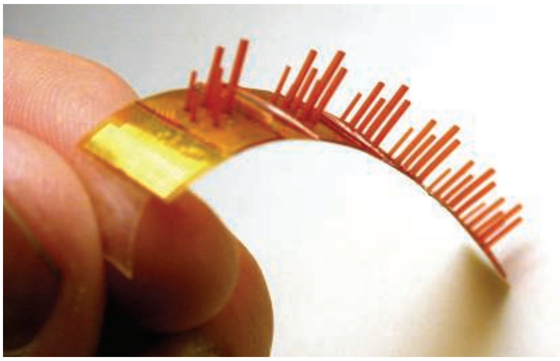
sensors. However, increasing the sensitivity of the sensor is a double-edged sword, says Liu, because of the added burden of filtering out unwanted noise. Scientists are using fish biology as a guide to tackle that problem as well, managing to mimic their hair cells' structural alignment that allows fish to weed out background noise.

Although the sensors were developed primarily to help guide small, robotic vehicles, Liu suggests that they could also assist submarines. For example, submarines now employ passive sonar to avoid giving away their position. But because that technology reads signals generated by noise, it cannot detect a stationary submarine or the subtle vortexes shed by large rocks. In addition, active sonar requires the emitted "ping" to travel away from the ship so that the feedback can be analyzed. That constraint creates a blind zone around the craft that makes subs vulnerable to sabotage by bomb-carrying divers, says Liu.



**The right bent.** The artificial hair cells are only 500 to 700 micrometers long and can be adapted to function as both vibration and tactile sensors.

Liu says that his array can eliminate that problem by detecting movement within a radius of about three to four times the length of the vessel, 200 meters or less for a full-sized submarine. Liu's hair cells are sensitive enough to detect both divers and large, unmoving bodies such as rock faces that are normally invisible in dark or murky conditions. Hair-cell sensors also have shown the potential to track other submarines based on wakes created minutes before, just as seals use their whiskers to track their prey. To turn those applications into reality, however, the artificial hair cells must be robust enough to withstand a marine environment.

Scientists can also imagine nonmilitary applications for the sensors. Changing the shape of the hair, Liu speculates, could yield vibration or tactile sensors in addition to flow sensors. Scaling up production could lower the cost of semiconductor sensors from $12 to $1 per unit, opening up markets as diverse as sneakers, MP3 players, and stress gauges in buildings in earthquake-prone areas.

Despite the many challenges, Stone predicts that DARPA will pick up the project for a second term beginning this fall. And if all goes well, someday hair cells might alert your iPod as well as your ear to the rumbling of an approaching subway train.

–BRIAHNA GRAY

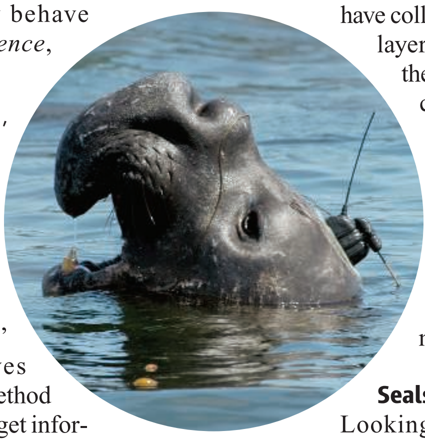
CLIMATE SCIENCE

# Sea Animals Get Tagged for Double-Duty Research

**Elephant seals and other deep-diving species are providing an unexpected boost to a global oceanographic database**

Eight years ago, Dan Costa tagged nine elephant seals to learn how the sea mammals would respond to an expected El Niño event, a shift in a cold-water current in the Pacific. Sensors glued to the seals' backs were designed to record the depth at which they dived and the temperature of the water, while transmitters glued to their heads gave out their position. Once tagged, the giant pinipeds lumbered out from their rookery on Año Nuevo Island near Santa Cruz, California. Some went to the Aleutian Islands, others to the Gulf of Alaska, and a third group shot straight out West into the central Pacific.

After one season, the seals returned to Año Nuevo toting detailed records of 75,000 dives in the North Pacific. Costa, a biologist at the University of California, Santa Cruz, learned that the seals dive more frequently and deeper than previously thought—some 60 times a day, routinely as far down as 600 meters, and sometimes as deep as 2000 meters. In the last decade, tagging of this kind has given researchers increasingly sophisticated data from fishes, turtles, seals, and whales, revolutionizing our understanding of how they behave under the surface (*Science*, 11 August, p. 775).



**In depth.** The frequent, deep dives of California elephant seals provide a wealth of information about the ocean.

CREDITS (TOP TO BOTTOM): CHANG LIU AND JONATHAN ENGEL; DAN COSTA/UCSC/TOPP

But in addition to the bounty of information on the animals' movements, their dives also pointed to a new method for scooping up hard-to-get information about the ocean that's useful for climate research. The method promises a wealth of physical data from the deep that will soon dwarf the amount gathered by ships and research buoys. And whereas the first wave of tagged elephant seals could only record depth and temperature, today's more sophisticated tags also capture salinity. "Different water masses have unique temperature and salinity signatures, and these can be used to trace the origin of the oceanic water in a given region," says Costa.

Researchers want to learn about temperatures and water density in the polar regions, for example, because they affect circulation and climate. James Hansen, chief of NASA's Goddard Institute for Space Studies in New York City, says that although researchers have collected data from the upper layers of most of the oceans, the polar regions are poorly covered. With support from ocean scientists, Costa and others are now tagging animals in these less explored areas, taking advantage of their ability to reach places where no machines can go.

### Seals as lab assistants

Looking over the collection of 75,000 depth profiles from elephant seals, Costa and his team thought the results might interest oceanographers. "But we had no idea what to do with the data, who to give it to, or how to prepare it," he recalls. That sum-



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mer, Costa presented the findings on El Niño's effects on elephant seals (surprisingly slight) at a meeting at the Scripps Institution of Oceanography in San Diego, California.

In the audience sat George Boehlert, then a lab chief at the U.S. National Oceanic and Atmospheric Administration (NOAA). "This was incredible data," recalls Boehlert, now head of Oregon State University's Hatfield Marine Science Center in Newport. "I was really surprised at the frequency of the dives and how deep these seals go." After the presentation, Boehlert told Costa he knew how to check the figures against existing data and, if they were accurate, how to enter them into a massive depot called the World Ocean Database (WOD).

**Big picture.** Dan Costa's team has been tagging elephant seals for 10 years at Año Nuevo Island near Santa Cruz.

NOAA had funded the database to hold records from ships and submarines. Later, it added data from its 2500 "Argo" buoys, which drift around the world at about 1000 meters below the ocean's surface, rising every 10 days to transmit temperature profiles. According to Sydney Levitus, the NOAA scientist who manages the database, each year Argo buoys provide 100,000 depth profiles, whereas other buoys, ships, and submarines provide about 140,000.

Back in 1998, Boehlert recalls, few oceanographers knew about animal electronic tags, and "among those who knew, there was a great deal of skepticism about the quality of the data." But the data proved reliable after being checked against profiles obtained by ships and satellites. So the 75,000 profiles from elephant seals were added to the ocean database. Boehlert, Costa, and Levitus also published a proof-of-concept paper in 2001 in the *Journal of Atmospheric and Oceanic Technology*. "You can't understand a climate system without knowing what's going on at depth," Levitus says. "So we want all the data we can get."

But the flow quickly dried up. What happened? After the California elephant seal study, Costa says, "we stumbled around trying to get funds to get tags, but we got nothing for years. We reused the tags we had," he adds, but "we had no money to pay someone to process the data." Although he and Levitus had shown the utility of the data for oceanography, that community has been slow to recognize its value—and to seek funding from the relevant federal agencies.

But that situation is changing, as interest in using tagging data for ocean research is on the rise. Since 2000, the Tagging of Pacific Pelagics (TOPP) program, funded mostly by private foundations, has been tagging 23 species in the Pacific Ocean. Seven of those species—the air-breathing ones that carry location transmitters—now produce about 1 million depth/temperature profiles a year. And TOPP hopes to format the data and deposit it in WOD within a year.

### Under the ice

Two years ago, Costa and a team from Old Dominion University in Virginia won a 3-year, $800,000 grant from the National Science Foundation to join colleagues from France, the United Kingdom, and Australia in a program called Southern Elephant Seals as Oceanographic Sensors. The group is tagging 70 southern elephant seals, who then spend much of their time diving and feeding under the Antarctic pack ice. As they go about their business, the seals are gathering more than 10,000 profiles a year.

Antarctic data are critical for the study of ocean circulation, says Steve Rintoul, a U.S. oceanographer based at the Antarctic Climate and Ecosystems Cooperative Research Center in Hobart, Australia. Surface waters cool and become denser in the polar regions, sinking several kilometers to the ocean bottom. Warm water then flows in, creating the so-called thermohaline circulation. This process controls how much heat and carbon dioxide is stored by the ocean, influencing the rate of climate change. Climate models suggest that warming at the poles could slow down the circulation, driving further warming. But there are "almost no measurements," he says, because "subs aren't allowed … in this blind spot" and the Argo buoys can't transmit through the ice.

Meanwhile, Costa has turned over more than 1 million profiles—a decade of California elephant seal data—to Steven Bograd, an oceanographer with NOAA's Pacific Fisheries Environmental Laboratory in Pacific Grove, California. Bograd, another co–principal investigator for TOPP, is harmonizing and calibrating the data before comparing them with climatic events in the past decade, including two El Niño events. The goal, says Bograd, is to "better understand the mechanisms by which these climate signals impact the ecosystem."

So far, the most recent data from animal tags haven't gone into the ocean database, Costa says. "The reason it takes time is that we're coming up with much more precise and reliable methods of defining where the profiles were taken than we were in 1999," he says. "Five years ago, anything was valuable, but now it's compared to the Argo buoys, which are very precise."

How soon might these profiles be ready for the database? "We're working on it," Costa says. "I think we'll be able to turn over 2 years' worth of data, which is about 25,000 depth profiles, within 6 months." Oceanographers and climate researchers await the promised deluge.

**–CHRISTOPHER PALA**

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CREDIT: DAN COSTA/UCSC/TOPP