FEATURES

BREATHLESS OCEANS

Warming oceans are running short of oxygen, and the fiercest marine predators are already feeling the effects

By **Warren Cornwall**, *off the Canary Islands in Spain*

PHOTO: W. CORNWALL/*SCIENCE*

A captured blue shark will be fitted with sensors to study how low ocean oxygen affects its behavior.

Sometimes salvation arrives in the darkest hours. After nearly 4 days and nights of futility, the cry came from the back of the small fishing boat 3 hours after sunset. "*Azul*! *Azul*! *Azul*!"

Rayco Garcia Habas stood at the railing near the stern, straining against the fishing rod as a massive fish—a blue (*azul*) shark, he was sure—tugged it toward the dark Atlantic waters. He looked over his shoulder at a watching team of biologists, grinned, and called out "*Cervezas*! *Cervezas*!"

The beers (*cervezas*) would have to wait. First, this champion spearfisher–turned–fishing guide for scientists would need to reel in whatever was at the other end of the line. Then, the scientists would have to drag the shark—if it was a shark—to the boat's side, drill two holes in its dorsal fin, and attach a device resembling an oversize neon orange lightbulb.

If all went well, within minutes the shark

Off Gran Canaria, one of the Canary Islands, a small fishing boat carried a team of scientists hoping to tag sharks swimming toward an expanding low-oxygen zone.

PHOTO: LENA MUCHA

would return to the waters off the southern tip of Gran Canaria, an island 210 kilometers west of the Moroccan coast. The device it now carried would record every twitch of its scythe-shaped tail, every dive into the twilight depths, every current through which it swam. Its journey would offer a window into an unsettling environmental trend, called ocean deoxygenation, that is affecting marine life, including some of the sea's most potent predators.

Climate change is leaching oxygen from the ocean by warming surface waters. Two other climate-related threats to the seas—ocean acidification and marine heat waves—get more attention from scientists and the public. But some researchers believe deoxygenation could ultimately pose a more significant threat, making vast swaths of ocean less hospitable to sea life, altering ecosystems, and pushing valuable fisheries into unfamiliar waters. As global warming continues, the problem is sure to get worse, with disturbing forecasts that by 2100 ocean oxygen could decline by as much as 20%. Sharks—fast-moving fish that burn lots of oxygen, sit at the top of food chains and crisscross huge ocean expanses—should be sensitive indicators of the effects.

This is why a group of U.K. and Portuguese scientists took to the sea aboard Garcia Habas's boat in November 2022. His announcement of a shark on the line jolted them into action. Knee pads were tightened. Hands slid back inside gloves removed after a false alarm an hour earlier. "Finally!" said David Sims, the bearded marine biologist heading the expedition.

SIMS, FROM THE U.K. Marine Biological Association and the University of Southampton, has experienced his share of drama, disappointment, and occasional comedy over 3 decades of studying sharks. He's donned a chainmail suit to swim with 3-meter bull sharks. He once led a boat in hot pursuit of what he thought was a school bus–size basking shark—only to find the wake he was following came from a lone salmon. He tangled with a feisty catshark that sprang from the water and latched onto his flashlight. The lanky 53-year-old recounts these tales with a delight seemingly undiminished since, as a young child, he was enchanted by sharks that washed up on the beaches near his home on England's southeast coast.

Sims first noticed a link between shark behavior and oxygen levels in the early 2000s. He and several friends had spent years deciphering the feeding and mating habits of small-spotted catsharks, meter-long, cream-colored fish with cartoonishly large eyes. They worked in an inlet on the southwest Irish coast, where the deeper waters grew stagnant over the summer. When Sims looked at data from tracking tags attached to the sharks, he saw the fish swam closer to the surface in summer, skirting a pocket of low oxygen. "It was really a classic case of decreasing oxygen clearly displacing the sharks from where they wanted to be," Sims says.

The discovery was just a footnote in his catshark work. But the observation came back to him around 2011, when he was tracking blue and shortfin mako sharks traversing the eastern side of the Atlantic Ocean. After affixing satellite-connected tags to a handful of the fish, he was mystified when the sharks seemed drawn to a large patch of water where northwest Africa bulges into the Atlantic, a region known to be low in oxygen. These open-ocean sharks are the Olympic sprinters of the marine world—makos are capable of bursts of up to 35 kilometers per hour. Why would they head toward places with less oxygen? And what could it mean for the future of marine life as vast stretches of low-oxygen water grow bigger around the world?

SCIENTISTS FOR YEARS have documented oxygen-starved dead zones in places like the Gulf of Mexico and the Baltic Sea. There, pollution from nutrients running off the land, such as synthetic fertilizer, sparks algae blooms. Microbes feast on the rotting vegetation, consuming oxygen. A surge of low-oxygen water can flood an area so quickly that crabs, sea stars, and even fish suffocate before they escape. Low-oxygen zones also form naturally along the western edges of the Americas and Africa, where oxygen-depleted water that hasn't seen daylight for decades wells up.

In the open ocean, currents and storms churn the water, keeping oxygen levels higher. Yet since the 1990s climate models have foretold that a warming climate would deplete oxygen there, too. Surface water warmed by rising air temperatures holds less oxygen, and the growing temperature contrast between surface layers and colder, deeper water slows the mixing that transports oxygen into the depths. At higher latitudes, melting ice can flood surface layers with fresh, low-density meltwater, strengthening the layering and reducing mixing.

In 2008, a paper in *Science* sounded the alarm. German and U.S. scientists found that the low-oxygen zones off Africa and the Americas were growing deeper and losing still more oxygen. Since the 1960s these areas had expanded by about 4.5 million square kilometers, close to the area of the European Union. In the waters frequented by Sims's sharks off Africa's northwest coast, the low-oxygen layer had nearly doubled in thickness over 5 decades, from 370 meters to 690 meters. By 2008 its top had risen to less than 150 meters below the surface. The global trend, the scientists warned, "may have dramatic consequences for ecosystems and coastal economies."

In 2017, scientists delivered more troubling news in *Nature*. Overall, the world's oceans had already lost some 2% of their oxygen since 1960, roughly double what climate models predicted.

For Andreas Oschlies, a biogeochemist at the GEOMAR Helmholtz Centre for Ocean Research Kiel and a leading expert on modeling oxygen in the ocean, the implications were staggering. If the trend continues, it could mean a potential loss of 20% by 2100, he says. That's equal to going from sea level to more than 2000 meters elevation on land. "I thought 'Wow!'" Oschlies recalls. "That's the biggest change and maybe the most worrying change that we see in the ocean. Immediately I thought of (past) major extinction events." For example, at the end of the Permian period 256 million years ago, rising ocean temperatures and an 80% plunge in oxygen levels helped drive the largest extinction in Earth's history. Up to 96% of all marine species disappeared.

By comparison, the 2% drop in oxygen levels seen so far might not sound like much. But global averages can be misleading, warns Lisa Levin, a biological oceanographer at the Scripps Institution of Oceanography who has studied the effects of low oxygen on ocean ecosystems for more than 30 years. "There are places in the ocean where there's been much bigger declines," Levin says. "These changes are probably very important."

OFF THE COAST OF OREGON, fishers in 2002 began pulling up traps full of suffocated crabs. Low oxygen levels are routine in those waters, which are fed by a deep, oxygen-depleted current from the North Pacific Ocean that wells up near the coast. Nutrients in the upwelling make the area a fertile fishing ground. They also nourish algae that deplete oxygen even further as they decay.

But 2002 was extreme. Scientists found oxygen levels had fallen by 65%, compared with historical averages, in more than 800 square kilometers of coastal waters. "I thought it was just a one-off. This is the Pacific Ocean with waves and winds. We're not supposed to run out of oxygen," says Francis Chan, a marine ecologist at Oregon State University (OSU), Corvallis, who studied the event. "Then it happened again the next year, and then the year after, and the year after, and the year after."

Today, scientists in Oregon talk of a "hypoxia season." Some summers, low-oxygen waters off the coast cover as much as 15,000 square kilometers, equal to the Gulf of Mexico's dead zone. It's not unusual for shifting currents or a flush of pollution to temporarily deplete oxygen in a patch of ocean. But this decline looks unlikely to relent. Oxygen levels have dropped steadily, by 30% over the past half-century, in the current that washes the Oregon coast. At the same time, coastal winds that drive the upwelling have strengthened, possibly because of rising land temperatures. Jack Barth, an OSU oceanographer, wonders whether oxygen in the region will drop by another one-third in the next 50 years. "That's what's a little scary," he says.

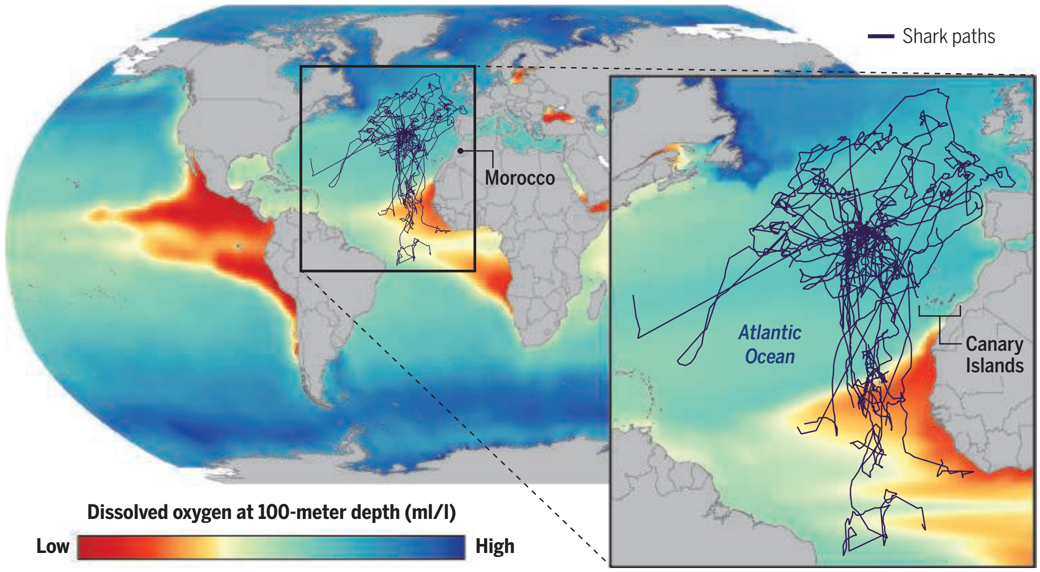
Even if falling oxygen doesn't kill marine animals, it can affect them in myriad ways. It can interfere with fish hormones crucial to reproduction, stunt growth in young fish, weaken immune systems, and even strike animals blind. "We have species off of southern California that are fairly susceptible to oxygen loss, and they are going to be affected," says Lillian McCormick, a postdoctoral researcher at the University of California, San Diego.

Working as a Ph.D. student in Levin's lab, McCormick found that larvae of two species common in southern California waters—the market squid and graceful rock crab—start to lose their eyesight when oxygen drops by less than 10%. At lower levels, the animals are nearly blind. Vision problems could make it harder for them to hunt—or avoid becoming something else's meal, she says.

On a larger scale, some organisms could be pushed out of their habitats. As water warms, ocean dwellers consume oxygen more quickly, putting them on a collision course with falling oxygen supplies. Based on metabolic

Sea changes

Low-oxygen zones that form where currents concentrate depleted water along the western edges of continents have grown over the past half-century. Migratory blue and shortfin mako sharks tagged with tracking devices showed a preference for a large patch of low-oxygen water off the northwest coast of Africa, perhaps because it confines their prey in shallower waters.



CREDITS: (GRAPHIC) K. FRANKLIN/*SCIENCE*; (DATA) NOAA *WORLD OCEAN ATLAS*, VOL. 3 (2009); GLOBAL SHARK MOVEMENT PROJECT

limits and changing ocean conditions, scientists in 2015 calculated that the amount of habitable space in shallow ocean waters for common species such as Atlantic cod, rock crab, and tropical sea bream could shrink as much as 26% by the end of the century.

In 2018, the scientific arm of the United Nations, UNESCO, issued a report titled *The Ocean is Losing its Breath*. A year later, the International Union for Conservation of Nature (IUCN) published a 588-page tome detailing the threat to ocean ecosystems and the people who rely on them. In a 2020 paper, scientists concluded that in this century, declining oxygen would likely have a bigger impact on the ocean than underwater heat waves and ocean acidification. Those threats are familiar, but "oxygen still isn't on most people's radars," says Levin, who worked on the study.

That's why it's important to watch the sharks, Levin says. Not only are they potentially vulnerable to oxygen loss, but sharks also capture headlines. "If [Sims] wrote the exact same paper and it was about some fish that nobody had heard of with an obscure name that's 6 inches long, it wouldn't have the same impact," Levin says. "Observations on species that people care about will really help."

SINCE FIRST NOTICING that sharks were drawn toward the African coast, Sims has pieced together an explanation for their behavior. He suspects the low-oxygen zone acts like a fence, confining mackerel, saury, and other prey into a smaller, oxygen-rich pool of water near the surface. That creates rich hunting grounds for the sharks.

Tags that he and collaborators have placed on more than 100 blue and mako sharks support the idea. Normally, both shark species dive to 1000 meters or more in search of food. But when tagged makos arrived in the zone, they stayed above 200 meters. The blue sharks, which have a bigger appetite for hypoxia-tolerant squid and octopuses, still swam into places with lower oxygen. But their average diving depth of 750 meters was 40% shallower than usual. That scenario mirrors decade-old observations that other large predatory ocean fish—marlin and sailfish—also keep near the surface in areas where deeper water is depleted of oxygen.

The sharks aren't the only predators in those waters. Fishing fleets spooling out longlines—kilometers-long floating lines festooned with hooks—zero in on these same spots in pursuit of blue sharks. Worldwide, as many as 20 million blue sharks are caught each year for their fins and meat, and IUCN now labels the species as "near threatened." Although trade in shortfin makos is restricted, these endangered sharks also die when they are accidentally hooked.

The sharks' habits could increase their peril. Sims's research showed that fishing ships congregating above the low-oxygen hot spots off the African coast catch more sharks in less time than in more oxygenated waters just to the north. Spanish fishing boat captains have told him they "know they are able to go there and catch them [blue sharks] in higher rates," he says.

Sims's initial work couldn't prove low oxygen was driving the sharks to shallower depths, however, nor explain what metabolic trade-offs the sharks were making as they dove into oxygen-poor waters. All he had was a relatively coarse picture of shark movements, and his estimates of oxygen levels were based on models rather than direct measurements. So Sims teamed up with Nuno Queiroz, a former Ph.D. student now at the University of Porto, to build fish tags that could directly trace water conditions and capture more detail about the sharks' behavior. The November expedition to the Canary Islands was part of what could be called Shark Tracking, Version 2.0.

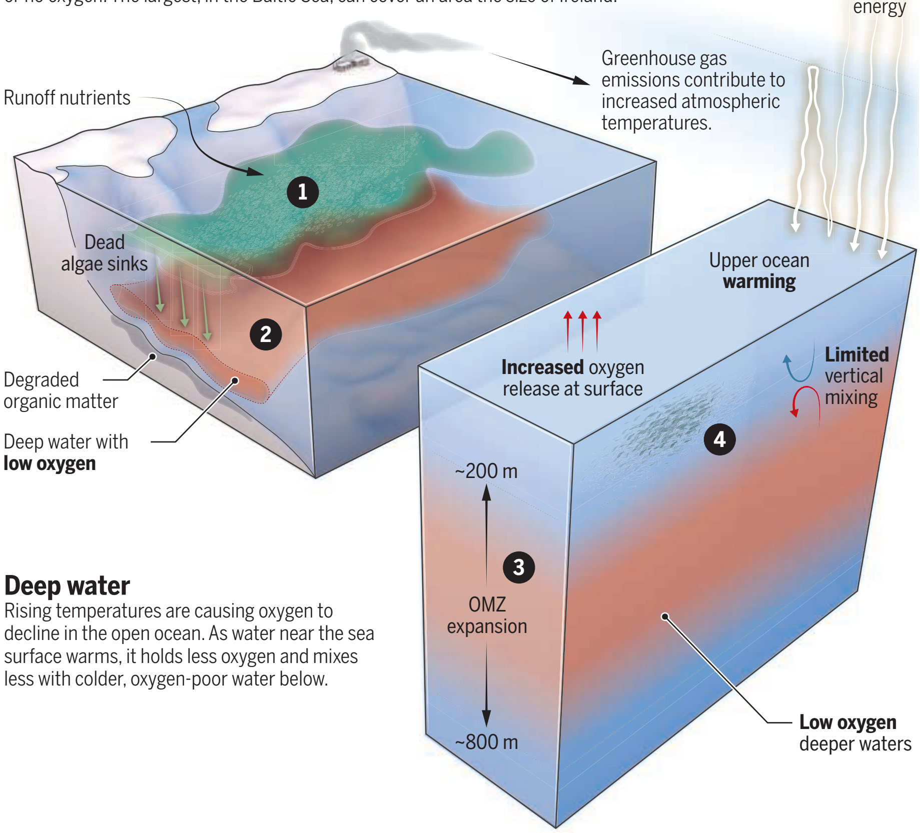
ABOARD THE *ADONEY*, Sims pulled one of the newest tags from a backpack. Hefting the orange device in one hand, he explained that it had sensors to measure oxygen in seawater, as well as temperature and pressure. An accelerometer can track subtle changes in the shark's position, even counting tailbeats to gauge when it sprints to

Troubled waters

Average oxygen levels in the ocean have fallen by 2% over the past 50 years, and could fall 20% by the end of this century, making some parts of the ocean less habitable to sea life.

Coastal regions

Nutrients such as synthetic fertilizer fuel so-called dead zones—deep water with little or no oxygen. The largest, in the Baltic Sea, can cover an area the size of Ireland.



Deep water

Rising temperatures are causing oxygen to decline in the open ocean. As water near the sea surface warms, it holds less oxygen and mixes less with colder, oxygen-poor water below.

1 Biomass production
Nutrients such as nitrogen and phosphorus are flushed into coastal waters, sparking algae blooms.

2 Dead zone
The algae dies and sinks to the bottom, where microbes feast on it and consume oxygen.

3 Expanding oxygen minimum zones (OMZs)
As oxygen levels fall in the open ocean, regions that are naturally low in oxygen because of current patterns are expanding vertically. Their area also grew by some 4.5 million square kilometers over the past half-century.

4 Compressed habitat
As these OMZs grow, they threaten to displace fish that seek more oxygen-rich water near the surface. There are concerns this could make them more vulnerable to overfishing.

GRAPHIC: C. BICKEL/*SCIENCE*

Marine biologist David Sims shows how to fasten a tracker to a shark's fin (left). Sharks also carry a larger tag (right) that can monitor ocean oxygen and shark behavior.

catch prey. Another, similar-looking model attached to some sharks contains a tiny video camera offering a shark's-eye view of its travels, a small propeller to measure swimming speed, and a sensor for muscle temperatures, a clue to how hard the shark is working. Either tag pops off after 2 days and floats to the surface to be retrieved. Tagged sharks also often carry smaller, longer lived sensors, to track their movements.

Members of Sims's team had already tested the devices on sharks swimming near the Azores, 1300 kilometers northwest of the Canary Islands. Now, Sims had come to the southern tip of Gran Canaria, one of the only land bases for tagging sharks near the low-oxygen zone. So far, though, he had seen little more than gulls.

Team members had spent the previous week trolling off nearby Tenerife island and tagged just a single blue shark. By day four on this foray, the odds of using up Sims's stash of five of the fanciest sensors seemed extremely low. Yet he showed few chinks in his upbeat demeanor. "Raring to go," he announced in the hotel lobby early one morning, after several fruitless trips to sea.

As the team motored toward new fishing grounds farther west on the fourth day, sightings of other sea life raised hopes. A pilot whale spouted in the distance. In the afternoon, Garcia Habas landed several skipjack tuna. Shortly after nightfall, a fierce tussle ended when he reeled in a silver, goggle-eyed swordfish. It was hoisted briefly for a photo, then heaved overboard. Finally, the drought seemed to end when Garcia Habas announced he had a shark on the line. After 10 minutes of tug-of-war, the sleek, ghostly form of a 2.4-meter blue shark suddenly materialized, illuminated by the green glow of a light lowered into the water. Garcia Habas eased the fish toward the boat and into the hands of the waiting scientists.

Like a pit crew at a Formula One race, they worked in a controlled frenzy. Ph.D. student Ivo Costa looped a rope over the shark's tail to hold it tight, then reached over the railing and grasped its two pectoral fins. He wrestled it onto its back to calm it, then flipped it onto its belly. Sims leaned far overboard and with both hands held a piece of plastic tight against the shark's dorsal fin to guide where the holes would be drilled. Matt Waller, another Ph.D. student, crowded in, drill in hand. The boat rocked, periodically lowering the entire melee into the waves, making the procedure akin to doing surgery while riding a bucking horse.

After 11 long minutes, Garcia Habas pulled the hook from the corner of the shark's mouth. It lazily descended out of sight, seemingly dazed by the ordeal, its fin adorned with the orange sensor. Costa gave Garcia Habas a high-five. Giddy laughter rose into the darkness. "It's like scoring a goal," Sims said with a grin.

It proved to be the only goal for the week. The following day, the last chance to catch a shark, the team fished the same area until 10:30 p.m. and saw little but swarms of mackerel. As they cruised back toward the hotel lights lining the hillsides, Sims stood quietly on the deck gazing to sea, thinking, he said, about "what might have been."

There will be more chances. In April, a Ph.D. student is scheduled to board a Spanish commercial fishing boat for a 3-month stint tagging sharks directly inside the low-oxygen area. In November, Sims is traveling to Mexico's Sea of Cortez to tag whale sharks. He wonders whether the low-oxygen zone there might be causing them to swim closer to the surface, making them vulnerable to boat strikes. He and others are developing a new oxygen sensor that could stay on a fish for months, and he is finalizing plans to build a $2.2 million shark "treadmill." Hung from the side of a ship, it would enable him to gather a detailed picture of how much oxygen a shark actually needs.

As Sims's team returned to the harbor empty-handed on that final night, the blue shark they had caught—which he dubbed "Warren Jr." (I'm honored)—swam steadily south. When the large sensor popped off after 2 days, the fish had already traveled 47 kilometers. Twenty-five days later, when a second, smaller sensor surfaced, the shark was 413 kilometers southwest of Gran Canaria, closing in on the low-oxygen zone and the waiting fishing boats. ■

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PHOTOS: LENA MUCHA