HYPOXIA:
How Is It Affecting Ocean Life, and Why?

A tale of three Oregon Sea Grant researchers, probing the mysteries of hypoxia

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Acknowledgments

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How Is It Affecting Ocean Life, and Why?

The causes and effects of hypoxia have been confounding marine scientists since the 1970s, when so-called "dead zones" first started appearing in oceans and large lakes. Currently there are more than 400 dead zones worldwide. How did this happen, and how can it be fixed? As Nathan Gilles, Oregon Sea Grant's 2011 Science Communication Fellow, spent time with Sea Grant-funded researchers Francis Chan, Lorenzo Ciannelli, and Stephen Brandt, he uncovered a rich and complex story.

Francis Chan and the missing fish

On the rough seas just past Cape Perpetua on the Oregon coast, the research vessel sways back and forth. Oregon Sea Grant researcher Francis Chan steadies himself against the roll of the *Elakha* as he threads his way through boxes of research gear in the ship's cabin. A marine ecologist at Oregon State University, Chan is on board to solve the mystery of missing oxygen in the water.

Francis Chan (right) and Mike Donnellan (left) run a test on dissolved oxygen levels near Cape Perpetua on the Oregon coast.

Chan knows ocean water usually contains five to eight milligrams of dissolved oxygen per liter. He also knows that when dissolved oxygen gets low enough, it becomes dangerous for the fish and invertebrates that live in it. Below 1.4 milliliters of dissolved oxygen per liter of water, according to the literature he has pored over, bad things happen: fish disappear and some invertebrates die. To determine what the dissolved-oxygen level is, the researcher will run two tests: one with a scientific instrument called a CTD, a device that measures the oxygen level of water using electricity; the second, a chemical evaluation called the Winkler Test. Chan does the chemical test first.

Chan opens special, airtight vials that contain seawater samples and adds his chemical reagents. If the water contains high levels of oxygen, it will turn brown; if it is low in oxygen, it will become whiter. The chemical reaction starts, and what Chan sees shocks him. The water turns a pure white—whiter than he has ever seen it. Convinced something must have gone wrong with the test, he gropes for an answer. Perhaps there was a problem with the reagents? He had seen low oxygen before. But the levels couldn't be as low as the test was showing.

Putting his vials aside, he starts the next test.

Chan lowers the bulky CTD—Conductivity-Temperature-Depth—device into the water. It measures oxygen levels in voltages; the lower the voltage, the lower the dissolved oxygen. On a monitor attached to the CTD via a long cable, Chan sees the voltage in the ocean, as it's measured. Bummer: like the chemical test, the voltage test also shows low oxygen.

The following day, upon returning to his lab at Oregon State University (OSU), *Below 1.4 milliliters of dissolved oxygen per liter of water, bad things happen: fish disappear and some invertebrates die.*

Chan confirms his results. The dissolved oxygen levels in the water were zero. "Or as close to zero as I could physically measure it," remembers Chan. The water in the Perpetua reef had been stripped of its dissolved oxygen and had gone hypoxic, or had lost such a large percentage of its dissolved oxygen that the water was now harmful to many of the aquatic species in it.

Two days later, Chan would see what this meant for the fish and invertebrates that live in the reef off Cape Perpetua.

Lying about two hours out to sea by boat, the Perpetua reef usually has a large and stable fish population as well as a large population of crabs and other invertebrates. Stationed above the reef, Chan, together with colleagues from the Oregon Department of Fish and Wildlife (ODFW), lowered a remotely operated vehicle, or ROV, off the side of their research vessel, to get a fish's perspective on exactly what had happened in the waters below. Watching the video feed from the ROV, the researchers were astonished.

"We didn't see anything," remembers Chan. The memory of that August 2006 trip is still vivid five years later, as Chan recounts it from his cramped office in Cordley Hall on OSU's Corvallis campus. "No fish! All we saw were parts of crabs and sea stars that looked like they were rotting away." Chan says he and his colleagues hadn't expected to see these drastic images. But equally surprising to the researchers were the oxygen levels themselves. Chan and others had known dissolved oxygen in Oregon's coastal waters shifted with the seasons, but they had not expected to see such low numbers. In fact, hypoxic events like this one were relatively new to Chan and his fellow researchers.

In July 2002, ODFW biologists found the bodies of large numbers of bottom-dwelling sculpins. The agency had also heard reports from Oregon crabbers that crab pots were coming up full of dead crabs. The state agency decided to contact a group of OSU scientists to investigate. Chan, an OSU post-doc at the time, was about to head out on a prescheduled research trip when he and others at OSU received the call. As it turned out, his vessel would be near where the ODFW had reported the dead crabs. He and the other researchers on board decided to change their plans and investigate the strange reports.

On the open ocean, the water was calm—eerily so. What had killed the crabs was clearly a mystery, and Chan and the other OSU researchers started speculating. Was it a chemical pollutant? An algae bloom? Lacking hard data, they didn't know. After conducting chemical tests, they discovered the water was hypoxic, containing only about .3 milliliters of oxygen for every liter of water. The levels weren't as low as Chan would discover in 2006, but they got the researcher thinking.

Chan knew that other hypoxic zones around the country and world were often caused by algae blooms that resulted from agricultural nutrient runoff. Nitrogen, which is used in fertilizer, feeds the algae. As algae grow and die, it depletes the water's oxygen at a phenomenal rate, killing aquatic communities in its wake and producing what some media outlets have called "dead zones." But while algae blooms were the approximate cause of hypoxia in the United States' largest dead zones—namely Lake Erie, the Chesapeake Bay, and the Gulf of Mexico—algae blooms were not a major factor in the hypoxia that hit Oregon's coast in 2002 and 2006. Something else was at work.

Chan knew that oxygen levels fluctuate in Oregon's coastal waters, changing with seasons; rising in the winter and falling by early summer. He also knew that the low dissolved oxygen levels he saw in 2002 and 2006 weren't, historically speaking, normal. Unfortunately, Chan and his fellow researchers didn't know much more than that. This, along with the images of dead invertebrates he saw with the ROV, motivated the young scientist to continue his investigation. Concerned and curious, Chan decided to pin down exactly what was happening to the biological communities that live on Oregon's continental shelf. Over the next few years, he would successfully piece together the reason Oregon's coastal shelf occasionally turns hypoxic in the summer months—and why these events would become more likely in the future.

Chan is one of a growing number of researchers alarmed by the onset of hypoxia around the world. He is also one of several researchers associated with Oregon Sea Grant who is investigating Oregon's own periodic coastal hypoxia. While Chan continued to work through the hypoxia puzzle, another OSU Oregon Sea Grant researcher was approaching the problem from a different angle.

Lorenzo Ciannelli and the flipping fish

Lorenzo Ciannelli (left) looks into how the marine community off Oregon's coast has been responding to low oxygen.

Moving swiftly over the ocean floor a thick metal chain hangs between two poles. The center of the chain is submerged in the sandy bottom, kicking up sand, rock, and occasionally a bottom-dwelling flat fish as it travels along. This process, called trawling, is a great way to catch bottom-dwelling creatures, such as the speckled sanddab or English sole. From his office in Burt Hall, Oregon Sea Grant researcher Lorenzo Ciannelli points to the video on his computer monitor of a recent trawling expedition. Ciannelli is a biologist at OSU's College of Oceanic and Atmospheric Sciences who focuses on ocean fisheries. The video on his computer represents hours of ship time and shows a species affected by hypoxia, English sole, which the researcher is eager to learn more about. As the chain kicks up the sand in the video, the startled fish emerges. Acting quickly, the fish darts for safety. The animal appears to escape unharmed, but the next one isn't so lucky. Ciannelli explains that just behind the chain is a large net that will catch the less-than-energetic fish. When the chain reaches it, the pancake-shaped English sole hits the chain, flipping over it like a hot cake being turned on a griddle.

After capturing the video, students from OSU's Research Experience for Undergraduates program will carefully sift through the frames and count exactly how long it takes each fish to flee from the chain and net. After three years, hundreds of hours at sea, and hundreds of hours of video, Ciannelli and his students have discovered something interesting: the reaction time of each animal is correlated to the amount of dissolved oxygen present in the water—the more oxygen in the water, the faster and longer the fish swim. Likewise, when the water contains very low oxygen, the fish tend to be a little sluggish. When this happens, "Swoosh!" says Ciannelli, moving his hand in a sweeping gesture, "The fish almost immediately fall back [behind the chain]." And when they fall back, the net gets them.

Like Chan, Ciannelli has a keen interest in the biological effects of hypoxia and has been looking into how the marine community off Oregon's coast has been responding to low oxygen.

From 2008 to 2010, Ciannelli examined the larval and juvenile stages of species from plankton to vertebrates and invertebrates, including larval and juvenile flatfish, such as the butter and English sole as well as larval and juvenile anchovies and rockfish. What the biologist found is that creatures that experienced low oxygen not only tended to move more slowly than populations that hadn't experienced low oxygen, but there also seemed to be fewer of them. Ciannelli observed that populations that encountered low oxygen also tended to have fewer larvae than populations that hadn't faced low oxygen. While he says it is too soon to tell whether the low oxygen levels caused the low larvae counts,

Creatures that experienced low oxygen tended to move more slowly than populations that hadn't.

Collaborator Sarah Henkel (left) and graduate assistants Bobby Ireland and Tim Lee count samples of small marine invertebrates for Lorenzo Ciannelli's 2008–11 project on the effects of hypoxia on offshore fisheries. Photo: Lorenzo Ciannelli.

he does says that data does suggest some species appear to fare better in lower oxygen environments than others. For example, Ciannelli says, the English sole (that bottom-dwelling creature whose speed of escape he has worked so hard to measure) is not as abundant in Oregon's coastal waters as it once was, though the researcher says he can't say for certain whether low oxygen levels are the direct cause of the animal's decreased numbers.

Commonly referred to as a flat fish because of the fish's flat body shape, the English sole, like other flat fish including halibut and flounders, has evolved to live comfortably supine on the ocean's floor. When it comes to hypoxia, this evolutionary adaptation works to the animal's disadvantage. The ocean floor naturally tends to be a low-oxygen environment, says Ciannelli. The deeper the water, the less oxygen it contains. Turning from his computer, Ciannelli explains his research. Just examining how quickly newly settled juvenile English sole could flee his net was not enough, he says. It might give him a general sense of how much energy the creatures had, but in designing his research, Ciannelli determined something more was needed. The scientist knew measuring just the speed of the flat fish might be criticized for not being rigorous enough. After all, the flight response isn't an aerobic, or oxygen-dependent, reaction but an anaerobic reaction, based on accumulated energy storage. Ciannelli determined that, in much the same way a human can make a quick sprint without taking a breath, a fish could do the same. So he decided to put his juvenile flat fish under the microscope.

On the screen in front of him, Ciannelli cycles through pictures of animals he has taken from the sea back to his lab. There are fish, crabs, and, in one poorly framed picture obviously taken with one free hand, a small, translucent octopus sits in the palm of one of his assistants' hands. Animals not lucky enough to escape Ciannelli's trawl and net, including this octopus, ended up sorted, bagged, frozen on dry ice, and sent back to OSU, where his graduate and undergraduate assistants weighed and measured the creatures.

In the lab, Ciannelli discovered that the aquatic animals raised in lower-oxygen environments were physiologically different in a number of ways from fish raised in waters containing higher oxygen levels. By measuring the lipid content of animals caught in his net, Ciannelli noted that juveniles that grew up in more-oxygenated waters had higher lipid counts than ones that grew up in low-oxygen environments. The researcher also noted that animals that spent more time in more-oxygenated waters also had higher levels of triglycerides over sterol lipids, suggesting that animals that developed in low-oxygen environments had fewer reserves to draw on than animals that grew up in higher-oxygen environments. This, says Ciannelli, explains why the juvenile English sole he recorded seemed so languid.

Animals that developed in low-oxygen environments had fewer reserves to draw on than animals that grew up in higher-oxygen environments.

"When something like low oxygen comes in and wipes the slate clean, we don't have a good sense of what the pattern is. Will it take five years, ten years, one hundreds years to recover? We don't know."

Ciannelli had determined two things: there were fewer larvae than usual, and the juvenile fish were not only slower, they were also physiologically different from juveniles raised in higher-oxygen environments. For his future research, the biologist says he is in the process of planning a series of controlled laboratory experiments. Ciannelli says this will help him determine how dissolved oxygen, as well as other variables such as water temperature, are affecting fish behavior and physiology.

As Ciannelli turned to the lab, Francis Chan continued his research on the ocean. By examining numerous species, Ciannelli had determined that some creatures were more vulnerable than others to the effects of hypoxia—something Francis Chan had begun to notice in his own research.

Francis Chan has gained a much better picture of what happens to Oregon's aquatic creatures when hypoxia strikes.
Photo: Jane Lubchenco.

Francis Chan channels *A Clockwork Orange* for science

The *Elakha* rises and falls, sloshing from side to side with each passing wave. It's a bumpy ride under the gray, overcast August sky. But the choppy seas aren't bothering Francis Chan; from the neck down, he is practically waterproofed and has the look of a child bundled up to play in the snow. Standing in the middle of the *Elakha*'s deck with nothing to hold on to for balance, Chan takes each dip of the boat in stride. At times he seems to be standing unnaturally forward, as if at any moment he might topple over and fall flat on his face. But he doesn't. He is firmly in his element.

"When something like low oxygen comes in and wipes the slate clean," says Chan, "we don't have a good sense of what the pattern is. Will it take five years, ten years, one hundreds years to recover? We don't know." Chan is on the *Elakha* to find out.

Chan's research is part of a joint effort with the ODFW and OSU being funded in part by Oregon Sea Grant. Chan's chief collaborator at ODFW is Mike Donnellan, who is also co-principal investigator with Chan on his most recent Sea Grant-funded research. They are joined by Bill Miller, also from ODFW. The three researchers are going to use a remotely operated vehicle, or ROV, named The Sea Cow to peer into the waters underneath their rocking vessel. Miller is The Sea Cow's keeper, a job that entails staying off deck and instead keeping to *Elakha*'s cabin, where he will stare at several computer screens and control The Sea Cow with a device that looks like it came out of a 1980s arcade. While Miller sits transfixed in front of two laptops inset in durable cases, Donnellan and Chan are out on the ship's deck, enduring the spray and the ocean waves as they lower the ROV into the ocean with the help of a hydraulic crane. The vehicle's four back and side propellers will guide The Sea Cow once under water, while various cameras will record what it sees and will send these images back to Miller via a water-tight cord, aptly named the umbilical cord, which Chan unspools slowly as the vehicle moves away from the *Elakha*. This, believe it or not, is the easy part.

Once the video is collected and the data has been transported back to land via a hard drive, one of the researchers will sit in front of a video monitor and endure the seemingly endless task of naming and totaling the aquatic critters they see. Every animal will be counted. It's meticulous work, and Chan jokingly likens the endeavor to torture, saying the process involves chains and devices from *A Clockwork Orange* to keep the viewer's eyelids open. But from the hours of laborious video watching, a bigger picture has emerged for Chan and his fellow researchers.

The rockfish that live in the reefs on Oregon's continental shelf appear to be much more mobile than was originally thought.

Rockfish that are absent during a hypoxic event reappear when oxygen levels rise again.
Photo: Claire Fackler, NOAA National Marine Sanctuaries.

Chan and Donnellan have been using ROVs to collect data for years. No longer the novice post-doc, since his first experiences with hypoxia in 2002 and 2006 Chan has gained a much better picture of what happens to Oregon's aquatic creatures when hypoxia strikes. Chan, like Ciannelli, has found that not all species respond to hypoxia in the same way. How species respond to the sudden onset of low oxygen is also changing how biologists think about animal behavior.

The region's invertebrates—a classification that includes crabs, sea stars, and sea cucumbers, among other creatures—were especially hard hit by the low oxygen levels of 2006. From the hours of video he has collected on multiple trips, Chan has found that one invertebrate in particular, a brick-colored sea cucumber known scientifically as *Parastichopus californicus*, seems to have nearly vanished from the Oregon coast. Chan says the species could be considered a diagnostic species, an indicator for hypoxia, meaning that if *Parastichopus californicus* is absent from a particular reef, it could indicate that the reef experienced a hypoxic event. While the little brown sea cucumber has all but disappeared from Oregon's coastal waters, another invertebrate seems to have done all right.

A creature called *Pisaster brevispinus*, a large, pink-colored sea star, appears to have come out of the ordeal more or less unscathed. But like *Parastichopus californicus*, this could also be a diagnostic species. Where the sea cucumber's absence could point to hypoxia, the presence of *Pisaster brevispinus* could also point in the same direction. In fact, Chan says this species of starfish has appeared over and over again on the ROV video he has collected, suggesting the creature now predominates much of Oregon's coastal waters while other invertebrates, including other starfish, are conspicuously absent. As to why some invertebrates seem to be hit harder than vertebrates, Chan has a simple answer: Vertebrates, in this case fish, are simply more mobile and able to swim to safety, while many invertebrates apparently can't scurry away fast enough. This explains why in 2006 Chan saw plenty of dead crabs but no fish, dead or alive. However, says Chan, the fact that some species of fish move at all was surprising.

"This is my rock," says Chan, explaining how rockfish must think. "There aren't a lot of rocks in the ocean, and this is my rock. This is where I am going to stay, and I am never going to leave this rock, because it's habitat." This attitude, says Chan, is referred to in biology as high home fidelity, and it was what biologists thought rockfish had—that is, until hypoxia came along. The 52 species of rockfish that live in the reefs on Oregon's continental shelf now appear to be much more mobile than was originally thought.

In performing multiple surveys on different reefs, Chan has noticed that rockfish populations that are totally absent during a hypoxic event will suddenly reappear when the oxygen levels rise again. Chan's suspicion is that rockfish, for all their homebody ways, are nonetheless getting out of harm's way when the oxygen levels drop.

Both Chan's and Ciannelli's research has shown there have been winners and losers in the aquatic communities of the Oregon coast. As it turns out, another Sea Grant researcher had discovered similar trends in United States' other hypoxic zones.

Stephen Brandt studies winners and losers

Stephen Brandt (left) found that how well the fish do in low-oxygen environments depends, in part, on how warm their water is.

The deep waters where the crabs live have succumbed to hypoxia. Driven out by this unseen force, a community of hundreds of crabs seeks refuge in the shallow waters just off the Chesapeake Bay. But in scuttling from one danger, the creatures have inadvertently wandered too close to another. On the beach are hundreds of hungry bipeds, eager to take advantage of the crabs' predicament. Soon, after a few locals notice the animals huddling for protection in the knee-deep waters, the word gets out. It's a crab jubilee. Within hours the beach fills with people with dip nets and coolers in hand. In a very short period the crowd has scooped the crabs out of the shallow water, taking them home for dinner.

This was the scene Stephen Brandt witnessed in the early 1990s just three-fourths of a mile from his home near the Chesapeake Bay. Now the director of Oregon Sea Grant, Brandt has studied hypoxia for over 20 years. From the late 1980s to the mid '90s, Brandt was working at the University of Maryland for the university's Chesapeake Biological Laboratory. Nestled between Maryland and Virginia, the Chesapeake Bay is the largest estuary in the United States. Rich in fish and shellfish, the bay has long been a source of seafood for much of the east coast, and since the 1970s the Chesapeake Bay has also been the site of one of the nation's largest, most persistent, and most studied hypoxic zones. Brandt has kept an eye on it—as well as hypoxia found in Lake Erie and the Gulf of Mexico—for years. Like Chan and Ciannelli, Brandt has discovered there are winners and losers in the biological communities affected by hypoxia.

When hypoxia happens, fish are forced to migrate from the cooler hypoxic deep waters to higher strata and higher-oxygen, warmer waters that may be too warm for the animals to develop normally.

Beyond the crabs that, because of hypoxia, fell victim to the Chesapeake Bay's human population, other creatures in the bay appear to be susceptible to predation when hypoxia pushes them from their safe havens into the clutches of predators. The Chesapeake Bay anchovy is one such creature.

"What bay anchovy normally do is try to avoid predators during the daytime. So they school and they go to the bottom," says Brandt, looking out on OSU's Corvallis campus from his office in the Kerr Administration Building. Notable in his office are two orange-colored ceramic fish on the wall next to his desk, reminders of Brandt's love for aquatic biology and for research, which he still practices along with his duties as program director. The ocean's bottom is a dark place, says Brandt, where the schooling fish can more easily hide from predators such as the striped bass. But

It's still seafood

Back in 2002, one of the reasons Chan started studying hypoxia was to figure out exactly what was happening to fish and invertebrates off the coast. But the researcher says he was also concerned that there was a lot of misinformation about hypoxia. In 2002 and 2006, the media had used words like "dead zones" to describe what was happening. By polling people, Chan also learned of a widespread misconception that fish and other creatures that had been in low-oxygen environments were somehow inedible, a complete falsehood.

But the idea seemed to have stuck in people's minds, and fishermen that charter expeditions for tourists told Chan they were having a hard time attracting clients with "dead zones" on everyone's minds. But by and large, Chan says, fishermen, like the animals they catch, seem to be adapting to hypoxia. Fishermen have learned to move as the fish move—something Brandt says is also happening in Lake Erie. And the crabbers that took a hit in 2002 seem to be recovering as well. In spite of the low oxygen levels that affected those crabs, Chan says, recently the overall catch has been fairly high. "This tells us these populations have some resilience," he says. "That they can withstand these pretty strange biochemical events." But, he continues, this could be just a short-term effect. "In the long term, if there is some impact on how productive these fish populations are, then we need to take that into account. And we just don't have that kind of scientific information yet." This, says Chan, is why it is so important to continue research into hypoxia.

with low-oxygen zones forming on the bottom of the ocean, the fish are forced to flee to the well-lit surface waters where the striped bass can easily gobble them up. Brandt's research has shown that the Chesapeake Bay's striped bass community has benefited from their increased consumption of anchovies. But, he says, this benefit might be short lived.

Brandt experimented with striped bass in his lab and found that how well the fish do in low-oxygen environments depends, in part, on how warm their water is. Warmer water and low oxygen is more dangerous than cooler water and low oxygen. "The warmer temperatures tend to increase the level of metabolic activity," explains Brandt. "This increases the demand for energy, and if you can't get that because you can't breathe well, then the demand for oxygen is going to be higher under warmer temperatures."

Temperature is important for another reason, says Brandt. Hypoxia normally takes place in the deeper, cooler waters. When hypoxia happens in these waters, fish are forced to migrate from the cooler hypoxic deep waters to higher strata and higher-oxygen, warmer waters that may be too warm for the animals to develop normally. And, says Brandt, even though the hypoxia he studies is the result of nutrient runoff that feeds algae blooms, the duration of hypoxia is largely determined by water stratification, or the layering of the water into different strata of varying temperatures. Brandt has observed that the length of time it takes the deeper, cooler waters to mix with the warmer, higher waters not only determines how long it takes the lake's temperature to cool, but it also determines the duration of the hypoxic event.

Brandt studies the United States' three big hypoxic zones, so-called dead zones, found in the Chesapeake Bay, Lake Erie, and the Gulf of Mexico. The lack of oxygen in these three bodies of water results largely from nutrient runoff. This runoff feeds algae blooms which, in the process of growing and dying, consume the oxygen in the water. The solution to algae blooms is, in principle, simple enough—assuming the nutrient tap that feeds the algae could just be turned off.

However, while algae blooms appear to have been a factor in Oregon's hypoxic events, what seems to be driving the Oregon coast's hypoxia are changes in the earth's ocean currents. As Francis Chan found out when he first encountered hypoxia in 2002, depleted oxygen levels resulting from ocean currents was not only a new phenomenon, but when it first hit the Oregon coast it was also a mystery.

Francis Chan peers into the black box of climate change

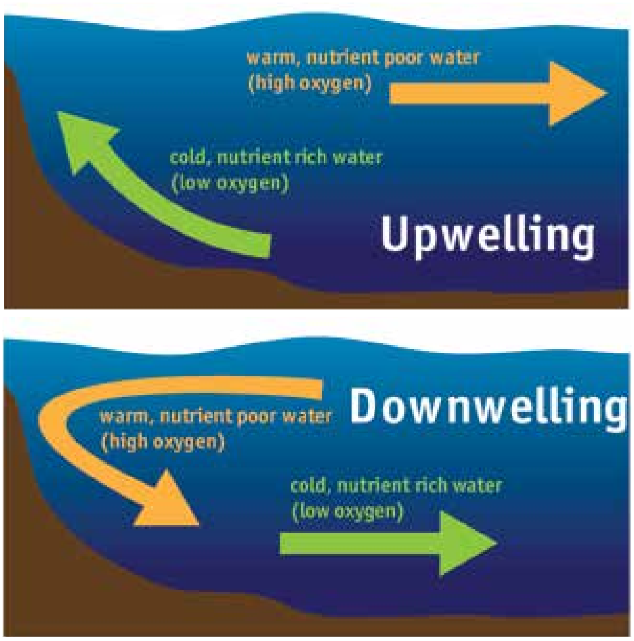
When Chan first became aware of hypoxia in July 2002, the young researcher was pretty convinced he knew what was causing it. Off Cape Perpetua, staring at the eerily calm waters around him from the deck of the *Elakha*, the answer seemed obvious. The waters were calm, and there was no wind. Thinking of the hit movie *The Perfect Storm*, he even joked with a fellow post-doc that the title of their paper explaining hypoxia should be called "The Perfect Calm." After all, Chan knew that in other areas that experienced hypoxia, the worst fish

Because scientists now know dissolved oxygen is sensitive to climate change, it has become imperative to understand the biological response to that change.

die-offs always happened in the summer months when the winds died down or stopped entirely. Chan says the wind is a little like a bubbler in a fish tank: rough winds make rough waters, which—aside from making post-doc oceanographers seasick—also percolate oxygen into the ocean. It stood to reason, then, that if the waters around him were calm—frighteningly, perfectly calm—the water would contain lower-than-normal levels of dissolved oxygen. As it turned out, this assumption was dead wrong.

In research trips during the following weeks, as the winds picked up and the waters became choppy, Chan's crew members became seasick, but dissolved oxygen levels didn't rise. Instead, they remained low. The ocean's perfect calm was a red herring, he realized. Looking the half-mile or so into the distance back to the Oregon coast, something clicked for Chan. The low dissolved oxygen he was measuring in the environment immediately around him must be connected to something much larger. The coast's inner shelf must be tied in some way to the broader ocean, he thought.

In 2006, along with other researchers at OSU and the National Oceanic and Atmospheric Administration, Chan did a series of surveys. Measuring the amount of dissolved oxygen in the waters up and down the Oregon coast, Chan and others were able to piece together a map of the region's dissolved-oxygen levels. The levels differed in different parts of the coast—something that seemed to suggest that dissolved oxygen levels correlated with the topography of the region. This finding seemed to verify what other researchers had found: that the low-oxygen water from the deep ocean was welling up onto Oregon's continental shelf. This upwelling of low-oxygen water, Chan learned, flushes the shelf in late spring and early summer. These cold, deep ocean waters originated as warm surface waters in the south; they reach Oregon via the California undercurrent, part of a large, oceanic conveyor belt that includes the California current. Chan learned that while the rise and fall of dissolved oxygen in Oregon's coastal waters is natural and predictable, it appears that the natural pattern is changing.



During upwelling, phytoplankton multiply rapidly. Some of the phytoplankton sink to the ocean floor and decompose, consuming oxygen. If downwelling doesn't happen for an extended period, low-oxygen waters can accumulate, resulting in a hypoxic zone.

Graphic: Adaline Padlina and Allison Walkingshaw.

"The water we are forming today is holding a little less oxygen in it," says Chan. Warm water holds less oxygen than cool water, and as the world heats up due to climate change, so do the world's oceans. "And, over time," Chan says, "we do expect to see a decline in the oxygen content of the ocean interior." But he says it is still too soon to tell.

"We may not be locked into that fate," says Chan. "Other things might change. There might be other climate cycles that could intervene. We might be just in a downside in the cycle right now where there is a lot of low-oxygen water that is feeding our system." But, he says, the science of how things might change isn't entirely clear. What is known is that the data seems to suggest there will be more hypoxic events in the future. Chan adds that, because scientists now know dissolved oxygen is sensitive to climate change, it has become imperative to understand the biological response to that change.

In September 2011, Chan measured dissolved oxygen levels off the coast at .5 milliliters per liters. He is waiting to review the video he collected from his recent trips on the *Elakha* to see how the aquatic communities are faring.

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