Changing Oceans Breed Disease

In the planet's warming and acidifying oceans, species from corals to lobsters and fish are succumbing to pathogenic infection.

By Christie Wilcox | July 1, 2016

A DEATHLY PALIOR: More than half of the northern Great Barrier Reef's corals, such as those at this Lizard Island

site, have succumbed to bleaching, a loss of their algal symbionts that leaves them vulnerable to infection.
XL CATLIN SEAVIEW SURVEY

The Great Barrier Reef stretches more than 2,300 kilometers along Australia's northeast coastline, from north of Bundaberg, Queensland, to the far corner of the continent, just south of Papua New Guinea. As the world's largest natural structure (visible from space), the reef is bursting with a diversity and abundance of life unlike anywhere else on Earth. More than 1,600 species of fish dart in and out of the calcium carbonate structures created by the system's 450 different types of coral. Thousands of species of sea stars, urchins, worms, clams, and other invertebrates live on, in, and around the reef, which is also home to 6 of the world's 7 sea turtle species and 14 species of sea snake. In addition, the Great Barrier Reef supports 215 species of birds, 30 different kinds of whales and dolphins, and one of the world's last remaining populations of dugongs, relatives of manatees.

But today, even with that immense biodiversity, the reef is a ghostly vestige of its former self. Overfishing has nearly wiped out some of the reef's once abundant inhabitants, such as the black teatfish and the pearl oyster. Every year since 1991, 3 percent fewer female hawksbill turtles have shown up to nest, and loggerhead populations at Wreck Island Natural Area Preserve at the southern end of the reef plummeted by 86 percent between 1977 and 2000. As for the corals themselves, half have died in the last three decades, and the once-colorful colonies that remain have very recently become eerily pale.

The death and destruction is overwhelming, says Terry Hughes, renowned reef researcher and director of the Australian Resource Council's Centre of Excellence for Coral Reef Studies. "The barrier reef north of Cairns will not look again how it did [before this bleaching event] in my lifetime."

> You need only look at what's happening to the Great Barrier Reef at the moment to see how scary the reality is.
> —Gareth Williams, Bangor University

The whitening, or bleaching, of the Great Barrier Reef, which struck in full force last summer, is due to the one-two punch of a steady climb in water temperatures and a strong El Niño event. Stagnant, warm waters stressed the coral organisms until they shed their algal symbionts, which produce food for the coral polyps. "We're now in a very precarious situation, where every time we get a warm summer—often but not always driven by an El Niño year—there's a high probability of the Great Barrier Reef bleaching," says Hughes. "El Niños never used to cause bleaching events, but now they sometimes do."

The current bleaching event is the worst to ever hit the Great Barrier Reef—a recent estimate suggests that bleaching may have killed more than half of the corals in the northern part of the reef—and history warns that it's only the start of the corals' difficulties. In 2002, when 60 percent of the Great Barrier Reef succumbed to bleaching, another threat emerged as the summer's unseasonably high water temperatures abated: infectious disease.[1]

From 1998 to 2003, the prevalence of a group of deadly coral diseases, collectively known as white syndromes, increased a staggering 20-fold in the Great Barrier Reef.[2] And in the past 15 years, dozens of infectious diseases have swept across reef-building corals around the globe. Epidemics follow on the heels of bleaching events, as the causative pathogens take advantage of the whitened corals' weakened immune state. "Only 7 percent of [Great Barrier] reefs are completely free of bleaching," says Hughes. In all likelihood, these corals are now vulnerable to the plethora of pathogenic bacteria, fungi, and viruses lurking in sediments and seawater.

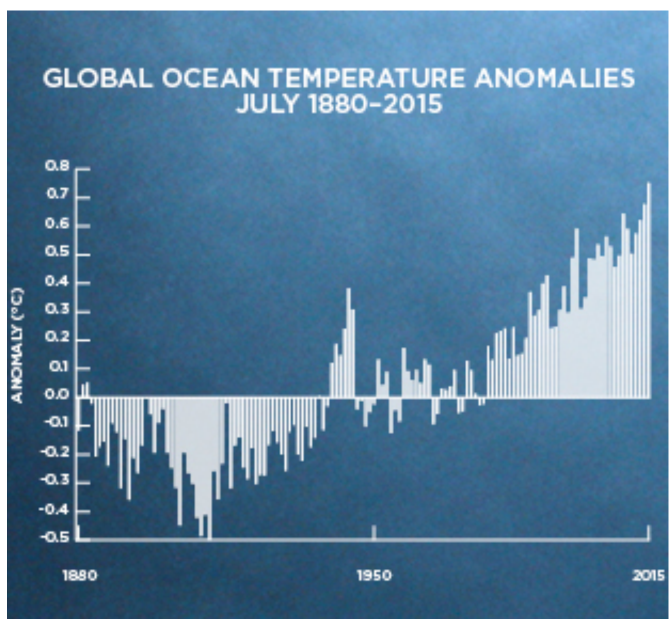
A QUICK BLEACH: In just three months—from December 2014 (left) to February 2015 (right)—the corals off the coast of American Samoa were stripped of their algal symbionts, turning the reef white.
XL CATLIN SEAVIEW SURVEY/GLOBALCORALBLEACHING

And corals are not alone. Warming and acidifying oceans appear to be contributing to an uptick in diseases among other species, too. From 2013 to 2015, an unprecedented outbreak of sea star wasting disease decimated populations of 20 different species from Mexico to Alaska, killing 90 percent of the sea stars in some areas. Since 2000, young Caribbean lobsters have been falling victim to a viral infection that leaves them with no energy to move or eat. Oysters[3] and abalone[4] have been plagued by *Vibrio* bacteria, and numerous fish species are regularly attacked by the protozoan Ichthyophonus.[5] In many of these cases, the disease outbreaks have been linked to climate change.

"We have a narrow window of opportunity to quickly reduce greenhouse gas emissions before the degradation of reefs becomes irreversible," says Hughes.

Warming oceans cause problems

Scientists use satellites to track the daily temperature of the planet both over land and across the seas. These data are then averaged over different time scales to determine how hot, globally speaking, a given month, year, or decade is. Each of the past 15 years (2001–2015) have been among the hottest 16 years on record (since 1880); 2014 and 2015 shattered temperature records. And if the first few months of 2016 are any indication, this year will make those years seem cool by comparison: this April marked the 12th consecutive record-breaking month.



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In the oceans, surface temperatures have increased at an average rate of 0.12°C per decade since 1976—triple the rate of warming that occurred in the 75 years before that (0.04°C per decade). And the warming is hastening: global ocean temperatures in 2016 have been 0.82°C (1.48°F) above average and 0.21°C (0.38°F) hotter than 2015, making them the hottest waters since record-keeping began 137 years ago.

According to Drew Harvell, an expert on marine infectious diseases and professor of ecology at Cornell University, the effects of climate change are "a double whammy" because they simultaneously help pathogens while harming their hosts. Because of the particulars of their environmental preferences, "a lot of marine bacteria, viruses, and fungi grow better at warmer temperatures," she explains. At the same time, the animals they infect are weakened by the hotter temps. "It's a perfect storm of trouble."

The gooey mess that remains of the sea stars in the Pacific from Mexico to Alaska is a prime example. Beginning in 2013, "melted" sea stars began appearing along the US West Coast en masse. The animals, which made their way to the shallow tide pools that become exposed at low tides, were infected with what scientists have dubbed sea star–associated densovirus, the causative agent of sea star wasting disease. A little more than two weeks after infection with the virus, lesions appear and the sea star's arms fall off, leaving behind a slimy, decaying disc. The virus isn't new; it has been around for at least 70 years, and there have been smaller densovirus outbreaks before, affecting just one or two sea star species in a localized area. But the recent epidemic dwarfed previous events, hitting 20 different species along thousands of miles of coastline—a catastrophe made possible by rising sea surface temperatures, according to research by Harvell lab graduate student Morgan Eisenlord.

MELTING AWAY: Starting in 2013, a densovirus spread rapidly along the North American west coast, from Mexico to Alaska, killing as many as 90 percent of the sea stars in some areas. Following infection, lesions begin to appear on the animals and their arms begin to fall off. Sea star wasting disease appears to be increasing in frequency and severity thanks to rising sea-surface temperatures.
MELISSA MINER/UC SANTA CRUZ

Surveying more than 6,500 ochre stars (Pisaster ochraceus) at 16 widespread sites between December 2013 and July 2015, Eisenlord and her colleagues watched as 80 percent of the adults disappeared. When the researchers modeled how the disease patterns correlated with various environmental variables, they discovered a strong link between wasting and heat. For every 1 °C increase in temperature, the probability of disease increased by 1.30. Laboratory experiments confirmed these results—the warmer the water, the more quickly the echinoderms succumbed to infection.[6]

Charlotte Eve Davies, a postdoctoral fellow at the National Autonomous University of Mexico, has seen the same pattern in crustacean diseases. In the 1990s, after nearly a decade of exceptionally warm summers, the lobster fisheries operating in the waters off Connecticut, Massachusetts, New York, and Rhode Island collapsed, at least in part due to the emergence of epizootic shell disease (ESD).[7] The fatal bacterial infection creates holes in infected lobsters' shells, preventing the animals from properly molting. The southern New England fishery has still not recovered, and Maine fishermen worry that their waters—which support a $465.9-million-a-year lobster fishery—are in ESD's path of destruction as the oceans continue to warm.[8]

Farther south, in the Caribbean, Davies is now tracking a disease threatening another lobster fishery. In the state of Quintana Roo, Mexico, more than 2,600 families rely on Caribbean spiny lobster fishing. But their livelihood is threatened by *Panulirus argus* virus 1 (PaV1), which enters the hemolymph (arthropod blood) and drains it of essential oxygen-carrying cells, turning the clear fluid white. This causes the lobsters to become extremely lethargic, unable to eat or move. Eventually the animals starve to death. The virus, first discovered in 2000,[9] infects 60 percent or more of the spiny lobsters (Panulirus argus) in some areas of the Caribbean. And once again, laboratory studies suggest that temperature is playing a big role: when kept in warmer waters, lobsters develop more-active and more-intense infections, while cooler waters reduce the pathogen's virulence.

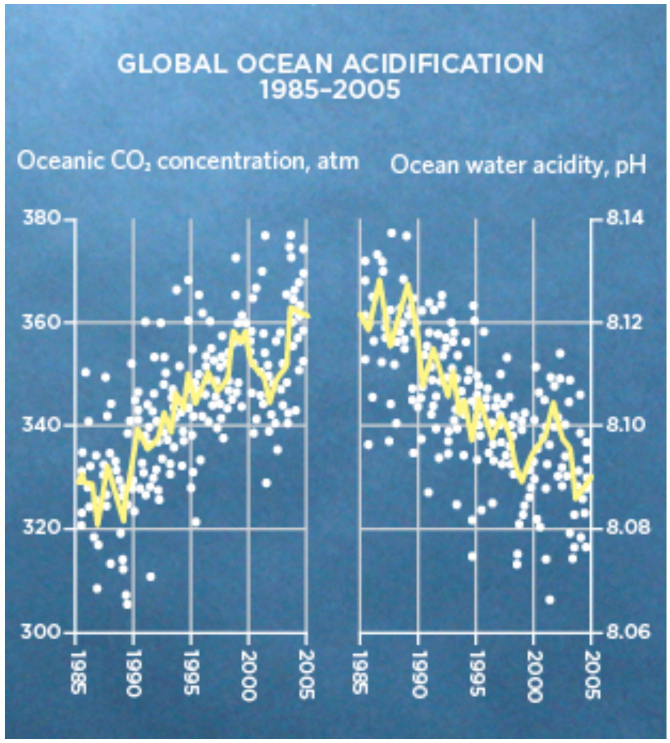
"It is thought that PaV1 is becoming an important source of mortality for juveniles," says Davies. "If PaV1 continues to spread, it could have significant effects on the health of Caribbean reefs as a whole, as well as on the valuable Caribbean lobster fishery."

LETHARGIC LOBSTERS: The hemolymph of Caribbean lobsters infected with the Panuliris argus virus 1 (PaV1) is drained of essential oxygen-carrying cells, causing it to turn white (top right) and making the crustaceans extremely lethargic to the point that they cannot eat or move. The virus can also cause discoloration and fouling of the carapace (middle and bottom). And just as with sea star–associated densovirus, the pathogen seems to be growing increasingly virulent as global ocean temperatures rise.
TOP: BEHRINGER ET AL., DIS AQUAT ORG, 94:153–160, 2011; Middle: COURTESY OF DONALD BEHRINGER; Bottom: JEFF SHIELDS, VIRGINIA INSTITUTE OF MARINE SCIENCE

Effects of increasing ocean acidity

Rising global temperatures are largely due to the increase in atmospheric carbon dioxide (CO_2) that primarily stems from automobile and industrial emissions. But higher atmospheric CO_2 doesn't just warm the planet; it also lowers the pH of seawater by reacting with H_2O to form carbonic acid. The ocean has become 30 percent more acidic in the last 200 years and, as with temperature, the rate of change is accelerating.[10]

Calcifying organisms, including corals and the coralline algae that paint the reefs' surfaces and cement their structures, are particularly vulnerable to ocean acidification. The lower pH makes it more difficult for these species to produce the calcium carbonate structures that form the foundation of the reef, and extreme acidification speeds the dissolution of existing carbonate structures, dissolving the very foundations upon which corals build their homes.



IPCC, 2007/GRID-ARENDAL

Because acidification stresses these reef-building organisms separately from temperature-related effects, it is thought that the combination of changes will present a worst-case scenario for coral and coralline algae. "I think many people assume global climate change impacts, such as ocean warming and acidification, will have additive or synergistic affects on disease impacts to reefs," says Gareth Williams, a lecturer in the School of Ocean Sciences, Bangor University, U.K. But as scientists delve deeper into marine epidemiology, they are discovering that the reality is far more complex.

In 2009, El Niño conditions led to an outbreak of coralline fungal disease (CFD), which afflicts coralline algae, in Palmyra Atoll, southwest of Hawaii. Once it has infiltrated its host, the fungus radiates outward, leaving patches of dead coral and bare rock in its wake. Studying the outbreak's destruction, Williams and his colleagues found that the temperature and acidification of the water worked against each other. Higher temperatures increased the disease's prevalence and lethality, while more-acidic waters, though they stressed and weakened its algal host, also slowed the fungus's spread.[11]
"Such complex, interactive effects between global climate change stressors on disease dynamics are important to consider if we are to accurately predict the response of coral reef communities to future climate change," says Williams.

Unfortunately, for most marine diseases, the role of acidification hasn't been well studied. "The component of climate change that we have stressed so much is temperature because it's just such a pervasive influence," says Harvell. "Ocean acidification is a whole other matter. We know almost nothing about its potential role or ability to affect diseases. It's a big knowledge gap that needs to be filled."

Tracking fish infections

Studying any marine organism is inherently challenging, as humans require expensive equipment to spend any amount of time beneath the waves. But some species are easier to examine than others. Sea stars and lobsters don't travel much, and corals don't relocate once they've settled down, so returning to them time after time to evaluate their health is fairly

PREDICTING MARINE OUTBREAKS

Scientists want to predict outbreaks of marine disease before they happen. With the appropriate tools, says Cornell University postdoc Jeffrey Maynard, "we can mobilize resources, generate political and social will, target research and monitoring, and potentially implement actions that reduce anthropogenic stressors that may interact synergistically with temperature."

Already, scientists have developed methods to predict coral straightforward. Fish, on the other hand, can travel great distances rather quickly. "One day, a herring school might be 50 miles from where it was yesterday, and so it if dies, first of all, you may not even see the mortality event, and if you do happen to see it, you don't really have a good feel for the scale," says fishery biologist Paul Hershberger, station leader of the US Geological Survey's Marrowstone Marine Field Station in Nordland, Washington.

Hershberger recalls studying an outbreak of the unicellular parasite Ichthyophonus among king salmon spawning in the Yukon River in the early 2000s; about 30 percent of the fish were infected. As the fish swam upstream, their symptoms worsened, until just before they got to the spawning grounds, when diseased fish died. And when they die, they sink, Hershberger says. "We could never find the diseased fish in the river because they'd die and sink to the bottom, and the water was the color of coffee with too much cream in it," he says. "At one point I was actually standing in the water, knee-deep, watching a fish die right in front of me. It would come to the surface and kind of roll over, and I'd try to grab it, and then it'd go down to the bottom. That was going on for about a half an hour, and I kept trying to grab it, and eventually it died and floated downstream. I never got it."

Because of the challenges in tracking fish and their diseases, researchers have little historical data on the frequency or scale of disease outbreaks in wild fishes, so it's impossible to say whether such maladies are increasing due to climate change. But some studies suggest that warming waters are likely to alter the status quo.[12] "Fish immune systems are extremely dictated by temperature," says Hershberger. "We see the difference of a couple degrees centigrade

disease outbreaks based on temperature. Twice a week, for example, the National Oceanographic and Atmospheric Administration's Coral Reef Watch uses a predictive algorithm and real-time NOAA satellite measurements of sea-surface temperatures around the world to ascertain areas at imminent risk for bleaching. Scientists and ecosystem managers receive alerts at the earliest signs of trouble.

Terry Hughes, director of the Australian Research Council Centre of Excellence for Coral Reef Studies, relies on similar meteorological predictions to monitor the risks affronting life in the Great Barrier Reef. "I formed a task force in November last year, when it was obvious that the coming austral summer was going to be very hot, with El Niño conditions—hot, calm, few cyclones—that favor bleaching," says Hughes. Christened the National Coral Bleaching Taskforce, the network consists of 10 institutions working together to collaborate on reef research and share data, responsibilities, and resources. So when the most recent event began, Australia had "an industrial-scale response to the bleaching," Hughes says. "We have done aerial surveys of bleaching on over 1,000 reefs, underwater surveys on more than 150 reefs to measure bleaching and mortality of corals, and collected samples to examine the physiological and cellular and molecular responses of corals, fish, and other organisms."

Data collected in the field will be fed back into NOAA's algorithms for Coral Reef Watch and into an Australian version written by the Bureau of Meteorology to improve the models' accuracy. Right now, such tools are still in their infancy, so they aren't perfect coral fortunetellers. "The predictions for bleaching by NOAA and the [Australian Bureau of Meteorology] wax and wane, and like any other meteorological forecast, they don't always get it right, especially early on," says Hughes.

Pioneering such efforts is ReefTemp, an experimental product created by researchers from the Australian Research Council's Centre of Excellence for Coral Reef Studies. ReefTemp works much as Coral Reef Watch does, but for coral white syndromes. So rather than predicting bleaching, it predicts disease outbreaks—whether they follow on the heels of a bleaching event or not. Its predictive algorithms integrate satellite data with variables linked to the disease to forecast what areas are at high risk for outbreaks.

And ReefTemp is just the beginning; the ultimate goal is to create a suite of tools that can predict marine disease outbreaks, from Vibrio to PaV1 and beyond. "This is a very new research area," says Maynard. "There are many host-pathogen systems with links to temperature for which predictive tools could be developed."

turning on or off certain immune-response genes and making fish more or less susceptible to pathogens."

Interestingly, the response is opposite to that of corals and other invertebrates: in fish, the expression of genes that help fight viral infections is enhanced at warmer temperatures. "So the fish become less susceptible because their immune system is ramped up and ready to deal," says Hershberger. How this plays out in the face of pathogens that also benefit from the change in temperature remains to be seen.

Beyond temperature and pH changes, Hershberger points to yet another effect of climate change: the alteration of global currents, which may affect patterns of plankton movement and accumulation. "Many of these plankton assemblages likely serve as the intermediate host for some of these fish pathogens," he says. "Unfortunately, we're just not there yet in our understanding of the parasite life cycles in the marine environment to be able to predict which ones are going to be the winners."

Marine diseases also affect humans

Climate change may do more than unleash scores of diseases that attack marine organisms. Lurking in ocean waters are pathogens, such as *V. parahaemolyticus* and *V. vulnificus*, which can infect people, either through open wounds on the body or via consumption of contaminated and undercooked seafood, such as raw oysters. With an unsettling case fatality rate above 50 percent,[13] Vibrio bacterial infections are the leading cause of seafood-related deaths in the United States.[14]

Vibrio outbreaks are becoming more frequent and are occurring in areas where they previously haven't. "If you asked 10 years ago, you would not have heard of Vibrio cases occurring in the North Sea," says Rachel Noble, director of the University of North Carolina's Institute for the Environment field site in Morehead City. "Nor would you hear of them occurring in the northern bays of Norway, Sweden, or Finland." But now, those waters, too, have changed enough to allow these pathogenic species to flourish. "They're very opportunistic," says Noble. As global temperatures rise, the seasonal range of these bacteria might also expand from their typical May-to-October time frame, increasing the potential for virulent infections to cause even more deaths worldwide.

Whether it's Vibrio in humans, viruses in lobsters, white syndrome in corals, or wasting disease in sea stars, marine pathogens are flourishing in today's changing oceans. Ensuring a healthy and sustainable future for the world's marine ecosystems relies on additional research into the factors that drive disease outbreaks. Although the US Congress has repeatedly threatened to reduce the budgets of major granting agencies such as the National Science Foundation and the National Institutes of Health, proposed legislation might lessen the financial burden of marine monitoring and responses to disease outbreaks that threaten the sustainability of marine species or the health of ocean ecosystems. In 2015, Representative Denny Heck (D-WA) introduced the Marine Disease Emergency Act, which would allow such outbreaks to be declared emergencies. In particular, the act stipulates the creation of a Marine Disease Emergency Fund to pay for disease-response efforts. If such legislation is signed into law, it could provide much-needed support in the fight against outbreaks.

"You need only look at what's happening to the Great Barrier Reef at the moment to see how scary the reality is," says Bangor University's Williams. "But we cannot lose sight of the fact that much of this could still be within our control."

Christie Wilcox is a freelance science writer living in Honolulu, Hawaii. Hitting bookshelves next month is her new book* Venomous: How Earth's Deadliest Creatures Mastered Biochemistry *on her up-close encounters with the world's most notorious species and the secrets they can reveal about evolution and disease.

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