



A World Without Corals?

Besieged by pathogens, predators, and people, the “rainforests of the sea” may soon face their ultimate foe: rising ocean acidity driven by CO₂ emissions

KHURA BURI, THAILAND—In the shallow waters off Lan Island in the Andaman Sea, Kim Obermeyer kicks his flippers and glides over a silent graveyard. Scattered below are shards of staghorn and other branching corals, shattered in fragments that look like detached finger bones. The conservation biologist swims farther out to sea, darts to the bottom, and peers under an overturned *Porites* coral head the size of a Volkswagen Beetle. Obermeyer points to a brown ribbon underneath: a ragged colony soaking up just enough sun to have survived the tsunami that struck on 26 December 2004.

As a horrific tragedy unfolded on shore that day, ecosystems below the ocean’s surface were getting hammered. Across Southeast Asia, the titanic waves ripped apart shallow reefs and buried others in silt. But tsunamis are not the worst threat. The main menaces are largely human-wrought: from divers clumsily breaking off chunks of coral to mass die-offs and bleaching of coral triggered by spikes in ocean temperatures. Last month, the Intergovernmental Panel on Climate Change (IPCC) forecast “more frequent coral bleaching events and widespread mortality” with average global temperature increases of 1° to 3°C.

Surveys suggest that 20% of the reefs on Earth, the largest living structures on the

planet, have been destroyed in the past few decades. Another 50% are ailing or verging on collapse. “Reefs are likely to witness a significant ecological crisis in the coming half-century—because of us,” says coral specialist Camilo Mora of Dalhousie University in Halifax, Canada.

The decline of coral reefs may have staggering consequences. Globally, reefs generate about \$30 billion per year in fishing, tourism, and protection to coasts from storm surges, says Mora. Although reefs cover a minuscule fraction (0.1%) of seabed, they are second only to rainforests in biodiversity, sheltering or nourishing up to 9 million species—a third of all known marine life forms—including 4000 kinds of fish. “To predict that reefs will change dramatically across the globe in the matter of a single generation should keep people up at night,” says Ove Hoegh-Guldberg, director of the Centre for Marine Studies at the University of Queensland in St. Lucia, Australia.

There are a few rays of light in this bleak seascape. Attempts to rehabilitate tsunami-damaged reefs are showing promising results. Some reefs blighted by bleaching have mounted spectacular comebacks. And efforts to limit fishing and human activity have paid dividends in healthier reefs and revived local

fisheries. Over the past decade, hundreds of marine protected areas have been established to safeguard reefs, including innovative MPAs in Palau designed to help corals bounce back after bleaching (see sidebar, p. 680).

Yet these gains could be erased by what’s shaping up as the gravest threat of all. As the oceans soak up more and more of the carbon dioxide that humans pump into the atmosphere, marine chemistry is changing. CO₂ emissions “have the potential to create chemical conditions in the ocean that have not occurred since the dinosaurs became extinct,” says ecologist Kenneth Caldeira of the Carnegie Institution of Washington in Palo Alto, California. Dissolved in water, CO₂ becomes carbonic acid. Caldeira coined a term for this process in a paper in 2003: “ocean acidification.” By midcentury, ocean pH could dip so low that corals would be unable to form their calcium carbonate skeletons.

“Acidification is the big elephant in the room,” says Terence Hughes, director of the Australian Research Council’s Centre of Excellence for Coral Reef Studies at James Cook University in Townsville, Australia. Reef building would grind to a halt, with grievous implications. If CO₂ emissions are not curtailed, Hughes predicts, “we’ll eventually see reefs dominated by sea anemones and

◀ **Artificial limbs.** Thai researchers attempt to save tsunami-damaged coral in January 2005; robust growth 2 years later (*below, right*).

algae.” Put another way, “soon we’ll be having jellyfish and chips,” says biologist Michael Kendall of the Plymouth Marine Laboratory in the United Kingdom. In the darkest scenarios, most corals will be toast.

A multiheaded monster

As coral reefs slip toward chronic frailty, a picture of what this means to the world has begun to emerge. Coral scientists, backed by an army of snorkeling and diving volunteers, have put a watch on critical reefs among the nearly 300,000 square kilometers charted to date. Hidden gems continue to come to light, including a giant deep-water reef in turbid waters off northern Australia. “Not much is known about the reef because nobody wants to swim in that area. It’s infested with crocodiles,” says oceanographer Alan Strong, senior consultant to the U.S. National Oceanic and Atmospheric Administration’s (NOAA’s) Coral Reef Watch.

A recurring theme of this heightened scrutiny is that reefs are vulnerable on many fronts. A March 2005 earthquake off Indonesia, for example, was as brutal as the 2004 tsunami, lifting some reefs clear out of the water (*Science*, 20 October 2006, p. 406). Corals are susceptible to pathogens and predators, too. The crown-of-thorns starfish, a periodic invader, denudes coral outcroppings with the efficiency of a slash-and-burn farmer. Meanwhile, corals are perpetually besieged by filamentous algae, which are held in check by fish that nibble at them. Overfishing can tilt the balance, as can sewage or agricultural runoff, which infuse seawater with algae-feeding nutrients. These abuses, along with coastal development, “are having fantastically large and negative impacts on reefs around the world,” says John Pandolfi, a coral reef expert at the University of Queensland in Brisbane, Australia.

The latest and perhaps biggest present danger for reefs is bleaching. When sea surface temperatures exceed their normal summer high by 1°C or more for a few weeks running, coral polyps, for reasons not entirely understood, expel their zooxanthellae, the symbiotic algae that lend corals color and provide nutrients. The polyps turn pale and starve. “If they don’t get their zooxanthellae back in a month or so, they die,” says Obermeyer.

The dangers of bleaching came to the fore in 1998, when a potent one-two climate punch—a strong El Niño warming in central tropical Pacific waters, followed by a La Niña that heated western Pacific regions—killed 16% of living corals worldwide (*Science*, 27 October

2000, p. 682). Some reefs have rallied from severe bleaching—recently and dramatically, off Darwin Island in the Galápagos. “We’d given up on the Galápagos” after a 1982–83 bleaching event annihilated most of the archipelago’s reefs, says Strong. Now, he says, “it seems to be really coming back.” However, many bleached reefs are still sickly. At least half of those destroyed in 1998 have not recovered, according to the authoritative *Status of Coral Reefs of the World: 2004*, compiled by the Global Coral Reef Monitoring Network (GCRMN).

The catastrophic 1998 bleaching, and regional occurrences since then, highlight the

vulnerability of reefs to global warming. “That’s when we realized that corals could be a kind of canary in a coal mine,” says Jeremy Goldberg, co-author of a GCRMN report on tsunami-inflicted reef damage. Delicate staghorn and elkhorn corals, for example, were listed as threatened in the Caribbean in May 2006 under the U.S. Endangered Species Act. “Branching corals that are sensitive to bleaching might disappear,” warns reef ecologist Thamasak Yeemin of Ramkhamhaeng University in Bangkok.

Some reefs are more tolerant to bleaching. However, says Hoegh-Guldberg, “the movement toward hardier communities of



FRACTURED PARADISE

PHUKET, THAILAND—Like thousands of tourists who flock to the chic resort island of Phuket in southern Thailand, marine biologist Nippon Phongsuwan recently spent a weekend under the waves, taking in the region’s breathtaking coral reefs. Unlike the tourists, Nippon had an extra reason to enjoy the view: His innovative attempt to rehabilitate tsunami-damaged reefs is showing remarkable progress.

Two of the most-savaged reefs lie off Phuket’s Paradise Beach and Lolana Bay on nearby Phi Phi Island. During surveys carried out a few days after the tsunami, Nippon and his colleagues at the Phuket Marine Biological Center discovered the shallow seabed at Paradise and Lolana littered with pieces of branching corals, particularly staghorn and other members of the *Acropora* genus. Realizing that the polyps would be abraded to death in the rough-and-tumble waters, Nippon’s group gathered up hundreds of *Acropora* fragments in a bid to save them.

Aboard a research vessel, the team glued the coral fragments into holes drilled in concrete cinder blocks. They joined blocks with steel bars to help the structure weather strong currents and placed them in various configurations in either shallow reef flats, less than 2 meters deep at low tide, or on reef slopes about 7 meters deep. Blocks in the reef flats—natural *Acropora* habitat—were battered by waves, and most polyps died. But corals transplanted to reef slopes at Lolana Bay thrived and have grown at a rate equivalent to naturally occurring Phuket corals, Nippon says. The “unexpected” findings, he says, suggest that *Acropora* “can adapt well to a new environmental setting.” The hope is that the growing thickets of branching coral will provide a breeding population: seed stock for polyps that mend damaged reefs and pioneer new ones.

The coral growth over 2 years is “impressive,” says oceanographer Alan Strong, senior consultant to the U.S. National Oceanic and Atmospheric Administration’s Coral Reef Watch. For *Acropora*, he says, the low-tech cinder blocks may offer a cheap alternative to the leading artificial reef product: Reef Balls, molded concrete forms that cost as much as several thousand dollars and range up to 2 meters in girth.

Strong and others caution that although coral reefs can be rehabilitated, they cannot be built from scratch. “No one has ever reconstituted a reef,” says Hughes. And some experts wonder whether reef rehab is worth the effort at all, as it addresses a symptom of decline, not the cause. “Inevitably, this kind of work is like treating cancer with a Band-Aid,” says John Pandolfi, a coral reef expert at the University of Queensland in Brisbane, Australia. “It makes us feel good, but our money is better spent elsewhere.”

—R.S.



Fragile beauty. Palau's marine protected areas aim to safeguard corals from bleaching.

PALAU COMBATS CORAL BLEACHING

BABELDOAB, PALAU—A giant clam's purplish-green intake valve, big enough to swallow a fist, snaps shut when a diver drifts close. The magnificent meter-wide mollusk in Ebiil Channel is a symbol of survival, whereas a beige, 2-meter-wide table coral nearby is a vivid example of rapid recovery. In the summer of 1998, unusually warm ocean temperatures killed a third of the reefs ringing this tiny archipelago in the western Pacific. But here in the Ebiil Channel Conservation Area off Babeldoab, Palau's main island, underwater denizens have roared back to life with exceptional vigor.

built an impressive record in marine stewardship. The country boasts one of the highest proportions of territory set aside for MPAs in the world, with about a third of its near-shore waters—1300 square kilometers of reefs and lagoons—under varying fishing restrictions. Other Pacific nations are following Palau's lead: In the past decade, the number of MPAs grew from two to 189 in Fiji and from one to 20 in the Solomon Islands. "One village closes fishing in an area, the fish come back after a few years, and soon the next village wants one too," says Michael Guilbeau

fewer coral species is hardly a 'win.' Coral abundance is still plummeting, and even resistant corals may succumb in a warmer world, he says. "As climate change accelerates, we will lose an increasing number of coral species, making ecosystems less resilient to other pressures."

A case in point is the widespread bleaching in the Caribbean Sea in 2005–06. At one reef off St. John, part of the U.S. Virgin Islands, "before people knew it, a disease infected the coral that had survived the bleaching. What was left was totally wiped out," Strong says. "You can see how this gets to be a multiheaded monster." NOAA and U.S. National Park Service scientists are now searching for clues to why some corals survived whereas others perished.

In an attempt to boost reef survival, governments have been setting up MPAs, which range from free-for-all recreational parks to no-take zones that bar fishing. Fewer than 3% of the world's reefs lie inside no-take MPAs, says Mora. Many reefs are being fished out. Raising the specter of a pending food crisis, a recent study found that 27 of 49 island countries are exploiting their reef fisheries in an unsustainable way, reports a team led by Nicholas Dulvy of the Centre for Environment, Fisheries, and Aquaculture

Science in Lowestoft, U.K., in the 3 April issue of *Current Biology*.

Lax enforcement and lack of local buy-in have undercut many MPAs. "If communities are not involved, they are very unlikely to support an MPA imposed on them," says



Morning commute. Kim Obermeyer (far right) leads Earthwatch volunteers on an inspection of a tsunami-damaged reef in the Andaman Sea.

Obermeyer, coordinator for Reef Check Thailand. With volunteers from Reef Check and a second nonprofit, Earthwatch, Obermeyer endeavors to involve villagers—and here near Khura Buri, the Ranong Coastal Resources Research Center of Kasetsart University—in

reef monitoring. "This is the only way to succeed," he says.

MPAs and measures such as stanching sewage and runoff cannot prevent bleaching. But resilience—the capacity of a reef to absorb recurrent bleaching and still function—*can* be enhanced, Hughes says. In 2002, more than half of Australia's 40,000-square-kilometer Great Barrier Reef bleached. Two years later, Australia created the world's largest no-take zones, extending fishing bans covering 4.6% of the reef to more than 33%. "This initiative provides real insurance cover against the inevitable impacts of climate change," says Hoegh-Guldberg.

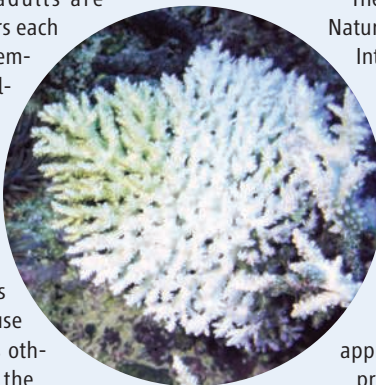
To test this approach, Hughes and colleagues caged some reef sections and left others open to grazing by parrotfish, known by their fused, beaklike teeth. Polyps reestablished on open reef three times faster than on caged sections, they report in the 20 February issue of *Current Biology*. The study shows that reef management after bleaching "has a big effect on the recovery

of the Community Conservation Network in Honolulu, Hawaii.

Palau got off to a flying start thanks to a traditional culture that frowns on overfishing and a leader who champions MPAs. “The best way to protect our natural heritage is to use it as a source of income,” President Thomas Remengesau Jr. told *Science*. “Tourism is the sustainable thing for us.” Palau’s prosperity—nearly all adults are employed—comes largely from its 50,000 tourist divers each year. Reefs vibrant with fish are a top priority. Last November, Remengesau sought to export that credo by challenging the rest of Micronesia to set aside 30% of near-shore waters for protection by 2020.

Even for conservation-minded Palau, the massive 1998 bleaching event, which decimated reefs around the world, was a wake-up call. Three-quarters of barrier reef corals at Palau’s Rock Islands lagoon, a popular diving site, perished. Ebiil, another barrier reef, was 98% destroyed. Inshore, many reefs fared better because they are accustomed to higher temperatures, whereas others survived because turbid waters and shade limited the sun’s damage, says Rod Salm, a marine scientist in the Conservancy’s Honolulu office who developed the bleach-resilience project.

A critical insight led to a bold plan. Most reefs like Ebiil that have bounced back from bleaching are down current from reefs that suffered little, suggesting that coral larvae and fish from healthy reefs fueled the rapid recovery, Salm says. With that in mind, Noah Idechong (pronounced Idd-ONG), founder of the Palau Conservation Society, and others proposed weaving the nation’s hodgepodge of MPAs into an ensemble, linked by



Burnt by the sun. Bleaching signals severe stress.

currents, called the Protected Areas Network. “The key is to protect all the different reef types that survived bleaching or recovered exceptionally fast, because they will provide the larvae that will help damaged areas recover,” says Salm. “These reefs don’t necessarily have the fish density that would make fishermen want to protect them.”

The proposal resonated with Western donors. In 2005, The Nature Conservancy pledged \$2 million, and Conservation International \$1 million, to a trust, provided that Palau raises \$9 million from other sources—which should not be a problem, says Eric Verheij, acting director of The Nature Conservancy’s Palau office. The endowment’s interest, along with a diver tax, should yield \$2.1 million a year for monitoring and antipoaching patrols. Idechong says he expects that the network, with one-third more area under protection than now, will be operational in 2 years.

Ebiil’s rainbow reefs testify to the promise of that approach. Gliding past 2-meter strands of black coral, so prized by jewelers that it has been wiped out in many parts of the Pacific, Verheij zeroes in on what appears to be lifeless coral rubble. On closer inspection, the coral skeleton has been melded together by coralline algae and is studded with young polyps: a nursery of tiny phoenixes rising from the ashes of bleaching. Back on the boat, Verheij explains his philosophy. “Since you can’t protect everything,” he says, “you try to protect the healthiest.” That philosophy seems to be paying off in Palau.

—CHRISTOPHER PALA

Christopher Pala is a writer based in Honolulu, Hawaii.

rate,” Hoegh-Guldberg says. But the strategy works only in the short run; nations must move rapidly to stem greenhouse gas emissions, he says. “It is next to useless not to do the two things together.”

A mortal blow?

Until bleaching reared its head, many experts viewed rising sea levels as the chief peril of global warming for coral—and a relatively toothless one at that. “We thought reefs would respond by just growing higher,” says Strong. “Nobody was talking about changing sea chemistry.” Then researchers came to the creeping realization that rising ocean acidity is likely to throw a spanner in coral physiology.

The threat is glaringly simple. Currently, ocean pH hovers around 8.1. Carbon dioxide absorbed into the water column lowers the pH, and as it falls, fewer carbonate ions are available for shell-building critters to grab. Even in present conditions, corals are fighting an uphill battle: Erosion removes 80% of the calcium carbonate laid down. Acidification will accelerate that process as rising carbonic acid levels deplete carbonate. Eventually, corals, plankton, and other organisms will fail to form skeletons. And coral skeletons are to reefs what girders are to skyscrapers. “You have a potential world in which reefs and the lime-

stone frameworks they have built are in net erosion,” says Hoegh-Guldberg.

IPCC scenarios of global emissions and ocean circulation indicate that by mid-century, atmospheric CO₂ levels could reach more than 500 parts per million, and near the end of the century they could be above 800 ppm. The latter figure would decrease surface water pH by roughly 0.4 units, slashing carbonate ion concentration by half, paleocoral expert C. Mark Eakin, coordinator of NOAA’s Coral Reef Watch, testified last month at a hearing in the U.S. House of Representatives. Ocean pH would be “lower than it has been for more than 20 million years,” he said. And that does not factor in possible acidification from carbon-sequestration schemes now being considered.

Some coral species facing their acid test may become shape shifters to avoid extinction. New findings indicate that corals can survive acidic conditions in a sea anemone-like form and resume skeleton-building when returned to normal marine conditions (*Science*, 30 March, p. 1811). However, by pH 7.9, says Caldeira, “there would be a good chance reefs would be gone.”

The potential for an acid-induced coral cataclysm has cast a pall on the tight-knit community of reef specialists. “The reality

of coral reefs is very dark, and it is very easy for people to judge coral reef scientists as pessimists,” says Mora. “We’re becoming alarmist,” adds Strong—for good reason, he insists. “How are reefs going to handle acidification? It’s not like sewage or runoff, where you may be able to just turn off the spigot.” Queensland’s Pandolfi, however, argues that it’s “too early to make really definitive doom-and-gloom statements.”

No one disputes that urgent action on greenhouse gas emissions is essential. “We could still have vibrant reefs in 50 years time,” Hughes says. But these will not be the reefs we know today. “They will be dominated by a different suite of species,” says Hughes, who notes that the shakedown is already under way.

More likely, steps to rein in emissions will be too little, too late—and the world will have to brace for the loss of reefs. In Southeast Asia, says Hoegh-Guldberg, the threat of millions of people losing their livelihoods must be factored into policy planning. Coastal dwellings throughout the tropics will have to be strengthened against higher waves. Then there is the intangible, aesthetic deprivation if coral reefs wither and wink out. “Without their sheer beauty,” Hughes says, “the world would be an impoverished place.”

—RICHARD STONE