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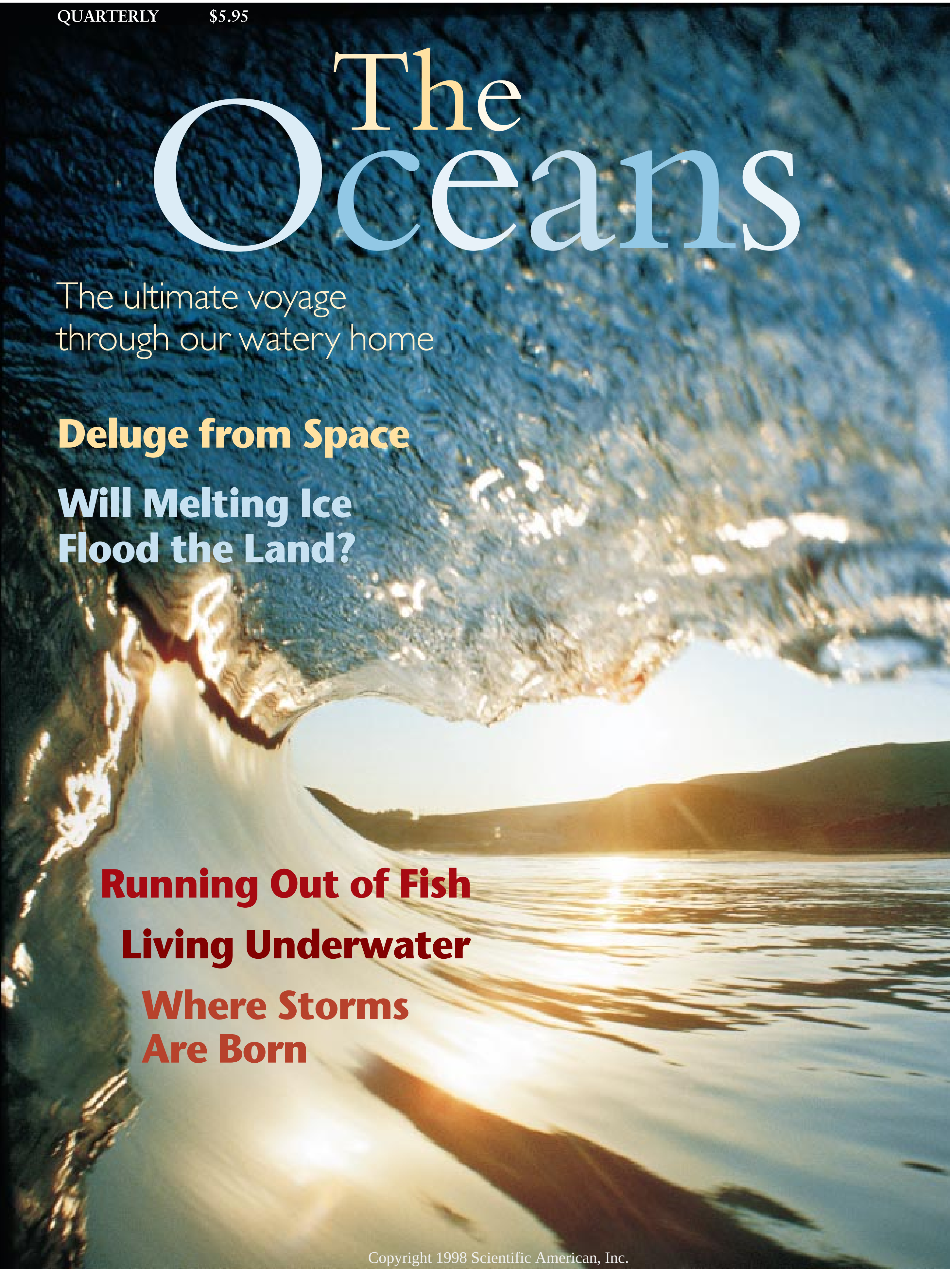

Deluge from Space

Will Melting Ice Flood the Land?

Running Out of Fish

Living Underwater

Where Storms Are Born

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The Oceans

Fall 1998 Volume 9 Number 3

BOB CRANSTON

A gray whale moves through a kelp forest

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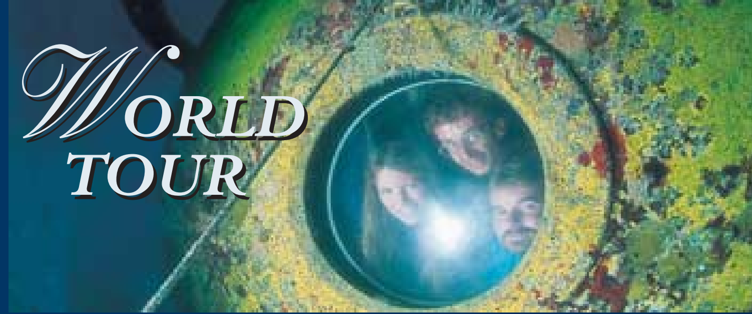

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Celebrating the Sea

VINCE CAVATAIO *Pacific Stock*

When the United Nations declared 1998 as the International Year of the Ocean, we thought it would be the ideal time to take our readers, at least vicariously, on the ultimate ocean cruise. Although the sea is too vast to cover comprehensively, the expert oceanographers, marine biologists, meteorologists and others gathered for this issue offer thoughtful excursions into many topics of the most pressing scientific and economic concern. Researchers around the globe also generously shared the experiences of their daily lives for our scientific "world tour" of work in, on, over and under the ocean. The detailed seafloor maps appearing on the next few pages are just a few products of such work. Amazingly, by measuring subtle undulations of the water's surface, satellites can determine the shape and size of submerged mountains, ridges and trenches thousands of meters below the waves. Those maps are the best introduction to the ever expanding perspective that marine scientists are developing on our ocean planet. *—The Editors*

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Atlantic Ocean

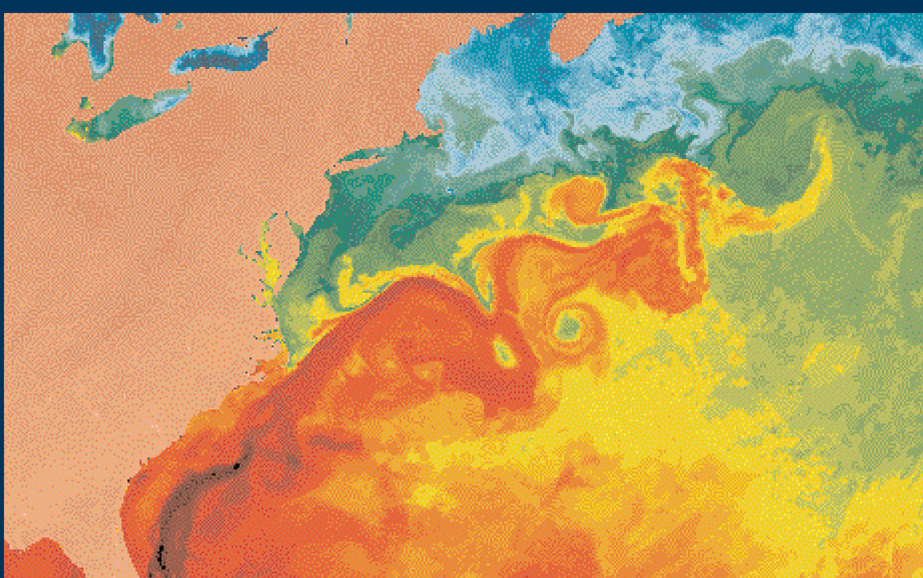
The Atlantic Ocean is named for Atlas, who according to Homeric myth held heaven up with great pillars that rose from the sea somewhere beyond the western horizon. Though not the boundary between heaven and earth, the Atlantic does separate Africa and Europe in the east from the Americas in the west. The Mid-Atlantic Ridge, which runs down the middle of this basin, marks the location of tectonic spreading, where frequent volcanic eruptions continually build up oceanic crust. This concentration of active volcanism can be seen firsthand in Iceland, where the Mid-Atlantic Ridge rises entirely out of the sea.

The tectonic motion away from the Mid-Atlantic Ridge sometimes generates offsets, which scar the floor of the ocean in long east-west-trending fractures. As with the other ocean basins, the movement of tectonic plates over deeply seated foci of intense heat, called hot spots, leaves traces of ancient volcanic activity. Some of these volcanic remnants, such as the New England Seamount Chain, appear only as subtle pinpricks in this global view (*right*); others, such as the Walvis Ridge and the Rio Grande Rise, make up prominent welts.

All this volcanic activity on the ocean floor hardly warms the Atlantic at all. But Atlantic waters do warm western Europe with heat that the Gulf Stream carries north from the balmy tropics. Other currents running near the surface of the North Atlantic form a huge, clockwise gyre, which circles in opposition to the pattern of the South Atlantic currents. (Arrows at the right show major surface currents.)

Area:	82,440,000 square kilometers
Average Depth:	3,330 meters
Maximum Depth:	8,380 meters

WARM- AND COLD-CORE RINGS shed from the Gulf Stream swirl about the North Atlantic in this false-color image obtained by the satellite-borne Coastal Zone Color Scanner. The Gulf Stream represents one half of a giant oceanic conveyor, which carries heat from the tropics northward on the surface and returns colder water at great depth.



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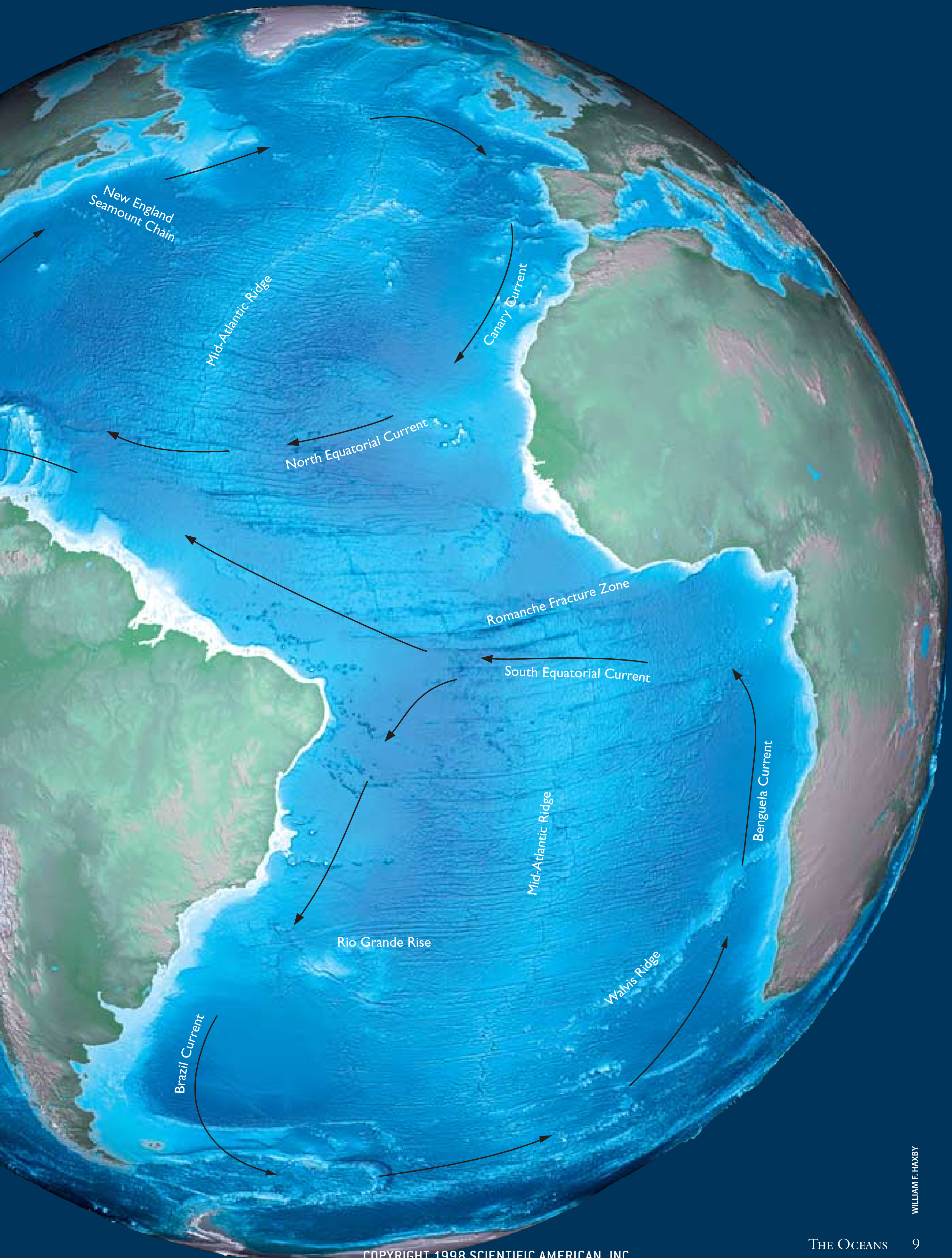

WILLIAM F. HAXBY

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Pacific Ocean

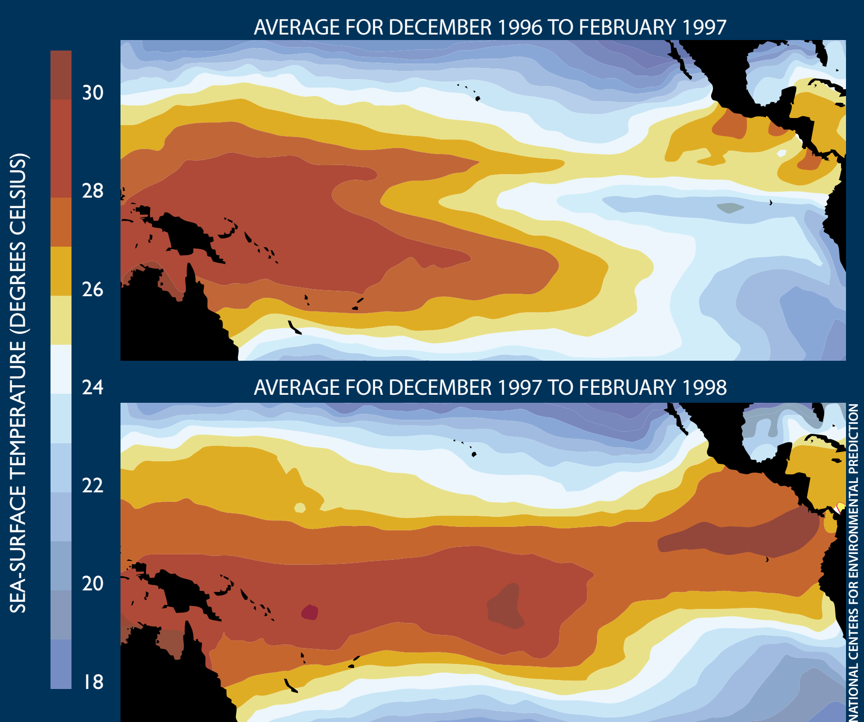
Named by Portuguese explorer Ferdinand Magellan, who believed it to be free of violent storms, the Pacific Ocean is not, in fact, so pacific. Its tropics can be roiled by typhoons, and its shores can feel the brunt of tsunamis—great waves generated by earthquakes. Traveling much faster than any of the Pacific's normal currents (*right*), tsunamis cross the open ocean at the speed of a modern jet. Yet they cannot be seen or felt far from land: only when tsunamis reach the shallows do they build into monstrously tall walls of water.

The Pacific is particularly prone to tsunamis because its underlying tectonic plates continually push under adjacent continents and seas at subduction zones. These collisions are marked by oceanic trenches such as the Mariana Trench (*right*), which includes the deepest spot on the earth. Grinding against one another along the periphery of the basin, the crashing plates cause powerful temblors.

Because sediments blanketing oceanic plates melt and create buoyant magma when they descend into the earth and heat up, the margins of the Pacific are studded with volcanoes. The rising magma at these sites contains small amounts of water, which burst into steam at the surface. Thus, Pacific rim volcanoes are often violently explosive—the eruptions of Mount Pinatubo in the Philippines and Mount St. Helens in Washington State being well-known examples.

Other Pacific volcanoes are more sedate. For instance, eruptions from Hawaiian volcanoes are comparatively gentle because their magma has very little water. The dry magma emerges from above a hot spot deep within the earth's mantle. And just as a blowtorch poised below a slab of moving metal would burn a charred line at the surface, the Hawaiian hot spot leaves a trace of volcanic islands and seamounts on the Pacific plate, which inches slowly to the northwest. The pronounced bend seen in the Hawaiian-Emperor Seamount Chain (*right*) reflects a change in the direction of plate motion that occurred 43 million years ago. (*Editors' note:* To allow the entire Pacific hemisphere to be seen clearly, an unconventional map projection has been used here.)

Area:	165,250,000 square kilometers
Average Depth:	4,280 meters
Maximum Depth:	11,034 meters



TROPICAL PACIFIC usually has its warmest waters pushed westward by the prevailing winds, so that cooler water rises to the surface at the east along the equator (*top*). But from time to time these breezes fail, and the western Pacific warm pool sloshes back east, causing the sea there to become oddly warm (*bottom*). This change, called El Niño (Spanish for "the boy child," after the infant Christ) by South American fishermen who observed it to arrive in December, can alter weather throughout the world.

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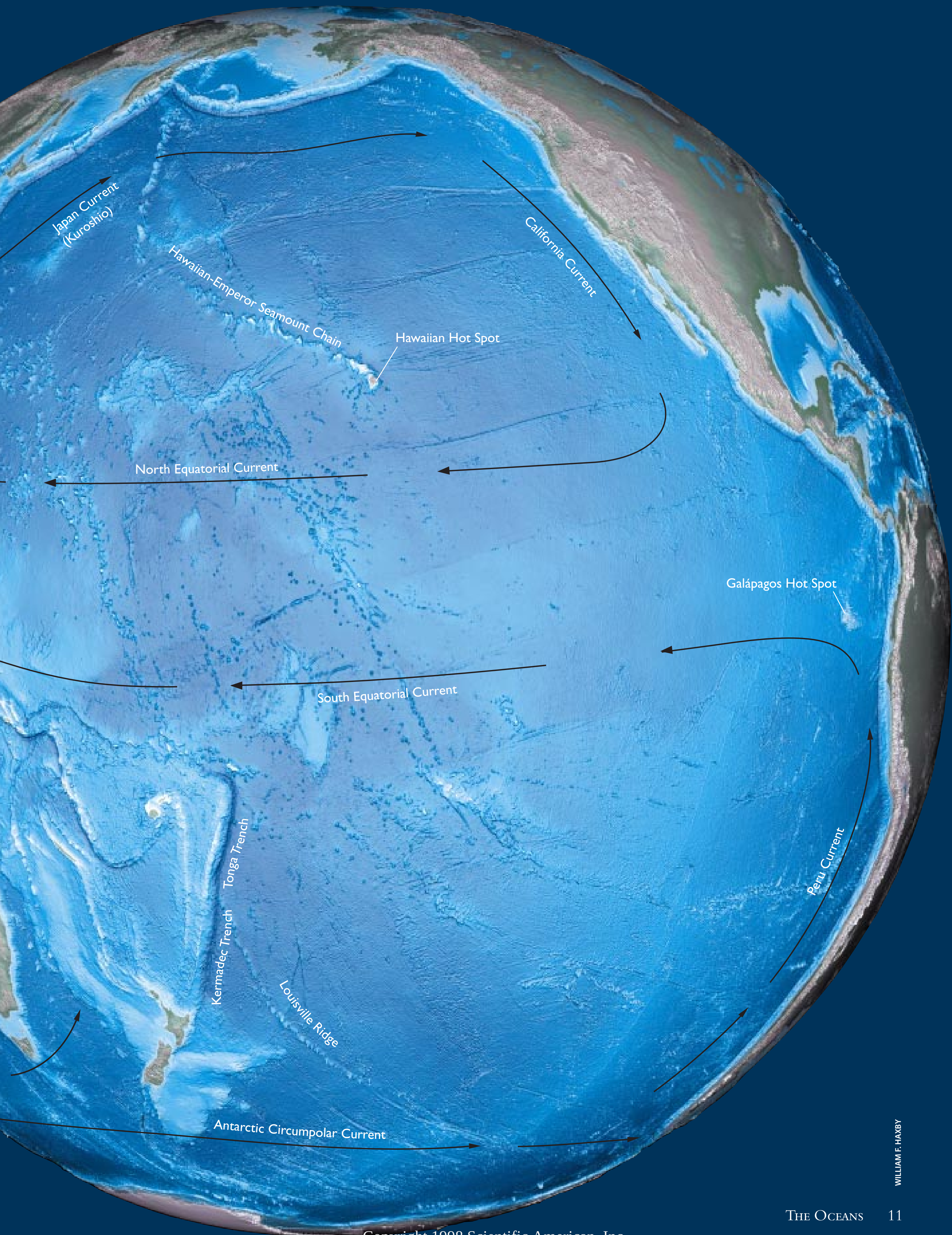

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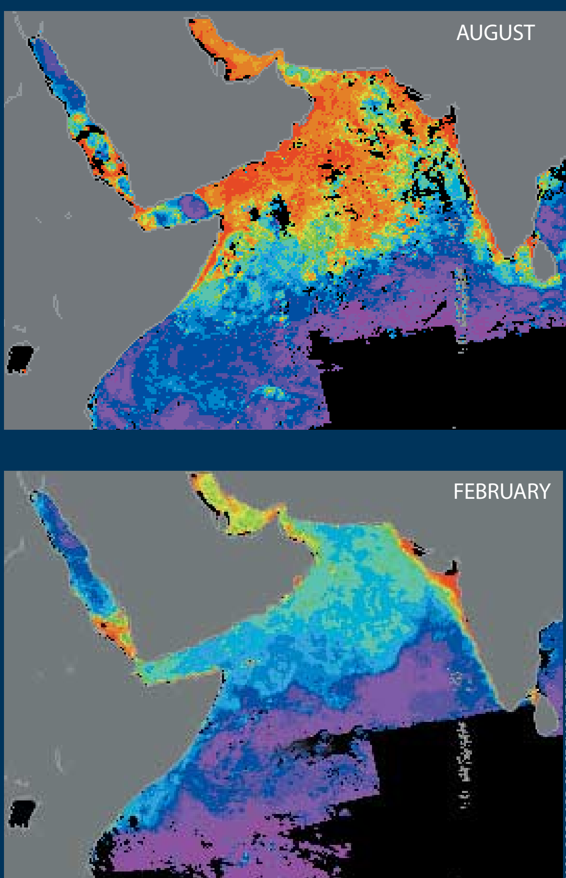
Indian Ocean

Unlike the Atlantic or Pacific, the Indian Ocean is completely enclosed on the northern side, a configuration that gives rise to drastic seasonal changes in the winds and currents. These monsoons, a variation on the Arabic word *mausim,* meaning "season," carry moisture northward from the southern Indian Ocean (causing torrential rains to lash India) during much of the summer there [see "The Oceans and Weather," by Peter J. Webster and Judith A. Curry, on page 38]. These winds induce a distinctive set of currents in summer (*right*).

The Indian Ocean basin is also involved in more long-term climatic shifts. When the northward-drifting Indian subcontinent collided with Asia tens of millions of years ago, it pushed the Tibetan Plateau upward about five kilometers. This mountainous barrier changed the pattern of atmospheric circulation, which many scientists believe cooled the earth's surface substantially.

Other reminders of India's ancient journey northward are visible in this view of the seafloor (*right*). Volcanic island chains and submarine rises mark the places where large amounts of lava erupted above hot spots, heat sources embedded deep within the earth's interior. The trace of the Réunion hot spot appears interrupted because tectonic spreading outward from the Central Indian Ridge has separated what was once a continuous structure. The parallel trace of the Kerguelen hot spot, known as the Ninetyeast Ridge, is unbroken for a greater stretch, making it the longest linear feature on the earth.

Area:	73,440,000 square kilometers
Average Depth:	3,890 meters
Maximum Depth:	7,450 meters



NASA GODDARD SPACE FLIGHT CENTER

CHANGING MONSOON WINDS not only alter the weather, they also control the biological productivity of the ocean. These false-color images (*left*), made using satellite measurements from the Coastal Zone Color Scanner, reflect the density of phytoplankton at the sea surface. (Warm colors represent relatively high densities of phytoplankton.) From May through September, shallow currents driven by winds coming from the southwest veer away from the Arabian coast, causing nutrient-rich waters from greater depth to rise to the surface. Phytoplankton can then proliferate far offshore (*top*) and provide nourishment for creatures higher in the marine food chain. During the northeast monsoon, which runs from November to March, the surface currents travel in the opposite direction, preventing such upwelling of nutrient-rich water. Phytoplankton then grow well only close to the coasts, where nutrients constantly brought to the sea from rivers are still plentiful (*bottom*).

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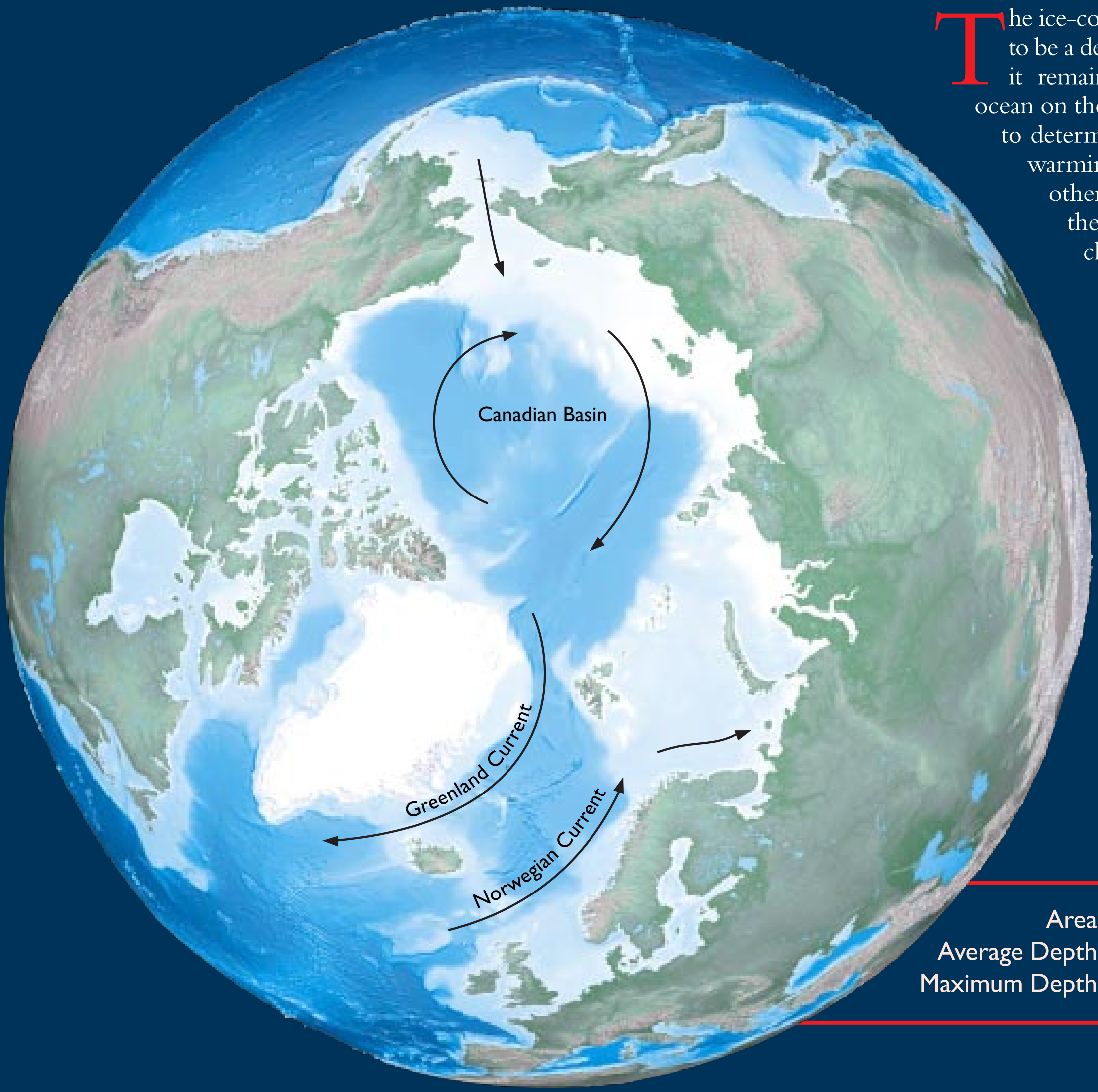
Polar Oceans

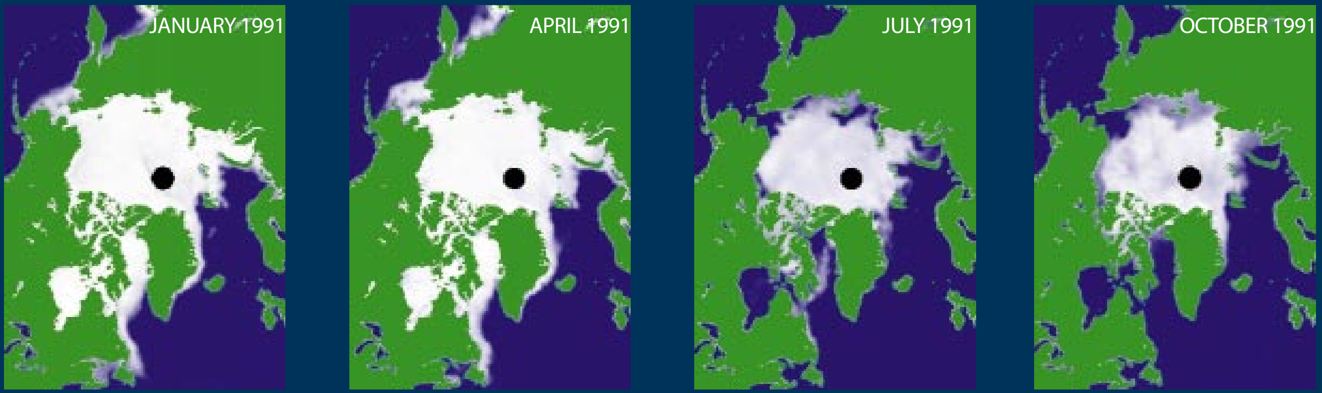


The ice-covered Arctic was first recognized to be a deep basin only a century ago, and it remains today the most enigmatic ocean on the earth. Scientists are still trying to determine, for example, whether the warming that has occurred in most other parts of the planet has caused the Arctic ice pack to thin. Such a change would be worrisome, because only a few meters of ice separate the frigid Arctic atmosphere from the comparatively warm water below. A breakup of the ice would thus allow a great amount of heat from the ocean to pass into the air above, accelerating any warming trend in that far northern region.

To help answer this question and many others, scientists are beginning to probe the Arctic Ocean in a number of novel ways [see "Forty Days in the Belly of the Beast," by Bernard J. Coakley, on page 36].

Area:	14,090,000 square kilometers
Average Depth:	988 meters
Maximum Depth:	5,502 meters

FROZEN BLANKET covers the Arctic Ocean. Polar-orbiting meteorological satellites chart the changing extent of this sea ice there. (The black area is not spanned by the satellite measurements.)



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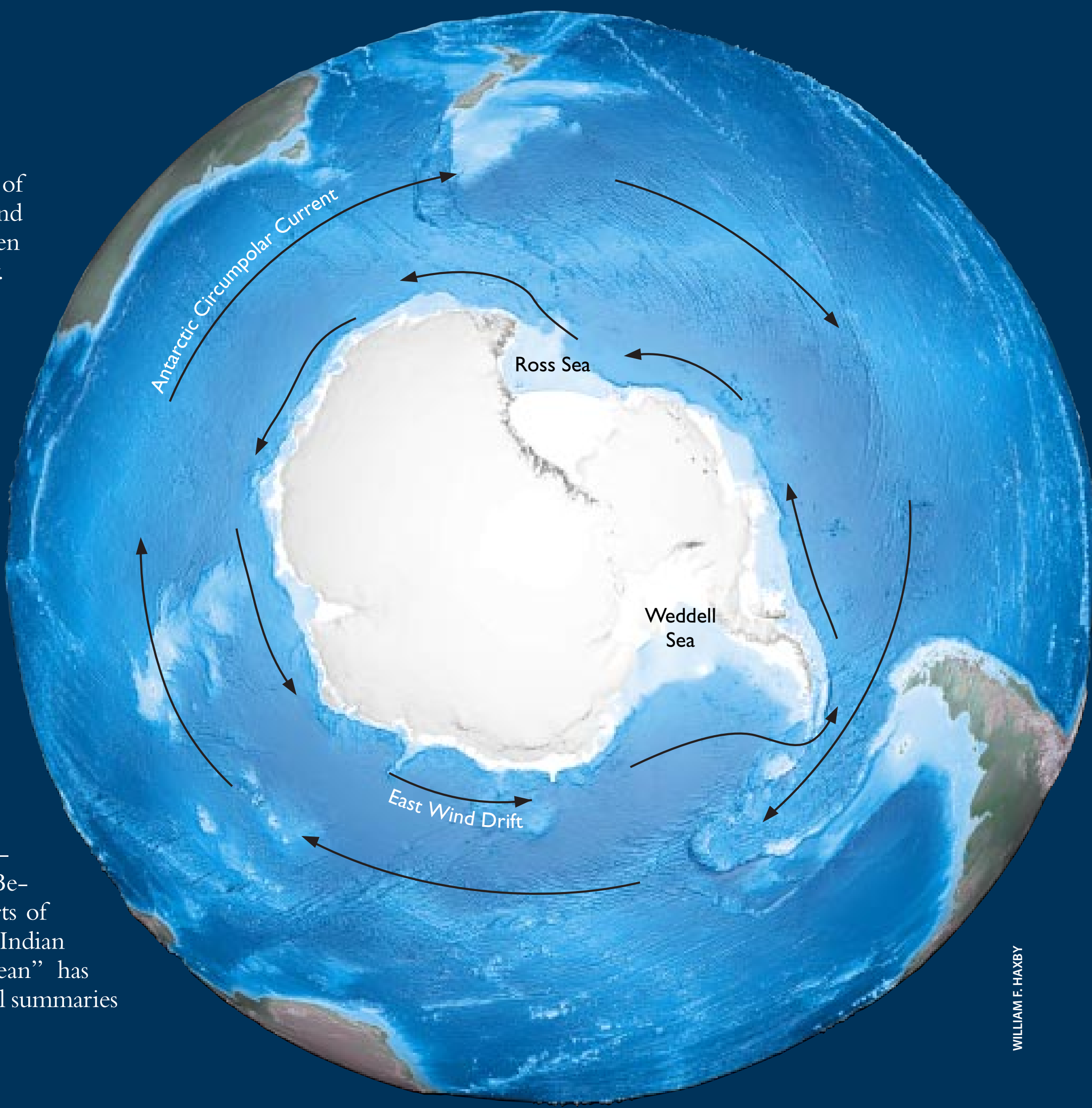
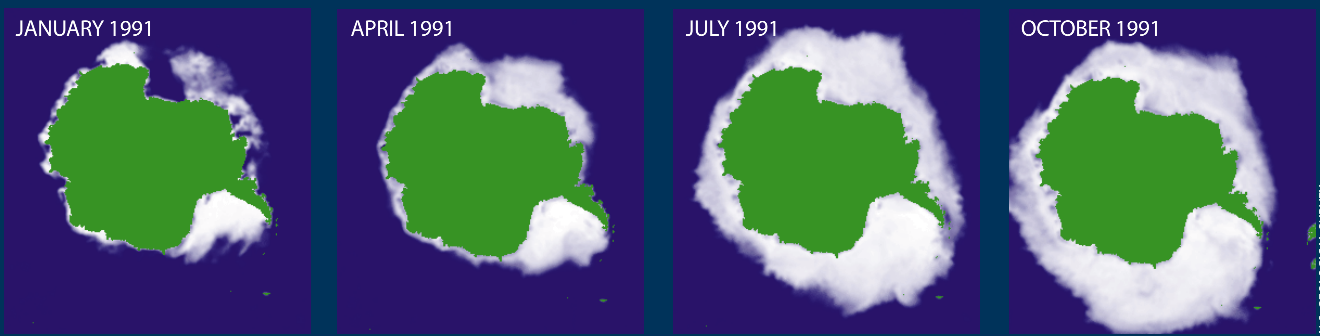
The southern reaches of the Atlantic, Pacific and Indian oceans are often considered a single entity. This vast "Southern Ocean" encircles the Antarctic continent with two counterrotating sets of currents. Hugging Antarctica and streaming from east to west is the so-called East Wind Drift. Farther north, the eastward-directed Antarctic Circumpolar Current prevails. This strong, wide current, and the winds that drive it, made for arduous journeys from the Atlantic to the Pacific when sailors had to navigate around Cape Horn, the southern tip of South America, before the construction of the Panama Canal. (Being merely the southern parts of the Atlantic, Pacific and Indian oceans, the "Southern Ocean" has been included in the statistical summaries given on pages 8, 10 and 12.)



WILLIAM F. HAXBY

SEA ICE around Antarctica during the southern summer recedes to a position close to the coast, except in the vicinity of the Weddell Sea. In winter the extent of this floating mass of ice increases enormously, although about 5 percent of the area nominally covered contains localized openings.



U.S. GEOLOGICAL SURVEY

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The Origins of

Evidence is mounting that other planets hosted oceans at one time, but only Earth has maintained its watery endowment

by James F. Kasting

DON DIXON

ICE-LADEN COMET crashes into a primitive Earth, which is accumulating its secondary atmosphere (the original having been lost in the catastrophic impact that formed the moon). Earth appears moonlike, but its higher gravity allows it to retain most of the water vapor liberated by such impacts, unlike the newly formed moon in the background. A cooler sun illuminates three additional comets hurtling toward Earth, where they will also give up their water to the planet's steamy, nascent seas.

Of all the planets in the solar system, why is Earth the only one fit for life? Simple: because Earth has a surface that supports liquid water, the magic elixir required by all living things. Some scientists speculate that forms of life that do not require water might exist elsewhere in the universe. But I would guess not. The long molecular chains and complex branching structures of carbon make this element the ideal chemical backbone for life, and water is the ideal solvent in which carbon-based chemistry can proceed.

Given this special connection between water and life, many investigators

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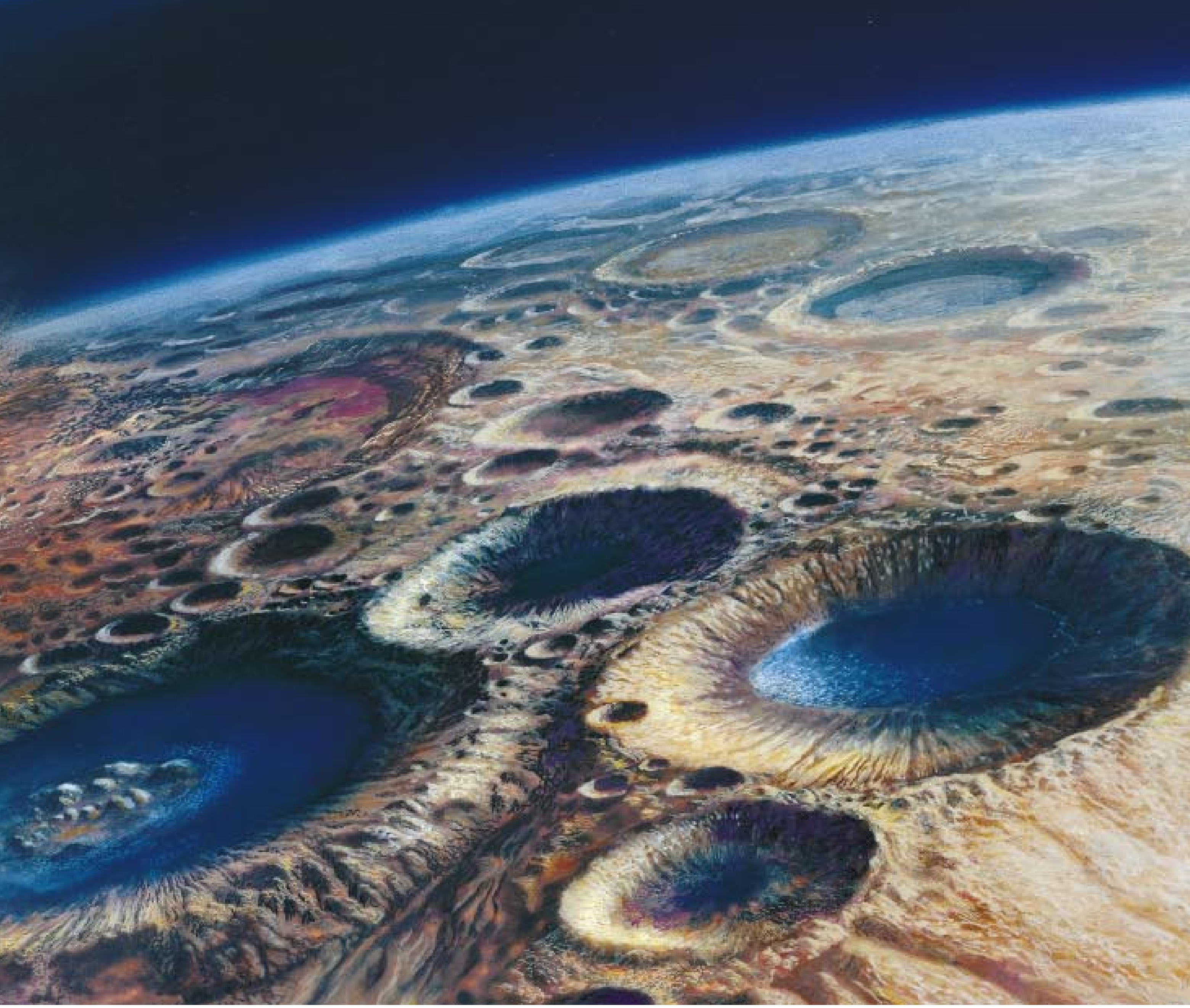
Water on Earth



have lately focused their attention on one of Jupiter's moons, Europa. Astronomers believe this small world may possess an ocean of liquid water underneath its globe-encircling crust of ice. Researchers at the National Aeronautics and Space Administration are making plans to measure the thickness of ice on Europa using radar and, eventually, to drill through that layer should it prove thin enough.

The environment of Europa differs dramatically from conditions on Earth, so there is no reason to suppose that life must have evolved there. But the very existence of water on Europa provides sufficient motivation for sending a spacecraft to search for extraterrestrial organisms. Even if that probing finds nothing alive, the effort may help answer a question closer to home: Where did water on Earth come from?

Water from Heaven

Creation of the modern oceans required two obvious ingredients: water and a container in which to hold it. The ocean basins owe their origins, as well as their present configuration, to plate tectonics. This heat-driven convection churns the mantle of Earth—the region between the crust and core—and results in

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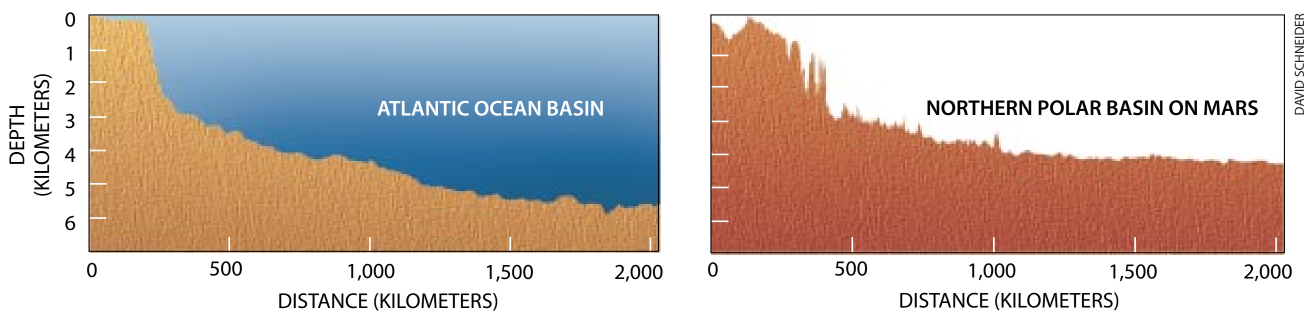
BARRAGE OF COMETS nears an end as a late-arriving body hits at the horizon, sending shocks through the planet and stirring up this primordial sea.

the separation of two kinds of material near the surface. Lighter, less dense granitic rock makes up the continents, which float like sponges in the bath over denser, heavier basalt, which forms the ocean basins.

Scientists cannot determine with certainty exactly when these depressions filled or from where the water came, because there is no geologic record of the formative years of Earth. Dating of meteorites shows that the solar system is about 4.6 billion years old, and Earth appears to be approximately the same age. Yet the oldest sedimentary rocks—those that formed by processes requiring liquid water—are only about 3.9 billion years old. This observation proves that at least some water was present on the surface of Earth by that time. But earlier conditions remain something of a mystery.

Kevin J. Zahnle, an astronomer at the NASA Ames Research Center, suggests that the primordial Earth was like a bucket. In his view, water was added, not with a ladle



TOPOGRAPHIC MAPPING of Mars has recently revealed remarkable similarities to the ocean basins on Earth. For example, the western Atlantic near Rio de Janeiro (*left*) presents a similar profile to that of the northern polar basin on Mars (*right*).

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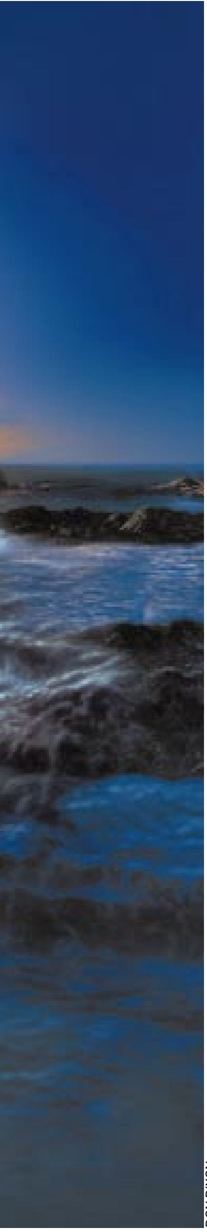


DON DIXON

but with a firehose. He proposes that icy clumps of material collided with Earth during the initial formation of the planet, injecting huge quantities of water into the atmosphere in the form of steam.

Much of this water was lost back into space. Some of the steam immediately streamed skyward through holes in the atmosphere blasted open by these icy planetesimals themselves. Many of the water molecules (H_2O) were split apart by ultraviolet radiation from the sun. Hydrogen produced in this way most likely escaped into space, and the oxygen left behind would have become bound to minerals in the crust. But enough of the initial steam in the atmosphere survived and condensed to form sizable oceans when the planet eventually cooled.

No one knows how much water rained down on the planet at the time. But suppose the bombarding planetesimals resembled the most abundant type of meteorites (called ordinary chondrites), which contains about 0.1 percent water by weight. An Earth composed entirely of this kind of rubble would therefore have started with 0.1 percent water—at least four times the amount now held in the oceans. So three quarters of this water has since disappeared. Perhaps half an ocean of the moisture became trapped within minerals of the mantle. Water may also have taken up residence in Earth's dense iron core, which contains some relatively light elements, including, most probably, hydrogen.

So the initial influx of meteoric material probably endowed Earth with more than enough water for the oceans. Indeed, that bombardment lasted a long time: the analysis of the impact craters on the moon, combined with the known age of moon rocks, indicates that large bodies continued to strike the moon—and, by implication, Earth—until about 3.8 billion years ago. The latter part of this interval, starting about 4.5 billion years ago, is called, naturally enough, the heavy bombardment period.

One of the unsolved mysteries of planetary science is exactly where these hefty bodies came from. They may have originated in the asteroid belt, which is located between the orbits of Mars and Jupiter. The rocky masses in the outer parts of the belt may contain up to 20 percent water. Alternatively, if the late-arriving bodies came from beyond the orbit of Jupiter, they would have resembled another water-bearing candidate—comets.

Comets are often described as dirty, cosmic snowballs: half ice, half dust. Christopher F. Chyba, a planetary scientist at the University of Arizona, estimates that if only 25 percent of the bodies that hit Earth during the heavy bombardment period were comets, they could have accounted for all the water in the modern oceans. This theory is attractive because it explains the extended period of heavy bombardment: bodies originating in the outer solar system would have taken longer to be swept up by planets, and so the volley of impacts on Earth would have stretched over billions of years.

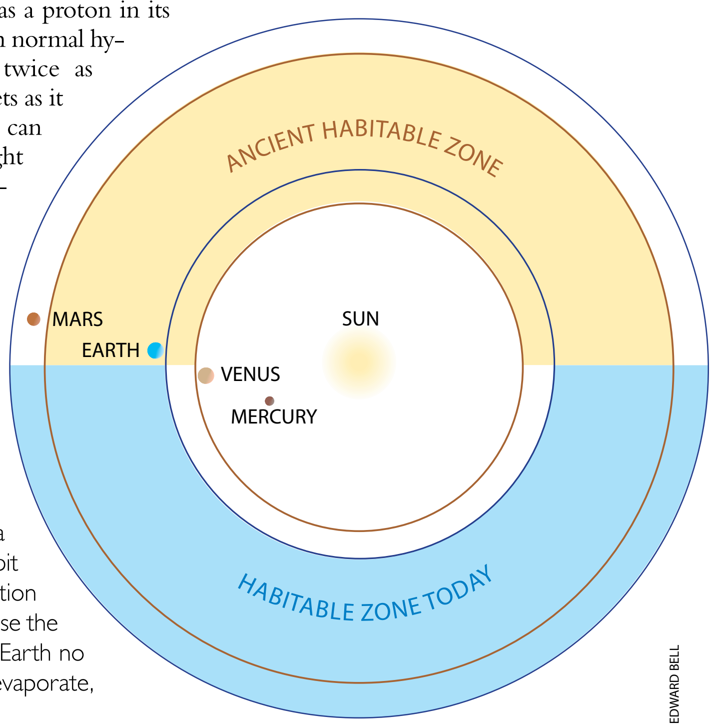
This widely accepted theory of an ancient, cometary firehose has recently hit a major snag. Astronomers have found that three comets—Halley, Hyakutake and Hale-Bopp—have a high percentage of deuterium, a form of hydrogen that contains a neutron as well as a proton in its nucleus. Compared with normal hydrogen, deuterium is twice as abundant in these comets as it is in seawater. One can imagine the oceans might now contain proportionately more deuterium than the cometary ices from which they formed, because normal hydrogen, being lighter, might escape the tug of gravity more easily and be lost to space. But it is difficult to see how the oceans could contain proportionately less deuterium. If these three comets are representative of those that struck here in the past, then most of the water on Earth must have come from elsewhere.

A recent, controversial idea based on new observations from satellites suggests that about 20 small (house-size) comets bombard Earth each minute. This rate, which is fast enough to fill the entire ocean over the lifetime of Earth, implies that the ocean is still growing. This much debated theory, championed by Louis A. Frank of the University of Iowa, raises many unanswered questions, among them: Why do the objects not show up on radar? Why do they break up at high altitude? And the deuterium paradox remains, unless these "cometesimals" contain less deuterium than their larger cousins.

The Habitable Zone

Whatever the source, plenty of water fell to Earth early in its life. But simply adding water to an evolving planet does not ensure the development of a persistent ocean. Venus was probably also wet when it formed, but its surface is completely parched today.

How that drying came about is easy to understand: sunshine on Venus must have once been intense enough to create a warm, moist lower atmosphere and to support an appreciable amount of water in the upper atmosphere as well. As a re-



EDWARD BELL

HABITABLE ZONE, where liquid water can exist on the surface of a planet, now ranges from just inside the orbit of Earth to beyond the orbit of Mars (*blue*). This zone has migrated slowly outward from its position when the planets first formed (*yellow*), about 4.6 billion years ago, because the sun has gradually brightened over time. In another billion years, when Earth no longer resides within this expanding zone, the water in the oceans will evaporate, leaving the world as dry and lifeless as Venus is today.

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sult, water on the surface of Venus evaporated and traveled high into the sky, where ultraviolet light broke the molecules of H_2O apart and allowed hydrogen to escape into space. Thus, this key component of water on Venus took a one-way route: up and out [see "How Climate Evolved on the Terrestrial Planets," by James F. Kasting, Owen B. Toon and James B. Pollack; Scientific American, February 1988].

This sunshine-induced exodus implies that there is a critical inner boundary to the habitable zone around the sun, which lies beyond the orbit of Venus. Conversely, if a planet does not receive enough sunlight, its oceans may freeze by a process called runaway glaciation. Suppose Earth somehow slipped slightly farther from the sun. As the solar rays faded, the climate would get colder and the polar ice caps would expand. Because snow and ice reflect more sunlight back to space, the climate would become colder still. This vicious cycle could explain in part why Mars, which occupies the next orbit out from Earth, is frozen today.

The actual story of Mars is probably more complicated. Pictures taken from the Mariner and Viking probes—and from the Global Surveyor spacecraft now orbiting the Red Planet—show that older parts of the Martian surface are laced with channels carved by liquid water [see "Global Climatic Change on Mars," by Jeffrey S. Kargel and Robert G. Strom; Scientific American, November 1996]. Recent measurements from the laser altimeter on board the Global Surveyor indicate that the vast northern plains of Mars are exceptionally flat. The only correspondingly smooth surfaces on Earth lie on the seafloor, far from the midocean ridges. Thus, many scientists are now even more confident that Mars once had an ocean. Mars, it would seem, orbits within a potentially habitable zone around the sun. But somehow, aeons ago, it plunged into its current chilly state.

A Once Faint Sun

Understanding that dramatic change on Mars may help explain nagging questions about the ancient oceans of Earth. Theories of solar evolution predict that when the sun first became stable, it was 30 percent dimmer than it is now. The smaller solar output would have caused the oceans to be completely frozen before about two billion years ago. But the geologic record tells a different tale: liquid water and life were both present as early as 3.8 billion years ago. The disparity between this prediction and fossil evidence has been termed the faint young sun paradox.

The paradox disappears only when one recognizes that the composition of the atmosphere has changed considerably over time. The early atmosphere probably contained much more carbon dioxide than at present and perhaps more methane. Both these gases enhance the greenhouse effect because they absorb infrared radiation; their presence could have kept the early Earth warm, despite less heat coming from the sun.

The greenhouse phenomenon also helps to keep Earth's climate in a dynamic equilibrium through a process called the carbonate-silicate cycle. Volcanoes continually belch carbon dioxide into the atmosphere. But silicate minerals on the continents absorb much of this gas as they erode from crustal rocks and wash out to sea. The carbon dioxide then sinks to the bottom of the ocean in the form of solid calcium carbonate. Over millions of years, plate tectonics drives this carbonate down into the upper mantle, where it reacts chemically and is spewed out as carbon dioxide again through volcanoes.

If Earth had ever suffered a global glaciation, silicate rocks, for the most part, would have stopped eroding. But volcanic carbon dioxide would have continued to accumulate in the atmosphere until the greenhouse effect became large enough to melt the ice. And eventually the warmed oceans would have released enough moisture to bring on heavy rains and to speed erosion, in the process pulling carbon dioxide out of the atmosphere and out of minerals. Thus, Earth has a built-in therm-

GALEN ROWELL *Mountain Light*

NASA/JET PROPULSION LABORATORY

ICY BLOCKS cover the Weddell Sea off Antarctica (*left*); similarly shaped blocks blanket the surface of Europa, a moon of Jupiter (*right*). This resemblance, and the lack of craters on Europa, suggests that liquid water exists below the frozen surface of that body.

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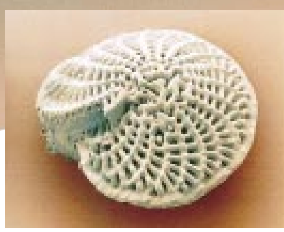
TOM MOORE



ANDREW SYRED *SPL/Photo Researchers, Inc.*

GEOCHEMICAL THERMOSTAT, called the carbonate-silicate cycle, holds the surface temperature of Earth in the range of liquid water. Atmospheric carbon dioxide dissolves in rain and reacts with eroding rocks, liberating calcium and bicarbonate ions into streams and rivers (*a*). Carried into the oceans, these ions are used by various marine organisms, such as foraminifera (*inset*), to construct shells or exoskeletons of calcium carbonate, which are deposited on the seafloor when the creatures die (*b*). Millions of years later the carbonate deposits slide under continental crust in subduction zones. Here high temperature and pressure cook the carbonates to release carbon dioxide gas through subduction-zone volcanoes (*c*). Carbon dioxide then reenters the atmosphere, and the cycle begins again.

ostat that automatically maintains its surface temperature within the range of liquid water.

The same mechanism may have operated on Mars. Although the planet is now volcanically inactive, it once had many eruptions and could have maintained a vigorous carbonate-silicate cycle. If Mars has sufficient stores of carbon—one question that NASA scientists hope to answer with the Global Surveyor—it could also have had a dense shroud of carbon dioxide at one time. Clouds of carbon dioxide ice, which scatter infrared radiation, and perhaps a small amount of methane would have generated enough greenhouse heating to maintain liquid water on the surface.

Mars is freeze-dried today, not because it is too far from the sun but because it is a small planet and therefore cooled off comparatively quickly. Consequently, it was unable to sustain the volcanism necessary to maintain balmy temperatures. Over the aeons since Mars chilled, the water ice that remained probably mixed with dust and is now trapped in the uppermost few kilometers of the Martian crust.

The conditions on Earth that formed and maintain the oceans—an orbit in the habitable zone, plate tectonics creating ocean basins, volcanism driving a carbonate-silicate cycle and a stratified atmosphere that prevents loss of water or hydrogen—are unique among the planets in our solar system. But other planets are known to orbit other stars, and the odds are good that similar conditions may prevail, creating other brilliantly blue worlds, with oceans much like ours. SA

The Author

JAMES F. KASTING received his bachelor's degree in chemistry and physics from Harvard University. He went on to graduate studies in physics and atmospheric science at the University of Michigan, where he obtained a doctorate in 1979. Kasting worked at the National Center for Atmospheric Research and for the National Aeronautics and Space Administration Ames Research Center before joining Pennsylvania State University, where he now teaches in the departments of geosciences and of meteorology. Kasting's research focuses on the evolution of habitable planets around the sun and other stars.

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WORLD TOUR

PACIFIC OCEAN:

Bikini's Nuclear Ghosts

The atoll survived some of the worst destruction that humankind has ever dished out to become a lush paradise once again

by Glenn Zorpette

LAURIE GRACE (*map*); WILLIAM F. HAXBY (*globe*)

ANTONIO RAMÓN-LEBLANC

BAKER BLAST (*right*) on July 25, 1946, was the fifth atomic explosion ever and the first beneath the surface of the sea. At the base of the mushroom cloud are obsolete warships, positioned near ground zero to test blast effects. Among the ships sunk by early tests is the destroyer USS *Lamson* (*above* and *above right*), whose guns still point skyward.

I am at ground zero of the most powerful explosion ever created by the U.S. Forty-six meters (150 feet) underwater near the edge of Bikini Lagoon in the central Pacific, I am kneeling in the sand with a 27-year-old Majorcan divemaster at my side. At this moment, he's laughing into his scuba regulator at the sight of an array of big, five-pointed starfish on the seafloor, which evokes for him an American flag.

The divemaster, Antonio Ramón-LeBlanc, and I have come to a place where very few have ever ventured: a submerged crater formed shortly before dawn on March 1, 1954, when the U.S. military detonated a thermonuclear bomb on a spit of sand jutting out from Nam Island, in the northwest corner of Bikini Atoll. The experts anticipated that this nuclear test, code-named Bravo, would have an explosive yield equivalent to somewhere between three and six megatons of TNT. Instead they got 15 megatons, a crater 2,000 meters wide and a fireball that swelled far beyond expectations, terrifying the nine technicians left as observers in a concrete bunker 32 kilometers away.

The Bravo blast was roughly 1,200 times more powerful than the atomic explosion that destroyed Hiroshima. Its fallout trapped the nine technicians in their bunker and sickened the 82 residents of Rongelap and Ailinginae atolls, 195 kilometers downwind, as well as the 23 Japanese fishermen on the trawler *Fukuryu Maru* (*Lucky Dragon*), which was 137 kilometers to the east. In September of that year, one of those fishermen died; whether it was from radiation-related complications is a moot point.

Seeing Bikini for the first time now, I find it difficult to picture the island as it was during those days. The atoll, a precious necklace of some two dozen islets surrounding a sapphire lagoon, is inhabited by only two or three dozen people at any given time. Almost all of them live on Bikini Island, the largest, and are studying the atoll's radioactivity, running a recently established scuba-diving and fishing resort or building infrastructure. The Bikinians themselves are living on other islands and atolls, as they have been since 1946, when the start of nuclear testing on Bikini rendered it unfit for habitation.

In the era of testing, which lasted until 1958, as many as tens of thousands of military people, technicians and scientists camped on Bikini's islands or lived on navy vessels just offshore. The nuclear blasts sank surplus ships, vaporized whole islands and sent millions of tons of seawater and pulverized coral kilometers into the sky. The atoll was the site of 23 atomic and thermonuclear tests that had a combined yield of 77 megatons. (On nearby Enewetak Atoll, there were 43 tests, with a total yield of 32 megatons.) The Bravo blast so contaminated the entire atoll that the remaining five tests in that series had to be set up by technicians wearing protective suits and respirators.

Paradise Reborn

The site of some of the most intense destruction wreaked by humankind, Bikini today is a testament to nature's ability to heal itself. Although the white, powdery floor of Bravo crater is desertlike, I am surprised by how much marine life we

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ANTONIO RAMÓN-LEBLANC

encounter. Besides abundant starfish, we see scores of basketball-size anemones, dozens of sea cucumbers, a school of thousands of tiny, silvery, free-swimming fish larvae and, unexpectedly, a lionfish surrounded by little blue-and-yellow damselfish. Later, hiking along the western shores of nearby Nam Island, just tens of meters from ground zero, we encounter purplish lobsters and a huge sea turtle. A silvery-white, speckled moray eel flashes in the sun as it slithers amphibiously from one tidal pool to another, hunting the crabs scurrying on the rocks at water's edge. A more animated or idyllic scene would be hard to imagine.

As fishermen avoided the atoll for decades, the local sea life proliferated, and the atoll now has some of the most thriving and diverse populations of marine creatures on the earth. The small groups of anglers staying at the resort on Bikini Island routinely run into vast schools of tuna, as well as mahimahi, wahoos, snappers, barracuda, leatherskin jacks, trevally, mackerel, coral trout, sharks and marlin.

During a fishing excursion, I watch an angler hook a mackerel, which is struck by a big barracuda, which is chomped off behind the gill plates by a shark, all in the space of six or seven minutes. On a single dive to a coral reef just inside the lagoon, I spot tangs, sergeant majors, butterfly fish,

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ANTONIO RAMÓN-LeBLANC

KEVIN DENLAY *Action Unlimited*

U.S. DEFENSE NUCLEAR AGENCY, COURTESY OF NATIONAL GEOGRAPHIC SOCIETY

BRAVO BLAST (*right*), at 15 megatons, was the largest ever created by the U.S. It vaporized two small islands and left an underwater hole two kilometers across. This crater is the dark-blue, circular area seen above and slightly to the right of Nam Island (*top right*). Author Glenn Zorpette (*above*) displays a starfish, which are common on the silty crater floor.

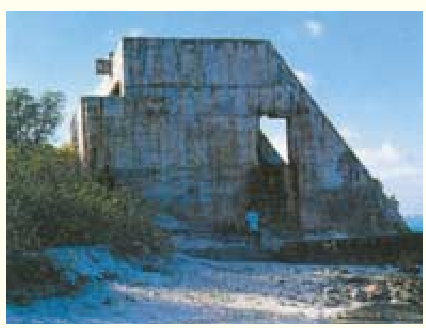
parrot fish, groupers, a lizardfish, striped grunts, snappers, giant clams and a few other species I cannot identify. Above the surface huge flocks of boobies, shearwaters and terns swoop and dive for baitfish.

Swimsuits, Bravo and Godzilla

More than just a pretty place, Bikini is a 20th-century cultural icon. But few remember the details of how it became one. On July 5, 1946—four days after the first atomic test on the atoll—French fashion designer Louis Reard introduced a two-piece swimsuit. The coincidence of earthshaking events forever attached the name "bikini" to the suit, perhaps to suggest its explosive effect on the heterosexual male libido. And in the 1954 Japanese motion picture *Gojira,* nuclear tests aroused the titular monster from hibernation near the fictional Pacific island of Ohto, a thinly disguised Bikini. The Tokyo rampage of Gojira, known to English-language moviegoers as Godzilla, was a cinematic resonance of the tragedy that befell the crew of the *Fukuryu Maru.*

On Bikini, too, there are reminders of the days when business was (literally) booming. As I step off the airplane that brought me to the island of Eneu, in the southeast corner of the atoll, one of the first things I see is the control bunker for the Bravo blast. It is overgrown with vines, a forgotten relic behind the airport's tiny terminal building. Inside, the bunker is cool, musty and full of old truck tires and bags of cement mix; behind it stretches Bikini's impossibly blue lagoon. It takes considerable effort to imagine the room as it was 44 years ago, with nine frightened technicians in it, awaiting rescue after the Bravo blast.

Unfortunately, landmark bunkers are not the only mementos of the nuclear years on Bikini and Enewetak. The topsoil on the atolls has high levels of radioactive cesium 137, strontium 90, plutonium 239, plutonium 240 and americium 241. Of these fallout elements, only



GLENN ZORPETTE

CRUMBLING BUNKER on Aomen Island, in the north of the atoll, was used 45 years ago to film the thermonuclear tests.

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the cesium 137 precludes permanent habitation because it emits relatively energetic and penetrating gamma rays, and it is present in high levels in the atoll's vegetation and fruits, such as coconut and pandanus. Studies by Lawrence Livermore National Laboratory have shown that if people lived on Bikini and regularly ate fruits grown on the islands, up to 90 percent of their radiation exposure would come from the cesium in the local produce. Almost all the rest of their dosage would come from the cesium in the soil. On the beaches and in the sea, cesium is not a problem: it is soluble in water, so the tides and currents washed it away long ago.

Taking Back Bikini

In addition to the Livermore group, which began doing research on Bikini in 1978, there have been five other scientific panels that have studied the atoll. All have concurred with a plan developed by William L. Robison, the leader of the Livermore contingent. Under Robison's proposal, which the displaced Bikinians are now considering, the atoll's topsoil would be treated with potassium chloride. In a matter of months, Livermore's experiments have shown, the potassium would replace most of the cesium in the vegetation and fruits. There would still be cesium in the topsoil, so the plan also calls for the soil to be stripped away in the areas where homes are to be built. Robison says that Bikinians would be exposed to radiation dosages no greater than those of people living in the continental U.S.

Some 2,400 people are eligible to live on Bikini. The number includes some of the 167 Bikinians moved off the atoll by the U.S. before testing began in 1946, as well as the direct descendants of those 167 and others who are related by marriage. All of them benefit to some extent from a total of $195 million in three trust funds set up with reparations paid by the U.S. government starting in 1978.

Today, although a plan exists to make Bikini suitable for habitation again, there is no timetable for resettlement. "The major issue for us is that the president of the United States has to give us assurances that the U.S. government agrees with and believes in the conclusions of these scientific studies," says Jack Niedenthal, who, having married a Bikinian, has become a liaison and spokesperson for the group.

There is historical precedent for this insistence. In 1968, on the recommendation of the U.S. Atomic Energy Commission, President Lyndon Johnson officially declared Bikini Atoll safe for habitation. A decade later, however, radiologic studies showed the declaration to be premature, and the small group of Bikinians who had resettled on the atoll had to be moved off once again. Because of Johnson's assurance, the Bikinians were in a strong position to demand reparations from the U.S.

"We believe that, morally, the U.S. government is in the exact same position," Niedenthal says. "I mean, as laymen, how are we to believe these studies, if the president of the United States, as a layman himself, can't believe in them?"

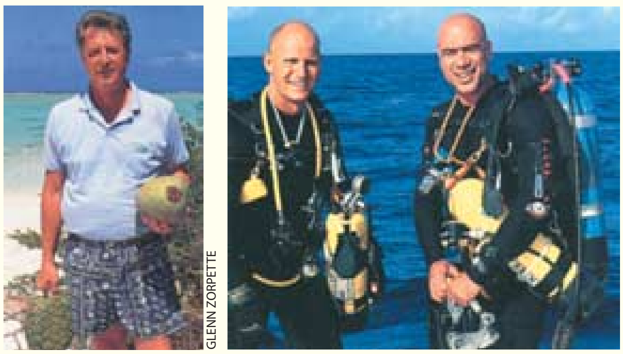
Although resettlement of the atoll is years off, a tourism program is well under way. Many Pacific atolls host impressive marine menageries, but few can boast almost a score of storied naval wrecks. During the early atomic tests here in 1946, military officials studied the effects of the blasts on ships by anchoring obsolete vessels around the intended ground-zero site in the lagoon. What they unwittingly created, in a 3.75-square-kilometer patch of lagoon, is perhaps the best wreck-diving spot on the earth.

Wreck Diving: It's a Blast

In 1996 the Bikinians, preparing for the day when they will need to generate income from their singular homeland, began operating a scuba-diving and fishing resort catering to well-to-do adventurers. In an economically grim part of the world, where tourism is essentially the only hope for earning foreign exchange, Bikini's past tragedy could be the foundation of its future success.

Scuba divers are paying almost $3,000 and anglers nearly $4,000 for a week's stay on the atoll. Is it worth it? So far there haven't been many dissatisfied customers. I found the diving to be spectacular and even moving. The 270-meter-long *Saratoga,* for example, was the first U.S. aircraft carrier and the victim of kamikaze attacks at Iwo Jima that killed 123 sailors. Damage from the attacks is still visible on its flight deck. Swimming down its elevator shaft to the hangar deck, I come across a Helldiver airplane in excellent shape, with its gauges, stick and windshield intact.

The diving is not only stirring, it is challenging as well. Seven of my eight dives range between 39 and 52 meters, and each requires decompression in stages at the end of the dive so that I can surface without risking a case of decompression sickness (the dreaded "bends").



GLENN ZORPETTE / EMIL JONAIE

RADIOACTIVE FRUITS are exhibited by Lawrence Livermore National Laboratory's William L. Robison, who is studying ways to reclaim Bikini Atoll. Zorpette (*at right*) prepares to descend 48 meters to the wreck of the USS *Arkansas* with diving buddy Antonio Ramón-LeBlanc.

On the deepest dive, I experience severe nitrogen narcosis in the dark underneath the stern of the wreck of the famous Japanese battleship *Nagato*. The 216-meter-long flagship of the Imperial Navy during World War II rests upside down on its massive rear gun turrets. Although narcosis is temporary, it is not taken lightly among divers, because it impairs judgment. Glancing at my primary depth and pressure gauges, I see they are flashing zeroes, and I become confused. (I later realize that the unit is either malfunctioning or unable to cope with the depth.) Fortunately for me, Antonio, the divemaster, is vigilant and inured to narcosis. He spots my predicament and guides me toward open water. As we ascend to about 50 meters, the murk in my head clears instantly.

By the time I leave the atoll, I begin to understand why many Bikinians, especially those of the older generation, long to go back. At 245 hectares, Bikini is huge for a coral atoll island. In addition, it is completely ringed by a broad, powdery, white-sand beach, a highly unusual feature among such islands.

"It is an overwhelming place," Niedenthal says. "You realize what the Bikinians gave up when you've been there." SA

GLENN ZORPETTE is a staff writer for SCIENTIFIC AMERICAN.

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The Rising Seas

by David Schneider, *staff writer*

Many people were awakened by the air-raid sirens. Others heard church bells sounding. Some probably sensed only a distant, predawn ringing and returned to sleep. But before the end of that day—February 1, 1953—more than a million Dutch citizens would learn for whom these bells tolled and why. In the middle of the night, a deadly combination of winds and tides had raised the level of the North Sea to the brim of the Netherlands's protective dikes, and the ocean was beginning to pour in.

As nearby Dutch villagers slept, water rushing over the dikes began to eat away at these earthen bulwarks from the back side. Soon the sea had breached the perimeter, and water freely flooded the land, eventually extending the sea inward as far as 64 kilometers (nearly 40 miles) from the former coast. In all, more than 200,000 hectares of farmland were inundated, some 2,000 people died and roughly 100,000 were left homeless. One sixth of the Netherlands was covered in seawater.

With memories of that catastrophe still etched in people's minds, it is no wonder that Dutch planners took a keen interest when, a quarter-century later, scientists began suggesting that global warming could cause the world's oceans to rise by several meters. Increases in sea level could be expected to come about for various reasons, all tied to the heating of Earth's surface, which most experts deem an inevitable consequence of the mounting abundance of carbon dioxide and other heat-trapping greenhouse gases in the air.

First off, greenhouse warming of Earth's atmosphere would eventually increase the temperature of the ocean, and seawater, like most other substances, expands when heated. That thermal expansion of the ocean might be sufficient to raise sea level by about 30 centimeters or more in the next 100 years.

A second cause for concern has already shown itself plainly in many of Europe's Alpine valleys. For the past century or two, mountain glaciers there have been shrinking, and the water released into streams and rivers has been adding to the sea. Such meltwaters from mountain glaciers may have boosted the ocean by as much as five centimeters in the past 100 years, and this continuing influx will most likely elevate sea level even more quickly in the future.

But it is a third threat that was the real worry to the Dutch and the people of other low-lying countries. Some scientists began warning more than 20 years ago that global warming might cause a precariously placed store of frozen water in Antarctica to melt, leading to a calamitous rise in sea level—perhaps five or six meters' worth.

Yet predicting exactly how—or whether—sea level will shift in re-

SEA DIKES protect low-lying areas of the Netherlands from the ocean, which rises well above the land in many places. The Dutch government must maintain hundreds of kilometers of dikes and other flood-control structures on the coast and along riverbanks.

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Although some voice concern that global warming will lead to a meltdown of polar ice, flooding coastlines everywhere, the true threat remains difficult to gauge

NETHERLANDS MINISTRY OF TRANSPORT AND PUBLIC WORKS

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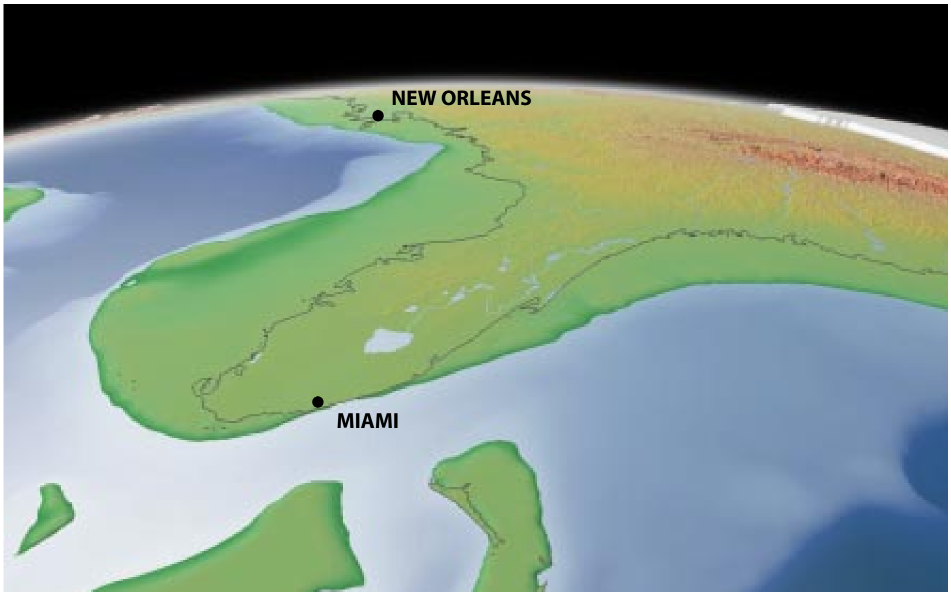
sponse to global warming remains a significant challenge. Scientists trained in many separate disciplines are attempting to glean answers using a variety of experimental approaches, ranging from drilling into the Antarctic ice cap to bouncing radar off the ocean from space. With such efforts, investigators have learned a great deal about how sea level has varied in the past and how it is currently changing. For example, most of these scientists agree that the ocean has been creeping upward by two millimeters a year for at least the past several decades. But determining whether a warmer climate will lead to a sudden acceleration in the rate of sea-level rise remains an outstanding question.

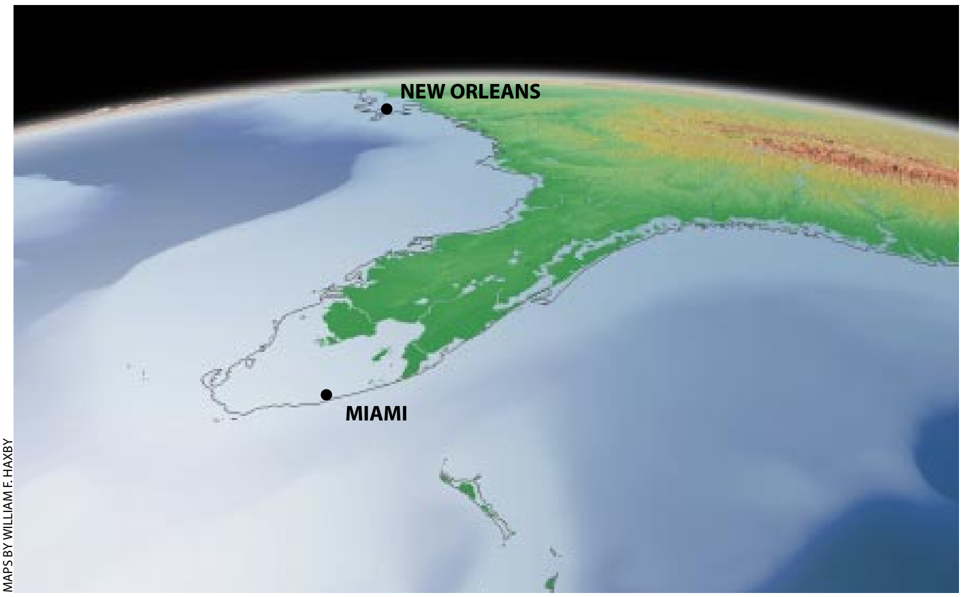
Antarctic Uncertainties

One of the first prominent geologists to raise concern that global warming might trigger a catastrophic collapse of the Antarctic ice cap was J. H. Mercer of Ohio State University. Because the thick slab of ice covering much of West Antarctica rests on bedrock well below sea level, Mercer explained in his 1978 article "West Antarctic Ice Sheet and CO_2 Greenhouse Effect: A Threat of Disaster," this marine ice sheet is inherently unstable. If the greenhouse effect were to warm the south polar region by just five degrees Celsius (by nine degrees Fahrenheit), the floating ice shelves surrounding the West Antarctic ice sheet would begin to disappear. Robbed of these buttresses, this grounded ice sheet—a vestige of the last ice age—would quickly disintegrate, flooding coastlines around the world in the process.

Mercer's disaster scenario was largely theoretical, but he pointed to some evidence that the West Antarctic ice sheet may, in fact, have melted at least once before. Between about 110,000 and 130,000 years ago, when the last shared ancestors of all humans probably fanned out of Africa into Asia and Europe, Earth experienced a climatic history strikingly similar to what has transpired in the past 20,000 years, warming abruptly from the chill of a great ice age.

That ancient warming may have achieved conditions a bit more balmy than those at present. The geologic record of that time (known to the cognoscenti as interglacial stage 5e) remains somewhat murky, yet many geologists believe sea level stood about five meters higher than it does now—just the additional dollop that would be provided by the melting of the West Antarctic ice sheet. If such a collapse had occurred in Antarctica during a slightly hotter phase in the past, some reason, the current warming trend might portend a repeat performance.





MAPS BY WILLIAM F. HAXBY

FLORIDA looked quite different 20,000 years ago, during the last ice age. At that time, vast amounts of water remained locked within continental ice sheets to the north, and sea level was nearly 120 meters lower than today (*top*). As the ice melted, the coastlines retreated inland to their present positions (*black line*). Future melting of ice in West Antarctica may yet raise sea level an additional five meters, inundating large areas (*bottom*).

That possibility spurred a group of American investigators to organize a coordinated research program in 1990, to which they attached the title "SeaRISE" (for Sea-level Response to Ice Sheet Evolution). The report of their first workshop noted some ominous signs on the southernmost continent, including the presence of five active "ice streams" drawing ice from the interior of West Antarctica into the nearby Ross Sea. They stated that these channels in the West Antarctic ice sheet, where glacial ice flows rapidly toward the ocean, "may be manifestations of collapse already under way."

But more recent research suggests that the dire warnings expressed up to that time may have been exaggerated. In the early 1990s researchers using so-called global circulation models, complex computer programs with which scientists attempt to predict future climate by calculating the behavior of the atmosphere and ocean, began investigating how a warmed climate would affect the Antarctic ice cap. These researchers found that greenhouse heating would cause warmer, wetter air to

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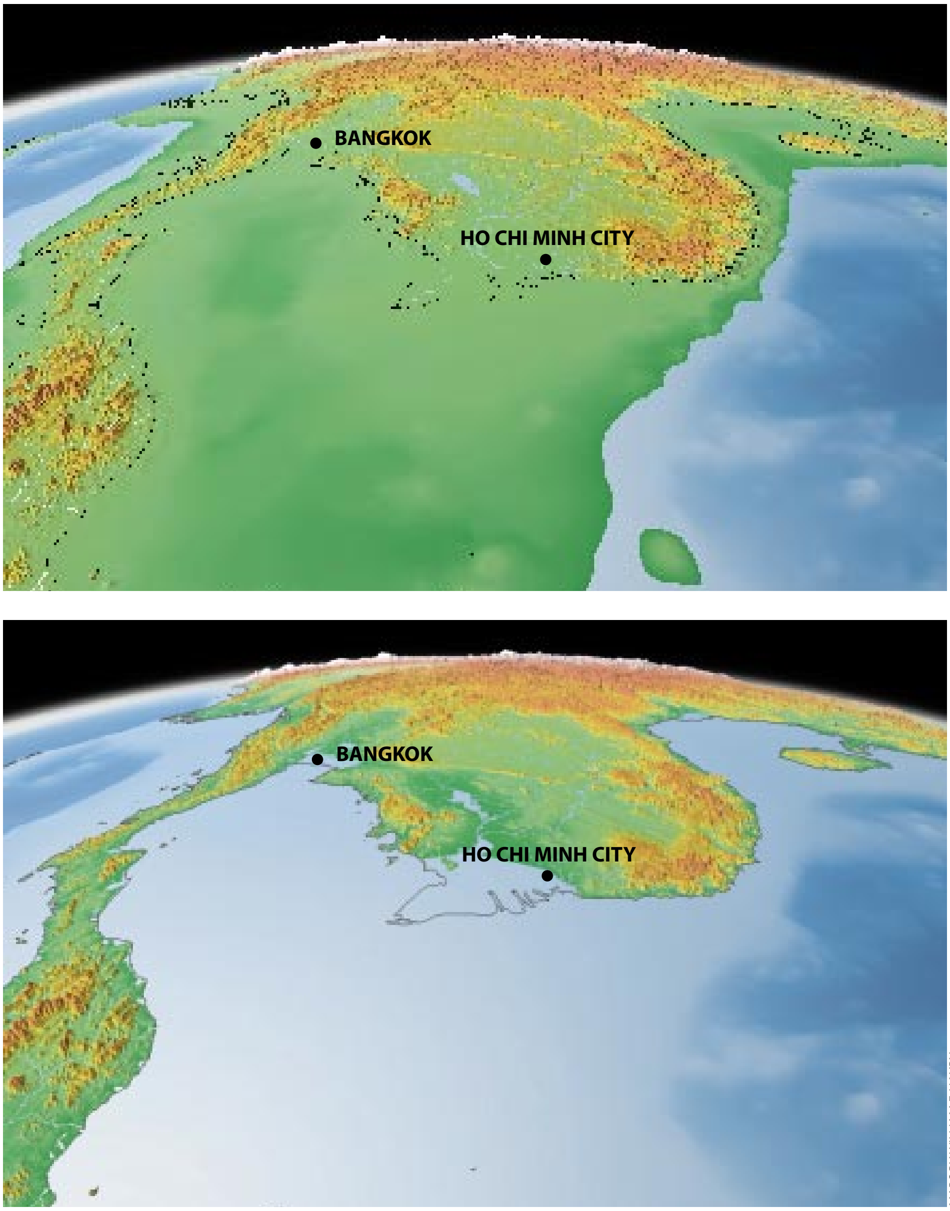

MAPS BY WILLIAM F. HAXBY

SOUTHEAST ASIA during the last ice age included a huge tract of land along what is now the Sunda Shelf. That terrain connected the mainland of Asia with the islands of Indonesia, forming one great continental mass (*top*). Should the West Antarctic ice sheet melt, the resulting five-meter rise in sea level would flood river deltas, including the environs of Ho Chi Minh City and Bangkok (*bottom*), substantially altering the present coast (*black line*).

reach Antarctica, where it would deposit its moisture as snow. Even the sea ice surrounding the continent might expand.

In other words, just as SeaRISE scientists were beginning to mount their campaign to follow the presumed collapse of the West Antarctic ice sheet, computer models were showing that the great mass of ice in the Antarctic could grow, causing sea level to drop as water removed from the sea became locked up in continental ice. "That really knocked the wind out of their sails," quips Richard G. Fairbanks, a geologist at the Columbia University Lamont-Doherty Earth Observatory.

Other observations have also steered the opinion of many scientists working in Antarctica away from the notion that sudden melting there might push sea level upward several meters sometime in the foreseeable future. For example, glaciologists now realize that the five major ice streams feeding the Ross Sea (named, rather uninventively, ice streams A, B, C, D and E) are not all relentlessly disgorging their contents into the ocean. One of the largest, ice stream C, evidently stopped moving about 130 years ago, perhaps because it lost lubrication at its base.

In fact, the connection between climatic warming and the movement of West Antarctic ice streams has become increasingly tenuous. Ellen Mosley-Thompson of the Ohio State University Byrd Polar Research Center notes that ice streams "seem to start and stop, and nobody really knows why." And her own measurements of the rate of snow accumulation near the South Pole show that snowfalls have mounted substantially in recent decades, a period in which global temperature has inched up; observations at other sites in Antarctica have yielded similar results.

But the places in Antarctica being monitored in this way are few and far between, Mosley-Thompson emphasizes. Although many scientists are now willing to accept that human activities have contributed to global warming, no one can say with any assurance whether the Antarctic ice cap is growing or shrinking in response. "Anybody who tells you that they know is being dishonest," she warns.

That uncertainty could disappear in just a few years if the National Aeronautics and Space Administration is successful in its plans to launch a satellite designed to map changes in the elevation of the polar ice caps with extraordinary accuracy—perhaps to within a centimeter a year. A laser range finder on this forthcoming satellite, which is scheduled to be placed in a polar orbit in 2002, should be capable of detecting subtle changes in the overall volume of snow and ice stored at the poles. (Curiously, a similar laser instrument now orbiting Mars may be charting changes in the frozen polar ice caps on that planet well before scientists are able to perform the same feat for Earth.) During the first decade of the 21st century, then, scientists should finally learn whether the Antarctic ice cap as a whole is releasing water to the sea or storing water away in deep freeze.

Other insights into West Antarctica's vast marine ice sheet may come sooner, after scientists drill deeply into the ice perched between two of the ice streams. The researchers planning that project (who have replaced the former moniker "SeaRISE" with the less alarmist acronym "WAIS"—for West Antarctic ice sheet) hope to recover ice, if it indeed existed, dating from the exceptionally warm 5e interval of 120,000 years ago. Finding such a sample of long-frozen West Antarctic ice would, in Mosley-Thompson's words, "give you some confidence in its stability."

Until those projects are completed, however, scientists trying to understand sea level and predict changes for the next

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century can make only educated guesses about whether the polar ice caps are growing or shrinking. The experts of the Intergovernmental Panel on Climate Change, a body established in 1988 by the World Meteorological Organization and the United Nations Development Program, have adopted the position that both the Antarctic and the smaller Greenland ice caps are most likely to remain constant in size (although they admit the possibility of substantial errors in their estimate, acknowledging that they really do not know whether to expect growth or decay).

Up or Down?

Whatever the fate of the polar ice caps may be, most researchers agree that sea level is currently rising. But establishing that fact has been anything but simple. Although tide gauges in ports around the world have been providing measurements of sea level for many decades, calculating the change in the overall height of the ocean is a surprisingly complicated affair. The essential difficulty is that land to which these gauges are attached can itself be moving up or down. Some regions, such as Scandinavia, are still springing back after being crushed by massive glaciers during the last ice age. Such postglacial rebound explains why sea level measured

Fertilize the Sea to Stop It from Rising?

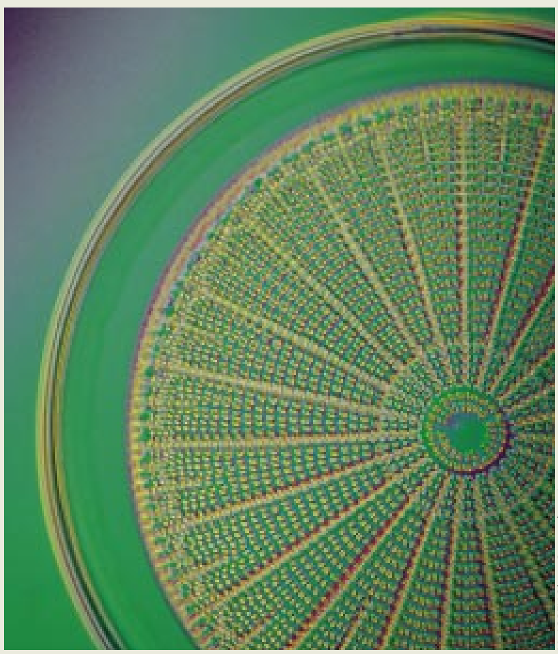
Discussions about ocean and global warming tend to focus on the threat of rising sea levels or the possibility that hotter tropical waters might spawn more frequent typhoons. But one also needs to remember that, in a fundamental sense, the oceans are important allies in the struggle against troubling climatic change. Of all the heat-trapping carbon dioxide that is released into the atmosphere every year from tailpipes and smokestacks, about a third goes into the sea, which scientists therefore recognize as an important "sink" for this gas.

The carbon dioxide dissolves in the shallow layers of the ocean, where, thankfully, it cannot contribute to warming the atmosphere. Much of the carbon transferred in this way is used by phytoplankton, the ubiquitous microscopic plants that grow near the surface of the water. After these short-lived organisms die, some of the carbon in their tissues sinks to great depths. Climatologists call this process the "biological pump" because it draws carbon out of the atmosphere and stores it deep in the sea. Naturally enough, some people have pondered whether this phenomenon could be artificially enhanced. This tactic would be the marine equivalent of planting more trees to isolate carbon in a form that does not contribute to greenhouse warming.

One researcher closely associated with this concept is the late John H. Martin of Moss Landing Marine Laboratories in California. Martin and his colleagues were aware that large oceanic regions contain high levels of nitrate (a normally scarce nutrient) but show low concentrations of the photosynthetic pigment chlorophyll. That combination was curious: with abundant nitrate to fertilize their growth, tiny marine plants should multiply rapidly, greening the sea with chlorophyll. Yet vast high-nitrate, low-chlorophyll areas can be found in the equatorial and northern Pacific and over large stretches of the southern oceans.

Martin and his co-workers knew that the growth of phytoplankton in these places was not limited by any of the major nutrients—nitrate, silicate or phosphate. They believed that the deficiency of a trace element, iron, was curbing the growth of phytoplankton, because experiments with cultures had shown that adding a dash of iron to water taken from these areas boosts its ability to support the growth of common types of phytoplankton.

They reasoned that this connection between iron and plant growth, if it indeed operated the same way in the ocean, would have profound consequences. For example, it could explain why carbon dioxide levels in the atmosphere were much lower during the last ice age: iron carried in dust blown off the cold, dry continents of the time would have fostered the growth of marine phytoplankton, which then acted to pump carbon from the atmosphere to the



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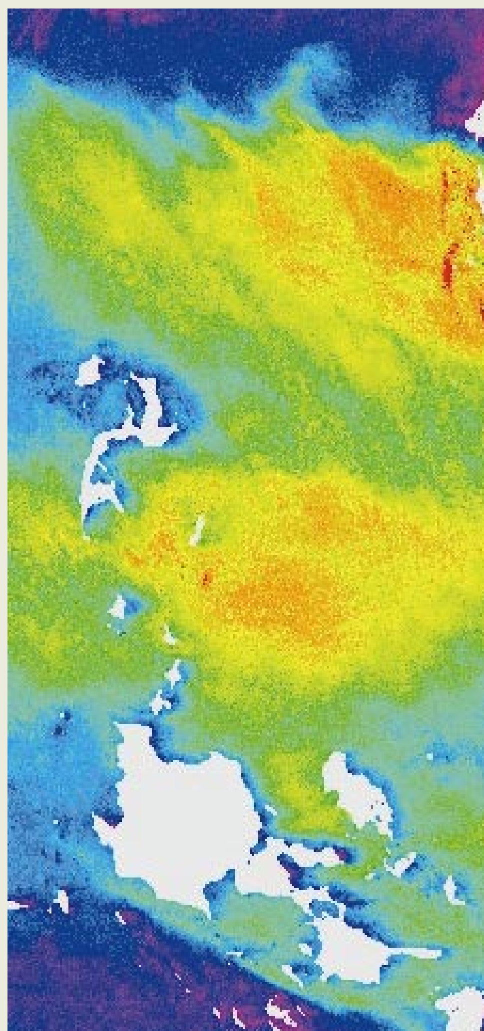

SATELLITE OBSERVATIONS, such as this false-color image made with the Coastal Zone Color Scanner (*right*), reveal that the concentration of phytoplankton to the west of the Galápagos Islands is often much higher (*red*) than that in surrounding waters (*blue*). Such blooms of microscopic plants, typically diatoms (*above*), probably occur because iron-rich particles are carried westward from these volcanic islands by the prevailing winds and currents.

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in Stockholm appears to be falling at about four millimeters a year, whereas it is rising by one and a half millimeters a year in Honolulu, a more stable spot.

In principle, one could determine the true rise in sea level by throwing out the results from tide gauges located where landmasses are shifting. But that strategy rapidly eliminates most of the available data. Nearly all the eastern seaboard of North America, for instance, is still settling from its formerly elevated position on a "peripheral bulge," a raised lip that surrounded the depression created by the great ice sheet that covered eastern Canada 20,000 years ago. What is more, local effects—such as the buckling that occurs at the edges of tectonic plates or the subsidence that ensues when water or oil is pumped from the ground—dominate in many tide gauge records, even in the tropics. In Bangkok, for example, where residents have been tapping groundwater at a growing rate, subsidence makes it appear as if the sea has risen by almost a full meter in the past 30 years.

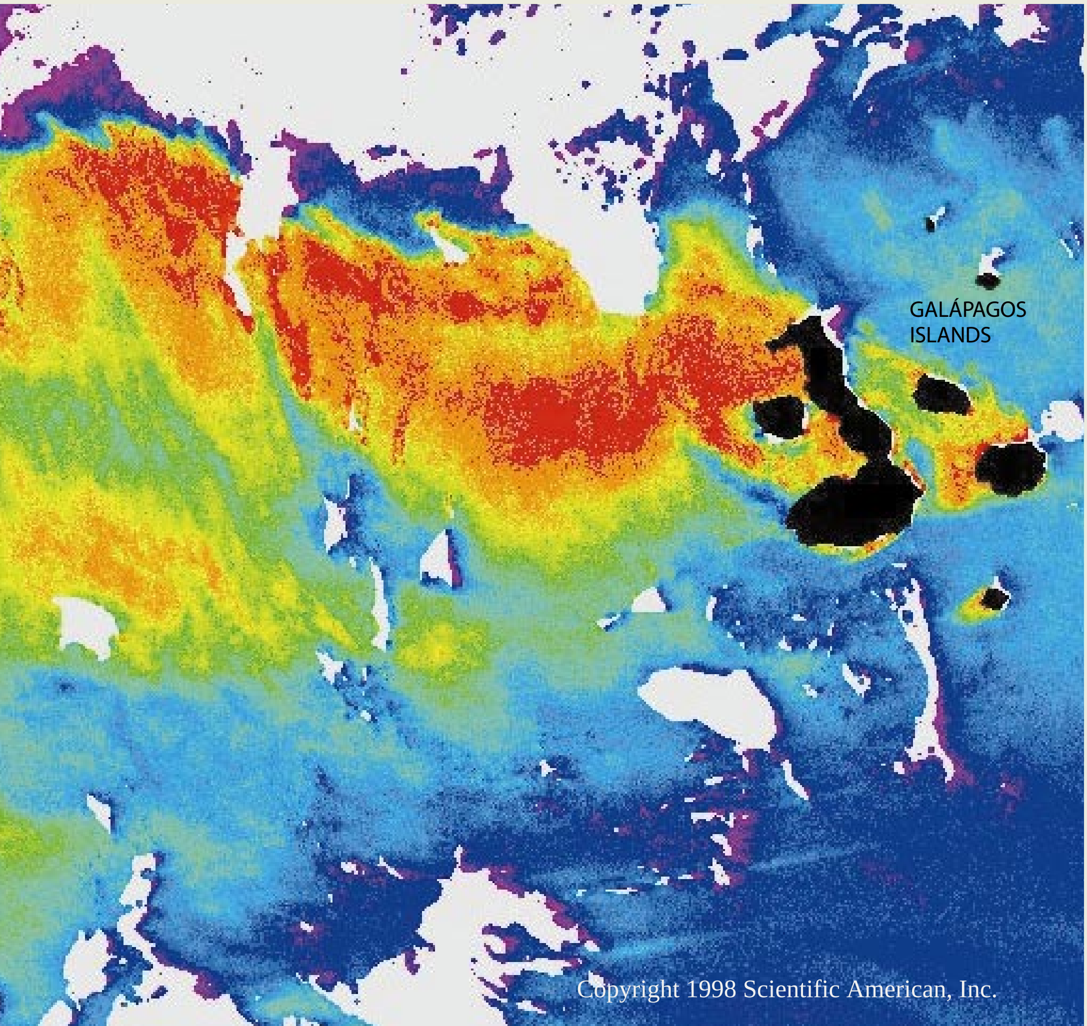
Fortunately, geophysicists have devised clever ways to reconcile some of these discrepancies. One method is to compute the motions expected from postglacial rebound and subtract them from the tide gauge measurements. Using this approach, William R. Peltier and A. M. Tushingham,

seafloor. When the continents became warmer and wetter at the end of the Pleistocene (roughly 10,000 years ago), the land gave off less dust to ocean-bound winds, robbing some marine phytoplankton of the iron needed for growth.

Although this argument was compelling, many other theories could also explain past changes in atmospheric carbon dioxide levels. To impress on some of his skeptical colleagues the importance of iron as a plant nutrient, Martin jokingly proclaimed in a lecture in 1988 that adding even modest amounts of iron in the right places could spur the growth of enough phytoplankton to draw much of the heat-absorbing carbon dioxide from the atmosphere. His often quoted jest "Give me a half a tanker of iron, and I'll give you an ice age" foreshadowed more serious considerations of actually using this approach to help cool the planet.

By 1991 other scientists had examined whether such a solution to global warming could be effective. Using computer models, they concluded that the most successful iron fertilization scheme would reduce carbon dioxide levels in the atmosphere by only about 20 percent at most. Still, the following year an influential panel from the National Academy of Sciences reported that such a program of geoengineering might provide a relatively cheap way to alleviate some of the expected greenhouse warming. But at that point, the very idea that adding iron to parts of the sea would enhance the growth of marine phytoplankton remained only a hypothesis.

To test the basic theory better, Martin and his co-workers organized an expedition to the equatorial Pacific in 1993 to scatter a solution of iron over a 64-square-kilometer patch of open water. Promising results from this first experiment encouraged a second expedition to the region in 1995, which provided further evidence that iron indeed limits the proliferation of phytoplankton in these high-nitrate, low-chlorophyll waters.



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Martin died of cancer in June 1993, so he was not able to witness the success of these demonstrations. Yet even before the actual tests of his idea were carried out, he and many other oceanographers began to worry that performing planetary engineering on the scale required to put a dent in the problem could very well cause unforeseen environmental hazards in the sea—depleting oxygen disastrously in places, disturbing the marine food web and perhaps even worsening the buildup of atmospheric carbon dioxide in the long run.

In 1996 the Intergovernmental Panel on Climate Change concluded in their summary report that iron fertilization "is not a feasible mitigation tool, given our current knowledge of the potential ramifications of such a procedure." Nevertheless, several oceanographic expeditions to fertilize patches in the southern oceans with iron are now in preparatory stages, and these experiments will undoubtedly keep this controversial idea under debate for some time. —*D.S.*

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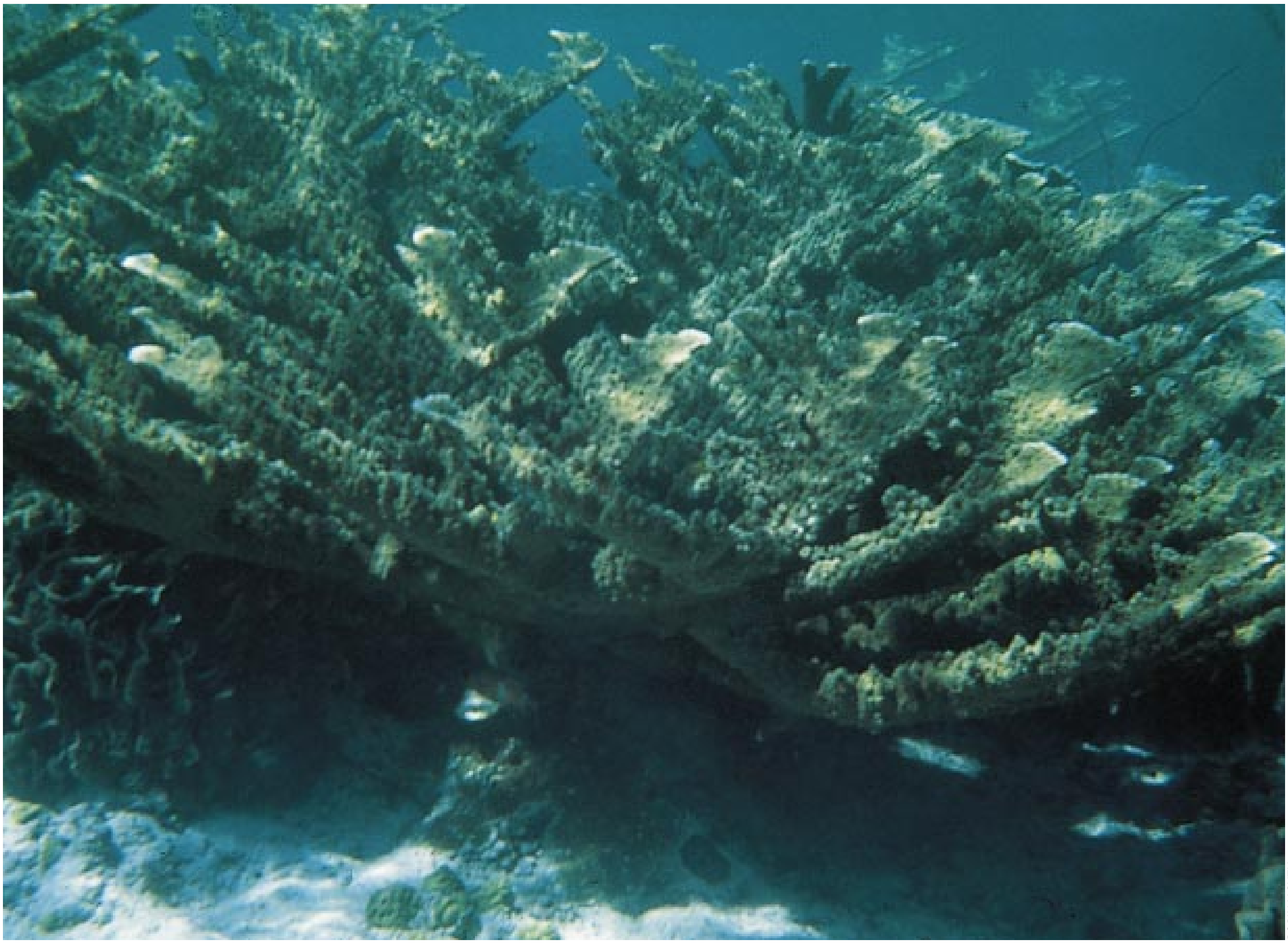

ROBIN LIGHTY

NEAR-SURFACE-DWELLING CORALS of the species *Acropora palmata* help to determine past changes in sea level. By drilling into coral reefs and recovering ancient samples of this species from deep under the seabed, scientists have been able to reconstruct how sea levels rose as the last ice age ended.

both then at the University of Toronto, found that global sea level has been rising at a rate of about two millimeters a year over the past few decades. Many other investigators, using different sets of records from tide gauges, have reached similar conclusions.

Further confirmation of this ongoing elevation of the ocean's surface comes from more than half a decade of measurements by the TOPEX/Poseidon satellite, which carries two radar altimeters aimed downward at the ocean. Because the position of the satellite in space is precisely known, the radar measurements of distance to the sea below can serve as a spaceborne tide gauge. The primary purpose of the TOPEX/Poseidon mission is to measure water circulation in the ocean by tracking surface undulations caused by currents. But the satellite has also been successful in discerning overall changes in the level of the ocean.

"When you average over the globe, you get much less variability than at an individual tide gauge," explains R. Steven Nerem of the Center for Space Research at the University of Texas at Austin. He had published results from the TOPEX altimeter that indicated that global sea level was rising at almost four millimeters a year—twice the rate previously determined. But, as it turns out, these were affected by a bug in the software used to process the satellite data. Subsequent analysis appears to confirm the land-based assessment of two millimeters a year in sea-level rise. "Of course, this estimate changes every time I put in some more data," Nerem admits, "but the current number is completely compatible with the estimates that have come from 50 years of tide gauge records."

Looking Backward

With few exceptions, scientists believe they have established a reliable value for the rate of recent rise in sea level: two millimeters a year. But the key question still facing these researchers—and civil planners—is whether this trend will hold steady or begin to accelerate in response to a warming climate. Geologists have helped address this problem by tracing how sea level has fluctuated in the past in response to prehistoric climate changes.

Columbia's Fairbanks, for example, has studied one species of coral that grows near the surface of the sea, particularly in and around the Caribbean. By drilling deeply into coral reefs in Barbados and locating ancient samples of this surface-dwelling species, he and his colleagues were able to follow the ascent of sea level since the end of the last ice age, when tremendous quantities of water were still trapped in polar ice caps and the oceans were about 120 meters lower than they are today.

Although his coral record shows episodes when the sea mounted by as much as two or three centimeters a year, Fairbanks notes that "these rates are for a very different world." At those times, 10,000 to 20,000 years ago, the great ice sheets that had blanketed much of North America and Europe were in the midst of melting, and the ocean was receiving huge influxes

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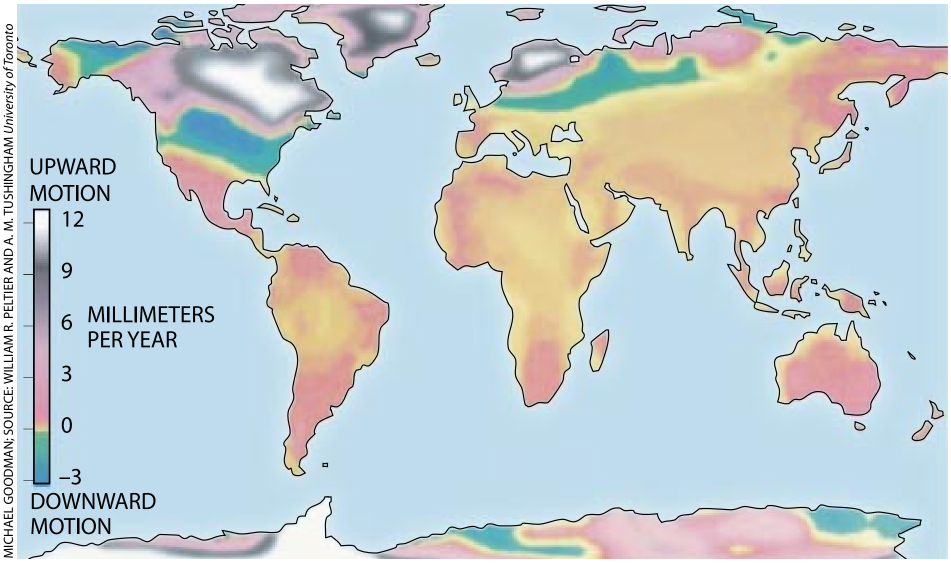
of water. The more recent part of the sea-level record indicates a progressive decline in the rate of ascent, with the height of the ocean seemingly stagnating during the past few millennia. Thus, the current climatological regime would appear to be inclined toward a relatively stable sea level.

But this reassuring picture is called into question by John B. Anderson, a marine geologist at Rice University. The data collected by Fairbanks and his colleagues are "not accurate enough to see the kinds of events predicted by the glaciological models," Anderson contends. There were at least three episodes of sudden sea-level rise in the past 10,000 years, he elaborates, but these are invisible in the coral record simply because "there's a five-meter error bar associated with that method."



MICHAEL GOODMAN; SOURCE: WILLIAM R. PELTIER AND A. M. TUSHINGHAM *University of Toronto*

POSTGLACIAL REBOUND, the slow recovery from the deformation caused by weighty ice sheets, accounts for the vertical movement of land in many parts of the world. These shifts, which have been continuing since the last ice age ended, affect relative sea level at the coastline in a manner that varies from place to place. Such movements can confound tide gauge records obtained from coastal sites and thus complicate efforts to track the overall change in global sea level.

Anderson and his co-workers have garnered evidence from such places as Galveston Bay in the Gulf of Mexico, where sediment cores and seismic soundings reveal how that estuary has responded to rising sea level since the last ice age. A steady increase in sea level would have caused the underwater environments that characterize different parts of the estuary to move gradually landward. But the geologic record from Galveston Bay, Anderson points out, shows "very dramatic" features that indicate sudden flooding of the ancient strand.

The most recent episode of sudden sea-level rise that Anderson discerns occurred about 2000 B.C., when global climate was presumably similar to present conditions. His work indicates that sea level may have jumped considerably in just a few centuries. But so far Anderson has been unable to establish just how large a rise actually occurred.

Archaeologists should be able to help track ancient changes in sea level with further examination of coastal sites submerged by rising seas. Numerous analyses done so far in the Mediterranean, spanning only the past 2,000 years, indicate that sea level has risen an average of only two tenths of a millimeter a year. Unfortunately, those studies give little insight into whether the ocean may have suddenly mounted 4,000 years ago. Nor is the archaeological work yet adequate to discern exactly when sea level began to quicken in its rise, ultimately reaching the modern rate of two millimeters a year.

Despite many such troubling gaps in the scientific understanding of how sea level has varied in the past and how it could change in the future, the experts of the Intergovernmental Panel on Climate Change have provided some broad guidelines for what the world might expect by the end of the next century. The panel's forecasts for sea-level rise range from 20 centimeters to almost one meter. The low end of these estimates corresponds, in essence, to the rate of sea-level rise that has probably been occurring for the past century or two—since before humanity began releasing carbon dioxide and other greenhouse gases into the atmosphere with abandon. That is to say, the next century might see only a continuation of the natural rise in sea level that has long been tolerated. The high-end estimate of the panel represents a substantial acceleration that could plausibly happen but so far has not been evidenced.

Weathering the Future

Of course, responsible international authorities must take the full range of possibilities into account in planning for the future. Although the fivefold uncertainty in the amount of sea-level rise might trouble some, John G. de Ronde, the head of hydraulic modeling at the Ministry of Transport and Public Works in the Netherlands, seems unruffled by it. Whatever the eventual trend in global sea level, he is confident that his country can cope: "Sea-level rise—you can measure that, you can see it and do something about it."

Although the necessary expenditures might seem enormous, de Ronde reports that the cost of improving Dutch dikes and other waterworks to accommodate 60 centimeters of sea-level rise over the next century amounts to no more than what people there now pay to maintain their bicycle paths. He shows greater concern for poor, land-scarce coastal nations and for an aspect of future climate that is much more difficult to forecast than sea level: changes in the frequency and intensity of violent storms. "You would need 20 years to see a change in statistics," de Ronde notes, "then a bad storm could happen the next day."

So as long as the West Antarctic ice sheet remains reasonably behaved, the real question facing residents of coastal regions may be how greenhouse warming affects local weather extremes and the size of damaging storm surges. Yet for those kinds of changes, scientists are especially hard put to offer predictions.

Perhaps with the results of further research and more refined computer models, climatologists will eventually be able to pinpoint where conditions will deteriorate and where they will improve. But such precise forecasts may, in the final reckoning, prove unreliable. It may just be as de Ronde says, imparting a lesson that nature keeps forcing on him and his colleagues: "We have to live with things we don't know exactly." SA

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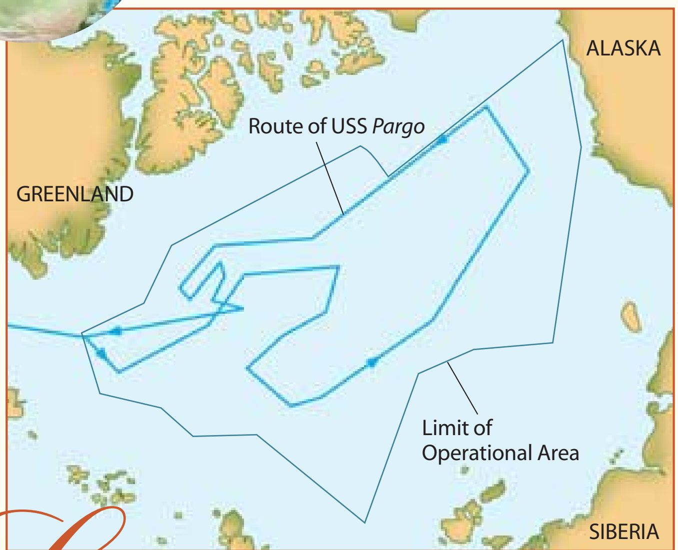
WORLD TOUR

ARCTIC OCEAN: *Forty Days in the Belly of the Beast*

Or, a marine geologist's account of life on board a U.S. Navy nuclear attack submarine under the Arctic ice

by Bernard J. Coakley



LAURIE GRACE (*map*); WILLIAM F. HAXBY (*globe*)

Lying prone on my narrow bunk, I heard the unmistakable sound of water trickling, as though from a faulty faucet. It did not soothe me, as I tried to get some sleep during my first night on a nuclear submarine, cruising below the surface of the sea. Like a camper in a suspect tent on a rainy night, I checked my bunk for damp spots and braced for the inevitable arrival of the drips.

Nestled next to a torpedo tube, I was bathed in dim light. I heard the trickling, the hum of pumps, the click of electrical relays and, from time to time, bits of nearby conversations. Once every hour a navy enlisted man would open an access hatch in the floor near my bunk and climb down into the bilge below. This was to be my life for the next 40 days, a witness to deliberate, continuous action, a confused observer.

"Blind Date" on a Submarine

What was a marine geologist doing on the USS *Pargo,* a Sturgeon-class fast-attack submarine? Heading toward the Arctic Ocean on what had been called a "blind date" between the navy's submarine fleet and the academic research community. I was one of five scientists participating in the first unclassified science cruise, which would exploit the extraordinary mobility of navy submarines to characterize the ocean below the Arctic ice.

As on any blind date, there were surprises for both parties. Many crew members, I discovered, were intensely curious about the science that was taking them to the Arctic. Then, too, life on board a submarine was new and rather strange to me and my four colleagues—Ted DeLaca and Peter C. McRoy of the University of Alaska–Fairbanks, James H. Morison of the University of Washington and Roger Colony, then at the University of Washington. The ship's navy complement consisted of about a dozen officers, 120 enlisted men and two ice pilots, Jeff Gossett and Dan Steele of the navy's Arctic Submarine Laboratory, civilian navy employees specially trained and adept at moving the ship through icy waters.

BERNARD J. COAKLEY

CRAMPED QUARTERS on board a nuclear submarine put privacy at a premium. Here a junior sailor slumbers next to a Mark-48 torpedo in the torpedo room.

On a surface ship, you feel connected to the sea, sometimes uncomfortably so. In a submarine, you are both immersed in it and utterly isolated from it. At 100 meters (328 feet) or more deep, doing what submariners call "making a hole in the water," there is little sense of motion and no sensual connection to the world outside. You are in the "people tank." Position is just a pair of numbers. Time is what the clock reads.

We had toured the submarine before the trip but did not fully appreciate how close the quarters were until we were under way. The submarine is a marvel of three-dimensional design, a maze of pipes, cables, wires, struts, bulkheads, walkways, machinery and electronics. The trickling that kept me up during my first night, for example, was the drain in the crew shower, which I later learned was not even one meter from my pillow. Storage on board a sub also suggests impressive resourcefulness: passageways where we once walked upright were now paved with 23-centimeter-high food cans, making it necessary to walk hunched over through the vessel's middle level.

After leaving Groton, Conn., we reached the Arctic Ocean in a few days, cruising north past Iceland, through the Fram Strait, to arrive in the operational area, an approximately three-million-square-kilometer expanse of deep Arctic Ocean within which we would conduct our research.

My attention was devoted to making bathymetric (total water depth) and gravity measurements along the submarine's track. The gravimeter I used is basically an extremely precise scale, measuring minute variations in the gravitational force exerted on a mass. After accounting for the earth's shape and changes in the sub's position relative to the earth's rotational axis, I was left with infinitesimal variations

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USS *Pargo* surfaced in August 1993 to put out meteorological buoys and take water samples. The sailor in the conning tower is keeping "polar bear watch."

that could be attributed to the density distribution below the submarine. That was why I needed the bathymetric data, so I could account for the influence of bathymetry and use the gravity anomaly data to examine the distribution of mass below the seafloor. These subseafloor variations reveal much about how the ocean basins formed.

The Arctic Ocean has not been well mapped. The high ridges and plateaus in the basin shape the currents that move water and the contained chemical species and heat, redistributing what enters the basin from the Atlantic and Pacific oceans and the many rivers that drain the northern regions of North America and Eurasia. Predicting this circulation is important for understanding the transportation of contaminants and the formation and persistence of the ice pack. Understanding the present-day circulation will one day provide a better understanding of how the ocean responded to the last ice age. That understanding, in turn, could be an important piece of the puzzle of how the Arctic's unusually sensitive climate system works—and how it may respond to such forces as greenhouse warming in the future.

During 21 days in the operational area, I collected new bathymetric and gravity anomaly data over a track approximately 10,000 kilometers long. We worked below and within the floating pack ice that in the past had so severely constrained oceanographic work in the Arctic Ocean basin. For the first time, we systematically sampled and mapped this remote basin.

Football at the Pole

A highlight of our Arctic itinerary was the obligatory stop at the North Pole. To travel in an isolated environment to a geographic abstraction is a singular experience, but every Arctic cruise that approaches the Pole is drawn to it, like water swirling down a drain. On my 1993 trip, on board the *Pargo,* we surfaced in open water and marked the occasion by venturing out onto the ship's hull. On a later SCICEX cruise, in 1995 on board the USS *Cavalla,* we came up through ice at the Pole. My colleagues and I collected water samples while some crew members played touch football in the perpetual daylight.

Whenever I have sailed for science, I have been very aware of being a guest in the crew's "house." When that house is as cramped and isolated as a submarine, the awareness is unusually acute. I am proud of the data we collected on both the submarine science cruises in which I participated, but what I remember most about each trip is the camaraderie and teamwork we enjoyed among ourselves and with the crew and officers who ran the ships.

SCIENTIST peers into a hole in the ice (*top*), about a meter thick, for a water-sample bottle coming up from 1,400 meters below the ice. Author Coakley writes software for a workstation in the main passageway through the torpedo room, where the scientists worked.

PHOTOGRAPHS BY BERNARD J. COAKLEY

Although it may sound like a cliché, there is no room for discord on board a submarine. Crew members must be comfortable with one another, having been acclimated by the process that takes them from NUBs ("nonuseful bodies"—the most junior sailors) to fully qualified submariners. To some on this precision team, the other scientists and I must have appeared to be grit in the gears of their fine-tuned machine. But after a brief period of mutual wariness, the scientists and sailors began to understand one another and develop a collective mentality of the cruise, like a small village at sea. With time, we scientists were accepted into the daily round of discussions that marked time in the torpedo room, where we did most of our work.

The first SCICEX cruise was deemed a success by both the academic community and the submarine fleet. In recognition of this fact, in 1994 the U.S. Navy, the National Science Foundation (NSF), the Office of Naval Research, the National Oceanic and Atmospheric Administration and the U.S. Geological Survey agreed to support five more cruises, one each year from 1995 until 1999. The fourth of these cruises is under way as this article goes to press.

In the geophysics program—my primary interest—we have collected approximately 66,000 kilometers of new bathymetric and gravity anomaly profiles during some 130 days in the deep Arctic Ocean. In support of other scientific disciplines, this program has also collected tens of thousands of water samples, hundreds of conductivity, temperature and depth profiles, and voluminous data on the pack ice cover. All this information is improving our understanding of the deep Arctic Ocean basin, which many scientists regard as the canary in the coal mine of global climate change.

We have yet to take full advantage of what submarines offer to scientific research. Although we collected scientific information in places where it had never been collected before, we did so in a manner not much different from the way surface ships did it 30 or 40 years ago—by mapping a point directly below the vessel.

The 1998 and 1999 SCICEX cruises, on board the USS *Hawkbill,* will deploy a sonar system that maps the sea bottom across a 20-kilometer-wide swath. It was specially constructed and adapted with funds from the NSF's Arctic program for use on submarines in Arctic waters. The mission will also make use of a subbottom profiler, which will provide the first ever systematic imaging of the shallow stratigraphy of the Arctic Ocean. The data collected with these two sonars will revolutionize what we know about the history of this ocean basin and the currents that circulate through it. SA

BERNARD J. COAKLEY is an associate research scientist at the Columbia University Lamont-Doherty Earth Observatory.

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The Oceans and Weather

The sea is as important as the atmosphere in controlling the planet's weather

by Peter J. Webster and Judith A. Curry

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In the hierarchy of unavoidables, weather is as inevitable as death and taxes. No matter where people live, they must think about it—whether they are checking the local news in England to see if they will need an umbrella, sowing seeds in anticipation of monsoon rains in India or rebuilding in the wake of a catastrophic hurricane in the U.S. When most people ponder the weather, they instinctively look to the sky. But the atmosphere does not determine the weather by itself. It has a less obvious but essential partner: the ocean.

One demonstration of this synergy has been quite obvious of late. The disastrous El Niño of the past year increased public awareness that many unusual events all over the globe—relentless series of storms, prolonged droughts, massive floods—were directly caused by changing conditions in the tropical Pacific Ocean.

Such connections between the ocean and the atmosphere can influence, and often dominate, changes in the weather and longer-term climate everywhere. Effects range from storms and hurricanes generated over hours and days to ice ages that develop over millennia. In between, the ocean is the engine that drives seasonal shifts in weather, such as monsoons, and sporadic events, such as El Niño. Understanding the linkages between the atmosphere and the ocean has engaged meteorologists and oceanographers for decades. Fortunately, scientists now have a reasonable understanding of how these mechanisms work.

Midlatitude Battle Zone

Some of the most familiar weather systems occur at middle latitudes, although the driving forces behind this activity are oceans far away. The sea near the equator is especially warm, because solar heating is generally most intense there. To the north or south, the curvature

HURRICANE ELENA swirls over the Gulf of Mexico in August 1985, collecting energy from the warm sea below it.

NASA Corbis

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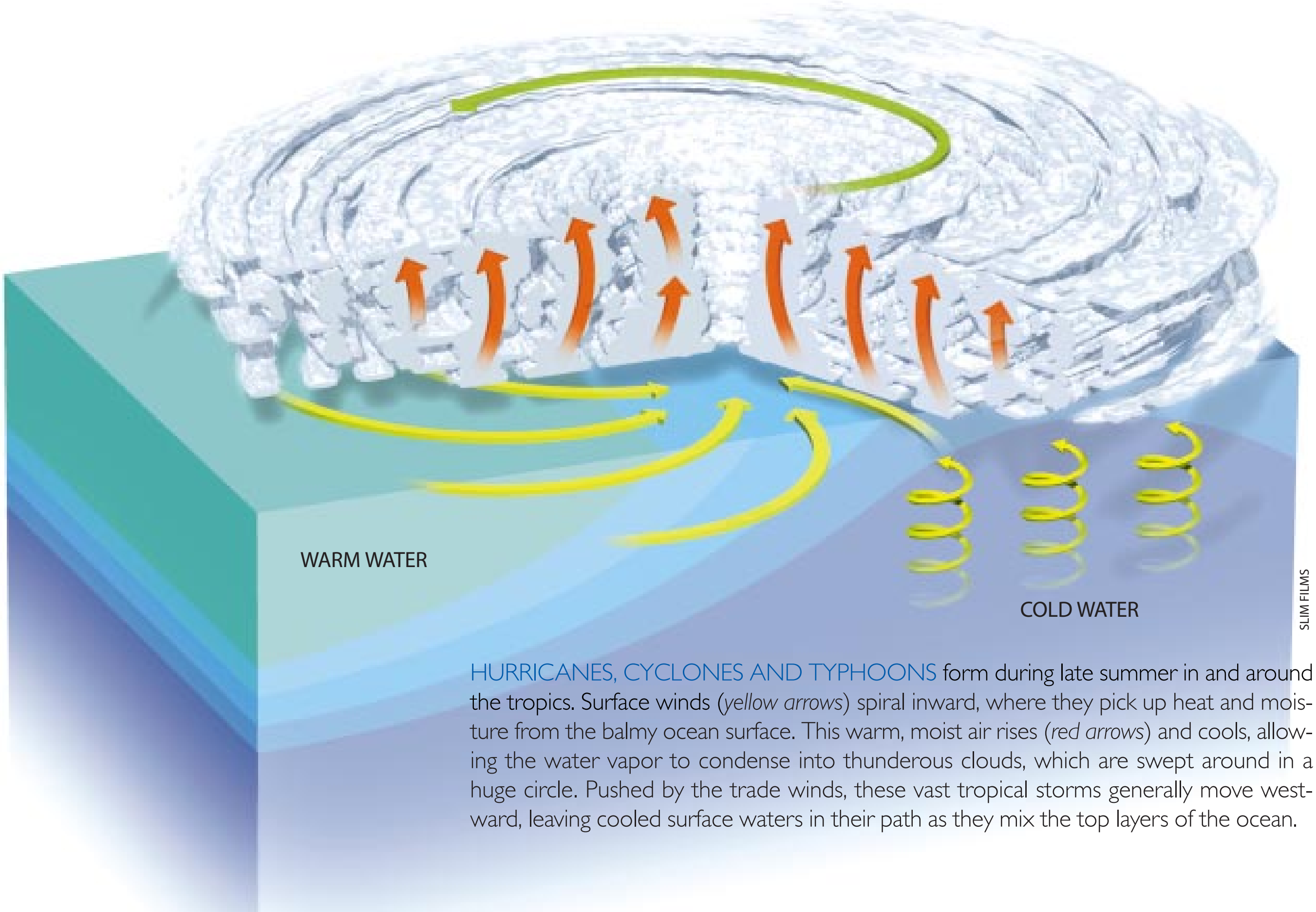

HURRICANES, CYCLONES AND TYPHOONS form during late summer in and around the tropics. Surface winds (*yellow arrows*) spiral inward, where they pick up heat and moisture from the balmy ocean surface. This warm, moist air rises (*red arrows*) and cools, allowing the water vapor to condense into thunderous clouds, which are swept around in a huge circle. Pushed by the trade winds, these vast tropical storms generally move westward, leaving cooled surface waters in their path as they mix the top layers of the ocean.

of the planet causes the sun's rays to spread out over a greater area. Solar heating at high latitudes is reduced even further in winter, when the axis of the planet tilts away from the sun. Also, like all objects immersed in a colder medium, the earth constantly loses heat to space. Near the equator the energy gained from the sun exceeds the amount lost in this way, but at higher latitudes the reverse occurs. If nothing intervened, the low latitudes would fry while the high latitudes froze.

The ocean and the atmosphere work together like a planetary thermostat, sharing nearly equally the task of exporting heat from equatorial regions toward the poles. Some of this heat is carried in warm currents such as the Gulf Stream. But the tropical ocean also passes large amounts of heat to the atmosphere. The warm, moist air created in this way rises because it is less dense than the surrounding atmosphere. If the earth did not rotate, this heated air would travel directly toward the poles. In addition, cold, dry air originating over the polar oceans and high-latitude landmasses would pass unhindered toward the equator, slipping under the warmer air and moving near the surface of the earth.

But the rotation of the earth deflects air masses into ribbons of air that spiral around the globe, westward in polar and equatorial regions and eastward in the midlatitudes. This pattern inhibits a clean transfer of heat between north and south. Instead cold and warm air masses collide in midlatitudes, where they often mix in huge swirlings, creating powerful storms.

Within these storms, the warm air rises up and over the incursion of cold, denser air. Pushed aloft, the warm air cools, and its water vapor condenses into clouds and rain. In the process the air releases large amounts of so-called latent heat—the energy difference between water in its vapor and liquid forms. Thus, copious amounts of heat, along with moisture and wind energy, flow across the borders between the air masses. Over a period of four to six days, this stormy boundary drifts from west to east, producing much of the rain that falls at midlatitudes—in the U.S., for instance. Finally, the thunderclouds dissipate, the battling air masses achieve a new equilibrium, and the temperature difference between the tropical and polar regions decreases for a time—only to build again under the constant barrage of the equatorial sun and the intense cooling at the poles.

Sometimes the link between oceans and storms can be more explosive. For example, outpourings of frigid Arctic air frequently sweep down across North America and Asia during winter. When these air masses arrive over the warm Gulf Stream and the Kuroshio (Japan Current), which flow northward from the tropics along the western side of the Atlantic and Pacific oceans, respectively, warmth and moisture rise from the sea, fueling the development of intense storms called bombs.

Bombs develop extremely quickly, taxing the ability of weather forecasters and often causing death and destruction. The storms have central pressures that are as low as many hurricanes, sometimes as little as 960 millibars. About two of these storms form in both the western Pacific and western Atlantic each winter. They last for days, migrating eastward and northward, thus crossing some of the busiest shipping lanes in the world. The winds can be so strong (more than 100 kilometers per hour) and the surface ocean waves so powerful that large ships can be easily lost. For instance, in September 1978 the fishing trawler *Captain Cosmo* sank in the North Atlantic, and the passenger liner *Queen Elizabeth II* suffered severe damage. In 1987 a bomb with wind speeds exceeding 160 kilometers per hour hit the coasts of Britain and France, killing 25 people, injuring 120 more and destroying 45 million trees.

Stormy Tropics

The ocean also generates intense storms at lower latitudes, in or around certain tropical regions. In the western Atlantic and eastern Pacific off Mexico and California, these storms are called hurricanes after the Mayan god of winds, Hunraken. In

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the Indian Ocean and near northern Australia, they are known as cyclones, a variation of the Greek word for "coiled serpent." In the northwestern Pacific, they are called typhoons, from the Chinese phrase for "great wind," *tai fung*.

Despite their different names and locations, the mechanics of all these immense circular storms are much the same. Hurricanes form only in places where the ocean-surface temperature exceeds 27 degrees Celsius (81 degrees Fahrenheit), which is why they usually form in late summer, when the ocean surface is the warmest. The storms occur somewhat away from the equator, where the rotation of the earth causes the tropical trade winds to bend poleward, a force needed to initiate the characteristic spiral of these storms.

Each hurricane develops from some original eddy in the wind that causes a low-pressure center to form. Such disturbances may initially be small and innocuous. But if conditions in the ocean and the upper atmosphere are right, about 10 percent of them intensify into full-fledged hurricanes.

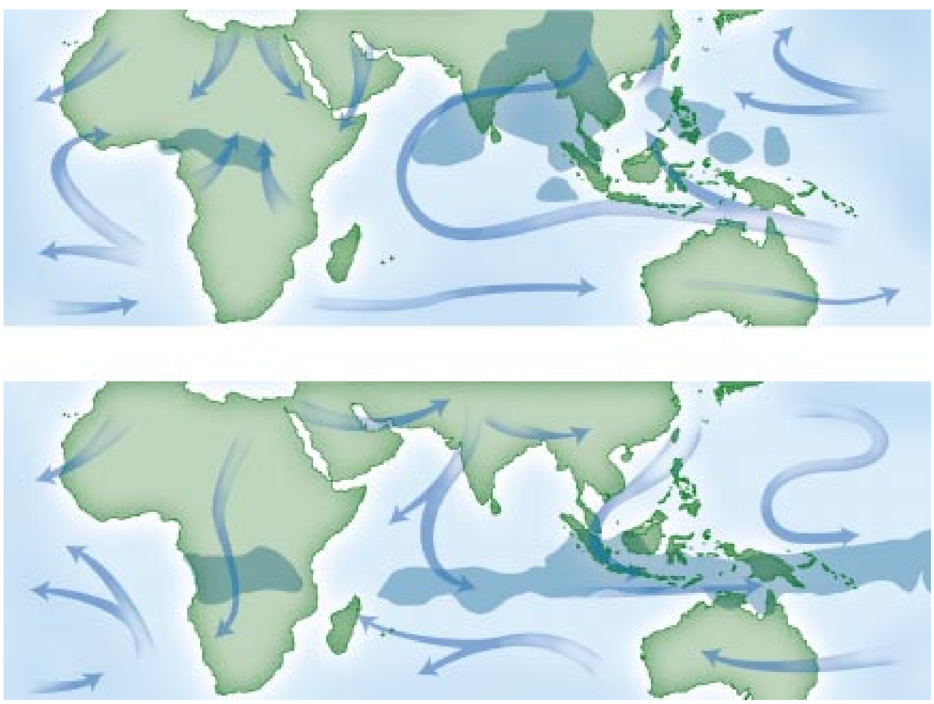
Air moves inward from all directions toward the low-pressure center of the developing hurricane, picking up moisture evaporating from the warm ocean. As more and more air converges toward the central low-pressure void, or the "eye," of the storm, it has no place to go but upward, where it creates clusters of thunderstorms and releases large amounts of rain and latent heat. The density of the superheated air then decreases markedly, forcing it to rise even more and to spread outward in the upper atmosphere. This movement causes the atmospheric pressure at the surface of the ocean to drop significantly.

At this stage, winds near sea level begin to circle (counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere) at ever-increasing speeds around the eye. Friction with the ocean surface causes these winds to spiral even more quickly inward and toward the warm center of the storm.

The temperature at the surface of the sea now becomes the critical factor. The exceptional warmth of the tropical ocean boosts the amount of evaporation, allowing the converging winds to pick up more moisture and to release more latent heat when the water vapor condenses into thunderstorm clouds. Air flowing along the ocean surface toward a low-pressure center might be expected to cool and dampen the storm. But in a hurricane, direct heating from the ocean surface offsets this effect, further intensifying the tempest. The rotating storm sustains itself by picking up as much energy from the surface of the ocean as it releases in its many thunderous clouds.

But that equilibrium does not last forever. The turbulence created by the strong winds mixes the upper ocean and brings colder water from below up to the sur-

STEVE McCURRY *Magnum*



LAURIE GRACE (*maps*)

MONSOON RAINS deluge Varanasi, India, during the summer months there (*photograph*), because the prevailing winds (*blue arrows*) from May to September (*top map*) soak up moisture from the ocean and bring heavy rains to large parts of Africa and Asia (*shaded regions*). Between November and March (*bottom map*), the pattern reverses, drenching more southerly lands in Africa, Indonesia and Australia.

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EL NIÑO of 1997 and 1998 caused extreme weather in many places, including flooding and landslides in California (*photograph*). Such conditions occur when the normal trade winds ebb or reverse direction, allowing a warm layer to cover the tropical Pacific (*far right, top*). More usually, and under a regime dubbed "La Niña," the westward-directed trade winds are strong enough to push surface waters toward Indonesia, forming the western Pacific warm pool (*far right, bottom*).

VINCE STREANO *Corbis*

face. That change cuts off the source of energy to the storm and leads ultimately to its demise. This mixing is why hurricanes can develop only where the layer of warm water at the surface of the sea is sufficiently thick—at least 60 meters. Otherwise cold water reaches the surface too easily. In that case, just as when a hurricane moves over cooler water or over land, its supply of heat and moisture disappears and the great storm dissipates.

Reversals of Fortune

When the ocean provides a more stable source of moisture to the atmosphere, it can create weather patterns that affect society even more than hurricanes do—the monsoons. The term "monsoon" comes from the Arabic *mausim,* which means "season." It refers to a circulation pattern that brings especially wet weather for part of the year.

During summer in the Northern Hemisphere, Asian and north African lands heat up considerably. Warm air rises over the Himalayas, the Plateau of Tibet and the mountains of central Africa, drawing in air from south of the equator. The resultant northward-moving winds pick up considerable moisture as the rotation of the earth deflects them to the east over the warm Arabian Sea, and the South Atlantic and Indian oceans. These surging air masses rise over the heated land areas and release their moisture in the form of monsoon rains in Asia and in central Africa north of the equator. Asians celebrate the onset of this "southwest monsoon" (named for the prevailing winds, which come from the southwest) because it marks the end of a period of intense heat and because the rainfall is essential for their crops.

The rains continue roughly until winter returns to the Northern Hemisphere and the lands there begin to cool. Air masses now reverse direction, with northeasterly winds moving across the equator, picking up moisture from the oceans before they reach southern Africa and northern Australia. Weaker versions of this same process also occur in the tropical Americas, bringing wet seasons to northern South America and southern Central America in Northern Hemisphere summer and to central South America in Northern Hemisphere winter.

It is a mistake, however, to think of the monsoon simply as a period of continuous rainfall. Within the rainy season are periods of intense precipitation, called active monsoon periods, and 20- to 30-day minidroughts, called monsoon breaks. Climatologists hypothesize that these oscillations occur because the soil becomes saturated and cools considerably; warm air then no longer rises more over land than sea. So the moisture-laden air from the ocean ceases to rush in over the continents. When the land dries out, warm air rises once again over land with vigor, moist air advances from the sea and the rains begin again.

Not surprisingly, the overall amount of moisture carried across the coastline to interior regions depends on the temperature of the adjacent ocean. Thus, a warm Arabian Sea in springtime portends a strong summer monsoon, and vice versa. But perhaps the greatest effect on the monsoons—accounting for about a 35 percent difference in the monsoon rains over India, for example—comes from the climatic phenomenon that is second only to the seasons themselves in driving worldwide weather patterns: El Niño.

The Christ Child

The ocean and the atmosphere in the Pacific perform an intricate, delicately poised pas de deux. The dance begins with the vast tropical Pacific Ocean, which under the glare of the intense tropical sun receives more solar energy than any other ocean on the earth. Ordinarily, the trade winds push the warmed Pacific surface waters westward so that they accumulate in a large, deep "pool" near Indonesia. In the eastern Pacific, off the west coast of South America, relatively cold waters rise from depth to replace the warm waters blown west.

As springtime arrives in the Northern Hemisphere, the trade winds lose strength. Surface temperatures in the central and eastern Pacific rise by a few degrees, and the east-west temperature difference diminishes. But this warming of the central Pacific is usually transitory: the onset of the Asian summer monsoon brings freshening winds, which create turbulence that mixes cold water up from below. All in all, the winds and waters form a dynamic, delicately balanced mechanism.

But like most machines with many moving parts, this system can break down. Every three to seven years the trade winds fail to pick up in summer. The warming of the central Pacific that begins in the spring continues to intensify and spreads eastward through the summer and fall.

Below the surface, invisible "internal waves," thousands of kilometers in length, propagate eastward along the interface between the warm layer at the top of the ocean and colder water at depth. These waves do not actually transport water eastward from the western Pacific warm pool. Rather, they serve as a cap to reduce the upwelling of cold water in the eastern Pacific. So the warm pool grows eastward across the entire Pacific.

The many schools of anchovy that thrive in the cold, nutrient-rich waters that normally rise to the surface off the Peruvian

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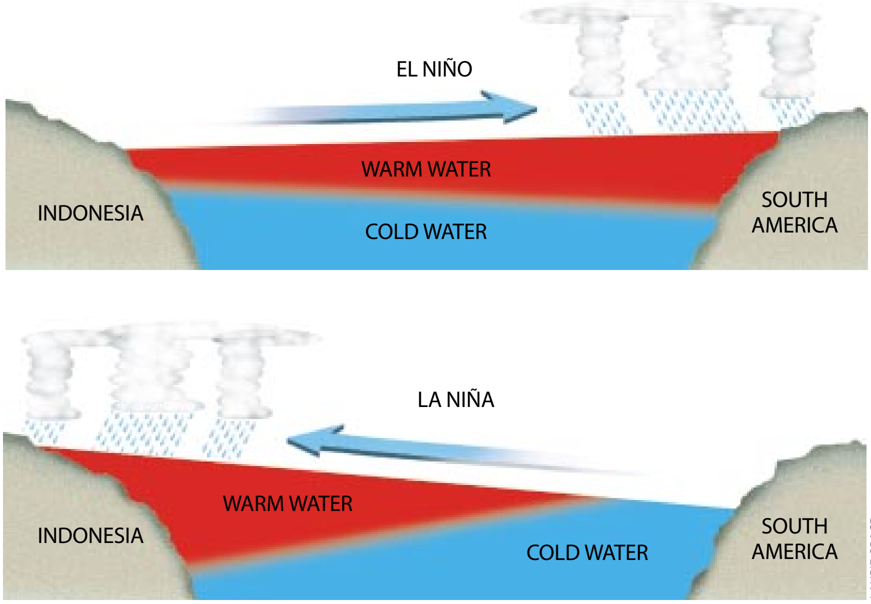

LAURIE GRACE

coast then disappear. Because this warming of the eastern Pacific occurs around Christmastime, Peruvian fishermen have long called it El Niño, literally "the boy child," after the infant Christ. The opposite extreme of the cycle, in which eastern Pacific waters become especially cold, has more recently been christened La Niña, "the girl child."

If the effects of El Niño were restricted to the ocean, it probably would have remained a concern only of Peruvian fishers. But as the warm pool migrates eastward, it injects heat and moisture into the overlying air. This shift of the warm pool profoundly rearranges atmospheric circulation all around the globe and changes the locations where rain falls on the planet.

El Niño can, for instance, cause severe droughts over Australia and Indonesia, with accompanying forest fires and haze. It weakens the summer monsoon rains over southern Asia, but it often causes heavy rainfall and catastrophic flooding along the Pacific coast of South America. El Niño also affects the frequency, severity and paths of storms, lowering the probability of hurricanes in the Atlantic but increasing the chances of cyclones and typhoons in the Pacific.

In more circuitous but no less dramatic ways, El Niño alters the probability of certain weather regimes outside the tropics. It can intensify the western Pacific jet stream and shift it eastward, for example, increasing the chances of stronger winter storms over California and the southern U.S., with accompanying floods and mudslides.

El Niño can thus have dire consequences for society and the global economy. Indeed, it affects nearly everyone: farmers, relief workers, transportation experts, water resource and utilities managers, commodities traders, insurance brokers—even people searching for vegetables at the market. In many parts of the world, El Niño sparks the spread of waterborne diseases such as typhoid, cholera, dysentery and hepatitis as well as vector-borne diseases such as malaria, yellow fever, dengue, encephalitis, plague, hantavirus and schistosomiasis.

During the past two decades, several major warmings have occurred. In 1982 and 1983 El Niño caused thousands of deaths and over $13 billion in damage worldwide. In 1986 and 1987 a less dramatic El Niño transpired, and a far weaker event developed in 1992. The latter was unusual because it continued for two full years, albeit with relatively low intensity.

In the spring of last year, the tropical eastern Pacific Ocean warmed to an unprecedented extent. The surge in ocean temperatures continued at a much faster rate than usual: by October 1997 the surface temperature of the eastern Pacific had risen by more than six degrees C from its state a year before. Although temperatures there have since dropped from their peak, nearly everyone on the earth has felt the effects of this recent El Niño in some way.

Looking over the Horizon

The devastation wrought by the El Niño of 1982 and 1983 spurred meteorologists to look beyond the typical one-week range of most forecasts and to try to predict the weather a season, or perhaps a year or more, in advance. To accomplish that feat, scientists turned to the ocean, whose influence on the climate increases as the time span in question lengthens.

One manifestation of this focus on the ocean came in 1985, when researchers from many countries established a network of oceanographic sensors across the tropical Pacific. With warning from this array, meteorologists knew months in advance that the El Niño of 1997 was approaching and that it would be strong. Forewarned, some farmers planted more rice and less cotton in anticipation of especially heavy rains. Others took steps to start conserving water in preparation for the coming drought.

With a better understanding of the ocean, scientists may yet be able to forecast climate changes from year to year or even from one decade to the next. For example, they might be able to predict shifts in the frequency, duration or severity of hurricanes, monsoons and El Niño in the face of global warming. For such long-term forecasts, Bob Dylan may have been right when he sang, "You don't need a weatherman to know which way the wind blows." You need both a weatherman and an oceanographer. SA

The Authors

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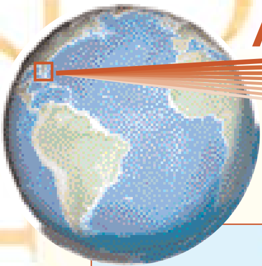
WORLD TOUR

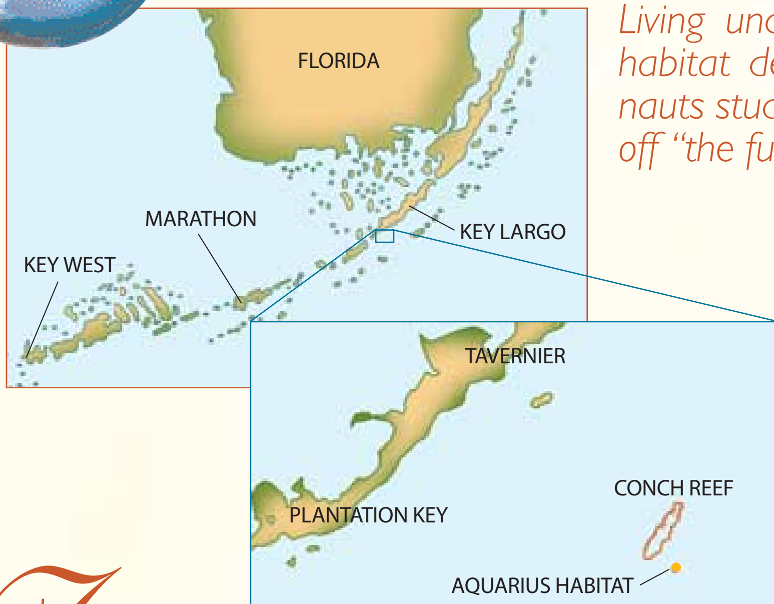
ATLANTIC OCEAN:

Ten Days under the Sea



Living underwater in the world's only habitat devoted to science, six aquanauts studied juvenile corals and fought off "the funk"

by Peter J. Edmunds



LAURIE GRACE (*map*); WILLIAM F. HAXBY (*globe*)

It was seven on a July morning, and I already felt like I had been awake for hours. I was standing with my research team in a cigarette-style motorboat speeding toward Conch Reef off Key Largo, Fla. When we reached our destination on the reef, we would descend into the clear, dark-blue water and stay there for rather a long time.

We were about to start our first mission in the Aquarius underwater habitat, a six-person research station situated 6.5 kilometers (four miles) off Key Largo and 15 meters below the waves. For the next 10 days, we would be aquanauts, living every marine researcher's fantasy: we would spend as many as six hours a day working in the water and then retire to a warm, dry, comfortable shelter for meals, discussions, relaxation and sleep.

The powerful, streamlined boat sliced easily through the morning swells as it pushed eastward toward the rising sun and the support barge, which was anchored directly above the habitat. My team and I had gone through a lot to get to where we were. There had been a year of planning, four days of intensive training and, in my case, a lifetime of ambition to work underwater as a marine biologist. Still, I couldn't help thinking about the things I would miss while living underneath the sea: sunshine, fresh air, open spaces, even the squadrons of pelicans that soared silently over the boat.

My teammates, pensive and quiet, seemed to be ruminating on much the same theme as we arrived at the barge, moored and exchanged our dry shirts and sandals for damp wet suits and ungainly fins. After years of use, the scuba gear I donned had the comfort of well-used tools, except for one critical omission: my familiar red face mask no longer had a snorkel attached to the strap. The most basic of my regular equipment was conspicuous in its absence, reminding me that where I was going, the surface would no longer provide a safe haven from trouble.

In the realm that my team and I would shortly enter, the Aquarius habitat would be our only refuge and the surface a dangerous place where we could die in minutes. Within 24 hours of submerging, our bodies would become saturated with nitrogen gas. In this state, a rapid return to the surface would induce a severe and possibly crippling or even fatal case of decompression sickness, better known as the bends. Although I had long been aware of this fact, I realized there was no turning back as I sat on the diving platform at the stern of the boat, straining to prevent myself from being pushed into the water by the heavy set of twin tanks on my back.

Yet as I plunged into the water, I was freed from my concerns and from the weighty terrestrial world. Finally, I was able to focus my attention on the immediate goals of my research and the excitement and challenges of living underwater.

My four scientific team members hovered below me as I adjusted my mask, purged the air from my buoyancy compensator and sank below the surface. Creole wrasses, barracuda and other fish darted in and out of my peripheral vision. I exchanged an "OK" sign with my buddy, and we descended through a fine snow of planktonic organisms to the hidden reef nearly 17 meters below.

I had started hundreds of dives in similar fashion, but this one was different. Instead of surfacing after a brief visit, my colleagues and I would be down as deep as 30 meters for nearly three hours, completing three times the tricky maneuver of exchanging empty scuba tanks for full ones at depth.

As I continued my descent, the reef be-

DAN BURTON

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AQUARIUS HABITAT sits on the seafloor off Key Largo, Fla. The white "gazebo" in the foreground (*left*) is full of air, offering a temporary refuge for divers. Author Peter Edmunds (*wearing eyeglasses in photograph above*) peers out of the bunk-room porthole with aquanauts Dione Swanson and Sean Grace.

neath me took shape, becoming a rolling landscape of underwater hills and valleys cloaked in a forest of sponges, stony corals and soft corals waving in the current. As on previous occasions, I was struck by the odd similarity between this reefscape and a frosty winter scene in my native England.

Our dive location, known simply as the northeast site, was half a kilometer from the habitat and formed a blunt spur at the end of one of the rope "highways" secured to the sea bottom. Their purpose was to provide guidance to the habitat in the event of strong currents, poor visibility or impaired vision caused by the loss of a face mask. Closer to the bottom I saw the edge of the reef sloping down to more than 40 meters' depth; the mosaic of coral colonies, sediment and algae that covered much of the reef surface; and the filling station where I would soon grow accustomed to swapping my scuba tanks.

Here among the corals, being chased incessantly by feisty and territorial but (fortunately) small damselfish, we started to count and measure the small juvenile corals that were the subject of our research. A fair amount of our underwater work involved searching for these khaki-brown, golf-ball-shaped objects, which are known as coral recruits, nestling among tufts of algae.

I had my first ideas about this project in the late 1980s, when I was struck by the devastation wreaked by Hurricane Hugo on Caribbean reefs, particularly those off St. John in the U.S. Virgin Islands. It had taken nearly six years for those reefs to recover. My surveys suggested that many of the coral recruits that had managed to survive by attaching themselves to solid surfaces did so in cracks and on the undersides of ledges and pieces of rubble. I began to wonder whether this kind of settlement, in so-called cryptic locations, provided a springboard for growth onto the open reef. During our first mission in Aquarius in July 1995, my colleagues and I would begin trying to find out.

Although I did not realize it at the time, those 10 days under the ocean would also alter the direction of my research over the next several years. Experiments I began in 1995 during my stay in Aquarius were completed the next summer, when I returned to Key Largo. I was not able to use the habitat in 1996, so I tended to those experiments by diving from the surface. The experience of working on similar experiments from two different diving environments drove home to me the value of saturation diving, which offers vastly more time in the water.

Using the tools and technologies that I began working with in 1995 and 1996, I started a new set of experiments in the summer of 1997. As in 1996, I operated from the surface. As this article is being prepared for publication in the summer of 1998, however, I am planning a second saturation mission in the Aquarius habitat. I will lead a team with seven other researchers, four of whom will be saturating with me in the habitat. We will be following up on the work begun in 1997 on a malady called bleaching, which since the mid-1980s has harmed or killed countless corals all over the world.

Water View

It was at the end of that first dive in July 1995 that we first entered the 13-meter-long pressurized cylindrical chamber that would be our home for the next 10 days. People who have never been inside the Aquarius habitat invariably believe it to be

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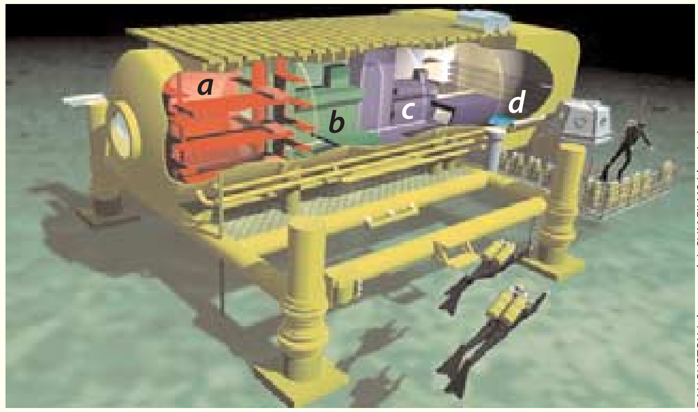

DAN BURTON (*photographs*); SLIM FILMS (*drawing*)

MAIN QUARTERS of Aquarius habitat (*above right, bottom*) include a bunk room (*a*), in which six beds crowd the walls, a kitchen area with a small table under a porthole (*b*), a small laboratory area (*c*) and a "wet porch" (*d*), which serves as a kind of vestibule between the main quarters and the sea. Aquanaut David Carlon spends a quiet moment in the bunk room (*above left*). Edmunds and aquanauts Swanson and Grace relax in the kitchen area after lunch (*above right, top*). Christopher Borne, a member of the support crew, arrives in the wet porch entrance, or "moon pool," to deliver the day's lunch to Kenneth Johns (*right*).

damp and claustrophobic, which it is not. The ocean merges with the habitat through a "moon pool" in a wet porch. This porch is joined by a pressure door to a main living and working space and, beyond it, a bunk room, in which six beds crowd the walls. Other than the wet porch, the habitat is air-conditioned, with decor dominated by stainless steel, blue carpeting and stunning, watery-blue light. Just off the wet porch, in the main section, the laboratory area accommodates a submarine-style toilet and a bench with computers and digital displays for marine sensors. From this room, we could collect data from corals in their natural environment and talk with divers in the water as they positioned sensors on the reef, for example.

The rest of the main room was where we relaxed, ate meals, discussed plans and, whenever possible, allowed ourselves to be distracted by whatever was happening outside the largest porthole in the habitat. Though strangely analogous to visiting an aquarium, our observations sometimes left us unsure whether we were watching or being watched.

The main room was also where we decompressed at the end of our mission. This is the great advantage of saturation diving: once the body is saturated with nitrogen, decompression—the period required to bring the diver gradually back to surface pressure without inflicting decompression sickness—is the same regardless of how much time has been spent underwater. During decompression, the main room was sealed off from the wet porch and, over a period of 16 hours and 30 minutes, the pressure was slowly reduced to one atmosphere. We could then swim up to the terrestrial world without ill effects.

During the 1995 mission, our days began with a three-hour dive, followed by lunch in the habitat and a second dive of similar duration in the afternoon. On most forays we swam about 500 meters along the reef. When the currents were strong, we hauled ourselves hand over hand along the rope highways affixed to the sea bottom. At one end of each line we found spare scuba tanks and an air-filled dome; we could stick our heads into this hemisphere to eat fruit or candy and, of course, talk science with our buddy.

The lengthy periods in the water inevitably made us feel a greater affinity for the resident marine life than for our fellow humans visiting regularly from the surface with food and supplies. These feelings were accentuated at night, when we made short

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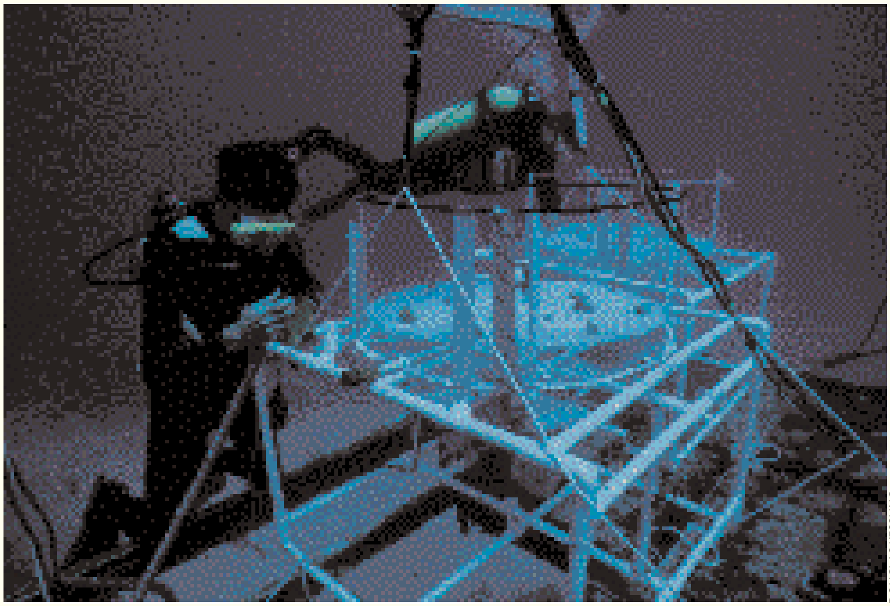
CORAL INCUBATOR was designed and built by the author, who kneels to the left of it. At the top, a plexiglass collar surrounds a rotating table, on which corals can be exposed to different temperatures, water-flow rates and levels of ultraviolet light.



DOUGLAS KESSLING

forays into an inky darkness alive with silvery tarpon and big, inquisitive barracuda.

Although we worked in warm, tropical waters, our long dives left us bone-tired and so ravenous that even a dwindling chocolate supply could trigger quite an argument. Fortunately, however, hefty dinners were delivered daily and cheerfully consumed against the backdrop of a teeming ocean, along with conversation that dwelt on marine creatures and our life underwater.

In the early evenings, as the effects of fatigue and nitrogen narcosis seemed to intensify, extraneous subjects occupied more of our discussions, and we found something to laugh about on almost any topic. On one occasion, the discovery that one of our team had developed an outbreak of "the funk," an unpleasant rash brought on by dampness and abrasion, caused our select scientific team to run around erratically, laughing so hard that for 10 minutes we were unable to answer the worried calls from the surface crew. Although we were warned that such behavior is common in divers whose tissues are saturated with nitrogen, we did not realize how much harder it would make the planning and execution of our research.

During many of our lengthy forays along the reef, we painstakingly quantified coral recruits in both conspicuous and hidden, confined locations as deep as 33 meters. Our working hypothesis—that such cryptic locations provided a springboard for coral growth onto the open reef—seemed unsupported by the data. Instead of finding juveniles crammed disproportionately into cryptic locations, we found that more than half of them were on open, horizontal surfaces, up to a third were on vertical surfaces and only the remainder were hidden in caves and cracks. Most of the areas that we examined contained an average of six juveniles per square meter.

Cryptic locations may still be important; it is possible that the hidden juveniles have higher survival rates than those on open surfaces. To investigate this hypothesis, we permanently marked juveniles to determine their survivorship between 1995 and 1996, when we visited the same sites in dives from the surface. Because many of these sites were at a depth of about 30 meters, our forays were necessarily short. Although we maximized our bottom times by breathing a mixture of 64 percent nitrogen and 36 percent oxygen, we were allowed only about 35 minutes at depth, during which time we frantically brushed away a year's worth of sediment and algae to find the aluminum tags used to mark the corals. Once they had been found, we noted whether the corals were alive or dead and then used plastic calipers to measure the diameter of the living corals to determine their growth rates.

Fond Memories of "the Funk"

Though essentially simple, these tasks became time-consuming and difficult when undertaken under the duress of short bottom times and with fingers swollen and abraded by repeated brushing against various rough surfaces. Between dives, we spent hours on the surface, rolling around in the swells or baking in the sun, waiting until it was time to enter the water again. Feeling alternately nauseated and fried, we began to feel that "the funk" and lack of sun were a small price to pay for the opportunity to live underwater and to have almost limitless bottom time.

As I write these words, I am deep (so to speak) into the preparations for my second mission in the habitat. My team and I will focus on coral bleaching, an increasingly common disease in which corals lose their algae, with which they live in symbiosis and without which they cannot survive. Bleaching is caused by a combination of several factors, including high temperatures and increased levels of ultraviolet radiation. Because these environmental conditions are intensifying and have probably been fostered by human activity, coral bleaching is one of the severest threats now facing the world's reefs.

My colleagues and I will use incubation chambers designed and built in my own garage for the purpose of exposing corals to precisely controllable temperatures, water-flow rates and levels of ultraviolet radiation. We hope to gain new insight into how these factors act together in nature to cause coral bleaching.

The tasks involved are daunting: simultaneously running 14 pumps, six ultraviolet lamps, a water heater, a water chiller and numerous sensors and meters. Even the veteran professional divers of the Aquarius support team have shaken their heads in consternation at the prospect of using so much alternating electric current and having so much electrical wiring in the water. Nevertheless, my confidence that the incubators will work is based on trials we ran in the summer of 1997. We deployed the equipment from a boat moored over Conch Reef and tested it with power supplied from the surface.

After a long week of broiling-hot weather, I dived down to the unit and verified that it was actually receiving hot water and controlling water flow and ultraviolet light. The incubator was resting on one of the supports for the Aquarius habitat at a depth of 15 meters, with a curious barracuda hovering a few meters away. Sitting there under its tangle of umbilical wires and hoses, the incubator might have seemed an ungainly contraption to some. But it sure was beautiful to me.

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Enriching the Sea to Death

by Scott W. Nixon

An excess of nutrients flowing from the land into the sea has created serious environmental problems in many coastal waters. Only recently have measures been taken to forestall the worst effects

The widespread pollution of Narragansett Bay began with a great celebration on Thanksgiving Day, 1871. For 10 full minutes, the church bells of Providence, R.I., rang out, and a 13-gun salute sounded. The townspeople were giving thanks for the completed construction of their first public water supply. Soon afterward clean water flowed through taps and flush toilets, liberating residents forever from back-breaking trips to the well and freezing visits to the privy. Millions learned the joys of running water between about 1850 and 1920, as towns throughout North America and Europe threw similar parties. But homeowners gave scant thought to how their gleaming new water closets would change the makeup of the oceans.

With the wonder of running water came the unpleasant problem of running waste. No longer was human excrement deposited discreetly in dry ground; the new flush toilets discharged streams of polluted water that often flowed through the streets. Town elders coped with the unhappy turn of events by building expensive networks of sewers, which invariably routed waste to the most convenient body of water nearby. In this way, towns quickly succeeded in diverting the torrent of waste from backyards and city streets to fishing spots, swimming holes and adjacent ocean shores. In many cases, the results were disastrous for the aquatic environment. And as the flow continues, society still struggles with the repercussions for the plants and animals that inhabit coastal waters.

Untamed Growth

Even a century ago the unsightly consequences of dumping raw sewage directly into lakes and bays were quite troubling. Dead fish and malodorous sludges fouled favorite beaches as sewage rode back toward land on the waves. Unwilling to return to the days of chamber pots and privies, people were soon forced to clean up their waste somewhat before discharging it.

The wastewater-treatment technologies put into place between about 1880 and 1940 removed visible debris and pathogenic organisms from sewer effluent, effectively eliminating the distasteful reminders that had once washed up on the shore. By the 1960s many treatment plants had begun to remove organic matter as well. But the various methods failed to extract the elements nitrogen and phosphorus, nutrients indispensable to human life and abundant in human waste. These invisible pollutants were flushed into rivers, lakes and oceans in prodigious quantities, and no telltale sign heralded the harm they could inflict.

As every farmer and gardener knows, nitrogen and phosphorus are the essential ingredients of plant fertilizers. Plants that live underwater often respond to these nutrients just as beets and roses do: they grow faster. Of course, aquatic plants are different from the trees and shrubs familiar to landlubbers—most are microscopic, single-celled organisms called phytoplankton that drift suspended in the currents.

Where nutrients are scarce, phytoplankton are sparse and the water is usually crystal-clear. But in response to fertilization, phytoplankton multiply explosively, coloring

BLOOM OF PHYTOPLANKTON colors a stretch of Japanese coastline a vivid hue. Dissolved nutrients shed from land cause the growth of such blooms, which can deprive life at lower depths of light and oxygen.

SUSAN AVIATION

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the water shades of green, brown and red with their photosynthetic pigments. These blooms increase the supply of organic matter to aquatic ecosystems, a process known as eutrophication.

Pollution-driven eutrophication was not recognized as a serious threat to many larger lakes in Europe and North America until the 1950s and 1960s—Lakes Erie and Washington in the U.S. are well-known examples. Why was the accelerating growth of phytoplankton a concern? After all, people welcomed the "green revolution" that fertilizers helped to bring to agriculture around that time. The difference underwater results from the precarious balance between oxygen supply and demand in aquatic ecosystems.

Terrestrial ecologists do not usually worry about oxygen, because the air is full of it: each cubic meter contains some 270 grams. And the atmosphere is constantly in motion, replenishing oxygen wherever it is used. But water circulates less readily than air and holds only five to 10 grams of oxygen per cubic meter at best—that is, when freely exchanging its dissolved gases with the atmosphere. Although fish and a number of other aquatic animals have adapted to live under these conditions, a small decrease in the oxygen content of their surroundings can often be deadly to them.

Phytoplankton floating near the surface of nutrient-rich lakes fare better in the oxygen equation. They receive ample sunlight to carry out photosynthesis during the day and have access to plenty of oxygen to support their metabolism at night. But even under the best circumstances, phytoplankton are short-lived: the tiny organisms continually die off and sink, leaving new generations growing in their place. The more abundant the bloom, the heavier the fallout to the lower depths. And therein lies the problem: the bottom-living bacteria that digest this dead plant matter consume oxygen.

COURTESY OF FUNEN COUNTY COUNCIL DEPARTMENT OF TECHNOLOGY AND ENVIRONMENT

USDA FOREST SERVICE

FOREST BUFFERS prevent plant nutrients in the runoff from these agricultural lands from going directly into Chesapeake Bay.

Getting the Nutrients Out

by Mia Schmiedeskamp

North Americans pour nutrients into bays and estuaries at alarming rates. Is there any way to kick this century-old habit? Recent efforts in some of the hardest-hit areas—the coastlines of Florida, North Carolina and Chesapeake Bay—show that the answer is yes.

The first line of attack is effective sewage treatment. Nitrogen can be removed from wastewater through denitrification, a process carried out by bacteria native to sewage. When wastewater managers cater to these microbes' preference for lots of food and little oxygen, the "bugs" consume troublesome nitrates and belch out harmless nitrogen gas.

Denitrification can be cost-effective as well as good for the environment. "We already see many facilities in our watershed implementing [it] even where they aren't required to," says Allison P. Wiedeman of the Environmental Protection Agency's Chesapeake Bay Program. Although capital expenditures can run from about $1 million to retrofit a modern plant to some $20 million for a complete redesign of an older one, savings in operation and maintenance offset costs over the long term.

The additional microbial treatment step cuts down on the time energy-guzzling fans must be run to aerate the sewage, for

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instance. Denitrification also modulates the acidity of wastewater, making some chemical additives unnecessary, and reduces the amount of sludge that must be disposed of. Currently 43 treatment plants in the Chesapeake Bay watershed have been converted to denitrification, and plans are under way to outfit 58 more in the next five years. "In the early part of the next millennium, [denitrification] is going to be standard," Wiedeman predicts.

Yet reducing nitrogen in sewage alone will not do the entire trick. In the Chesapeake Bay watershed, for instance, the goal is to reduce nutrient load by 40 percent—but only 25 percent of the nitrogen comes from sewage. Much of the rest is runoff from farmlands. Efforts to stem this flow take two forms, explains Russell L. Mader of the Chesapeake Bay Program's nutrient subcommittee: reducing the total amount of fertilizer applied to fields and keeping it where it belongs.

Land management is the key to the latter goal. "We work to minimize high-velocity flows of water that strip away soil and nutrients," Mader says. This end can be achieved by proper grading of farmland and by tillage that minimizes soil disturbance, leaving a mat of plant debris to protect the surface. And forests or artificial wetlands can serve as a buffer between field and stream, providing a place for sediments to settle from runoff and for plants to take up dissolved nutrients.

Fertilizer-reduction strategies, on the other hand, are geared at giving crops as much nutrient as they need but no more. Methods range from simple soil tests to computerized tractors that use satellite-based navigation equipment to direct the application of fertilizer. Mader estimates that in the Chesapeake Bay watershed alone, about 600,000 hectares (1.5 million acres) are already under various forms of nutrient management.

But some of the toughest problems are just now being recognized. Regions with high concentrations of livestock farming—where fields are fertilized by manure—are becoming overloaded with phosphorus even when their nitrogen needs are perfectly met. Reducing the phosphorus burden on the soil will leave farmers with a lot of excess manure; one of the emerging questions of nutrient management is what to do with the stuff.

Tampa, Fla., was one of the first cities to tackle the nutrient problem, with dramatic effect. In the late 1970s the city embarked on an ambitious program to restore normal life to its polluted bay, instituting a regimen of nitrogen removal from sewage and of wastewater recycling by local fertilizer manufacturers.

J. O. Roger Johansson of the city's Bay Study Group has monitored the progress since 1978. "We reduced the amount of nitrogen going into the bay by about half," he notes. "It took about two years to expend the nutrients already in the bay's sediments, and then the phytoplankton population dropped by half." Lower phytoplankton counts have been followed by fewer days without oxygen in the depths and by the return of sea grasses to the shallow waters. This bay, which was nearly ruined by human imposition, has been rescued by human intervention—good news for the Chesapeake and the many other waters still in harm's way.

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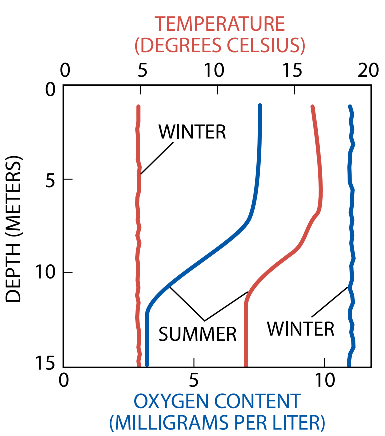
When organic material is abundant in a lake and where surface and bottom waters seldom mix—for example, where winds are calm—oxygen rapidly becomes scarce below the surface. Animals that cannot escape to better-aerated zones will suffocate, and dead creatures may begin to litter the shoreline as bacteria take over the otherwise barren bottom waters. During the 1970s, such awful conditions used to regularly overcome oxygen-starved Lake Erie, which was said to be "dying."

SEA GRASS is smothered by the macroalgae growing in shallow Danish waters enriched with nutrient runoff from farms and sewers (*left*). In winter, the water is well mixed, and oxygen levels are uniform throughout (*below*). In summer, warm, sluggish surface water floats on top of cooler, saltier bottom water, which rapidly becomes depleted of oxygen as phytoplankton decay.



LAURIE GRACE; SOURCE: FUNEN COUNTY COUNCIL

Dead Zones

Until about 40 years ago, the oceans were thought to be immune to the combined forces of nutrient enrichment and oxygen depletion, which were then commonly observed at work in lakes. After all, the seas are vast and restless—the waste discharged from land seemed just a drop in a giant, sloshing bucket.

Scientists now know this assumption was wrong. The fertilization of coastal waters constitutes a major environmental threat to the Baltic Sea, the Gulf of Mexico, Chesapeake Bay, the Lagoon of Venice, the North Sea and a great many other estuaries, bays and lagoons in the industrial world. Most at risk are sheltered regions that do not experience winds or tides strong enough to keep the sea thoroughly mixed the whole year around. For just like nutrient-rich lakes, polluted bays and estuaries can become starved of oxygen when their bottom waters are cut off from the atmosphere.

Coastal areas are especially vulnerable to oxygen depletion because freshwater draining into the ocean from rivers and streams—often laden with nutrients—tends to float on top of denser saltwater. In summer, the surface layer becomes even more buoyant as it warms in the sun. Unless some energetic mixing ensues, the lighter, oxygen-rich veneer will remain isolated from the denser water below. In areas of weak wind and tide, such stratification can last an entire summer.

When a polluted bay or estuary remains relatively still for weeks, months or whole seasons, the difference between life at the top and life at the bottom becomes stark. The surface waters, rich in nutrients and bathed in sunlight, teem with phytoplankton and other forms of floating plant life. The bottom layers become choked with dead plant matter, which consumes more and more oxygen as it decomposes. Below the surface, entire bays can suffocate. And the problem is not necessarily limited to protected waters near the shore. Where enough nutrients arrive and currents are configured just right, even open waters can fall victim. For instance, oxygen deprivation cuts a lethal swath through some 18,000 square kilometers (7,000 square miles) of the deep waters of the Gulf of Mexico every summer, creating a barren region called the "dead zone."

The effects of eutrophication trickle up

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into human affairs in various ways. Bays and estuaries provide some of the richest fishing grounds, yet oxygen depletion kills fish, and nutrients may cause certain toxic varieties of phytoplankton to bloom, contaminating the shellfish that feed on them. Picturesque shores are sullied by dead fish and rotting plant waste, and the water may reek of rotten eggs as bacteria on the ocean floor spew out hydrogen sulfide.

Fertilization of coastal waters also changes life underwater in more subtle ways. For example, as the balance of nutrients changes, the mix of phytoplankton may shift in response. In particular, diatoms, which need about as much silicon as nitrogen, cannot benefit. Because pollution increases the supply of nitrogen but not the amount of silicon, these important organisms may be crowded out by other species of phytoplankton that are less useful to feeding fish and shellfish.

What is more, sunlight does not penetrate deeply into water clouded by blooms. Thick layers of phytoplankton may shade out the sea grasses and seaweeds that typically grow in coastal waters and shelter vulnerable creatures such as crabs and young fish. As a result, complex aquatic food chains may be broken apart.

Cattle, Corn and Cars

The assault on the waters of the developed world that began with urban sewage systems in the mid-1800s has only escalated since that time. Because nitrogen and phosphorus are essential for human nutrition, the rapidly growing world population consumes—and excretes—ever larger amounts of both elements. This factor alone almost doubled the release of nutrients from human waste between 1950 and 1985. And not only are there more people on the earth but also the typical diet is becoming ever richer in protein. All this protein contains abundant nitrogen, which just increases the burden on the environment when it is metabolized and finally excreted.

As the human population has skyrocketed, so has the number of animals raised for food. The count of livestock—animals that also consume and excrete large amounts of nitrogen and phosphorus—has grown by 18 percent during the past 20 years. To produce the huge quantities of crops needed to feed both humans and livestock, farmers have been applying exponentially increasing amounts of fertilizer to their fields since the 1950s. The main ingredients in these fertilizers are nitrogen and phosphorus. Rain washes these nutrients off the land and into rivers and streams, which then carry them to lakes and oceans.

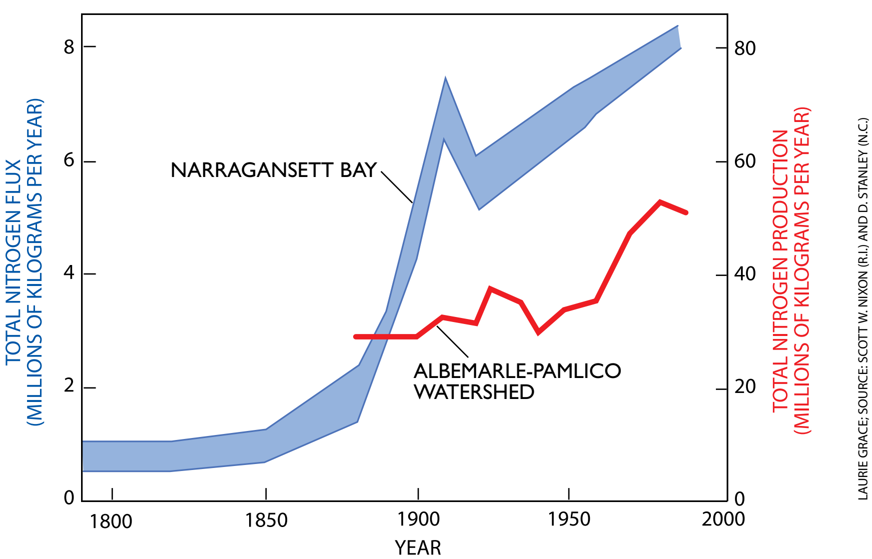
Between 1960 and 1980 the application of nitrogen fertilizer increased more than fivefold, and in the decade that followed, more synthetic fertilizer was spread on land than had been applied throughout the entire previous history of agriculture. Farmers have also been raising increasing quantities of legumes (such as soybeans), which live in partnership with microorganisms that convert nitrogen to nutritive forms. Vast quantities of enriching nitrogen compounds—perhaps equal to half of what is produced as fertilizer—have become available from this source.

That there have been widespread changes in the oceans is not surprising. The dead zone that forms in the Gulf of Mexico every summer probably results from excess fertilizer washed from farms and carried down the Mississippi. Unfortunately, such nutrient injections may be even more dangerous to coastal waters than to lakes. Research early on showed that phosphorus rather than nitrogen induces aquatic plants to bloom in most freshwater environments. This news was in a sense good for lakes, because phosphorus is more easily managed than nitrogen.

Phosphorus is chemically sticky and binds easily to other substances. Thus, it tends to adhere to soil and is less likely than nitrogen to leach out of fertilized fields. And phosphorus can be easily removed from sewage by taking advantage of the same stickiness: during treatment, chemicals are added that bind up the element and then settle out along with other sludge. Largely because of improved phosphorus removal from sewage and a widespread ban on the use of phosphate in products such as laundry detergent, the eutrophication of many lakes and rivers has been stopped or greatly reduced.

There is increasing evidence that the phytoplankton of most temperate estuaries, bays and other coastal ocean waters respond not so much to phosphorus as to nitrogen. Marine scientists still do not fully understand the reasons for this difference, but the implications are quite profound. Nitrogen washes easily from fertilized fields into streams and rivers; many sewage-treatment plants are not yet configured to remove nitrogen from wastewater; and there is an additional, copious supply of nitrogen to the oceans—the atmosphere.

Lightning has always converted a tiny amount of inert nitrogen gas, which makes up 78 percent of air, into soluble compounds that plants can take up in their roots and metabolize. But the combustion of fossil fuels has unleashed a torrent of such nitrogen compounds into the atmosphere. When oil, gas and coal burn at high temperatures in engines and electric-power generators, they produce nitrogen oxides. Rain and wind carry these soluble compounds to the earth, further enriching coastal waters already replete with sewage and agricultural runoff. In all, fos-



NITROGEN LEVELS in Narragansett Bay, R.I., increased dramatically before the turn of the century, after installation of a public water supply and sewer system. Certain other watersheds did not experience a sharp rise in nitrogen levels until fertilizer use took off in the 1950s and 1960s; an example is the Albemarle-Pamlico watershed in North Carolina.

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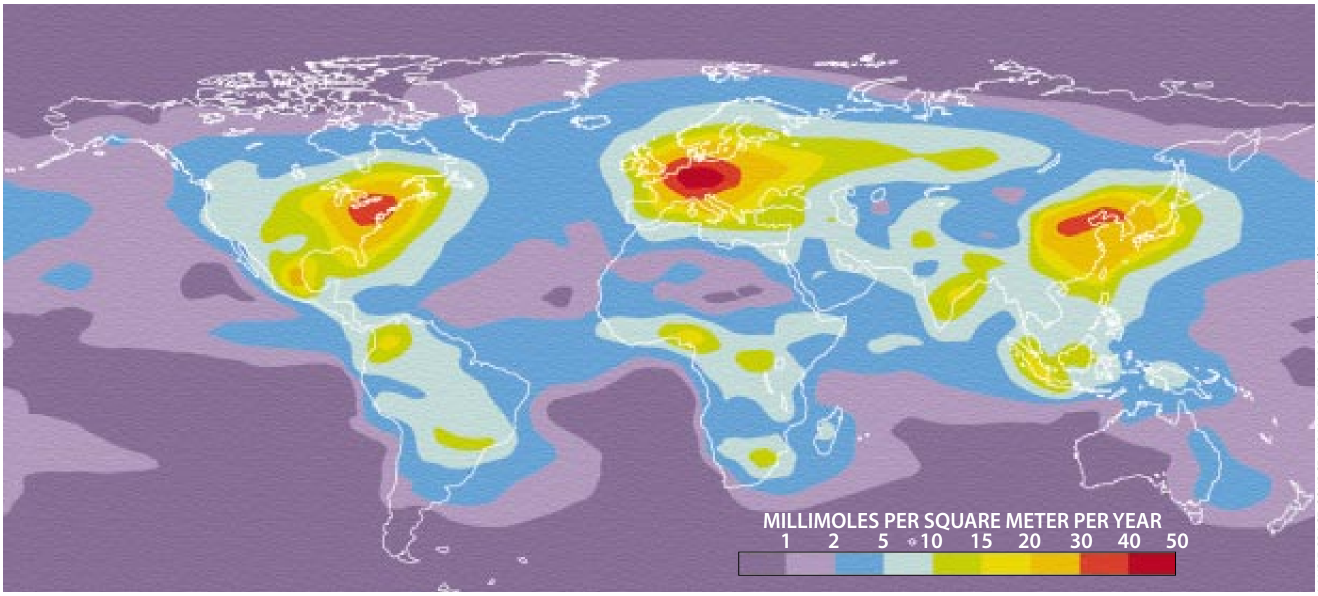

LAURIE GRACE; SOURCE: HIRAM LEVY NOAA Geophysical Fluid Dynamics Laboratory

ATMOSPHERIC DEPOSITION of reactive nitrogen has large geographic variations over the continents and oceans, as shown by computer modeling (*above*). Most of this nutritive nitrogen comes from the combustion of fossil fuels in highly developed areas.

sil-fuel combustion accounts for about 15 percent of the biologically available nitrogen that human activities add to the world every year.

Future Shock

In the 1990s marine eutrophication remains a problem of many wealthy nations. Countries such as the U.S. spend billions on fertilizer, automobiles, power plants and sewer systems, all of which feed nitrogen into the oceans. In fact, the amount of nitrogen available per square kilometer of land from fertilizer application, livestock and human waste alone is currently more than 100 times greater in Europe than in much of Africa.

Fortunately, at least the richer nations may be able to afford high-tech remedies. Sewage-treatment facilities that can eliminate nitrogen from wastewater are springing up, and man-made wetlands and precision application of fertilizers may stem the flow from farms [*see box on page 50*]. But just as people are seeing improvements in some of the worst-polluted coastal waters in the U.S. and Europe, the developing world is poised to repeat what industrial countries experienced over the past 100 years.

Part of the problem will come directly as a result of population growth. With the occupancy of the planet set to reach more than nine billion by 2050, there will be that many more mouths to feed, more fields to fertilize, more livestock to raise and more tons of waste to dispose of. Many experts predict that the release of nutritive nitrogen from fertilizer and fossil-fuel combustion will double in the next 25 years, most of that increase occurring in the developing world.

The United Nations Population Fund estimates that 80 percent of the rise in global population is taking place in the urban areas of Africa, Asia and Latin America. This increase amounts to about 81 million more people every year, a situation akin to spawning 10 cities the size of Moscow or Delhi. Compounding this source of urban growth is the continuing movement of people from the countryside into cities. It was city sewers that first overloaded waterways such as Narragansett Bay with nutrients, and the scenario is not likely to play out differently in the developing world. Sewers there, too, will likely carry raw sewage initially, and where treatment of these sludges does occur, it will probably not remove nitrogen for many years.

With large stretches of coastline exposed to unprecedented levels of nitrogen, it seems inevitable that ocean waters around the world will become greener, browner and redder and that there will be more frequent periods when the bottom of the sea in vulnerable locations becomes lifeless. Much of the next round of pollution will take place in the waters of the tropics, where both the corals and the fish that inhabit these delicate ecosystems are at risk. Yet it remains difficult to gauge exactly how damaging this inadvertent fertilization will ultimately prove. Scientists are still far from understanding all the ways the oceans will pay for keeping human life so widespread and abundant. But as far as the residents of the ocean are concerned, there seems little cause for celebration. SA

The Author

SCOTT W. NIXON is professor of oceanography at the University of Rhode Island and director of the Rhode Island Sea Grant College Program. He studied botany at the University of North Carolina at Chapel Hill and received his Ph.D. there in 1970. For nearly three decades, Nixon has studied the flow of nutrients and the biological productivity of bays and estuaries, including Narragansett Bay, closest to his home.

Further Reading

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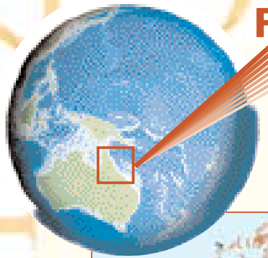
WORLD TOUR

PACIFIC OCEAN: *Why Are Reef Fish So Colorful?*



LAURIE GRACE (*map*); WILLIAM F. HAXBY (*globe*)

Bright patterns on reef fish are key to astoundingly complex strategies to attract mates, repel rivals and hide from predators

by Justin Marshall

Strangely enough, I became curious about the colors of fish not while diving in the crystal-clear waters of Australia's Great Barrier Reef, surrounded by countless incredibly colorful fish. On the contrary: I was in the murky, turbid waters of Heron Island's Coral Cay Lagoon, near the southeastern edge of the reef, close to Shark Bay.

Sitting slightly apprehensively at a depth of only two meters, I was trying to catch fish in a hand net. Suddenly I became dimly aware of hundreds of little black dots shooting past me almost at the limits of my vision in the silty water. Sucking air through my dive regulator and pondering this strange event, I was stunned to realize the black dots were the eyes of an enormous school of kyphosids swimming past on their way to the reef edge. The bodies of these fish, which are also known as drummers, are about 30 centimeters (nearly 12 inches) long and are a silvery-blue color. When vertical in water, they merged perfectly with the dim, blue light pervading the lagoon.

Here was a wonderful example of camouflage underwater. I was humbled by my ineptitude as a predator—I allowed literally tons of fish to pass within a meter or two of me and my net before I even realized what they were. As a marine biologist interested in vision in the sea, however, I immediately thought of several questions. How is the skin of drummers so well adapted to merge with the sea? What is it about the visual capabilities of the fish that prey on drummers that enables them, presumably, to see the drummers while mine was so ineffective?

I noticed that many of the fish and other reef creatures that the school had by now joined were boldly colorful, their bright patterns making them pop out from the background—and also, it would seem, making them an obvious meal. I wondered how the environment of the coral reef could have given rise to the virtually invisible drummer and frogfish as well as the highly conspicuous angelfish and butterfly fish.

Extreme Biodiversity

It is such questions that occupy me on field trips to the University of Queensland's research stations on Heron and Lizard islands. These two islands are at either end of the 2,300-kilometer expanse of the Great Barrier Reef (*map*), which is by far the largest reef system in the world and rightfully one of its seven natural wonders. The huge expanse is a living area of 200,000 square kilometers consisting of some 3,000 small reefs that include more than 400 species of hard and soft corals. For comparison, a typical Caribbean reef might be tens of kilometers long and have perhaps 40 kinds of hard and soft corals.

Like terrestrial rain forests, coral reefs are isolated enclaves that are important for their extreme biodiversity. In this respect, too, the Great Barrier Reef is superlative: it is home to around 1,500 species of fish. This huge variety is all the more surprising in light of the relatively young age of the reef. It began to form 12 to 18 million years

JUSTIN MARSHALL

BARBARA BURGER

JUSTIN MARSHALL

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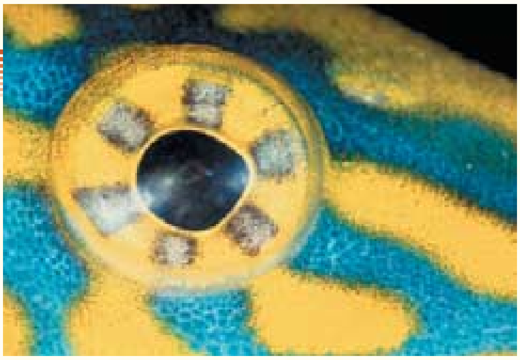


FISH EYE of this beaked leatherjacket sees the light spectrum in a slightly different way than a human eye does.

PHOTOGRAPHS BY JUSTIN MARSHALL

ago and in some places is only two million years old; reefs of the western Atlantic and central Pacific formed 25 million years ago.

The diversity of colored fish and invertebrates on the Great Barrier Reef is truly awe-inspiring. Yet the color patterns exhibited by these inhabitants did not evolve for human eyes. The brilliant blue spots of the semicircle angelfish, or the contrasting yellow and blue fins of the yellowtail coris wrasse [*see illustrations at top of pages 56 and 57*], are a vital component of the survival strategies of these species on the reef.

To understand this role of color and appearance requires some understanding of survival on the reef and also of the optics of the undersea realm. At its most fundamental level, survival for any animal species demands three things: eating, not being eaten and reproducing. Unfortunately for sea creatures, the demands on appearance imposed by the first two of these survival requirements conflict with those of the third.

A good way to avoid being eaten, or, indeed, to lurk undetected while waiting for prey to swim by, is to be camouflaged to match the background (the scientific term is "cryptic"). Masters of camouflage include the frogfish [*see illustration at bottom of page 57*] and the school of kyphosids I saw in the Heron Island lagoon. But to attract a mate, chase rivals away or provide other warnings, bright colors that are easily seen underwater may be the order of the day. In the blue waters of the reef, the colors yellow and blue travel the farthest, so many reef animals have evolved bodily patterns of yellow and blue in striped or spotted combinations. Because yellow and blue are also widely separated in the spectrum, they offer strong contrast underwater.

Just what does a butterfly fish look like to another butterfly fish? How does a drummer appear to a shark? It is this goal to understand color vision and its evolution from the point of view of the animals themselves that my colleagues and I at the University of Queensland's Vision, Touch and Hearing Research Center are striving toward at present. Our research has revolved around three critical questions: One, what are the animals' visual capabilities? To explore this matter, we are carrying out experiments in which we are quantifying colors nonsubjectively, using the world's first underwater spot-reflectance spectroradiometer. Two, what are the light and surroundings like in the habitat where these creatures live? Experienced divers know that seawater is so blue that all red light is absorbed within 20 meters of the surface; a bright-red fish at this depth therefore appears black. And three, under what circumstances, and to what other creatures, do fish show off their color patterns? Clearly, displaying bright colors to impress a potential mate would be unwise when visually guided predators are lurking nearby.

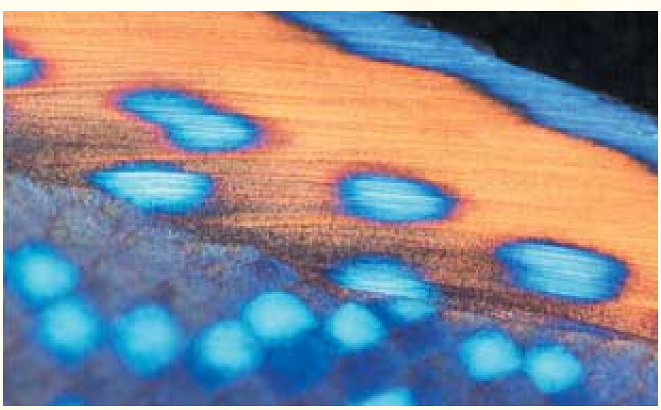
Compared with some species of fish and other creatures, humans are relatively colorblind. People have three color receptors in their eyes: the blue-, green- and red-sensitive cones. Some reef fish (and indeed amphibians, reptiles, birds and insects) possess four or more. The record is currently held by the mantis shrimp (a stomatopod), a reef dweller whose eyes have 12 color receptors. With these additional receptors, the animals can see the region of the near ultraviolet, with wavelengths between about 350 and 400 nanometers (humans cannot see wavelengths shorter than about 380 nanometers). Also, they can see in greater detail some of the colors humans see.

Such impressive visual capabilities might seem to be unnecessary on the reef, where so many creatures have evolved bold patterns that emit strong visual signals. Alternatively, it may seem incredible that these brightly colored fish manage to survive with markings so striking that they would seem to attract the attention of even weak-eyed predators.

Could it be that coral reefs are colorful, and therefore that colorful animals fit in and may even be camouflaged? Logical though it may seem, the notion does not hold up to scrutiny. A reef stripped of its fish and other mobile life-forms is actually relatively monochromatic. Most of the corals are brown or green, their colorful splendor coming out only at night when the polyps open or under the falsely bright illumination of the camera strobe or video light.

Another possible explanation revolves around disruptive coloration, a principle first described in detail in the 1940s and subsequently used for military camouflage. The central idea is the use of large, bold patterns of contrasting colors that make an object blend in when viewed against an equally variable, contrasting background.

STRIKINGLY PATTERNED REEF FISH include (*from far left*) the threadfin butterfly fish, which has a "false eye" above the caudal fin to confuse predators; the humphead Maori wrasse; and the Moorish idol, whose vertical stripes make it difficult to discern head from tail. Bright patterns also appear on the dorsal fin of the yellowtail coris wrasse (*below left*) and on the anal fin of the regal angelfish (*below*).



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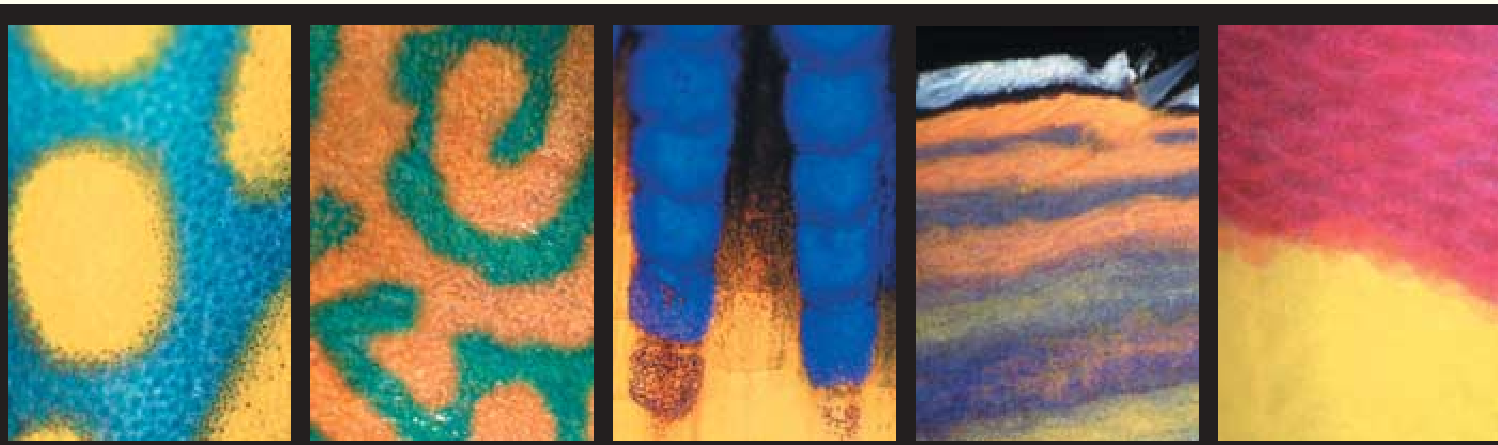


FISH COLORS include vivid patterns, as seen above (*from left to right*): the midbody of a beaked leatherjacket; nose of a surf parrot fish; tail of a yellowtail coris wrasse; dorsal fin of a regal angelfish; midbody of a royal dottyback; fin of a regal angelfish; cheek of a harlequin tuskfish; dorsal fin of a harlequin tuskfish; tail of a semicircle angelfish; and another fin of a regal angelfish. Blues and yellows, which travel far underwater, are common.

The light and dark branches, pockets and shafts of light on a reef provide just such a background.

Good examples of disruptive camouflage on land are the striking patterns of some snakes or the stripes of a zebra. These colorations, when viewed against the kinds of highly patterned backgrounds common in the animals' natural habitats, aid camouflage or at least make it difficult to see where the animal begins and ends. For example, zebras—like many boldly colored fish—group together for protection. In these groupings, the context against which predators see individual patterns and colors is not, typically, a natural background but rather the school or herd itself, enabling one animal to become lost in the swirling mass of its neighbors.

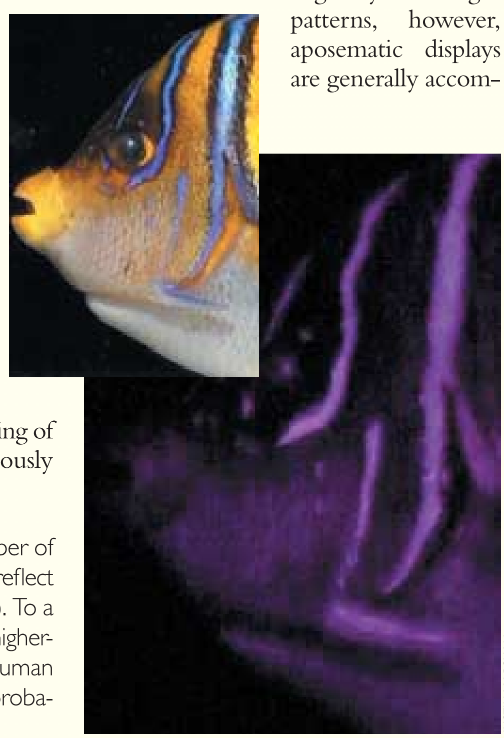
Complicating matters is the fact that most reef fish are capable of changing colors to some degree. Some, notably the triggerfish and goatfish, can do so at nearly the speed and complexity of chameleons. In other fish, color changes may take several seconds, may be associated with night and day, or may occur during maturation. Parrot fish change color in association with a sex change, a drab female in a harem changing into a gaudy dominant male if the resident male is lost. Changes are also known to occur with "mood"—for example, during conflicts or flight from a predator. Although one can guess at the causes behind these and other color changes, at present almost no convincing hypotheses explain their function.

Parts of fish may be disguised by a pattern, such as the dark stripes that run near the eyes of the Moorish idol [*see illustration on page 54*]. Similarly, colorations may make it difficult for a predator to determine which end is the head and which is the tail. Many species of butterfly fish, for example, have a black dot on either side of the body near the caudal fin; these dots are easily mistaken for eyes [*see illustration on page 54*]. In patterns on other fish species, blocks of blue match the blue of the ocean.

The effectiveness of highly contrasting body stripes, spots and blotches as a means of reef camouflage can be fully appreciated only under natural illumination. Yet few people get to see fish this way: often reef creatures are viewed in photographs, their colors set ablaze by the flash of a strobe and against a background that is nothing more than a featureless, dark field. Lit up in this manner, the fish are being seen as they are when they are "displaying." Fish sometimes position themselves in shafts of sunlight to reveal the full splendor of their colors to a rival or potential mate. At other times, even the multicolored harlequin tuskfish or iridescent blue angelfish disappear under the dim, highly textured illumination of the coral ledges where they spend much of their time.

Also, just as birds will puff out and spread their feathers in dramatic displays, some reef fish will erect highly colored fins or reveal bright patterns on frontal head areas or even inside the mouth. The positioning of the fish relative to the viewer is obviously critical here; frontal regions are obscured when the fish is seen from the side, whereas the erect-fin displayers such as the butterfly fish will intentionally turn sideways to present a broadside of color to a rival or mate.

Bright colors can also warn of toxicity. Boxfish, blue-ringed octopuses [*see illustration at right*] and nudibranchs are all known for such aposematic displays, in which, again, yellow and blue are a common theme underwater. In contrast to the furtive behavior of animals that are disruptively camouflaged by their bright patterns, however, aposematic displays are generally accom-



REGAL ANGELFISH is one of a number of reef creatures having body stripes that reflect near-ultraviolet light (*large photograph*). To a fish whose eyes are sensitive to this higher-frequency band, the stripes that to human eyes seem a pale bluish-white (*inset*) probably have some particular significance.

JUSTIN MARSHALL

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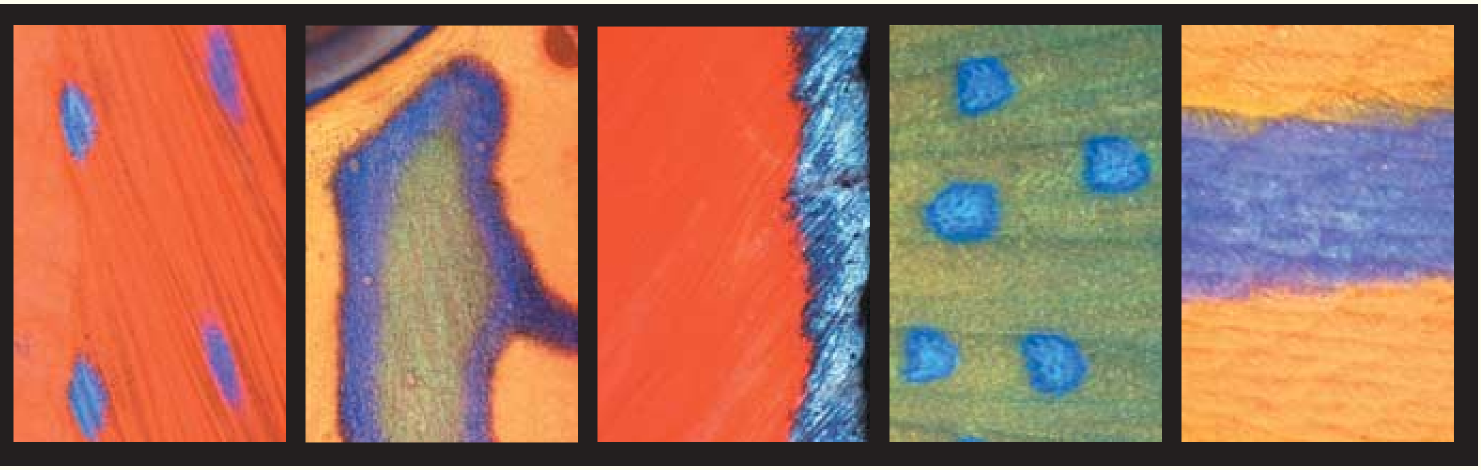

BLUE-RINGED OCTOPUS'S brilliant coloration warns of toxicity. The bite of the Australian reef creature contains a poison that induces muscular weakness and, in the worst cases, respiratory paralysis.

FRED BAVENDAM *Peter Arnold, Inc. (octopus)*; JUSTIN MARSHALL *(gallery of fish colors)*

panied by bold and indiscreet behavior. As an interesting side note, evolution has produced aposematic animals unable to see their own beautiful colors. This is the case for nudibranchs and for the blue-ringed octopus. Both these invertebrates lack the retinal features necessary to see colors, indicating that their bright patterns evolved solely in response to their predators' much more capable visual systems.

Whether for display or camouflage, the visual signals emanating from reef fish all depend strongly on contrast, and this aspect appears to have evolved with unexpected elegance. As noted earlier, yellow and blue are an effective combination, with peaks in different parts of the spectrum. The two colors are said to be complementary—exhibiting a high degree of contrast—because of this spacing of their spectral peaks.

The spectral characteristics of the colors of several other reef fish are even more complex, with three rather than two peaks. Where this is the case—in the facial displays of wrasses and parrot fish, for example—adjacent colors are also complementary, with each color having a spectral peak that fits neatly into the trough of the adjacent color. Three years ago we began to suspect that some of these exquisitely tuned combinations, not obviously contrasting to us because of the relatively limited color perception of humans, provide particularly strong visual signals to certain fish species.

As noted, color vision in some reef fish and other animals may be based on four photoreceptor types rather than three, as in humans. Because the additional sensitivity afforded by the extra photoreceptor is often in the ultraviolet, we became interested in the possibility that the visual signals sent by a select number of reef fish encompass the ultraviolet as well as the colors visible to humans.

Using our spot-reflectance spectroradiometer, we found this indeed to be the case. The advantage of this device is that it can "see" colors we cannot, including both the near-ultraviolet and the near-infrared regions of the electromagnetic spectrum (with wavelengths of 300 to 400 nanometers and 700 to 800 nanometers, respectively). As a result, we can begin to understand how color patterns have evolved for animals that see these colors. Our work has involved trying to establish what the various reef fish can see. Our most recent results indicate that in adult life, a relatively small proportion of reef fish see the near ultraviolet. As with aposematic coloration, however, it is becoming clear that animal colors are not necessarily correlated with their own visual systems.

Although the exact function of this possibly "secret waveband" remains a mystery, ultraviolet is in theory a good color for local signaling. The fact that ultraviolet is highly scattered and attenuated by water means, for example, that the visual signals of a sexual display could be sent to a nearby potential mate—and that the signal would degrade to invisibility over the longer distances at which predators might lurk.

There are many related issues about which we know little. For instance, color vision changes substantially during the life spans of reef fish. For example, it appears that the eyes of reef fish larvae do not block ultraviolet, and yet most of the adults of these species cannot see this part of the spectrum. We know that the change is to accommodate the demands of a new mode of life—the emergence from the plankton, where all fish begin life. So far, however, the details of this vision change are known for only two of the 1,500 species on the Great Barrier Reef.

This is just one of the mysteries that leave vast gaps in our knowledge. We still have only fragmentary ideas about what the colors of a reef mean to its inhabitants, making each visit to this world of secret color communication an endeavor as tantalizing as it is beautiful. SA

JUSTIN MARSHALL is a research fellow in the Vision, Touch and Hearing Research Center at the University of Queensland in Brisbane, Australia.

JUSTIN MARSHALL

FROGFISH is shown in "cryptic" mode, matching its background as it waits to pounce on unsuspecting prey.

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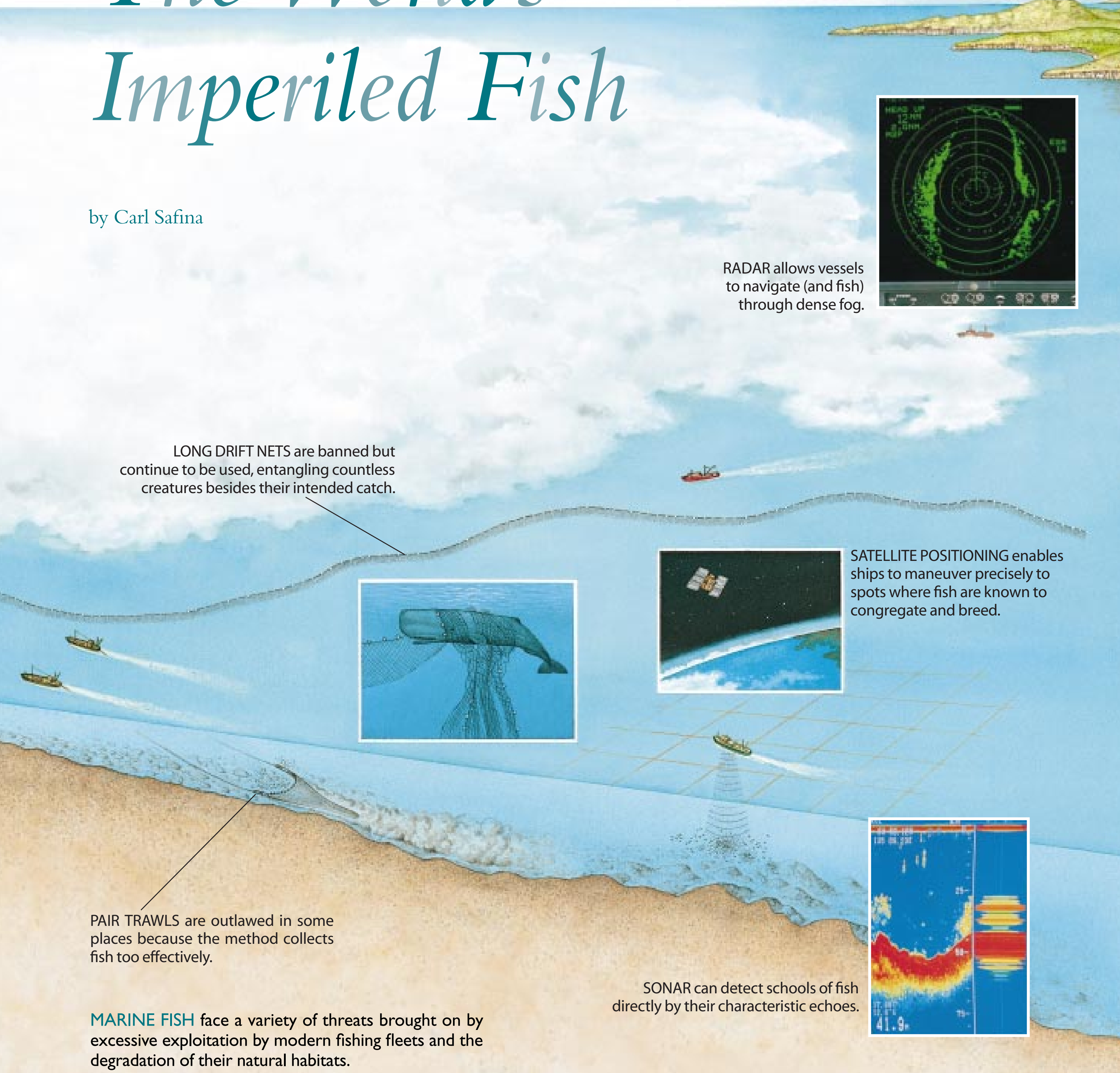
The World's Imperiled Fish

by Carl Safina



RADAR allows vessels to navigate (and fish) through dense fog.

LONG DRIFT NETS are banned but continue to be used, entangling countless creatures besides their intended catch.

SATELLITE POSITIONING enables ships to maneuver precisely to spots where fish are known to congregate and breed.

PAIR TRAWLS are outlawed in some places because the method collects fish too effectively.

SONAR can detect schools of fish directly by their characteristic echoes.

MARINE FISH face a variety of threats brought on by excessive exploitation by modern fishing fleets and the degradation of their natural habitats.

Wild fish often cannot withstand the onslaught of modern industrial fishing. The collapse of fisheries in many regions shows the danger plainly

The 19th-century naturalist Jean-Baptiste de Lamarck is well known for his theory of the inheritance of acquired characteristics, but he is less remembered for his views on marine fisheries. In pon-

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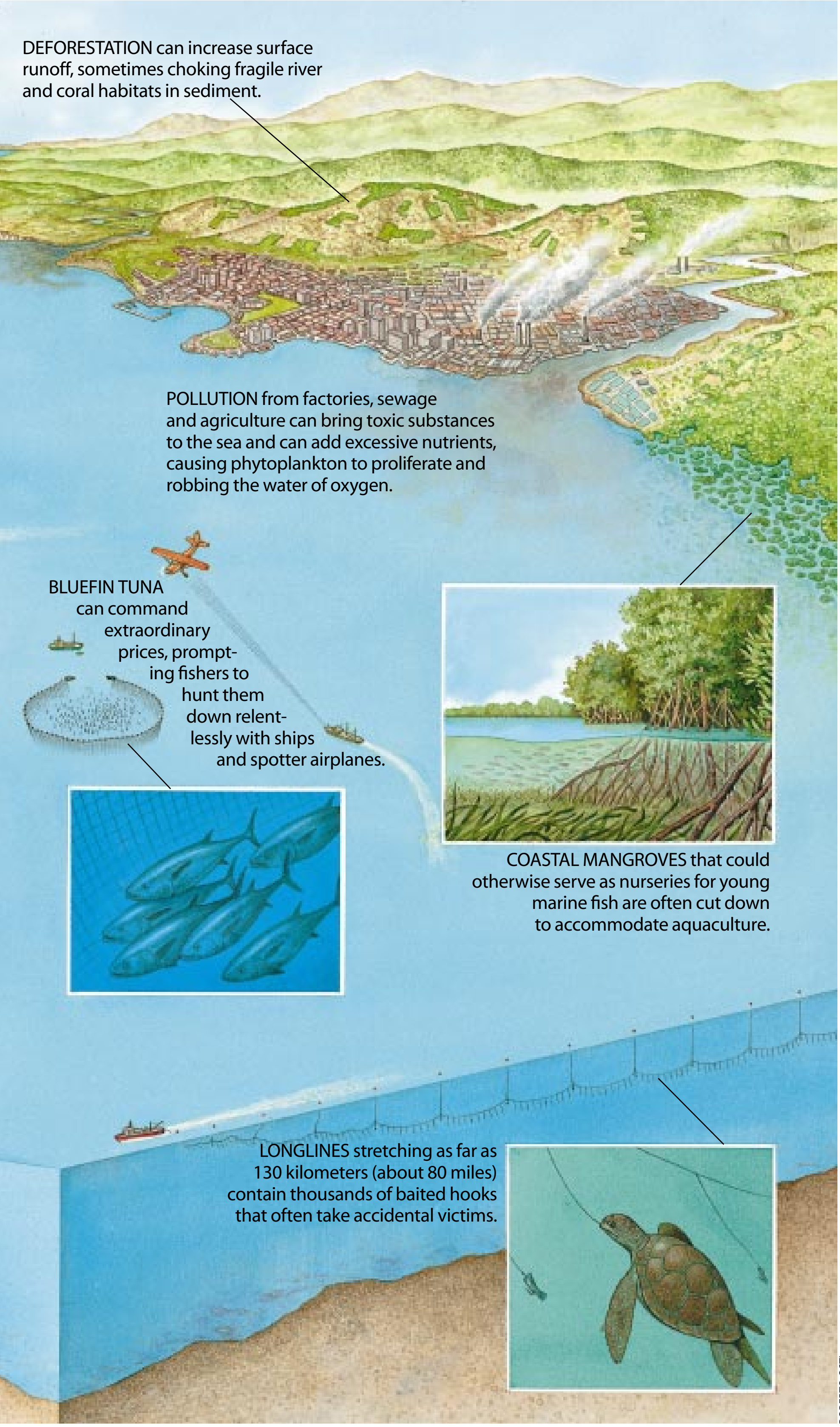

ROBERTO OSTI

dering the subject, he wrote, "Animals living in … the sea waters … are protected from the destruction of their species by man. Their multiplication is so rapid and their means of evading pursuit or traps are so great, that there is no likelihood of his being able to destroy the entire species of any of these animals." Lamarck was also wrong about evolution.

One can forgive Lamarck for his inability to imagine that humans might catch fish faster than these creatures could reproduce. But many people—including those in professions focused entirely on fisheries—have committed the same error of thinking. Their mistakes have reduced numerous fish populations to extremely low levels, destabilized marine ecosystems and impoverished many coastal communities. Ironically, the drive for short-term profits has cost billions of dollars to businesses and taxpayers, and it has threatened the food security of developing countries around the world. The fundamental folly underlying the current decline has been a widespread failure to recognize that fish are wildlife—the only wildlife still hunted on a large scale.

Because wild fish regenerate at rates determined by nature, attempts to increase their supply to the marketplace must eventually run into limits. That threshold seems to have been passed in all parts of the Atlantic, Mediterranean and Pacific: these regions each show dwindling catches. Worldwide, the extraction of wild fish has seemingly stagnated at about 84 million metric tons.

In some areas where the catches peaked as long ago as the early 1970s, landings have since decreased by more than 50 percent. Even more disturbingly, some of the world's greatest fishing grounds, including the Grand Banks and Georges Bank of eastern North America, are now essentially closed following their collapse. The formerly dominant fauna have been reduced to a tiny fraction of their previous abundance and effectively rendered commercially extinct in those areas.

Recognizing that a basic shift has occurred, the members of the United Nations's Food and Agriculture Organization (a body that encouraged the expansion of large-scale industrial fishing during the 1980s) recently concluded that the operation of the world's fisheries cannot be sustained. They now acknowledge that substantial damage has already been done to the marine environment and to the many economies that depend on this crucial natural resource.

Such sobering assessments are echoed in the U.S. by the National Academy of Sciences. It reported in 1995 that human actions have caused drastic reductions in many of the preferred species of edible fish and that changes induced in composition and abundance of marine animals and plants are extensive enough to endanger the functioning of marine ecosystems. Although the scientists involved in that study noted that fishing constitutes just one of many human activities that threaten the oceans, they ranked it as the most serious.

Indeed, the environmental problems facing the seas are in some ways more pressing than those on land. Daniel Pauly of the Fisheries Center at the University of

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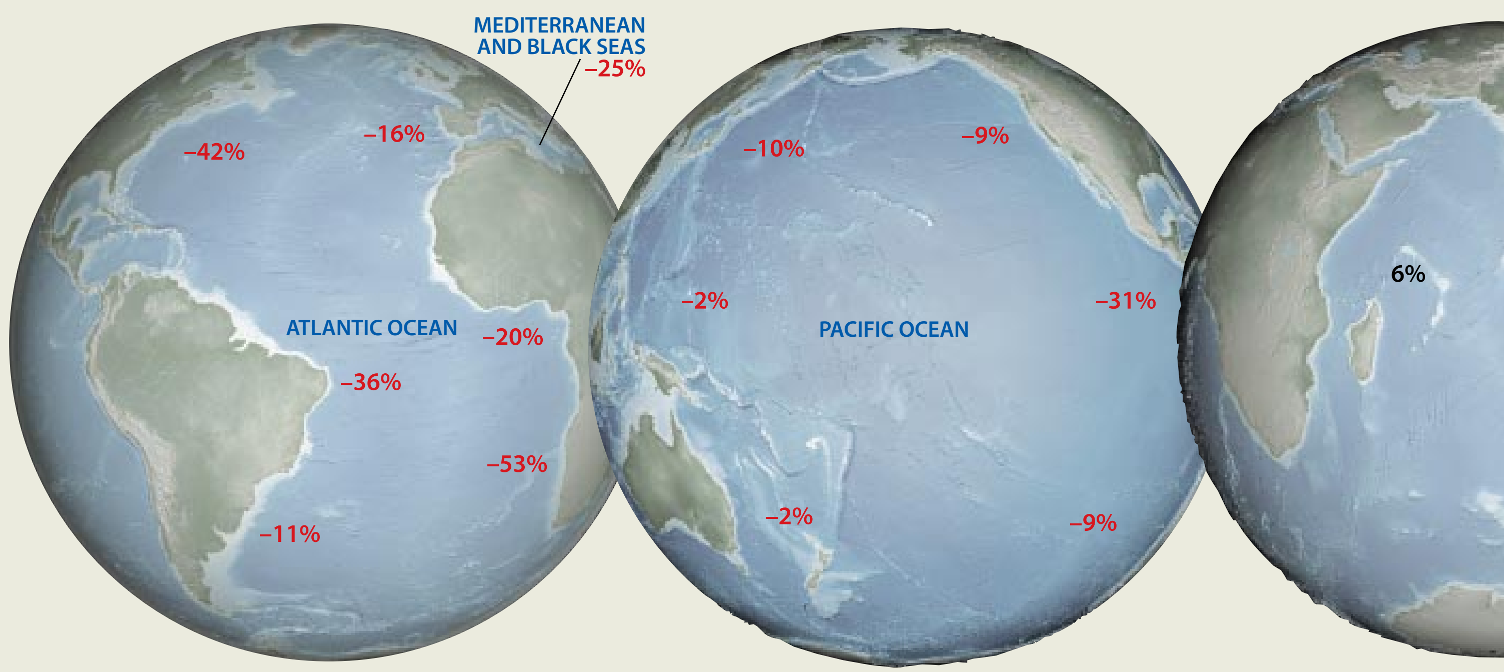
Major Fishing Regions of the World: Changes in Catch



British Columbia and Villy Christensen of the International Center for Living Aquatic Resources Management in Manila have pointed out that the vast majority of shallow continental shelves have been scarred by fishing, whereas large untouched tracts of rain forest still exist. For those who work with living marine resources, the damage is not at all subtle. Vaughn C. Anthony, a scientist formerly with the National Marine Fisheries Service, has said simply: "Any dumb fool knows there's no fish around."

A War on Fishes

How did this collapse happen? An explosion of fishing technologies occurred during the 1950s and 1960s. During that time, fishers adapted various military technologies to hunting on the high seas. Radar allowed boats to navigate in total fog, and sonar made it possible to detect schools of fish deep under the oceans' opaque blanket. Electronic navigation aids such as LORAN (Long-Range Navigation) and satellite positioning systems turned the trackless sea into a grid so that vessels could return to within 15 meters of a chosen location, such as sites where fish gathered and bred. Ships can now receive satellite weather maps of water-temperature fronts, indicating where fish will be traveling. Some vessels work in concert with aircraft used to spot fish.

Many industrial fishing vessels are floating factories deploying gear of enormous proportions: 129 kilometers of submerged longlines with thousands of baited hooks, bag-shaped trawl nets large enough to engulf 12 jumbo jetliners and 64-kilometer-long drift nets (still in use by some countries). Pressure from industrial fishing is so intense that 80 to 90 percent of the fish in some populations are removed every year.

For the past two decades, the fishing industry has had increasingly to face the result of extracting fish faster than these populations could reproduce. Fishers have countered loss of preferred fish by switching to species of lesser value, usually those positioned lower in the food web—a practice that robs larger fish, marine mammals and seabirds of food. During the 1980s, five of the less desirable species made up nearly 30 percent of the world fish catch but accounted for only 6 percent of its monetary value. Now there are virtually no untapped marine fish that can be exploited economically.

With the decline of so many species, some people have turned to raising fish to make up for the shortfall. Aquaculture has doubled its output in the past decade, increasing by about 10 million metric tons since 1985. The practice now provides more freshwater fish than wild fisheries do. Saltwater salmon farming also rivals the wild catch, and about half the shrimp now sold are raised in ponds. Overall, aquaculture supplies one third of the fish eaten by people.

Unfortunately, the development of aquaculture has not reduced the pressure on wild populations. Strangely, it may do the opposite [see "The Promise and Perils of Aquaculture," on page 64]. Shrimp farming has created a demand for otherwise worthless catch that can be used as feed. In some countries, shrimp farmers are now investing in trawl nets with fine mesh to catch everything they can for shrimp food, a practice known as biomass fishing. Many of the catch are juveniles of valuable species, and so these fish never have the opportunity to reproduce.

Fish farms can hurt wild populations because the construction of pens along the coast often requires cutting down mangroves; the submerged roots of these salt-tolerant trees provide a natural nursery for shrimp and fish. Peter Weber of the Worldwatch Institute reports that aquaculture is one of the major reasons that half the world's mangroves have been destroyed. Aquaculture also threatens marine fish because some of its most valuable products, such as groupers, milkfish and eels, cannot be bred in captivity and are raised from newly hatched fish caught in the wild. The constant loss of young fry then leads these species even further into decline.

Aquaculture also proves a poor replacement for fishing because it requires sub-

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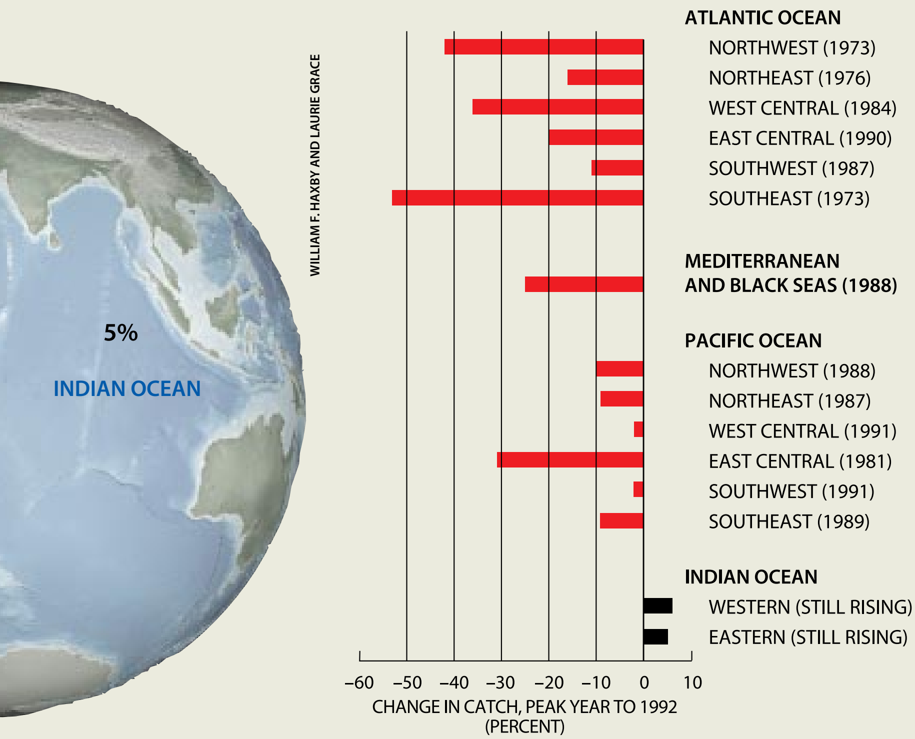

REGIONAL TAKES of fish have fallen in most areas of the globe (*red*), having reached their peak values anywhere from seven to 25 years ago. (The year of the peak catch is shown in parentheses.) Only in the Indian Ocean region, where modern methods of mechanized fishing are just now taking hold, have marine catches been on the increase. (Black indicates average annual growth between 1988 and 1992.)

LAURIE GRACE; SOURCE: Food and Agriculture Organization

stantial investment, land ownership and large amounts of clean water. Most of the people living on the crowded coasts of the world lack all these resources. Aquaculture as carried out in many undeveloped nations often produces only shrimp and expensive types of fish for export to richer countries, leaving most of the locals to struggle for their own needs with the oceans' declining resources.

Madhouse Economics

If the situation is so dire, why are fish so available and, in most developed nations, affordable? Seafood prices have, in fact, risen faster than those for chicken, pork or beef, and the lower cost of these foods tends to constrain the price of fish—people would turn to other meats if the expense of seafood far surpassed them.

Further price increases will also be slowed by imports, by overfishing to keep supplies high (until they crash) and by aquaculture. For instance, the construction of shrimp farms that followed the decline of many wild populations has kept prices in check.

So to some extent, the economic law of supply and demand controls the cost of fish. But no law says fisheries need to be profitable. To catch $70 billion worth of fish, the fishing industry recently incurred costs totaling $124 billion annually. Subsidies fill much of the $54 billion in deficits. These artificial supports include fuel-tax exemptions, price controls, low-interest loans and outright grants for gear or infrastructure. Such massive subsidies arise from the efforts of many governments to preserve employment despite the self-destruction of so many fisheries.

These incentives have for many years enticed investors to finance more fishing ships than the seas' resources could possibly support. Between 1970 and 1990, the world's industrial fishing fleet grew at twice the rate of the global catch, fully doubling in the total tonnage of vessels and in number. This armada finally achieved twice the capacity needed to extract what the oceans could sustainably produce. Economists and managers refer to this situation as overcapitalization. Curiously, fishers would have been able to catch as much with no new vessels at all. One U.S. study found that the annual profits of the yellowtail flounder fishery could increase from zero to $6 million by removing more than 100 boats.

Because this excessive capacity rapidly depletes the amount of fish available, profitability often plummets, reducing the value of ships on the market. Unable to sell their chief asset without major financial loss, owners of these vessels are forced to keep fishing to repay their loans and are caught in an economic trap. They often exercise substantial political pressure so that government regulators will not reduce allowable takes. This common pattern has become widely recognized. Even the U.N. now acknowledges that by enticing too many participants, high levels of subsidy ultimately generate severe economic and environmental hardship.

A World Growing Hungrier

While the catch of wild marine fish declines, the number of people in the world increases every year by about 100 million, an amount equal to the current population of Mexico. Maintaining the present rate of consumption in the face of such growth will require that by 2010 approximately 19 million additional metric tons of seafood become available every year. To achieve this level, aquaculture would have to double in the next 15 years, and wild fish populations would have to be restored to allow higher sustainable catches.

Technical innovations may also help produce human food from species currently used to feed livestock. But even if all the fish that now go to these animals—a third of the world catch—were eaten by people, today's average consumption could hold for only about 20 years. Beyond that time, even improved conservation of wild fish would not be able to keep pace with human population growth. The next century will therefore witness the heretofore unthinkable exhaustion of the oceans' natural ability to satisfy humanity's demand for food from the seas.

To manage this limited resource in the best way possible will clearly require a solid understanding of marine biology and ecology. But substantial difficulties will undoubtedly arise in fashioning scientific information into intelligent policies and in translating these regulations into practice. Managers of fisheries as well as policymakers have for the most part ignored the numerous national and international stock assessments done in past years.

Where regulators have set limits, some fishers have not adhered to them. From

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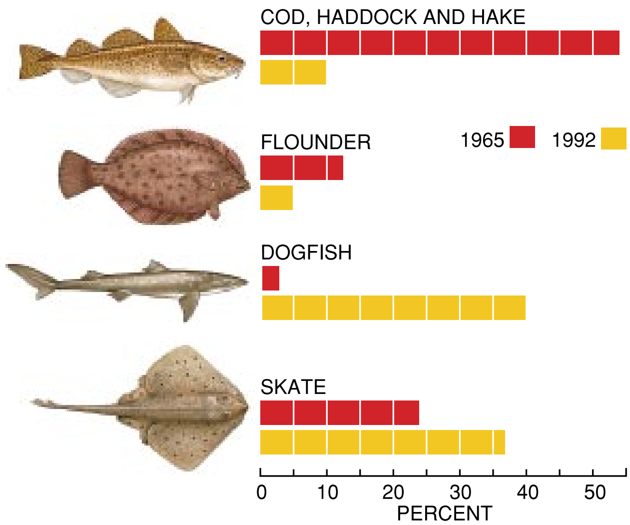

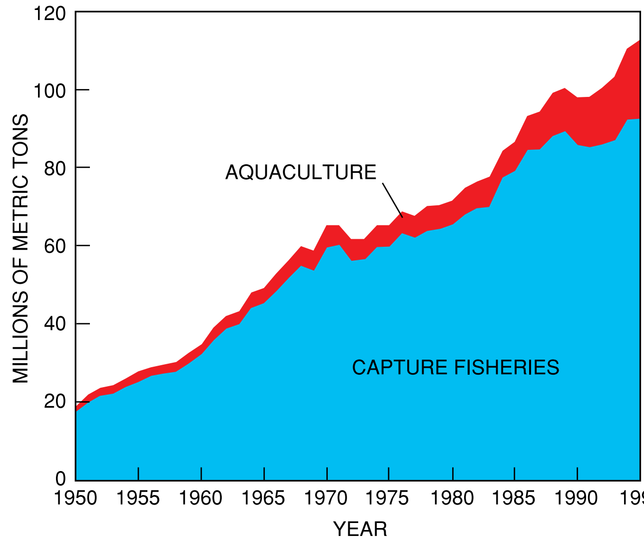

LAURIE GRACE (*graphs*); ROBERTO OSTI (*drawings*); SOURCE: NATIONAL MARINE FISHERIES SERVICE (*left*); SOURCE: FOOD AND AGRICULTURE ORGANIZATION (*right*)

RELATIVE ABUNDANCE of common fishes in the Gulf of Maine has changed drastically because of overfishing. The horizontal bars indicate the fraction of the catch made up of each of these species in 1965 as compared with 1992.

FISH SUPPLIES derived from aquaculture continue to rise steadily, but the total amount available from capture fisheries (which provide the greatest share of the global yield) has entered a period of minimal growth over the past decade.

1986 to 1992, distant water fleets fishing on the international part of the Grand Banks off the coast of Canada removed 16 times the quotas for cod, flounder and redfish set by the Northwest Atlantic Fisheries Organization. When Canadian officials seized a Spanish fishing boat near the Grand Banks in 1995, they found two sets of logbooks—one recording true operations and one faked for the authorities. They also discovered nets with illegally small mesh and 350 metric tons of juvenile Greenland halibut. None of the fish on board were mature enough to have reproduced. Such selfish disregard for regulations helped to destroy the Grand Banks fishery.

Although the U.N. reports that about 70 percent of the world's edible fish, crustaceans and mollusks are in urgent need of managed conservation, no country can be viewed as generally successful in fisheries management. International cooperation has been even harder to come by. If a country objects to the restrictions of a particular agreement, it just ignores them.

In 1991, for instance, several countries arranged to reduce their catches of swordfish from the Atlantic; Spain and the U.S. complied with the limitations (set at 15 percent less than 1988 levels), but Japan's catch rose 70 percent, Portugal's landings increased by 120 percent and Canada's take nearly tripled. Norway has decided unilaterally to resume hunting minke whales despite an international moratorium. Japan's hunting of minke whales, ostensibly for scientific purposes, supplies meat that is sold for food and maintains a market that supports illegal whaling around the globe.

KAKU KURITA *Gamma Liaison*

WHALE MEAT sold in Japan includes many species from all over the world, although the legal catch (taken nominally for scientific purposes) is limited to minke whales.

Innocent Bystanders

In virtually every kind of fishery, people inadvertently capture forms of marine life that collectively are known as bycatch or bykill. In the world's commercial fisheries, one of every four animals taken from the sea is unwanted. Fishers simply discard the remains of these numerous creatures overboard.

Bycatch involves a variety of marine life, such as species without commercial value and young fish too small to sell. In 1990 high-seas drift nets tangled 42 million animals that were not targeted, including diving seabirds and marine mammals. Such massive losses prompted the U.N.

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to enact a global ban on large-scale drift nets (those longer than 2.5 kilometers)—although Italy, France and Ireland, among other countries, continue to deploy them.

In some coastal areas, fishing nets set near the sea bottom routinely ensnare small dolphins. Losses to fisheries of several marine mammals—the baiji of eastern Asia, the Mexican vaquita (the smallest type of dolphin known), Hector's dolphins in the New Zealand region and the Mediterranean monk seal—put those species' survival at risk.

Seabirds are also killed when they try to eat the bait attached to fishing lines as these are played out from ships. Rosemary Gales, a research scientist at the Parks and Wildlife Service in Hobart, Tasmania, estimates that in the Southern Hemisphere more than 40,000 albatross are hooked and drowned every year after grabbing at squid used as bait on longlines being set for bluefin tuna. This level of mortality endangers six of the 14 species of these majestic wandering seabirds.

In some fisheries, bykill exceeds target catch. In 1992 in the Bering Sea, fishers discarded 16 million red king crabs, keeping only about three million. Trawling for shrimp produces more bykill than any other type of fishing and accounts for more than a third of the global total. Discarded creatures outnumber shrimp taken by anywhere from 125 to 830 percent. In the Gulf of Mexico shrimp fishery, 12 million juvenile snappers and 2,800 metric tons of sharks are discarded annually. Worldwide, fishers dispose of about six million sharks every year—half of those caught. And these statistics probably underestimate the magnitude of the waste: much bycatch goes unreported.

There remain, however, some glimmers of hope. The bykill of sea turtles in shrimp trawls had been a constant plague on these creatures in U.S. waters (the National Research Council estimated that up to 55,000 adult turtles die this way every year). But these deaths are being reduced by recently mandated "excluder devices" that shunt the animals out a trap door in the nets.

Perhaps the best-publicized example of bycatch involved up to 400,000 dolphins killed annually by fishers netting Pacific yellowfin tuna. Over three decades since the tuna industry began using huge nets, the eastern spinner dolphin population fell 80 percent, and the numbers of offshore spotted dolphin plummeted by more than 50 percent. These declines led to the use of so-called dolphin-safe methods (begun in 1990) whereby fishers shifted from netting around dolphin schools to netting around logs and other floating objects.

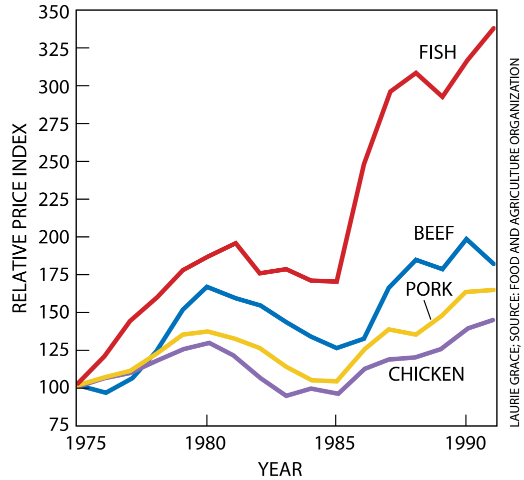
This approach has been highly successful: dolphin kills went down to 4,000 in 1993. Unfortunately, dolphin-safe netting methods are not safe for immature tuna, billfish, turtle or shark. On average, for every 1,000 nets set around dolphin herds, fishers inadvertently capture 500 dolphins, 52 billfish, 10 sea turtles and no sharks. In contrast, typical bycatch from the same number of sets around floating objects includes only two dolphins but also 654 billfish, 102 sea turtles and 13,958 sharks. In addition, many juvenile tuna are caught under floating objects.

One solution to the bycatch from nets would be to fish for tuna with poles and lines, as was practiced commercially in the 1950s. That switch would entail hiring back bigger crews, such as those laid off when the tuna fishery first mechanized its operations.

The recent reductions in the bycatch of dolphins and turtles provide a reminder that although the state of the world's fisheries is precarious, there are also reasons for optimism. Scientific grasp of the problems is still developing, yet sufficient knowledge has been amassed to understand how the difficulties can be rectified. Clearly, one of the most important steps that could be taken to prevent overfishing and excessive bycatch is to remove the subsidies for fisheries that would otherwise be financially incapable of existing off the oceans' wildlife—but are now quite capable of depleting it.

Where fishes have been protected, they have rebounded, along with the social and economic activities they support. The resurgence of striped bass along the eastern coast of the U.S. is probably the best example in the world of a species that was allowed to recoup through tough management and an intelligent rebuilding plan.

Recent progress provides added hope. The 1995 U.N. agreement on high-seas fishing and the 1996 Sustainable Fisheries Act in the U.S., along with regional and local marine conservation efforts, could—if faithfully implemented—help to guide the world toward a sane and vital future for life in the oceans. SA



EXPORT PRICES for fish have exceeded those for beef, chicken and pork by a substantial margin over the past two decades. To facilitate comparison, the price of each meat is scaled to 100 for 1975.

The Author

CARL SAFINA earned his doctorate in ecology in 1987 at Rutgers University, where he studied natural dynamics among seabirds, prey fishes and predatory fishes. He founded and now directs the National Audubon Society's Living Oceans Program. He also teaches at Yale University, serves as deputy chair of the World Conservation Union's Shark Specialist Group, is a founding member of the Marine Fish Conservation Network and was formerly on the Mid-Atlantic Fisheries Management Council. Safina received the Pew Charitable Trust's Scholars Award in Conservation and the Environment. He has fished commercially and for sport.

Further Reading

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The Promise and Perils of Aquaculture

AQUACULTURE OPERATIONS, such as this salmon farm in British Columbia, constitute a small but growing percentage of total fisheries production. Representative species from each of the major families used for aquaculture show the wide range of animals involved [*see box on opposite page*].

Aquaculture, or fish farming as it is often called, might appear to be the perfect solution to the dire problems facing many overly exploited varieties of marine fauna. If people can raise enough fish on farms, it stands to reason that they will be less inclined to hunt them from the sea. So the phenomenal growth of aquaculture in recent years might take some of the pressure off wild populations. Unfortunately, this seemingly logical supposition is surprisingly hard to confirm.

The complication is that aquaculture often exploits wild populations indirectly. Many of the species raised on farms are fed fish meal produced from capture fisheries. And countless farming operations rear juvenile fish taken from the ocean. For example, shrimp farmers in Latin America often shun larvae produced in hatcheries, because they believe that nature's shrimp are more robust. As a result, they will pay twice the price for captured larvae, and vast numbers of collectors take to shallow waters with fine mesh nets seeking them out. This intensive fishing constitutes a threat, but

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NATALIE B. FOBES

one is hard-pressed to demonstrate that it has actually diminished the numbers of wild shrimp.

Such uncertainty is one reason for the difficulty in weighing the benefits of aquaculture against its biological and environmental costs. Another stems from the very diversity of this industry. Farmers raise everything from fish to crustaceans, from mollusks to aquatic plants. In all, they produce in excess of 25 million metric tons every year of more than 260 different species. And these farmers employ many kinds of equipment in the process, including cages of netting suspended offshore, indoor tanks recirculating filtered water and open-air ponds flushed with seawater. So broad statements—both those that disparage and those that support the practice of aquaculture—rarely apply universally.

To illuminate some of the subtleties involved, the following four pages spotlight two common subjects of this industry—shrimp and salmon. Rearing such animals in captivity rather than fishing for them could help foster conservation. But making sure that these enterprises truly benefit wildlife remains a significant challenge for the future. —*The Editors*

Commonly Raised Species

FISH

Asian seabass (*Lates calcarifer*)
Atlantic salmon (*Salmo salar*)
Atlantic cod (*Gadus morhua*)
Ayu sweetfish (*Plecoglossus altivelis*)
Bagrid catfish (*Chrysichthys nigrodigitatus*)
Bastard halibut (*Paralichthys olivaceus*)
Bluefish (*Pomatomus saltatrix*)
Cachama blanca (*Piaractus brachypomus*)
Channel catfish (*Ictalurus punctatus*)
Climbing perch (*Anabas testudineus*)
Common sole (*Solea vulgaris*)
European seabass (*Dicentrarchus labrax*)
Flathead gray mullet (*Mugil cephalus*)
Giant gourami (*Osphronemus goramy*)
Greasy grouper (*Epinephelus tauvina*)
Japanese eel (*Anguilla japonica*)
Japanese jack mackerel (*Trachurus japonicus*)
Kissing gourami (*Helostoma temmincki*)
Largemouth black bass (*Micropterus salmoides*)
Mangrove red snapper (*Lutjanus argentimaculatus*)
Milkfish (*Chanos chanos*)
Nile tilapia (*Oreochromis niloticus*)
North African catfish (*Clarias gariepinus*)
Northern pike (*Esox lucius*)
Pangas catfish (*Pangasius pangasius*)
Pike-perch (*Stizostedion lucioperca*)
Red seabream (*Pagrus major*)
Silver carp (*Hypophthalmichthys molitrix*)
Southern bluefin tuna (*Thunnus maccoyii*)
Snakeskin gourami (*Trichogaster pectoralis*)
Starry sturgeon (*Acipenser stellatus*)
Striped snakehead (*Channa striata*)
Turbot (*Psetta maxima*)

CRUSTACEANS

American lobster (*Homarus americanus*)
Chinese river crab (*Eriocheir sinensis*)
Danube crayfish (*Astacus leptodactylus*)
European lobster (*Homarus gammarus*)
Giant tiger prawn (*Peneaus monodon*)
Giant river prawn (*Macrobrachium rosenbergii*)
Indo-Pacific swamp crab (*Scylla serrata*)
Longlegged spiny lobster (*Panulirus longipes*)
Red swamp crawfish (*Procambarus clarkii*)
Whiteleg shrimp (*Peneaus vannamei*)
Yabby crayfish (*Cherax destructor*)

MOLLUSKS

Blood cockle (*Anadara granosa*)
Blue mussel (*Mytilus edulis*)
Common edible cockle (*Cerastoderma edule*)
European abalone (*Haliotis tuberculata*)
Giant clam (*Tridacna gigas*)
Globose clam (*Mactra veneriformis*)
Japanese corbicula (*Corbicula japonica*)
Japanese pearl oyster (*Pinctada fucata*)
Northern quahog (*Mercenaria mercenaria*)
Pacific cupped oyster (*Crassostrea gigas*)
Pacific geoduck (*Panopea abrupta*)
Peruvian calico scallop (*Argopecten purpuratus*)
Pink conch (*Strombus gigas*)
Sand gaper (*Mya arenaria*)

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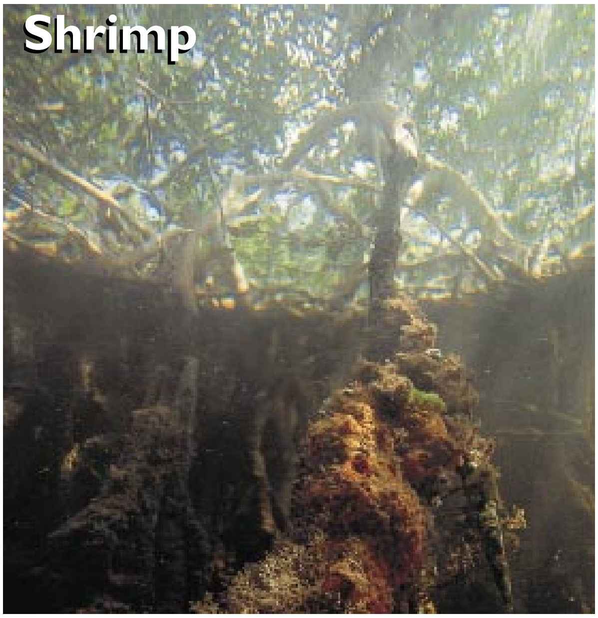
Giant Questions about Shrimp



CHIP CLARK *Smithsonian Institution*

The explosive growth of shrimp aquaculture in recent years has created worries about the environmental toll from this industry. One of the charges voiced by environmentalists is that the people constructing shallow ponds for shrimp farming all too often destroy mangroves, salt-tolerant trees that line the coast in much of the tropical world (*green on map above*). These partially inundated mangrove forests filter excessive nutrients washed off the land before they reach the sea, and the submerged roots (*left*) shelter a variety of creatures, including young fish. Although the destruction of man-

Notes from an Adviser to the Shrimp Industry

It cannot be denied that a great deal of environmental damage has arisen from poor planning and management by shrimp farmers and lax government agencies in countries where this form of aquaculture is widespread. But shrimp farming is not always harmful to the environment. Unfortunately, some environmentalists have unfairly made sweeping condemnations of the entire industry.

One charge leveled against shrimp farming is that rich investors make quick profits and then abandon farms. Here the critics are just plain wrong. Although some shrimp farms have proved unsustainable and been abandoned, these farms usually were small, often consisting of only one or two cheaply constructed ponds, which were situated on unsuitable sites and operated without sufficient capital and expertise. Properly sited and well-constructed shrimp farms cost from $10,000 to $50,000 per hectare of pond and are expensive to operate. Such large investments cannot be recovered quickly, so owners want to make sure that their farms are productive for many years.

CONNER BAILEY

PROPERLY CONSTRUCTED SHRIMP PONDS cost tens of thousands of dollars per hectare to build. So their owners have great incentive to ensure that they do not have to be abandoned after a short while.

Shrimp farming is an interesting example of a situation in which a disproportionate amount of the environmental damage has resulted from smaller operators rather than from bigger ones. But it is possible for small-scale farmers to pool their resources in cooperatives or producer associations and greatly improve their management. Well-run operations require many workers up and down the line—for hatcheries, farms and processing plants—typically creating one or two jobs for each hectare of pond in production. Shrimp farming also stimulates local economies and provides import earnings for many developing nations.

So it would be a sad loss for many people if shrimp aquaculture disappeared. The trick is to manage these operations sensibly. Many shrimp farmers are, in fact, acutely aware of the damage that shrimp farming can do. They have learned that their long-term success depends on maintaining healthy conditions for their shrimp and that their prosperity is linked directly to environmental quality along nearby coasts. Degradation of the coastal zone makes aquaculture more difficult, so it is easy to convince most shrimp farmers that they have a vested interest in being good environmental stewards.

Several recent developments indicate that shrimp farmers are indeed moving toward environmentally friendly forms of production. The Australian Prawn Farmers Association established a formal code of practice for its members; the Association of Southeast Asian Nations Fisheries Network

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ROBERTO OSTI

groves also comes about for many reasons besides the construction of shrimp ponds, all these losses bode badly for the affected shores and ocean nearby. The essays here present two perspectives on this concern and other environmental problems arising from shrimp farming.

published a manual of good shrimp farm procedures; and the Food and Agriculture Organization of the United Nations presented technical guidelines for responsible fisheries that apply to shrimp farming. In addition, the Network of Aquaculture Centers in Asia-Pacific has created a detailed plan to improve the sustainability of aquaculture in general.

What is more, several recent scientific and trade meetings have focused on the connection between shrimp farming and the environment. Most countries now require environmental impact assessments for new shrimp farms. Thailand has instituted regulations in an effort to make sure that shrimp farmers adopt the best management practices possible. A particularly important development is the recent formation of the Global Aquaculture Alliance. This industry group is fostering responsible shrimp aquaculture, developing an elaborate code of practice and promoting consumer awareness with an "eco-label" for environmentally friendly shrimp. —*Claude E. Boyd*

CLAUDE E. BOYD is a professor in the department of fisheries and allied aquaculture at Auburn University. He shares his expertise with shrimp farmers around the world through workshops and consulting tours.

Comments from an Environmental Advocate

Many businesspeople see natural resources as free for the taking. They count as costs only the labor and investment needed to extract them. There is no thought given to the cost of replacement or maintenance for the resources they use. Nowhere is this blindness more true than with shrimp aquaculturists, who often depend on access to public resources that, traditionally, have been used by many different groups.

Shrimp farmers must decide if they indeed want to address the environmental problems their industry has created. True, all economic activities have environmental consequences. Nevertheless, the goal of shrimp producers should be to reduce the deleterious effects on the environment as much as possible.

Some practices that would make shrimp farming more sustainable are already used by more progressive and well-financed shrimp producers. Around the world, however, there are hundreds of thousands of shrimp farmers. Each one makes decisions that affect his or her own future as well as those of others in this business. Shrimp aquaculture as it is conducted today in most parts of the world is not sustainable for very many decades into the future.

Perhaps an ideal, indefinitely sustainable system for shrimp farming is not possible, at least with current knowledge. Yet most shrimp farmers and others affected by this industry could agree that some practices are better than others, and the industry as a whole would benefit from the swift adoption of these improved techniques.

There are a number of business reasons to adopt more efficient and sustainable methods of shrimp production. For example, increasing the survival rates of young shrimp from less than 50 to 75 percent or more will reduce the initial outlays required for each crop. Similarly, more effective ways of feeding shrimp can reduce expenditures on food by a quarter to a half. These two simple changes would reduce the cost of cleaning effluents and moving ponds periodically. Ecuadorian shrimp farmers have been able to double their profits by such means.

Although other improvements may be more expensive, the boost to income in many instances will compensate for the required expenditures. Yet it is important to understand that some investments will not result in increased efficiency. These costs will have to be passed on to consumers, who are, after all, the ultimate polluters in the economic system. Regulations might bring increased prices. Or perhaps "green" shrimp will prove to command a premium from environmentally conscious consumers.

ALFREDO QUARTO

CLEARING OF MANGROVES results from a variety of human activities, including shrimp farming, which accounts for perhaps as much as 10 percent of the total global loss of these forests.

But producers who try to differentiate their product to gain market advantage must be able to prove their claims. People will pay more only if a reliable third party has verified assertions about the product being environmentally benign. Because there are no "name brands" of shrimp, such assurances will be difficult to judge.

Who should establish the guidelines for sustainable shrimp production? Today environmentalists, producers and some governments are each developing their own guidelines for sustainable shrimp aquaculture. But no single group, certainly not the producers themselves, will be able to create a credible system. Attaining that goal will require that these diverse groups agree on general principles, which can then be adapted to specific local conditions. Only through the adoption of such sustainable production systems will shrimp aquaculture be part of the solution for the next millennium rather than just another environmental problem that must be put right. —*Jason W. Clay*

JASON W. CLAY, a research fellow at the World Wildlife Fund in Washington, D.C., has taught at Harvard University. He has also worked for the U.S. Department of Agriculture and for Cultural Survival, a human-rights organization.

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TOM AND PAT LEESON *Photo Researchers, Inc.*

Struggles with Salmon

DEFYING GRAVITY on their way to spawn, salmon struggle against sundry obstacles. Some people fear that salmon farms nearby might harm these wild populations.

Producing almost 800,000 metric tons a year, salmon aquaculture has become a worldwide industry. Norway raises nearly half this tonnage, with Chile contributing 24 percent, Scotland 14 percent and British Columbia 4 percent. In all, aquaculture accounts for about a third of the salmon consumed annually. This now thriving industry burgeoned after wild stocks of salmon became too depleted to satisfy demand.

Populations of Atlantic salmon may have first begun to falter in the face of intensive fishing as early as the 1860s, and during the ensuing decades many fishers on both sides of the Atlantic moved to the western coast of North America to take advantage of the salmon there. Nevertheless, by the early 1970s, the numbers of Atlantic salmon had fallen sharply. The salmon fishery of the Pacific Northwest also proved fragile, essentially collapsing in 1994. Today in the U.S., only the Alaskan salmon fishery survives at a significant level.

To compensate for the failing production from capture fisheries, salmon farmers began setting up operations at coastal sites, beginning in Norway during the 1970s. These farmers learned to simulate the natural life cycle of wild salmon, which live most of their days in the ocean but lay their eggs in freshwater streams. The newly hatched fish typically spend up to a year meandering their way to the sea, where they migrate north to cold, nutrient-rich waters, allowing them to feed more easily. Three years later they return to breed in the same freshwater streams where they hatched. Although Pacific salmon die shortly after spawning, Atlantic salmon (the type used predominantly for aquaculture) can make the circuit twice.

On a farm, aquaculturists hatch eggs in freshwater and grow the fish for a year in tanks before transferring them to pens of netting suspended near shore in bays or estuaries. They feed the salmon pellets composed primarily of fish meal, vegetable matter and vitamins and, after three years, harvest and sell the fattened fish.

The success of salmon farms has been a boon for consumers, who have seen prices drop. But for others the results have been mixed. For example, some environmentalists are concerned about uneaten food and fish feces building up underneath densely stocked pens where currents are weak, resulting in a large deposit of nutrient-rich sediment on the seafloor. They fear that this sludge will overload bottom-dwelling organisms living in the vicinity [see "Enriching the Sea to Death," by Scott W. Nixon, on page 48].

NATALIE B. FOBES

UNDERWATER PENS suspended offshore in bays or estuaries contain the farmed salmon as they grow to adulthood. Some worry that escapees or the high concentration of nutrients could harm the surrounding natural environment.

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Insufficient flushing may also foster the spread of disease among farmed salmon. This problem for farmers becomes an environmental concern if the salmon get loose. Fish can escape by accident during transport or through holes in faulty nets, and when released they are free to roam the oceans and coastlines. So disease-carrying salmon from farms could, at least in theory, pass pathogens to wild stocks.

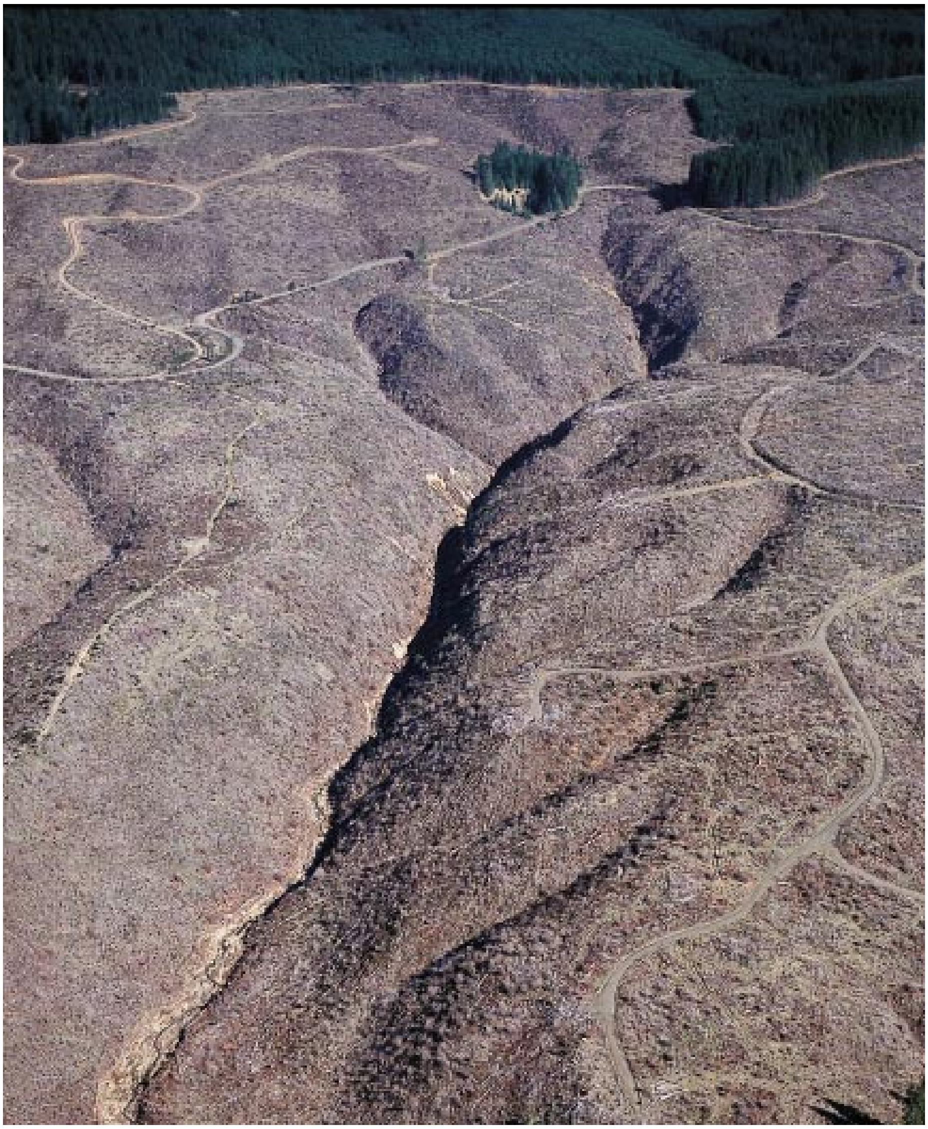
On the western coast of North America, escaped Atlantic salmon can interact with the native Pacific species, and some people worry that the nonnative Atlantics could take over. Despite the large numbers involved (the government of British Columbia reported that more than 60,000 Atlantic salmon had slipped from their nets in 1994 and 1995 alone), thus far there is no evidence that Atlantic salmon pose any serious danger.

Robert R. Stickney, a fisheries researcher at Texas A&M University, points out that efforts to establish Atlantic salmon populations on the western coast began as early as the last century. Since then, there have been multiple attempts, but none were successful. Because those projects failed repeatedly, it is unlikely that renegade Atlantic salmon could pose a threat to the Pacific species. "It's a nonissue as long as you use the right fish," Stickney remarks. Atlantic salmon are good for farmers because they grow quickly and are more docile than the Pacific species, so the likelihood of them taking over local salmon runs is slim. William K. Hershberger of the Western Regional Aquaculture Center at the University of Washington agrees. "Results indicate that the competition with native fish is not a serious issue," he says, "but it is wise to continue monitoring the situation." John M. Epifanio, a geneticist with Trout Unlimited, a national nonprofit organization, is less optimistic. He notes that "the risk of displacing the native salmon is probably low." But he warns that "if the scale at which [salmon aquaculture] is happening is large enough, it'll happen eventually."

Another worry about the mass production of salmon arises because the densely populated pens tend to attract predators. Marine mammals and seabirds tear holes in the nets, releasing fish and swallowing profits. Farmers have tried everything from sonic devices to plastic whales to deter these animals, but to date their only successful recourse has been to shoot them. For example, between 1989 and 1997 more than 3,800 harbor seals and sea lions were reported killed by salmon farmers in British Columbia alone; the actual number of creatures involved is very likely to be much higher. Although these killings do not significantly threaten future populations of these animals, the public generally disapproves when farmers resort to using guns against wildlife.

Competing with marine mammals, seabirds and farmers are the people involved in commercial salmon fisheries. Farms have produced enough to lower prices, making fishing for salmon much less profitable.

Were overfishing the only cause of the decline of wild salmon, this development might be welcomed by those interested in protecting marine life. But the fact that the numbers of wild salmon are not rebounding shows that the recent declines probably have more to do with the loss of habitat than with the problems of overfishing or aquaculture. With many rivers and streams blocked by dams, polluted by chemicals and choked by silt, salmon have found spawning runs increasingly difficult to make. People who fish for these creatures want to maintain large populations and understand that to do so freshwater habitats have to be protected. So, ironically, these fishers—the very group most threatened by the rise of salmon aquaculture—may turn out to be among wild fish's strongest advocates. —*Krista McKinsey,* staff writer



DESTRUCTION OF SALMON HABITAT occurs in the Pacific Northwest when the forests bordering streams and rivers are clear-cut of timber and sediments wash down the slopes (*above*). Dams for irrigation and hydroelectric power generation have also been responsible for the demise of spawning runs for this migratory fish.

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WORLD TOUR

INDIAN OCEAN: *Fishing the "Zone" in Sri Lanka*

Sri Lanka depends on data to protect its rich coastal fisheries, but something stronger is needed to keep the poachers at bay

by Anton Nonis

LAURIE GRACE (map); WILLIAM F. HAXBY (globe)

The sun has not yet risen on this Friday morning in March as I step on board the *Kamalitha,* a 10.4-meter (34-foot) fishing trawler tied to a dock in the harbor at Beruwala, on the Sri Lankan coast 55 kilometers south of the capital city of Colombo. Around the vessel, the busy little harbor bustles in the darkness as scores of other small but sturdy trawlers either are getting under way or are pulling up to unload their weary crews and the previous night's catch.

As we head out of the harbor, I duck into the boat's cabin to join my shipmates for the voyage. There is a tense moment as the skipper barks out crisp orders to the crew and we swerve to avoid a massive inbound ship. Then it is smooth sailing as we head southwest under a cloudless sky.

Dressed in a striped, cotton Henley shirt and madras shorts, the 29-year-old skipper, Kapila Nishantha, already has 17 years of experience fishing in Sri Lankan waters and has been a captain for the past five. His three-man crew—Gamini Silva, Palitha Dodampe and Vincent Vithana—is also seasoned, having been recruited into the same profession as their fathers and grandfathers. My role is that of an observer; as a newspaper reporter based in Colombo, I have written several articles on commercial fishing and am eager to see the industry from a new perspective.

As it turns out, I am not the only observer on board. A fisheries inspector, Susantha Wijesuriya of the Ministry of Fisheries and Aquatic Resources Development, has been charged with collecting data on the catch, which the ministry will use for statistical purposes. The data will also be put to scientific use: the ministry routinely shares information and works closely with the National Aquatic Resources Research and Development Agency (NARA), a governmental research center in Colombo.

The official interest reflects the fact that fishing has for many years been a prime foreign-exchange earner for Sri Lanka, raking in billions of rupees (tens of millions of dollars) annually. Some 100,000 Sri Lankans support their families comfortably as fishermen, and thousands more work in related jobs, such as mending nets and selling seafood to the resort hotels along the coast and in the central hills. Not surprisingly, the number of young people seeking to become fishermen is on the rise.

So far there has been plenty of fish for all. The total catch was around 217,000 metric tons in 1997. Tuna constituted almost half the catch, followed by shark at about 35 percent and billfish (marlin, sailfish and swordfish) at around 10 percent.

Ministry sources say the tuna varieties are actually increasing at present. A drop in the shark catch, however, which consists mostly of blue shark, has been observed over the past year. Officials hope that the blue shark fisheries will recover as larger boats and access to better bait allow fishermen to increase their catch of the more desirable tuna.

A more difficult problem involves poaching within Sri Lanka's 370-kilometer (200-nautical-mile) exclusive economic zone (EEZ), within which only Sri Lankan vessels have the right to fish. Estimates are that foreign trawlers, which are typically much larger and better equipped than their Sri

BERUWALA HARBOR, a major fishing port, is located 55 kilometers south of Colombo, the capital of Sri Lanka. Relatively small, wooden trawlers (*top photograph*) are the standard fishing vessel. Two of the boats based in the harbor (*right*) are fisheries ministry craft devoted to helping fishermen in trouble.

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CAPTAIN Kapila Nishantha (*left, in striped shirt*) collects floats that are to be tied to the gill nets. Fishers Palitha Dodampe (*center, in white T-shirt*) and Gamini Silva (*center, in green shirt*) attach floats to a net. The catch (*above*) includes a mahimahi and a tuna.

Lankan counterparts, snatch up to 25,000 tons of fish every year from Sri Lanka's waters. For years, Sri Lankan officials had only two boats to patrol the country's 460,000-square-kilometer EEZ and could do little to stop the poaching. More recently, the administration of President Chandrika Bandaranaike Kumaratunga has pledged to create a larger, better-equipped coast guard to address the problem.

Such concerns seem far away on the *Kamalitha,* as we push out to sea. With the sun rising into the sky behind us and the

waves thudding on the hull, we are headed to a point about 90 kilometers from shore, well within the EEZ. Filling the time, Vincent rhapsodizes about a young woman in a neighboring village with whom he is smitten. Later, Gamini fires up the tiny stove in the cabin and begins preparing a meal of rice, vegetables and (what else?) fish curry. We eat heartily, the sea air having made us ravenous.

By three P.M., it is finally time to cast bait. The longlines go out first. There are five segments, tied end to end, for a total length of 2,500 meters. Evenly spaced buoys keep the lines near the surface. Along each 500-meter segment are some 25 branch lines, spaced at intervals of about 20 meters. Each of these vertical branch lines measures about 15 meters and has a baited hook at the end. Many of the hooks are baited with hunks of squid, a favorite of tuna. Scraps of beef are also used to lure sharks.

The longlines are followed by the gill nets, which are held in place between a top rope kept near the surface by polyurethane floats, and a weighted bottom rope. There are a total of 25 pieces of net, each measuring about 100 meters wide, suspended side by side between the top and bottom ropes. So when deployed, the net is like a wall of mesh 2,500 meters wide. A thick, 50-meter rope secures the end of the gill net to the stern.

With the lines and nets deployed, once again there is nothing to do but wait. To amuse themselves, the crew members sing or hop overboard for a swim. After the sun slips below the horizon, a chilly breeze blows past intermittently, reminding us that we are in water kilometers deep. Around us the murky ocean seems endless.

In the darkness on deck, the only light comes from the cabin's windows and, on the eastern horizon, the dim glow of coastal towns. Inside the cabin, crew members take turns napping on two narrow bunks. For skipper Nishantha, though, there is no rest. He spends most of the evening in the captain's seat, going out on deck from time to time to peer into the night.

In the early-morning darkness, the catch is hauled in. It amounts to almost 400 kilograms (about 880 pounds) and includes three tunas, each weighing around 25 kilograms, and some blue sharks. To keep them from biting, fish still struggling are clubbed on the head, blood spattering on the deck.

As the catch is tallied, Wijesuriya, the fisheries inspector, begins collecting data. For each fish he measures various dimensions, such as the length from snout to caudal fin, and notes the approximate location where it was caught and the type of fishing method that snared it. The type of net or length of longline (and number of hooks) are all recorded. According to Champa Amarasiri, the head of NARA's marine biology division, the data are used to estimate the age of the fish and to make inferences about the status of the fisheries.

Wijesuriya's presence on the *Kamalitha,* however, is unusual. With only 173 inspectors and a fishing fleet of 15,000 to 20,000 "day" and "multiday" fishing boats in Sri Lanka, the fisheries ministry and NARA must rely on the fishermen themselves to log most of the data on their hauls.

For the captain and crew of the *Kamalitha,* data logging is already as much a part of their world as gill nets and compasses. And in the chilly, predawn darkness 90 kilometers out at sea, with the fish stored, the nets stowed and the data logged, it is time to return to port. Nearing the harbor, we join dozens of boats returning from all directions. As the fish are unloaded and sold or auctioned, other trawlers put out to sea, sleepy fishermen head home to their families and a new day dawns on Beruwala Harbor. SA

ANTON NONIS is editor at the Sunday Observer, *an English-language newspaper based in Colombo, Sri Lanka.*

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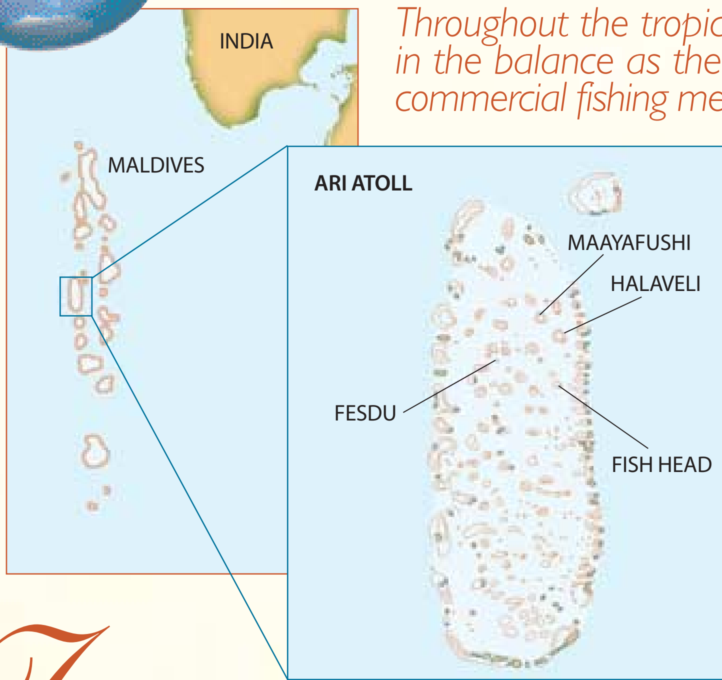
WORLD TOUR

INDIAN OCEAN:

Sharks Mean Business

Throughout the tropics, the future of reef sharks hangs in the balance as the interests of tourism and those of commercial fishing meet head-on

by R. Charles Anderson



LAURIE GRACE (*map*); WILLIAM F. HAXBY (*globe*)

I am on a wooden motorboat, over a small reef inside Ari Atoll, in the Maldive Islands. It is seven at night. Around me, the warm Indian Ocean is placid, and the lights of half a dozen small resort islands—Maayafushi, Halaveli and Fesdu, among others—glitter in the distance. In a few minutes I'll be in the dark water, scuba diving in the midst of feeding sharks.

I am neither as brave nor as foolhardy as that disclosure may suggest. The boat is moored in only eight meters (26 feet) of water, and I will be observing whitetip reef sharks (*Triaenodon obesus*). Inoffensive and fairly small, they are almost as far removed from "Jaws" as a shark can be.

A good shark dive is one of the great wildlife experiences, like a safari in East Africa or a cruise in Antarctic waters. And this particular spot in Ari's lagoon is one of the best shark-watching sites in all of the Maldives, a nation of some 1,200 tiny islands stretching about 1,000 kilometers southwest of the southern tip of India. Unfortunately, though, such places are becoming increasingly scarce.

A few days earlier I had visited Fish Head (Mushimasmingili Thila), another dive site in the same lagoon. Until recently, it was the premier shark dive site in the Maldives, being home to about 20 gray reef sharks (*Carcharhinus amblyrhynchos*). Stocky and mean-looking, they are nonetheless dedicated fish eaters, so they thrill divers without really endangering them. When I visited Fish Head last time, however, there was only a solitary shark in residence. Local fishermen had taken all the others. Strands of fishing line caught on the reef remained as evidence of their visits.

Operators of local dive shops are not happy about the loss. The warm, clear waters, extensive coral reefs and abundant sea life—including sharks—are the main attractions for the tens of thousands of divers who flock to the Maldives every year and form the backbone of the country's major industry: tourism. One estimate puts the annual number of dives made by visiting tourists at more than half a million; each dive costs roughly $35. From the Maldivian perspective, that is a lot of money—the country's gross domestic product was only $423 million in 1995.

Apart from tourism, the only industry of any importance is fishing. Maldivian fishers have traditionally targeted tunas such as skipjack and yellowfin using the same live-bait pole-and-line method that their ancestors used 1,000 years ago. This preference for tunas, which are caught out at sea, left the reef-dwelling fish essentially undisturbed—until relatively recently. Over the past 15 to 20 years, East Asian buyers

PHOTOGRAPHS BY R. CHARLES ANDERSON

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GRAY REEF SHARKS (*above* and *right*), whose numbers are plummeting in the Maldives, are a favorite of diving tourists. A whitetip reef shark (*opposite page*), whose numbers are also declining, hunts bluestreak fusilier fish (*below*) on a reef inside Ari Atoll in the early evening.

have encouraged Maldivian fishers to turn to the reefs. Sea cucumbers, groupers, giant clams and reef sharks such as the grays have all taken a hammering. As is true for countless other idyllic islands, two important industries—diving and fishing—are on a collision course in the Maldives.

Dinnertime on the Reef

Such developments are the backdrop for my reef dive in Ari Atoll. After struggling into my scuba gear in the darkness, I duckwalk off the bow and swim down through the cloud of bubbles caused by my entry. Almost immediately my flashlight beam picks up the reef below.

The reef top is a seething mass of fish. Bluestreak fusilier fish (*Pterocaesio tile*) are milling over the reef and among the rocks, like a living carpet. These fish feed by day, forming great schools above the reef where they peck at incoming plankton. At night the fusiliers sleep in crevices in the reef. Now, just after dusk, they are trying to settle down for the night.

Out of the darkness a shark appears. Then another and another. They are whitetip reef sharks; at about a meter and a half long, they are hardly the efficient killers of popular imagination. Perhaps dazzled by my dive light, they bump into rocks and snap their jaws shut on empty water a full second after startled fusiliers have darted off. Eventually, and right in front of me, one whitetip bites down on a fusilier and with much headshaking makes off with its dinner. The fresh wounds on many other fusiliers attest to recent and frequent near misses. After an hour watching a dozen or

so sharks, I return to the mooring line and slowly ascend to my boat.

Although there's nothing like being next to feeding sharks to pump up the adrenaline, it took bloodless calculations to shed light on the conflict over reef resources. To estimate the value of sharks to the two industries, tourism and fishing, I did a survey of shark diving in the Maldives in 1992 with Hudha Ahmed, my colleague at the Ministry of Fisheries and Agriculture. We found that the money spent by divers on shark dives in the Maldives amounted to some $2.3 million a year. Some $670,000 came from dives at Fish Head alone.

We further estimated that for all shark-watching dive sites, the average value of a live gray reef shark was about $3,300 a year. Because the sharks can live for at least 18 years, and recognizable individuals have been seen at dive sites in the Maldives for many years in a row, the total value of each shark is actually several times higher. In contrast, a dead reef shark has a onetime value (cut up for meat and fins) of about $32 to a local fisherman. Thus, at dive sites, gray reef sharks are worth at least 100 times more alive than dead.

From an economic point of view, it clearly makes sense to ban shark fishing and leave the sharks as high-earning attractions for visiting divers. That, however, would deprive the fishermen—who gain few direct benefits from tourist income—of even the meager benefit conferred by dead sharks.

As one step toward protecting sharks and other marine life, the Maldivian government designated 15 popular dive sites as Marine Protected Areas in 1995. Eight of the sites, including Fish Head, were major shark-watching dive sites. Unfortunately, there was no means of enforcing the protected status of these areas. During 1995 and 1996, the shark population at Fish Head plummeted, as did the number of divers visiting the site. The loss of revenue is difficult to estimate, but my back-of-the-envelope calculations suggest that it is on the order of $500,000 a year. All this potential revenue was lost for the sake of about 20 sharks, which probably earned their captors less than $1,000.

What has occurred at Fish Head has happened at innumerable other locations around the world. The only difference is that I and other divers have monitored the change at Fish Head, and we are trying to do something about it. There is talk of banning shark-fin exports, but such a move would unfairly affect those fishermen who target oceanic sharks, which are more abundant than reef sharks. There is also talk of extending the system of protected areas, but lack of enforcement remains a problem.

The Maldives, moreover, are not the only trouble spot. Shark fisheries are in decline all over the world. Part of the problem is the sharks' biology: they grow slowly, mature late and have small numbers of young. Whitetip reef sharks, for example, mature at about five years and gray reef sharks at seven or eight. Both species give birth to typically two or three offspring at a time—a tiny brood in comparison to the hundreds or thousands of eggs produced by most bony fishes. As a result, shark populations are unusually sensitive to being overfished. Unfortunately, a quarter of the world's population craves shark's fin soup.

In many tropical countries, where shark fishery regulations are difficult to enforce, reef shark populations have dwindled to a small fraction of their original numbers. Even the lure of tourist dollars has not yet stemmed the losses. It is possible that we have already entered the twilight of one of nature's great and stirring spectacles: the sight of sharks feeding in the wild.

R. CHARLES ANDERSON is a marine biologist who has lived and worked in the Maldive Islands since 1983.

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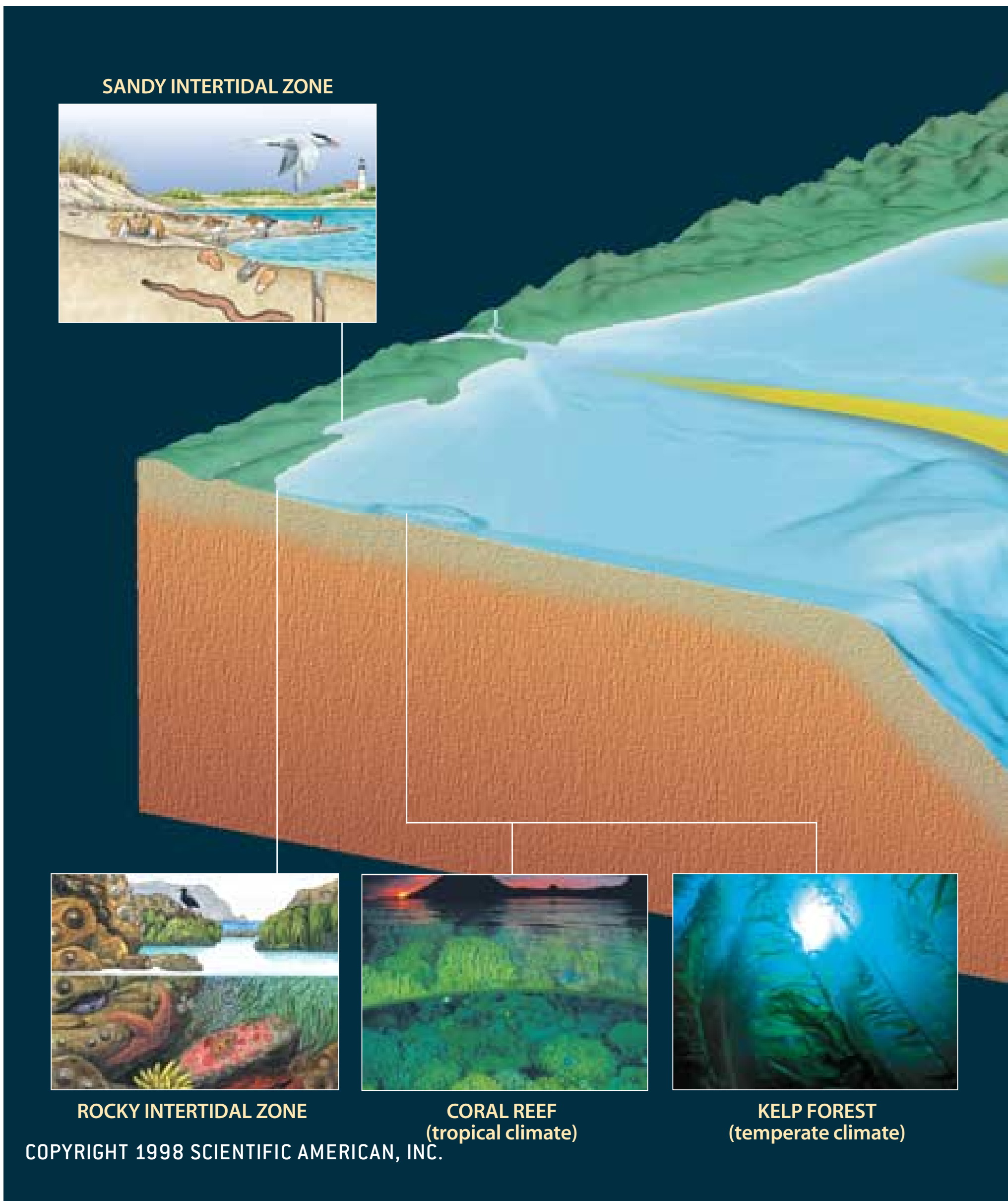
Life in the Ocean

The richest realm on the earth remains largely mysterious

by James W. Nybakken and Steven K. Webster

Earth is misnamed. Even though the planet is largely made up of rock, 71 percent of its surface is covered with ocean. Like the wet film coating a newly washed plum, this water makes up a thin layer compared with the globe as a whole. Yet that watery veneer comprises more than 90 percent of the biosphere by volume: it covers 360 million square kilometers (140 million square miles) and runs, on average, a few kilometers deep. It is in these salty depths that life first emerged four billion years ago, and it is there that life continues to teem today in many strange forms. This blue planet would be better dubbed Oceanus.



OCEAN ECOSYSTEMS exhibit great diversity. Those closest to shore are best known: the intertidal zones, for example, as well as the coral reefs and kelp forests, which occur at the same depth but are mutually exclusive. Parts of the deep sea—including the midwaters and the ocean floor—are only slowly being explored as researchers develop the requisite technology. The movement of nutrients through these ecosystems is fairly well understood (*yellow arrows*): rivers and coastal vegetation supply nutrients to the ocean, just as the upwelling of deep, cold waters provides nutrients to many coastal areas.

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The ocean has long been mysterious, its interior largely inaccessible. And although it may not hold the sea monsters that mariners once envisioned, it continues to hold many questions for scientists. Researchers have studied less than 10 percent of the ocean and, because of the difficulty of getting safely to the bottom, have explored no more than 1 percent of the deep ocean floor. Marine biologists know most about the near-shore environments—the coasts, the coral reefs, the kelp forests—and a few other areas that divers can study with ease. But researchers remain ignorant about many aspects of oceanic ecosystems, particularly about life in the midwaters—those between the light-filled upper 100 meters (328 feet) and the near-bottom realm of the deep sea.

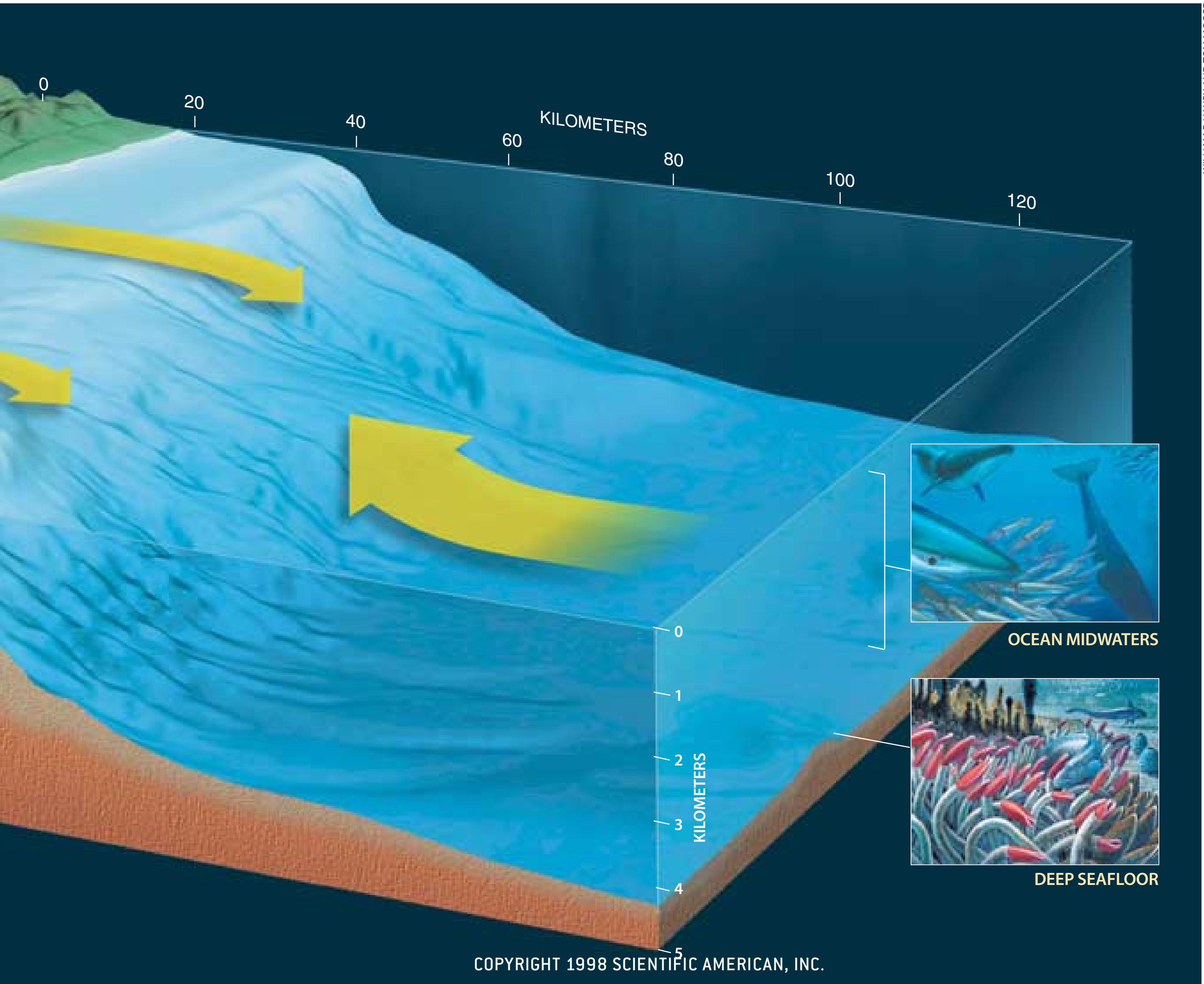
From what investigators do know, it is clear that marine animals display a greater diversity of body types than land animals do. Their scientific description requires more broad categories—that is, more phyla (the second most general taxonomic grouping)—than are needed to categorize their terrestrial cousins. Of the 33 animal phyla, 30 describe residents of the ocean, 15 exclusively so. Only 16 phyla include animals found on land or in freshwater—and of those, only one is exclusively terrestrial. This phenomenon reflects the fact that life evolved in the sea and that few life-forms were able to adapt to the absence of water around their bodies.

Yet at the species level, the reverse appears to be true. One and a half million terrestrial species have been described—mostly insects and vascular plants—but total estimates range from five million to more than 50 million. Of the organisms that live in the ocean, however, only 250,000 species have been identified; total estimates run closer to 400,000 to 450,000. This count may change considerably once scientists get a better grasp of life on the ocean floor: some experts posit that between one million and 10 million benthic species have yet to be described.

Watery Properties

From people's often terrestrially biased perspective, marine organisms can seem odd. Some of these creatures glow in the dark, many are soft and boneless, and most saltwater plants grow fast and die young—unlike trees, which live to a ripe old age. These differences have arisen because of the physical and chemical characteristics of the ocean.

Seawater is about 800 times as dense as air and is much more viscous. Therefore, marine organisms and particles of food can float endlessly through the water—whereas no creatures drift permanently in the air. Because small life-forms and organic particles are constantly wafting about, some sea animals spend their



WILLIAM F. HAXBY AND TOM MOORE

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Denizens of the Open Ocean

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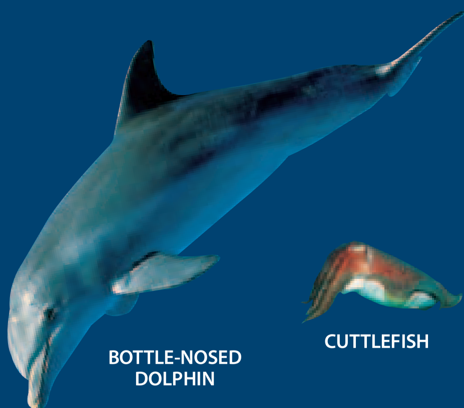
TUBE WORM

EELPOUT

GLASS SPONGE

CLAM

SPAGHETTI WORM

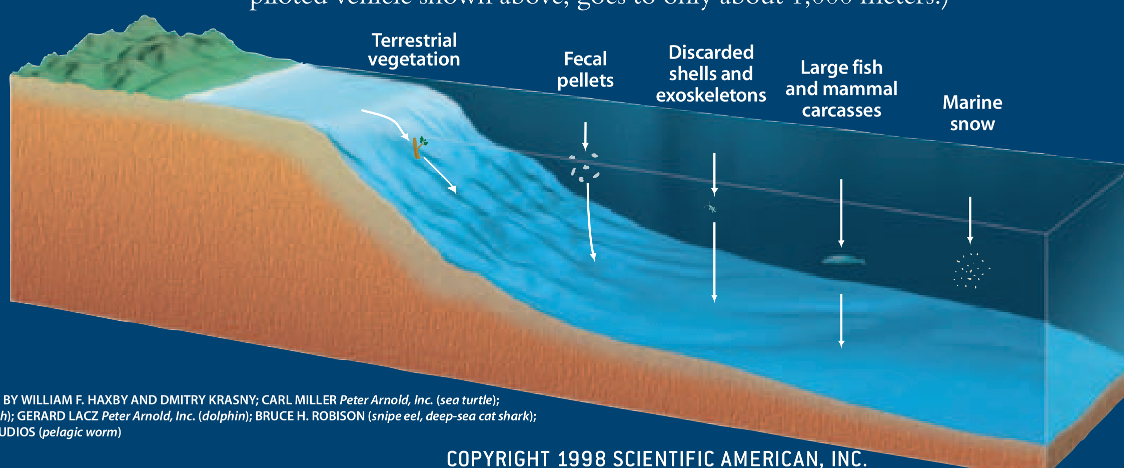


BOTTLE-NOSED DOLPHIN

CUTTLEFISH

GREEN SEA TURTLE

The creatures of the ocean are extremely diverse, reflecting the varied conditions in which they live. Depicted here—and not drawn to scale, so that it is easier to see the organisms clearly—is a small sample of oceanic biodiversity. Many marine organisms stay in the upper waters, feeding on the zooplankton and phytoplankton found there (*at left and top of page*). For their part, residents of the ocean bottom (*at right and directly above*) exist in darkness and under great pressure. Most of the scant food supply in this realm originates in the shallows (*diagram below*). For now at least, the lowest depth that scientists can safely visit is about 6,500 meters (21,300 feet), and so their knowledge of the creatures of the deep seafloor is limited. (*Deep Rover,* the piloted vehicle shown above, goes to only about 1,000 meters.)



DEEP-SEA CAT SHARK

VAMPIRE SQUID

SNIPE EEL

PELAGIC WORM

ILLUSTRATION BY ROBERTO OSTI; DIAGRAM BY WILLIAM F. HAXBY AND DMITRY KRASNY; CARL MILLER *Peter Arnold, Inc.* (*sea turtle*); CARL ROESSLER *Bruce Coleman Inc.* (*cuttlefish*); GERARD LACZ *Peter Arnold, Inc.* (*dolphin*); BRUCE H. ROBISON (*snipe eel, deep-sea cat shark*); KIM REISENBICHLER (*vampire squid*); SEA STUDIOS (*pelagic worm*)

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lives fixed in place, grazing on food in the water around them; on land, only spiders achieve anything like this sedentary lifestyle. The density of water also buoys up organisms, obviating the need for structural supports of cellulose or bone to counteract gravity.

Life underwater has a unique hue as well. Water absorbs light differently than air does. Shorter wavelengths—such as those of the blues and greens—penetrate more deeply than the longer wavelengths of the reds and yellows do. So the view 10 meters below the surface is mostly blue. A few hundred meters deeper there is no sunlight at all and hence no photosynthesis. The midwater and deep-sea communities must depend on the photosynthesizers that reside in the sunlight-filled surface waters. As they sink, these microscopic phytoplankton, zooplankton and decaying particles sustain the fauna of the deep sea.

This rain of plant food is hardly constant, however. Phytoplankton are seasonal and vary by region. Most of the larger species—the ones that turn the ocean green or brown or red when they bloom—thrive in coastal and certain equatorial areas where nutrients are abundant. Much smaller species—called prochlorophytes—are found in tropical and mid-ocean waters. Bottom-dwelling large algae, such as kelp, and seed plants, such as surf grasses, are confined to such a restricted shallow zone around the continents and islands that they contribute little to the overall biological productivity of the ocean, which is relatively modest.

The ocean does not contain much plant life, because concentrations of critical nutrients are lower than they are on land. Phosphorus and nitrogen, for example, are present at only $^{1}/_{10,000}$ of their concentration in fertile soil. As a consequence, the ocean supports only a small fraction of what can be grown on reasonably productive land. One cubic meter of soil may yield 50 kilograms (110 pounds) of dry organic matter a year, but the richest cubic meter of seawater will yield a mere five grams of organic matter in that same interval.

The global distribution of what few nutrients there are depends largely on the temperature stratification of the ocean. In the tropics, surface waters are always quite balmy; in temperate regions, these upper waters warm in the summer and are cold the rest of the year. Below the well-mixed surface layer is a narrow zone—called the thermocline—that separates the warm surface from the colder, and thus heavier, water beneath. (An exception to this common configuration occurs near the poles, where the upper and lower levels of the ocean are equally cold.)

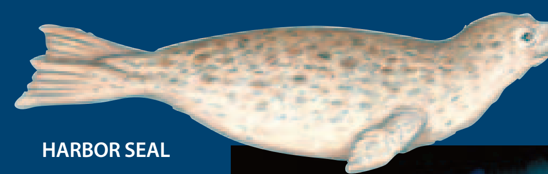
It is this cold, heavy water that is the key to the food chain. Because it receives a constant rain of organic detritus from above, deep, chilly water is richly supplied with nutrients. And because no light reaches it, no photosynthesis takes place there—so few organisms take advantage of this abundant nourishment. In contrast, surface water is often barren of nutrients because the sun-loving photosynthesizers have depleted them.

In the tropics, the separation between the warmth at the surface and the cold at depth is so great that even hurricanes and typhoons cannot completely mix the two. As a result, the waters of the tropics remain bereft of nutrients and of the phytoplankton that depend on them. Lacking these clouds of microscopic life, tropical seas normally stay crystal-clear. In temperate regions, winter storms can churn up the ocean, bringing some of the nutrients to the surface. In certain places such as coasts, where steady winds blow the warm surface waters offshore, deep waters rise to take their place. Such areas of nutrient-rich water support some of the world's largest fisheries.

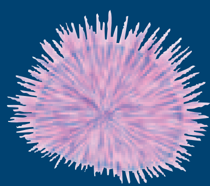
Under Pressure

Temperature and depth also play an important role because these variables control the availability of oxygen. On land, air provides plants and animals with a fairly constant mixture of this life-giving gas: 210 milliliters per liter. In the sea, oxygen enters only at or near the surface. And because most of the water found in the deep ocean originated at the surface in the coldest parts of the world, it sank carrying large amounts of dissolved oxygen. These water masses may spend centuries in the deep sea before they rise again to the surface. But because life is sparse and moves slowly down there, oxygen is rarely depleted. So, strangely, the ocean is often most oxygen depleted at intermediate depths. For example, in certain areas of the Pacific Ocean an "oxygen minimum

The Kelp Forest



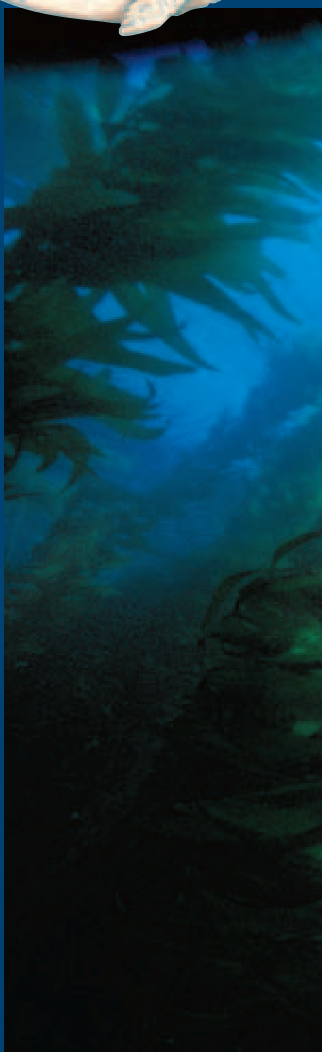
HARBOR SEAL



PURPLE SEA URCHIN

ANEMONE EATING A STARFISH

TOP SNAIL



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Kelp forests occur in temperate coastal waters, at depths of about 30 meters. Kelp—large, brown algae, which appear green in these underwater pictures—offer fish and invertebrates food as well as shelter from waves and strong currents. As a result, the kelp ecosystem is a rich one: otters, seals, abalone, sea urchins, rockfish, starfish and sea anemones, among many other fauna, thrive in these watery forests. Certain species of kelp can grow as much as half a meter in a single day, reaching great lengths (*lower left inset*).

BLACK ROCKFISH

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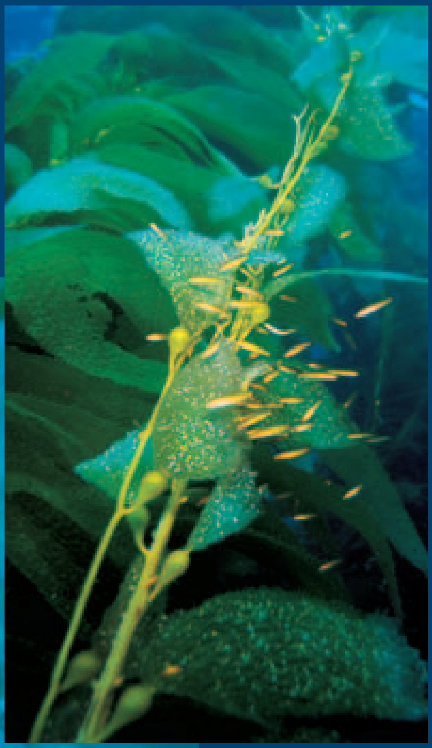
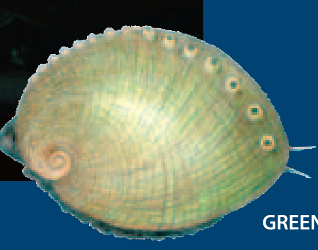


SENORITA FISH

SEA OTTER



GREEN ABALONE

ILLUSTRATIONS BY PATRICIA J. WYNNE; GREGORY OCHOCK *Photo Researchers, Inc. (kelp forest, senorita fish)*; BARON WOLMAN *Tony Stone Images (aerial view of kelp)*; DOUG WECHSLER *Animals Animals (sea anemone and starfish)*

zone" occurs between 500 and 1,000 meters below the surface. Only a few organisms are adapted to life in this oxygen-poor environment. Most creatures just travel through it quickly on their way to the surface or back down, where the water is richer in oxygen.

Life in that deep realm is under a great burden. Every 10 meters of seawater adds roughly another atmosphere of pressure: at one-kilometer depth the pressure is 100 atmospheres (100 times what people normally experience). In the profoundest ocean trenches, the pressure reaches more than 1,100 atmospheres. Many invertebrates and some fishes can tolerate the trip from one kilometer deep up to the surface—if they do not have gas-filled sacs that expand as they ascend—and can then survive at one atmosphere for years in refrigerated aquariums.

Despite this opportunity to study them in tanks, marine biologists know relatively little about the organisms that live down in those cold, dark regions. Investigators have learned only that the inhabitants of these realms have unusual adaptations that equip them to live in this environment. For this reason, they are some of the most interesting of all oceanic residents.

The Deepest Mystery

Recent studies of the deep sea suggest that although the diversity of species is high, their density is quite low. Food for these organisms arrives in the unending shower of organic particles called marine snow—although sometimes a large carcass, a clump of kelp or a waterlogged tree may settle on the seafloor. Of these sources, though, the marine snow is the most important. As it sinks toward the bottom, microbes, invertebrates and fishes feed on it—and so there is less and less to fall downward. This diminishing supply means there are fewer and fewer consumers at greater depth.

Even more important than the meager, uneven supply of food are the effects of pressure. Deep-sea animals and invertebrates with shells tend to be gelatinous and to have sluggish movements. Their shells are poorly developed because it is difficult to accumulate calcium carbonate under high pressure. If the creatures have skeletons, they are lightweight.

Most deep-sea animals are also small. Many midwater fishes, for instance, are no more than 20 centimeters long. But there are exceptions. Giant squid may reach 20 meters. And the largest comb jellies and siphonophores (relatives of the Portuguese man-of-war) live in the midwater zone, where the absence of strong currents and waves enables these delicate animals to achieve astounding proportions. In fact, the longest animal in the world appears to be a siphonophore of the genus *Praya,* which grows to 40 meters in length and is only as thick as a human thumb. Comb jellies can become the size of basketballs, and the mucus house of the giant tadpole-shaped larvacean *Bathocordaeus charon* may be as large as a Great Dane.

Many of these ghostly creatures glow in their dark abode [see "Light in the Ocean's Midwaters," by Bruce H. Robison; SCIENTIFIC AMERICAN, July 1995]. Bioluminescence can be found in 90 percent of the midwater species of fish and invertebrates, and many deep-sea fishes have relatively large eyes, so they can see by this faint light. The luminosity serves a variety of purposes: to identify and recognize species, to lure potential prey, to startle a predator and to warn mates of dangers. At depths of a few hundred meters, where dim light still penetrates, the light enables some organisms to blend in with the brighter surface and render their silhouettes invisible from below. Other advantages probably exist that scientists have not yet discovered.

Although they are able to flash light, midwater fishes are often black in color, and many of the crustaceans are red. Because red light cannot penetrate into deep water, this color provides excellent camouflage. Some large jellyfish and comb jellies tend to be purple or red as well.

The top carnivores, which roam near the surface, seldom have such tints. Tuna, billfish, whales, dolphins, seals, sea lions and even seabirds often move through well-lit surroundings as they travel sometimes thousands of kilometers every year. Their movements to feed—whether they are going from deep water to the surface or moving around the globe—result in the longest migrations of animals on the planet.

Some of these creatures have come to represent sea life for most people, so

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it remains amazing how little biologists know about their habits. How do sperm whales dive a kilometer deep to locate and capture giant squid? Do the yellowfin tuna of the tropical and the semitropical Pacific intermingle? Or are they separate genetic stocks? Part of the reason for this paucity of knowledge is that whales and open-water fishes are extremely difficult to study because they roam the world. Some whales, for example, migrate every year to feed in areas of cold upwelling near the poles and then travel again to reproduce in warmer latitudes. These creatures are the living oil tankers of the sea: using their blubber as fuel, they undergo vast fluctuations in weight, sometimes losing 30 percent of their body mass during migration.

Right under Our Feet

Not surprisingly, the ocean communities and creatures that researchers know best are those nearest shore: coral reefs, sea-grass beds, kelp forests, coastal mangroves, salt marshes, mudflats and estuaries. These areas are the places people fish, dive, dig for clams, observe shorebirds and, when not paying attention, run boats aground. As a result, these habitats are also the ones people have damaged most severely.

Such environments constitute less than 1 percent of the ocean floor by area, but because they are shallow, well lit and adjacent to landmasses, concentrations of nutrients and biological productivity are relatively high. These coastal areas also link saltwater and freshwater environments. Anadromous fishes, such as salmon, striped bass, shad and sturgeon, reproduce in freshwater rivers and streams, but their offspring may spend years feeding in the ocean before they return to complete the cycle. Catadromous fishes, such as the American and European eels, do the opposite, spending most of their lives in freshwater but going to sea to reproduce.

Perhaps the most familiar near-shore communities of all are those of the intertidal zone, which occupies a meter or two between the high- and low-tide marks. This intertidal stratum is inhabited almost exclusively by marine organisms—although deer, sheep, raccoons, coyotes and bears visit occasionally, as do some insects and a wealth of shorebirds. Organisms living there must be able to endure dryness, bright sunlight and severe shifts in temperature during low tide, as well as the mechanical wear and tear of the waves—which can produce forces equivalent to typhoon winds. It is not surprising, then, to find hard-shelled animals that grip rocks or hide in crevices living there: limpets, periwinkles, barnacles and mussels. Intertidal plants and animals usually occupy distinct horizontal bands that become more densely populated and rich in species at the deeper—and therefore more protected—extreme.

The composition of these littoral communities varies with the shoreline. Sandy shores, for instance, are constantly churned by the waves, so no plants or animals can get a grip for long. Instead most inhabitants are found burrowing underneath the surface. Some tiny animals—called meiofauna—actually live in the interstitial spaces between grains of sand.

Weather patterns and seasonal variations also influence the makeup of the intertidal zone. Temperate areas have the most developed intertidal communities because summer fogs often protect creatures from direct sunlight. In contrast, rocky shores in the tropics are usually quite bare—consisting of a few diatoms, coralline red algae, cyanobacteria, chitons and nerites (both of which are mollusks).

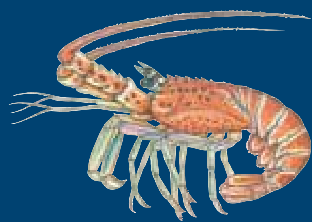
Farther offshore sit the "rain forests" of the marine world: kelp beds and coral reefs. These ecosystems are mutually exclusive but similar in some ways. Both require abundant sunlight and grow within 30 meters or so of the surface. Both contain dominant species that provide a massive, three-dimensional foundation for the community—giant kelp and reef-building corals, respectively. And both house a vast number of species, although coral reefs surpass kelp forests in this regard.

Despite these similarities, their differences are also dramatic. Coral reefs are almost exclusively confined to the tropics, where sea-surface temperatures do not fall below 18 degrees Celsius (about 64 degrees Fahrenheit). Kelp forests do

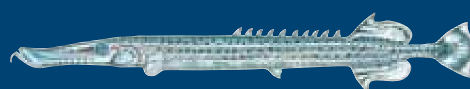
ILLUSTRATIONS BY PATRICIA J. WYNNE; FRED BAVENDAM *Minden Pictures (coral reef, soft coral)*; PETER/STEF LAMBERTI *Tony Stone Images (yellow sea fan)*

The Coral Reef

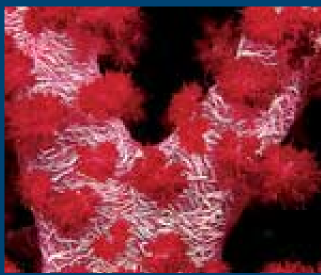
Like kelp forests, coral reefs also occur at depths of 30 meters or so but, unlike them, must have warm, tropical water to survive. Corals are colonial animals that live in symbiosis with tiny photosynthetic creatures called zooxanthellae and that produce a hard calcium carbonate skeleton, which forms the essential architecture of the reef. As their varied pigments and the beauty of their inhabitants suggest, coral ecosystems have the highest marine biodiversity recorded so far. They are also highly vulnerable to changes in water temperature and clarity, to infection and to damage by divers, boaters and fishers.



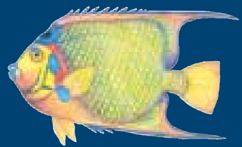
SPINY LOBSTER



TRUMPET FISH



SOFT CORAL



QUEEN ANGELFISH

YELLOW SEA FAN

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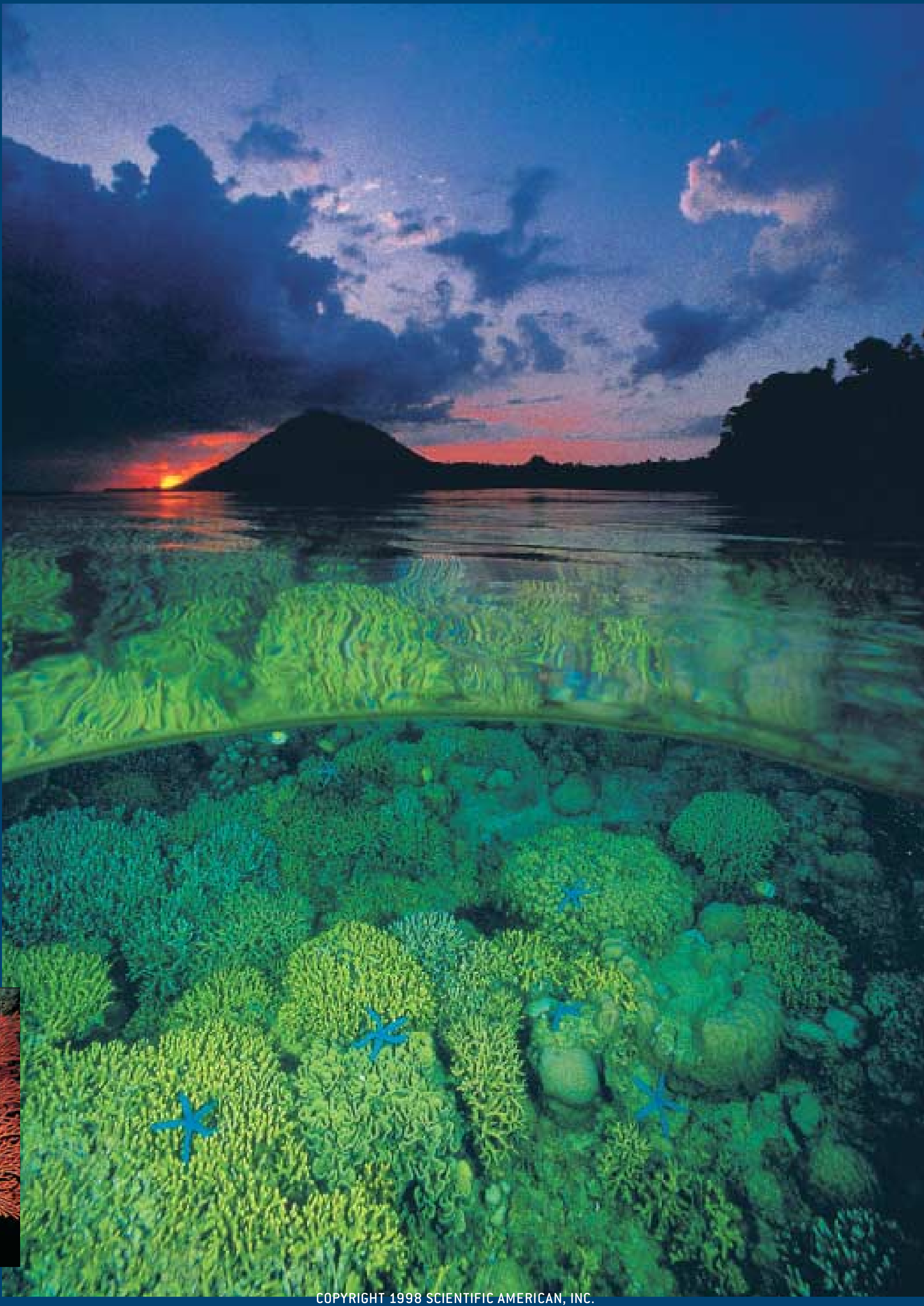

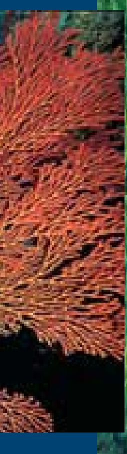

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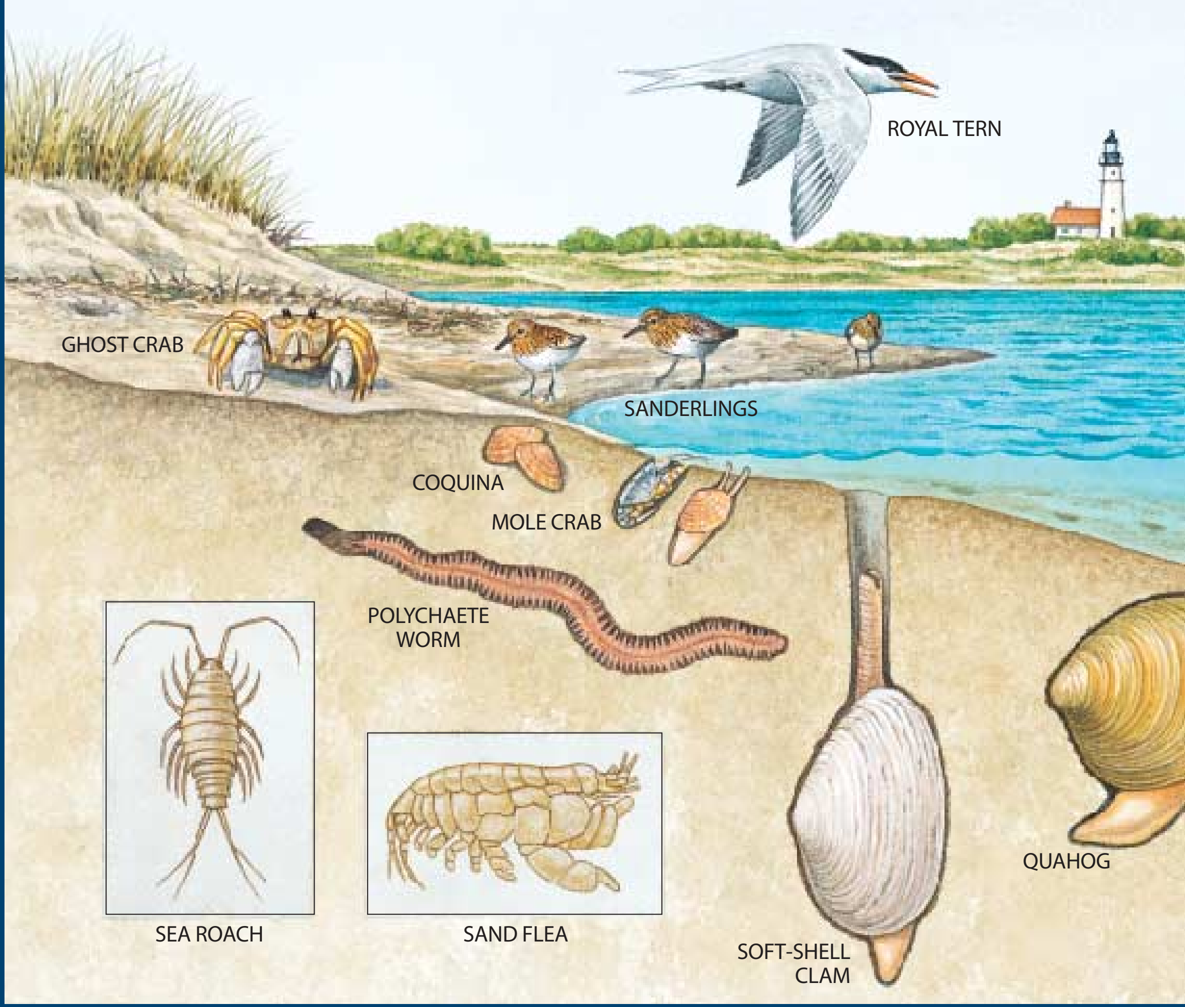
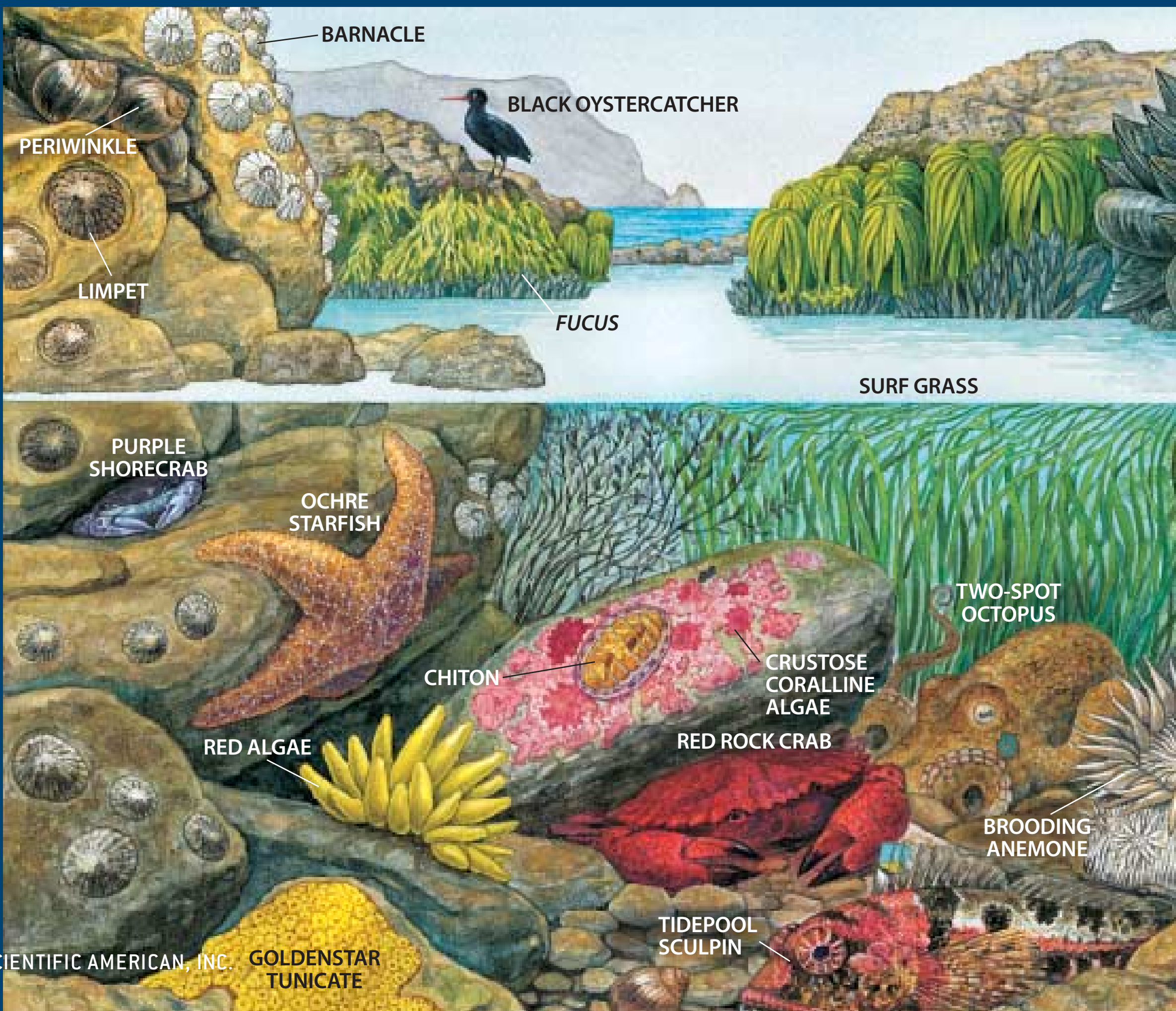
The Intertidal Zone

Near-shore habitats are liminal areas, places simultaneously sea and land, where some forms of marine life can be observed with relative ease. (For that reason, these areas often provide people with a window into the adverse effects of coastal development, habitat destruction and estuarine pollution.) Of the many different coastal ecosystems—including mangrove forests, mudflats and salt marshes—two are shown here: a sandy (*top*) and a rocky (*bottom*) intertidal area. The denizens of these places are familiar to most observers.





CUP CORAL

CLOWN NUDIBRANCH

STRAWBERRY ANEMONE

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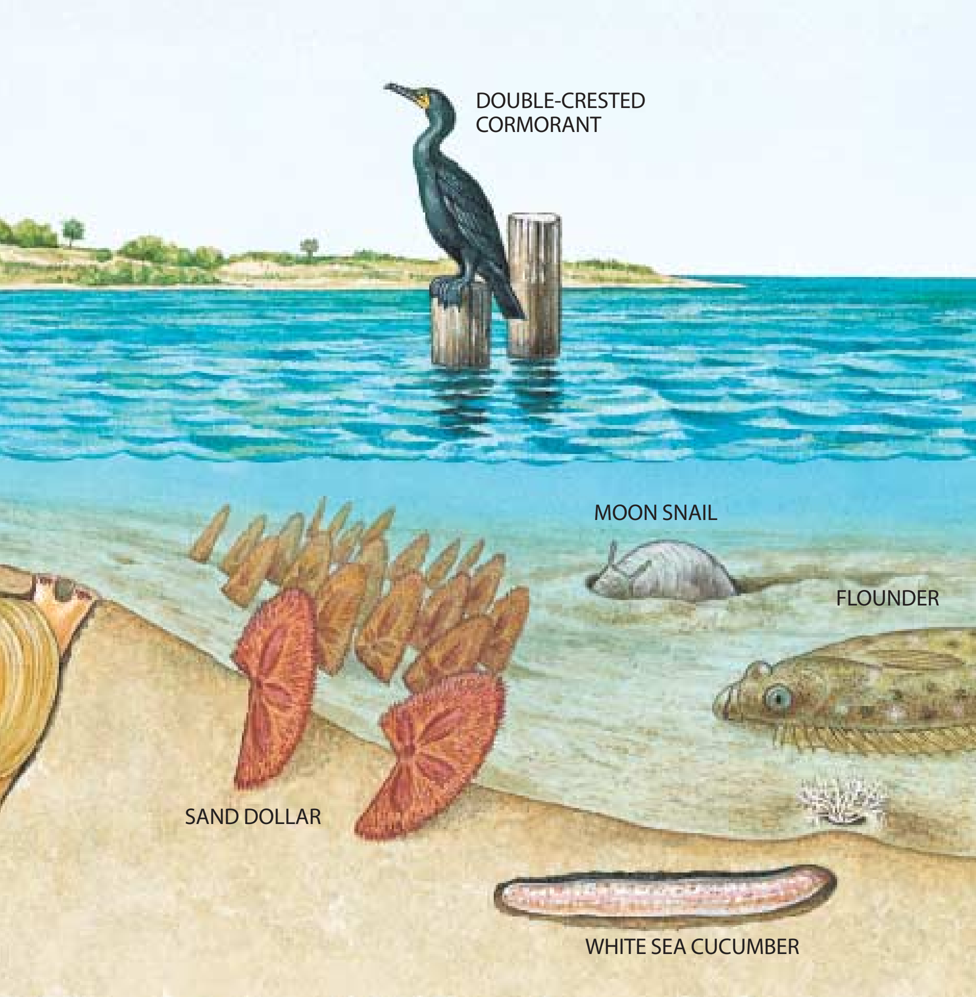

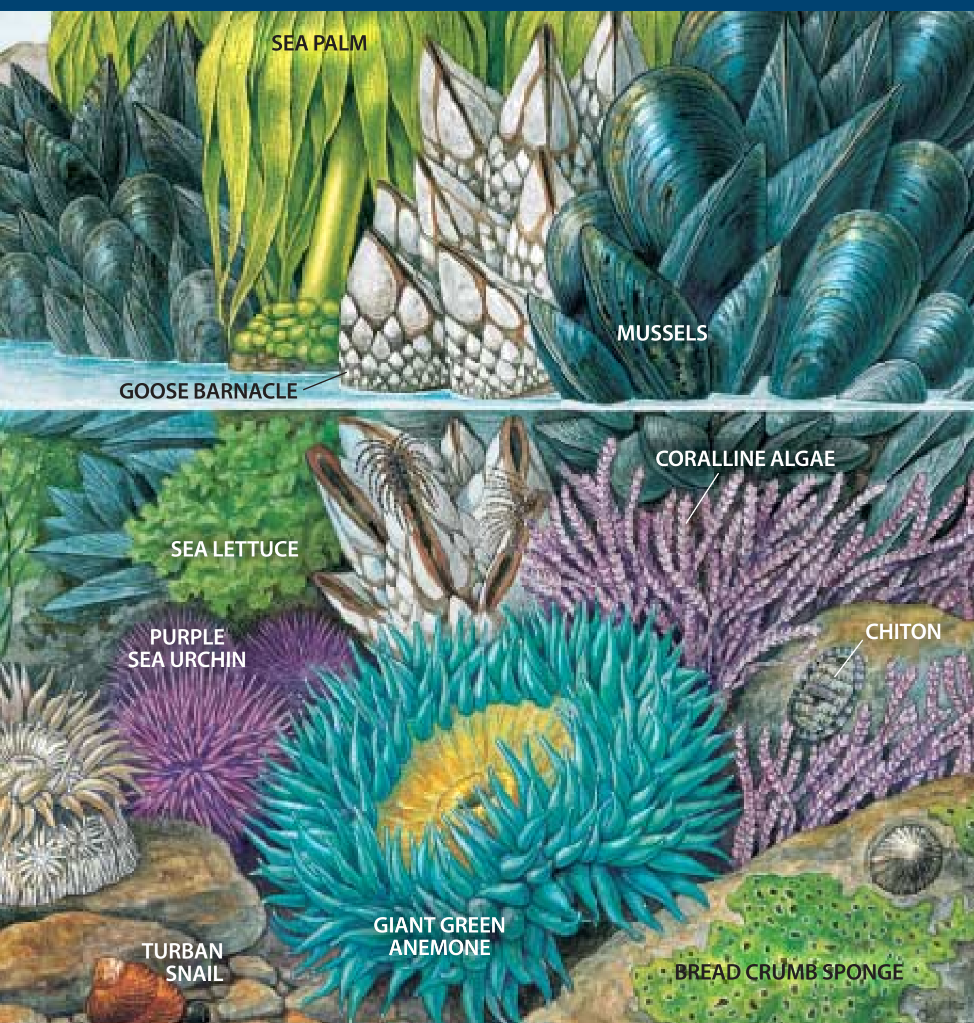

ILLUSTRATIONS BY ROBERTO OSTI; PHOTOGRAPHS BY STEVEN K. WEBSTER

poorly in waters this warm; they are best adapted to temperatures between six and 15 degrees C.

Kelp forests are dominated by the large, brown algae for which they are named. The giant kelp (*Macrocystis pyrifera*) can reach 60 meters in length, stretching 30 meters from the seafloor to the surface and then floating to create a thick canopy. Kelp grow very quickly—as much as half a meter a day in some places. Ninety percent of this plant matter is eaten immediately or washes away to the beach or deep sea, where herbivores later consume it.

These aquatic trees soften the waves and currents and provide food and shelter for many kinds of fish and invertebrates. They are principally grazed by sea urchins and abalone, marine invertebrates that are delicacies for humans and sea otters alike. In some years the urchins get the upper hand, eating the local kelp and other algae—and some invertebrates—to near extinction. It may take several years before the giant kelp can reestablish itself. But in areas where sea otters abound, the urchins are usually kept in check. Indeed, before humans began to hunt for sea otters in the 18th and 19th centuries, populations of urchins and abalones probably never reached the sizes that have supported contemporary commercial fisheries.

Human actions have also profoundly affected many coral ecosystems. These communities are built by stony scleractinian corals, by gorgonians (sea whips and sea fans) and, in the Caribbean, by the hydrozoan fire corals. Scleractinian corals are found in all oceans at a variety of depths. But only the tropical, colonial species construct shallow reefs. These species have photosynthetic dinoflagellates (called zooxanthellae) in their gastric tissues—indeed, 80 percent of corals' soft parts can be made of these creatures. The zooxanthellae photosynthesize and provide the corals with food. These symbiotic dinoflagellates also trigger the corals' rapid calcification, which in turn provides the foundation of the reef structure.

Most reef corals need clear water and a depth of no more than 30 meters so that sunlight can reach their zooxanthellae. The reefs usually do not support many fleshy algae, because grazers—such as sea urchins, parrot fish,

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surgeonfish and damselfish—constantly nibble at any plant growth. In the early 1980s the importance of these grazers was demonstrated when a pathogen killed 99 percent of the long-spined sea urchins in the Caribbean and algae grew unimpeded, crowding out the corals.

A World Ignored

Despite their obvious richness, marine ecosystems have been left out of most discussions about saving biodiversity. Part of the reason is that they are out of sight and, hence, out of mind to many scientists and laypersons alike. Nevertheless, it is important to expand their scope as quickly as possible. Current research suggests that at least 70 percent of the world's fisheries are operating at or beyond sustainable levels [see "The World's Imperiled Fish," by Carl Safina, on page 58], and as human populations grow this pressure will only increase.

The intricate connections between the coastal areas, the surface waters, the midwaters and the deep sea are becoming clearer. If society wants the ocean and its myriad creatures to thrive, people must further study these links—and learn to recognize how human actions can alter, perhaps irrevocably, life in the sea.

The Authors

JAMES W. NYBAKKEN and STEVEN K. WEBSTER share a long-standing love of marine biology and the ocean. Nybakken is professor of biological sciences at Moss Landing Marine Laboratories, where he teaches marine ecology and invertebrate zoology. He received his Ph.D. in zoology at the University of Wisconsin and is the author of several books on marine ecology. Webster is senior marine biologist at the Monterey Bay Aquarium, which he founded 20 years ago with three colleagues. He received his Ph.D. in biological sciences from Stanford University and has taught coral reef biology for 30 years.

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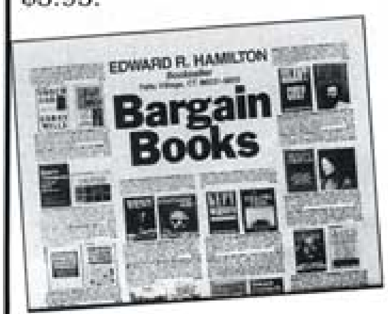

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ATLANTIC OCEAN: *The Atlantic's Wandering Turtles*

The Atlantic's Wandering Turtles

LAURIE GRACE (*map*); WILLIAM F. HAXBY (*globe*)

Newborn loggerhead turtles embark on a transoceanic crossing of thousands of kilometers. Researchers are trying to determine where they go and how they survive in the featureless, blue expanse

by Thomas Dellinger

It is high noon. Around us, the sea is motionless under a clear, blue sky and a scorching sun. In the distance, Madeira Island is a reddish-brown mound emerging from the mirrorlike surface of the water.

On closer inspection, the mirror is dotted with cobbles here and there that disrupt the flat surface. We aim our orange, rubber inflatable boat toward the nearest one and try to make out the droplike silhouette.

These brownish bumps are juvenile loggerhead sea turtles, and they are fast asleep. As we approach the one we've spotted nearby, we attempt to figure out where the head should be. The idea is to come at it from behind, carefully, so as not to wake it.

We glide the last few meters, with the 40-horsepower motor idling. Notwithstanding the noise, the turtle continues its deep slumber. Only when my colleague Carla Freitas bends over the bow of the boat and grabs the shell firmly with both hands does the turtle paddle helplessly with its flippers.

After driving around in the boat for two hours, we have finally made our first capture of the day. There is no time to make measurements of its shell—more properly known as a carapace—and head and flippers, because before long the sleeping turtles will all be gone. This basking behavior, as it is called, happens only around the middle of the day, and each turtle sleeps for only an hour or so. When they resume diving after their nap, we'll have almost no chance of spotting and capturing them. So for this first capture, and all the others that follow it, we simply note the Global Positioning System coordinates, clip the turtle with little metal identifying tags on the inner rims of both foreflippers and leave it in the boat. A short distance away another turtle drowses and is next to be grabbed.

By three o'clock we have hauled in a total of 20 turtles, and there are no more to be seen on the surface. After measuring them, we clean their carapaces, removing the algae and barnacles for later analysis. At about 5:30 it is time to release them into their vast, blue lair. Stroking strongly away from the boat with its front flippers, our first capture appears to have suffered very little from its short time in captivity. After a couple of meters, it pauses and looks back, as though questioning whether the ordeal even took place.

CARLA FREITAS

YOUNG LOGGERHEAD sea turtle named Lìdia was the first outfitted by the author's group with a small data collection and transmission unit, enabling her movements to be tracked in the open ocean. In June, she was between Madeira and the Azores.

Mystery of the Turtles

Where do these turtles come from, and what are they doing here? The first question was answered only recently after several decades of research; the second is the subject of our current work. There are a total of seven different species of sea turtles, all of which are endangered to some extent. Five of these species are seen in the sea surrounding Madeira, its sister island Porto Santo and the Azores. Practically all the turtles seen in these waters are loggerheads, but we are occasionally visited also by leatherbacks, the largest species of sea turtle, as well as by green, hawks-

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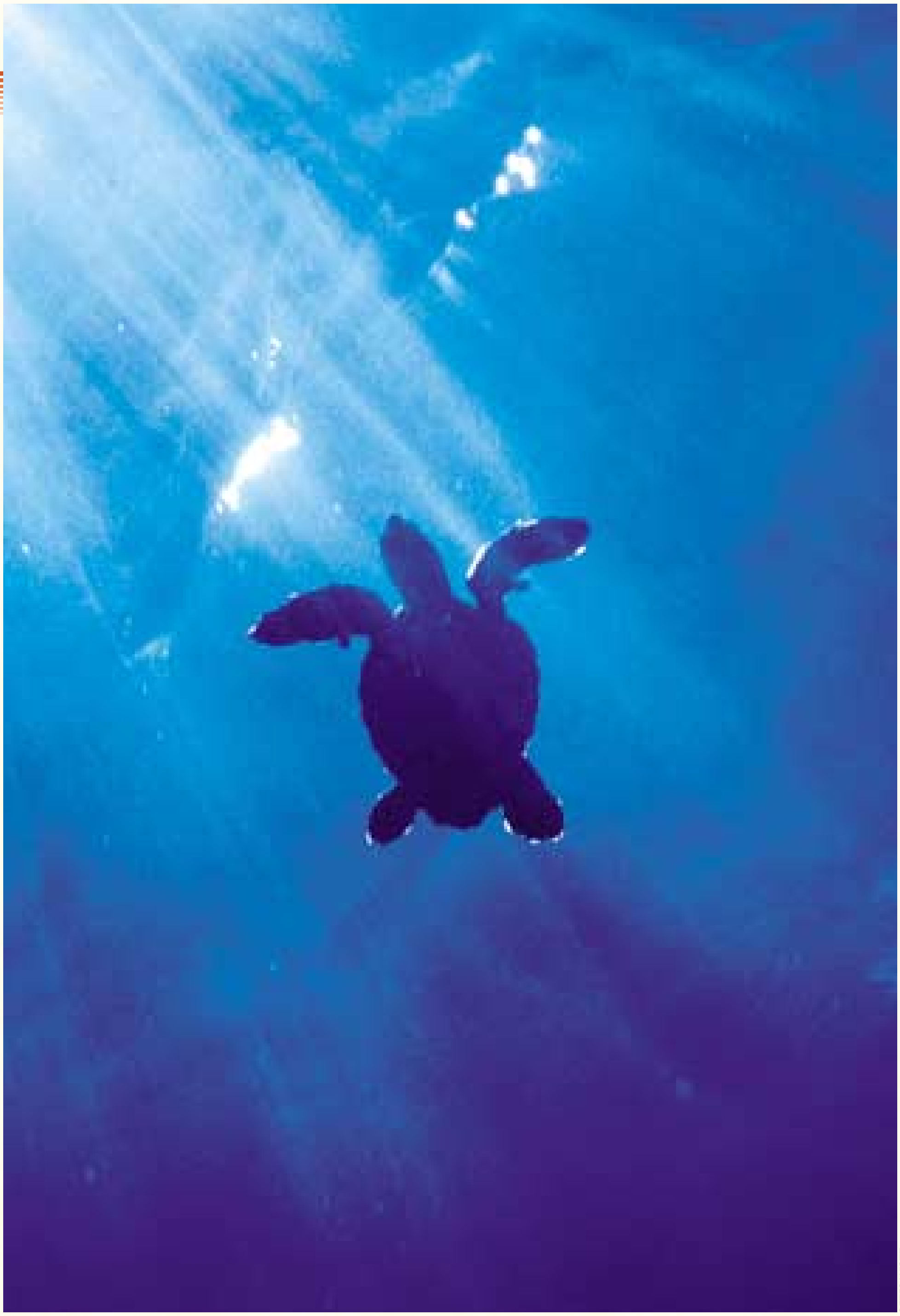

SWIMMING TURTLE was photographed off Funchal, capital of the Madeira Islands in the North Atlantic. After hatching, typically on southeastern U.S. beaches, loggerhead turtles embark on a transatlantic journey that can take a decade or more.

bill and, very rarely, Kemp's ridley turtles.

The profusion of turtles around the Portuguese islands puzzled naturalists for many years. All species of sea turtles lay their eggs in nests dug into sandy beaches, which are in short supply on these islands. Madeira, for instance, has no sandy beaches whatsoever. Porto Santo, on the other hand, does boast a gorgeous, nine-kilometer-long stretch of uninterrupted, white sandy beach—but has no record of turtle nesting.

The lack of turtle nests on Porto Santo was established back in the 1930s, when the island had only a small fishing village and the sandy beach was viewed as an obstacle to fishing rather than as a tourist bonanza. By interviewing fishers, Artur Sarmento, a Madeiran naturalist, found that sea turtles did not nest on the beach.

Almost 40 years went by before someone else took an active interest in the question. While studying stranded and accidentally caught turtles on European coasts, Leo Brongersma, a Dutch scientist, marveled at Madeira's plentiful supply. "I estimate that a thousand (and probably more) are taken each year," he wrote, based on interviews with local fishers and souvenir-shop owners who sold crudely stuffed and varnished turtle corpses to the tourists who poured out of the cruise ships in Funchal Harbor. In 1967 Brongersma noted that most turtles found in British and other European waters were, at 10 to 15 years old, fairly young. Loggerheads, for example, do not mature until they are at least 13 years old and perhaps as old as 30 years, and it is believed they can live from 60 to 90 years (no one knows for sure how long loggerheads can live in the wild). Brongersma proposed that the turtles came from the Gulf of Mexico and suggested that "migrations across the ocean may form part of their normal pattern of life."

On the other side of the Atlantic, meanwhile, the absence of turtles of a certain age and size was puzzling scientists. They saw adult turtles digging their nests on beaches in Florida, Georgia, the Carolinas and along the Gulf coast. They also saw the hatchlings run for their lives down to the sea and disappear into the rolling waves. Then they saw little or nothing of them for a period that American naturalist Archie Carr dubbed the "lost year."

Carr was the driving force behind American efforts to solve the mystery. He collaborated for years with Helen Martins of the University of the Azores, who had measured turtles in Azorean waters and found that their size distribution exactly fitted the gap in the Florida size distribution. Shortly before his death in 1987, Carr elaborated on Brongersma's hypothesis that ocean currents in the Atlantic carry the juvenile turtles from their southeastern U.S. birthplaces to the Portuguese islands and eventually return them to the U.S. later in life for nesting.

The idea that Atlantic currents could carry objects great distances to the east was not new. Even Christopher Columbus is said to have noticed strange objects on the beach at Porto Santo while pondering routes to what he believed to be the Indies (the flotsam helped to convince him that land lay somewhere over the horizon).

Like all other oceans, the North Atlantic has a large-scale, looping current system called a gyre. The North Atlantic gyre starts with the Gulf Stream, which flows northeastward from the Gulf of Mexico, the Caribbean and the waters off the south-

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THOMAS DELLINGER

BASKING BEHAVIOR, in which sea turtles float for about an hour in a deep slumber, occurs around midday. To catch the turtles for tagging, researchers study the bobbing forms and then approach the creatures from what appears to be the rear.

eastern U.S. The Gulf Stream divides itself around the Azores into the northeastward-going North Atlantic Drift and the Canary Current. This latter current then circles around clockwise to the south and begins its return trip across the Atlantic as the North Equatorial Current. Finally, it flows back into the Caribbean and Gulf region as the Caribbean and Antilles currents. Thus, loggerhead turtles born along the U.S. Atlantic beaches are picked up by the Gulf Stream; once there they do not need to do anything except survive and make their way into the Canary Current [see "How Sea Turtles Navigate," by Kenneth J. Lohmann; Scientific American, January 1992]. This way, they reach Portuguese waters both at the Azores and here at Madeira.

A Mystery Solved

During his lifetime, Carr had access only to circumstantial evidence that the turtles in the Portuguese islands are the ones missing from Florida. Yet his former students and collaborators, Alan B. Bolten and Karen A. Bjorndal, worked with Martins in the mid-1980s to tag large numbers of turtles off the Azores; a few were later recovered off Florida.

We now know that loggerheads are found throughout the world's tropical and subtropical waters. Most of the nesting sites of the large Atlantic population are on southeastern U.S. beaches. A smaller loggerhead population lives in the eastern Mediterranean and nests primarily in Greece and Turkey. For Pacific loggerheads, the major nesting areas seem to be in Japan and, to a lesser extent, Australia.

Irrefutable proof for the long, strange trip of the Atlantic loggerheads awaited the genetic-identification techniques that became available in the 1990s. Female turtles generally nest on the same beaches where they were born and therefore have a distinct DNA identity from females born elsewhere. In a project led by Bolten, now at the University of Florida, Martins, Bjorndal, four other researchers and I compared the DNA of female loggerheads taken from Madeira and the Azores with that of females at nesting beaches in the North Atlantic and Mediterranean. Our finding, published earlier this year, was that between 88.1 and 91.9 percent of the turtles at the Azores and Madeira were born on Florida beaches (the rest are probably from Georgia, South Carolina and Cuba). We also showed that the loggerheads found in Madeira and those in the Azores are genetically indistinguishable and therefore are part of the same population.

The so-called lost year of the Atlantic loggerhead is actually not just one year but more like 10 to 15 years. During this time, the hatchling loggerheads are believed to drift for a few months in the Sargasso Sea, sheltered within enormous mats of sargassum seaweed. Then, as juveniles, it seems that they search for and inhabit open-ocean eddies and frontal systems, where their favored foods—jellyfish, squid, various floating dead sea creatures—accumulate. In this stage they are truly "pelagic," living far from the nearest landmasses.

Still, astonishingly little is known for certain about these lost years of the loggerheads. As Carr wrote in 1984, "It is frustrating not to know where the Azores migrants are spending the years it takes them to grow from saucers and dinner plates to the heft of the Florida subadults." The statement remains true to this day.

Understanding more about this stage in the sea turtle's life cycle is the aim of our program, Projecto Tartaruga Madeira. As we accumulate information about juvenile pelagic-stage sea turtles, one of our most important priorities will be using the knowledge to protect them more effectively in the future.

As their numbers declined worldwide

PHOTOGRAPHS BY THOMAS DELLINGER

DATA COLLECTOR and transmitter was attached to the sea turtle Lìdia with fiberglass resin. The 380-gram unit will drop off the loggerhead after about a year.

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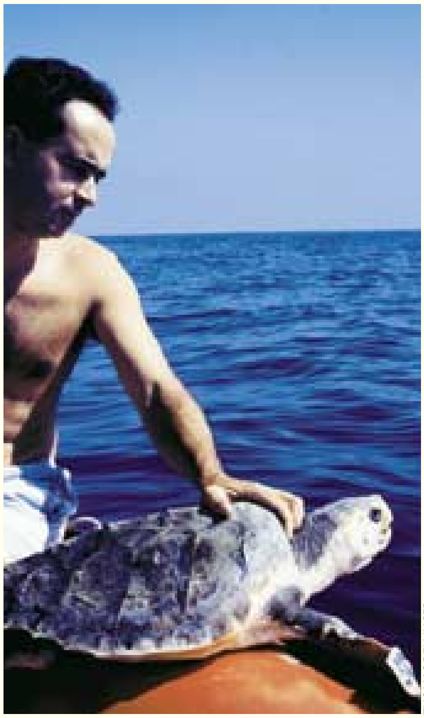
over the past half a century, sea turtles became a "poster species" for animal conservation efforts because they are so defenseless to human encroachment and destruction. In many parts of the world, sea turtles face mortal threats throughout their lives: nesting habitat is being destroyed, eggs are being eaten or trampled, and adults are being caught and sold for their meat and carapaces. In their pelagic habitat, innumerable creatures are killed by longline hooks. Ordinary plastic bags, mistaken for jellyfish and swallowed, bring sea turtles a slow and painful death.

Madeira has been turtle-friendly since 1985, when its parliament proclaimed the first Portuguese law protecting a reptile. Nevertheless, the precarious state of sea turtle populations worldwide is apparent in Madeira, where, according to fishers, turtles are not nearly as numerous now as they have been in the past.

Part of the problem is well-meaning but poorly conceived conservation efforts. Most such activities concentrate on nesting habitat, even though eggs and hatchlings suffer high mortality naturally. Thus, recovery efforts would be more profitably concentrated on the other life stages. Madeira and the Azores are among the very few places right in the middle of the pelagic sea turtle habitat. Concentrating efforts here would probably have the largest effect on the future of breeding populations.

Projecto Tartaruga Madeira started in 1993 as a tagging program. Indeed, we still go out regularly to catch and tag turtles, and whenever I am stuck sifting through piles of paper on my desk I am generally looking forward to another day out at sea. So, luckily for me, tagging still plays an important role in our work. We use metal tags a few centimeters long bearing a unique identifying number, the name and address of the Archie Carr Center for Sea Turtle Research at the University of Florida, and the promise of a small reward for the return of the turtle and tag. The main objective of the tagging program is to measure how much a given creature has grown between taggings. The secondary objective is simply to record where it went.

Though useful and economical, tagging cannot answer many of the most pressing questions about these animals, whose home is the vast, open ocean. For example, we need to know if turtles prefer certain areas within this vastness and, if so, how they use them. Exactly where do they feed, and where do they rest? Do they form groups or lead essentially solitary existences, like humans in big cities? We need this information so that we can evaluate it in terms of what we know about the threats to sea turtles. Once we have the data on the turtles' feeding grounds and other preferred habitats, for instance, we can begin comparing them with the areas frequented by fishing trawlers. And when we know how long the turtles stay near densely populated islands, with their constant output of plastic and other rubbish, we can get a better idea of the extent of the threat posed by the trash.


THOMAS DELLINGER

TAGGED LOGGERHEAD is about to be released by Renato Barradas, a technician at the University of Madeira.

Only satellite-based tracking can provide this kind of detailed geographic information. So last spring, with funding from the European Union's Life Program, we began a new initiative in which we are affixing small data recorder–satellite transmitting units to the carapaces of sea turtles. The units, which weigh only 380 grams, are affixed to the carapace with a fiberglass resin in such a way that as the carapace grows, after about a year it eventually forces the unit to drop off (the same resin is used to repair broken carapaces of sea turtles).

Each unit has a depth sensor that records data on the creature's vertical movements in the water. Twice a day, when the turtle is on the surface, signals are beamed to satellites operated by the U.S. National Oceanic and Atmospheric Administration. Under a tracking service that uses the satellite and is run by a joint French-U.S. venture called Argos, we can download updates over the Internet two hours after information is beamed from a turtle. We outfitted our first turtle, a loggerhead we named Lìdia, on April 1 and released her just off Funchal. Freitas and I and another colleague, Idoya Cabrera, attached the satellite transmitter and covered it with a glass-fiber protective coating, with the help of Bolten.

Every day Freitas and I connect to the space center in Toulouse, France, and excitedly type the commands and passwords to find out what Lìdia has done in the past 24 hours. The little technical wonder on her back not only reports Lìdia's position every day but also tells us how often, for how long and how deep she dived during the previous day, and how often she rested. Such information has never before been collected on sea turtles. We found that Lìdia had spent the first month with her transmitter swimming and diving in the waters off Madeira. Then she headed north, in the direction of the Azores; as of early June, she was in open ocean roughly midway between Madeira and the Azores.

Within three weeks of Lìdia's release, another four creatures had been outfitted with the units and released off Funchal. They all headed in a more westerly direction than did Lìdia. Our plans are to similarly equip and track a total of 10 sea turtles.

We hope this excitement will translate soon into knowledge that can be put to use in protecting not only turtles but a variety of other pelagic creatures, such as the American wreckfish, that migrate in the open ocean. As Madeirans, we would be especially proud if, in this International Year of the Ocean, our budding project leads eventually to methods of bolstering pelagic populations. EXPO '98, the centerpiece exposition of International Year of the Ocean activities, is being held in Lisbon, where the Madeira Pavilion is showing a film in which our turtles appear.

We Portuguese boast that we have given new worlds to the world. It would therefore be fitting for us if our work on pelagic-stage sea turtles helps to conserve the open-ocean habitat—a world in its own right, which only true international cooperation can save.

THOMAS DELLINGER is assistant professor of biology at the University of Madeira in Portugal.

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COURTESY OF RAYMOND A. BINNS

The Mineral Wealth of the Bismarck Sea

Discoveries of valuable minerals on the floor of the southwestern Pacific have renewed interest in deep-sea mining. But can metallic ores be recovered there without endangering marine ecosystems?

by Raymond A. Binns and David L. Dekker

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Last November the government of Papua New Guinea granted a private company permission to prospect for minerals on the floor of the adjacent Bismarck Sea. Other mineral deposits on the bottom of the ocean had drawn attention during the 1960s and 1970s, when people talked about mining zinc-rich oozes two kilometers (1.2 miles) down on the bed of the Red Sea or of harvesting nodules with nickel and copper from five-kilometer-deep abyssal plains in various parts of the world. In more recent years, some have considered mining volcanic seamounts encrusted with oxides thought to contain cobalt and platinum. Yet none of those submarine deposits proved sufficiently valuable to make their extraction worthwhile. So why have the deposits under the Bismarck Sea sparked commercial interest now?

The difference is that the newly found sources of ore on the seabed are massive sulfides, dense minerals rich in copper, zinc, silver and gold. To prospectors, massive sulfides are a familiar prize, because these minerals are often mined on land for their metals. Unlike other deep-sea deposits previously considered for mining, the massive sulfides of the Bismarck Sea occur at relatively shallow depths (less than two kilometers). They also lie in calm waters within an archipelago of Papua New Guinea, which thus owns the right to mine them under international law. These attributes, along with the richness of the deposits, make them much more attractive than any deep-sea mineral prospect ever before contemplated.

Scientists first discovered massive sulfides on the seafloor two decades ago in the eastern Pacific using the research submersible *Alvin*. Marine geologists have since found more than 100 similar sites in the Pacific, Atlantic and Indian oceans, all located on ridges where hot magma rises and tectonic plates spread apart. But the massive sulfides of the Bismarck Sea are found in a completely different geologic setting. There metal-rich minerals occur at a subduction zone, where one plate thrusts below its neighbor. The descending slab heats up and gives rise to magma that may erupt onto the ocean bed. Although geologists have only just begun to examine the seafloor for its mineral wealth, they believe that ores in subduction zones may be much richer in valuable metals than those found at mid-ocean spreading centers. Curiously, until about a dozen years ago no one knew that the seafloor near subduction zones contained economically interesting deposits at all.

A Lucky Find

In 1985 marine researchers from the U.S. set sail to the southwest Pacific to study plate tectonic movements. In the course of their expedition, they towed an underwater camera close to the seafloor and were

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METAL-RICH CHIMNEYS called black smokers spew sulfurous particles from the seafloor near Papua New Guinea, as seen in these video mosaics.

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C. TAYLOR CSIRO

CROSS SECTION of one of the chimneys collected from the flanks of the undersea volcano Su-Su shows an enrichment in copper throughout.

lucky enough to photograph a patch of massive sulfides in the middle of the Bismarck Sea, well away from the major oceanic spreading ridges. Their serendipitous discovery was later dubbed the Vienna Woods because the deposits form a dense forest of narrow chimneys called black smokers, which exude hot water and clouds of black particles superficially resembling smoke. The hot water leaches metals from deep in the crust and deposits them in the walls of the chimneys as it cools.

The Vienna Woods site has since been visited by a German research vessel, which collected large pieces of the massive sulfide chimneys, by Russia's two *Mir* submersibles (now famous for their role in the movie *Titanic*) and by Japan's *Shinkai-6500* submersible. Scientists do not yet know the full extent of these "woods." But this locus of hydrothermal activity must hold an appreciable amount of metal, with its countless towering smokestacks—many 10 to 20 meters high—set on massive sulfide mounds that are 20 to 30 meters across. And this site is not the only metalliferous zone in the region.

In 1991 one of us (Binns) set off with a group of scientific colleagues on an expedition to a depression on the bottom of the Bismarck Sea called the eastern Manus Basin. We were not seeking to discover exploitable mineral deposits but rather to find a natural laboratory where we could examine how this type of massive sulfide ore forms. Our ultimate goal was to facilitate the search on land for such deposits, which can be found buried within slices of former seafloor that had long ago thrust onto the continents.

At the beginning of this expedition, our strategy was to dredge pieces from various submarine volcanoes and pick out those samples that best matched the rocks hosting such ores on land. We also towed an underwater video camera over the sea bottom at many sites and lowered special instruments in hopes of detecting the plumes of cloudy water emitted from black smokers. We scrutinized hours and hours of video recordings, searching for the characteristic shape of hot spring chimneys or for concentrations of sea life known to form biological halos around deep-sea vents.

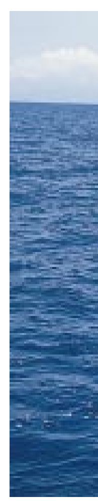
The first video sighting of volcanic chimneys in the eastern Manus Basin occurred about 170 kilometers east of the Vienna Woods. The view lasted only a few seconds, but it was unmistakable. People mumbled words like "El Dorado" as excitement spread through the ship, galvanizing both scientists and crew for the four days of dredging and deep-sea photography remaining in our tight schedule.

In the time allowed us, we mapped deposits scattered over several kilometers and named the site PACMANUS, after the nations involved in the expedition (Papua New Guinea, Australia and Canada) and the Manus Basin. Our attempts at dredging failed, but we managed to recover a few grams of these massive sulfides before our expedition came to an end. And the re-

AUSTRALIAN RESEARCH VESSEL *Franklin* (*left*) carried investigators to the Bismarck Sea. A system for detecting and sampling plumes of hot, particulate-rich water (*center*) helped them home in on the deposits, as did their underwater video camera (*right*).

RAYMOND A. BINNS

C. TAYLOR CSIRO



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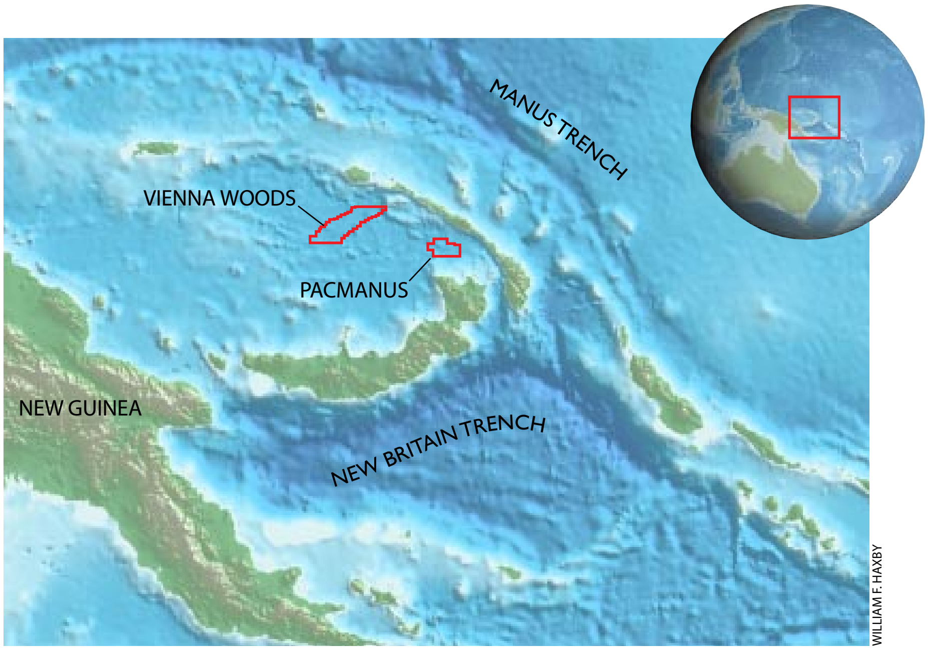
sults of that initial foray prompted us to go back. In the course of six more research cruises, including two that employed piloted submersibles, we—along with an expanded group of colleagues from France, Germany and Japan—have been able to inspect these remarkably rich deposits at close range and to collect numerous samples containing high concentrations of copper, zinc, silver and gold.

After mapping the area in detail with the help of many other investigators, we now know that these accumulations of metallic minerals extend for 13 kilometers along the top of a volcanic ridge made of dacite, a type of lava that is rare on the ocean floor. The greatest concentration occurs within a two-kilometer part of the ridge, where several fields of active chimneys dot the bottom. The people involved in their discovery have given them playful nicknames such as "Roman Ruins" (where fallen chimneys are especially common), "Satanic Mills" (where the chimneys belch out particularly thick clouds of black particles) and "Snowcap" (where a white bacterial mat coats a small hill). To those fortunate enough to see them, the diversity of sights in the Manus Basin is indeed tremendous.

In 1996 we participated in the discovery of yet another accumulation of massive sulfides, 50 kilometers east of our previous find and not far from the port of Rabaul, Papua New Guinea. Having improved our techniques for finding black smokers, we rapidly homed in on the site by tracking a large plume of sulfide particles emanating from the twin peaks of an undersea volcano named Su-Su. (This apt if unoriginal moniker means "breasts" in Melanesian Pidgin.) Densely packed chimneys cover a 200-meter-long strip of seafloor on the flanks of one summit. These massive sulfides proved to be more richly endowed with precious metals than any we had sampled before at PACMANUS.



EXPLORATION RIGHTS have been granted to Nautilus Minerals Corporation in two locales (*red*) within the national waters of Papua New Guinea. The New Britain Trench marks the site of ongoing subduction, whereas the Manus Trench has long been inactive.

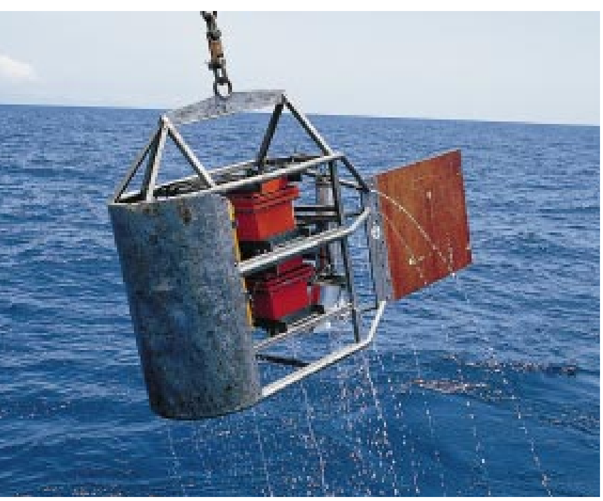
Money Matters

Current evaluations suggest that each cubic meter of rock in these deposits is worth about $2,000, which almost certainly means that ore could be extracted, raised to the surface and processed at a tidy profit. But Nautilus Minerals Corporation (based in Port Moresby, Papua New Guinea, and Sydney, Australia), which obtained the licenses to explore for minerals on the floor of the Bismarck Sea, has much work to do before it can begin deep-sea mining operations. We and our co-workers at the Commonwealth Scientific and Industrial Research Organization in Australia are now doing studies under contract from Nautilus to help the company face the many challenges ahead.

First, Nautilus must carry out a thorough examination of the area to determine the extent of the massive sulfides and to estimate the amount and grade of ore available at each deposit. This work will initially involve dredging samples from the bottom with high precision in many places and perhaps drilling into the seafloor at selected spots. Geologists hired by the company will have to study the ore carefully to evaluate the density, porosity, abrasiveness and mechanical properties of this sulfide-rich rock. Mining engineers can then begin the task of developing special methods for excavating, hoisting and processing the ore.

Remotely operated equipment like that used to dig trenches or shovel ore in an open pit mine presumably offers the most straightforward means for scooping up the minerals. Hoisting ore to the surface by cable would work but might be prohibitively time-consuming and expensive, given the 1,000 tons or so of rock the company would probably want to raise each day. Perhaps the engineers will favor a scheme similar to the one used in 1978 on board the *Glomar Explorer,* which successfully deployed a series of buckets on huge conveyors to retrieve metal-rich nodules from the floor of the Pacific. Lifting a slurry of crushed ore with pumps might also be a workable tactic.

Siemag Transplan, a German firm, has in fact developed just such a system. It can lift particles of rock or coal from deep in a mine using a U-shaped tube, with water pumped down one leg and a wet slurry of ore rising up the other. Similar devices might perform even better under the sea, because the pressure at the bottom of the pipe could be adjusted to match that of the seafloor. If the velocity of water in the pipe is maintained at several meters per second, the upward force would be sufficient to lift small chunks of rock that are a few centimeters across. But whatever method proves best, before seeking approval from the government of Papua New Guinea,



C. TAYLOR CSIRO

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Nautilus must first show that the mining it plans to do will not harm the biota living in this unusual seafloor environment.

Some Like It Hot

The active chimneys on the floor of the Bismarck Sea are teeming with marine life of extraordinary and stunning variety. At these depths, no sunlight penetrates, so photosynthesis of the kind that sustains life near the surface is impossible. The energy source for the communities living around the chimneys is chemical.

These and most other deep-sea hydrothermal vents emit hydrogen sulfide, which nourishes specialized bacteria living around them. The microbes form the bottom link of a strange food chain coupling them to bacterial-mat grazers, symbiotic organisms, carnivores and scavengers. Such deep-sea vent communities were first recognized in 1977 and 1979, when *Alvin* descended to hot springs west of Ecuador on the Galápagos Ridge and the nearby East Pacific Rise. The scientists found heat-resistant microbes, such as *Pyrolobus fumarii* and other so-called hyperthermophiles, growing in the walls of these vents and thriving at searing temperatures of about 105 degrees Celsius (221 degrees Fahrenheit).

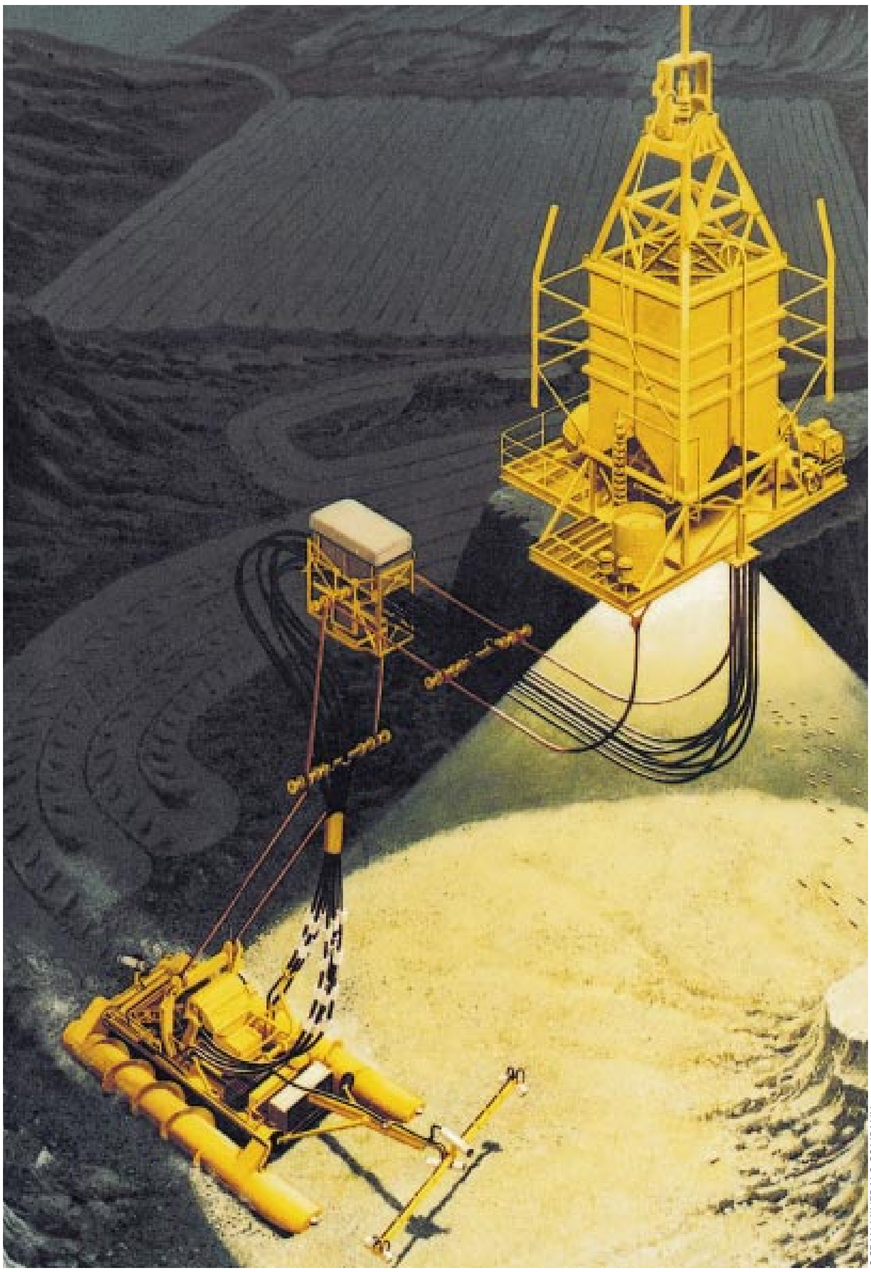
Of the more than 300 species of organisms since recognized at such sites, the vast majority proved to be new to science. Although tube worms and clams predominate at the hydrothermal vents of the east Pacific and mid-Atlantic, the dominant animals around the active chimneys of the Bismarck Sea are gastropods (snails). On the outside of some chimneys, a square meter of surface can be covered by as many as 400 gastropods, accompanied by bresiliid shrimp, carnivorous bythograeid crabs, scavenging zoarcid fish and galatheid crabs. On the cooler fringes of the hot springs, there are mussels, several newly recognized kinds of anemones and long-necked barnacles, which until recently were thought to have died out with the dinosaurs at the end of the Mesozoic era, 65 million years ago. At Vienna Woods, Russian biologists have measured as many as 5,000 animals packed onto a single square meter of chimney wall.

Clearly, mining these sites would be unacceptable if it threatened this unique biological assemblage. The diversity of these organisms and their potential value to biomedical research or as a source of pharmaceuticals remain largely unknown. But a number of observations suggest that the environmental effects of mining this habitat may not be especially worrisome.

The fauna in question normally tolerate highly acidic waters containing sulfur, thallium, arsenic and mercury. So the release of these substances from mining into the surrounding water should not harm the local biota. Indeed, when the venting of hot water carrying these seemingly toxic elements ceases, the colonies either die or migrate to a more active site. What is more, these vent creatures live quite happily in conditions in which the seawater is thick with particulate smoke as well as clouds of dead and partly mineralized bacteria. And they are perfectly capable of surviving the strong earthquakes that repeatedly disrupt these volcanic fields, snapping tall chimneys like matchsticks and raising tons of sediment into suspension.

Although the vent communities appear quite resilient, great care is still warranted. One cautious strategy would be to mine progressively up-current, selecting sites where the flow would carry clouds of fine particles and other mining debris away from the intact deposit. In this way, if only part of the area is mined, the rest of the deposit and its fauna will remain undis-

DEEP-SEA MINING METHODS being considered by Nautilus Minerals Corporation include a scheme worked out two decades ago by Ocean Minerals Company for harvesting manganese nodules from the bottom of the sea (*artist's conception shown below*).



OCEAN MINERALS COMPANY

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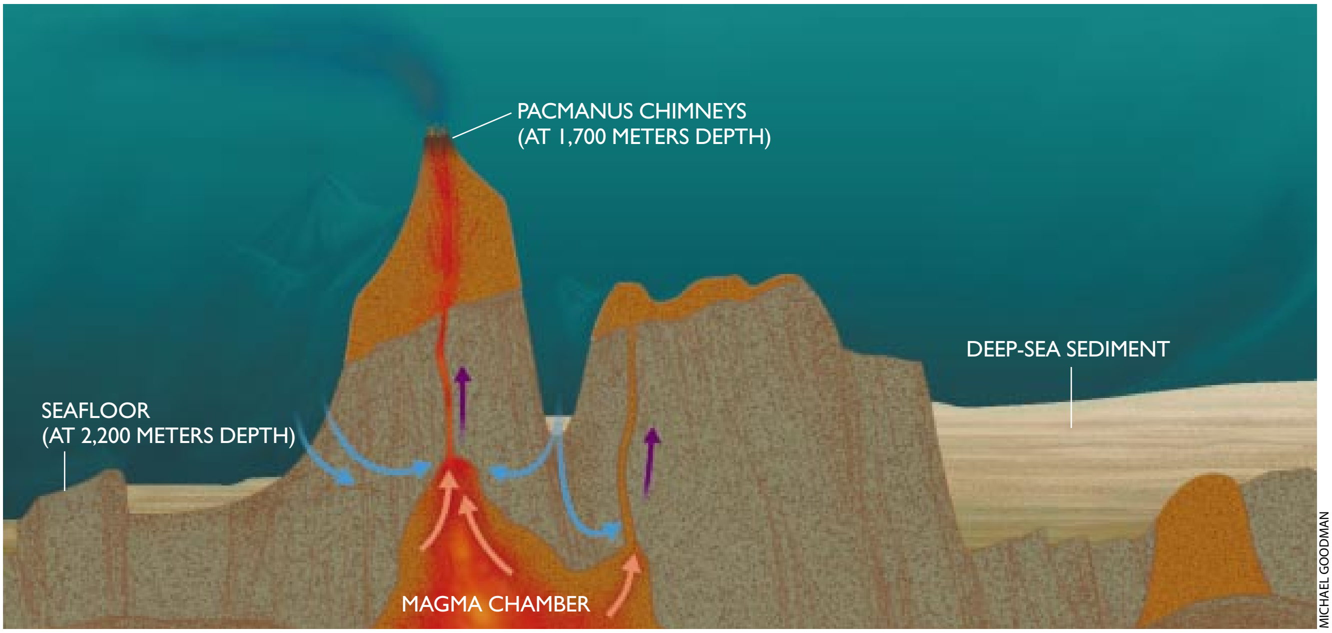

MASSIVE SULFIDES of the PACMANUS fields form above a buried magma chamber (*orange*). Cold seawater (*blue arrows*) percolates deep into the crust, where it warms and mixes with fluids from the magma (*pink arrows*). The combination (*purple arrows*) then rises carrying dissolved metals, which drop out of solution at the seafloor, forming sulfide chimneys and particle-laden plumes.

turbed. The creatures living there could then recolonize nearby mined-out areas that were still actively venting.

Hidden Treasures

Even if it were deemed desirable to preserve the vent communities in their entirety, it may still be possible to extract valuable minerals from formerly active chimneys that are now largely devoid of life. The challenge is finding such sites. We have learned how to home in on active hot springs quite readily by following their plumes with special detectors. Yet this method will not lead us to dormant vents. Nor will detailed photographic surveys of the seafloor necessarily reveal older deposits: many of these extinct chimneys are completely covered by the ooze that is forever settling on the bottom.

Fortunately, a variety of geophysical techniques routinely employed to hunt for concealed ore deposits on land can be adapted for use on the seafloor. Gravimetric mapping should detect the larger deposits, and magnetic or electromagnetic techniques could pinpoint smaller accumulations of massive sulfides. Measurements of the resistivity of crust might also delineate buried sulfides (assuming that engineers can find a way to inject electric currents into the seafloor for such surveys). And the natural radioactivity of potassium, uranium and thorium in exposed but inactive chimneys might be sufficient to signal their presence to prospectors towing sophisticated sensors over the seafloor. This technique could provide an easy way to find dormant chimneys without having to conduct laborious video or photographic surveys of the bottom.

Although we are optimistic that the necessary procedures can be worked out so that the vent communities of the Bismarck Sea will not be endangered, we believe mining should not proceed on the basis of what some might call hopeful speculation. Instead a rigorous program of research and testing should precede any decision to move forward with mining, even in a limited way.

At this early stage, as with most ambitious new endeavors, the proposition of mining deep-sea hydrothermal vents is fraught with questions. Yet plucking valuable metals from the bed of the ocean is a tantalizing concept, one that intrigues us immensely. Sizing up the threat to the biota and the true economic potential of these deposits will require an immense effort—but it may ultimately yield immense rewards. SA

The Authors

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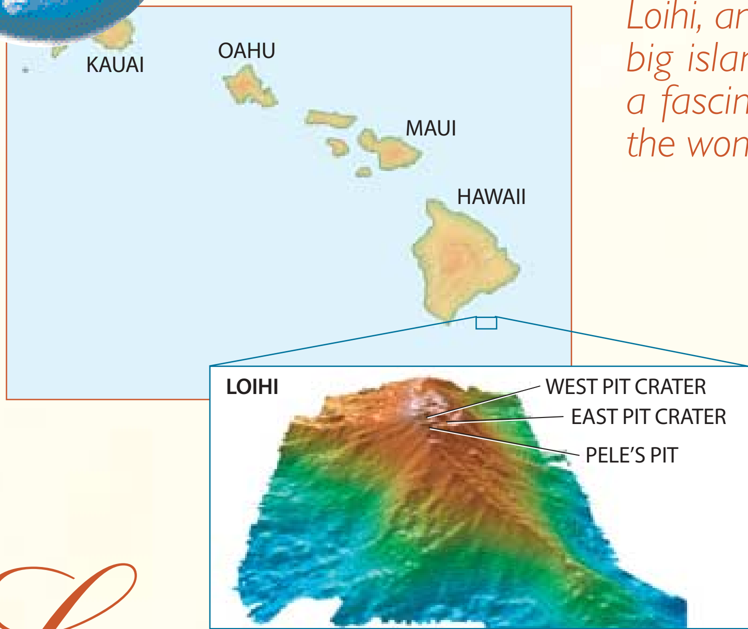
WORLD TOUR

PACIFIC OCEAN:

An Island Is Born

Loihi, an undersea volcano south of the big island of Hawaii, offers geologists a fascinating glimpse of an "island in the womb"

by Alexander Malahoff



LAURIE GRACE (*map*); WILLIAM F. HAXBY (*globe*); J. R. SMITH (*contour map*)

Lying on my left side, peering through the small porthole, I gazed on a fantastic, jagged undersea landscape, just 47 days old. No human had seen it before. I was 1,328 meters (4,357 feet) below the sea, at the very bottom of a brand-new pit crater in Loihi, an undersea volcano 34 kilometers south of the big island of Hawaii.

Before July 16, 1996, the top of Loihi was marked by two pit craters, each about one kilometer in diameter and 300 meters deep, and a large hill, known as a cinder cone, underlain by magma (molten rock). Then, by August 10, and for largely unknown reasons, the magma inside the cone withdrew into the volcano's interior "plumbing," and Pele's Cone, as we called it, collapsed in a volcanic event as cataclysmic as the Mount St. Helens eruption in 1980. Some 300 million tons of rock fell into the volcano, creating a third pit crater, which my colleagues and I now call Pele's Pit.

We made our momentous first descent into Pele's Pit on September 15 on board the research submersible *Pisces V,* operated by my group at the University of Hawaii's Undersea Research Laboratory. Three of us—pilot Terry Kerby, co-pilot Allen Wright and I—were squeezed into the sub's tiny command sphere, which is just under two meters in diameter and crammed with electronic and mechanical equipment, gauges, dials, video monitors and levers. We wore thick layers of clothing and woolen caps in the unheated sphere to ward off the cold of the ocean depths. As I lay on my left side on a small bench on the port side of the sphere, Wright was across from me, on his right side. Between us, Kirby, kneeling, peered intently through the center porthole as he maneuvered the ship over the terra incognita.

The sights we saw were straight out of a science-fiction movie. As we drifted over the edge of the new crater, preparing to descend, we glimpsed the top of a rock pinnacle, one of a dozen or more left standing when the rock around them collapsed into the volcano. The pinnacle, the likes of which we had not seen in the other craters, was hundreds of meters tall. It loomed up in our lights like a skyscraper-size stalagmite.

The water was still murky from the upheaval, so we relied primarily on sonar to guide our cautious descent. When we arrived at the bottom, I was amazed to see that in the five or so weeks since the collapse, large mats of hydrothermic bacteria had already formed near the vents where water, superheated and expanded by contact with the underlying magma, shot out.

At that moment we had no time for gawking, however. We found ourselves close enough to a vertical wall to be entombed if a landslide happened to come down it. And judging from the relatively fresh piles we had seen, there had been frequent landslides, prompted by the many seismic spasms that had followed the collapse. So we retreated to an area with a gentler slope, where we set the craft down at a depth of 1,297 meters. All around us, hot vents shimmered in our lights, which played over rocks covered with the huge, white mats of bacteria. We videotaped these mats and backed up to visit some other vent sites about 20 meters away.

But as we viewed some mats at a depth of 1,310 meters, we were snapped out of our engrossment by the unmistakable, high-frequency rattle over the hydrophone of rocks sliding down the inner walls of the crater. "Landslide," I said.

"Yeah, landslide," Wright agreed. "Coming toward us."

Kerby, a veteran of some 300 dives in the *Pisces V,* quickly steered us toward the cen-

HUGE OCTOPUS, over three meters (10 feet) long, was captured on the summit of the Loihi volcano using a submersible's manipulators, but it escaped in a cloud of ink as the craft ascended.

PHOTOGRAPHS BY ALEXANDER MALAHOFF

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PISCES V SUBMERSIBLE (*above, left*) is lowered from its support vessel, the *Ka'imikai-o-Kanaloa*. Ocean-bottom observatory (*above*) has a time-lapse video camera on top, a seismometer to the right and temperature probes, which are inserted into hot-water vents.

ter of the pit crater and jettisoned our ballast weights, initiating a slow, buoyant ascent to the surface. By ascending from the center, not only would we be safely away from debris falling along the inner walls of the crater, but also we would eliminate the possibility of colliding with, and becoming trapped under, any rock ledges that may have formed on the inner walls.

Birth of an Island

Even before the cataclysmic formation of Pele's Pit, Loihi presented a unique opportunity for geologists: the chance to monitor closely an island in the making. The underwater volcano sits above a hot spot, the very same one that has been forming the Hawaiian island chain over the past 85 million years. (A hot spot is a local source of the heat embedded deep within the earth.) In dozens of places around the earth, the heat expands parts of the plastic, deformable rock deep down in the mantle. This expanded rock, now less dense than its surroundings, rises through the mantle toward the surface, much like a hot-air balloon in the atmosphere. Why this heat wells up in some places and not in others is not well understood at present.

The rising rock ultimately reaches and cracks the lithosphere, the relatively thin and brittle slab on top. The upwelling rock liquefies as it is released from the high-pressure mantle, and the resulting magma comes up through the cracks. An example of this magma is the lava flowing from a hot-spot volcano during eruption.

Because the earth's tectonic plates are in motion, the upwelling of rock can crack the lithosphere in a series of places as a plate moves relative to the hot spot over millions of years. In the case of the Hawaiian chain, the Pacific plate is moving to the northwest at 9.6 centimeters a year. This fact explains why the chain is oriented as it is.

Some five million years ago magma flowed up through underwater volcanoes and formed the chain's northwesternmost high islands, Niihau and Kauai. Then, as the plate moved northwest, it carried the newly formed islands off the hot spot. As they were moved off the underlying source of their heat, the volcanoes went dead, and new, active volcanoes formed underwater over the spot. The process repeated itself until a succession of volcanoes created, in order, Oahu, Molokai, Lanai, Maui, Kahoolawe and, finally, the big island of Hawaii. In fact, the big island is so young, at less than a million or so years old, that it is still partially over the hot spot. At present, the same upwelling of heat that feeds Loihi, just to the south, is also feeding the Kilauea and Mauna Loa volcanoes on the big island.

Percolating Magma

Our dives to Loihi on board the *Pisces V* and other research submersibles have added many fresh details to geologists' understanding of the long, convulsive process by which a volcanic island is born. We are using a variety of instruments to make sonar images of the volcano, to record its seismic spasms, to monitor the temperature and chemical composition of the emissions from the vents, and to record the salinity of the water at many different sites.

By analyzing and combining these data, we are slowly piecing together a picture of the volcano's interior, whose most important feature is a large chamber of magma. Driven by the heat from below, the percolations within this magma chamber are responsible for most of the key phenomena that interest us—for example, the volcano's growth, earthquakes and collapses, such as the one that formed Pele's Pit two years ago.

Changes in temperature at the many vents scattered all over the volcano, from the base to the summit, are an indication of how the hot magma is moving inside the chamber. Chemical analyses of the superheated water shooting out of the vents also reveals much about this magma.

We have also been studying the bizarre menagerie that congregates around the vents, living off the chemicals, such as hydrogen sulfide and methane, that come up with the hot water. The organisms include iron- and sulfur-oxidizing bacteria and hydrothermal worms (Vestimentifera). Up a link in the local food chain, a species of shrimp (*bresiliid*) feeds on the bacteria, and (continuing upward) a variety of larger creatures drop in opportunistically to feed on the shrimp or other organisms. We often see goosefish and various deepwater fin fish and were once treated to the sight of a 3.2-meter-long octopus (*Cirroteuthis, opposite page*), which we unsuccessfully attempted to capture. Over the years, we have seen perhaps 100 different species of animals, including 20 or 30 species of soft corals.

In all probability, scientists will be monitoring Loihi for the next 50,000 years, by which time it will have broken the surface and emerged as the next island in the Hawaiian chain. Hundreds of thousands of years after that event, another volcano will rise from the seafloor southeast of Loihi, and yet another Hawaiian island will start taking shape in this watery womb of the Pacific Ocean.

ALEXANDER MALAHOFF is professor of oceanography and director of the Hawaii Undersea Research Laboratory at the University of Hawaii at Manoa.

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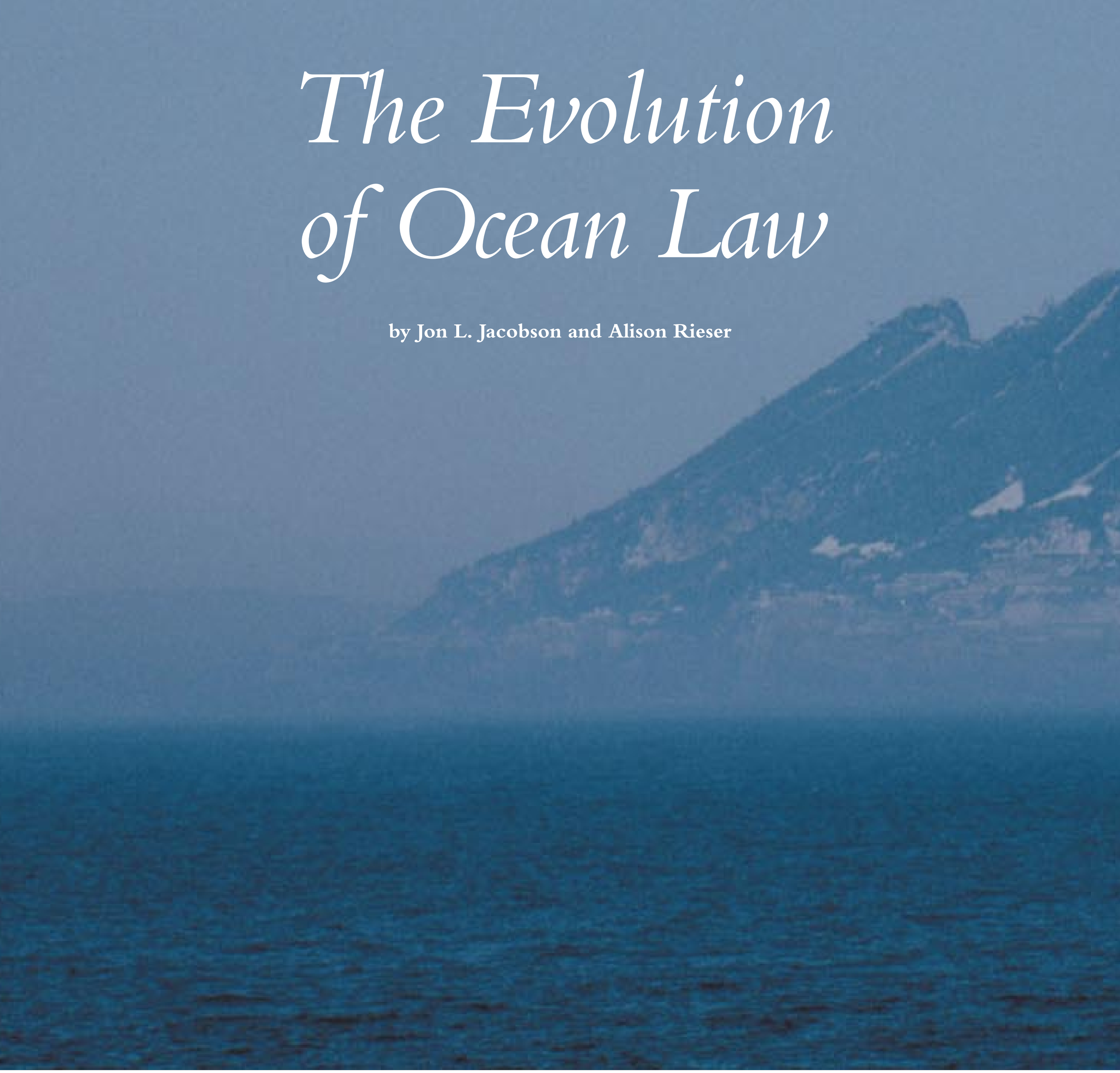
The Evolution of Ocean Law

by Jon L. Jacobson and Alison Rieser



Who owns the oceans? A quick glance at most maps of the world suggests that no one does. The oceans usually are depicted as an uninterrupted wash of pale blue, seemingly representing free seas subject to no nation's sovereignty or jurisdiction.

But this picture is inaccurate: it disregards the centuries-old political and legal struggles that have divided the oceans. To understand those tensions and the evolving international law of the sea, imagine instead an animated historical map of the world oceans in which one year whizzes by every four seconds.

In the early 17th century the waters appear calm, the seas a swath of undivided blue, while other colors battle for dominance over the continents. For the first 20 minutes (300 years), the oceanic parts of the map do not change much: only thin lines of fluttering color along the shores indicate national claims to the seas. When the map hits the mid-20th century, the waters suddenly explode in a fireworks display, starting at the coasts and expanding seaward. About two minutes later nearly 40 percent of the initial blue expanse is covered with many hues representing coastal nations. This final configuration reflects the oceans as they stand today.

The journey to establish this modern ocean geography has not been smooth sailing. Naval powers and coastal nations have fought to protect their watery domains and all the resources they contain—mineral and living, military and economic. Now, after decades of diplomacy, many

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In fits and starts, the international law of the sea has evolved to keep pace with the world's changing political, economic and environmental concerns

NARROW STRAITS, such as the outlet of the Mediterranean Sea near Gibraltar (*above*), contain important shipping lanes. But commerce was not the prime concern of the U.S. and the Soviet Union in the 1960s, when both opposed the extension of coastal nations' territorial seas into such choke points: these superpowers worried about interference with the navigation of their submarines.

JONATHAN BLAIR *Corbis*

nations have adopted an international law of the sea that outlines their rights and responsibilities regarding the use and management of the oceans. But whether agreement at the conference table means that cooperation will truly reign at sea remains an open question.

Free Seas

Scholars frequently mark the start of the era of free seas—the opening 20 minutes of running time on the imaginary animated map—with the 1609 publication of *Mare Liberum,* or "Free Seas." Written by Dutch jurist Hugo Grotius, the document supported the right of the Dutch East India Company to send its ships through seas claimed by Portugal. Grotius argued that the ocean was too wild to be occupied by nations and that its limitless resources made ownership absurd.

Although *Mare Liberum* itself did not necessarily spawn the age of free seas, its arguments were generally embraced by European nations that were pursuing profit and colonization throughout newly discovered regions. By the mid-17th century it was common practice for maritime nations to use the open ocean freely for the passage of vessels and for fishing.

The only widely recognized exception to the rule of free seas relates to the "territorial sea," a narrow offshore belt of national authority bordering the coast. By the 18th century the maximum breadth of this territorial sea, long subject to dispute, began to settle on a value of three nautical miles (around five kilometers). Although this measure has often been attributed to the distance that a land-based cannon could supposedly fire a ball, it is

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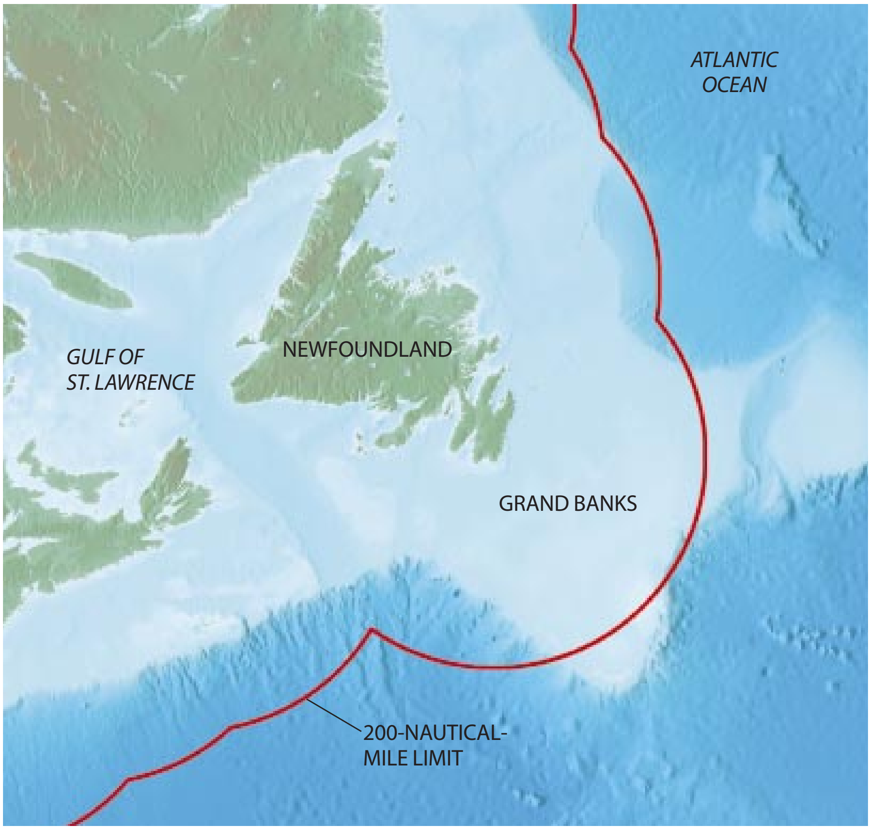


WILLIAM F. HAXBY

GRAND BANKS off Newfoundland, Canada, have historically provided rich fishing grounds. Although these fisheries are now largely depleted, the parts of these shallows that lie just beyond the limit of Canada's exclusive fishing zone (*red line on map*) once attracted distant-water fishing vessels from many countries.

probably based on the length of the English league.

Within the territorial sea, each coastal country had nearly complete authority over the waters and seabed—including living and mineral resources—and the airspace above. Foreign vessels on the surface were allowed the right of innocent passage—that is, movement that does not threaten the peace and security of coastal nations. Beyond these territorial seas, surface vessels and submarines were free to navigate the "high seas." Ships from all countries were also allowed to fish these blue waters. By the early 20th century even the newfangled flying machines were accorded the right to fly over this vast, unbounded area.

The 200-Mile Club

The era of the free seas survived three centuries and two world wars. Although the U.S. emerged from World War II as a global naval power with a consequent interest in preserving the broadest range of liberty on the seas, just weeks after the end of the war, America triggered a revolution in international law that led to the serious erosion of freedom of the seas.

In September 1945 President Harry Truman issued two proclamations pertaining to the oceans off U.S. coasts. One addressed the management of national fisheries beyond the territorial sea and the other, often referred to as *the* Truman Proclamation, claimed exclusive U.S. jurisdiction and control over the natural resources of the continental shelves adjacent to U.S. coasts—areas that, in many places, extended far beyond the outer limit of the three-mile territorial sea. This assertion of national authority was illegal, but it was quickly approved and emulated by the international community. The proclamation thus created a doctrine of customary international law that recognized the exclusive right of coastal nations to control and extract the natural resources of the continental shelves off their shores.

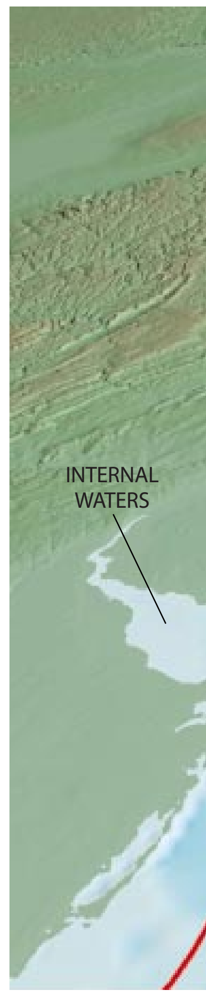
Although it championed the traditional freedoms of navigation, the Truman Proclamation initiated a reaction that eventually turned the old Grotian order into a shambles. Many factors fueled this historic overthrow. Perhaps the most important was the suspicion and resentment raised by technologically rich nations, including the Soviet Union and Japan, that used their distant-water fishing fleets to harvest fish from the high seas just offshore from many foreign lands. To protect their coastal fisheries, several countries extended their territorial seas to 12 nautical miles.

Others carried this trend of expansion much farther. In 1947 Chile and Peru each asserted national control over the resources of the ocean and the seabed out to 200 nautical miles from their coasts. And in 1952 Ecuador joined its southern neighbors and claimed its own 200-mile-wide zone. Despite protest from various seafaring nations and those with distant-water fishing fleets, the so-called 200-mile club gradually added to its membership, first from Latin America and then from Africa.

In the midst of growing confusion over the state of international ocean law, the United Nations convened the first two conferences on the "Law of the Sea" in Geneva. The first one, conducted in 1958, adopted four conventions designed to codify and establish a set of principles and rules for sharing the oceans of the world.

The package of conventions painted a rather traditional view of marine geography, with the waters divided into high seas, territorial seas and a contiguous zone—extending beyond the territorial sea for no more than 12 miles—within which coastal countries could exercise limited jurisdiction for customs control and other defensive actions. But the countries recognized a new continental shelf doctrine.

The delegations were unable, however, to agree on a rule establishing the maximum outer limit of the territorial sea. (A second conference, held in 1960, also failed to reach a consensus on this issue.) Certainly none of the 1958 Geneva conventions on ocean law endorsed anything as extreme as the 200-mile claims asserted by a growing number of coastal nations. Instead countries attending the conference agreed to promote cooperation between coastal countries and distant-water fishing nations in the conservation and management of fisheries. Unfortunately, none of the most important distant-water fishing nations chose to join this



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particular convention, preferring instead to enjoy the customary freedom to fish the high seas.

The Seabed Question

Despite the Geneva accords, national expansion into the seas continued apace. By the mid-1960s this trend became so alarming to the two main naval powers of the day, the U.S. and the Soviet Union, that these cold war adversaries began to plot together to hold back the expansionist tide. The U.S. and Soviet Union feared creeping jurisdiction—the prospect that nations making claims over fish and other natural resources might also try to interfere with navigation and overflight in broad areas. The U.S. was especially concerned that the extension of territorial seas would inhibit the passage of its ballistic-missile nuclear submarines—the main cold war deterrent to nuclear exchange with the U.S.S.R.—through such vital choke points as the straits of Gibraltar and Hormuz. The establishment of territorial seas even 12 miles wide would cause these and other straits to be blanketed by coastal waters in which, under traditional rules, submarines would be required to surface.

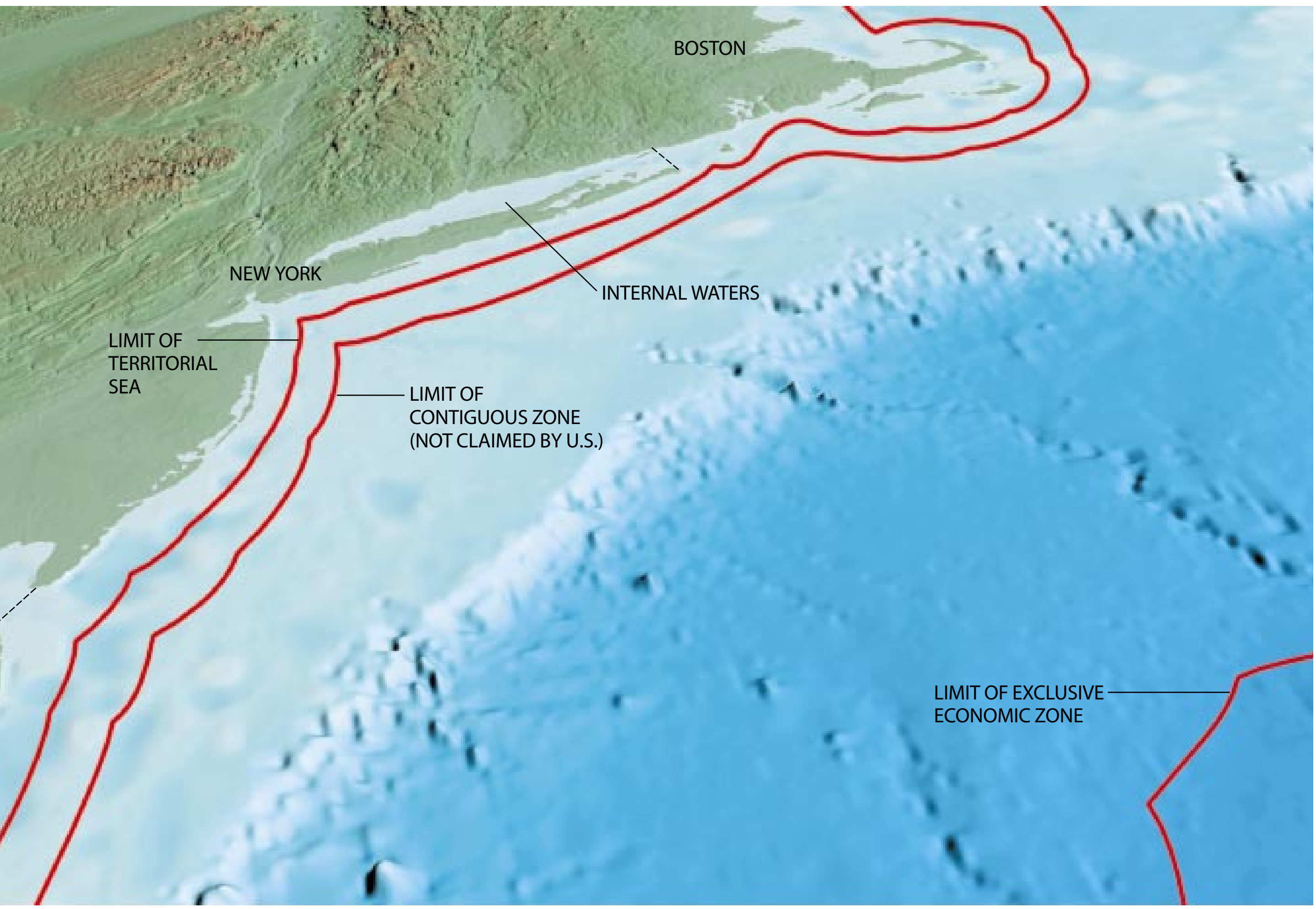
While the superpowers plotted, Ambassador Arvid Pardo of Malta addressed the delegates at the 1967 annual meeting of the U.N. General Assembly. He reminded the gathered members that recent investigations had shown that vast areas of the deep seabed—most beyond national jurisdiction—were literally paved with nodules containing valuable minerals, such as nickel, copper and manganese. Pardo urged the assembly to declare the deep ocean floor the "common heritage of mankind" and to see that its mineral wealth was distributed preferentially to the poorer countries of the global community. The General Assembly responded by adopting resolutions embodying Pardo's noble vision and calling for a new U.N. conference on the Law of the Sea.

The diplomats were charged to develop the concept of common heritage and to create a scheme for mining the seabed. But by the time the conference convened in New York City for its first session in 1973, its agenda had expanded to include nearly every conceivable use of the ocean, including fishing, navigation, protection of the marine environment and freedom of scientific research.

The New Map

The Third U.N. Conference on the Law of the Sea (dubbed UNCLOS III) was the most ambitious lawmaking endeavor ever undertaken by the interna-

OFFSHORE WATERS are divided by the 1982 United Nations Convention on the Law of the Sea into a territorial sea (which stretches 12 nautical miles from the coast), a contiguous zone (out to 24 miles) and an exclusive economic zone (to 200 miles). The convention also equated the minimum legal boundary of the continental shelf with the limit of the exclusive economic zone. Yet the physical continental shelf rarely extends that far, as can be seen in this map of the seafloor off the northeast coast of the U.S.



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LAURIE GRACE

NATIONAL GOVERNANCE ZONES surround every landmass on the earth except Antarctica. Most coastal nations claim the waters and seabed that lie within this area as their exclusive economic zone, within which they maintain exclusive control over the management of fisheries and other resources. Some nations claim these waters as fishing zones or as territorial seas.

tional community. In a series of sessions that spanned nearly a decade, diplomats juggled and balanced the multitude of interweaving and highly politicized maritime concerns of more than 150 nations. The major naval powers and those countries with distant-water fishing fleets vied with coastal nations, and potential seabed miners argued with developing countries over control of the seafloor. In the end, UNCLOS III generated a complex constitution that regulated all human activities on, over and under the 70 percent of the planet that is covered by seawater.

The resulting treaty—the 1982 U.N. Convention on the Law of the Sea—endorsed the authority of coastal nations to govern an array of maritime activities within an area up to 200 nautical miles from their shores. In their territorial seas, which were to extend no farther than 12 nautical miles from the coast, these nations would retain their traditional sovereignty over all activities and resources but allow the right of innocent passage for foreign ships. In addition, the convention established exclusive economic zones (EEZs) that extend beyond the territorial sea to the 200-mile limit. Within their EEZs, coastal nations would now have exclusive control over the management of fisheries and other resources, subject to international duties of conservation and of sharing "surplus" fish. These nations would also have extensive rights and jurisdiction concerning such activities as marine scientific research and the construction and operation of artificial islands.

The contiguous zone, first recognized in the 1958 Geneva conventions, was extended to 24 nautical miles from shore. Within this zone, which overlaps the EEZ for 12 miles beyond the territorial sea, a coastal nation is allowed to enforce its laws on customs, immigration, sanitation and fiscal matters.

The 1982 treaty also expanded the boundaries of the legal continental shelf. Coastal nations would now have the right to exploit the natural resources of the seabed and subsoil as far out as 200 miles—or even beyond, to the edge of the entire shelf, slope and rise of the physical continental margin. This right holds even when that margin extends beyond 200 nautical miles, as it does in several parts of the world.

The establishment of EEZs and the expanded definition of "continental shelf" constituted a major victory for the developing countries that formed the 200-mile club after World War II. The final impetus for global acceptance of the 200-mile zone, however, came not from UNCLOS III but from the U.S. Congress. In 1976 it established a 200-mile exclusive fishing zone for the U.S., causing a cascade of similar claims around the world. By the time the convention was adopted in 1982, the 200-mile concept had become customary international law.

The interests of the naval and maritime powers did not get subsumed in this process of national enclosure of the seas. These countries successfully negotiated for freedom of navigation and overflight within all EEZs. Moreover, the 1982 convention established a set of rules that would permit submarines to pass submerged through narrow straits, even those in which the waters consist only of territorial seas. Although the convention authorized island nations to designate the sea spaces within their island groups as "archipelagic waters," it granted foreign vessels and aircraft the freedom to navigate through them.

The convention also included many complex provisions on the marine environment. It expanded the rights of port nations and other coastal countries to

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guard against an influx of contaminants, and it declared that all countries would be responsible for protecting the marine environment from pollution, including that originating from sources on land.

In the end the 1982 U.N. Convention on the Law of the Sea was adopted in the General Assembly by a vote of 130 to 4 (with 17 abstentions), a stunning and unprecedented achievement for the community of nations.

U.S. Balks

Although the delegations had agreed on the treaty as a package deal, the U.S. objected to the provisions on mining the deep seabed. The delegates' attempt to actualize Ambassador Pardo's grand vision for sharing the common heritage of mankind had created a legal quagmire so controversial and massively complex that in 1982 the U.S. rejected the entire treaty.

The U.S. and other mining nations would have undoubtedly preferred that the convention establish a simple registry system that would limit overlapping mining operations. Part of the proceeds from mining the areas of the seabed that lie beyond national jurisdiction could then be deposited in a special fund to be distributed to the poorest countries of the world. Instead the 1982 convention established the International Seabed Authority, headquartered in Jamaica, to which mining nations would apply for a lease. Miners would have to pay substantial up-front fees and royalties to the special fund and provide the technology and financing for the International Seabed Authority to mine an economically similar site in parallel. American free-marketeers strongly objected to this scheme.

Instead of signing the Convention on the Law of the Sea, President Ronald Reagan declared that those parts of the treaty concerning traditional uses of the ocean—including rights of navigation and fishing—were consistent with the customary law and practice of nations. And in 1983 he issued a presidential proclamation that established a 200-mile EEZ within which the U.S. would exercise all the rights and responsibilities recognized in the convention and other international customary law. The U.S. could thus arguably take advantage of the legal protections that the treaty afforded without endorsing the convention. (In 1988 the U.S. extended its territorial sea from three to 12 miles.)

Because the U.S. opposed the seabed-mining provisions, it appeared for a time that the convention might never be ratified by the 60 countries needed to turn it into law. But by 1994 the U.N. secretary general had worked out a separate agreement on deep-seabed mining, effectively replacing the mining provisions that had so offended the U.S. delegates. President Bill Clinton subsequently sent the convention and the mining agreement to the Senate, where they currently remain awaiting approval. By that time, enough countries had ratified the convention to allow it to enter into force, at least for participating nations, in late 1994.

Fishery Storms

During the 1980s, while diplomatic attention was focused on the international control of deep-seabed minerals, a storm was gathering over the management of a much more significant marine resource: fisheries. Distant-water fishing fleets had responded to their exclusion from EEZs by perfecting techniques that would allow them to exploit the prized species that roam the high seas, where freedom to fish is still the rule.

Other fishing fleets opted to take advantage of places around the globe where valuable fish inhabited rich, productive waters just outside the 200-mile limit, such as parts of the Grand Banks off Newfoundland, Canada. They also homed in on coastal stocks of fish that swam through so-called doughnut holes, areas that are surrounded by but not part of EEZs.

Coastal nations whose stocks of fish were most vulnerable to these accidents of marine geography agreed that stronger international regulations were necessary. When discussions at the 1992 Earth Summit in Rio de Janeiro failed to resolve the issue, the U.N. General Assembly convened a new round of discussions to improve the management of high-seas fishing.

In March 1995, when the fish talks seemed stalled, a Canadian patrol boat arrested a Spanish trawler on the high seas for exceeding the internationally established quotas for the Grand Banks. This bold act signaled that at least one prominent coastal nation was willing to take the law into its own hands to protect the fish, even though the violation occurred outside the Canadian 200-mile limit and the forceful response threatened to undermine years of maritime diplomacy. Within a few months, the U.N. had adopted a new agreement on international fisheries to strengthen the standards by which nations collectively manage fishing on the high seas. That agreement, not yet in effect, calls for more careful setting of quotas for fish landings. Further, it allows coastal nations to inspect any vessel fishing on the high seas to ensure that it adheres to international regulations.

The effectiveness of this new agreement, and of the Law of the Sea in general, will depend on the willingness of many nations to be bound to its principles. We hope their commitment to international cooperation proves strong enough, even with few penalties and no high-seas police to enforce the rules. SA

The Authors

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Further Reading

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THE NEW LAW OF THE SEA. Edited by Christopher C. Joyner. Special double issue of *Ocean Development & International Law,* Vol. 27, pages 1–179; January–June 1996.

THE INTERNATIONAL LAW OF THE SEA. E. D. Brown. Dartmouth Publishing, 1994.

INTERNATIONAL FISHERIES LAW, OVERFISHING AND MARINE BIODIVERSITY. Alison Rieser in *Georgetown International Environmental Law Review,* Vol. 9, No. 2, pages 251–279; Winter 1997.

COASTAL OCEAN LAW. Third edition. Joseph Kalo, Richard Hildreth, Alison Rieser, Donna Christie and Jon L. Jacobson. West Publishing, 1998.

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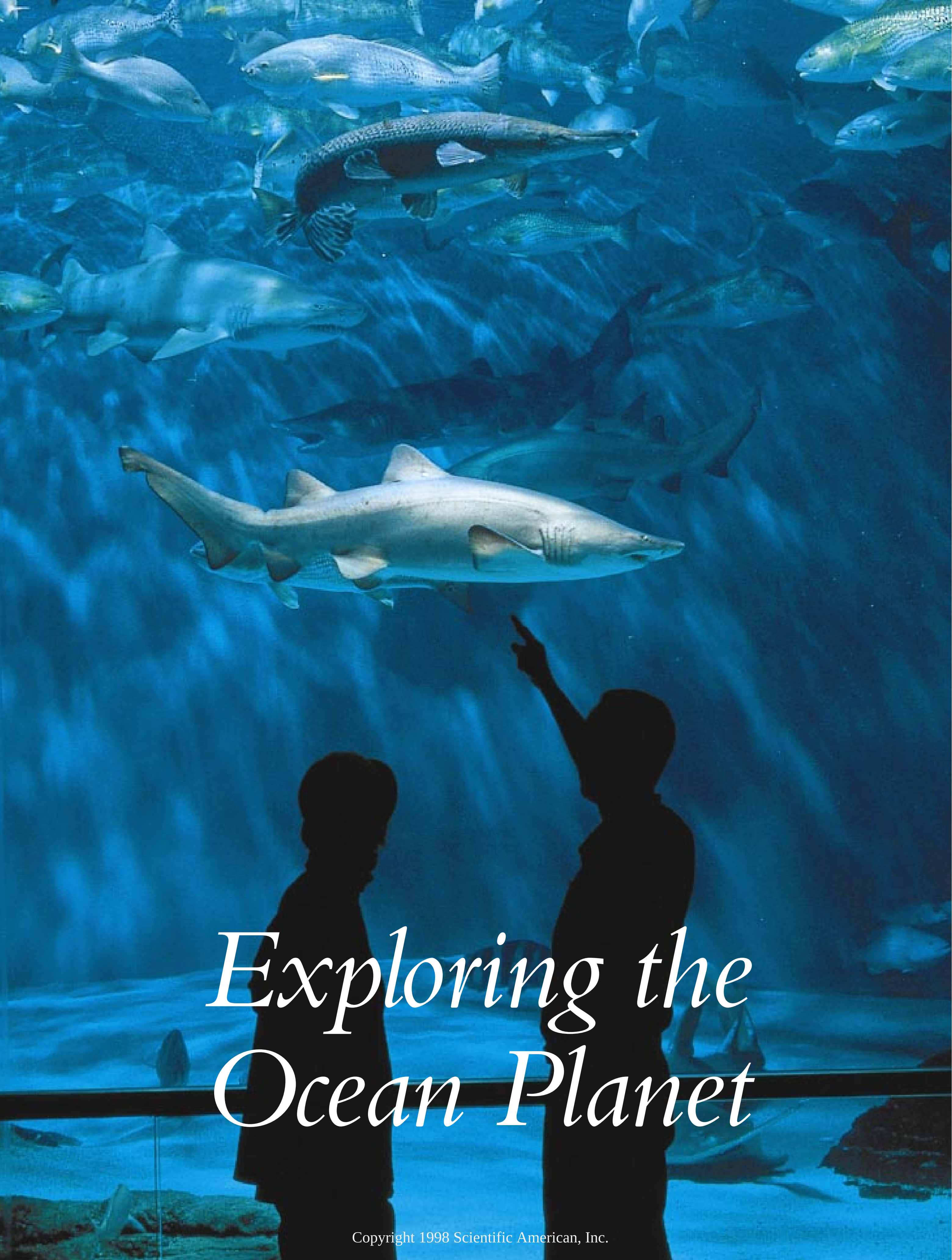

Exploring the Ocean Planet

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In this Year of the Ocean, the options range from visiting a maritime museum or aquarium to swimming with sharks, sleeping in an underwater hotel and visiting the Titanic

by Michael Menduno

With El Niño kicking up a storm and the motion picture *Titanic* setting box-office records, public awareness of the ocean may have reached an all-time high in 1998. But those whose knowledge about the marine realm comes mainly from television meteorologists and Hollywood are missing the boat (if you'll pardon the expression). The ocean is far more complicated, compelling, critical and—unfortunately—threatened than they may have been led to believe. A few alarming facts:

Bullfrog

TENNESSEE AQUARIUM

- Fifteen out of 17 of the largest fisheries on this planet are so heavily exploited that reproduction is not sustaining them.
- Sixty percent of the world's coral reefs, known as the rain forests of the ocean because they contain so much biodiversity, are threatened by pollution, sedimentation and bleaching (which is believed to be caused primarily by rising water temperatures).
- Two thirds of the world's population live within 60 kilometers (37 miles) of the coast (in the U.S., the proportion is just over 50 percent). As the global population swells toward six billion, pollution and coastal development are overloading ecosystems along vast stretches of shoreline. In the U.S. alone in 1996, these pressures led to more than 2,600 beach closings, 2,200 fishery advisories and dozens of documented "dead zones," in which large areas of ocean become largely and suddenly devoid of life.

"We have shown very little regard for the management of these resources," says Jean-Michel Cousteau, the California-based conservationist and filmmaker, who represented the U.S. at the EXPO '98 World's Fair in Lisbon. "We're gobbling up our capital instead of living off the interest." The exposition is the centerpiece of the United Nations's International Year of the Ocean observance, intended to raise public awareness and initiate the changes needed to sustain the marine environment. The problem is that despite a wealth of scientific information about the ocean, many, if not most, people remain unaware of the fundamental mechanisms at work in the sea.

What can you do? To borrow the slogan of promoters of the International Year of the Ocean: "Get into it!" Set aside a little time, whether next weekend or your next vacation, to do some exploring. The following pages offer a collection of unique adventures and links to help you and your family take the plunge.

Winnowing down the possibilities was no easy task. To come up with this list, I queried dozens of educators, tour operators, conservationists and adventurers for their recommendations and reviewed hundreds of brochures, World Wide Web sites, videos, CDs and trip reports. The result is an eclectic blend of offbeat experiences ranging from peering through the portals of a top-notch aquarium to descending almost four kilometers on board a Russian submarine to the deck of the *Titanic*—for a mere $32,500!

MARINE MENAGERIE (*opposite page*) mills about near a model of an offshore oil rig at the Aquarium of the Americas in New Orleans. Bullfrog (*above*) is part of the Discovery Falls gallery in the Tennessee Aquarium in Chattanooga, which has the most extensive freshwater exhibits in the U.S.

COURTESY OF THE AUDUBON INSTITUTE

Windows on the Underwater World

Nose-to-nose with about 100 circling sharks, tuna and toothy barracuda, the safety of the 17-meter-wide, seamless acrylic viewing wall—all that stands between me and mealtime—offers little comfort. I'm peering into a four-million-liter (one-million-gallon) indoor ocean, part of the new $57-million Outer Bay Exhibit at the Monterey Bay Aquarium in Monterey, Calif. Since it opened two years ago, the exhibit has enabled more than four million people to experience a world that few of them would otherwise have seen.

The Outer Bay display is an excellent example of how far aquariums have come since the 1960s, when aquarists seemed to be taking their cues from staid museum curators. Today, in a more competitive environment, aquariums are producing technologically sophisticated, Zen-like experiences unabashedly designed to provoke and amaze.

"There's something utterly primal about the direct contact," explains architect Peter Chermayeff, whose groundbreaking designs are redefining the aquarist's art. "To look a fish in the eye … is a spiritual experience," he says.

Last year more than 35 million visitors flocked to U.S. aquariums. And given numbers like that, some names more identified with entertainment than with education are getting involved. Believe it or not, Ripley's Believe It or Not just opened a new $43-million aquarium in Myrtle Beach, Fla., to the dismay of some purists. Like other institutions, aquariums are struggling to find the right balance of education and entertainment, to elucidate everything from the thought-provoking social relationships of big-brained cetaceans to the strange harems formed by transsexual reef fish called wrasses.

Take Chermayeff's latest creation, the Oceans Pavilion (now

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called Oceanarium) at EXPO '98. It presents the world as a single ocean by combining four distinct habitats: tropical corals, the Antarctic, a Pacific kelp forest and the rocky North Atlantic coast—one in each quadrant of a 5.3-million-liter wraparound tank containing more than 15,000 animals. "It may provoke controversy among those who say it isn't a strictly scientific presentation," admits Chermayeff, who explains that he strove to show "the unity of the world's oceans."

If you can't get to Lisbon, don't despair: there is probably a pretty good aquarium within reasonable driving distance. Choice destinations include California's Long Beach Aquarium of the Pacific, which opened this past June, and the National Aquarium in Baltimore, whose current killer exhibit is entitled *Venom: Striking Beauties.* And although landlocked Tennessee might not be the first place that springs to mind in this context, the Tennessee Aquarium in Chattanooga has perhaps the country's best exhibits on freshwater ecosystems. In Mystic, Conn., the Mystic Aquarium has already attracted attention with a planned deep-sea exploration exhibit that will open next year.

Of course, aquariums aren't the only windows on the underwater world. Filmed with dual cameras enclosed in a single, 408-kilogram waterproof housing, IMAX 3-D is the closest you'll come to a diver's-eye view without actually getting wet. To date, 10 underwater IMAX films have been produced, featuring subjects such as great white sharks, the migration of whales and the majestic underwater kelp forests of southern California. The most recent, *Dolphins—The Ride,* filmed by Bob Talbot of *Free Willy* fame, will take you on a dizzying undersea ride with a pair of Atlantic bottlenose dolphins.

Time and Tide

Less flashy perhaps than a cinematic dolphin ride, but no less stirring to the historically inclined, are the treasures on view at a first-rate maritime museum. As a group, these institutions chronicle our heritage as a seafaring nation and serve as time capsules for great voyages of trade and discovery, epic sea battles and the development of maritime technology.

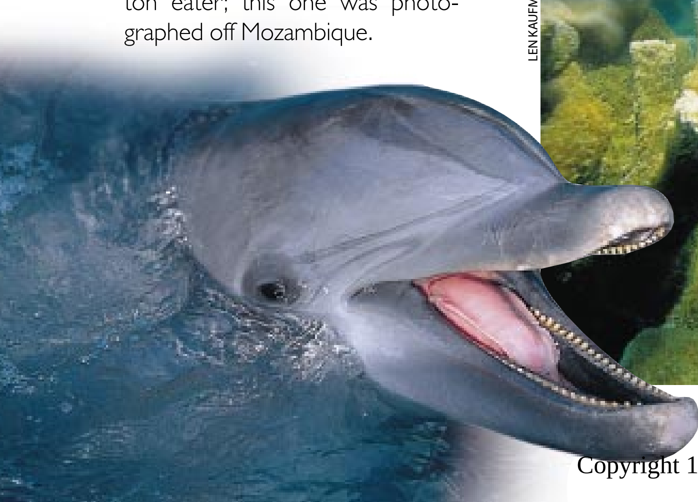
More than 100 maritime museums are scattered throughout the U.S. seaboards and around the Great Lakes. Most of them are small and built around a single collection or historical event as an outgrowth of community or family interest. Notable larger museums include Independence Seaport Museum in Philadelphia, which specializes in turn-of-the-century industrial maritime and Delaware River history; the Mariner's Museum in Newport News, Va., featuring one of the largest general-interest maritime collections in the world; Mystic Seaport, which is home to a 65,000-volume research library and a unique seven-hectare re-creation of a working 19th-century Connecticut village; and the San Francisco Maritime National Historical Park, which includes nine historical ships, several exhibits and an extensive research library. And don't miss the Bay Model Visitor Center in nearby Sausalito. The center showcases an indoor 6,100-square-meter, computer-controlled hydraulic model of the San Francisco Bay and surrounding waterways, which runs through a complete tidal cycle every 15 minutes.

Whales and Other Marine Mammals

Although the U.S. whaling industry is now the stuff of maritime history, whale-watching is a burgeoning enterprise, one that brings in an estimated half a billion dollars a year worldwide. This segment of adventure tourism was nurtured significantly by the passage of the Marine Mammal Protection Act of 1972, which outlawed the killing of cetaceans and protected other mammals in the territorial waters of the U.S. "Keeping whales alive is more economically beneficial than killing them," says Greenpeace co-founder Paul Watson, now president of the Sea Shepherd Conservation Society in Marina del

DOLPHIN (*below*) is the main attraction at the Dolphin Quest program at resort hotels. The underwater trail (*right*) at Trunk Bay, off St. John in the U.S. Virgin Islands, was one of the first in the world and has been so heavily trafficked that most of the coral has suffered. The underwater IMAX 3-D camera (*above right*) weighs more than 400 kilograms on land and requires two skilled operators. The whale shark (*top right*) is a gentle plankton eater; this one was photographed off Mozambique.

LEN KAUFMAN *Dolphin Quest (below);* JOHN BROOKS *U.S. National Park Service (right)*



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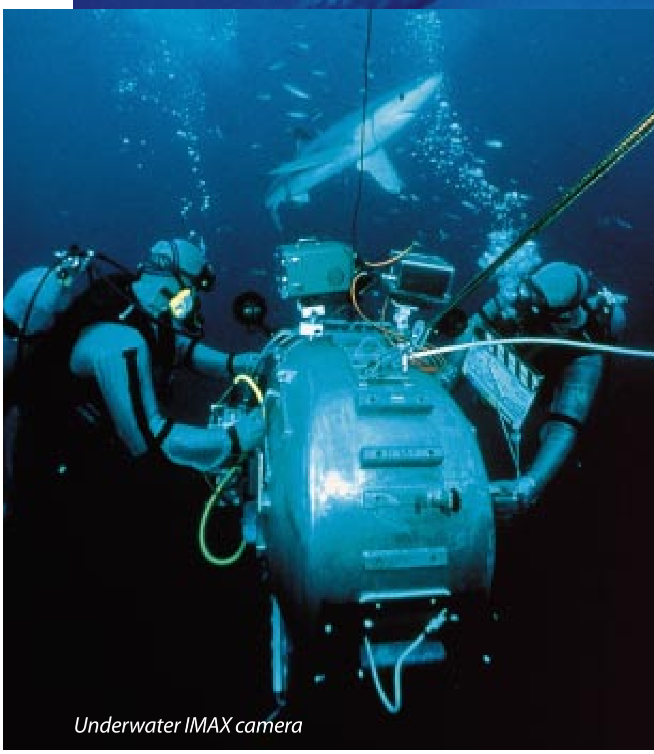
Whale shark

PAUL A. SUTHERLAND *Other World Images*



Underwater IMAX camera

TOM CAMPBELL *ANM/Imax Corporation*

Rey, Calif. If you live near a coast, you don't have to go far to encounter one of these magnificent leviathans. Information on whale watching is available through a site maintained at the University of Helsinki in Finland (see URL list on the next page).

For more in-depth encounters with whales and other marine mammals, naturalist-led tours are the way to go. Founded in 1972, Oceanic Society Expeditions in San Francisco offers more than 30 guided natural-history and research expeditions to observe whales, dolphins and manatees in habitats ranging from Florida's Crystal River Refuge to South America's Patagonia.

Intimate encounters with wild dolphins are the specialty of a small outfit in Cayucos, Calif., which conducts six-person, six-day trips for $1,700 a person. The trips, led by writer and naturalist Carlos Eyles, depart from Miami Beach, cruising to the dolphin grounds 80 kilometers off Grand Bahama. Participants eat and sleep on board the boat, spending up to five days swimming and cavorting with small groups of wild Atlantic spotted dolphins.

You can also encounter a dolphin without leaving your hotel. Dolphin Quest in Middleburg, Va., operates three dolphin research facilities at resort hotels in French Polynesia, Hawaii and Bermuda that feature interactive programs. Their latest arena, a $1.6-million, 1.2-hectare habitat at the Southampton Princess resort in Bermuda, offers daily personal encounters with these captivating creatures.

If you're in the western U.S., it's not even necessary to go to an island to learn about dolphins. Las Vegas might seem like the last place you would go for enlightenment about cetaceans (or anything else), but the Mirage Hotel houses a 9.5-million-liter dolphin facility where naturalists conduct daily tours and lectures.

Encounters of the Frenzied Kind

Those who crave higher adrenaline levels may get their fix by participating in an activity often portrayed as the ultimate in undersea excitement: the shark dive. To get the full effect, you'll need to be scuba-certified.

My first shark dive, in the summer of 1987, took place off southern California's Channel Islands. The crew lowered a "chum box" full of ground mackerel over the transom, and we waited about 20 minutes before the arrival of the first blue shark. Before long, half a dozen fins were slicing through the water. Our dinner guests had arrived, and it was time to lower the steel shark cage into the water.

The door to the cage was located below the water (who designed this thing?), requiring those of us who were going to occupy it to make a leap of faith. I took a deep breath through my scuba regulator, eyed the circling fins one last time and made a giant stride off the boat. I swam into the cage alongside our guide, who wielded a piece of pipe to keep the sharks at a distance.

I can assure you that watching from the safety of a cage as a dozen hungry sharks tear into chunks of chum will give you a fresh new perspective on food-chain dy-

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namics. There are a number of dive operators more than willing to help you in your quest for this kind of awakening.

Snorkle with Sharks

Cruising off the Channel Islands, Hydrosphere in Pacific Palisades, Calif., specializes in shark and marine encounters for nondivers. A two-and-a-half-day trip, including food, lodging and one dive, costs $259; bring your own mask, fins and snorkel. Certified divers can get closer to the fray on the three- to five-day excursions led by San Diego Shark Expeditions. Priced at about $300 a day, trips range from the Channel Islands and Costa Rica in the Americas to a great white shark expedition off the coast of South Africa. Mike Ball Dive Expeditions in Townaville, Australia, also conducts five- to eight-day great white shark trips led by naturalist Rodney Fox at a cost of $2,800–$4,160, excluding airfare.

There are also opportunities for those who want to do more than just watch during their wildlife encounters. Conservation-minded expeditioners will find a wealth of ongoing research programs in which they can take an active role.

The Shark Research Institute in Princeton, N.J., operates a worldwide tagging program for whale sharks designed to help scientists learn more about these gentle, plankton-eating giants, which can reach 20 meters in length. In recent years, whale sharks have come under pressure from Asian fishers who hunt them for their fins and to make fertilizer out of their remains. The program is dependent on volunteer sport divers and snorkelers who tag the sharks and take DNA samples. The information is used to investigate their reproductive habits and migration patterns and to devise and implement effective conservation measures.

Activist-minded volunteers are also needed at the Sea Shepherd Conservation Society. Formed in 1977, the society investigates and enforces international laws and agreements that protect marine wildlife. Its fall campaign seeks to prevent the Makah Indians from killing gray whales in the Olympic National Marine Sanctuary. Under an 1855 treaty, the Washington State–based tribe is exempt from a federal regulation prohibiting whaling and is reportedly planning to begin its hunt in October.

Coral reefs are also being threatened. Experts estimate as much as 36 percent of the world's hard corals have been destroyed over the past 40 years. Coral Cay Conservation in London conducts year-round, two- to 12-week working eco-expeditions to help protect endangered coral reefs and coastal rain forests in Belize, Indonesia, Australia and the Philippines. In the U.S., interested community groups and dive clubs can help restore the reefs through the assistance of the Reef Ball Development Group in Sarasota, Fla.

Immerse Yourself

Although the beauty of a coral reef is apparent to anyone who has been snorkeling on one, to appreciate the splendor of these complex ecosystems fully, you will need to be scuba-certified. A typical course, which costs several hundred dollars, includes a series of classroom sessions and supervised dives. Home-study multimedia materials such as CD-ROMs and videos

Exploring the Ocean Planet: Links

International Year of the Ocean (IYO)
United States IYO: 888-4YOTO98 or www.yoto98.noaa.gov
United Nations IYO: http://ioc.unesco.org/iyo
American Oceans Campaign: 800-8-OCEAN-0 or www.americanoceans.org
U.S. National Park Service: 505-988-6750 or www.nps.gov/scru/home.htm
National Marine Sanctuaries: 301-713-3145 or www.nos.noaa.gov/ocrm/nmsp
Ocean 98: www.ocean98.org/ocean98.html

Aquariums
Aquarium links: www.aza.org
Aquarium of the Americas: 800-774-7394 or www.auduboninstitute.org
Long Beach Aquarium of the Pacific: 562-590-3100 or www.aquariumofpacific.org
Monterey Bay Aquarium: 408-648-4800 or www.mbayaq.org
Mystic Aquarium: 860-572-5955 or www.mysticaquarium.org
National Aquarium in Baltimore: 410-576-3800 or www.aqua.org
New England Aquarium: 617-973-5200 or www.neaq.org
Oceans Pavilion: www.expo98.pt/en/pavoceanos.html
Tennessee Aquarium: 423-266-3467 or www.tennis.org
IMAX: www.imax.com

Museums
Bay Model Visitor Center: 415-332-3871
Independence Seaport Museum: 215-925-5439 or www.scat.temple.edu/seaport
The Mariners' Museum: 757-596-2222 or www.mariner.org
Museum of Man in the Sea: 850-235-4101
Mystic Seaport: 860-572-5315 or www.mysticseaport.org
San Francisco Maritime National Historical Park: 415-556-3002 or www.maritime.org
Graveyard of the Atlantic: 919-986-2995
Maritime museum links: www.bobhudson.com/Smiths/index.html and http://pc-78-120.udac.se:8001/www/Nautica/Pointers/Museums.html

Reefs
Coral Cay Conservation: 44-171-498-6248 or www.coralcay.org
Reef Ball Development Group: 941-752-0169 or www.reefball.com
Reef education guide/links: www.reef.org
Project AWARE: 714-540-0251 or www.projectaware.org

Scuba Diving
NAUI: 813-628-6284 or www.naui.org
PADI: 800-729-7234 or www.padi.com
SSI: 970-482-0883 or www.ssiusa.com
YMCA: 770-662-5172 or www.ymcascuba.org

Sharks
Great white shark stories: www.greendivers.com
Hydrosphere expeditions: 310-230-3334 or www.hydrosphere-expedition.com
Mike Ball Dive Expeditions: 888-MIKEBALL or www.mikeball.com/great_white.html
San Diego Shark Diving Expeditions: 888-SDSHARK or www.sdsharkdiving.com
Shark bytes and links: www.sharkbites.com
Shark Research Institute: 609-921-3522 or www.sharks.org
Stuart Cove's Dive South Ocean: www.stuartcove.com

Submersibles, habitats and space
Aquarius undersea habitat: www.uncwil.edu/nurc/aquarius
Atlantis Submarines: 888-732-5782 or www.goatlantis.com
Clips of deep-sea vents: www.pmel.noaa.gov/vents/geology/video.html
Jules' Undersea Lodge: 305-451-2353 or www.jul.com
Ocean from space: http://eospso.gsfc.nasa.gov/eos_homepage/images.html
U.S. submarine tourist information: http://ussubs.com
Zegrahm DeepSea Voyages: 888-772-2366 or www.deepseavoyages.com

Whales, dolphins and manatees
American Cetacean Society: www.acsonline.org
Dolphin Quest: 540-687-5958 or www.dolphinquest.org
Manatees: www.wwclyde.com/manateejunction and www.adventurequest.com/adven/nature.htm
Mirage Hotel: 800-627-6667 or www.mirage.com
Oceanic Society Expeditions: 800-326-7491 or www.oceanic-society.org
Sea Shepherd Conservation Society: 310-301-7325 or www.seashepherd.org
Whaleclub: www.whaleclub.com
Wildquest: 800-326-1618 or www.wildquest.com
World Wide Web Virtual Library—Whalewatching: www.physics.helsinki.fi/whale

Youth
ExploraMar: 415-389-6644 or www.exploramar.com
JASON Project: www.jasonproject.org
Jean-Michel Cousteau Institute: 805-899-8899
Outward Bound: 914-424-4000 or www.outwardbound.org
School for Field Studies: 978-927-7777 or www.fieldstudies.org
Sea Education Association: 800-552-3633 or www.sea.edu

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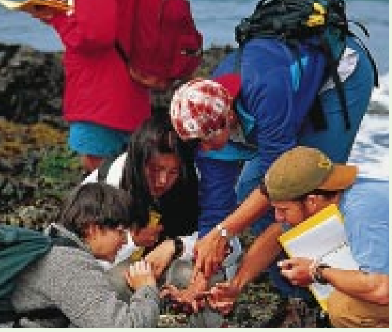

DAVID SILVERBERG

STUDENTS get their feet wet at the School for Field Studies in Beverly, Mass.

For the Young

"Young people are the hope of tomorrow," says Jean-Michel Cousteau, who represented the U.S. at the EXPO '98 World's Fair. His foundation, the Jean-Michel Cousteau Institute in Santa Barbara, Calif., specifically focuses on exposing young people to the ocean realm. "It's faster that way. The decision makers who are running the show have no time."

The institute hosts a series of marine education programs, including a family camp on the island of Catalina off San Pedro, Calif., a snorkeling discovery trip in the Bahamas, Project Ocean Search and an annual gray whale expedition off Baja California.

ExploraMar in Mill Valley, Calif., offers a 12-day, $2,400 marine biology sailing program for teens ages 13 to 17 in the Gulf of California on board a 15-meter sailing yacht. Environmental stewardship, survival skills, sailing and sea kayaking are part of the curriculum at Outward Bound in Garrison, N.Y., which conducts a variety of one- to four-week programs on both coasts priced between $80 and $110 a day.

Students interested in expanding their environmental education should contact the School for Field Studies in Beverly, Mass. Founded in 1980, the school conducts college-accredited semester and summer field-study programs in places such as Mexico, the British West Indies and Pacific Northwest Canada designed to provide hands-on environmental training. The Sea Education Association in Woods Hole, Mass., also offers semester and summer interdisciplinary ocean-studies programs. After completing six weeks of classwork, students head for the open sea on board one of the association's tall ships—the *Westward* and the *Corwith Cramer*—to conduct ocean research. Financial aid is available for both programs. —*M.M.*

are also available. Another way is to complete the classroom part locally and then travel to a tropical destination for the required open-water dives. Most dive destinations offer a one-day Discover Scuba program, complete with a closely supervised diving experience that will let you get your feet wet but won't conclude with the awarding of a certification ("C") card, which would enable you to go on escorted dives, rent gear and fill air tanks.

There are dozens of agencies that provide dive training and can help you with dive travel. The four largest in the U.S. are the National Association of Underwater Instructors (NAUI) in Tampa, Fla.; the Professional Association of Diving Instructors (PADI) in Santa Ana, Calif.; Scuba Schools International (SSI) in Fort Collins, Colo.; and the YMCA Scuba Program in Norcross, Ga.

Once you're certified, the more than 800,000 hectares of underwater parks managed by the U.S. National Park Service can become your playground. A description of the parks and their diverse ranges of habitats, which include coral reefs, kelp forests, historical shipwrecks and underwater caves, is detailed in a new 344-page guidebook, *Underwater Wonders of the National Park System,* by Daniel J. Lenihan and John D. Brooks (Random House, $19.95). The U.S. National Oceanic and Atmospheric Administration also manages 12 National Marine Sanctuaries encompassing 4.7 million hectares and offers a variety of discovery programs in partnership with local organizations.

As a recreational scuba diver you will, with experience, be qualified to dive as deep as 39 meters. It is unlikely that you'll run out of things to see at these depths, within which live almost all the world's hard corals and most of its reef life. Nevertheless, there are options for going even deeper: more advanced ("technical") dive training or submersible craft. Of the two, the submersibles will expose you to less personal risk.

Once accessible only to research scientists and filmmakers, deep-sea submersibles are now being operated by adventure travel companies to provide unique educational experiences. Zegrahm DeepSea Voyages in Seattle is kicking off its 1998–1999 expedition series with a 3,800-meter dive to the *Titanic* on board the two Russian *Mir* submersibles used by James Cameron to film his blockbuster motion picture. The roundtrip fare is $32,500 a person.

Subsequent expeditions, priced from $4,000 to $10,000, will take well-to-do adventurers to the wreck of the HMS *Breadalbane* 107 meters beneath Canadian Arctic ice or on a search for nine-meter six-gilled sharks inhabiting the seafloor 200 meters down off Vancouver Island. Also planned is a series of dives to the deep-sea vents off the coast of Mexico.

Submariners on a budget can take the plunge with Atlantis Submarines in Vancouver, which operates a total of 14 tourist submarines in the Caribbean, Mexico, Hawaii and Guam. Priced at around $60 for an hourlong dive, these smallish subs (which carry from 28 to 64 people) are rated to 46 meters and offer large viewing ports and lectures by specialists on marine ecosystems. The company also operates a two-passenger submersible that makes 300-meter dives off Grand Cayman in the Caribbean.

Years ago when someone suggested that you might be sleeping with the fishes, it was cause for alarm. Today, if you're a certified diver, it can be something to look forward to. What is it like to be on the other side of the aquarium glass, to wake up and see a parrot fish peering *in* at you? You can find out for as little as $175 a night. Jules' Undersea Lodge, operated by Key Largo Undersea Park in Florida, sleeps groups up to six and offers amenities that you might not expect from a nine-meter-deep, converted research habitat. Gourmet meals, air conditioning, hot showers, cable television and even Internet access are all part of the package.

If any of these journeys have piqued your interest, by all means log on to the Internet (use the URL list on page 110 to get started), talk to friends or your travel agent, or visit a library. There are myriad other adventures besides the ones described in this tiny sampling. Any one of them could change your worldview.

Having explored the ocean all his life, Jean-Michel Cousteau explains it this way: "The second you put your head underwater, you become a different person. Some transformation takes place. It goes beyond just having a good time. You end up becoming an ambassador."

Use this newfound status wisely. The future of the oceans may depend on it. SA

The Author

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