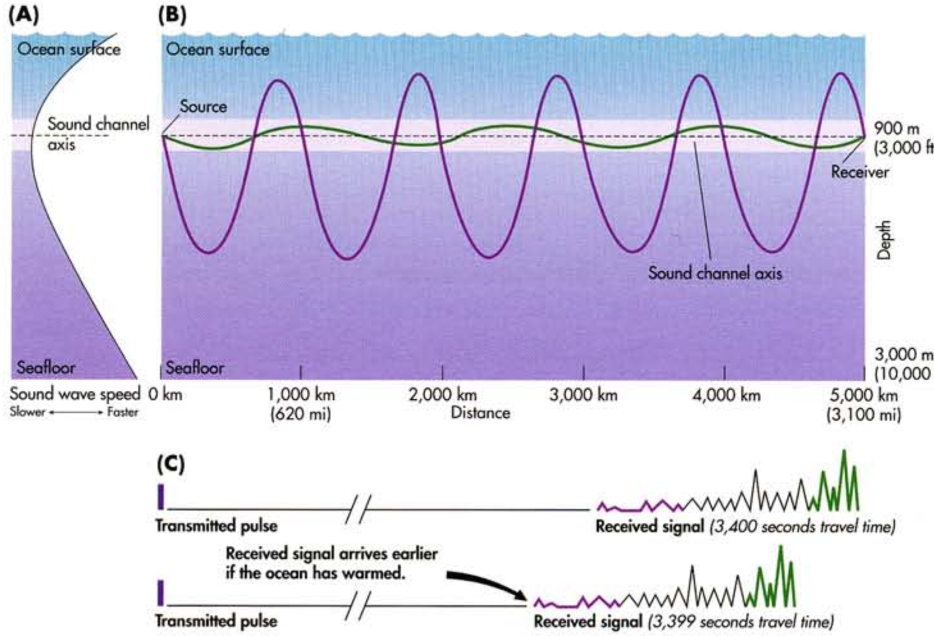
Students continue to find their way to Munk's IGPP office to seek advice on whether to go into oceanography. His counsel: Follow your heart.

The Munks—Walter, Judith, and daughters Kendall (on Judith's lap) and Edie—lived on station at Tutuila, American Samoa, in 1963 while engaged in a survey to measure Pacific Ocean swells.

During many years of work at sea, Munk has delighted in a hands-on approach to shipboard operations.

At sea with ATOC colleague Robert Spindel (left) of the University of Washington.

Walter and Judith Munk at home in La Jolla.



(A) The curved line shows the effect of depth on the speed of sound in the ocean. It is shaped by the relationship of water temperature and pressure. As the ocean becomes deeper, water temperature decreases and pressure increases. Because sound travels more slowly in colder water, initially, as depth increases, sound waves move more slowly. However, sound travels faster under high pressure conditions. In deep water the temperature stablizes so the effect of cold temperature is overridden by the effect of pressure, and sound waves move faster.

(B) A sound channel is created around the point pressure takes over from temperature as the dominant effect on sound waves. Some sound waves are trapped here, and travel undisturbed for thousands of miles along the channel axis. Most sound waves travel further from the axis. They will reach a distant receiver more quickly than sound traveling down the channel axis, but their strength will be greatly diminished by traveling the longer distance.

(C) Acoustic thermometry utilizes the sound channel to transmit sound over very long distances. A long-term series of tests that recorded increasingly faster travel times for sound signals over the same path would indicate increasingly warmer ocean temperatures. This could serve as a possible indicator of global warming.

Below, Array cable trails across the deck from its attachment beneath the subsurface float. The cable is wrapped with a plastic fringe called "hairy fairing," which reduces noisy vibration along the cable.

meters (approximately 330 ft) of the ocean," Worcester said. "It turned out, at least in the area where our acoustic paths were, not to be a very good proxy. That came as a big surprise."

This finding calls into question basic calculations of ocean heat content derived from satellite measurements that are used in computer models to predict future changes in global climate.

Munk said he fears that if the climate models are not accurate in predicting season-to-season changes in heat content, they are unlikely to be accurate in predicting more complicated changes associated with long-term global change.

"One of the major goals of ATOC all along has been to compare the data we obtained with climate models, and we find that the models are not all that accurate," he said.

The ATOC project scientists originally planned to start in 1994 but were delayed for about 18 months because of questions about whether the acoustic transmissions might affect the hearing of whales and other marine mammals that rely on sound to navigate and communicate. After rounds of public hearings in California and Hawaii, the planned effort to determine if the transmissions had any impact on marine life was significantly expanded.

Using traditional visual observation methods, some novel acoustic monitoring techniques, and a variety of ingenious telemetry tags that allow animals to be tracked by satellite, a team of independent marine-mammal experts have been observing a variety of marine mammals to determine if they behave differently when the ATOC source is activated. Experiments conducted to date have found the sound transmissions to be biologically innocuous, said Christopher Clark of Cornell University's Bioacoustic Research Program.

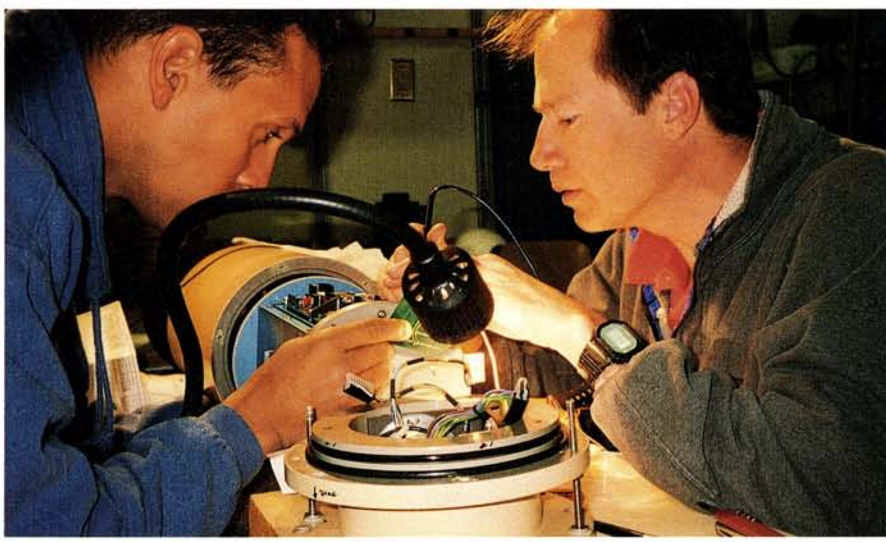
For the past year and a half, researchers have been conducting aerial surveys off the coast of San Francisco to discern whether blue, humpback, or sperm whales avoid the Pioneer Seamount—where the ATOC source is located—during periods when transmissions occur. Only a slight difference in the distributions of sperm and humpback whales has been observed, and it does not appear to be directly related to the sound level, Clark said. The scientists also fitted deep-diving elephant seals with radio tags, released them west of the Pioneer Seamount, and tracked their movements by satellite.

"We would turn on the ATOC source, and the seals would swim right by it and come home," Clark said. "We were thinking we might see a deflection or something around the source, but they didn't pay any attention to it."

In Hawaii, scientists played a scaled-down version of the ATOC sound in close proximity to humpback whales. Intense observations of the whales revealed they did not respond to the sound at levels they would be exposed to from the real source operating in the deep sea, Clark said. The researchers also are conducting detailed observations off the north shore of Kauai to determine whether humpback whales respond to the sound from the ATOC source. To date, however, they have detected no consistent or obvious responses, he said.

"We found more variability in animal behavior was explained by the day-to-day traffic in the harbor and the bay than by ATOC," Clark said. "There were weekends on the Kauai coastline in peak season when helicopters flew over whales 90 times."

Project scientists said they hope the results from the marine mammal studies will help convince environmental groups to support new environmental permits so that the project can continue. The current permits expire at the end of this year for the sound source located off San Francisco and at the end of 1999 for the source off Kauai.



Above, Matt Norenberg (in sunglasses) and Kevin Hardy (leaning outboard) of Scripps. Hardy is holding a pole to retrieve the pop-up buoy floating on the sea surface. Minutes earlier the scientists commanded the pop-up buoy to release from the subsurface buoy 1,300 feet (400 m) below. **Left,** Americo Rivera (left) of Scripps and Bruce Howe of the University of Washington's Applied Physics Laboratory make at-sea repairs of an ultra-short baseline navigation system used to ensure precise deployment of instrument arrays. **Below,** With the Golden Gate Bridge astern, R/V *Melville* makes a mid-cruise port call at San Francisco.

Even if granted new environmental permits, however, the scientists must still find funding to continue their work. The current six-year, $40 million swords-to-plowshares grant awarded by the Department of Defense will expire at the end of this year.

Both Munk and Worcester remain cautiously optimistic. "I think we have shown that what we originally hypothesized is true, and this is a good technique for monitoring the ocean," said Worcester. "So, our intent is to work hard to get the necessary funding and permits to continue. How successful we are going to be is unpredictable."